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On-orbit servicing as a future accelerator for small satellites



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Currently valued at around \$600 billion, the space economy is expected to reach \$1.8 trillion by 2035, with vital terrestrial systems increasingly dependent on space infrastructure. Growth is largely driven by the rising deployment of small and medium satellites in low Earth orbit (LEO), yet most are single-use and quickly decommissioned after failure, contributing to orbital debris and challenging sustainability. This article examines opportunities and challenges in developing orbital servicing infrastructure for small satellites, highlighting how such technologies can extend operational lifetimes, reduce replacement costs and enhance the reliability of future constellations, supporting the long-term development of the LEO space economy.

At the small satellite scale^{1,2}, rapid miniaturisation of sensors^{3,4}, processors⁵ and propulsion technologies^{6,7}, including the electric propulsion platforms^{8,9}, have propelled an era of highly capable small and medium satellites¹⁰ that can perform tasks once reserved for much larger satellite platforms¹¹. As manufacturers push capabilities into ever-smaller form factors, design emphasis must shift from mere functionality to long-term reliability, maintainability and modularity^{12,13}. Robust systems engineering, standardised interfaces, on-orbit upgradeability and fault-tolerant software¹⁴ will be essential if these satellites are to deliver continuous service across multi-year missions rather than being treated as short-lived throwaway assets¹⁵.

However, we should first define the term ‘small satellite’ (SmallSat), recognising that definitions vary across communities and that this choice affects classification, regulation and comparative analysis. Industry trackers such as BryceTech often adopt a pragmatic cutoff of ‘below 1200 kg at launch’ to capture the commercial market and simplify reporting¹⁶. Regulators and certification bodies use tiered mass class schemes that split vehicles into categories for licensing and safety, so a platform termed a SmallSat in market reports may fall into a specific regulatory class¹⁷. Technical and academic taxonomies use finer bins tied to form factor and engineering practice, for example, CubeSats, nanosats, microsats and minisats, with ‘SmallSat’ serving as an umbrella term that overlaps those bins¹⁸. These differences affect licensing, launch manifesting, insurance, standards and comparative statistics¹⁹. For clarity and reproducibility, state the working definition up front, for example, here we follow BryceTech’s convention and define small satellites as launch mass ≤ 1200 kg, and note alternative

regulatory and technical schemes. The accompanying Table 1 maps common mass classes to these labels for reader reference.

Over the last decade, the number of small and medium satellites in near-Earth environment has grown rapidly, with the number of satellites in LEO increased by 127 times in five years²⁰. Starlink has already reached tens of thousands. Other projects also plan launches in the hundreds or thousands. As of 20 October 2025, SpaceX has launched more than 10,000 Starlink satellites²¹. Current on-orbit counts are lower than total launches, and independent trackers estimate roughly 8500–8700 Starlink satellites presently in orbit²². This explosive increase in near-Earth small and medium satellite population intensifies orbital congestion, raises collision and debris risk and places an increasing load on tracking and regulatory systems.

Replacing failed or end-of-life satellites at scale imposes steep recurring costs on operators and national budgets, particularly for constellations that number in the thousands. Furthermore, their disposal via de-orbiting and burning in the Earth’s atmosphere raises significant environmental concerns, with 29 tons of satellites projected to re-enter the atmosphere per day²³ and the rocket launches to maintain these constellations estimated to release soot in the atmosphere equivalent to 7 million diesel dump trucks. Rather than accepting this increasingly high cost of disposal and replacement, investing in on-orbit servicing infrastructure offers a strategic alternative: life-extension through refuelling, repair and module replacement reduces launch cadence, lowers capex over constellation lifetimes and improves resiliency against single-point failures. For commercial and government constellations alike, a mature servicing ecosystem converts replacement costs into lower incremental maintenance expenditures and enables more sustainable, upgradeable satellite architectures.

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We stress here that the primary focus of this paper is on LEO constellations, with geostationary Earth orbit (GEO) operations mentioned sometimes only for comparative purposes, and thus the aim of the manuscript aligns with this principal scope as outlined in Table 2. Many satellites in these constellations fall below the 1200 kg threshold commonly used to define small satellites (SmallSats), and this classification underpins several of our cost and operational arguments as noted in Table 1. Servicing large and expensive satellites could deliver substantial savings, redirecting the resources towards the development, deployment and operation of more advanced platforms. For example, prolonging the service life of satellites

used for long-range television communications, Earth and ocean observation and other purposes would be highly cost-effective²⁴.

The large number of increasingly capable satellites, together with advances in space-grade materials and technologies, creates favourable conditions for developing on-orbit servicing infrastructure, particularly for medium-mass, moderately complex spacecraft that carry relatively expensive payloads and require life-extension through refuelling, repair, or replacement of consumables.

Satellites—do we have many to service?

The sheer scale and accelerating cadence of small- and medium-size satellite deployments mean this question is no longer rhetorical as there are now thousands of operative spacecraft in LEO and many more planned, spanning diverse missions and architectures (Table 2). The following table summarises the largest and most relevant constellations, their planned scales and current deployment status to understand where on-orbit demand for servicing infrastructure will be concentrated.

The variety of already launched constellations and satellites (Table 2), spanning different sizes, orbital regimes, payload types²⁵ and construction materials, implies a correspondingly diverse set of servicing needs: refuelling, repair, module replacement and on-orbit upgrades. With tens of thousands of satellites either already in orbit or planned, the potential servicing demand is large and geographically dispersed, requiring architectures that scale across mass classes, orbits, and thermal/structural constraints. We therefore need to define core principles for orbital-servicing architectures: modular, service-ready satellite designs; standardised mechanical and electrical interfaces; compatible rendezvous and grappling aids; and supply/logistics layers that support in-situ fabrication and repair. Where this article focuses primarily on key considerations and guiding principles for the design of such architectures, coordinated efforts and significant investment from the stakeholders will be necessary to achieve measurable progress in this area.

Table 1 | Common satellite mass classes and corresponding labels¹⁶.

