AIAA STANDARDS PROJECT PROPOSAL FORM

(Rev. 2018)

Date: 11 July 2024

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Designation of Proposed Document: (Special Project, Guide, Recommended Practice, or Standard)	Standard	
Title of Document:	Best Practices, Functional Requirements, and Norms for In-space Servicing, Assembly, and Manufacturing (ISAM) Power and Data Interfaces	
Project Intent: (Check the applicable box below)	**Supersedes or Affects:** (Specify designation of approved AIAA standard(s) affected or superseded.)	
Create new document	X	
Revise current document		
Revise and Redesignate current document		
Revise, Redesignate and Consolidate current document(s)		
Revise and Partition current documents(s)		
Reaffirm current document		
Reaffirm and Redesignate current document		
Supplement to a current document		
Withdraw current document		
This document contains excerpted text from an international standard, but is not an ISO or IEC adoption.		Check here if this standard includes excerpted text from an ISO or IEC standard but is not an identical or modified adoption of an international standard.
This document is intended to become an American National Standard (ANS)	X	Yes
		No
Purpose and justification of the proposal What is the verified market need for the proposal? What problem does this standard solve? What value will the standard bring to end-users? Identify the stakeholders (e.g., satellite manufacturers, aerodynamic test facility operators, launch providers, etc.). Approximately how many end-users do you expect will obtain this standard? Provide a brief rationale (1-2 sentences) from 2 or more stakeholders regarding the importance of this project.	Based on a recent internal survey, the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) members identified an AIAA standard as a market preferred priority project. CONFERS has 80+ member companies. As spacecraft rendezvous and servicing (including docking/berthing) and assembly grow, the need for free-flyer capture and release becomes significant. Spacecraft operators and autonomous systems will conduct free-flyer capture and release. Current membership of CONFERS includes 80+ space companies. Many of them will obtain this standard. Government organizations have expressed interest in this effort as well. The CONFERS Technical Committee identified priority of this standard. These include established space companies as well as well funded entrepreneurial space companies.	
Identify the Technical Committee or Program Committee chartered with oversight of the area (see www.aiaa.org):	There are no TCs or PCs in the AIAA for On-Orbit Servicing or Assembly. That may change. The AIAA Spacecraft Architecture group will be interested in this effort (Fred Slane chairs the group).	

Description of Contents of Standard: (provide a one paragraph description. If more information is needed, please add on separate page.)	Attached

Consumer Product or Service:		Check here if document covers Consumer or Service Product.		
Patents Included: Will the document include a patented invention?		Yes (must provide response to Item 11)		
	X	No		
Patent requirement: If the document includes a patented invention, will this be a requirement? (Review section 4.6 in *AIAA Standards Program Procedures*)		Yes		
	X	No		
Units of Measurement: Will the document use SI units? **If yes,** will the document also use U.S. units?	X	Yes		No
		Yes	X	No

Committee on Standards Sponsorship (indicate the CoS or other approved consensus body that will undertake this project)**:**	An AIAA Committee on Standards for On-Orbit Servicing and Assembly (OSA CoS) has been established. Several members of the AIAA OSA CoS are members of related work for AIAA S-155, AIAA S-157, and AIAA S-158
Proposed membership of new CoS (if a revision, provide the members of current CoS): List the Chair and initial participants, affiliations and Interest Category (see last page); There must be membership balance. **No one interest category can comprise more than 50% of the CoS membership.**	CoS Roster information on last page of this form.
Participation (indicate those materially affected organizations which have committed to supporting this project, use separate attachment if necessary):	To start: SpaceLogistics, CONFERS, Aerospace Corporation, MDA Space, AstroScale, CUAerospace, SIF, USSF, NASA

Resources:
(indicate an estimate of the commitment that will be necessary for committee members to effectively participate in this activity, e.g., participation will be by teleconference only with X frequency, participation will be by teleconference and face-to-face meetings with X frequency, etc.)

Direct meetings of the CoS will be held quarterly. Sub-groups, as needed, will meet monthly. This will also be a topic of interest to the CONFERS Technical Working Group, which meets monthly.

Schedule:
(indicate the schedule envisioned for document development, include critical milestone dates that can be used to assess progress.)

Date	Milestone
11 July 2024	Initialize the development of AIAA/ANSI S-xxx ISAM Power and Data Interface
15 Mar 2025	Complete working draft of AIAA/ANSI S-xxx ISAM Power and Data Inteface; Ballot for Release for public review; Release for public review
8 Sep 2025	Complete resolution of public review comments; Ballot committee for publication
17 Dec 2025	Publication

Risk:
(indicate any risk factors that may impact the above schedule and possible measures to be taken to mitigate the risk)

While government organizations are expected to participate in the development of this standard, there may be government procedures which interfere with the above schedule. In the event such a delay is substantial, the CoS will recommend the government participants approve a first published version of the standard with parallel adaptation of a second version to accommodate the government schedule.

Survey of similar work undertaken in other bodies:
(indicate relevant/similar activities currently underway in other bodies and/or relevant/similar documents to be considered)

ISO TC20/SC14 Space Systems ISO 24330 – Programmatic Principles for Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS) – this standard, based on the work of the Consortium for Execution of Rendezvous and On-Orbit Services (CONFERS) identifies key requirements for participants in the emergent On-Orbit Servicing industry. This AIAA standard will extend from those key requirements in the area of spacecraft fiducial markers used by spacecraft in proximity to and working with other spacecraft.

International Participation:	X	Check here if this project is open to international participation.

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CONFERS Document # xxxxx

CONFERS Recommendations for

Best Practices, Functional Requirements, and Norms

for In-space Servicing, Assembly, and Manufacturing (ISAM) Power and Data Interfaces

June, 2024

Contents

1 Introduction

This document provides best practices, functional requirements, and norms associated with the power and data interfaces between a Servicing Spacecraft and a Client Space Object. The intent is to provide guidance to developers and operators of both the Servicing Spacecraft and the Client Space Object.

This document builds upon the foundation of other CONFERS documents including the CONFERS Guiding Principles, the CONFERS Recommended Design and Operational Practices, and CONFERS On-Orbit Servicing (OOS) Mission Phases (Figure 1) which are the foundation of international standard ISO 24330 Space Systems – Rendezvous and Proximity Operations and On-Orbit Servicing Programmatic Principles and Practices. The scope of this document addresses mission functions for activities requiring power and data interfaces, associated with phases 9, 10 and 12.1 in Figure 1, as well as Launch Vehicle Integration (prior to 4.1) and the environmental considerations associated with Quiescent Operations phases.

CONFERS is an independent, self-sustaining forum created to advocate and promote the on-orbit spacecraft servicing industry and encourage responsible commercial rendezvous and proximity operations/on-orbit servicing (RPO/OOS). CONFERS collaborates on research, development, and publication of voluntary consensus principles, best practices, and technical and safety standards. CONFERS also engages with national governments and international bodies on policy and oversight of spacecraft servicing activities.

There are no patent licensing issues associated with the content of these recommendations.

On orbit servicing (OOS) mission functional diagram – all phases

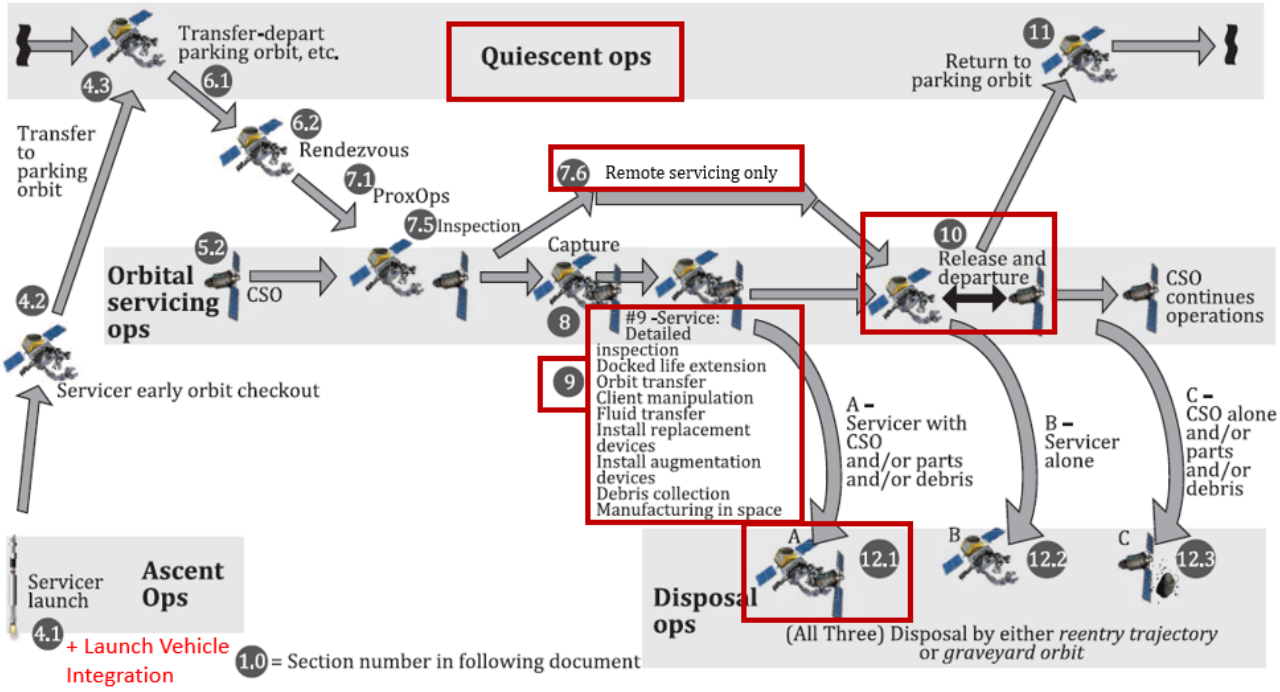


Figure 1 OOS Mission Functional Diagram

These recommendations inform voluntary consensus standards (VCSs) developed by standards development organizations (SDOs) in order to expand progress by building common understanding, enabling collaborative endeavors, simplifying interfaces and operations, and streamlining development. In addition, the recommendations benefit VCS standards for in-space servicing, assembly, and manufacturing (ISAM) activities by focusing on *functional requirements* and norms that accrue from leveraging past and early mission lessons learned. After a period of innovation, discovery, and experience, evolved VCS standards can address form, fit, and function through *interoperable standardized interface specifications* enabling cross-mission interoperability by increasing commonality across servicers and clients.

2 Scope

This document provides current industry best practices for functional and operational requirements and norms associated with the design, testing, and operations of power and data interfaces between a Servicing Spacecraft and a Client Space Object. The intent is to provide guidance to developers and operators of both the Servicing Spacecraft and the Client Space Object. The standards and recommendations collected here are informed by years of engineering development experience garnered through NASA, Canadian Space Agency, European Space Agency, and DARPA work on in-space servicing operational and technology development programs augmented by relevant commercial industry experience.

Objectives of this document are to inform standards to:

1) Ensure safe and reliable operations for prepared in-space use of power and data interfaces.

2) Facilitate future in-space operations by developing standards for power and data interfaces.

The recommendations in this document are a collection of best practices that should be considered in the development of any power and data interfaces related to ISAM missions. Figure 2 illustrates the concept of operations assumed for the use of power and data interfaces related to ISAM and identifies the scope for a standards development organization to develop an associated voluntary consensus standard. This document focuses on the design, verification, and operations of the power and data interfaces and associated combined servicer and client considerations and does not address the servicer spacecraft to client space object capture.

This document does not specify a particular form factor. The intent is to leverage existing standards to the maximum extent practical and promote progress, safety, capability, reliability, and capacity while not hindering innovation or specific mission requirements. Any successful power and data interface hardware that 1) completes qualification and 2) becomes widely adopted could form the basis of a future power and data standard interface. The content of this document intends to inform an "interface standard," whereas normative statements for form, fit, and function would be addressed in program/project interface specifications.

While the prominent scope is limited to power and data interfaces in-space, there is consideration of the impact on such interfaces due to planetary surface environments. This is applicable given the concept of operations for NASA's Gateway mission includes interaction of hardware on-orbit with spacecrafts arriving from planetary surfaces (i.e. the lunar surface), and vice versa.

Power and data interfaces that are relevant to ISAM fit into the following categories:

- Connections between space station modules, which can be integral to the docking/berthing connection, or on the interior or exterior and mated after the docking/berthing connection.
- Between a space station and a visiting spacecraft, such as a cargo or crew spacecraft, which are usually all through the docking/berthing connection.
- Between an Orbital Replacement Unit (ORU) and its host, either during ground to space transport, during on-orbit stowage, or operational installation.
- Between a robot arm end effector and the object being grasped, either a tool, another spacecraft, or an ORU.
- Between a robot arm and its base, for a 'walking arm' like the Space Station Remote Manipulator System.

- Between a servicer spacecraft and a client space object, at a capture, docking or berthing interface.
- Data interfaces in all the above cases can also be wireless.
- Wireless power, through various modes currently implemented on Earth (inductive, radio frequency identification (RFID), light beam, magnetic coupling, etc.)
- A special category is for Extravehicular Activity (EVA), for which there are hard connections between the suit and airlock, and wireless data connections during EVAs.

2.1 Concept of Operations

Figure 2 below portrays the Concept of Operations specific to the phases of the OOS Mission Functional Diagram (Figure 1) applicable to this document, with the green boxes in Figure 2 indicating the applicable scope.

The scope of the power and data interface standards recommendations span the life of the asset, from design to end-of-life. In general, the recommendations are applicable after a Client Space Object is mated/rigidized to its Servicer Spacecraft. For example, Rendezvous and Proximity Operations (RPO), CSO capture, and CSO rigidize are not in scope. It is assumed that wired power and data interfaces are engaged after CSO capture and rigidize is complete. The exception to this approach occurs when the act of rigidizing the CSO to Servicer and/or berthing interface also, simultaneously, mates the power and data connectors, i.e. push-pin connectors. The Remote Servicing block (7.6) in Figure 1 and Figure 2 considers the scenario where wireless power and/or data transfer are utilized in mission operations.

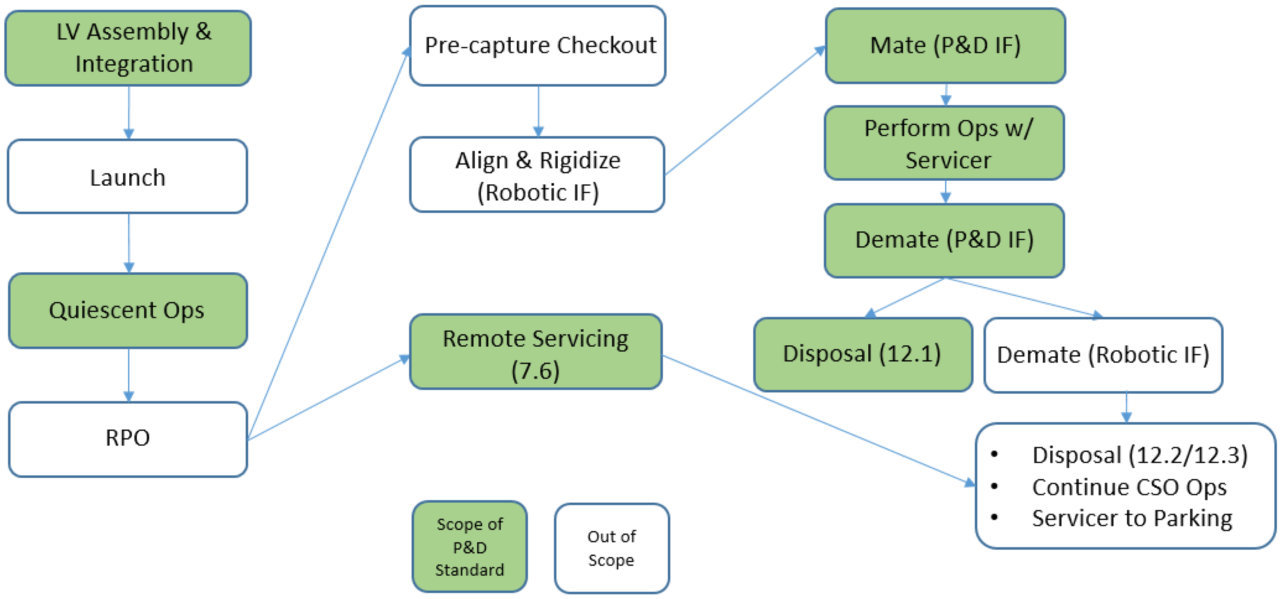


Figure 2 ConOps and Scope Diagram for Power and Data Interfaces

3 Normative References

The following documents, as applicable to specific concept /architecture, are references of other existing standards that should be applied as appropriate to power and data interfaces or an equivalent existing Aerospace standard proposed by the developing authority. Use of this standard can be adapted or tailored, including substitution of governing documents to standards preferred by the government, agency, company, or other organization.

1. ISO 24330 Space Systems – Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS) Programmatic Principles and Practices

2. NASA-STD-8739 Series - For applicable to flight article general & electrical workmanship and software standards and qualification

3. SLS-SPEC-159 - Cross-Program Design Specification for Natural Environments (DSNE)

4. NASA-STD-6016 - Standard Materials and Processes Requirements for Spacecraft

5. NASA Contractor Report 4661 Part 1, document number 19960000860 - Space Environmental Effects on Spacecraft: LEO Materials Selection Guide

6. NASA Technical Publication 1999-209260, document number 19990064119 - Material Selection Guidelines to Limit Atomic Oxygen Effects on Spacecraft Surfaces

7. NASA-STD-5017 - Design and Development Requirements for Mechanisms

8. SMC Standard SMC-S-008 - Space and Missile Systems Center Standard Electromagnetic Compatibility Requirements for Space Equipment and Systems

9. SSP 30256:001 Rev F - EVA Standard ICD

10. ECSS-Q-ST-70C Rev.2 and ECSS-Q-ST-70-71C Rev.1 - Space product assurance Materials, mechanical parts and processes

11. EEE-INST-002 - Instructions for EEE Parts Selection, Screening, Qualification, and Derating

12. AIAA G-042-1991 - Guide to Design for On-Orbit Spacecraft Servicing

13. MIL-STD-1553 - Department of Defense Interface Standard: Digital Time Division Command/Response Multiplex Data Bus

14. JSC 64399 - Handbook for Designing MMOD Protection

15. NASA-HDBK-4002B – Mitigating In-Space Charging Effects—A Guideline

16. GSFC-STD-7000B – General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects

17. MIL-STD-461G – Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

18. ECSS-E-ST-50-13C – Interface and Communication Protocol for MIL-STD-155B Bus Data Onboard Spacecraft

19. ECSS-E-ST-50-12C – Space Wire – Links, Nodes, Routers, and Networks

20. ANSI/TIA/EIA-644 – Electrical Characteristics of Low Voltage Differential Signaling (LVDS) Interface Circuits

21. IEEE 802.3 - Ethernet Working Group

22. ARINC 664-P2 – Ethernet Physical and Data Link Layer Specification

23. NASA-STD-6001B w/CHANGE 2 – Flammability, Offgassing, and Compatibility Requirements and Test Procedure

24. IEST-STD-CC1246D Product Cleanliness Levels – Applications, Requirements, Determination Details
25. ECSS-E-ST-50-14C Spacecraft discrete interfaces (31 July 2008)

26. HFTA-010.0: Physical Layer Performance: Testing the Bit Error Ratio (BER)

27. IEC 61000-4-2 Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test

28. AIAA S-158 DRAFT, Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS)—Prepared Free-Flyer Capture and Release.

29. MSFC-PROC-547 Rev. E, “MSFC Technical Standard: Polyurethane Coating, Application of”, 13 June 2014.

30. NASA Report CR-1999-209008, Wilkes D R, “Thermal Control Surfaces Experiment”, NASA MSFC, Jan. 1999.

31. CCSDS 880.0-G-3 Wireless Network Communications Overview for Space Mission Operations

32. Brusse J. A., et al. Tin Whiskers: Attributes and Mitigation, CARTS 2002: 22nd Capacitor and Resistor Technology Symposium, 25-29 March 2002.

33. ECSS-E-ST-33-01C Space Engineering: Mechanisms (6 Mar 2009)

34. GSFC 420-01-09 Change 01 6-22-2015, External Payloads Proposer’s Guide to the International Space Station

35. CCSDS 141.0-B-1 Optical Communications Physical Layer

4 Terms and Definitions

For the purposes of this document, the CONFERS Lexicon terms and definitions apply. Terms which are not in the CONFERS Lexicon at the time of publication of this document will be added to the Lexicon after publication.

Berthing (verb): The act of effecting a rigid connection between a Servicing Spacecraft and a Client Space Object with the aid of a robotic arm.

Capture: The act of establishing a physical connection between two space objects.

Capture Interface: Interface intended for soft and/or hard capture in any of the following manners: docking, grapple, berthing.

Client: Organization contracting for the service.

Client Space Object: The space object being serviced by the Servicer spacecraft.

Docking (verb): The act of effecting a rigid connection between two satellites without the aid of a robotic arm.

Free-Flyer Capture Operations: A subset of proximity operations where the Servicer Spacecraft and Client Space Object intentionally perform mutually agreed actions to make and maintain physical contact.

Free-flyer: orbiting objects with no mechanical connection prior to initiation of capture operations.

Grapple: First contact leading to a Berthing operation with the aid of a robotic arm.

Hard Capture: Final rigid connection between spacecrafts; also period where spacecrafts are physically mated, and servicing activities may commence.

Prepared: Client Space Object equipped with interfaces and accommodations intentionally designed to enable in-space servicing.

Passive Capture System: Traditionally on the Client Space Object, the passive system involved in mating the Client Space Object and Servicer Spacecraft.

Rendezvous: Process wherein two space objects (artificial or natural body) are intentionally brought close together through a series of orbital maneuvers at a planned time and place.

Servicer: An entity/organization that provides On-Orbit servicing operations.

Servicer Spacecraft: Spacecraft performing the On-Orbit Servicing action.

5 Power and Data System Requirements and Recommendations

5.1 Power and Data General System Requirements

This section addresses the general power and data system level requirements that apply to the client, servicer, interface, and generally during pre-launch integration and in-space assembly and manufacturing.

5.1.1 Connector Selection Overview

The selection of connectors to use for Power and Data interfaces should take into account the specific parts requirement of the other connectors already in use in the program, but adds the mechanical requirements needed for a blind mate or vision-guided mate. The former part of these requirements include the normal EEE selection criteria such as screening, materials, temperature range, outgassing requirements, etc. These are normally per Section C2 of EEE-INST-002 for many NASA programs and are discussed in later sections. For the additional mechanical aspects, the connector should be used in concert with a mechanical design to take into account the expected maximum misalignment between the mating halves. The source of these misalignments can include temperature difference of the two halves as well as mechanical alignment uncertainty. Features to handle this could include a suspension system to float or position the connector, as well as generous lead-in features to guide the two halves to a successful mate. In addition, attention should be paid to the associated harnessing as their bulk can impede the motion of the connector that was assumed by the designer. Proper dressing of harnesses include suitable service loops and strain relief.

One detail that may be useful is to consider a connector with multiple pin lengths to control which circuits get connected first. It may be beneficial to connect system return between the two sides first. There is expected to be a charge equalization feature in place to handle differential spacecraft charging of the respective structure/chassis, but the connection between signal/power circuits and chassis is commonly done via a Single Point Ground. Since this resides on one side of the interface, there may be some small current flow to equalize the two circuits on initial contact. This current may be damaging if the first contact closed is a sensitive signal circuit. Of course it is recommended to power down or de-energize the connector for mating. This minimizes current flow and arcing that may compromise the contact surfaces.

Expanding the focus out a bit from the connector itself, it is recommended to have dust guards to prevent the intrusion of Foreign Objects into the mating faces of the connectors. This FOD can short out pins or prevent the insertion of a pin into a socket. This protective feature has in the past been a challenge in itself to accommodate without interfering with the main goal of the connector, so careful design and a test program is needed here to iterate on the final design. Usually, to reduce the number of actuators (motors), the same action that mates the connector is used to first push the covers out of the way. Combining the pushing of covers out of the way with mating may require a longer stroke of the mechanism. Proper sequencing in the mechanism is usually then needed to properly separate the actions.

5.1.2 Foreign Object Debris (FOD) and Cleanliness

The de-mating and mating of flight hardware connectors on the ground generally requires procedures to ensure that connectors have no bent pins and no Foreign Object Debris (FOD) that could result in a short circuit or failure to mate. This includes use of connector covers, and in some cases “connector savers” which are non-flight short extenders which reduce the number of mate/de-mate cycles of flight connectors and reduce the flight connector’s exposure to damage. These procedures include an inspection immediately prior to mating for bent pins and FOD. In space, an astronaut can perform this function, and historically astronauts have a contingency tool available to straighten bent pins or remove debris, similar to what a technician would have on the ground.

For robotic operations, various approaches have been used successfully, or are planned for upcoming missions.

- Perform visual inspections via cameras before and/or after mate/demate actions.
- Protect pins and sockets behind a contamination shield in the form of doors, louvers or other features, except during mating operations, making inspection not necessary.
    - Note that these features can double as an EMI shield, if conductive.
- Accept the risk of mating exposed connectors without an inspection step, by mitigating the bent pin and FOD risks via other means.

