

A Framework for Interoperability in Multi-Provider Space Servicing Ecosystems

Shannon Z. Morgan¹

*The Aerospace Corporation, Chantilly,
VA, 20151, U.S.A.*

Aditya Baraskar⁶

*Orbital Lasers Co Ltd, Tokyo, 107-0052,
Japan*

Noah Gladden²

*Arkisys Inc, Los Alamitos, CA, 90720,
U.S.A.*

Mike Curtis-Rouse⁷

*Satellite Applications Catapult Ltd,
Aylesbury, HP18-0XB, U.K.*

Stephen Leete³

*Northrop Grumman Systems Corporation
Sterling, VA, 20166, U.S.A.*

Yann Tincelin⁸

*European Space Agency, Paris, Ile-de-
France, 75738, France*

Azita Valinia⁴

*Valinia Strategy Group LLC, Potomac,
MD, 20854, U.S.A.*

Chris Gurjao⁹

CONFERS, Dover, DE, 19901, U.S.A.

Ji Hyun Park⁵

*Seoul National University, Seoul, 08826,
South Korea*

Thomas A. Schervan¹⁰

iBOSS GmbH, 52062 Aachen, Germany

I. Introduction and Motivation

In-space servicing and assembly has a long history across the Skylab, Salyut, Mir, Space Shuttle, International Space Station (ISS), and Tiangong programs. These programs demonstrated that spacecraft can be captured, docked, berthed, refueled, repaired, reconfigured, and assembled on orbit. Most of these capabilities, however, were developed within centrally managed program architectures in which the participating vehicles, interfaces, and operating procedures were coordinated in advance. Despite the potential benefits of the widespread adoption of in-space servicing, assembly, and manufacturing (ISAM), the technologies and capabilities supporting ISAM have struggled to transition from government programs to individual demonstrations and sustained commercial services. It is not clear how heritage approaches appropriate for previous demonstrations will support an ecosystem involving independently developed client space objects, servicer spacecraft, logistics vehicles, infrastructure, and replacement units.

¹ Senior Engineering Specialist, Mechanical Systems Department, The Aerospace Corporation, and AIAA Member.

² Lead I&T Engineer, Arkisys Inc, and AIAA Member.

³ Staff Engineer Systems, SpaceLogistics LLC, and AIAA Member.

⁴ President and Founder, Valinia Strategy Group, LLC.

⁵ BK Assistant Professor, Department of Aerospace Engineering, Seoul National University.

⁶ Senior Scientist and Global Business Lead, Orbital Lasers Co, Ltd.

⁷ ISAM Lead, Satellite Applications Catapult Ltd.

⁸ Programme Manager, In-Space Proof-of-Concepts, European Space Agency.

⁹ Technical Writer, CONFERS.

¹⁰ CEO and Co-founder, iBOSS GmbH.

The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is working to establish the technical and operational foundations needed to ease transition. CONFERS principles and practices have been published as ISO 24330:2022, “Space systems - Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) - Programmatic principles and practices.” A CONFERS task force also developed the prepared storable fluid-transfer standard published as ANSI/AIAA S-157, “In-Space Storable Fluid Transfer for Prepared Spacecraft.” Related standards-development efforts address power and data interfaces, spacecraft fiducial markers, prepared free-flyer capture, and cryogenic fluid transfer. These efforts define important interface domains, but a broader organizing structure is needed to explain how individual standards, proprietary interfaces, operational agreements, and transitional solutions can collectively enable system-level interoperability.

The need for such coordination is not unique to commercial servicing. The Artemis Accords identify interoperability as a principle of cooperative space exploration and call for reasonable efforts to use existing interoperability standards and establish new ones where needed. A particularly useful comparison is the International Deep Space Interoperability Standards, a suite spanning nine discipline areas: avionics, communications, docking, environmental control and life support, power, rendezvous, robotics, thermal, and software. Developed collaboratively with NASA and ISS partner agencies, these standards were intended to allow independently developed systems to work together without prescribing internal designs beyond necessary boundaries or interfaces. Gateway was the first planned programmatic application of the suite; the standards continue to be referenced in broader Moon-to-Mars and cislunar architecture work. This paper examines that federated approach as evidence that coordinated standards across several domains can enable interoperability without prescribing a single universal connector.