	Mass class name	Kilograms (kg)
SmallSats	Femto	0.01–0.09
	Pico	0.1–1
	Nano	1.1–10
	Micro	11–200
	Mini	201–600
	Small	601–1200
Other spacecraft	Medium	1201–2500
	Intermediate	2501–4200
	Large	4201–5400
	Heavy	5401–7000
	Extra heavy	>7001

Mass ranges are given as launch mass and map femto, pico, nanosat, micro, mini and small labels, among other classes, to the industry and regulatory classes.

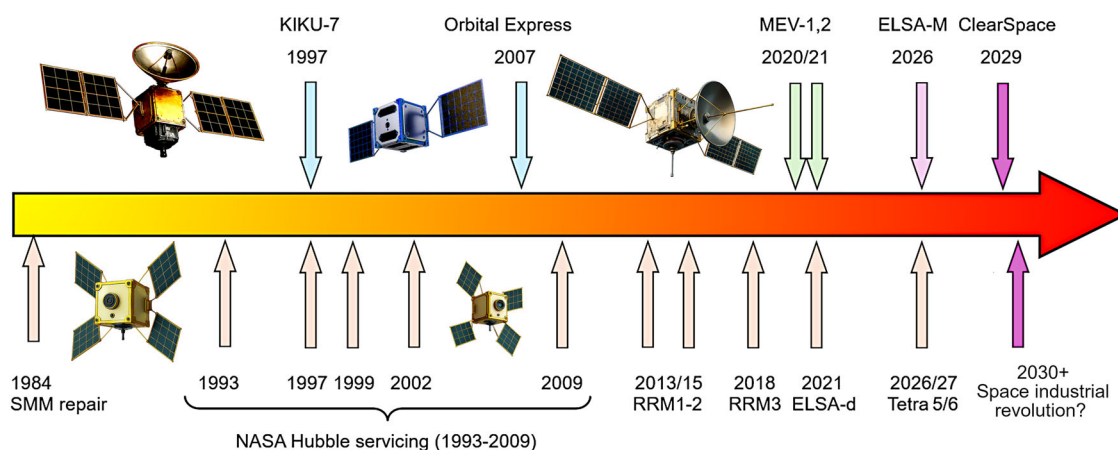
Table 2 | Major large satellite constellations — latest counts and status

Constellation	Planned/nominal size	Latest status (deployment)	Refs.
Starlink (SpaceX)	12,000+ approved; 42,000 potentially in long-term perspective	Passed 10,000th Starlink satellite launched in Oct 2025; active deployment continues	97
Project Kuiper (Amazon Kuiper)	~3200 planned (initial constellation)	Deployment started in April 2025; multiple launches underway	98
OneWeb LEO	About 650 (Phase 1 design)	Majority of Phase-1 satellites are launched and operational	99
Guowang (satellite internet series satellites)	About 6000	127 satellites at LEO and 3 satellites at high orbit	100
Qianfan (Spacesail constellation/ G60 Starlink)	15,000 internet satellites 1296 satellites in the first phase	About 120 operational satellites	101
Geespace	240 planned	Over 60 operational satellites	102
Telesat lightspeed	198 (1600 was initially planned, reduced from the earlier 298)	Launches with SpaceX in late 2026. Development and phased deployment plans; prototype activity ongoing	103
Galileo (GNS System through the ESA)	27 satellites in service, 30 satellites launched	12 planned (Galileo second generation)	104
IRIS ²	Infrastructure for Resilience, Interconnectivity and Security by Satellite—290 satellites	First launches expected in 2029, service in 2030	105
O3b mPOWER (SES)	Dozens (incremental MEO HTS constellation)	Multiple satellites launched and entering service; phased ramp of capacity	106
Iridium (Iridium NEXT/network)	~66 (operational crosslinked LEO constellation)	Replacement constellation completed previously; ongoing upgrades	107
Globalstar (next-gen)	Tens (replenishment programs)	Replacement/augmentation launches underway for Globalstar-2/Globalstar-3	108
AST SpaceMobile	Target: up to 60 by 2026 (initial campaign)	Small-scale deployments and business updates through 2025	109

The principal large satellite constellations with their most recently reported satellite counts and a concise statement of operational status. The Table could serve as a reference point for assessing trends in constellation growth and operational readiness.

These figures are approximate and provided for reference only. Launch schedules, deployment plans and operator strategies change rapidly so constellation sizes can vary substantially over short periods. Major operators such as SpaceX conduct frequent batch launches and other providers revise plans, so report counts with retrieval date and source to indicate the snapshot in time. More comprehensive information could be found in the recent relevant publications available^{110,111}.

SIMPLIFIED ROADMAP FOR SATELLITE ON-ORBIT SERVICING



Scheme 1 | Simplified roadmap for satellite on-orbit servicing, showing key milestones from early crewed repairs (SMM, Hubble) through robotic demonstrations to anticipated commercial life-extension, refuelling and module-replacement services from 2026 onward, with a broader industrial revolution expected around 2030 as

routine servicing scales and transforms space operations. Images of satellites are artistic representations for illustration only. The yellow-to-red gradient along the arrow is purely decorative and does not encode quantitative information, with warmer red tones placed near the present to highlight temporal proximity.

Now that so many satellites already occupy Earth orbit, and orders of magnitude more are planned, the operational and logistical challenges span diverse mass classes, orbital regimes and mission lifetimes. To guide coordinated response, we present here a simplified roadmap summarising what has been demonstrated, what is planned and what is expected in the near term.

A diverse landscape of satellite constellations creates a complex pattern of servicing requirements that extend across multiple orbital regimes and technical domains. Meeting these demands will depend on scalable architectures that integrate modular design, standardised interfaces and reliable logistics.

Current status and roadmap of orbital servicing

This roadmap (Scheme 1) succinctly charts key dates and the principal features of on-orbit servicing systems, satellites and demonstrations; it highlights milestones for demonstrations, emerging commercial services and expected operational rollouts from 2026 onward. The reader can use the timeline to overview the progress and anticipations, to quickly see what has been flown, what is planned, and which capabilities to prioritise for near-term coordination and testing.