A special case is the electrical connection to the launch vehicle (LV). Detailed guidance is provided in the user's guide for the particular LV, and later in the interface control document. A satellite will have connections to the LV through connectors at the separation plane, where the satellite is attached to the LV. This is typically a clamp-band system attaching two halves of a ring, with springs to cause the two halves to separate once the clamp band is released. At the interface are connectors which separate at that plane. The spacecraft side is exposed to the environment after that separation, and is potentially a source of EMI if the connector pins and wires are allowed to act as an antenna.

Connector savers are often used to prevent over-exertion and over-use of connector interfaces and preserve their life.

5.1.2.1.1 Connector savers should be used during the build, integration and test of the power and data connectors, depending on the space asset’s constraints and requirements.

Connector covers are also used as ground support equipment (GSE) during the build, integration and test of power and data connectors. Connector covers prevent ingress of Foreign Object Debris (FOD) into the connector interface and protect the components from damage due to handling and shipment.

5.1.3 Mission Safety and Reliability

Top level program requirements are frequently the driving factor in system design for fault tolerance. NASA crewed spacecraft requirements traditionally impose dual fault tolerance requirements for critical systems where failures have limited time to effect, and no abort capability. Single fault tolerant systems are more common through traditional spacecraft systems.

5.1.3.1.1 The system shall be dual fault tolerant to any credible catastrophic hazard (on-orbit explosion of Servicer Spacecraft or Client Space Object or both).

5.1.3.1.2 The system shall be single fault tolerant to any credible critical hazard (loss of mission transfer operational capability).

5.1.3.1.3 Probabilities of hazard occurrence shall be taken into consideration when determining the level of fault tolerance. Where determined as non-credible or extremely highly unlikely by design, qualification or test, the documented risk may be accepted.

The entire service life of the servicing and client spacecraft should be determined early in the spacecraft system design and propagate down to component requirements. Examples of factors to be used in these assessments include number of ground and on-orbit engagements, thermal cycles, etc.

5.1.3.1.4 Autonomy and fault management systems shall be incorporated into the servicer and client spacecraft systems to safely monitor the power and data transfer process, detect anomalies, and safe the system to prevent other critical failures.

5.1.3.1.5 To minimize EMI/EMC problems between the Servicer and Client Spacecraft, all electronics and control system parts shall be designed and selected in accordance with space rating using such standards as GSFC-EEE-INST-002, Instructions for electrical, electronic, and electromechanical (EEE) Parts Selection, Screening, Qualification, and Derating or equivalent.

5.1.3.1.6 Electrical workmanship and software standards (if utilized) and qualification shall meet the requirements as outlined in NASA-STD-8739 series for applicable flight article design, development and test.

5.1.3.1.7 Electrical Bonding of the interface shall be mitigated throughout capturing, docking, or berthing and combined operations (Reference NASA-STD-4003 or equivalent).

5.1.3.1.8 Mechanical fasteners shall utilize recommendations of NASA 540-PG-8072.1.2, Mechanical Fastener Torque Guidelines and NASA 541-PG-8072.1.2, Fastener Integrity Requirements or equivalent in design of interface assemblies.

5.1.3.1.9 Per mission-specific requirements, representative testing shall occur at the appropriate system and subsystem level in flight-like environments, including thermal, thermal vacuum, EMI/EMC, vibration, and shock testing.

5.1.3.1.10 For robotic applications, test beds representative of the robotic system characteristics shall be used to verify and validate the performance of the power and data connectors.

5.2 Operational Requirements (CONOPS)

The CONOPS for power and data interfaces follow those shown in Figure 2 above.

5.2.1 Launch Vehicle Assembly & Integration

5.2.1.1.1 The vehicle I&T and QA functions shall ensure that fit checks and functional checks have been performed and properly documented for systems that the power and data interfaces will mate to in flight.

5.2.1.1.2 The vehicle I&T and QA functions shall remove any connector savers and connector covers, following ‘remove before flight’ protocols, and inspect the exposed connectors for bent pins and foreign object debris (FOD).

5.2.1.1.3 Appropriate levels of security shall be implemented in order to prevent threatening agents from impacting the integrity of power and data connectors, and by extension, the spacecraft, during launch vehicle assembly and integration.

5.2.2 Quiescent Operations

5.2.2.1.1 The spacecraft operations function shall perform periodic maintenance as needed to ensure the proper operation of any connector advance or retract mechanisms by exercising the mechanism.

5.2.2.1.2 The spacecraft operations function should protect exposed connectors from environmental exposures, such as overheating or UV exposure.

5.2.3 Remote Servicing

These requirements consider the scenario where wireless power and/or data transfer are utilized in mission operations.

5.2.3.1.1 For power and/or data connections which are remote, yet need to be aligned to within a specified range of relative pose for transmission, the spacecraft operations function shall confirm that telemetry indicators have the correct state, and any camera views indicate an acceptable geometry configuration.

5.2.3.1.2 The spacecraft operations function shall confirm that all preparations are complete before authorization to proceed with transmission.

5.2.3.1.3 The spacecraft operations function shall command the transmission operation to commence.

5.2.3.1.4 The spacecraft operations function shall verify completion of the transmission operation, and any telemetry indicators have the correct state.

5.2.3.1.5 The spacecraft operations function shall return the transmitters to a de-energized state.

5.2.4 Mate of Power and Data Interfaces

5.2.4.1.1 The spacecraft operations function shall confirm that prior operations needed to align connectors to within their specified alignment tolerances for mating have been performed, and any telemetry indicators have the correct state, and any camera views of the connectors indicate an acceptable configuration.

5.2.4.1.2 The spacecraft operations function shall acquire imagery of connectors prior to mating to confirm that pins are not bent and the absence of FOD in the connectors (if possible).

5.2.4.1.3 The spacecraft operations function shall remove power and deactivate data bus signals prior to mating of connectors, unless these have been proven safe under space environmental conditions.

5.2.4.1.4 The spacecraft operations function shall confirm that all preparations are complete before authorization to proceed with connector mating.

5.2.4.1.5 The spacecraft operations function shall command the mating operation to commence.

5.2.4.1.6 The spacecraft operations function shall verify completion of the mating operation, and any telemetry indicators have the correct state.

5.2.4.1.7 The spacecraft operations function shall apply power and activate data bus signals after mating is complete.

5.2.4.1.8 The spacecraft operations function shall adjust flight software to accommodate the new electrical configuration resulting from the mating of the power and data connections.

5.2.5 Perform Operations with the Servicer

5.2.5.1.1 The spacecraft operations function shall apply and remove power (heater power, operational power, etc.) through the mated power interfaces as needed to perform servicing functions.

5.2.5.1.2 The spacecraft operations function shall sense telemetry status (status, temperature, etc.) as needed to perform servicing functions.

5.2.5.1.3 The spacecraft operations function shall flow data over data bus channels as needed to perform servicing functions.

5.2.6 De-mate Power and Data Interfaces

5.2.6.1.1 The spacecraft operations function shall remove power and deactivate data bus signals prior to de-mating of connectors, unless these have been proven safe under space environmental conditions.

5.2.6.1.2 The spacecraft operations function shall confirm that all preparations are complete before authorization to proceed with connector de-mating.

5.2.6.1.3 The spacecraft operations function shall command the de-mating operation to commence.

5.2.6.1.4 The spacecraft operations function shall verify completion of the de-mating operation, and any telemetry indicators have the correct state.

5.2.6.1.5 The spacecraft operations function shall adjust flight software to accommodate the new electrical configuration resulting from the de-mating of the power and data connections.

5.2.7 Disposal

Case 1: CSO being transported to a disposal orbit is capable of passivation under ground control.

5.2.7.1.1 Power and data connections shall be disconnected in a way that will not impede the CSO's ability to perform its passivation process under ground control.

Case 2: CSO being transported to a disposal orbit needs commands relayed to it prior to release, and will then perform an automated disposal sequence.

5.2.7.1.2 The power and data connections shall be maintained until all commanding needed to prepare for CSO passivation are completed and verified.

5.2.7.1.3 Power and data connections shall be disconnected in a way that will not impede the CSO's ability to perform its pre-programmed passivation process.

Case 3: CSO being transported to a disposal orbit needs to be fully passivated while attached to the servicer, before being released.

5.2.7.1.4 The power and data connections shall be maintained until the CSO has been fully passivated.

5.2.7.1.5 After confirmation of CSO passivation, the power and data connections will be disconnected, followed by mechanical release and departure.

5.3 Physical Architecture Requirements

5.3.1 Part Selection and Sizing Considerations

5.3.1.1.1 When selecting connectors and contacts, sizing considerations should follow derating tables provided by either SSP 30312, EEE-INST-002 or ECSS-Q-ST-30-11C, depending on project requirements. Harness design should take into account special derating rules for bundles. There is no general limitation in terms of power transfer as long as derating rules are properly followed.

It is preferred to keep power lines separated from other sensitive signals, either by passing them through a different connector or adding ground pins between signals to provide an isolation barrier. The MIL-HDBK-83575 standard provides guidance to identify and categorize signals for proper segregation.

As discussed in Section 5.2, for any power transfer between spacecraft interfaces, de-energizing should be used to avoid any arcing during mating/de-mating operations. This should be ensured by the side providing the power, also to avoid live open connectors. Relays or solid state relays (SSRs) are usually implemented, with voltage feedback to confirm no voltage is present on the interface prior to mating.

5.3.1.1.2 Parts should be selected using the EEE-INST-002 levels, depending on the application criticality.

5.3.1.1.3 Commercial-of-the-shelf (COTS) connectors and wire qualification data or standards should be compared to the EEE-INST-002 to identify any gaps and assess the adequacy of the product.

5.3.2 Mate/De-mate

As discussed in the prior sections, prior to initiating the mate/de-mate sequence between the Servicer and Client Space Object, it is standard practice to de-energize the power and data interfaces. Specifically, there shall be no live power or data connectors prior to mating connectors in orbit.

5.3.2.1.1 Manufacturer ratings shall be followed for contact resistance limits.

5.3.2.1.2 A voltage drop analysis should be performed as it indicates acceptability for the end-to-end connector system. The voltage drop analysis would inform the need for additional parallel contacts.

5.3.2.1.3 The mate and de-mate forces required for connection and disconnection of the Power and Data interfaces should be minimized. The total force for all Power and Data connectors across an interface must be considered with the appropriate factors of safety, given the same device or actuator must engage/disengage all connectors across an interface simultaneously.

Staged connections can also be considered, with the total peak force, during the entire travel of engagement/disengagement, driving the device or actuator sizing.

5.3.2.1.4 The design of the Power and Data components, or the operational constraints of the Power and Data system, shall prevent jamming or overdriving of the active half into the passive half of the connector.

5.3.2.1.5 The device responsible for mating and de-mating the interface shall have the appropriate force margins, per NASA-STD-5017B, over the life of the mission, including all environmental impacts.

The de-mate sequence, especially in the case where the power and data connectors de-mate simultaneously with the rigidized robotic/docking interface, can cause tip-off rates of the Client Space Object.

5.3.2.1.6 The de-mate sequence shall not cause the Client Space Object to tip-off at rates greater than allowable for the given mission profile.

5.3.2.1.7 The electrical interface mate/de-mate capability shall have a qualification level of at least four times the minimum cycle-life-use-margin (including ground test and flight operations) with service life certification.

5.3.3 Cable Harnesses

The design of an in-space power and data interface with a moving connector shall include consideration of the mechanical stiffness of the harness that will move with the moving connector under the range of temperatures it will experience during the mission profile.

5.3.3.1.1 The design of an in-space power and data interface with a moving connector shall consider the lifetime of the harness under repeated flexing during mate and de-mate cycles, including breakage of conductors and wearing and degradation of insulation.

5.3.4 Electrostatic Discharge (ESD) During Ground Handling

Electrostatic discharge (ESD) events can damage electrical hardware, even with considerably low voltage discharge events.

5.3.4.1.1 In order to prevent ESD events during handling, assembly, and test, the design of power and data connectors shall ensure proper grounding/bonding of connectors to chassis and connector back shells.

Proper grounding/bonding of connector also significantly impacts the EMC/EMI performance of the power and data system. For EMI/EMC considerations, refer to Section 5.3.5.

For ESD charging consideration on-orbit, refer to Section 5.5.4.

5.3.5 Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC)

Specific EMI and EMC requirements are mission-specific, with design and verification requirements being specified via contractual specifications.

GSFC-STD-7000B establishes interface and associated verification requirements for the control of EMI emission and susceptibility characteristics of electronic, electrical, and electromechanical equipment and subsystems designed or procured for use on GSFC Spacecraft. Requirements and testing make heavy reference to MIL-STD-461G.

5.3.5.1.1 MIL-STD-461G shall be referenced when designing Power and Data interfaces that require EMI/EMC considerations.

There are 22 test series listed in MIL-STD-461G; while all tests may be required for Class A missions, a shorter more commonly recommended test series are listed in Table 1**.** Testing may be relaxed if intended for CubeSats; and guidelines outlined in GSFC-STD-7000B (Appendix B) indicate that higher risk and reduced scope of testing is acceptable for CubeSats.

Table 1 MIL-STD-461G commonly recommended EMI testing for NASA-STD-7000B

Test	Type
CE102	Conducted Emissions, Power Leads, 150 kHz to 50 MHz
CS101	Conducted Susceptibility, Power Leads, 30 kHz to 150 kHz
CS114	Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads, 10 kHz to 100 MHz
RE102	Radiated Emissions, Electric Field, 2 MHz to 20 GHz
RS103	Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz

5.3.5.1.2 Shielded twisted-pair connections should be implemented to enable gigabit Ethernet connections and minimize potential impacts of EMI/EMC on data connectors. Unshielded wire should be used for power connections.

Connector shielding is one method to mitigate susceptibility to EMI/EMC pulses. The connectors may or may not be electrically connected to the satellite bus frame; if not, a bleed resistor can potentially be added from the connector to the bus frame to mitigate susceptibility to EMI/EMC pulses and ESD.

5.3.6 Blind Mate

Most flight connections of spacecraft connectors are performed on the ground by technicians, and include small screws to hold the connectors together or some other threaded interface such as on a coaxial connector. A connector that is mated and de-mated by activation of a mechanism are of the blind mate type. These are slid together and held in place by a mechanism, and pulled apart by a mechanism.

5.3.6.1.1 A blind mate connector shall tolerate a specified level of misalignment during mating by self-aligning features such as a lead-in on the shell or guide pins that refine the alignment of pins to sockets before pins make contact.

5.3.6.1.2 A blind mate connector actuation system shall provide a level of alignment that satisfies the allowed misalignment of the connector system.

5.3.6.1.3 A blind mate connector system shall ensure that at no point during the mate or de-mate sequence is it possible for pins to make contact with structure such as the shell of the other connector. Note that one solution for this is to use a 'scoop-proof' connector with pins recessed beyond where the mating connector can possibly contact them.

Refer to the Appendix Sections 6.1 and 6.2 for blind mate connectors with space flight heritage.

5.3.7 Misalignment Tolerance

Tolerance to misalignments is a key topic for power and data interfaces. There are two primary scenarios in which power and data interfaces are mated. First is the engaging of a connector that is at the end of a harness, generally called a plug, being attached to a receptacle, generally called a jack. Securing the connection mechanically may be achieved simply by engaging the plug into the jack, or it may require a secondary locking mechanism, such as a clamp or screws. Second is a two-stage attachment, in which a mechanical locking occurs first, after which a plug is advanced into a plug by a second mechanism.

Plug/Jack First

5.3.7.1.1 The plug/jack combination shall have a specified misalignment range in which the initiation of engagement is assured.

Rationale: initiation of engagement means that any post enters its corresponding hole.

5.3.7.1.2 The plug/jack combination shall have a specified misalignment range that allows full engagement.

5.3.7.1.3 The plug/jack combination shall have a specified misalignment range once fully seated and locked, for which all electrical requirements are met.

5.3.7.1.4 The plug/jack combination shall have specified forces and torques which can be tolerated during the engagement process.

Rationale: This will guide requirements on compliance.

5.3.7.1.5 The plug/jack combination shall have a specified maximum insertion force which will ensure full seating under the specified range of misalignment conditions.

5.3.7.1.6 If the plug and jack are mated after another means of locking the two halves of the system together, then the misalignments in the locking system shall provide for keeping the plug/jack within their limits for initiation of engagement.

Note: a similar set of requirements are needed for the mechanical locking system that precedes plug/jack engagement, but is out of scope for this standard.

5.3.7.1.7 A misalignment budget shall specify the 6-DOF limits under which the interfaces would be expected to mate after rigidization under worst-case mission specific CONOPS and associated stacked tolerances. Guidance on mechanical tolerances can be found in NASA-STD-5017.

Guidance:

As interfaces come together, include either guide rails or guide pins providing increasingly precise alignment. By the time the power/data connector faces come into contact, the alignment of those connectors is within the capability of those connectors for successful mating. If precise alignment cannot be ensured, consider scoop-proof connectors, such that mechanical engagement occurs before pins touch sockets or any other part of the socket side connector, ensuring pins enter sockets properly.

If a human in situ, human teleoperator, or autonomous robot agent will be actuating the connectors together and need feedback, provide visual cues that provide sufficient precision. If the agent, even with the visual cues, cannot achieve sufficient precision, then implement additional mechanical guides to further refine alignment during mating. The exit conditions of one stage of engagement should satisfy the needs for entering the next stage of engagement.

5.3.8 Compliance Mechanisms

The size and nature of Power and Data components require provision for potential misalignment during the mating process. This can be mitigated via compliant features in the Power and Data interface design.

5.3.8.1.1 The Power and Data interface design should incorporate methods to accurately mate with compliance across individual interfaces and compliance across multiple ports when applicable to mission requirements.

5.3.8.1.2 The Power and Data interface should include compliance in the insertion/retraction (axial), lateral, and angular directions.

In general, where there is a cascade of alignment stages, the margins should be distributed accordingly per the specific power and data connector system design, e.g. one level provides 50% margin against what you need for next level of compliance. This distribution is dependent on connector selection and system margin allocation, but this general methodology applies.

Compliance considerations are applicable prior to and after mating. Material mismatches in the connectors or in their mounting structures can demand compliance to accommodate differences in coefficients of thermal expansion.

Refer to the Appendix Section 6.1regarding specifications for the Souriau robotic connectors used on the SSRMS (Space Station Remote Manipulator System).

5.3.9 Mounting Structure

The Power and Data mounting structure refers to the material/panel/ISAM interface to which each side of a connector half is mounted, including any components accommodating connector misalignment and compliance.

5.3.9.1.1 The Power and Data components should be engaged after rigidization of the ISAM (docking/berthing/robotic/grapple) interface and separated from the structural load path of such interface. Exceptions can occur where, for example, the structural load path of the ISAM interface is considered the ground for a power and data circuit, or with the use of push-pin connectors, as described in Section 2.1.

5.3.9.1.2 Engineering analyses shall account for the structural mounting boundary conditions, including:

- Stiffness
- Mounting alignment tolerances
- Temperature-induced distortions
- Load-induced distortions
- Interface friction

Reference: NASA-STD-5017B Design and Development Requirements for Mechanisms

5.3.9.1.3 The Power and Data interface mounting structure shall be designed to accommodate impact forces and torques within established margins.

5.3.9.1.4 Materials shall be selected in accordance with NASA-STD-6016 Standard Materials and Processes Requirements for Spacecraft or/and in accordance with ECSS-Q-ST-70C Rev.2 and ECSS-Q-ST-70-71C Rev.1 Space Product Assurance Materials, Mechanical Parts and Processes.

5.3.9.1.5 The mated load capacity shall be defined with consideration to all forces applied to the Power and Data interface mounting structure including; axial, radial, torsion, vibration and shock. If the connectors are not mated for launch, the vibration and shock stresses should be evaluated in their respective launch state.

The connector structure needs to be robust enough to contend with multiple loads while remaining optimized for spaceflight in weight and volumetric characteristics.

5.3.9.1.6 The Power and Data interface mounting structure shall be designed to retain mechanical shape and function while bearing and offsetting reaction forces experienced during all phases of connected ground operations and flight.

Maintaining a precise known location and orientation of the Power and Data connectors is crucial to assembling components on orbit, and the mounting structure should be able to cope with reaction forces generated by installation, launch conditions, thermal stress, docking, mating, and on-orbit operations within a reasonably defined envelope.

5.3.9.1.7 The Power and Data interface mounting structure should be designed to obstruct inadvertent contact of the connector pins with surrounding hardware, tooling, or opposite connector, via a protective physical barrier for sensitive current-carrying components.

This could also be accomplished by including a connector flap/door system to exclude FOD/MMOD from entering the connector during detached stages of operation. See Section 5.5.6. Inadvertent contact may also be avoided by utilizing blind mate connectors, which may require special consideration for the mounting structure of the Power and Data connectors. See Section 5.3.6 for details on Scoop-Proof connectors.

5.3.10 Operating Motion

The operating motion of Power and Data connectors refers to the direction and magnitude of the relative change in position between the active and passive connector halves.

5.3.10.1.1 The direction of motion of the Power and Data interface connectors should be linear, within the tolerance specified by the mating connector halves, while also considering the misalignment accommodation of the compliance mechanism, if applicable.

5.3.10.1.2 The Power and Data interface connector insertion and retraction speeds shall be within the constraints specified for the connector components and within the capabilities of the actuating device(s), with appropriate margins.

5.3.10.1.3 The control system of the actuating device(s) shall ensure the active side of the connector interface engages at or above the minimum distance required for reliable performance, while also preventing over travel below the maximum limit as indicated by the most sensitive component(s) in the connector stack-up.

5.3.10.1.4 The travel of the compliance mechanism, if applicable, shall be considered for the total travel permitted for the connector system.

5.4 Data Protocol Requirements

5.4.1 Functional Requirements

Data protocols for Power and Data interfaces vary based on the mission design and client and user preferences. The following features should be considered when selecting a communication type for spacecraft design:

- Easy to implement with a good availability of commercial off-the-shelf or space grade parts,
- A standard is available, providing guidance for design and verification for the implementation,
- Widely used in the industry, to increase inter-compatibility and benefits from a large community support,
- Determinism of communication timing depending on mission criticality,
- Low power to reduce constraints on spacecraft power sources and thermal dissipation,
- Data rate or type in line with the Command and Data Handling (C&DH) needs and allowing for some growth (i.e. design trade between speed and signal integrity),
- Scalable, to allow adding additional devices to the system such as visiting servicing modules,
- Reliable, providing options to implement redundancy, to use extended temperature range and radiation hardened components, and good immunity to EMC environment.

5.4.1.1.1 When selecting communication (across Servicer to Client Space Object) types for OOS support, the following functions should be considered at a minimum:

- Electrical mating indication (loopback reading)
- Thermal control (may be covered by health monitoring)
- Spacecraft identification
- Spacecraft capabilities identification
- Command/Telemetry
  - Spacecraft control or manipulation
  - Installation of devices (enable/disable/basic testing)
  - Health monitoring

5.4.2 Data Types and Physical Media

The most basic data interfaces are commonly referred as analog and discrete (binary) lines. Those lines are usually used for simple control such as sensors (e.g. thermistors) and bi-level command and status (digital or mechanical e.g. relays). Designers should refer to the ECSS-E-ST-50-14C for the implementation of such lines. Depending on the architecture, additional considerations to mitigate common mode noise should be implemented (e.g. opto-isolators, extended voltage range).

For more advanced communication, a data bus will be selected to support a set of command and telemetry messages that can be transmitted at higher speeds. Those communication buses are usually implemented via:

- Wired connections
  - Copper cables (most common)
  - Fiber optics cables (glass cable, light travels through)
- Wireless connections
  - Short range (e.g. RF mmWave)

  - Medium range (e.g. WiFi, LiFi)

Wired data links provide better immunity to EMC environment and guarantee a better availability (less interaction with external physical elements). Copper medium offers excellent and proven reliability when used properly (twisted pairs, shielding), however they can be sensitive to EMC environment. Fiber optics provide complete immunity to EMI but are usually more sensitive to the radiation environment. Future power and data interfaces will be a mix of wired and wireless, depending on future design choices. The prevalence of wireless devices on Earth and the flexibility wireless provides may tip the scales in the favor of wireless for satellite servicing applications. An example is the use of WiFi on the ISS for external payloads.