II. Framework for System-Level Interoperability

This paper proposes a layered interoperability framework for commercial space servicing architectures. The framework is intended to guide the identification, coordination, assessment, and evolution of interoperable interfaces rather than prescribe a complete spacecraft architecture or a universal servicing interface. It distinguishes compatibility at an individual interface from interoperability at the vehicle, mission, and ecosystem levels. These four architectural layers define the scope of an interoperability claim, while the dimensions below identify the operating context, technical functions, and compatibility method that must be coordinated at each layer. Two implementations may be mechanically compatible while remaining unable to exchange power, communicate operating limits, coordinate control authority, or respond safely to off-nominal conditions. Conversely, useful system interoperability may sometimes be achieved between dissimilar interfaces through adapters, gateways, or other explicitly managed translation mechanisms. Interoperability is therefore treated as an outcome of coordinated technical and operational approaches rather than a property of a single connector.

A. Three-Dimensional Framework

The proposed framework organizes an interoperability claim along three dimensions: CONOPS Domain, Technical Domain, and Compatibility Method, as illustrated in Fig. 1. The CONOPS (or concept of operations) Domain describes when and under what operational conditions the interaction occurs; the Technical Domain identifies what functions or resources must interoperate; and the Compatibility Method describes how compatibility is achieved.

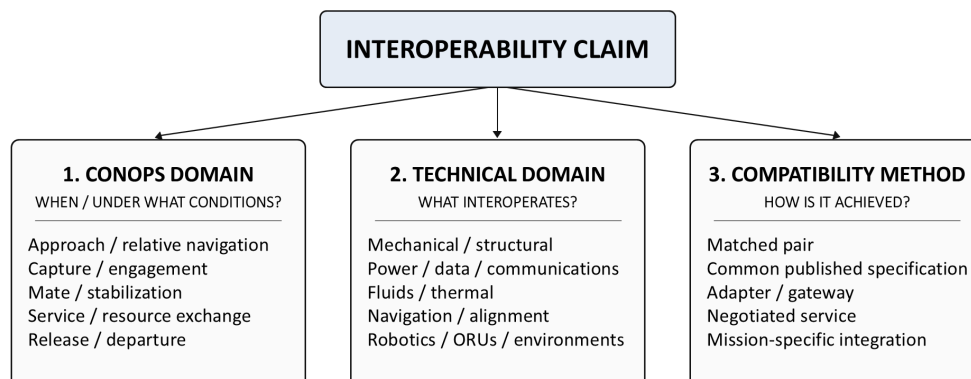


Fig. 1 The organizing dimensions used to bound an interoperability claim.

1. CONOPS Domain

The first dimension is the CONOPS Domain, describing the mission phase and operational context in which the interaction occurs: rendezvous; proximity operations; inspection and characterization of client motion; stabilization or detumbling where required; initial contact, capture, or engagement; structural mating and stabilization; mated servicing or resource exchange; and release, separation, and departure. Fig. 2 illustrates the relevant phases from the CONFERS Mission Functional Diagram. Organizing the framework by CONOPS makes it explicit that interoperability begins before physical contact. ISO 24330 defines RPO/OOS mission phases and operational practices; the International Rendezvous System Interoperability Standards (IRSIS) address operational regions, inter-vehicle telemetry, relative state information, and RF ranging; and IDSS defines navigation and alignment targets used during final approach. CONFERS-related work on fiducials addresses another part of the same problem. A common cross-link radio is one possible implementation, but the interoperability requirement is broader: the vehicles may need compatible communications options, coordinate and reference conventions, shared definitions of flight modes and readiness states, exchangeable relative-navigation data, and sensor/target characteristics that support independently developed navigation systems. The framework exposes where these pieces are already standardized and where commercial RPO still lacks a coherent common baseline.