1984 (SMM repair)—Early milestone in orbital repair

The first on-orbit repair was carried out in 1984 by astronauts J. Hofton and G. Nelson during a Space Shuttle mission to service the Solar Maximum Mission (SMM) satellite (Fig. 1). That mission not only restored SMM's instruments but also proved the feasibility of complex orbital rendezvous and hands-on servicing, establishing techniques and confidence that underlie later robotic and commercial servicing efforts²⁶.

1993–2009: NASA Hubble Servicing

Between 1993 and 2009, five Space Shuttle missions—STS-61, STS-82, STS-103, STS-109 and STS-125 performed human-led repairs and upgrades on the Hubble Space Telescope, repeatedly restoring and enhancing its instruments and extending its scientific lifetime²⁷.

1997—KIKU-7

Launched in 1997, Japan's ETS-VII (KIKU-7) was the world's first satellite equipped with a robotic arm, designed to demonstrate rendezvous, docking and on-orbit manipulation technologies²⁸.



Fig. 1 | Image of the Solar Maximum Mission satellite, first repaired on orbit in 1984 by astronauts James van Hofton and George Nelson during a Space Shuttle servicing mission. The operation restored SMM's instruments and demonstrated complex rendezvous and hands-on servicing techniques that established confidence and methods later adopted by robotic and commercial on-orbit servicing efforts. Credit: NASA Marshall Space Flight Center (NASA-MSFC).

2007—Orbital Express

The Orbital Express program was developed to demonstrate an autonomous, cost-effective method for servicing satellites in orbit. It used a two-spacecraft architecture: ASTRO, the servicing vehicle and NEXTSat, a prototype modular, serviceable spacecraft designed to demonstrate refuelling, component exchange and autonomous operations²⁹.

2013/15 (RRM1-2)—The Robotic Refuelling Missions—Phase 1 and 2

The experiment suite included propellant valves, nozzles and seals used on many satellites, plus refuelling tools mountable on the distal end of the Dextre robotic arm. NASA completed the Phase 1 demonstration in January 2013, and subsequent Phase 2 experiments proceeded over several days, successfully validating the tools and on-orbit fluid-transfer and handling procedures³⁰.

2018 (RRM3)—The Robotic Refuelling Mission, Phase 3

The system was delivered to the station in 2018 and installed on ELC-1 module on December 2018. Zero-boil-off storage of methane was demonstrated for four months, but a subsequent cryocooler failure required the methane to be vented in April 2019, and the remaining tests were deferred³¹. 2020/21 (MEV1,2)—MEV Mission. MEV-1, launched in 2019 and docked with Intelsat 901 in 2020, was the first commercial mission to dock with an operational GEO satellite and provide life-extension services by taking over spacecraft attitude and station-keeping functions semi-autonomously. Its success validated the ‘satellite takeover’ operational model. The second vehicle MEV-2, replicated the capability with a 2021 docking³². We should note that Intelsat 901 is not a small satellite but a large geostationary communications platform with a launch mass exceeding 4700 kg and its mission is one of the earliest and most illustrative examples of on-orbit servicing, so it is mentioned here for that reason.

2021 (ELSA-d)—Astroscale ELSA-d Mission

ELSA-D comprised two stacked spacecraft launched together: a servicer and a client. The servicer was built to demonstrate safe debris-removal and rendezvous-and-proximity-operations technologies, using a magnetic docking mechanism and autonomous RPO capabilities to capture, stabilise and manipulate uncooperative objects in orbit³³.

2026/7 (Tetra 5/6)—Tetra 5 and Tetra 6

Planned demonstrations Tetra-5 and Tetra-6 will evaluate refuelling hardware from Astroscale, Northrop Grumman and Orbit Fab—three competitors in the emerging orbital-refuelling market. Originally conceived in 2022 as a single \$44.5 million experiment for 2025, the effort was split into two missions: Tetra-5, now scheduled for launch in 2026, and Tetra-6, planned for 2027³⁴.

2026—ELSA-M

Astroscale UK completed the Critical Design Review for its ELSA-M (End-of-Life by Astroscale Multiple) on-orbit demonstration spacecraft, clearing the way for final assembly and testing ahead of a planned 2026 launch. ELSA-M is designed as a commercial end-of-life removal service that will use a magnetic capture interface to remove prepared defunct satellites from LEO³⁵.

2029—ClearSpace-1

ClearSpace-1 is an ESA-backed debris removal mission led by Swiss startup ClearSpace SA, targeting the capture and removal of the defunct PROBA-1 satellite. The mission will demonstrate autonomous rendezvous, capture and controlled deorbit technologies for end-of-life spacecraft, with a planned destructive reentry that will dispose of both the target and the chaser. Launch is currently expected in 2029³⁶.

2030+—Space Industrial Revolution?

We expect that in 2030, the on-orbit servicing will shift space into an industrial, service-based economy where satellites are maintained, upgraded and repurposed instead of replaced. By 2030 and after, routine refuelling, repairs and module swaps will cut lifecycle costs, accelerate capability refresh, and make constellations more resilient to failures and geopolitical shocks. A robust commercial servicing ecosystem—tugs, repair platforms, logistics hubs, and standards for interoperability will enable rapid recovery and flexible responses to emerging needs³⁷. The European on-orbit servicing market alone is projected to exceed \$5 billion by 2030, growing at about 11.5% per year, underscoring the sector’s economic and strategic momentum. Economic projections and early demonstrations indicate the sector will scale rapidly, turning one-off missions into repeatable infrastructure services that underpin secure, sustainable space operations³⁸.

The roadmap and mission highlights above show how demonstrations, commercial services and policy drivers are converging to make on-orbit servicing routine. Lessons from these key dates are technical approaches to rendezvous and capture, refuelling interfaces, modular payloads and

operational concepts such as takeover and tug models, directly inform design trade-offs for small satellite servicing. The next section presents those lessons as core principles to guide architects in creating resilient, interoperable and cost-effective small-sat orbital-servicing systems.