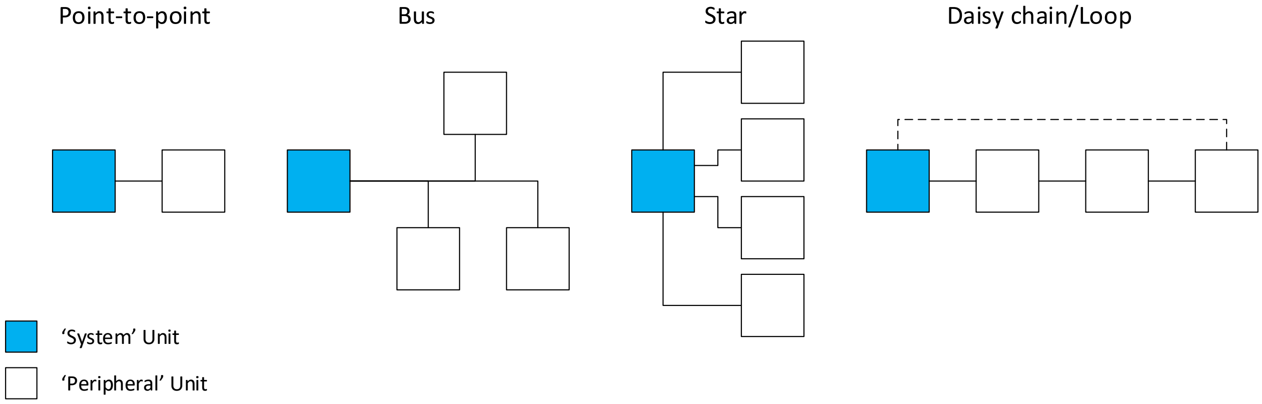
5.4.2.1.1 For wireless network communications standards, refer to CCSDS 880.0-G-3.

5.4.2.1.2 For optical communications standards, refer to CCSDS 141.0-B-1.

The physical layer implementation details are usually provided in the corresponding standard.

5.4.3 Communication Standards and Topologies

Communication links can be based on different topologies influenced by multiple factors. Physical architecture, control behavior, redundancy strategy, speed and cost will play a role when selecting the topology that will work best for a specific application. Main topologies are point-to-point, standard bus, star, and daisy chain/loop.



For OOS, the configuration will generally involve two parties connected via one link, and this link could be part of any type of topologies.

There are a large number of communication protocols for data transfer that are used throughout space systems. These include but are not limited to RS-422, RS-232, I2C, SPI, Spacewire, Ethernet, 1553, CanBus, etc. For future ISAM applications there may be combination of any of these that are used or considered. For discussion some of the current popular communication protocols that are prevalent inside a single spacecraft as data transport buses are discussed below:

- MIL-STD-1553
- SpaceWire
- Ethernet

Other communication standards could also be considered:

- CAN: simple, real-time and low-cost bus that is natively supported by many microcontrollers, processors and system-on-chip with a standard bus topology and low-speed data rate (< 1 Mbit/s)

- RS-422: simple, robust and low-cost bus also supported by many COTS devices, the standard only provides a physical layer specification while the protocol is left to the user to implement
- AFDX (ARINC 664): 100BASE-TX network based on Ethernet physical layer, widely used in the aviation industry for real-time deterministic applications
- EtherCAT: 100BASE-TX network based on Ethernet physical layer and compatible with many topologies which makes it ideal for complex mixed star/distributed systems such as a robotic arm or a spacecraft
- Time Triggered Ethernet (TTE): used on Orion, Ariane 6 (European space launcher) and the Lunar Gateway program, this Ethernet-based 100BASE-TX and 1000BASE-T network can provide up to triple redundancy with fully deterministic scheduling also compatible with AFDX (ARINC 664) and standard Ethernet traffic
- Time Sensitive Network (TSN): developed by IEEE with a principle similar to TTE, this network provide deterministic scheduling and is being adopted by several COTS manufacturers providing a more affordable alternative to TTE

5.4.3.1 Consideration of Termination of Communication Links

Termination of communication links will have to be evaluated depending on the chosen topology and standard. For point-to-point and derived topologies (star, daisy-chain), the link can usually be left open since other nodes are isolated from this link so there will be no impact in terms of signal integrity (impedance matching).

5.4.3.1.1 For a bus topology using standards such as MIL-STD-1553 or CAN, active bus termination techniques will have to be employed to guarantee proper impedance matching in all configurations (e.g., use of relays to switch termination resistors).

5.4.3.2 MIL-STD-1553

MIL-STD-1553 is simple, deterministic and reliable. However, it is getting supplanted by newer communication standards that provides more flexibility and capabilities on several aspects. This standard is based on a redundant bus topology with a master controlling up to 31 slaves, with a speed of 1 Mbit/s. The number of contacts required is 2.

Standard compliance:

5.4.3.1.2 All devices should adhere to ECSS-E-ST-50-13C to ensure interoperability, and follow the guidelines for the physical and logical implementation

Physical layer:

5.4.3.1.3 The stubs (small cable runs coming off main bus to different devices) should use the transformer-coupled method for fault tolerance

5.4.3.1.4 Bus termination (resistor) connect/disconnect schemes should be implemented for accommodating the Servicing Spacecraft.

This bus uses a STP (Shielded Twisted Pair) for a single channel.

The standard does not specify a connector for any applications, so the choice is left to the designer to select the most appropriate connector for mating/demating purposes (rectangular, circular, twinax/triax, etc.)

- Topology:

    - The standard implements a dual-channel configuration for redundancy, however it could be decided to use only one channel if redundancy is not critical to save costs
- A network on one vehicle should reserve a remote terminal ID on the other vehicle for use after they are connected.Data rate and bandwidth:
    - The mission should not require exchange of bandwidth-consuming data such as video since the speed is limited to 1 Mbit/s

5.4.3.3 SpaceWire

SpaceWire is a high-speed full-duplex communication standard that has been developed by ESA in collaboration with other international agencies. The goal was to develop a simple but modern standard to provide a suitable communication network for high-performance Command & Data Handling (C&DH) systems. It is based on a point-to-point topology that can be expanded into a star topology with the use of routing devices, and can transfer data up to 200 Mbit/s.

Standard compliance:

5.4.3.1.5 All devices should adhere to ECSS-E-ST-50-12C and ANSI/TIA/EIA-644 (Low Voltage Differential Signaling) to ensure interoperability, and follow the guidelines for physical and logical implementation.

Physical layer:

- The standard recommends the use of micro-miniature D-type (i.e. micro-D) but quadrax and octax could be considered for improved signal integrity (avoids exposure of unshielded wires and untwisted pairs at connector termination)
- SpaceWire has a limited length of 10 meters between two devices that could lead to constraints on devices location or cable routing
- Number of contacts: 8
    - This bus uses 4 x STP (Shielded Twisted Pair) for a single end-to-end link

Topology:

- Point-to-point and star are usually implemented and redundancy can be added for improved reliability of the system (mission dependent)

Data rate and bandwidth:

- Provides a much higher data rate than MIL-STD-1553 and other standards (CAN, RS-422) that allows more complex processing operations and high-resolution media processing (images, video, sound)
- With the emergence of multi-core high-frequency processing platform and the multiplication of high-resolution video systems, other standards such as Ethernet (1 Gbit/s up to 100Gbit/s) could be considered to go beyond the maximum speed offered by SpaceWire (200 Mbit/s)
- It should be noted that SpaceWire is not deterministic (some variants exist to add this functionality), so it should be used with caution for systems where real-time behavior is needed to ensure safety of the mission

5.4.3.4 Ethernet

Ethernet is used worldwide in all domains, including aviation, military and space. Many variations of Ethernet are available and its physical layer is used by many other standards like AFDX, EtherCAT, TTE and TSN. It is based on a point-to-point and star topology with speeds ranging from 10 Mbit/s up to 100 Gbit/s for space applications.

Standard compliance:

5.4.3.1.5.1 All devices should adhere to IEEE 802.3 with the specific version of the chosen standard to ensure interoperability, and follow the guidelines for physical and logical implementation.

Physical layer:

- ARINC 664-P2 provides a comprehensive guideline for Ethernet-based networks for avionics applications and should be taken as a starting point when developing a network
- Ethernet is more tolerant than SpaceWire and can easily accommodate runs longer than 50 meters
- Number of contacts: usually 4 or 8 depending on application (100BASE-TX, 1000BASE-T, etc.)
    - The ARINC 664-P2 details preferred connectors, contacts and pinout topology
- Depending on the application, different grades of cables and connectors can be considered: when the system is complex (multiple bulkheads and long runs) it is recommended to use higher quality contacts such as quadrax and octax to ensure the best signal integrity

Topology:

- Point-to-point and star are usually implemented and redundancy can be added for improved reliability of the system (mission dependent)

Data rate and bandwidth:

- Depending on the medium (copper or fiber), the data rate can go up to 100 Gbit/s addressing even the most demanding applications
- It should be noted that Ethernet by itself is not deterministic, this is why critical missions will use Ethernet-based standards like AFDX, EtherCAT TTE or TSN. If used in a controlled fashion (e.g. ensuring bandwidth margins, establishing priorities with VLANs), standard Ethernet protocols (UDP, TCP) could certainly be used for On-Orbit Servicing

5.4.4 Data Rates

OOS that involves robotics also involves high update rate control of robotic joints, sensors such as force-torque sensors being sampled at high update rates, and high resolution cameras being used for machine vision being sampled at fairly high update rates. The data rates can be quite high compared to normal spacecraft bus functions. This can extend to high downlink rates for providing robot operators a real-time situational awareness during robotic operations, plus a high uplink rate needed to send real-time teleoperations commands. Round trip latency can be a driver as well, as the delay between sending commands from the ground and receiving the telemetry and visual result can affect operator effectiveness, safety, and speed. The combination of high data volumes and low latency mean that onboard data rate capability can be quite high for OOS applications. The need to support high data rate across connections which may be unterminated at some times and connected at other times also drives the command and data handling design.

5.4.4.1.1 The data connection between a servicer spacecraft and CSO shall support the functional interaction, including the full range of possible needs for data throughput.

5.4.4.1.2 The data connection between a servicer spacecraft or CSO and an Orbital Replacement Unit shall support the full range of possible needs for data throughput, including consideration of later versions of the ORU with higher data rate needs than the original version.

If the needs are not known in advance, an example starting point for a new design could be to use recent technologies such as LVDS (e.g. SpaceWire, up to 400 Mbps) or Ethernet-based (TCP/UDP, TSN, EtherCAT, TTE, from 10 Mbps up to 100 Gbps depending on the standard and the physical medium).

Ethernet usually offers the flexibility of auto-negotiation that allows systems with different implementations to be able to communicate at the highest speed available for both parties.

5.4.5 Data Transfer

Effective and reliable data transfer is paramount for ensuring cohesiveness and operational proficiency between ORUs and S/C, as well as among various in-space modules. To facilitate this, data transfer methodologies within ISAM missions can principally be bifurcated into two distinct categories:

5.4.5.1 Physical Connection

Establishing a direct physical data connection entails the utilization of connectors to forge a tangible link through conduits such as copper cables or fiber optics.

- Benefits: Offers a stable and high-fidelity data transmission channel, minimally susceptible to interference.
- Challenges: Requires precision in connection and disconnection maneuvers and may undergo wear and tear with repetitive use.

5.4.5.2 Distant Data Link

This methodology encompasses establishing data communication over a distance, typically deploying Electromagnetic (EM) signals, via two principal avenues:

- Radio Frequency (RF) Communication: Involves broadcasting and receiving data through RF signals, ensuring a wire-free data transfer modality.
- Directed Electromagnetic Beams: Utilizes focused beams of electromagnetic waves, such as Lasers or Infrared (IR), to transmit data between entities in space.

Advantages of Distant Data Link include:

- Reduced Wear and Tear: The absence of physical connectors nullifies the potential for mechanical wear or breakage, especially pivotal for modules that necessitate frequent manipulation.
- Enhanced Robustness: This modality augments the system's robustness by negating physical coupling and decoupling actions, thereby minimizing mechanical vulnerabilities and enhancing compliance during various ISAM operations.

- Distant Communication: Allows handshake and communication protocol without touching interfaces potentially mechanical disturbing the S/C.
- Reduces wire runs within the spacecraft to device mounting locations.

Challenges of Distant Data Link include:

- Interference from radiation environment
- Degradation of optical elements exposed to UV light, ionizing radiation or atomic oxygen.

In engineering data transfer systems, acknowledging and strategically countering the intrinsic challenges of each method is vital. For direct physical connections, this may involve developing connectors resilient to repetitive use and the harsh conditions of space. Meanwhile, for distant data link technologies, ensuring signal integrity against the backdrop of interference is crucial.

Every ISAM mission must meticulously evaluate the pertinent advantages and challenges of each data transfer methodology, adopting a hybridized approach if necessary, to synchronize with the mission's objectives and operational context. Continuous advancements in technology should progressively refine these systems, enhancing the efficacy and reliability of data transfer amidst the rigors of space exploration and utilization. An example of an IR distant data link is provided by the iBOSS iSSI interface in the Appendix.

5.4.6 Signal Integrity

5.4.6.1.1 The designer should refer to the respective protocol standards to implement the best practices depending on the type of physical medium and the envisioned data rate, especially when dealing with speeds above 100 Mbps.

5.4.6.1.2 When using copper medium, it is recommended to use differential pairs and transceivers to reject any common mode-noise from external sources.

Each standard will provide guidance on the parameters to verify during development to ensure the signal going from one device to another device meets the signal quality requirements. A non-exhaustive list of usual parameters include:

- Peak-to-Peak Voltage (Sender and Receiver)
- Maximum Distortion Voltage (Overshoot)
- Rise and Fall Time
- Jitter
- Eye-diagram
- Insertion Loss
- Return Loss
- Crosstalk (for system with multiple signal pairs)

Bit-Error-Rate testing provides a good indicator of the health of the link by catching any dropped bit during data transmission between two devices. Using a binomial distribution function, a test duration can be calculated for a given Confidence Level (CL) and a Bit-Error-Rate target. The technical note “HFTA-010.0: Physical Layer Performance: Testing the Bit Error Ratio (BER)” by Maxim Integrated provides a good overview of the Bit-Error-Rate intent.

Wire selection, connector selection and workmanship are also important factors for Signal Integrity. For Ethernet-based links, ARINC 664P2 provides a list of connectors and contacts type with preferred wiring patterns. Guidance will be usually found in the communication standard.

5.4.6.1.3 Verification by test for Signal Integrity is required to ensure proper margins on signals characteristics for the sending and receiving element.

5.4.6.1.4 Worst-case link should be checked on ground using end-to-end representative cabling and measuring parameters to guarantee adequate margin with respect to the standard.

5.4.6.1.5 Bit-Error-Rate testing should ideally be performed with other services running in adjacent cables to check for any EMC issues.

5.4.6.1.6 Each terminal and its associated cabling will have to pass environmental qualification tests using Flight Software and checking for acceptable communication loss during operations.

5.5 Environmental Requirements

5.5.1 Orbital Environment

The following sections provide requirements and considerations to follow when designing power and data interfaces to meet environmental constraints.

5.5.1.1.1 The orbital conditions for the duration of the power and data interface's life shall be considered. This includes transit, operating, parking, and disposal orbits, if applicable.

5.5.1.1.2 The life of the hardware shall be considered in light of the amount of time the power and data interfaces are coupled and decoupled, i.e. exposed then connected.

5.5.1.1.3 The characteristics of the interfaces at the beginning of life (BOL) and end-of-life (EOL) shall be considered, due to aging in the respective orbital environments experienced by the power and data interfaces.

5.5.1.1.4 The design and hardware shall account for performance degradation over the life of the interfaces and be able to meet minimum performance requirements at end of life.

5.5.2 Ionizing Radiation

The power and data interfaces must be able to withstand the radiation environment applicable throughout the life of the hardware, including transit and operational orbits. Special attention should be paid to unmated and exposed connectors, which are normally not part of flight systems. Vendors of connectors may not have analyzed the connector for direct exposure in this configuration, and material incompatibilities that affect life or performance may exist.

If the vehicle has a radioactive power source, it must be taken into account as an additional source of ionizing radiation.

5.5.2.1.1 The Power and Data interface shall be designed taking into account the ionizing radiation environments per SLS-SPEC-159 Revision I Cross-Program Design Specification for Natural Environments (DSNE), Section 3.3.1 for Total Dose, Section 3.3.2 for Single Event Effects, and Section 3.3.3 for Plasma Charging. For gamma ray consideration, refer to section 3.3.10 Solar Illumination Environment for In-Space Hardware of SLS-SPEC-159 Rev I.

5.5.3 Atomic Oxygen

In LEO, exposure to Atomic Oxygen (AO) is a common threat to S/C components (including the Power and Data connector interface) which may rapidly oxidize and erode if not covered with a protective coating. Even with coatings applied, AO may still erode material. Polymers are particularly susceptible, especially those containing fluorine, which will synergistically accelerate erosion when exposed to elevated UV radiation.

5.5.3.1.1 Power and data interfaces in LEO shall be designed to limit the effects of atomic oxygen (AO) interactions with power and data surfaces so that the components maintain their performance over the life of the mission.

Guidelines for designing interfaces to withstand the LEO/AO environment are provided in:

- NASA Contractor Report 4661 Part 1, Space Environmental Effects on Spacecraft: LEO Materials Selection Guide, document number 19960000860

- NASA Technical Publication 1999-209260 Material Selection Guidelines to Limit Atomic Oxygen Effects on Spacecraft Surfaces, document number 19990064119

5.5.4 Charging Effects

Spacecraft charging is known to be a potential source of damage to spacecraft systems and has even been blamed for total spacecraft loss. NASA-HDBK-4002B [15] describes conditions under which spacecraft charging might be an issue, generally explains why the problem exists, lists typical design solutions, and provides an introduction to the process by which design specifics should be resolved.

Faraday Cage. A Faraday Cage is an enclosure used to block electromagnetic fields. A faraday cage may be formed by a continuous covering of conductive material, or by a mesh of conductive materials with the holes smaller than the characteristic dimension of electromagnetic field [15].

5.5.4.1.1 To the extent possible, shield all electronic elements using a Faraday Cage construction. The primary spacecraft structure, electronic component enclosures, and electrical cable shields should provide a physically and electrically continuous shielded surface around all electronics and wiring [15].

Contact discharge (direct discharge). This consideration is generally reserved for initial contact during free-flyer capture operations. For detailed recommendations, refer to AIAA S-158, Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS)—Prepared Free-Flyer Capture and Release.

5.5.4.1.2 The unit or subsystem, while in its expected operational configuration, shall operate without deviation from its specified performance while an electric arc per IEC 61000-4-2 Level 4 is discharged directly to each unit corner not bonded to a Spacecraft ground plane, at a pulse rate of 1 pulse per second for a period of 30 seconds at each location. (Reference [8]: SMC-S-008, Section 6.43).

5.5.4.1.3 As a protection method for internal electronics, when designing satellites for GEO or Polar orbits, the design should include a bleed resistor and a transient-voltage-suppression (TVS) diode in parallel across a signal-to-ground conductor.

However, in general, it is assumed that charge equalization has occurred between the Servicer and Client prior to engaging power and data connectors.

5.5.5 Regolith in Cislunar Environment

The scope of this standard considers the presence of regolith on Power and Data interfaces on the Lunar Gateway Space Station due to spacecrafts/payloads going to/returning from the lunar surface.

5.5.5.1.1 Power and Data interface connectors in a cislunar orbital environment shall function in the presence of lunar regolith. The amount of regolith deposition on surfaces is dependent on the specific mission parameters per NASA's Gateway On-orbit Lunar Dust Map Analysis Program (GOLDMAP).

The scope of this standard does not consider Power and Data interfaces on assets operating on the lunar surface.

5.5.6 Micrometeoroid and Orbital Debris (MMOD) and Connector Protection

Spacecraft are subject to micro-meteoroid and orbital debris (MMOD) impact damage which have the potential to degrade performance, shorten the mission, or result in catastrophic loss of the spacecraft (Reference: JSC 64399). As satellite constellations grow in LEO, considering orbital debris when designing power and data interfaces become imperative.

5.5.6.1.1 JSC 64399 Handbook for Designing MMOD Protection should be used when designing power and data interfaces for MMOD protection. JSC 64399 provides MMOD Environment Models in Section 2.6, followed by equations for designing MMOD shields in Section 4.

5.5.7 Security

5.5.7.1.1 The Power and Data connector design may incorporate defense mechanisms against threatening agents to protect spacecraft independence and operational integrity.

Modes of protection for Power and Data connectors may include, but are not limited to:

- Mechanical
    - Connector covers/flaps as described in Section 5.5.6
        - Prevents visual intelligence gathering from rogue spacecraft
            - Mode is only effective if the Power and Data connectors are protected information before assimilation with spacecraft, and public data would limit the protection given by obfuscating the connectors
        - Acts as FOD shield and environmental protection of connector contacts as mentioned in Section 5.5.6.
    - Proprietary keyway/lockout channel incorporated into the fitment mechanism
        - While a bad-actor may have access to the same type of Power and Data connector, a per-spacecraft basis of including a mechanical defense could inhibit unwanted docking/transfers
            - Unwanted docking could result in transfer/loss of sensitive information but may also open spacecraft to various offensive software techniques which may inhibit or otherwise improperly use spacecraft
        - Could include "key" requirement so that during downtime the Power and Data connector may be inaccessible and when authentication has been provided before physical connection is required the connector may "unlock"
            - Should be used with other authorization methods to add redundancy to spoofing or virtual twin attacks
- Software/Operational Architecture
    - Spacecraft level encryption required to authorize access to spacecraft data and power
    - Pre-servicing verification by ground and spacecraft before authenticating/authorizing any external communications
    - Threat analysis and response strategy should be considered on a per-spacecraft basis
        - Based on best practices for Space Situational Awareness operations

5.5.8 Thermal Effects and Distortion

Power and Data connectors will see various thermal regimes throughout their operational lifetime.

For the Power and Data interface connectors, the thermal control scheme is crucial to ensuring as-designed operation on orbit. While most S/C will operate at or around room temperature with various thermal control mechanisms, the connectors will likely be located on the external regions of a given S/C and the thermal control profiles of the connectors should be well known and within operational temperature limits of all components. A well-defined thermal control scheme will limit thermal cycling, shock, and potential failure modes due to material contract or expansion.

5.5.8.1.1 To minimize the potential for thermally induced connector misalignment, the thermal control scheme should ensure that the outward-facing section of the Power and Data connector interface maintains a similar temperature prior to mating, during mating, and while connected and operational.

This approach aims to restrict distortions and stress concentrations that could arise due to temperature variations. Moreover, the materials utilized in constructing the connectors should adhere to the referenced conductivity and insulation guidelines, see Section 5.5.12. It is advised to incorporate components that employ complementary materials, aligning or minimizing thermal contraction/expansion effects to further ensure the connectors' performance and reliability.

Due to the anticipated mounting locations of Power and Data connectors, they may be exposed to significant temperature fluctuations. This may lead to operational impacts arising from thermal cycling. Frequent shifts between extreme hot and cold temperatures can induce expansion and contraction in the connector materials.

The thermal stress and fatigue and adversely affect the connector's structural integrity and overall performance. It is essential to prioritize achieving a high degree of temperature stability within the designated temperature range for the Power and Data connectors throughout their operational lifespan. Extensive thermal modeling may provide feedback, along with manufacturer guidelines and material data sheets. This will give an overall picture of the dimensional changes the Power and Data connector may experience over the operational temperature regime, and if these changes will interrupt normal mate and de-mate actions.

5.5.8.1.2 The Power and Data connector shall withstand the thermal stress and fatigue over the course of mission lifetime.

Thermal shock poses significant risks to spacecraft electrical connectors, and efforts to limit the effects according to referenced sources should be undertaken to protect the Power and Data connectors. Rapid temperature changes can induce mechanical stress and fatigue, potentially leading to structural damage or connector failure. The variation in contact resistance can compromise electrical performance, affecting data transmission and communication. Repeated thermal shock can degrade materials and compromise seals, jeopardizing connector integrity and further exposing components to environmental contaminants. Moreover, differential thermal expansion might lead to temporary or permanent disconnects between connectors or binding of interconnect shells leading to disruption of spacecraft operations. To counter these dangers; thermal management, insulation, and material selection are vital, backed by thorough testing and qualification to ensure connectors endure the challenging space environment.

5.5.8.1.3 The Power and Data connector shall withstand the thermal shock cycles experienced during the course of mission lifetime.

5.5.9 Thermal Control

There are many options for thermal control and depending on the Power and Data connector/ISAM interface, the recommendation will vary. The following table lists factors that the designer should be aware of while building a thermally stable connector, and a short list of the most common thermal control options for S/C:

Thermal Control Decision Factors	Thermal Control Mechanisms
Localized spacecraft thermal conditions Nearby surface conditions/connections Accessibility and installation method of connector assembly Thermal Operating envelope Operating state (isolated, mated)	**MLI Wrap** -- Low emissivity materials, protection from radiation **ESA ECSS-E-ST-33-01C 4.7.4.3** **Thermal Straps** -- Efficiently transfer heat towards or away/between components via metallic straps

Localized spacecraft operation conditions Intended operation lifetime Optical Properties Glint prevention Electrical grounding RF conditions EMI conditions Contaminants Outgassing Thruster Plume deposition Atomic Oxygen Micrometeoroid protection/other debris (**JSC-64399**)	**Surface Coatings** -- Applied to surfaces to control absorption and emission ratios, including paint, anodization, passivation, etc **Louvers/covers** -- Shutters that can open and close to control temperature. There can be thermal benefit from a cover that also acts as an EMI cover and a 'dust cover' or debris cover. The cover can shield/isolate the unmated connector from direct sunlight and deep space. **Passive Radiators** -- Extend or retract to control thermal absorption or dissipation **Heat Pipes** -- Extension of a larger thermal control scheme **Heaters** – Kapton, Radioisotope Heating Unit (RHU)

5.5.10 Material Finishes

Polished external aluminum surfaces will degrade with time due to interactions with atomic oxygen in LEO, therefore anodized or coated aluminum is recommended for exposed surfaces. However, anodized aluminum builds up charge in GEO and Cislunar orbits, which causes ESD events on such surfaces. The orbital environment must be considered when deciding which material finishes to apply.