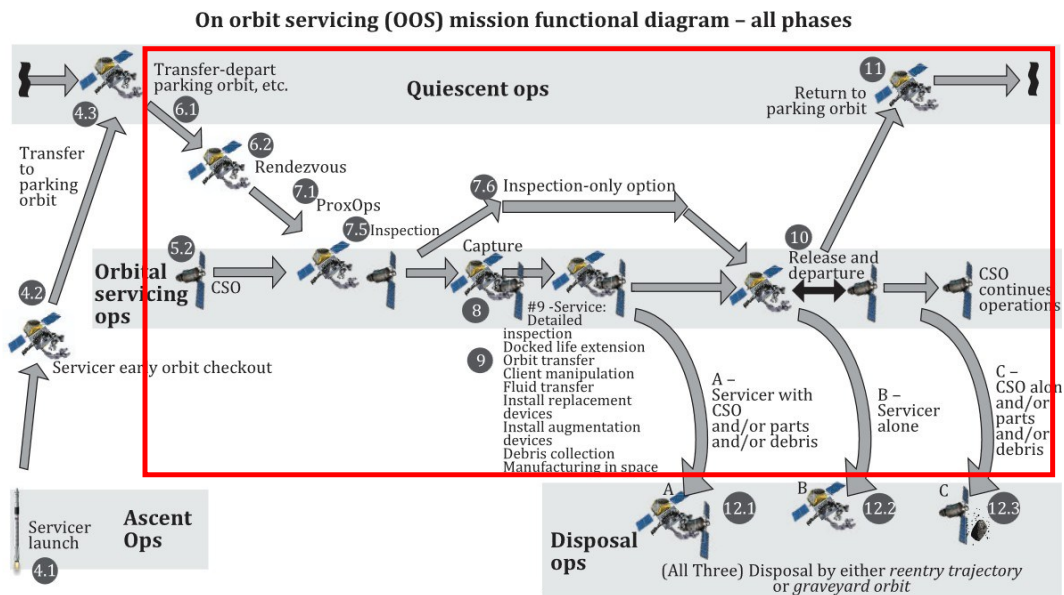


Fig. 2 CONFERS OOS mission functional diagram with highlighted relevant phases for this effort.

2. Technical Domain

The second dimension is the Technical Domain. Candidate technical domains include mechanical capture, rigidification, and structural load transfer; electrical power transfer, grounding, isolation, and protection; data, communications, timing, and software protocols; storable and cryogenic fluid transfer; thermal interaction; guidance, navigation, and control, including relative-motion characterization and stabilization; robotic accessibility and manipulation; orbital replacement unit (ORU) handling; physical and electromagnetic keep-out zones; and contamination or environmental constraints. Not every servicing concept requires interoperability in every technical domain. The framework instead provides a consistent way to identify which domains are necessary for a particular service, the dependencies among them, and the interfaces at which common requirements, published characteristics, or coordinated design information are needed.

3. Compatibility Method

The third dimension is Compatibility Method: the implementation strategy by which independently controlled systems are made compatible. Candidate methods include a provider-controlled matched pair, a configuration-controlled family of related interfaces, independently developed implementations of a common published specification, an adapter for otherwise incompatible systems, and negotiated services in which participants exchange capabilities and operating limits rather than conform to one fixed hardware configuration. This dimension avoids

assuming that a universal interface is the only valid path. It also makes roles and responsibilities explicit: which participant provides alignment, compliance, actuation, power conditioning, protocol translation, fault protection, or other active functions can be defined without requiring identical hardware on both sides of the interface.

B. Interface Taxonomy

Comparing interfaces for interoperability requires a stable interface taxonomy. Existing reference documents often mix design-defining properties with attributes that can change without any hardware modification. Geometry, load capacity, active/passive allocation, and mating features are intrinsic to an interface design; technology readiness, flight heritage, adoption, and standardization status may evolve while the hardware itself remains unchanged. The task force is therefore developing a classification that separates these categories by asking whether changing a value would require a new interface designation. This provides a more durable basis for comparing interfaces and for determining which parameters must match across an interoperability boundary and which may vary.

III. Interoperability as a System Trade

Interoperability is not automatically the optimum design objective for every mission. A tightly integrated mission-specific pair may be lighter, simpler, or higher performing than an interface designed for broad reuse. Interoperability becomes valuable when future partners are uncertain, assets are expected to be serviced by multiple providers, competition and supplier substitution matter, emergency or contingency interactions are desired, or repeated mission-specific nonrecurring engineering (NRE) costs dominate. The framework therefore treats interoperability as a tradeable system capability rather than a requirement to maximize openness in every domain. This framing preserves proprietary implementation choices behind shared interfaces while making explicit what must be common for the desired ecosystem outcome.

Rather than asserting a single linear maturity scale, the framework considers breadth and depth separately. A system may offer broad mechanical compatibility but limited functional interoperability, or deep integration within a bilateral partnership while remaining unavailable to other providers. This separation allows bilateral compatibility, interface-family compatibility, and multi-provider ecosystem interoperability to be compared without implying that the broadest solution is appropriate for every mission.

IV. Heritage Implementation Models

Heritage and commercial examples illustrate several of these compatibility mechanisms. The Space Shuttle and ISS achieved extensive interoperability through program-controlled families of matched interfaces, including robotic grapple fixtures, docking and berthing mechanisms, payload attachment systems, and ORU interfaces. Canadarm, Canadarm2, and their associated grapple-fixture families demonstrate how a controlled set of passive interfaces can support capture and relocation by multiple generations of robotic systems. Flight-Releasable Attachment Mechanisms (FRAMs) also enabled equipment and ORUs to be transported, stored, powered, and manipulated within the ISS architecture. These approaches were highly effective, but their interoperability depended on centralized requirements, configuration management, verification, and enforcement within a common program.