Core principles for designing small satellite orbital servicing architectures

While we address here some general principles of on-orbit satellite servicing, our focus is on those most relevant to small satellites. Separating the requirements for servicing large, high-value spacecraft from those for many small, low-cost platforms is not straightforward. Accordingly, this article concentrates on the distinctive architectural and operational features needed to make servicing scalable, affordable and reliable for small satellite constellations. Thus, we will first briefly overview the general principles, then examine in greater detail the specific architectural features and operational considerations unique to servicing small satellites.

We should mention here that the above outlined principles reflect the authors’ perspective and are offered just as a suggested starting point for discussion and further development rather than as definitive policy or standardised requirements.

Modular, service-ready satellite designs

Satellites could be conceived as assemblies of replaceable functional modules, such as typically propulsion platform, power system, communication equipment and payload. An effective strategy is to all systems be designed so that on-orbit replacement or upgrade is both feasible and economically efficient. It is recommended to adopt common mechanical footprints and standardised attachment points that enable rapid grappling and hot-swap replacement of units across platforms. Satellites need embedded diagnostic interfaces and continuous health-reporting telemetry³⁹ to support remote assessment, prioritise interventions and guide on-site or autonomous repair actions.

Where feasible, designers could try to incorporate passive alignment elements (tapers, kinematic locators, compliant pins) to guide mate/demate operations without complex active control (Fig. 2). Service-friendly access panels with standardised latches, tool interfaces, and protected harness routing give predictable entry points for robotic or human intervention. These measures shorten servicing timelines, reduce accidental damage risk, and simplify autonomous procedures by lowering perception and control requirements.

For small satellites, adopting the same passive, low-complexity features becomes even more important: minimal mass and power budgets make simple mechanical guides and standardised access the most practical way to enable high-volume, low-cost servicing. Standardised passive interfaces also allow for a single small servicer design to work across many platforms, which is essential for achieving the economies of scale needed for constellation maintenance.

Standardised mechanical and electrical interfaces

From the authors’ perspective, a minimal set of interoperable mechanical, electrical and fluid interfaces is essential to scale on-orbit servicing across platforms and architectures⁴⁰. Specifications for pinouts, voltage and current limits, communication protocols and fluid coupling tolerances must be part of baseline design deliverables to support safe hot-swap replacements and in-place diagnostics. It is recommended that designers include passive alignment aids and machine-readable fiducials to simplify autonomous capture and reduce operational risk, while service access procedures and tool requirements are recorded to permit rapid, third-party interventions. Regular qualification testing and open documentation will accelerate adoption and enable robust commercial servicing markets⁴¹.

For small satellites, this standardisation is especially critical in the context of the tight mass, power and cost constraints, which make minimal, well-defined interfaces the only practical route to high-volume, low-cost servicing. Widespread adoption of such standards allows a single class of

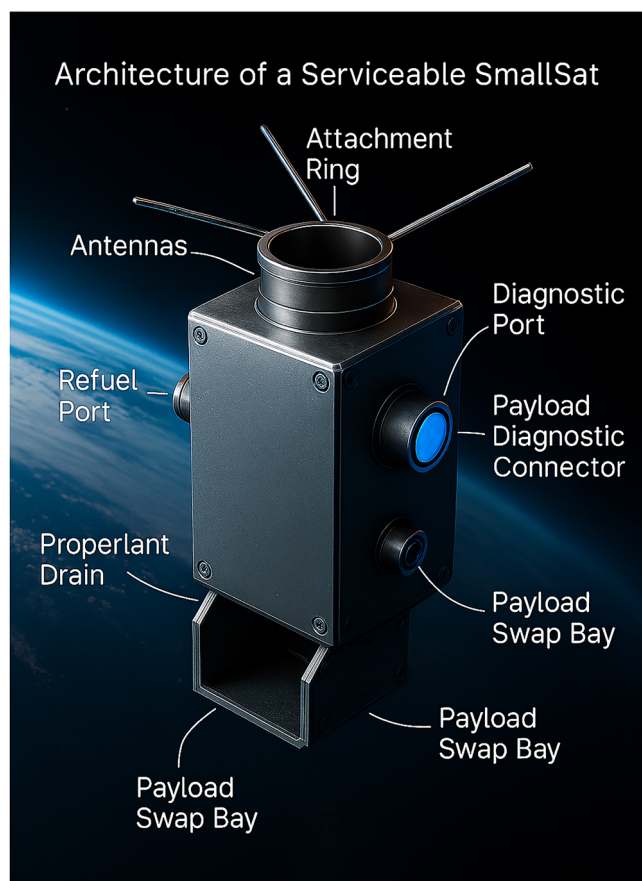


Fig. 2 | Artistic representation of a serviceable small satellite showing key service interfaces: an attachment/docking ring for secure capture and mechanical mating. A diagnostic port for health telemetry and fault interrogation; a payload diagnostic connector to enable in-place sensor and electronics testing; a propellant drain and refuelling ports for safe fluid transfer and lifetime extension; and a payload swap bay designed for rapid removal and replacement of modular tools and instruments. Each feature is located and sized to simplify robotic engagement, protect sensitive systems during interventions and support rapid, repeatable on-orbit maintenance and upgrades. Note that this illustration proposes a set of interfaces recommended for discussion, and is not exhaustive or fully developed. Other serviceable features and configurations could be considered within the broader scope of orbital servicing designs. In the Authors' opinion, the proposed set represents a practical foundation for further refinement and collaborative standardisation.

small servicer to service many platforms, unlocking the economies of scale that sustain constellation operations.

Compatible rendezvous, proximity operations and docking (RPOD) systems

In the authors' view, satellites need to be equipped with appropriate standardised rendezvous beacons, cooperative markers and docking interfaces (Fig. 3) so servicers can reliably recognise and mate with targets⁴². These interfaces must be compatible and standardised across vendors and mass classes to ensure mechanical matching and mutual recognition of satellites^{43,44}. Servicing vehicles could be able to use soft capture systems, adaptive force-controlled manipulators and tool changers to work with multiple fixtures and delicate payloads⁴⁵. Integrated sensing suites such as lidar, stereo vision and thermal cameras, together with force-torque control, enable safe proximity operations and precise manipulations, reducing risk and supporting autonomous or supervised interventions⁴⁶. Importantly, servicing small satellites would require purposely designed docking systems, which are currently under development (Fig. 4)^{47,48}.