High emissivity coatings on exposed surfaces can enhance heat rejection and improve thermal management of spacecraft systems. As an example, the application of a 15 μm layer Aeroglaze 9924 Primer followed by a 45 μm layer of Aeroglaze A276 provides a white coating with a high emissivity of $\varepsilon \sim 0.90$ [MSFC-PROC-547 Rev. E], which is ~ 0.7 higher than the emissivity of bare aluminum. Another high performance coating option with similar emissivity, but lower absorbance is AZ-93 [NASA Report CR-1999-209008], which has been used on the surface of portions of the ISS for over 10 years. Avionics boxes for satellite servicing may be difficult to keep or place on the interior of a spacecraft, where most 'black boxes' tend to be. However it is possible to place ORU's on the interior, or at least behind doors, as was done on the Hubble Space Telescope for all ORU avionics boxes. That allows use of conventional black exterior surfaces.

Material finishes with respect to the construction of Power and Data connectors for spaceflight can provide multiple benefits and have a substantial effect on the outcome of their extended operation in a harsh environment.

5.5.11 Tin Whiskers

Tin whiskers are hair-like growths of near perfect single crystalline structures of tin that grow from some electroplated tin surfaces. Tin whiskers are believed to grow in order to relieve mechanical stresses acting within the tin layer. Tin whiskers present two reliability issues for equipment manufacturers and users. The first is electrical shorting. Whiskers can grow between adjacent conductors of different potential and cause either a transient short as the whisker is burned open, or a permanent short. Second, whiskers can be broken loose from their substrate and as debris cause mechanical problems [Brusse J. A. et al.].

5.5.11.1.1 The use of tin in Power and Data interfaces should be avoided. Where tin is present in Power and Data interfaces, the following methods should be considered in order to minimize whisker formation:

- Conformal coating
- Physical barriers

- Solder dipping
- Tin surface reflow
- Minimizing elevated temperature exposure
- Performing burn-in in an inert environment
- Reference [Brusse J. A. et al.] provides more details regarding mitigation methods.

5.5.12 Surface Resistivity

The requirements for specific components within the Power and Data connector interface will vary including the desired surface resistivity, which will be a key factor in determining the surface finish applied.

5.5.12.1.1 Surface resistivity should be considered from both an electrical and mechanical standpoint, namely the possibility of corrosion due to galvanic incompatibilities in various paired materials. NASA-STD-6012A – Corrosion Protection for Space Fight Hardware may be referenced for control of galvanic corrosion in current carrying surfaces.

5.5.12.1.2 Components that require electrical current to be carried through them must have compatible material finishes with connecting parts, both for resistance purposes and surface finish variability, to ensure optimal electrical contacts. Description of terminology and discussion of ESD precautions and effects can be found in NASA-HDBK-8739.21 – Workmanship Manual for Electrostatic Discharge Control (Excluding Electrically Initiated Explosive Devices).

Proper surface resistivity will also reduce the risk of thermal stress and simplify required thermal control parameters while ensuring proper conductivity values for the component's intended application.

5.5.12.1.3 For either high or low-surface resistivity applications, the material finish must exhibit exceptional resistance to corrosion and withstand orbital hazards, including atomic oxygen and radiation effects, to prevent breakdown during mission lifetime. Choosing a material for mechanical properties and applying a coating to change the surface properties is common, and can be done in a variety of ways. The most common methods include metallic plating, painting, and electrolytic coatings.

Low surface resistivity -- facilitates electrical grounding and minimizes the accumulation of static that may propagate from electronics usage A material that has a surface resistivity of <10^5 ohms per square or a volume resistivity <10^4 ohms-cm.	**High surface resistivity** -- essential for insulating materials because it is much more difficult for current to flow along this type of surface A material having a surface resistivity ≥10^{12} ohms/square or a volume resistivity ≥10^{11} ohms-cm.

Types of material finishes that are commonly used to change surface resistivity

Noble Metal Plating -- Noble metals are desirable because they lack chemical reactivity and resist oxidation and corrosion, including but not limited to: Gold plating, Silver plating, Nickle plating (Forms a strong galvanic cell with aluminum. Difficult to anodize up to nickel plating. Apply organic primer), Alloy Plating, Palladium Nickel Plating (flashed with gold), Electroless Nickel

Electrolytic Coatings -- Anodization (II III and white or black for thermal reasons)

Chemical Films – Passivation, Alodine coating

5.5.13 Surface Roughness/Surface Finish

Surface roughness is important for the power and data connector as the function of connector components relies on the quality of contact between two surfaces. The goal of the power and data connector designer should be to utilize components with surfaces that require low activation force and robust electrical connections.

Flatness is an essential dimension to the effectiveness of electrical and thermal conductivity. Confidence in relative flatness can ensure that the amount of material that is intended to be in contact, actually is. Over large areas, the flatness of a machined surface can vary significantly if this dimension is not controlled.

Surface finish is most typically associated with the visual appearance of the component. Numerous variables should be considered, including resistivity, thermal radiation requirements, and glint which may interfere with S/C optics. If on an external surface of the S/C, the finish will also affect the radiative qualities of the part, altering the thermal control scheme. The natural surface finish of a given manufacturing process may need to be coated to contend with these issues.

5.5.14 Tribology

Space mechanisms designed in conjunction with the Power and Data connection interface must adhere to specific guidelines concerning tribological material compatibility, particularly when utilizing metals for mating or sliding surfaces.

5.5.14.1.1 To mitigate potential issues like cold welding, fretting, and galling, compatibility studies and life testing should be performed.

Depending on the Power and Data connector's physical interface mechanisms, the following options to limit failure are available:

Cold Welding Control and Mitigation Options
Material Finishes—Type 3 anodization and many others
Lubrication -- MoS2, PTFE, Graphite, HTPB grease (Hydroxyl-Terminated Polybutadiene)
Dissimilar metals (galvanic compatibility concerns)
Avoiding contact/sliding where possible

5.5.15 Outgassing

Materials used in the construction of the Power and Data connector interface should be subject to case-by-case standards such as the Flammability, Offgassing, and Compatibility Requirements (FOCR) required. In the case of the Power and Data connectors, the most likely requirement will be that the minimum amount of material will be outgassed due to exposure on orbit. In sensitive cases where mission critical optics are involved, materials that may otherwise be useable may need a coating to further limit the amount of material dispersed. Preconditioning of materials may be required, such as bakeout.

5.5.15.1.1 Material outgassing limits shall be limited to <1% total mass loss (TML) and <0.1% collected volatile condensable material (CVCM). (Reference NASA-STD-6001B w/CHANGE 2 – Flammability, Offgassing, and Compatibility Requirements and Test Procedure)

5.5.16 Cleanliness Requirements

Cleanliness plays a key role in the application of coatings as well as ensuring desired resistivity values. If the Power and Data connector uses a coating on a component to protect against AO or UV degradation, but is not sufficiently cleaned beforehand, the coating may fail to adhere to the substrate. Cleaning processes and standards have been developed to limit levels of non-volatile residue (NVR) and surface particles. The process used by individual connector designers will vary due to material compatibility constraints and the cleaning methods available at the time. The amount of acceptable surface particles and NVR is also to be chosen at the discretion of the Power and Data connector designer who would have the most robust understanding of the failure criteria of the connector. Note that NVR that is exposed to sunlight may polymerize and change properties, including conductivity of pins, thus affecting electrical performance.

5.5.16.1.1 Power and data interfaces should adhere to IEST-STD-CC1246D Product Cleanliness Levels, an industry standard reference document which provides insight on cleanliness requirements and information on testing and verification.

5.5.17 Coatings

The Power and Data connectors may require various coatings to effectively navigate the aforementioned material issues. Many of these coating techniques are interchangeable and co-compatible, yet thorough investigation into specific cases should be considered. The following table lists some of the considerations to be aware of and a sample of the application techniques commonly used for S/C:

Surface Finish Choice Selection Considerations	Surface Finish Application Techniques
Surface contacts (electrical or thermal) **Mated faces** (fretting, galling, cold welding) **Sliding** (lubrication) **Electrical Resistivity** (high or low) **Thermal** **Conductive Pathways** (electrical or thermal, high or low) **Radiation** (emissive or absorptive) **Materials compatibility** **Erosion** (Outgassing, AO) **Micrometeoroid Impact** **Radiation** **Galvanic Compatibility** **Coating Thickness** **Application techniques** (Substrates, Primers – applicable to aeroglaze) **Cleanliness** (NVR, Particle Contamination) **Expected lifetime** **EOL and BOL characteristics**	**Paints** (Aeroglaze A276, Aeroglaze Z306 for emissive and absorptive example) **Polishing** **Various plating techniques** (Electroplating, Electroless plating, Electroforming, Vacuum deposition, Immersion plating, Brush plating, Barrel plating, Rack plating, Pulse plating) **Anodization** **Sulfuric Acid** (Type II and III) **Mixed acid** (Bonding and hardness benefits per ratio of acids used) **Passivation** **Electropolishing** **Black Oxide** **Nitric Acid** **Lubricants** (tribology impacts, anti-galling) **Sealants, conformal coatings** **Epoxy, potting**

5.6 Orbital Replacement Unit (ORU) and Orbital Attachment Component (OAC) Considerations

5.6.1 Overview

ISAM operations are enabling attachment of articles that can augment existing spacecraft functionality, as well as new payloads which could be test articles, manufacturing plant elements, robotic arms, science and biological experiments etc. The act of "attaching" new elements to existing spacecraft requires much of the same considerations in the power and data transfer as discussed. Here we will discuss the current state-of-the-art that may provide guidance to new articles that can be attached and de-attached for ISAM operations, referred to as Orbital Replacement Units (ORU) and Orbital Attachment Components (OAC).

An Orbital Replacement Unit (ORU) is a component that can be installed or removed and replaced in space. Similarly, An Orbital Attachable Component (or Capability) (OAC) is a component that can be attached to an existing vehicle to provide additional capability. Some forms of OACs will interact directly with the host vehicle electrical system, while some may have no direct interaction. A servicing agent, human or robotic, removes or installs the ORU/OAC. Historically the mechanical attachment (latches) and the power and data connections can be actuated in a variety of ways. The latches may be actuated by the servicing agent or by a motor driven latch. The active latch may be in the ORU or OAC, or the structure being mounted to. The power and data connections can be actuated with the same range of options.

5.6.1.1.1 The installation of an ORU or OAC by a robotic agent shall be compatible with the force and torque capabilities of the robot, the precision of the robot, and the ability of the automation system or live operator.

5.6.1.1.2 An ORU or OAC installation site shall include alignment aids to enable ORU/OAC installation.

The most commonly used ORU/OAC interfaces on the International Space Station are the Field Replaceable Attach Mechanism (FRAM), used on the Express Logistics Carriers and Columbus Module. This module is attached to Bartolomeo and one attachment method is GOLD-2 connector from Oceaneering, discussed in the Appendix. The Kibo Japanese Experiment Module (JEM) External Platform (EP) uses the Payload Interface Unit. ISS command and data link specifications are provided in GSFC 420-01-09 Change 01 6-22-2015, page 17, Table 3.0-2. ISS external capabilities comparison.

The Gateway has new interfaces planned, as documented in the International Deep Space Interoperability Standards. These include the Small ORU Platform Interface (SORI), Time Triggered Ethernet, 28 VDC and 120VDC.

5.6.2 ORU/OAC Guidelines

5.6.2.1.1 In addition to a mechanical interface (I/F), an ORU/OAC shall have a power and/or data interface.

5.6.2.1.2 If a single actuation engages both the mechanical and power/data interfaces, then the ORU/OAC installation shall provide an approach corridor and progressive stages of alignment that result in both mechanical and electrical mating.

5.6.2.1.3 The ORU/OAC power I/F shall have protection against applied overvoltage from connected S/C.

5.6.2.1.4 ORU/OAC power and voltage requirements shall be compatible with the selected coupling I/F.

5.6.2.1.5 The ORU/OAC shall offer a data transfer protocol in accordance with the selected data transfer I/F.

5.7 Robotic Requirements

There are two major approaches to robotic installations of ORU/OACs. One is for the robot arm to serve only as a positioning arm, placing the ORU/OAC within the capture envelop of a berthing mechanism. An example of this is the Japanese Equipment Module (JEM, or Kibo) External Platform (JEM-EP), for which the active side of the latching system was on the JEM-EP side and a passive interface on the ORU/OAC. The other approach is for the robot to provide both positioning and latch engagement mechanical energy. This is the approach of the FRAM and GOLD connectors, with the latch engagement powered by the tool drive mechanism of the Dextre robot. This was also used on the Orbital Express mission, in which a robot arm tool drive powered the engagement mechanism of ORU/OACs. Other options are for a motor in the ORU/OAC to be activated by power from the robot arm, or bulk motion of the ORU/OAC, etc., but examples of these are lacking.

The other main consideration are robotic interfaces. ORU/OAC's can be built to be directly compatible with the robot end effector. However an adapter or tool can be made, which forms a bridge between the robot and the ORU/OAC's robotic interfaces. This raises the possibility of any robot being compatible with any ORU/OAC, given the appropriate adapter.

5.7.1.1.1 There must be compatibility between a robot arm plus adapter and an ORU/OAC's interfaces, and between the robot arm and the adapter plus ORU/OAC.

One key consideration becomes whether the robot arm needs to translate during the engagement, and if so, whether the robot arm has the level of compliance to follow the ORU/OAC's motion while keeping mechanical loads on the arm, ORU/OAC and latch within allowable limits.

Regarding electrical connections, it is possible for there to be electrical connections between the robot arm and the ORU/OAC, and between the ORU/OAC and the space object being installed onto.

5.7.1.1.2 The sequence of making and breaking electrical connections must be performed so as to avoid any undesirable electrical configurations, such as current surges or unstable electrical circuits.

For example, the robot arm might provide heater power to the ORU/OAC during translation, and the host provide it after installation, either through the same heaters or separate ones.

On the International Space Station program, guidance was provided by the Space Station Program Robotic Systems Integration Standards, including Volume 1: Robotic Accommodation Requirements (SSSP 30550 Volume 1). These are generic to all ISS dexterous robotic systems, and the document refers the reader to detailed accommodation requirements specific to a particular robotic system in the respective ICD for that system. Beyond the ISS, other commercial space robotic systems are being developed, with some being designed with specific ORU/OAC attachment mechanisms and concepts of operations in mind. For the Lunar Gateway, the International External Robotic Interface Interoperability Standards (IERIIS) apply.

5.8 Extravehicular Activity (EVA) Requirements

When considering the OOS Mission Functional Diagram in Figure 1 and ConOps and Scope Diagram for Power and Data Interfaces in Figure 2, the consideration for EVA is not explicitly shown within the scope of recommendations for this document. However, EVA will continue to play a role in ISAM activities, both until the retirement of the ISS and with the development of the Lunar Gateway, Commercial LEO Destinations and other commercial space station efforts. Given the foreseeable role of EVA, this document provides recommendations for considerations when designing power and data interfaces that are operated by astronauts.

The requirements for EVA compatibility on connectors are typically operation, accessibility, mating, coding, protective caps, alignment, and design. (Reference: ICES 2023_Paper-Draft_268_Finalrev.pdf (nasa.gov)). EVA involvement in actuation of connectors may be by direct actuation, such as by manually pushing a plug onto a jack, and by rotating a sleeve to complete the engagement. EVA might instead engage a blind mate connector by actuating a mechanism using a manual or powered hand tool, such as a socket wrench or powered screw gun.

5.8.1 Electrical Considerations

5.8.1.1.1 When designing electrical connectors and cables for operation by an EVA crew member, Section 4.6 of AIAA Guide G-042-1991 should be followed.

The aforementioned section includes requirements for:

- Alignment provisions
- Cable and wire harnesses
- Coding and identification
- Design
- Mounting configuration
- Operating requirements
- Safety
- Tools
- Types of connectors

5.8.2 Mechanical Considerations

5.8.2.1.1 For applications where EVA compatibility is required per mission requirements, standard bolt heads per Section 3.1.4 in SSP 30256:001 Rev F EVA Standard ICD should be used.

The aforementioned configurations will permit the use of standard EVA hand and power tools developed for the International Space Station Program.

5.8.3 Emergency Disconnect

Ensuring safe, reliable, and expedient disconnection capabilities between an ORU and its host S/C or another module is paramount in ISAM missions. This section delineates standards and guidelines related to the emergency disconnect feature, with a focus on both mechanical and power/data interface decoupling.

Guidelines:

5.8.3.1.1 The capability to enact an emergency disconnect shall persist even in instances where one side (either the ORU or the host S/C) experiences failure.

This safeguards both entities from malfunction risks and ensures mission critical operations can proceed with alternative strategies or systems.

5.8.3.1.2 ORUs shall incorporate a reliable mechanical disconnect system, ensuring physical decoupling can be achieved.

5.8.3.1.3 Both the ORU and the host S/C shall embody separate fail-safe mechanisms to sever power and data connections instantaneously in emergency scenarios.

5.8.3.1.4 Power and data interface connections shall be designed such that their disconnection processes do not inhibit or obstruct mechanical decoupling, even amid interface failures.

5.8.3.1.5 The Power and data interface design shall institute protocols for electrical isolation to safeguard against electrical feedback or surges during disconnection.

5.8.4 Safety and Hazards

The safety requirements will vary with the application. The ISS has a well-defined process that includes:

Phase 0 (hazard causes defined)

Phase I (hazard causes refined and hazard controls defined with preliminary verifications)

Phase II (identify design changes, new hazard causes and controls, and well-defined safety verification methods)

Phase III (completion of the hazard report safety verification method)

Post Phase III Safety Review and Safety Verification Tracking Log (close-out of all required safety verification)

For applications other than ISS, program-specific safety requirements will apply. The following requirements should be included in the safety program.

5.8.4.1.1 The safety team shall identify all hazards associated with separable power and data interfaces.

Rationale: These may include exposed pins or sockets with voltage applied on the ground or in flight. It may include unterminated wires that could act as antennas. It may include bent pins or foreign object debris (FOD) causing a short circuit.

5.8.4.1.2 The safety team shall identify controls for all hazards associated with separable power and data interfaces.

Rationale: Controls may include choice of connectors, including using sockets for the power source side of an interface to avoid exposed pins with live voltage.

5.8.4.1.3 The safety team shall verify all controls of hazards associated with separable power and data interfaces.

6 Appendices

This section provides examples of heritage and current state-of-the-art for Power and Data interfaces. However, it is recognized that not all examples, necessarily follow all of the aforementioned guidelines of the recommendations in this document.

6.1 Heritage Power and Data Interfaces – Souriau Connectors

The rectangular 8976 Series Souriau robotic connectors used on the SSRMS (Space Station Remote Manipulator System) specifications are as follows:

ORU receptacle misalignment

Δα= ± 0,5°	ΔY = 1,27 mm
Δβ = ± 0,5°	ΔZ = 2,03 mm
Δγ = ± 0,5°	

ORU receptacle overstroke

- ΔX= ± 2,29 mm

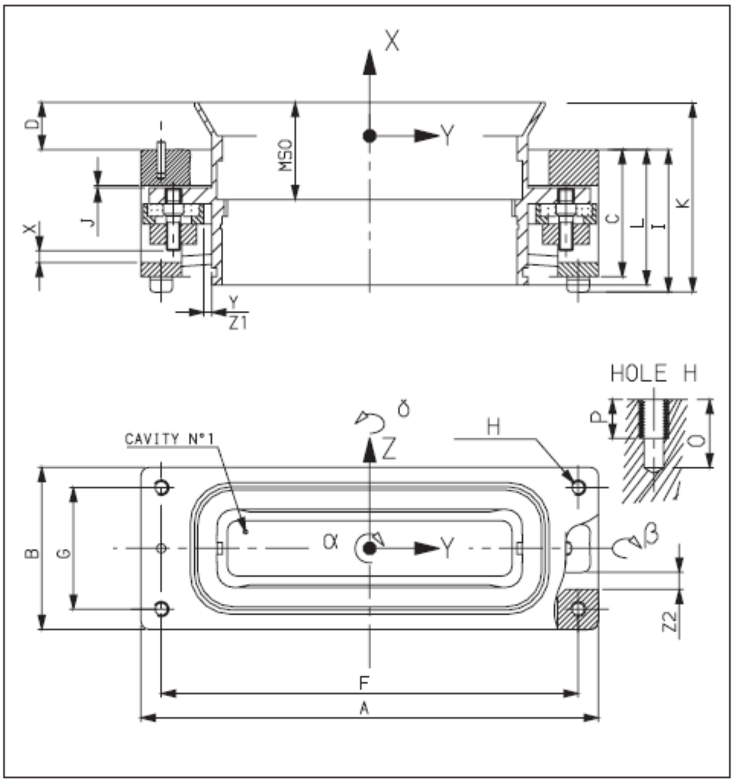


Figure 3 Rectangular 8976 Series Souriau robotic connectors

The circular 8977 Series Souriau robotic connectors used as ORU interfaces on the JEM (Japanese Experiment Module Exposed) Facility, which is part of the Japanese contribution to the Space Station. Their specifications are as follows:

ORU plug misalignments

- Δα = ± 0,9° (movement around the X axis)
- Δβ = ± 0,9° (angle authorized between the panels)
- ρ = 1,95 mm (plane movement according to Y and Z requirements)

ORU receptacle overstroke

- ΔX ≥ 1.5 mm

6.2 Blind Mate Mechanism - NASA

US Patent No. 10,958,014 B1 describes a robotically-driven blind mate mechanism capable of simultaneously making multiple connections in a single motion. A cross-section of the mechanism is provided in the figure below. The mechanism includes a removable side, which includes a drive bolt and connectors, with a fixed side operably connected to a device to be serviced. The fixed side includes a threaded receiving interface configured to receive the drive bolt and one or more connectors that align with the connectors on the removable side. The fixed side and the removable side are configured to facilitate mechanical and structural connections, transfer of fluids, transfer of communication signals, transfer of power, or any combination thereof. The mechanism has alignment features, as well as the capability to translate connectors through EMI/dust covers.

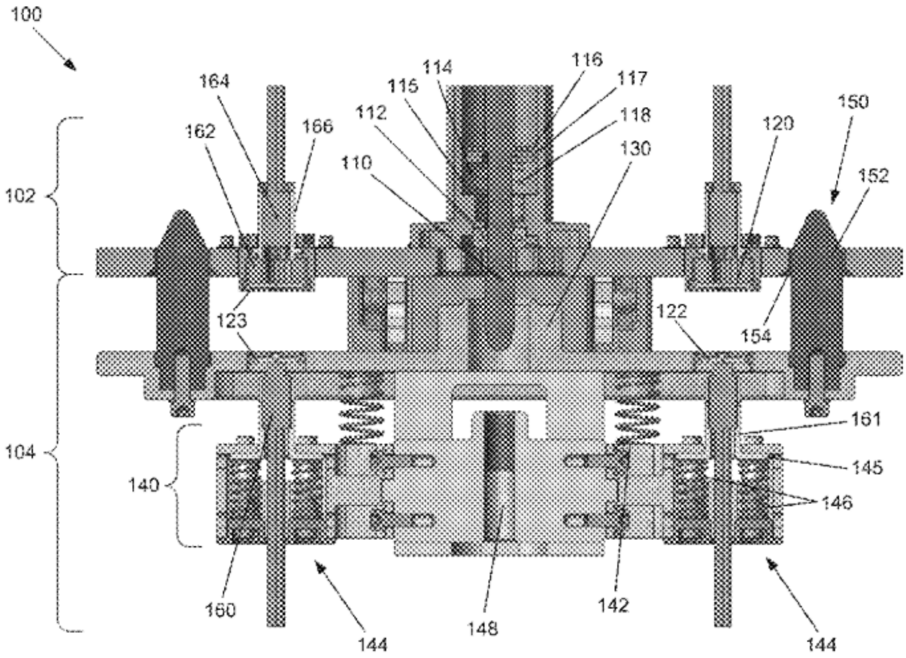


Figure 4 US Patent No. 10,958,014 B1 blind mate mechanism

6.3 FRAM (Flight Releasable Attach Mechanism) - GFE/NASA

A legacy interface for mounting equipment to the exterior of the International Space Station is the Flight Releasable Attach Mechanism, or FRAM. Further information on the implementation on this on ISS, including ISS robotics, is at 07A External-Payloads-Proposers-Guide-to-ISS-SSP-51071-Baseline Redacted.pdf (nasa.gov).

A Passive FRAM (PFRAM) is incorporated into a spacecraft that visits the ISS, such as the SpaceX Cargo Dragon, Northrop Grumman Cygnus, or the Sierra Space Dreamchaser. To date, the Cargo Dragon has been used to bring FRAM-based payloads to ISS and dispose of ones removed from ISS, and Cygnus is able to dispose of FRAM-based payloads as well. Dreamchaser will have similar capabilities to Cargo Dragon.