IDSS represents a more open model in which multiple organizations can independently design compatible docking systems against a shared interface definition. Orbital Express demonstrated docking, capture, fluid transfer, and ORU exchange with an expectation of future use, yet successful technical demonstration did not by itself create a broad installed base. Commercial Mission Extension Vehicle operations demonstrate another pathway: a servicer can exploit common legacy client features without a purpose-built client servicing interface, producing useful service interoperability but limited standardization at the client interface.

European and Japanese programs provide complementary examples. Engineering Test Satellite VII (ETS-VII) demonstrated autonomous rendezvous, docking, and robotic servicing between two uncrewed spacecraft, while the H-II Transfer Vehicle (HTV) operated through internationally defined grapple and berthing interfaces. The International Berthing and Docking Mechanism (IBDM) provides a separately developed, IDSS-compatible implementation, illustrating how a shared interface definition can support independently developed hardware. These examples distinguish program-controlled compatibility from independent implementation of a common specification.

Prepared-client hardware illustrates a complementary strategy in which a low-cost passive feature is installed before a future servicer exists. Altius Space Machines developed the DogTag grappling fixture with OneWeb, which ordered almost 600 units for its initial satellite fleet. The fixture combines a ferrous grapple target with optical fiducials and was designed to accommodate multiple capture techniques. Astroscale's Docking Plate applies a similar prepared-

client concept: a lightweight passive interface is installed on the client spacecraft to enable later end-of-life and other on-orbit services, and its first-generation design was demonstrated on orbit during ELSA-d. These approaches are significant because they can create an installed base before servicing demand matures. They also show why “installed on many spacecraft” and “open to many independent servicers” are different interoperability attributes and will be treated as such in the framework.

V. Current Implementation Models

ESA is pursuing a complementary contemporary model through its cross-directorate Spacecraft Servicing Interfaces (SSI) task force. Working with European integrators and suppliers, ESA is shaping an interoperability and modularity architecture for rendezvous, docking, fluid transfer, and interconnect functions that supports an “à-la-carte” approach to servicing. The architecture decouples interaction features into agreed zones for elements such as navigation aids, passive gripping interfaces, power and data ports, and fluidic coupling ports, allowing a spacecraft to select couplers from a toolbox of solutions while preserving a common integration structure. For individual features, ESA is using a co-opetitive market coalition approach to converge on shared, open passive-side designs and release interface requirements documents (IRDs), while leaving active-side implementations open for innovation. In terms of the proposed framework, this approach separates Technical Domains and standardizes selected passive interfaces without requiring a single universal interface or active-side design. ESA is coordinating this effort with the European Commission toward an open in-space infrastructure in which multiple stakeholders can provide and consume services in the orbital economy.

VI. Path to Voluntary Industry Adoption

The paper also addresses how the framework can move from analysis to voluntary industry use. CONFERS is positioned to coordinate rather than mandate adoption. Its Interoperability Task Force charter calls for collecting technical information on tested and commercially available interfaces, engaging manufacturers, developing consensus recommendations, and routing recommendations through CONFERS governance to standards development organizations. The framework supports that process by applying the task force’s developing taxonomy to catalog interfaces, identifying minimum interoperable guidelines and standards gaps, and comparing proprietary and published implementation paths. CONFERS can further promote voluntary adherence by socializing the framework across provider and client communities, defining useful conformance evidence and implementation guidance, and working with relevant SDO committees so mature consensus can become voluntary consensus standards.

This paper is intended as an early coordination step. Commercial providers, spacecraft developers, government users, researchers, and standards participants can test the proposed dimensions against real architectures, identify missing interfaces, and challenge assumptions about what should be standardized. Feedback from the community will refine the task force’s evolving taxonomy and framework and inform later recommendations to standards development organizations.

VII. Conclusion

By placing interface standards within a common CONOPS and architectural context, the framework helps mission developers determine what should be standardized, what may remain implementation-specific, and where coordinated information or translation is sufficient. It also exposes standards gaps and helps prioritize demonstrations between independently developed systems. Treating interoperability as a system capability rather than a collection of unrelated connectors can reduce recurring integration effort, lower barriers to entry, preserve design flexibility, and support a scalable commercial ISAM ecosystem.