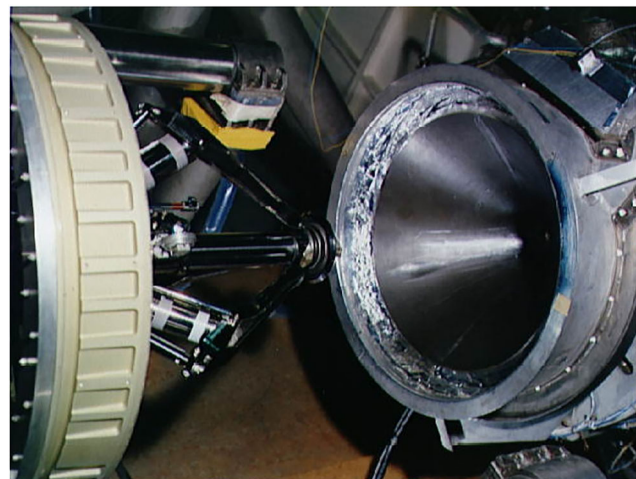


Fig. 3 | Closeup view of docking system of the Apollo spacecraft showing mating interfaces and alignment guides. The authors note that a spectrum of compatible, standardised docks for small satellites is needed to enable widespread, low-cost servicing and ensure mutual recognition and mechanical docking across platforms. Credit: NASA.

These small satellites, docking solutions would prioritise low mass, minimal power draw and simple, repeatable mechanical interfaces so they can be integrated without materially increasing unit cost. Widespread adoption will depend on definable performance envelopes, interoperable mechanical and electrical pinouts and simple, low-cost adaptors that allow a single servicer type to service many platforms across a constellation. Definitely, achieving even partial standardisation of these elements will require substantial, coordinated technical and regulatory effort across industry and agencies, but it would deliver significant benefits in reduced risk, lower cost, and faster, more reliable on-orbit servicing^{49,50}.

Supply, logistics and in situ fabrication layers

Authors recommend that satellites be supported by logistics nodes and supply chains in relevant orbits to stage spare modules, propellant and repair materials. Where transport is costly, in-space manufacturing assets would provide on-demand production of parts and consumables. Inventory standards, packaging and replenishment cycles must be compatible and standardised across operators to ensure mutual recognition, mechanical and procedural matching, and predictable mission planning and insurance. Several private and public teams are developing orbital fuel depots and spare caches⁵¹; SpaceX is pursuing on-orbit refuelling for Starship to keep large quantities of propellant available⁵², and other companies are likewise working on fuel stores and depot architectures to support sustained operations⁵³.

For small satellites, it is suggested that logistics prioritise ultra-compact, low-mass spare modules and consumables and rely on highly distributed depot architectures placed close to constellation orbital planes to minimise transfer Δv and turnaround time. In situ fabrication and standardised, modular repair kits become especially valuable for small satellite operations because they avoid the disproportionate cost of launching bespoke spares and allow rapid, low-cost field repairs that scale across thousands of units.

Novel materials and targeted repair technologies

We suggest that satellite designs take full advantage of the recent progress in the development of cutting-edge repairable material platforms, including those based on graphene^{54,55}, MXene materials⁵⁶ and carbon nanotube composites^{57,58}, together with repairable composites^{59,60}, multifunctional coatings and self-healing polymers⁶¹ to improve longevity. Designers can consider the use of adhesive, ultrasonic, plasma-based⁶² and thermal patching adapted for vacuum and thermal cycling and adopt methods for

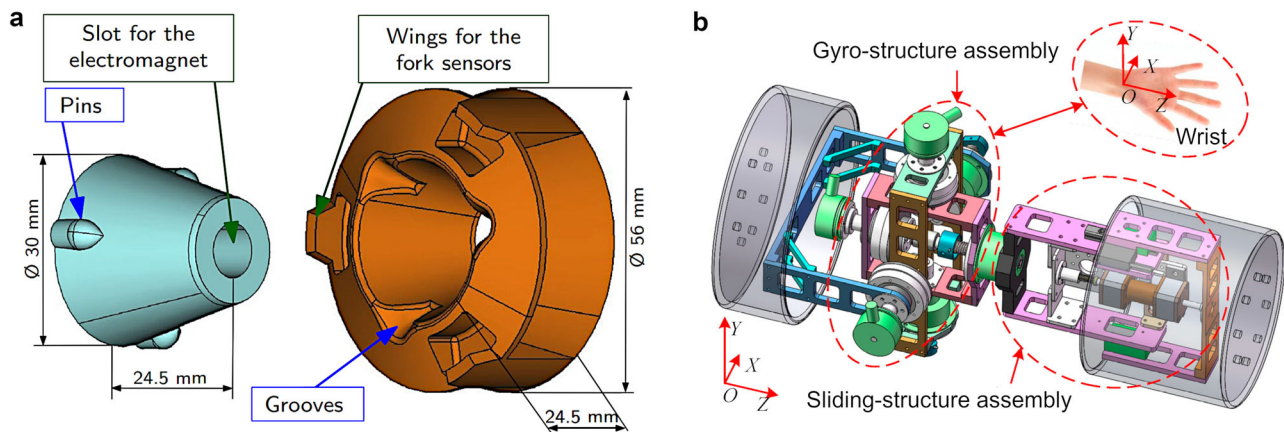


Fig. 4 | Docking mechanisms for microsatellites. **a** The centring cone features a base-mounted pin that enforces roll alignment and a slot for the electromagnet; the drogue incorporates three wings to actuate the fork sensors and axial grooves that accommodate the alignment pins. DOCKS is a smart docking system that integrates these elements to enable reliable mechanical capture and sensor-driven verification. Of particular importance is that this design is optimised for microsatellites: low mass, simple integration and minimal power draw make it suitable for high-volume

deployment in constellations. Reproduced from Lion et al.⁶¹ under terms and conditions of the CC BY licence. **b** A three-dimensional representation of the bionic docking mechanism, illustrating the assembly of the gyro structure along with the gyro mechanism, a flexible rotating component and an encoder, in addition to the assembly of the sliding structure featuring the sliding mechanism, a flexible linear element and a linear displacement sensor. Reproduced from Xu et al.⁶³ under terms and conditions of the CC BY licence.

large-structure repair such as fibre-reinforced patching, localised curing and vessel leak sealing. Common material standards and test protocols will make repair outcomes predictable and affordable.