A PFRAM is also mounted to the ISS in places where a payload will be placed for storing a logistics item or to host an engineering or science payload. The Express Logistics Carriers (ELC) on ISS each have two

PFRAM sites for payloads, and others for logistics items. Two of the ELCs each have nadir-facing sites, and the other two ELCs each have two zenith-facing sites, for a total of four zenith and four nadir sites. A commercial space station or platform could launch with empty PFRAMs, and have payloads be brought up on visiting spacecrafts. The ISS also has PFRAM sites on the exterior of the Columbus Module.

The payloads are attached to the Active FRAM Adapter Plate. These can have a volume as shown in Figure 5, with a volume of 46 in wide by 34 in deep and 49 in high. Payload mass can be up to 500 lb (226.8 kg), with the restriction on CG location depending on payload mass in order to be compatible with launch on a visiting spacecraft.

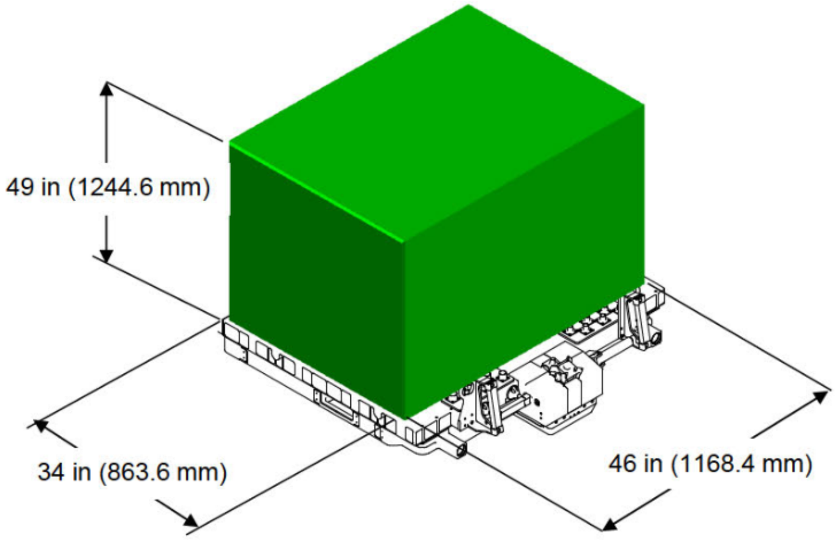


Figure 5 EXPA Payload Envelope

The Active FRAM has both EVA interfaces in the form of handrails for grasping by an EVA astronaut, and Extravehicular Robotics (EVR) interfaces in the form of an H-fixture with a latch actuation tool drive interface. The FRAM is normally removed and installed by EVR. On ISS, the Dextre robot, on the end of the Candarm2 positioning arm, has the ORU/Tool Change-out Mechanism (OTCM) ‘hand’, which can grip the H-fixture and turn the tool drive to release or engage the AFRAM from a PFRAM, and maneuver the released AFRAM with its payload. If the ISS-compatible robotics with a robotic gripper with retractable motorized socket wrench (or Socket Drive) is not available, a comparable other robotic end effector would be needed that can accomplish the same tasks. The AFRAM includes a Modified Truncated Cone (MTC) target that is viewed by the OTCM’s ORU/Tool Video Camera to facilitate alignment by a robotic operator. Machine vision use of the MTC is also possible for greater automation.

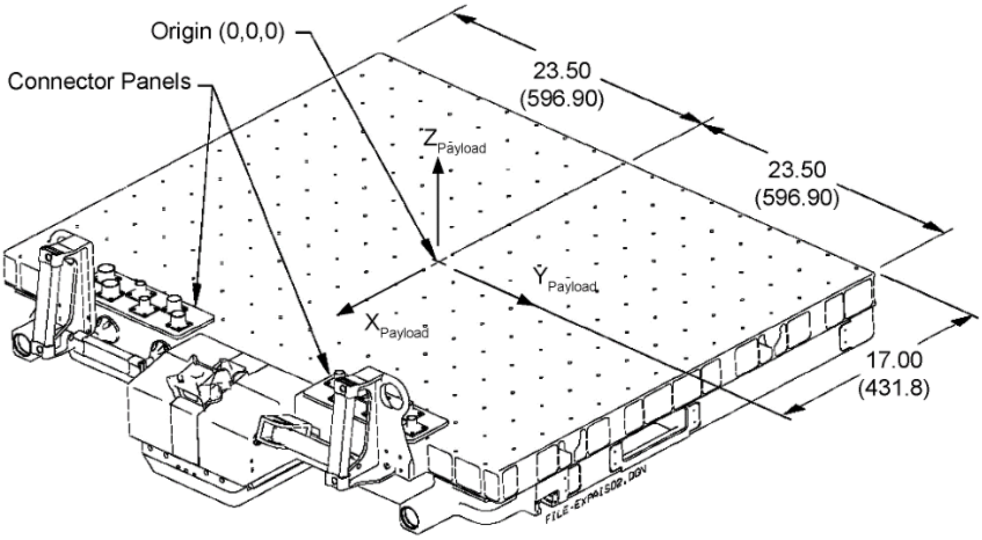


Figure 6 Generic ExPA Payload Coordinate System

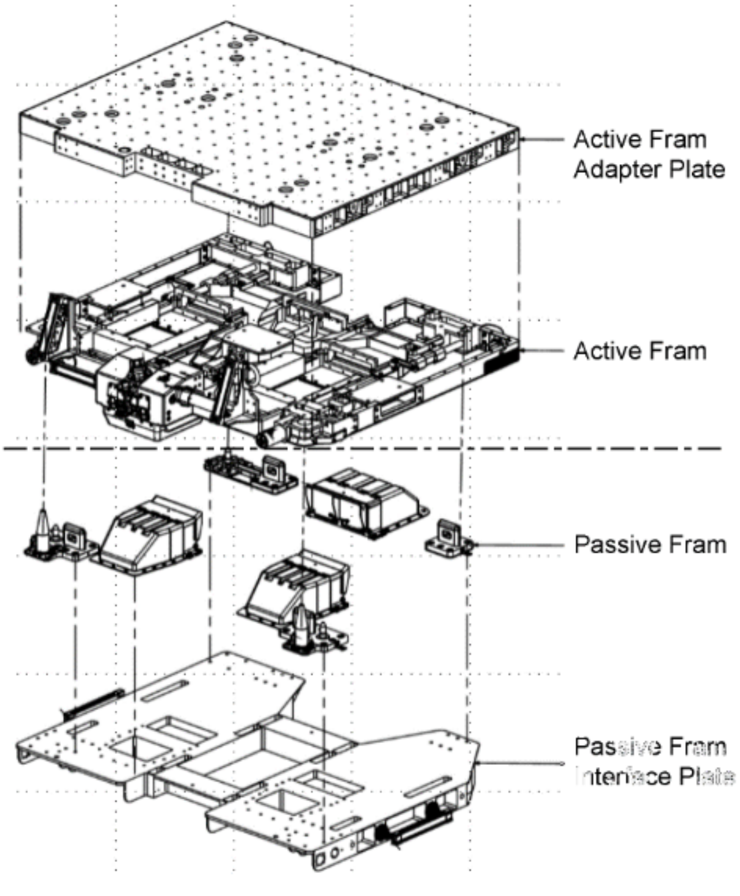


Figure 7 AFRAM and PDRAM Expanded View (Note: AFRAM Adapter Plate and the AFRAM is considered a single unit)

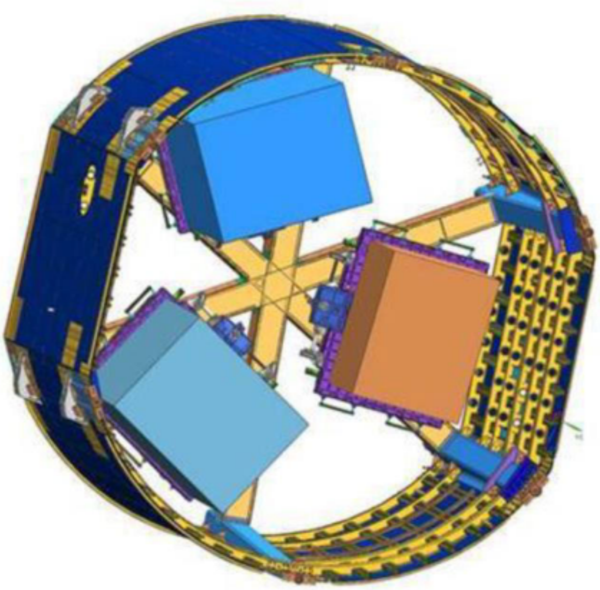


Figure 8 Three FRAM-Based Unpressurized Cargo Items in the Dragon Trunk

6.4 GOLD-2 Connector - Oceaneering

The GOLD-2 (General-purpose Oceaneering Latching Device) is a flight-proven TRL-9 connector developed by Oceaneering and is the common payload interface for the NanoRacks Airlock and the Bartolomeo platform on the International Space Station (ISS).

The GOLD-2 passive side is attached to an external platform and launched in place. It is outfitted with electrical socket connectors with incorporated spring-loaded doors to keep debris from settling in the sockets on the electrical connector. The passive side assembly also has a modified truncated cone (MTC) target attached to enable robotic alignment during attachment. The GOLD-2 active side assembly is attached to a payload prior to launch and is outfitted with either microsquare or microconical robotic interfaces.

The GOLD-2 standard connectors support power and communications functions and are easily customizable for different electrical connection needs (including fiber-optic connections) and can be modified to support fluid transfer.

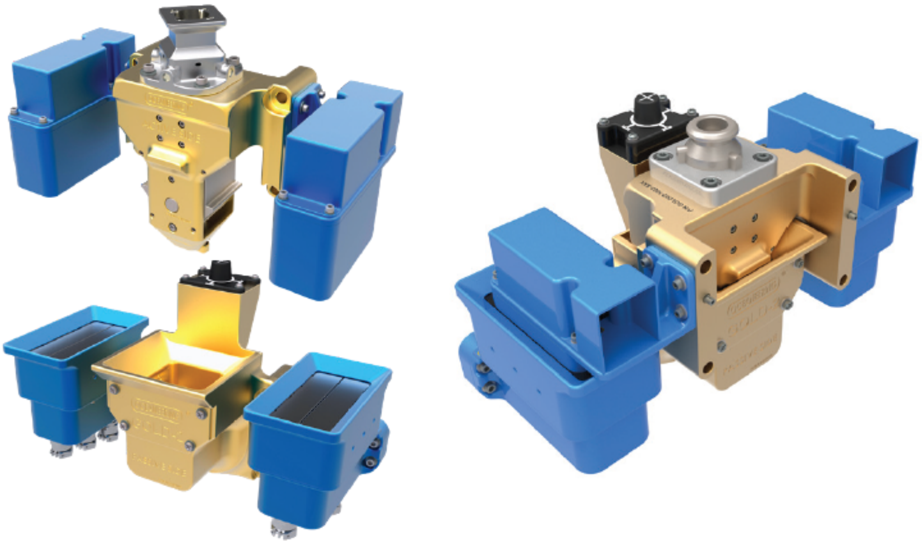


Figure 9 GOLD-2 Connector

6.5 iSSI (intelligent Space System Interface) Modular Coupling Kit – iBOSS

The iSSI is a patented, modular, multi-functional space interface technology that has been demonstrated and tested in space in 2022 (TRL 7). The iSSI interface is a multi-purpose component that enables ISAM, such as connecting space system building blocks, serving as a payload adapter, or functioning as a robotic end-effector, robot foot or tool exchanger, and more. The compact and lightweight disk-shaped and modular core unit (3-in-1 baseline) interface provides mechanical, power and dual optical data connectivity and can be adapted to a variety of use cases and requirements as future space infrastructure and associated logistics evolve.

Key differentiators include:

- a flat surface
- androgynous design
- multi-mounting options
- lubricant-free mechanics
- 90-degree rotational symmetry
- fast coupling with adjustable speed
- a security feature AIP (Anti-Intrusion Posture: avoiding approach or connection attempts by unwanted counterparts)
- a full fail-safe system BDRRM (Bi-Directional Redundant Release Mechanism: allowing to disengage the mechanical connection even if one of the iSSIs is non-operational or damaged)
- add-on-modules (formfit, heat transfer, dust cover, ranging, etc.)

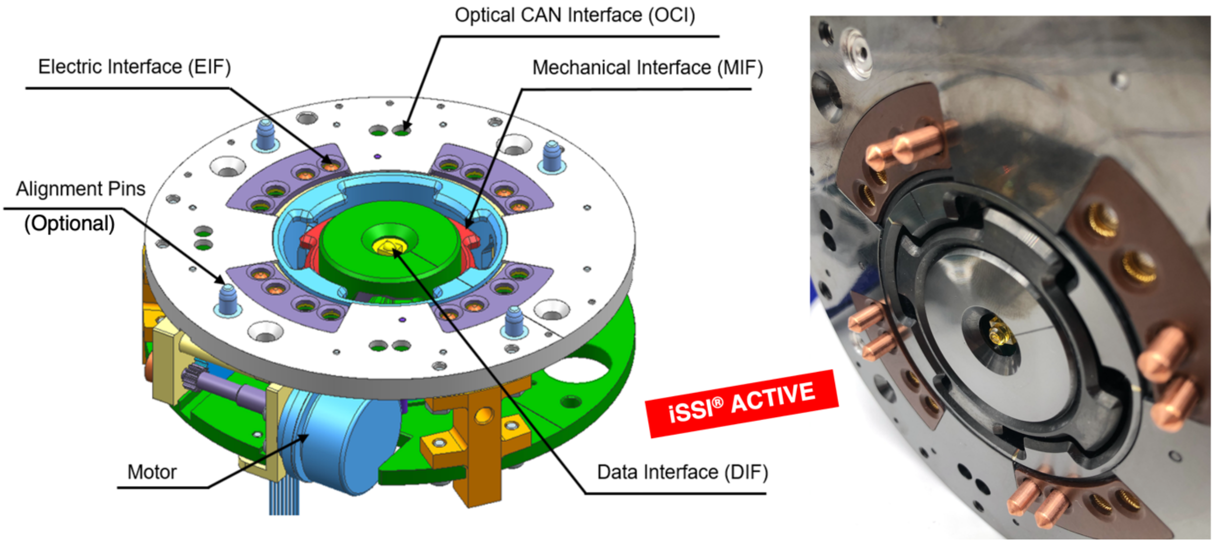


Figure 10 iSSI ACTIVE (3-in-1 Baseline) – CAD vs. Hardware (credit: iBOSS)

The iSSI is available in two basic versions ACTIVE + PASSIVE. While the iSSI ACTIVE is equipped with a motor-driven gear for active coupling, the iSSI PASSIVE is flatter and lighter, but with the same connection functionalities and core interface shape. ACTIVE/ACTIVE or ACTIVE/PASSIVE combinations with compatible functionalities are possible and can be selected and used without restrictions. Both can also be equipped with additional modules (e.g. formfit, thermal interface, dust cover or ranging modules) depending on the application and requirements. The optional and customizable formfit add-on module supports higher mechanical loads, misalignment tolerances and diagonal engagement (for docking, berthing and specific robotic applications) while iSSIs with and without formfit can couple, connect and transfer power and data in any combination.

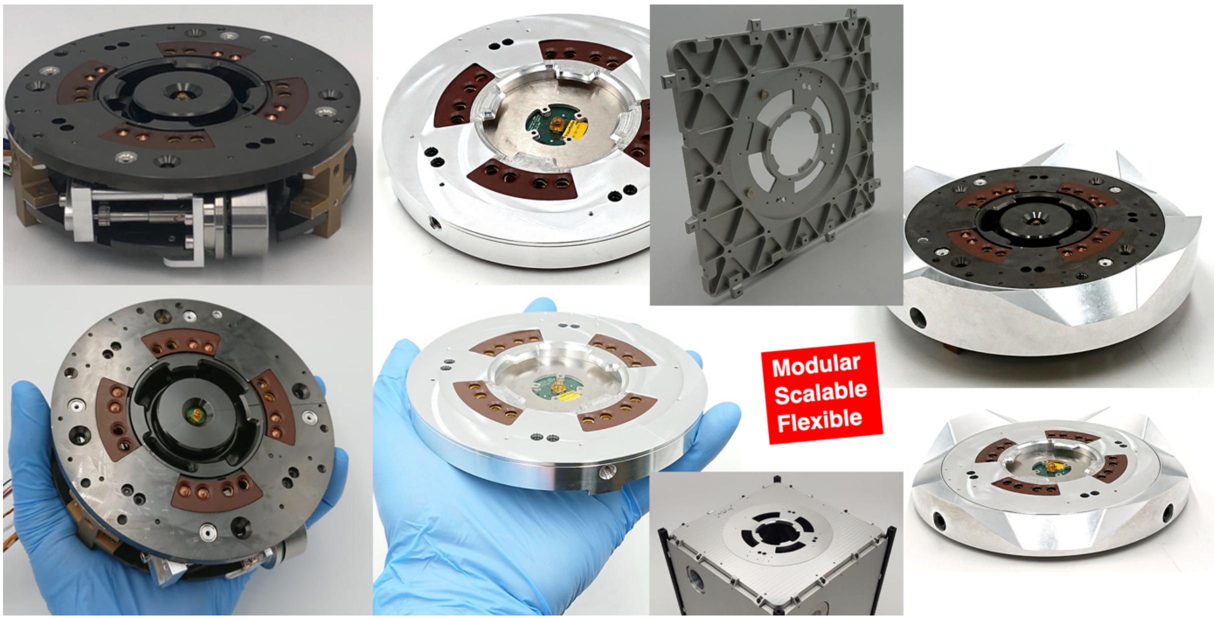
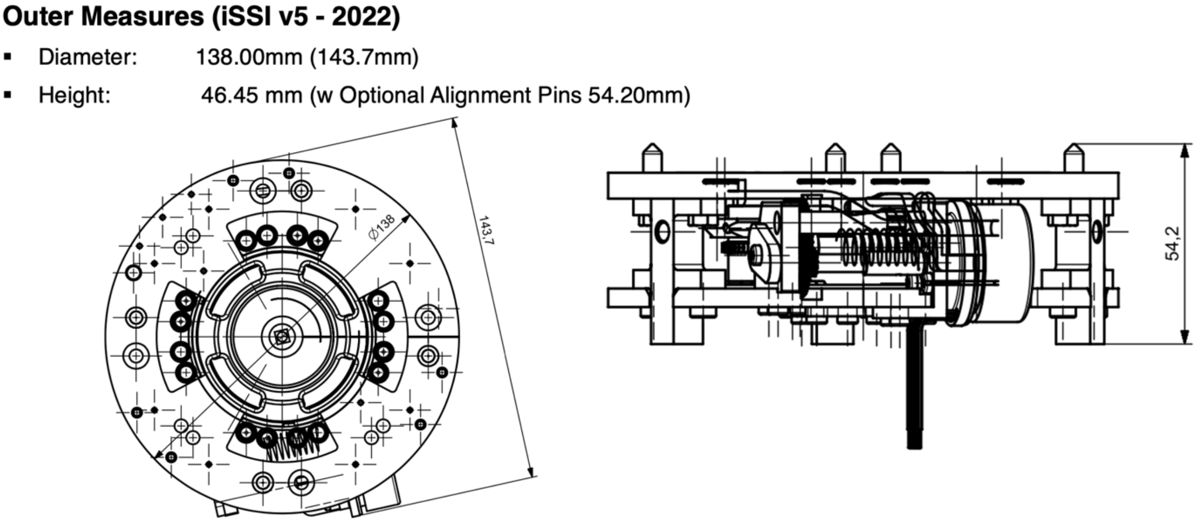


Figure 11 iSSI ACTIVE + PASSIVE and Formfit Add-on-Module (credit: iBOSS)

<u>Technical details (selected) of the 3-in-1 baseline core interface unit demonstrated in space:</u>

- Envelope: 140mm diameter/55mm height (PASSIVE: 17mm)
- Mass: 895g (PASSIVE: 275g)
- Connectivity:
  - Mechanical:
    - 6,000N axial, 400N lateral, 100Nm bending/torque (higher with formfit)
    - Coupling: 3-60s (adjustable, controllable)
  - Power: up to 5kW @ 120V
  - Data (2x optical): 1-10Gbit/s (Ethernet) and 0.5Mbit/s (CAN bus) – other protocols/data transfer rates possible



Outer Measures (iSSI v5 - 2022)

- Diameter: 138.00mm (143.7mm)
- Height: 46.45 mm (w Optional Alignment Pins 54.20mm)

Figure 12 iSSI Envelope (credit: iBOSS)

The iSSI has been produced (based on an Industry4.0 series manufacturing process) in various versions in more than 150 units - laboratory models used and tested by multiple stakeholders in different countries to date - and continues to evolve. Following the in-space demonstration, next versions will incorporate enhancements, mass optimization, and full integration of rad-hard electronics, leading to an orbital delta qualification mission in 2025 with commercial product rollout targeted in 2026.

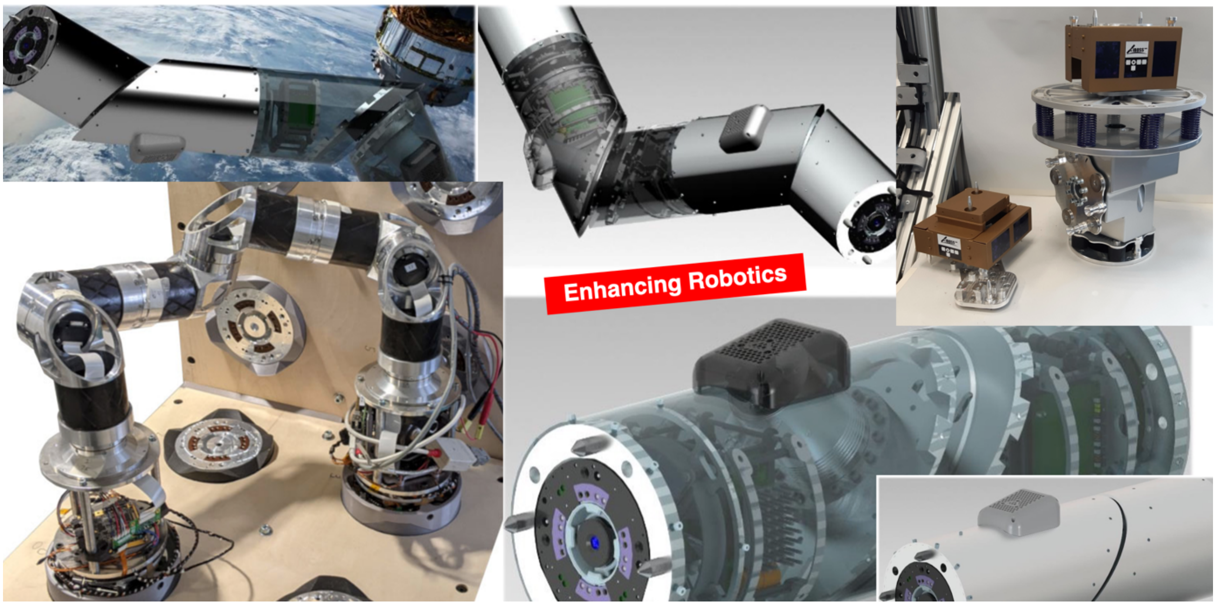


Figure 13 iSSI for Robotics: Robot End-Effector, Robot-Foot, Walking Robot, Modular Robotic Arms and Tool-Exchanger (credit: iBOSS)

Reference: *Thomas A. Schervan, Joerg Kreisel, Prof. Dr. Kai-Uwe Schroeder, Dennis R. Wingo: GLEX-21-7.3.2 NEW HORIZONS FOR EXPLORATION VIA FLEXIBLE CONCEPTS BASED ON BUILDING BLOCKS USING THE STANDARDIZED ISSI (INTELLIGENT SPACE SYSTEM INTERFACE) MODULAR COUPLING KIT BY IBOSS - Global Space Exploration Conference (GLEX 2021), St Petersburg, Russian Federation, 14-18 June 2021.*

6.6 SPDP (Structure, Power and Data Port) - Sierra Nevada Corporation

Designed as a tool holder for a robotic servicing satellite, the SPDP consists of an active unit and passive unit that can be mated and locked together or unlocked and demated. The active unit consists of 1) a launch-restraint system, 2) electrical pass-through cables, 3) a payload locking mechanism, and 4) a stepper gear motor to actuate the mechanism. The passive unit itself has no moving parts and is integrated structurally and electrically to the payload. The active unit contains onboard telemetry to indicate a ready-to-lock state, locked vs. unlocked, and excessive locking force fault.

The SPDP can support an 8.25 kg payload (with a CG offset of 125.4 mm (4.9 in) from the passive unit to payload-mating interface) through the launch environment with a first mode frequency above 200 Hz. The SPDP is designed to capture and release the payload repeatedly, up to 400 times on-orbit, and up to 1,600 times in ground testing. The port also supports the transfer of more than two dozen electrical power and data connections across the locked active-passive interface.