For small satellites, these materials and repair choices prioritise ultra-lightweight, low-power techniques and modular, snap-fit replacement panels so repairs can be performed quickly with minimal tooling. Standardised, compact patch kits and localised additive manufacturing feedstock tailored to small satellite architectures will make on-orbit repairs economically viable at the constellation scale.

Additive manufacturing and advanced fabrication in orbit

Satellites will support modular additive manufacturing units that can print metals, polymers and composite subassemblies with full qualification testing and traceability. Designs need to enable hybrid workflows that combine printed parts with prequalified inserts and fasteners to guarantee structural integrity^{63,64}. We recommend that certification standards for parts printed directly in space, along with qualification margins and post-print inspection, be harmonised across operators to ensure mutual recognition, mechanical matching and predictable mission assurance. The authors believe pursuing these standards now will make on-orbit fabrication reliable, affordable, and widely adoptable⁶⁵. Additive manufacturing techniques utilised in space for small satellites would prioritise compact, low-power printers capable of producing standardised, small-form-factor replacement units, fasteners and enclosure panels rather than large structural elements. Deploying distributed micro-fabrication nodes near constellation orbital planes and using common feedstock cartridges will minimise transfer Δv , shorten repair turnaround and reduce the need to launch spares, making fabrication economically attractive at constellation scale⁶⁶. In the future, strategies where waste materials are recycled may further contribute to making space economy more sustainable, and limit space debris, which presents a considerable threat to an ever more densely populated LEO environment⁶⁷.

AI, autonomy and remote supervision

The authors believe that an effective strategy for satellites is to integrate onboard AI for real-time perception, fault diagnosis and adaptive task planning during servicing operations^{68,69}. Control would rely on supervised autonomy, so ground teams can intervene at critical decision points while routine control is handled locally. Predictive maintenance analytics is applied to prioritise service targets and optimise fleet-level schedules. These

measures will increase operational resilience and efficiency while keeping human oversight where it matters most.

AI and autonomy must be engineered for extreme resource constraints, using lightweight, energy-efficient inference models and event-driven sensing that minimise power and data budgets for small satellites. Fleet-level autonomy, with distributed decision rules, collective learning and prioritised predictive tasking, allows low-cost servicers and satellites to coordinate repairs and deorbiting actions efficiently while preserving human oversight for high-risk interventions. Development of autonomous systems capable of earning trust of human operators is critical to realising effective cooperative Human-Machine Teaming (HMT) capabilities⁷⁰.

Cross-cutting verification, standards and business enablers

Qualification and verification protocols for service-ready hardware, printed parts and repair with particular attention to the requirements of small satellites. The authors contend that satellites to be developed with service-ready qualification and verification protocols for hardware, printed parts and repair methods to ensure repeatable safety and performance. Open standards and industry consortia need to be promoted so interfaces, tests and data formats are compatible and enable third-party servicers. Insurance, regulatory, and commercial models must be aligned to lower entry barriers, make servicing insurable, and create predictable demand. Standardisation and verified practices together will reduce fragmentation and unlock scalable, sustainable on-orbit servicing markets.

Here we should note that the above-mentioned regulatory and governance issues are complex and cannot be addressed by technical solutions alone. While regulation is not the main focus of the paper, mentioning it requires more precision. Technical procedures do not determine who has legal authority, who provides oversight, or how permissions and approvals are granted. Governance involves national and international laws, the roles of responsible institutions, rules on liability and transparency and clear procedures for granting, reviewing and withdrawing approvals. These elements should be defined outside the technical system itself, and this applies equally to large constellations and to the rapidly expanding domain of small satellites⁷¹.

The situation is further complicated by the dual-use nature of many enabling technologies⁷². Tools developed for beneficial purposes can also be misused, which creates additional regulatory challenges. This makes it necessary to include explicit risk assessments, defined approval thresholds, step-by-step authorisation processes, independent oversight, mandatory

reporting obligations and consistency with existing export control and non-proliferation rules. Addressing these governance aspects in a systematic way would help clarify whether the proposed technical measures are institutionally feasible and would give readers the context needed to evaluate their practical and policy implications, including those arising from the proliferation of small satellites⁷³.

Verification and standards for small satellite technology

need to accommodate extreme mass, volume and cost constraints by defining lightweight, modular qualification paths and common test fixtures that lower per-unit certification overhead. Pooled testing infrastructure, shared qualification data and insurance products tailored to fleet-level risk will make servicing commercially viable and allow third-party servicers to scale across multiple operators.

On-orbit servicing: possible ethical and legal challenges

We should note first of all that the on-orbit activities take place in outer space, which is not the sovereign territory of any state and where legal rules are still underdeveloped^{74,75}. Apart from above mentioned technical issues, the on-orbit servicing may raise numerous ethical and legal concerns. First, space servicing architecture could, in principle, enable third parties to approach, capture, modify, or de-orbit another operator's satellites, creating open questions about lawful intervention, consent and authorisation. Second, if not regulated, servicing tools could be dual-use and repurposed for surveillance or kinetic interference, increasing risks of misuse. Moreover, powerful actors could use servicing to dominate shared space infrastructure or prioritise their satellites. Unclear liability complicates responsibility for accidental damage or debris generation. Gaps in the international norms could make international cooperation inefficient and slow. Data privacy and protection of proprietary on-board software and hardware become particularly important when external agents can access or reconfigure systems.

To manage these risks, it would be helpful to establish clear procedures for obtaining permissions and authorisations before any servicing operation. Adopting strong technical protections so that only trusted parties can connect to or modify a satellite would reduce misuse. Establishing international procedures that assign responsibility and provide clear proof of fault would enhance liability and governance. Maintaining open registries and agreed procedures for visiting and capturing satellites would increase transparency on-orbit servicing⁷⁶. Finally, modernising export-control and verification practices while still supporting legitimate innovation would balance security and progress.

The next section discusses some key takeaways and implications for enabling small satellite serviceability. The goal is to help engineers, operators and regulators toward interoperable standards, reliable autonomous operations and governance frameworks that support safe, repeatable maintenance in orbit.

Small satellite servicing: key takeaways and implications

On-orbit servicing for small satellites is a different problem from servicing a handful of very high-value spacecraft. Instead of rare, bespoke missions to salvage single expensive assets, the small satellite context demands systems and operations that scale: many inexpensive, often short-lived clients deployed in large numbers, serviced either autonomously or not at all. This reality reshapes technical priorities, business logic and safety trade-offs: the goal is not to recreate full GEO-style servicing at a smaller scale but to design a minimalist, repeatable ecosystem that delivers the right interventions at the right cost.

Two servicing paradigms and their divergence

There are two clear paradigms directly stemming from the on-orbit satellite servicing architecture. The first is the classical, high-complexity mission extension model used for large GEO satellites: mission extension vehicles tailored to one client, able to perform dexterous manipulation, long-term station keeping and energy-intensive manoeuvres justified by the enormous

value of each target. The second is a high-throughput model for small satellites, where servicers must be inexpensive, reusable across many clients and optimised for brief visits and simple tasks. The key differences are scale, acceptable per-sat cost, acceptable risk and the range of manoeuvres considered economical: tasks seen as routine for GEO servicers (large inclination changes, long station keeping) are typically uneconomic for small satellite constellations.

SMEV architecture and unified operation

Small Mission Extension Vehicles (SMEVs) could be modular, standardised and deliberately simple. A practical SMEV emphasises reliable autonomous rendezvous and proximity operations, standard capture or adaptor engagement, limited repair or subsystem swap capability and provision or attachment of one-time deorbit or impulse kits. The unified systems approach, such as common mechanical grab points, simple service ports and a software stack that supports plug-and-play adaptors, lets one class of servicer handle many clients without bespoke engineering for each target. Design trade-offs favour robustness, low mass and easily replaceable tooling over full robotic dexterity; universality and repeatability are the primary enablers of volume economics.

Economic and operational decision rules

Servicing decisions for small satellites need to be governed by strict cost-benefit rules, and most probable, this is a cornerstone of the SMEV architecture of the future. If designing for servicing or executing a repair materially raises unit cost above the expected replacement-plus-launch price, replacement will usually win. Expensive, energy-intensive manoeuvres should be excluded from SMEV baselines; deorbiting and replacement is often the cheaper path when inclination changes or complex recoveries are required. Constellations afford tolerance for nonrecoverable units, so triage policies need to prioritise simple, standard failures for repair and schedule replacement for complex, nonstandard faults. The business case depends on amortising SMEV development and flight costs across many visits, so multi-target missions, servicer reuse, and standard client interfaces are essential.

On-orbit repair, deorbiting and environmental impact

On-orbit additive manufacturing and standard repair tooling can be strategic where mechanical damage is common, and repairs can be made using standard subassemblies; when a damaged subsystem is low-mass and standardised, repair in orbit can be far cheaper than replacement launches. At the same time, SMEVs would carry or attach small one-time deorbit kits to clients that lack end-of-life propulsion, shifting deorbit capability from each smallsat to the servicing infrastructure and preserving smallsat affordability while meeting debris mitigation goals⁷⁷. This reduces collision risk because failure to remove defunct satellites can trigger cascading collisions known as the Kessler syndrome⁷⁸, which would sharply increase debris and threaten the long-term usability of key orbits. Overall, the SMEV ecosystem should deliberately limit its functional scope to what is economically justified for mass servicing: simple capture, standard subsystem swap or attach, limited refuelling where warranted and deorbit support rather than complex, costly recoveries. This constraint both preserves per-sat economics and reduces operational risk across densely populated LEO.

It is advisable that the treatment of orbital debris considerations include collision risk assessment^{79,80}, and estimation of potential economic losses, integration of space environment management and lifecycle mitigation measures⁸¹, and monitoring for debris-generated radio bursts⁸² and secondary collision risk. Framing these capabilities as potential market opportunities^{83,84}, for risk assessment services, debris weather alerts and lifecycle compliance could strengthen the proposed measures, enhance the long-term sustainability of space assets in the context of on-orbit servicing of small satellites and align recommendations with operational and economic drivers⁸⁵.

We should also mention here the effort of a UN COPUOS Working Group on the Long-term Sustainability of Outer Space and the Aerospace Corporation assessment of collision risk from mega LEO systems, which has

addressed space debris concerns and space traffic management, together with the efforts of commercial entities to establish safety and operational standards for rendezvous and proximity operations through the CONFERS processes. These initiatives provide an important framework that complements engineering measures and highlight the broader governance context in which technical solutions are developed^{86,87}.

Further perspectives

The rapid expansion of small and medium satellite constellations makes on-orbit servicing an economic and strategic necessity. Extending satellite lifetimes through refuelling, repair and modular upgrades will materially reduce launch cadence and lifecycle costs, increase operational resilience and permit incremental capability improvement across fleets rather than expensive wholesale replacements.

Realising this shift requires coordinated technical and institutional effort. Technically, the industry must adopt standardised mechanical and electrical interfaces, modular payload architectures, embedded diagnostics and rendezvous aids and reliable autonomous proximity operations using advanced miniaturised propulsion systems^{2,88}. Institutionally, stakeholders must establish shared logistics platforms, insurance and commercial service models that allocate cost and risk and regulatory frameworks that permit safe, routine intervention in orbit.