The SPDP can be used for the following applications: deployment mechanisms, robotics, on-orbit upgrade, satellite docking, and launch restraint. Its heritage includes Geosynchronous Space Situational Awareness Program (GSSAP) and Space-Based Infrared System (SBIRS).

Note: The SPDP is export controlled under Export Administration Regulations (EAR). Export to foreign entities may require U.S. Government authorization. Approved for Public Release, Distribution Unlimited.

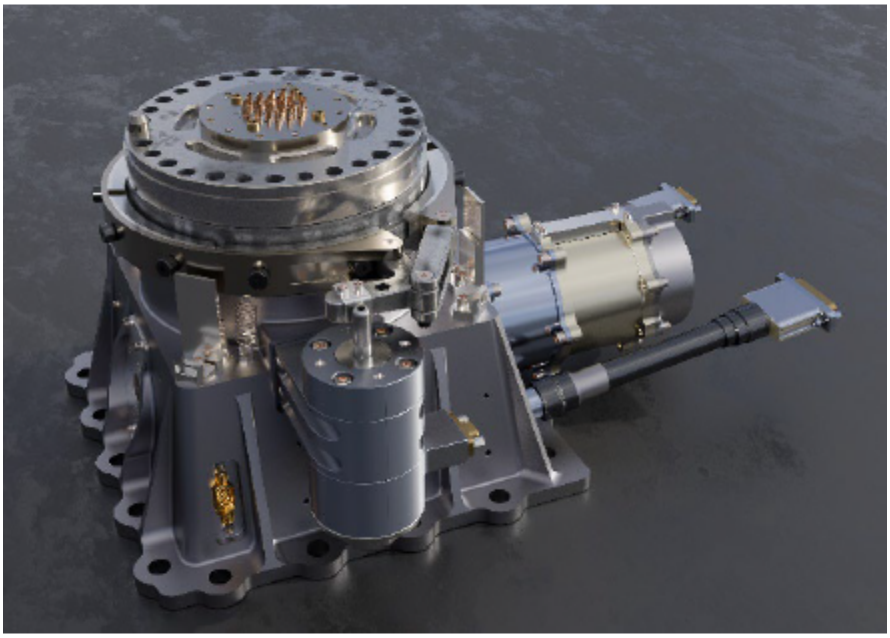
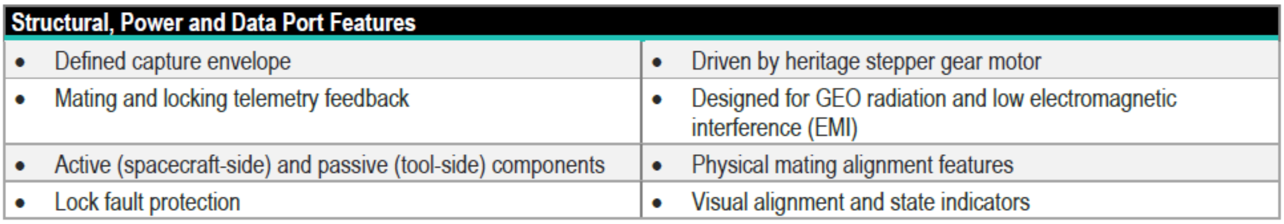
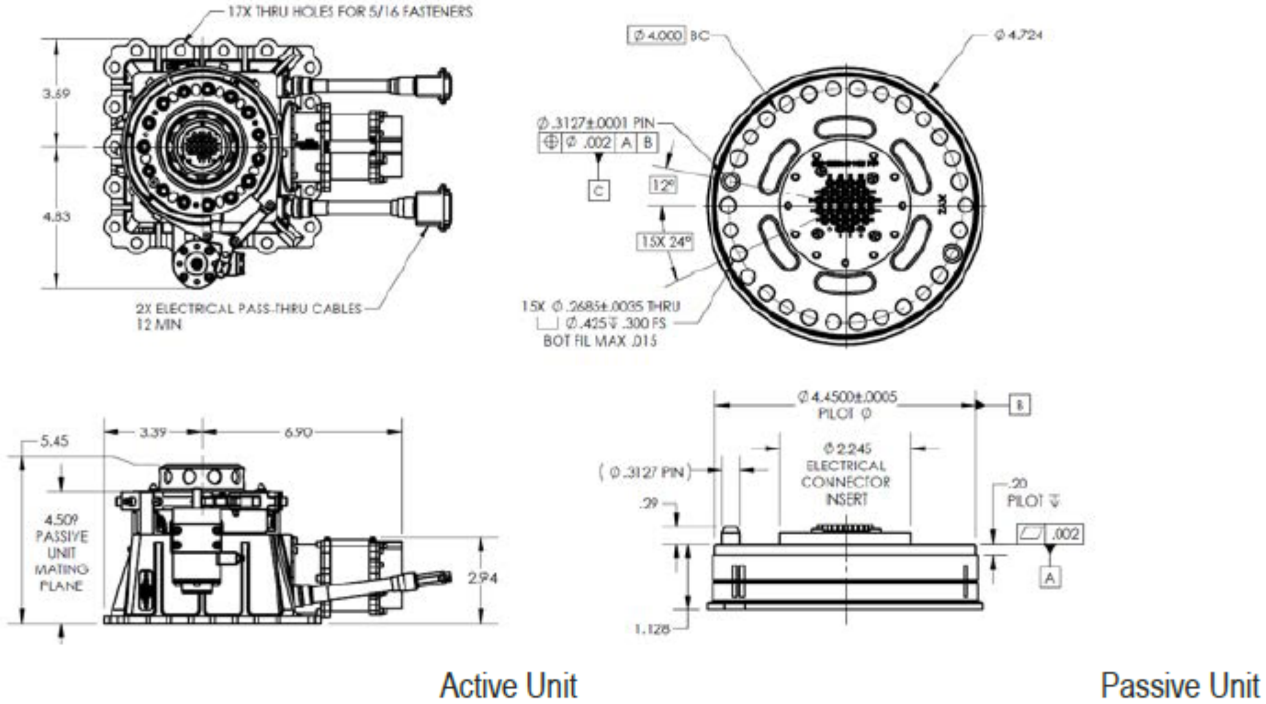


Figure 14 Structural, Power and Data Port

Table 2 SPDP Features

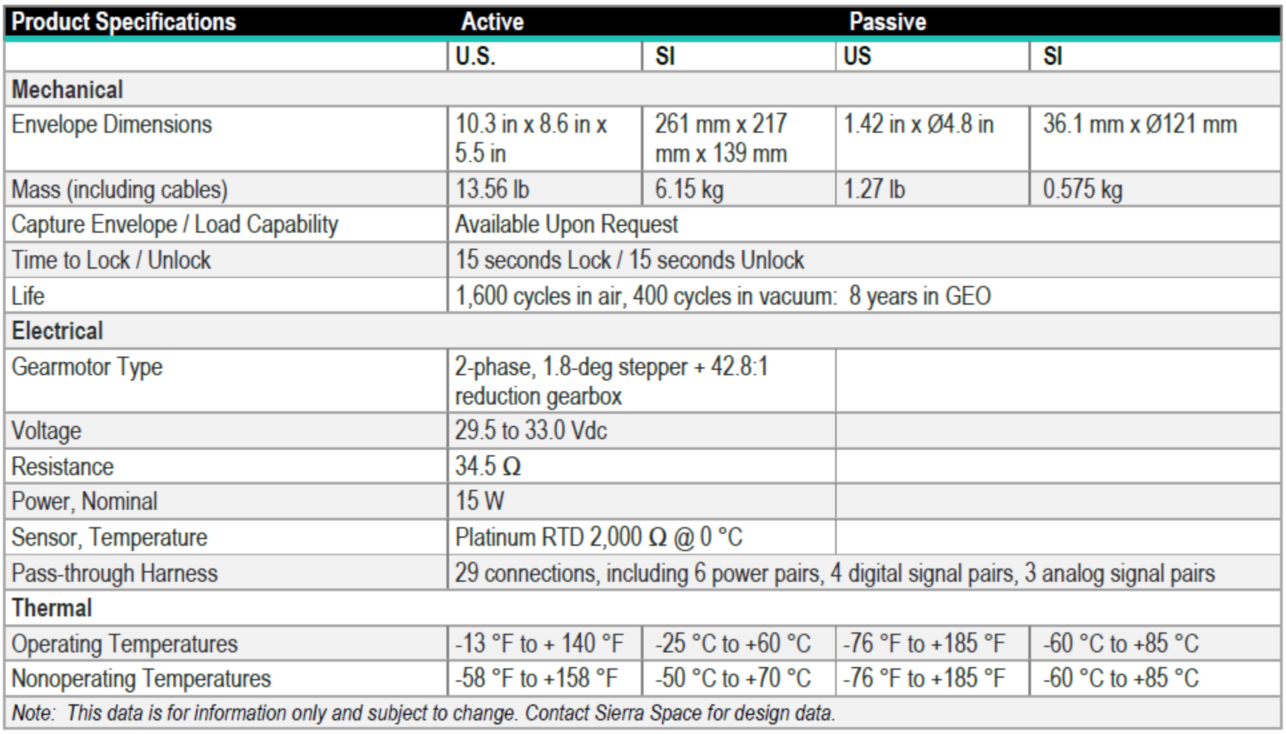


Structural, Power and Data Port Features	
• Defined capture envelope	• Driven by heritage stepper gear motor
• Mating and locking telemetry feedback	• Designed for GEO radiation and low electromagnetic interference (EMI)
• Active (spacecraft-side) and passive (tool-side) components	• Physical mating alignment features
• Lock fault protection	• Visual alignment and state indicators



Note: All dimensions above are in inches.

Figure 15 SPDP Dimensions



Product Specifications	**Active**		**Passive**	
	U.S.	**SI**	**US**	**SI**
Mechanical				
Envelope Dimensions	10.3 in x 8.6 in x 5.5 in	261 mm x 217 mm x 139 mm	1.42 in x Ø4.8 in	36.1 mm x Ø121 mm
Mass (including cables)	13.56 lb	6.15 kg	1.27 lb	0.575 kg
Capture Envelope / Load Capability	Available Upon Request			
Time to Lock / Unlock	15 seconds Lock / 15 seconds Unlock			
Life	1,600 cycles in air, 400 cycles in vacuum: 8 years in GEO			
Electrical				
Gearmotor Type	2-phase, 1.8-deg stepper + 42.8:1 reduction gearbox			
Voltage	29.5 to 33.0 Vdc			
Resistance	34.5 Ω			
Power, Nominal	15 W			
Sensor, Temperature	Platinum RTD 2,000 Ω @ 0 °C			
Pass-through Harness	29 connections, including 6 power pairs, 4 digital signal pairs, 3 analog signal pairs			
Thermal				
Operating Temperatures	-13 °F to + 140 °F	-25 °C to +60 °C	-76 °F to +185 °F	-60 °C to +85 °C
Nonoperating Temperatures	-58 °F to +158 °F	-50 °C to +70 °C	-76 °F to +185 °F	-60 °C to +85 °C
Note: This data is for information only and subject to change. Contact Sierra Space for design data.				

Figure 16 SPDP Product Specifications

6.7 Tool Changer/CRS (Common Receptacle Subassembly) – Oceaneering

The Tool Changer (TC) and Common Receptacle Subassembly (CRS) provide an electrical and mechanical interface for on-orbit attachment of tools and other separable items to the robotic arm. The interchangeable tools enable a robotic arm subsystem to perform a wide variety of servicing tasks. The subassembly provides a standardized robotic interface

- Electrical power and data connections through the robotic arm
- Torque delivery through the robotic arm tool drive (optional)

Tool Changer (TC)

- Mates to the robotic arm, serving as the active side of the interface
- Locking ball mechanism constrains axial movement of the CRS, providing a high-stiffness structural connection.
- V-guides provide coarse rotational alignment during mating.
- 32 lines provide connectivity across the interface, capable of transferring up to 54W.
- Connectors are arranged in 3 zones, for isolation of power, digital & analog signals.
- Axially-compliant socket transfers torque from the torque drive motor in the arm to the drive head in the CRS.

Common Receptacle Subassembly (CRS)

- Mates to the tool or separable item, serves as the passive side of the interface
- Provides structural and alignment features and electrical interface points
- Includes a pass-thru for the tool drive shaft, which is provided with an extended length to allow customization by the tool provider

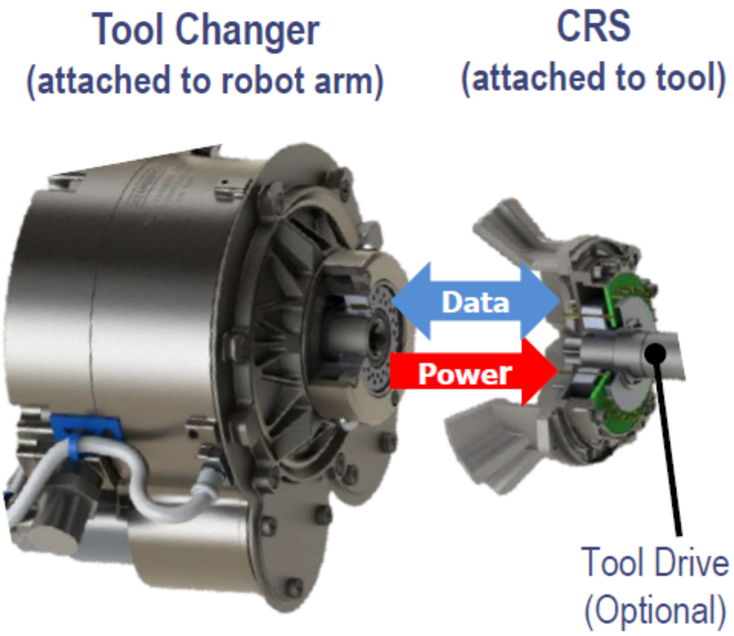
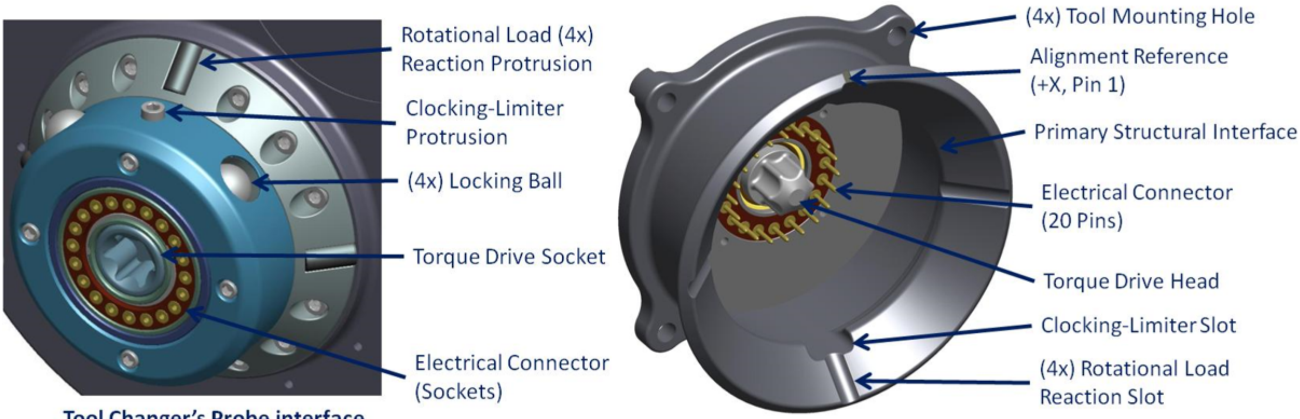


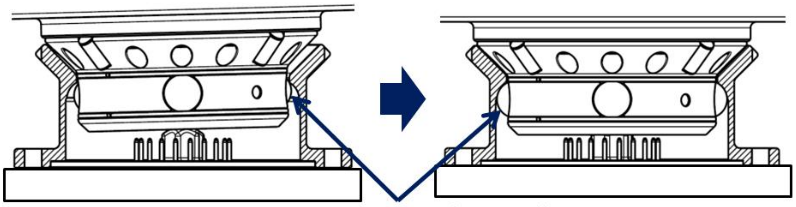
Figure 17 Oceaneering Tool Changer and CRS



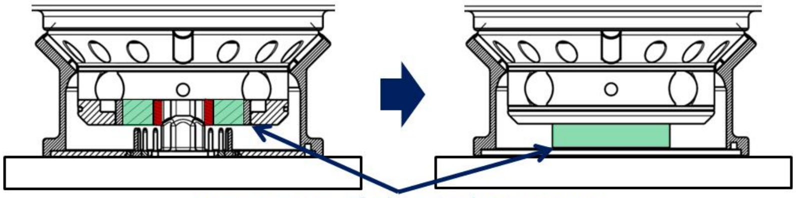
Tool Changer's Probe interface

Common Receptacle Subassembly (CRS)

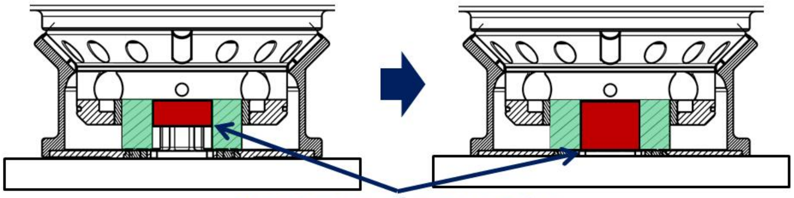
Figure 18 Oceaneering Tool Changer and CRS - Features



Engagement of Locking Balls



Engagement of Electrical Connector



Engagement of Torque Drive

Figure 19 Oceaneering Tool Changer and CRS Engagement Sequence

6.8 MDA Power and Data Interfaces for Commercial LEO Destinations (CLD) and Lunar Gateway

MDA has two classes of extravehicular robotics (EVR) system that build on the pedigree of Canadarm2 to offer state-of-the-art autonomous robotic capabilities.

The Large Arm is a long-reach EVR workhorse, providing:

- Assembly, maintenance and inspection of large infrastructure
- Capture, release, and berthing of visiting spacecraft
- Handling and installation of large modules, payloads and equipment pallets
- Supporting astronauts during extravehicular activity
- In combination with a dexterous tool, capable of handling and installing small packages to prepared worksites

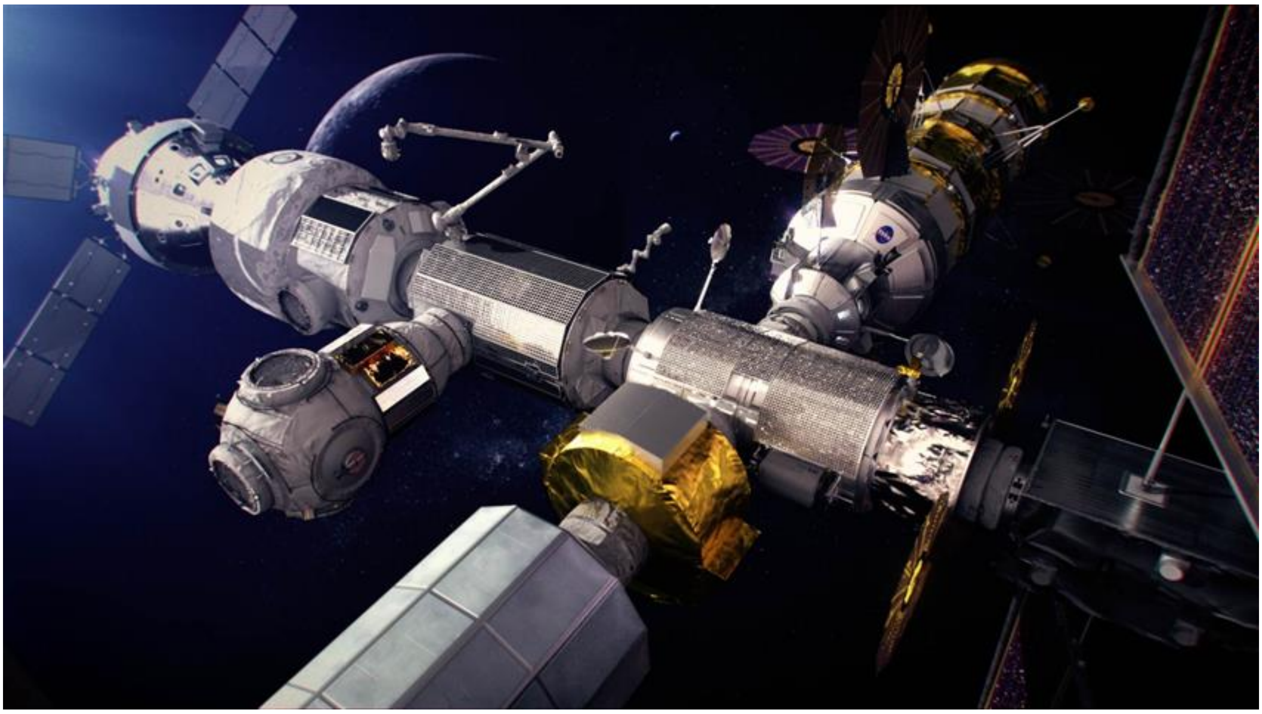


Figure 20 A rendering of a Large Arm performing inspection on the future Lunar Gateway Space Station (Image courtesy of NASA)

The Small Arm is a standalone spacecraft or platform tender, or the dexterous complement to the Large Arm, enhancing its capabilities in finer tasks with tighter clearances:

- Maintenance and resupply of stations and platforms and maintenance of the Large Arm
- Prepared and unprepared satellite servicing tasks
- Handling and deployment of payloads, instruments, resupply goods, and orbital replacement units (ORUs) up to 8000kg
- Capture, berthing and release of visiting spacecraft up to 8000kg
- Repair and replacement of payloads/ORUs, including those that require high precision alignment and force control

- Tool use

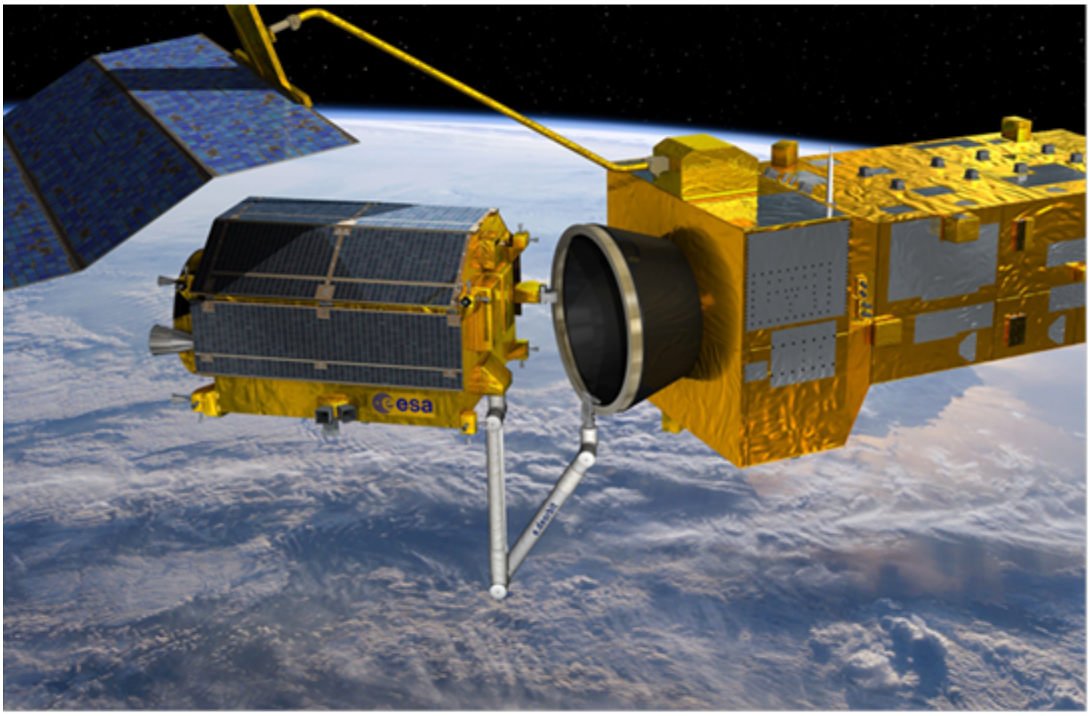


Figure 21 Notional Small Arm Operations (Image courtesy of CSA)

In combination or separately, the two arms provide a robust, vertically-integrated, turnkey EVR system that can operate autonomously across all orbital regimes from Low Earth Orbit (LEO) to Deep Space.

The integrated system includes a ground segment, as well as robotics interfaces to be integrated into the user's product.

- Grapple Fixtures
    - Dexterous: To interface the Small Arm, i.e. Dexterous Grapple Fixture (DGF), which interfaces with the Dexterous End Effector (DEE). See Section 6.8.1.
    - Low Profile: To support the Large Arm, i.e. Low Profile Grapple Fixture (LPGF), which interfaces with the Low Profile End Effector (LPEE). See Section 6.8.2.
    - ORU Robotics Interface: To support payloads and ORUs. See Section 6.8.1.