These technical and institutional changes must be tailored to extreme mass, volume and cost constraints typical of small satellites, favouring minimal, standardised interfaces and lightweight rendezvous aids that do not materially increase unit cost. Implementing distributed logistics nodes, compact spare kits and policies that prioritise replacement or simple fixes over complex recoveries will make servicing economically viable at a constellation scale.

Priority actions are clear. These include the need to develop and certify interface and servicing standards; accelerate demonstration missions that combine rendezvous, grappling, refuelling and module exchange; and create pilot commercial servicing contracts to validate business models and insurance approaches. Simultaneously, maturation of materials and repair technologies specifically adapted for on-orbit use need to be prioritised, including additive manufacturing for on-orbit fabrication and patching, adhesive and ultrasonic repair methods for large composite structures, and techniques for inspecting and restoring tanks, pressure vessels and other critical large components. Standardised, service-ready mechanical and electrical interfaces should be designed to accept modular replacements and in situ-fabricated parts, reducing the need for full satellite replacement and shortening repair turnaround⁸⁹.

For small satellites in particular, these priorities need to be considered within the context of extreme compactness and serial production, with standardised modules and interfaces engineered to be as light and simple as possible so they do not raise unit cost. Deploying distributed micro-depots, ready-to-swap repair kits and common feedstock cartridges for on-orbit additive manufacturing will cut logistics costs and enable economically viable servicing of large constellations.

Advance autonomous and AI-driven control for remote servicing operations, integrating on-board diagnostics, predictive maintenance algorithms, and supervised autonomy to manage complex repair sequences from the ground⁹⁰. AI systems should handle real-time perception for proximity operations, adaptive task planning for grappling and tool use, and closed-loop control for additive manufacturing and non-destructive inspection in microgravity. These systems need to be sufficiently robust to act reliably in the unpredictable, potentially data-limited environment of space, and in response to adversarial intelligent threats, particularly when safety-critical missions are concerned.

AI-enabled collision avoidance systems are also critical components for the safe and reliable operation of Multi-Mission Space Exploration Vehicles. These vehicles are designed to perform complex tasks such as orbital manoeuvres, docking and proximity operations near satellites, including repair operations. For servicing small satellites, the risk of collision with debris or mission targets could be particularly significant. Human

operators, whether onboard or on the ground, face limitations in reaction time and situational awareness, especially when communication delays occur during deep-space missions. By integrating AI into collision avoidance, MSEVs gain the ability to process sensor data in real time, predict trajectories and autonomously adjust their paths to prevent accidents^{91,92}. Recent studies highlight how AI-driven solutions and reinforcement learning approaches are increasingly applied to spacecraft safety, enabling adaptive responses to dynamic orbital conditions⁹³.

Addressing collision avoidance is not optional but fundamental to the success of MSEV operations. Without robust systems in place, the risk of mission failure due to damage or loss of the vehicle becomes unacceptably high. AI provides the adaptability and autonomy needed to handle hazards beyond human capacity, making it indispensable for long-duration and remote missions where immediate human intervention is impossible. Research from ESA and NASA emphasises that automated collision avoidance must be embedded into guidance, navigation and control architectures to ensure mission safety and protect valuable assets^{94,95}.

Small satellite limits mean autonomy must use very low power, compact models that do simple perception and act only on events to save compute and communications, where coordinated fleet management and edge tasking allow a relatively small number of servicers to maintain a much larger number of satellites by grouping repairs, placing micro-depots nearby and requesting human operator intervention and oversight for tasks with increased complexity or risk profile.

Together, standards, materials/repair technologies and AI-enabled autonomy will convert servicing from a niche capability into core infrastructure, enabling more sustainable, upgradeable and resilient satellite ecosystems⁹⁶.

Actions needed

On-orbit servicing opens a high-impact opportunity for small satellites. Their sheer numbers, short lifecycles, and constrained designs make serviceability a lever for system-level resilience and sustainability. Accelerating development across interface standards, materials and repair methods, and AI-enabled autonomy is essential. We here focus attention to catalyse coordinated research, demonstrations, and proactive collaboration across the small satellite ecosystem:

- **Universal interfaces.** Develop and validate mechanical/electrical standards for docking, power, data, and fluid transfer to enable cross-vendor, cross-mission compatibility.
- **Autonomous operations.** Demonstrate small satellite rendezvous, proximity operations, and refuelling with robust fault tolerance and verifiable safety.
- **Governance and transparency.** Establish an international registry and authorization protocols for servicing missions, ensuring consent, traceability, and mission accountability.
- **In-orbit fabrication.** Integrate additive manufacturing into maintenance workflows for rapid part replacement, structural repair, and life-extension.

Conclusion

The expansion of small and medium-sized satellites in low Earth orbit presents significant economic opportunity and environmental risk because most platforms are effectively single-use and are decommissioned after failure. Building infrastructure for orbital servicing of small satellites offers a practical pathway to reduce replacement costs, improve constellation reliability and advance sustainability in LEO. Serviceability is especially valuable for small satellites because their large numbers, short lifetimes and constrained designs make repairs, refuelling and modular upgrades a high-leverage intervention for system-level resilience. Realising this potential

requires coordinated progress on universal mechanical and electrical interfaces to enable cross-vendor compatibility for docking, power transfer and data exchange. It also requires demonstration of autonomous rendezvous, proximity operations and refuelling with robust fault tolerance and verifiable safety. Governance mechanisms and transparent authorisation protocols are needed to ensure consent, traceability and accountability for servicing missions. Integration of in-orbit fabrication and repair using additive manufacturing will enable rapid part replacement and life extension. Together, these technical, operational and regulatory advances will catalyse research and demonstration activities and support proactive collaboration across industry, academia and regulators, thereby enabling a more sustainable and resilient LEO economy.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

I.L., K.A. and C.R. conceptualised the study and wrote the manuscript. I.L. and O.B. created the technical diagrams and images. O.B., U.C., S.X., M.K. and H.E.R. wrote the manuscript. All authors provided critical revisions to the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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