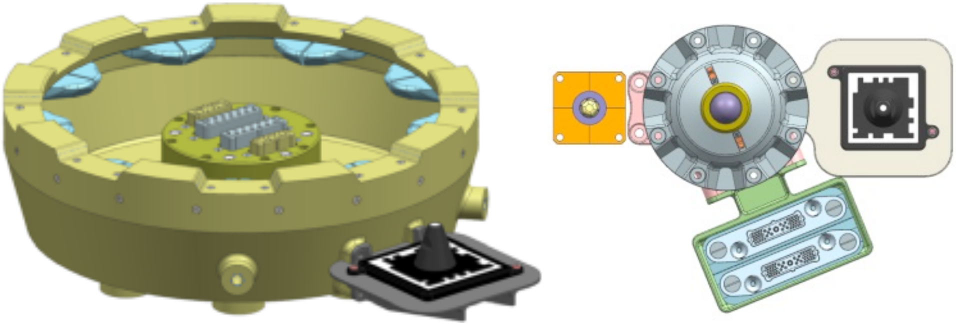


Figure 22 Low Profile Grapple Fixture (left) and Dexterous Grapple Fixture (right). Notional imagery, not to scale.

6.8.1 Dexterous Grapple Fixture (DGF) and Small ORU Robotics Interface (SORI)

As shown in the figures below, the DGF and the SORI are located on the same platform.

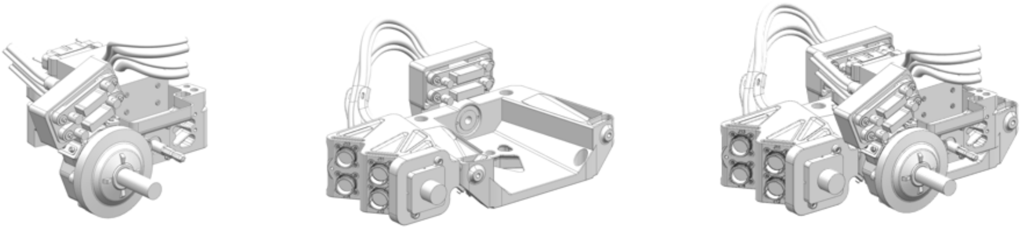


Figure 23 SORI-LV0 Concept Overview (Left: Platform, Center: Receptacle, Right: Fully Mated)

Given that the DGF and SORI are seen as a system, the electrical interfaces of the aforementioned system are provided in the schematic below, followed by an electrical interface parameters table. Specifications are provided for both the Lunar Gateway and Commercial LEO Destination (CLD) applications. Note the following terminology for the information that follows:

- Host: Any equipment or system that provides support services such as structure, power and communication links to and from the space station, spacecraft, module, satellite, etc. to the EVR.
- User: Any equipment or system receiving those support services from the EVR (e.g. payloads/Orbital Replacement Units (ORU), etc.).
    - There are a few cases where an equipment or system may be both a host and a user. In those cases, that equipment is considered a host when providing the services, and a user when receiving them.
- Payload/ORU: Generic term for any User equipment that is manipulated or otherwise supported by EVR services. This term encompasses more specific hardware types, such as Orbital Replacement Units (ORUs), robotic tools, etc. These terms are used interchangeably.
- SORI-P is used for the Platform upon which the User package is attached.
- SORI-R is used for the Receptacle which remains attached to its Host.
- HRM, Hold-down Release Mechanisms, represent the launch lock interfaces to the SORI.

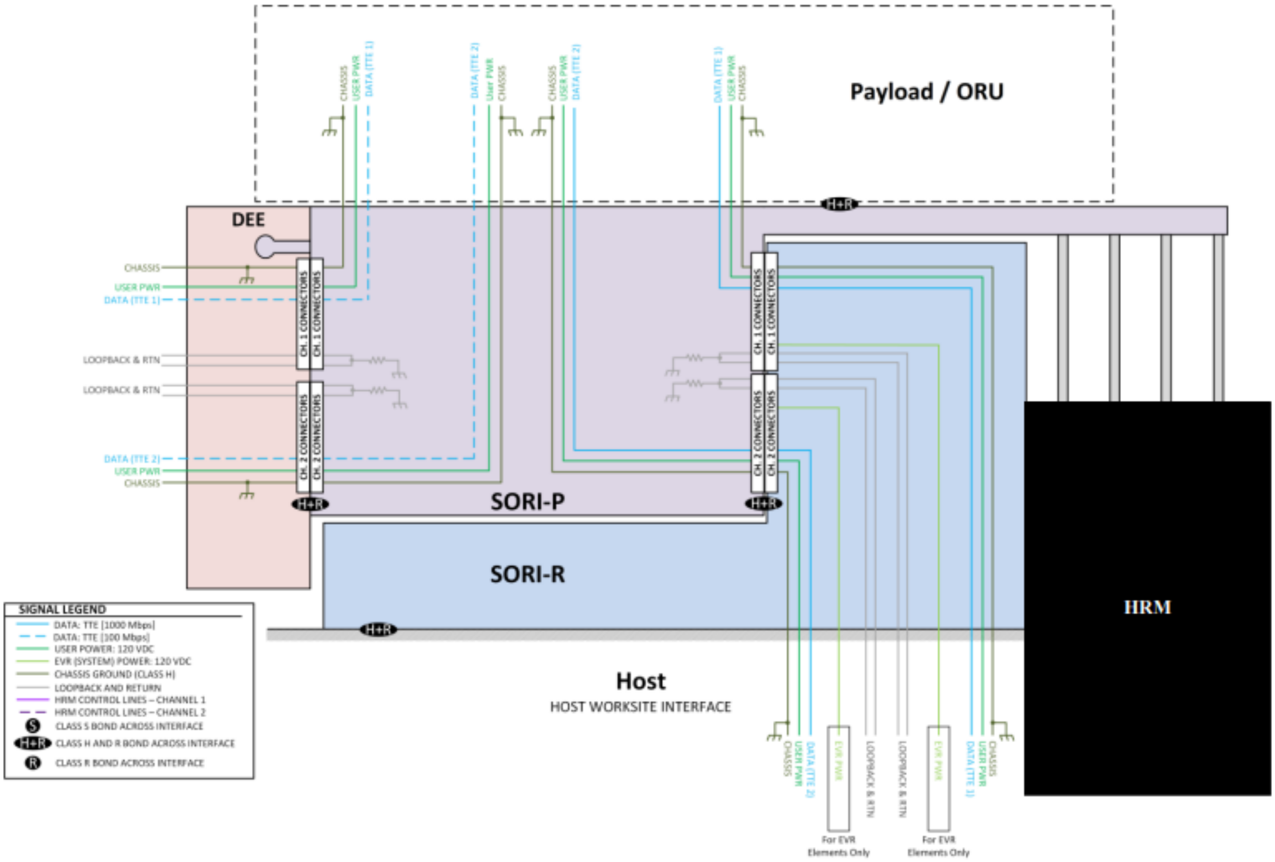


Figure 24 Gateway Host and EVR to SORI Electrical Interfaces

Table 3 Gateway Host to SORI Electrical Interface Parameters (for Channels 1 & 2)

Signal Name	Funct.	Signal Type	Spec.	Max Operation Current [A]	Data Rate [Mbps]	Cable Type	Wire Spec.	No. Conductors Per Instance	No. of Instances	Total No. of Conductors	No & Type of Contacts
Chan. 1 System Loop-back	Mating Confirmation	Bi-level Discrete	N/A	2.5	N/A	Single Wire	AWG 22	2	1	2	2×#23
Chan. 1 PL Power	Payload Power	Power / Return	120 VDC nominal; 105 V - 125V based on load	4.8	N/A	Twisted Pairs	AWG 20	2	2	4	4×#20
Chan. 1 Chassis Ground	Structure Safety, Shock and Fault Protection	Fault Current	N/A	4.8	N/A	Single Wire	AWG 20	1	1	1	1×#20

Chan. 2 System Loop-back	Mating Confirmation	Bi-level Discrete	N/A	2.5	N/A	Single Wire	AWG 22	2	1	2	2×#23
Chan. 2 PL Power	Payload Power	Power / Return	120 VDC nominal; 105 V - 125V based on load	4.8	N/A	Twisted Pairs	AWG 20	2	2	4	4×#20
Chan. 2 Chassis Ground	Structure Safety, Shock and Fault Protection	Fault Current	N/A	4.8	N/A	Single Wire	AWG 20	1	1	1	1×#20
Data-TTE1	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	1000	4 Shielded Twisted Differential Pairs, Overall Shielded	AWG 24, 100 Ω ± 15 Ω,	8	1	8	8×#23
Data-TTE2	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	1000	4 Shielded Twisted Differential Pairs, Overall Shielded	AWG 24, 100 Ω ± 15 Ω,	8	1	8	8×#23

Colour Legend	Power	Data

Table 4 CLD Host to SORI Electrical Interface Parameters

Signal Name	**Signal Type**	**Voltage Range [V]**	**Max Operating Current [A]**	**Protocol(s)-Standards(s)**	**Data Rate [Gbps]**	**Cable Type**	**Wire Spec.**	**Total No. of Conductors**
Chan. 1 Data 1	Digital Data	N/A	N/A	IEEE 802.3 10GBASE- T	up to 10	Cat 6A 4 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	8
Chan. 1 Data 2	Digital Data	N/A	N/A	IEEE 802.3 10GBASE- T	up to 10	Cat 6A 4 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	8
Chan. 1 Data 3	Digital Data (FO)	N/A	N/A	IEEE 802.3 100GBASE -SR4	up to 100	OM3 multimode fiber	50/125 MMF	8
Chan. 1 Loopback	Bi-level Discrete	N/A	< 1.7	N/A	N/A	Single wire	AWG 22	2
Chan. 1 Payload Power	Power/ Return	120 VDC Nominal 98 V - 136 V based on load	13.6	N/A	N/A	Twisted pair	AWG 22	8 pwr/rtn pairs
Chan. 1 Chassis Ground	Fault Current	N/A	10.2	N/A	N/A	Single wire	AWG 22	6
Chan. 2 Data 1	Digital Data	N/A	N/A	IEEE 802.3 10GBASE- T	up to 10	Cat 6A 4 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	8
Chan. 2 Data 2	Digital Data	N/A	N/A	IEEE 802.3 10GBASE- T	up to 10	Cat 6A 4 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	8
Chan. 2 Data 3	Digital Data (FO)	N/A	N/A	IEEE 802.3 100GBASE -SR4	up to 100	OM3 multimode fiber	50/125 MMF	8
Chan. 2 Loopback	Bi-level Discrete	N/A	< 1.7	N/A	N/A	Single wire	AWG 22	2

Chan. 2 Payload Power	Power/ Return	120 VDC Nominal 98 V - 136 V based on load	13.6	N/A	N/A	Twisted pair	AWG 22	8 pwr/rtn pairs
Chan. 2 Chassis Ground	Fault Current	N/A	10.2	N/A	N/A	Single wire	AWG 22	6

Colour Legend	**Power**	**Data**	**Data (Fiber)**

Table 5 Gateway Host-to-SORI EVR Power Parameters (For Channels 1 & 2)

Signal Name	Funct.	Signal Type	Spec.	Max Operation Current [A]	Data Rate [Mbps]	Cable Type	Wire Spec.	No. Conductors Per Instance	No. of Instances	Total No. of Conductors	No & Type of Contacts
Chan. 1 EVR (system) Power	System Power	Power/ Return	120 VDC nominal; 105 V - 125V based on load	5.0	N/A	Twisted Pairs	AWG 20	2	2	4	4×#20
Chan. 2 EVR (system) Power	System Power	Power/ Return	120 VDC nominal; 105 V - 125V based on load	5.0	N/A	Twisted Pairs	AWG 20	2	2	4	4×#20

Colour Legend	Power	Data

Table 6 CLD Host-to-SORI EVR Power Parameters

Signal Name	Signal Type	Voltage Range [V]	Max Operating Current(5) [A]	Protocol(s)-Standards(s)	Data Rate [Gbps]	Cable Type	Wire Spec.	Total No. of Conductors
Chan. 1 Data	Digital Data	N/A	N/A	IEEE 802.3 100BASETx (TBC)	up to 0.1	2 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	4
Chan. 1 Loopback	Bi-level Discrete	N/A	< 2.5	N/A	N/A	Single wire	AWG 22	2
Chan. 1 Power	Power/ Return	120 VDC nominal; 98V – 136V based on load	5.1	GP 10009	N/A	Twisted pair	AWG 20	4
Chan. 1 Chassis Ground	Fault Current	N/A	5.1	N/A	N/A	Single wire	AWG 20	1
Chan. 2 Data	Digital Data	N/A	N/A	IEEE 802.3 100BASETx (TBC)	up to 0.1	2 shielded twisted differential pairs, overall shielded	AWG 24, 100 Ω ±15 Ω	4
Chan. 2 Loopback	Bi-level Discrete	N/A	< 2.5	N/A	N/A	Single wire	AWG 22	2
Chan. 2 Power	Power/ Return	120 VDC; 98V – 136V based on load	5.1	GP 10009	N/A	Twisted pair	AWG 20	4
Chan. 2 Chassis Ground	Fault Current	N/A	5.1	N/A	N/A	Single wire	AWG 20	1

Colour Legend	**Power**	**Data**

Note that EVR Power is a mandatory service that must be supplied by all SORI Hosts. However, EVR power is reserved for use by the external robotics elements only. It is not for use by ORUs or Utilization Payloads.

6.8.2 Low Profile Grapple Fixture (LPGF)

The LPGF-to-User electrical interface requirements are provided in the schematic below, followed by the LPGF electrical interface parameters table. Specifications are provided for both the Lunar Gateway and Commercial LEO Destination applications. The LPEE should be interpreted as the interface to the Large Arm, as described in Section 6.8. The low-impedance Class R bond shown directly between the LPEE and the LPGF structure is established only once these two halves of the robotic interface are fully seated and mated.

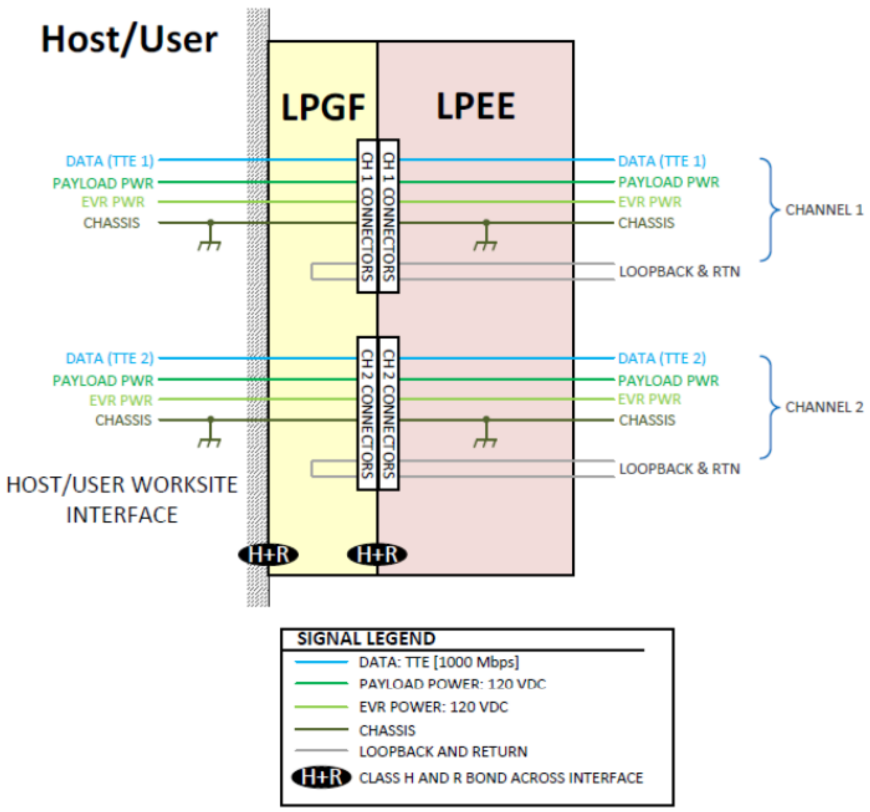


Figure 25 Gateway LPGF to User Electrical Interfaces

Table 7: Gateway LPGF Electrical Interface Parameters (For Channels 1 & 2)

Signal Name	Funct.	Signal Type	Spec.	Max Operation Current [A]	Data Rate [Mbps]	Cable Type	Wire Spec.	No. Conductors Per Instance	No. of Instances	Total No. of Conductors	No & Type of Contacts
Chan. 1 EVR (System) Power	System Power	Power/ Return	120 VDC nominal; 110 V - 125V based on load	18.2	N/A	Twisted Pairs	AWG 12	2	2	4	4×#12
Chan. 1 PL Power	Payload Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load	18.2	N/A	Twisted Pairs	AWG 12	2	2	4	4×#12
Chan. 1 Chassis Ground	Structure Safety	Fault Current	N/A	18.2	N/A	Single Wire	AWG 12	1	1	1	1×#12
Chan. 2 EVR (System	System Power	Power/ Return	120 VDC nominal; 110 V - 125V	18.2	N/A	Twisted Pairs	AWG 12	2	2	4	4× #12

) Power			based on load								
Chan. 2 PL Power	Payload Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load	18.2	N/A	Twisted Pairs	AWG 12	2	2	4	4× #12
Chan. 2 Chassis Ground	Structure Safety	Fault Current	N/A	18.2	N/A	Single Wire	AWG 12	1	1	1	1× #12
Data-TTE1	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	1000	4 Shielded Twisted Differential Pairs, Overall Shielded	AWG 24, 100 Ω ± 15 Ω	8	1	8	1× #8
Data-TTE2	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	1000	4 Shielded Twisted Differential Pairs, Overall Shielded	AWG 24, 100 Ω ± 15 Ω	8	1	8	1× #8

Colour Legend	Power	Data

Table 8 CLD LPGF Electrical Interface Parameters

Signal Name(1)(3)	**Funct.(3)**	**Signal Type(3)**	**Spec.(3)**	**Max Operating**	**Protocol(s)-Standard(s)(3)**	**Data Rate(3) [Mbps]**
Chan. 1 EVR Data(2)	Comm. Internal	Digital Data	EtherCAT	N/A	IEC 61158	100
Chan. 1 EVR Loop-back(5)	Loop-back	Bi-level Discrete	N/A	<2.5	N/A	N/A
Chan. 1 EVR Internal Video(2)	Video Internal	Digital Video	100BASE-TX	N/A	Ethernet	<500
Chan. 1 EVR Power(2)	System Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load(4)	18.2	GP 10009	N/A
Chan. 1 Payload Power	Payload Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load(4)	18.2	GP 10009	N/A
Chan. 1 EVR Enable(2)	Discrete line for on/off	Bi-level discrete	5 V	0.01	N/A	N/A
Chan. 1 EVR Thermistor(2)	Temperature sensing for thermal control	Analog	5 V	0.001	N/A	N/A
Chan. 1 Chassis Ground	Structure Safety, Shock and Fault Protection	Fault Current	N/A	18.2	N/A	N/A
Chan. 2 EVR Data(2)	Comm. Internal	Digital Data	EtherCAT	N/A	IEC 61158	100
Chan. 2 EVR Loop-back(5)	Loop-back	Bi-level Discrete	N/A	<2.5	N/A	N/A
Chan. 2 EVR Internal Video(2)	Video Internal	Digital Video	100BASE-TX	N/A	Ethernet	<500
Chan. 2 EVR Power(2)	System Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load(4)	18.2	GP 10009	N/A
Chan. 2 Payload Power	Payload Power	Power/ Return	120 VDC nominal; 110 V - 125 V based on load(4)	18.2	GP 10009	N/A
Chan. 2 EVR Enable(2)	Discrete line for on/off	Bi-level discrete	5 V	0.01	N/A	N/A
Chan. 2 EVR Thermistor(2)	Temperature sensing for thermal control	Analog	5 V	0.001	N/A	N/A
Chan. 2 Chassis Ground	Structure Safety/Shock/Fault Protection	Fault Current	N/A	18.2	N/A	N/A
Axiom Station Data – TTE 1	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	(Baseline) GP 10003	1000
Axiom Station Data – TTE 2	Comm. External	Digital Data	Time-Triggered Ethernet (TTE)	N/A	(Baseline) GP 10003	1000

Signal Name(1)(3)	Funct.(3)	Signal Type(3)	Spec.(3)	Max Operating	Protocol(s)-Standard(s)(3)	Data Rate(3) [Mbps]

Colour Legend	**Power**	**Data**	**Video**

Notes:

1) Chan. 1 and Chan. 2 signals are routed in separate harnesses and internal connectors.
2) EVR Power, EVR Data, EVR Internal Video, EVR Thermistor and EVR Enable services are reserved/intended for EVR elements only
3) Table columns do not contain harness implementation details, but rather the general signal parameters that are *required* for signal compatibility. These parameters are intended to reflect Station-level implementation decisions for power, data, etc.
4) This includes the voltage drop due to the EVR cabling when an LPGF-equipped User is at the end of a manipulator.
5) EVR loopback is intended to support EVR sensing of LPEE/LPGF mating. The LPEE provides the loopback source and sense lines and the LPGF closes the loop when fully mated with the LPEE.

6.9 Mission Augmentation Port (MAP) – Lockheed Martin

The Lockheed Martin Mission Augmentation Port (MAP) Standard (ASPN-STD-001) establishes a standard docking interface for satellite-to-satellite mechanical attachment for the purpose of mission augmentation and upgrade. The purpose of the Standard is to provide a basic set of design parameters sufficient to allow developers to independently design compatible docking systems.

The Standard is intended for use by missions across all orbit regimes. It is expected that docking spacecrafts using this interface would typically include small satellites ranging from approximately 27U to the “half-ESPA” and ESPA class missions. Specific limits on size and mass are constrained by Host spacecraft (or Host) GNC margins and mounting panel strength, as well as the strength of a specific port design.

This document specifies a docking system that provides the following capabilities:

- Bidirectional data transfer between Host and Satellite Augmentation Vehicle (SAV)
- Unidirectional power transfer from Host to SAV

The MAP system is composed of two mechanical docking ports: the Host docking port and the SAV docking port. The figure below shows an overview of the MAP system aligned for a docking maneuver.

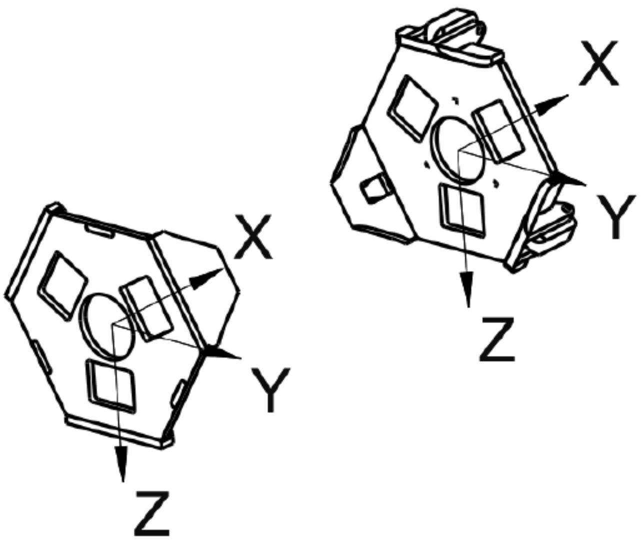


Figure 26 Overview of the MAP system, showing the SAV docking port (bottom left, without petal-mounted latches) docking to the Host docking port (top right, with petal-mounted latches)

The electrical connectors transfer data and power between the Host spacecraft and the SAV spacecraft after a successful docking maneuver. The electrical connectors are designed as a plug and receptacle, where the receptacle connector is mounted on the Host docking plate and the plug connector is mounted on the SAV docking plate.

The following is a recommended interface configuration for MAP compliant electrical connectors. Decisions for signal and power allocation specifics are left to MAP users. MAP electrical connections must be coordinated and documented between the two spacecrafts (e.g., available power and energy, electrical loads, etc.) to ensure mission compatibility.

Table 9 Recommended electrical interfaces for MAP compliant system

Signal	Quantity	Function
1 Hz LVDS Signal	1	1 Hz/PPS timing signal
Ethernet	1	Primary communication path for data and command/control
Chassis Ground	3	Ground reference
Active Analog Inputs	4	Status of health from the SAV
TLM Interlock	3	Discrete signal to indicate successful electrical mate has occurred
Signal Ground	33	Digital grounds
Power Remote Sense	2	Battery voltage and current measurements from SAV
Power 28Vdc	1	28VDC power connections to the SAV
Return 28Vdc	1	28VDC return connections to the SAV
Spares	19	Spare for future capability/expansion
No Connects	3	Isolation of power and ground pins

The following is an example of an electrical connector that can be used for the Host and SAV docking adapters. The design of the electrical connectors is left to MAP users. The electrical connectors must be coordinated and documented between the two spacecrafts to ensure mission compatibility.

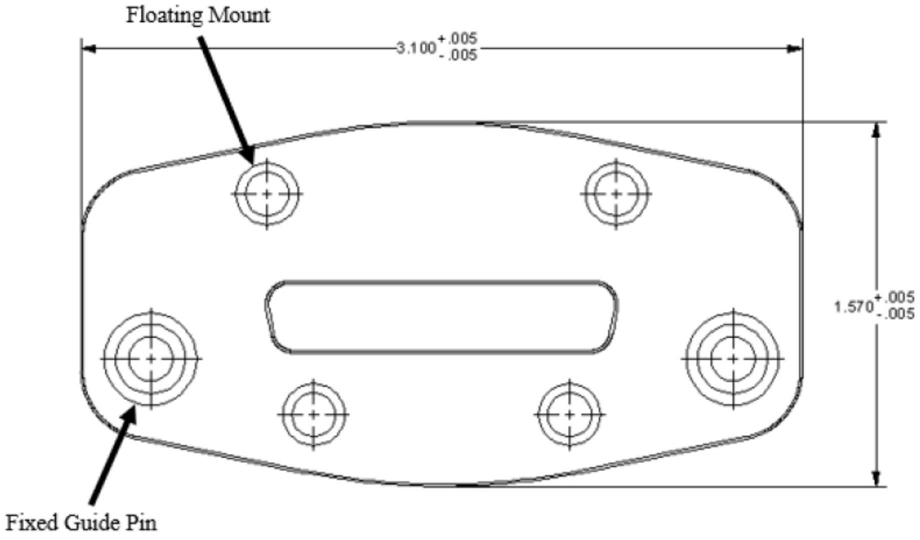


Figure 27 Front view of the Host electrical connector, looking in the +X direction calling out the floating mount and fixed guide pin features

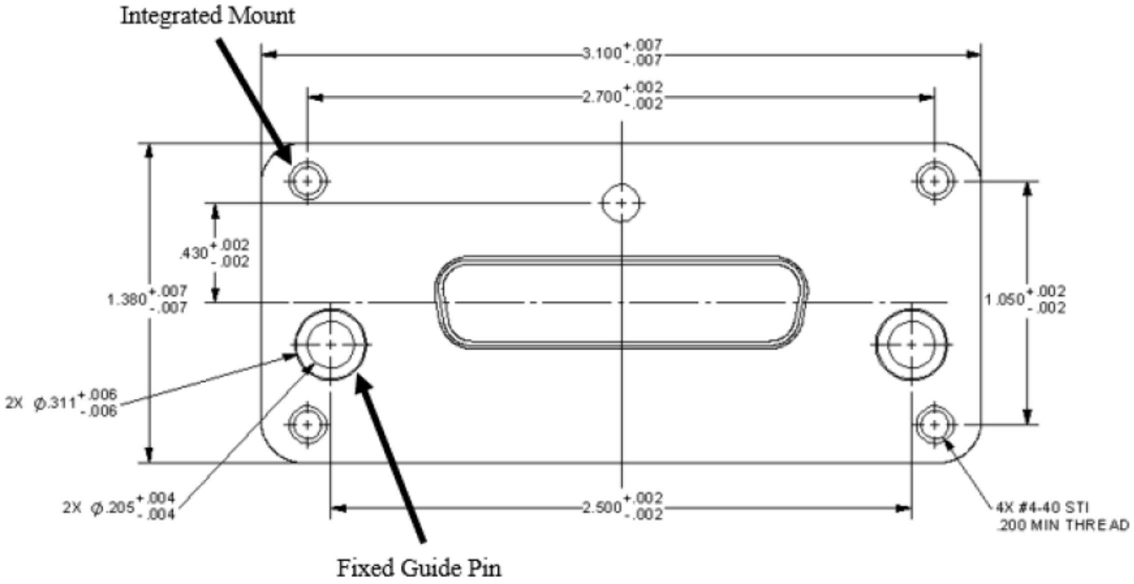


Figure 28 Front view of the SAV electrical connector, looking in the -X direction calling out the integrated mount and fixed guide pin features

6.10 GRASP Multifunctional Payload Interface power and data connector - CUA

CU Aerospace (CUA) has developed a versatile Power and Data connector based on a proven multifunctional payload interface. The system is designed to enable correct, reliable contact even with at least 1° of rotational misalignment in the guideless resilient androgynous serial port (GRASP), **Figure 1**. The connectors successfully underwent successful robotic docking ground testing during the GRASP experimental program, demonstrating its capabilities with *misalignments as large as 2° in yaw + 2° in roll axes.*

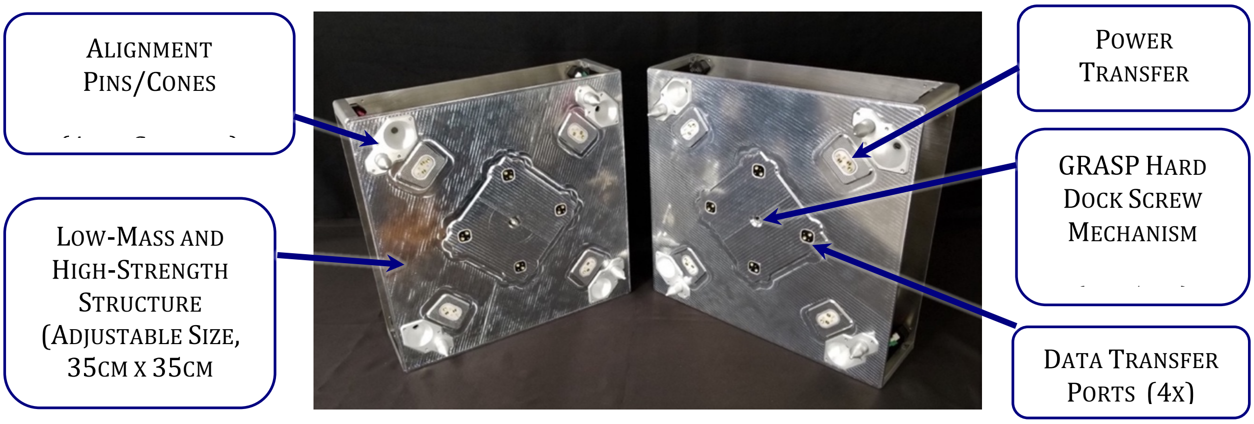


Figure 29 – The docking face (0.35 m x 0.35 m) of the GRASP-IV assembly interface demonstration hardware, including androgynous hard dock screw mechanism and CUA's Power and Data connectors.

Key features of the power and data connectors, **Figure 2**, include limited 6-degree freedom compliance (ensuring a stable connection while retaining alignment prioritization), floating spring pins and target pads (ensuring a stable connection while adding to misalignment correction capability), and a carefully designed interface system between pins and housing. The Power and Data connectors share components and design cues, making it easy to adjust pin count or redesign the footprint to match mission requirements for either-- including androgyny, power and data rates, and envelope size.

The 6-conductor, 3-channel Power connector power transmission was tested up to 1.3kW (estimated 1.9kW with vacuum de-rating) at 115VAC and 0.7kW (estimated 1 kW) at 32VDC and features a current rating of 9 A continuous (de-rated to 4.5 A for space applications). Additional connectors can be added to increase total power transmission, per customer requirements.

The 4-conductor- 4-channel Data connector has demonstrated data transfer rates up to 1 Gbps and features a current rating of 15 A continuous (de-rated to 7.5 A for space applications). The spring pins are carefully sized to achieve a maximum 15dB return loss, meeting the requirements for high data rate (HDR) applications. To bolster the gigabit Ethernet infrastructure, the spring pin array can be seamlessly integrated with shielded twisted pair cables or other established heritage network solutions.

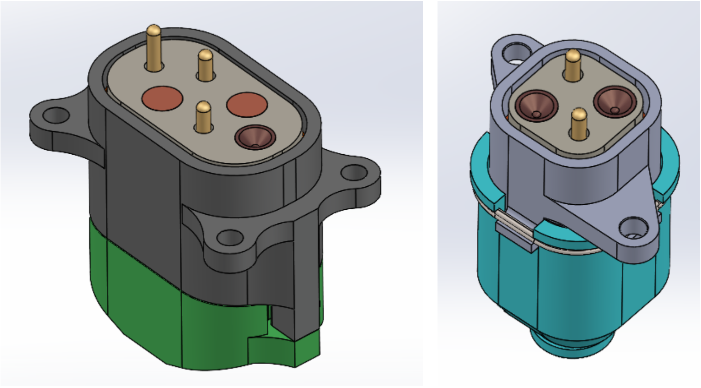


Figure 30 – GRASP Connector Left: 6-Conductor, 3-Channel Power

The connectors include both flat contacts and an "alignment contact", wherein the outward-facing contact target includes an indented feature centered on the contact, the indented surface being configured to compensate for relative misalignment between mating connectors when the "alignment pin" of the mating connector is in contact with the indented surface and the connectors are brought together. The "alignment pin" is identical to the other spring pins in the connector, but protrudes further from the contact face so it may contact the mating connectors alignment contact and travel partly along the indented surface before the other spring pins contact with their intended paired targets. This fine alignment helps correctly place the spring contacts centered on their target pads.

Materials for the shells, pins, and couplers, **Figure 3**, have been selected for their robust heritage in space applications. Optional interposer materials can be tailored to specific orbital environments. CUA's prototypes have used PEEK, a polymer with excellent outgassing, tensile strength, coefficient of thermal expansion, and radiation resistance properties. The PEEK material can be replaced by other materials as desired.

CUA's Power and Data connectors offer customizability for specific applications, including passive rotational full symmetry and variable pin-count and coupling options.

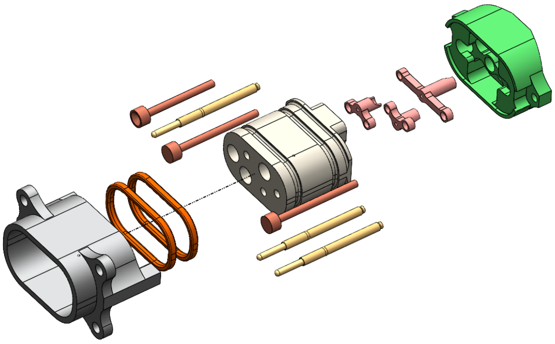


Figure 31 Figure 3 – Exploded view of the GRASP Power Connector, with targets, dampers, and pin couplers visible.

References

Hejmanowski N, Ghosh A, Carroll D, "Guideless Resilient Androgynous Serial Port Docking Mechanism," U.S. Patent 10,882,645, Jan. 5, 2021.

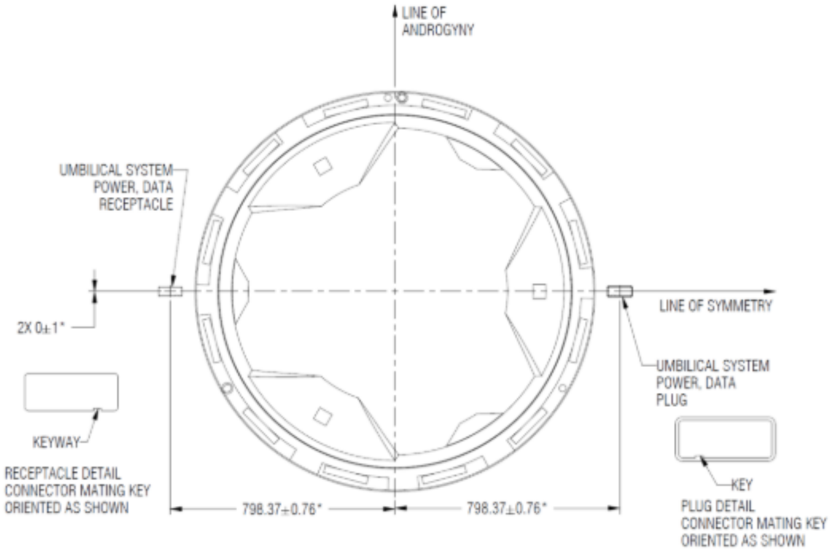
Hejmanowski N, Ghosh A, Carroll D, "Guideless Resilient Androgynous Serial Port Docking Mechanism" (Continuation-in-Part), U.S. Patent 11,401,054, Aug. 2, 2022.

Hejmanowski N, Ghosh A, Carroll D, "Guideless Resilient Androgynous Serial Port Docking Mechanism" (Continuation-in-Part, 2nd), U.S. Patent 11,485,522, Nov. 1, 2022.

GRASP Brochure, https://cuaerospace.com/Portals/0/SiteContent/assets/PDF/GRASP-Brochure-220725.pdf?ver=vnwLVCCESKxgIG5dcOt8ug%3d%3d, 2022.

6.11 International Docking System – NASA

The International Docking System Standard (IDSS) Interface Definition Document (IDD) describes a standard docking interface to enable on-orbit crew rescue operations and joint collaborative endeavors utilizing different spacecraft. The IDSS is intended for uses ranging from crewed to autonomous space spacecrafts, and from Low Earth Orbit (LEO) to deep-space exploration missions. Section 3.4 of the IDSS IDD describes the power and data transfer umbilical details. The androgynous design is shown in Figure 32, along with translational and rotational compliance capabilities of the standard connector design in Figure 33 through Figure 35.



* Connector positional tolerances with respect to Line of Symmetry or Line of Androgyny.

Figure 32 IDSS Standard Power/Data Transfer Umbilical Connectors

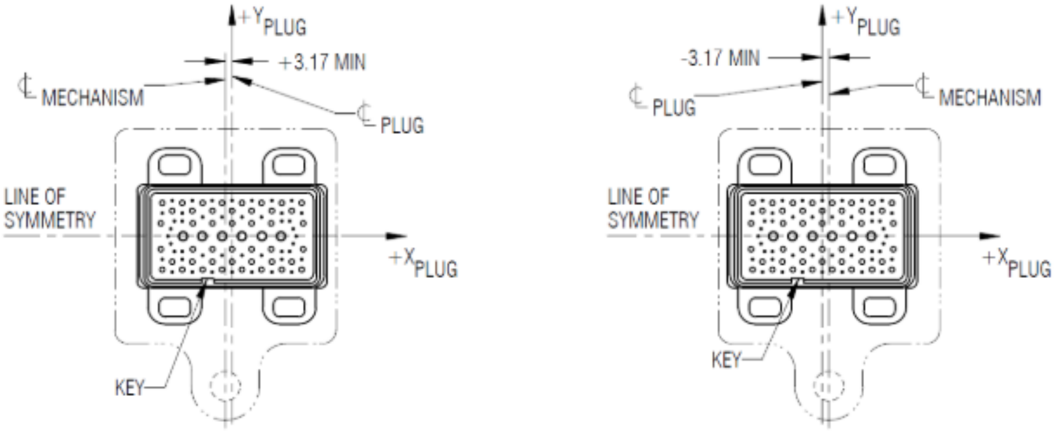


Figure 33 IDSS Power/Data Connector Plug Lateral Compliance in X Direction

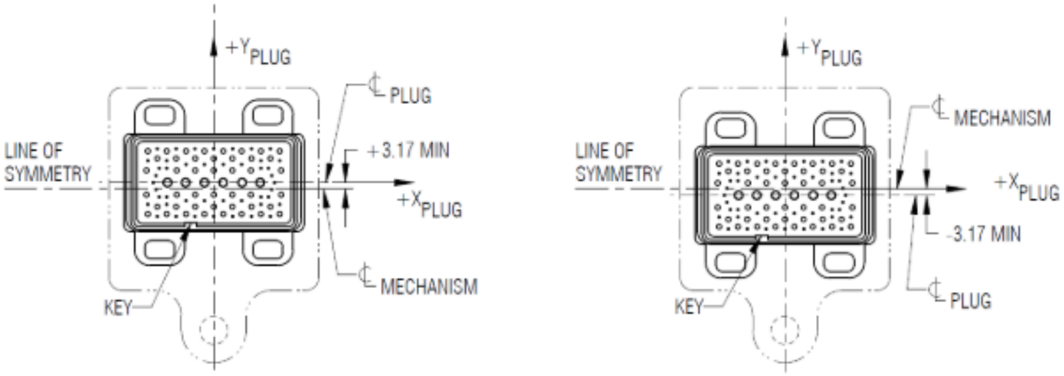


Figure 34 IDSS Power/Data Connector Plug Lateral Compliance in Y Direction

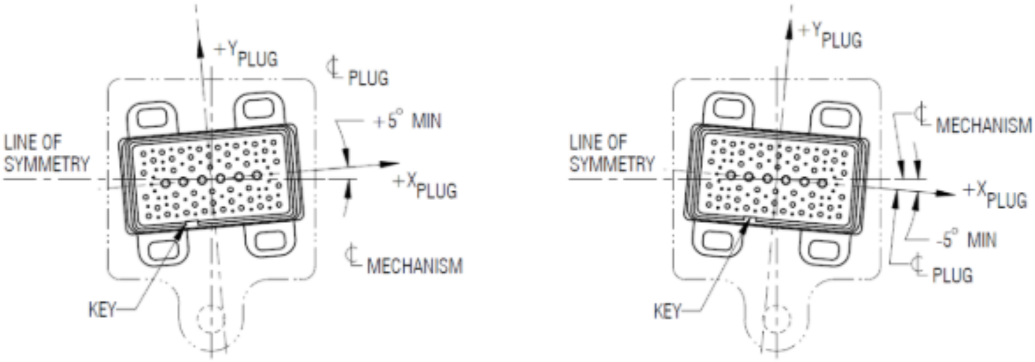


Figure 35 IDSS Power/Data Connector Plug Rotational Compliance About the Z Axis

6.12 FuseBlox™ – SpaceWorks

The FuseBlox™ connector system is an all-in-one spacecraft docking and connection device. Through its proprietary and patented internal claw mechanism, FuseBlox facilitates near-zero momentum transfer without requiring relative velocity between the spacecraft. Additionally, it provides high-reliability electrical power and data connectivity. The self-aligning grapple technique accommodates rendezvous misalignments while device symmetry enables four secure mated configurations. FuseBlox connector systems are natively androgynous and are designed to fit a variety of applications and configurations (see Figure 36). FuseBlox's advantages over competitors include a 2U small form factor, a weight under 5 kg, embedded computing for docking mechanism control, best-in-class tolerance to initial offset and drift conditions, and ruggedized enhancements that make it suitable as a reusable launch payload adapter for small payloads. FuseBlox supports up to 1000W of power transfer and data transfer through either MIL-STD-1553 or Gigabit Ethernet protocols. A FuseBlox-compatible modular fluid transfer interface is currently under active development. Table 10 shows the general specifications for FuseBlox.

Table 10. FuseBlox General Specifications

Parameter	Value
Length	10 cm
Depth	20 cm
Width	10 cm
Mass	< 3 kg

Power Transfer Capacity	1,300 W Nominal 1,500 W Max
Pass-Through Data Protocols	Gigabit Ethernet MIL-STD-1553

Figure 36 FuseBlox Flight Units. Left side shows an active-passive configuration, where the passive unit lacks grappling claw. Right side is showing an androgynous (active-active) configuration with left unit acting as male side

Every aspect of the FuseBlox design considers requirements for space-rated, high-reliability functionality, including selection of Grade 2 EEE (or higher) parts, and extensive qualification for thermal, vacuum, radiation, and vibration environments. FuseBlox minimizes power consumption through efficient power conversion and management. FuseBlox utilizes components, manufacturing procedures, and operating procedures that minimize outgassing of the flight system as per ASTM E595 guidelines.

History & Heritage

Under the DARPA Tactical Technology Office (TTO) program, SpaceWorks Enterprises, Inc. designed, built, and ground-demonstrated a connector device intended to support docking and mechanical interconnection between orbiting spacecraft as well as power and data transfer. The novel device, which later became FuseBlox, was designed to assist in the aggregation and disaggregation of modular building blocks for a persistent geosynchronous space platform. FuseBlox is a key enabling technology for numerous missions that require modular construction, offering unique advantages compared to traditional spacecraft architectures or connectors with a larger form factor. Modular spacecraft design with FuseBlox is expected to offer improved spacecraft systems-of-systems performance, greater space asset redundancy and resiliency, lower spacecraft acquisition costs, and enable missions such as on-orbit servicing, refueling, and assembly. Through DARPA and AFRL Commercial Readiness Program sponsorship, FuseBlox completed extensive environmental and performance qualification testing, thus attaining TRL-6 in 2021 (see Figure 37) and its first commercial unit sale to a US domestic customer in 2022. SpaceWorks is pursuing opportunities for first flights to occur in the 2025-2026 timeframe.

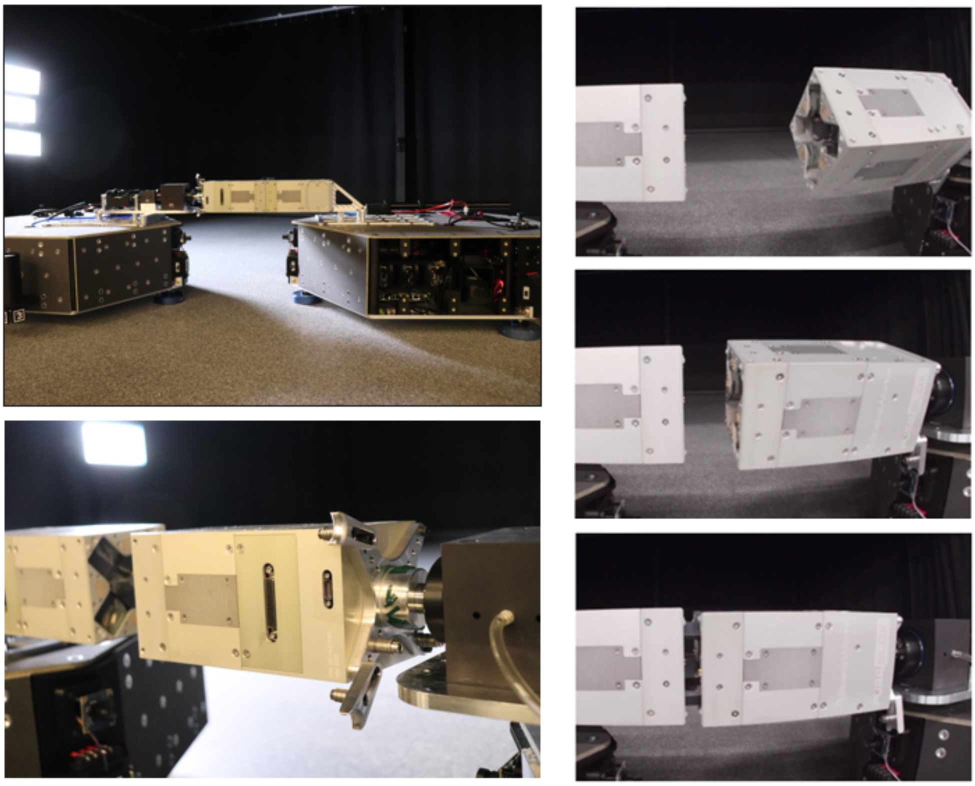


Figure 37 FuseBlox Flight Model Performance Testing at AFRL ROC Lab

To encourage early adoption of servicing interfaces, SpaceWorks also offers the passive half of FuseBlox as a compact, standalone component (Figure 38). This lightweight, 10x10x4 cm adapter can be installed on any external surface of a spacecraft to enable future access by an active FuseBlox claw. The passive half also facilitates power and data transfer. In the future, this passive half will also support FuseBlox's fluid transfer interface.

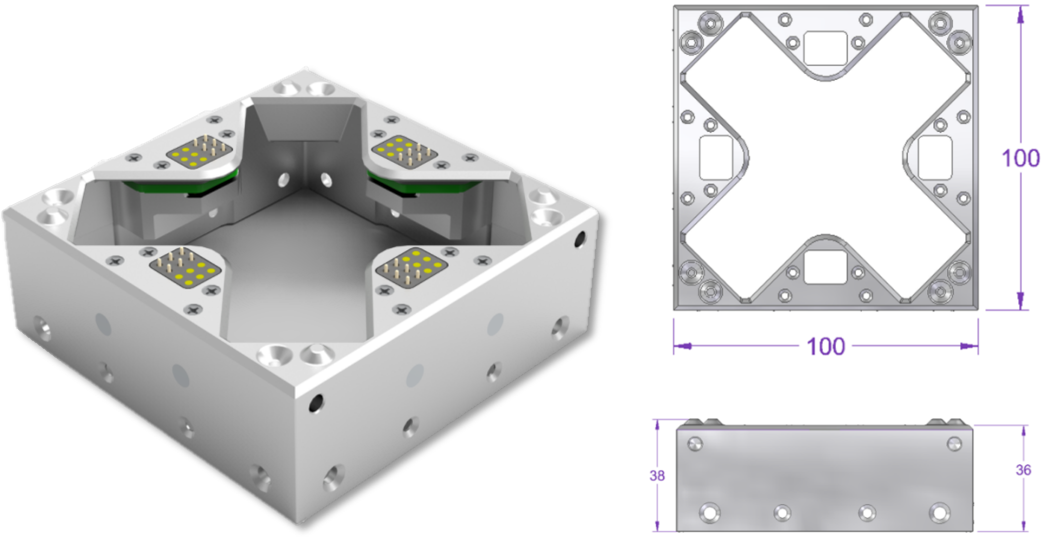


Figure 38 FuseBlox Passive Half with power and data interface

Data & Power Interfaces

The FuseBlox system provides connections to the host spacecraft through two M83513 micro-D connectors (J1 and J2). The pass-through interface to connect to another spacecraft is brokered through an array of four spring-loaded connectors, which enable power and data transfer once the systems have completed docking. An overview of interface features is presented in Figure 39.

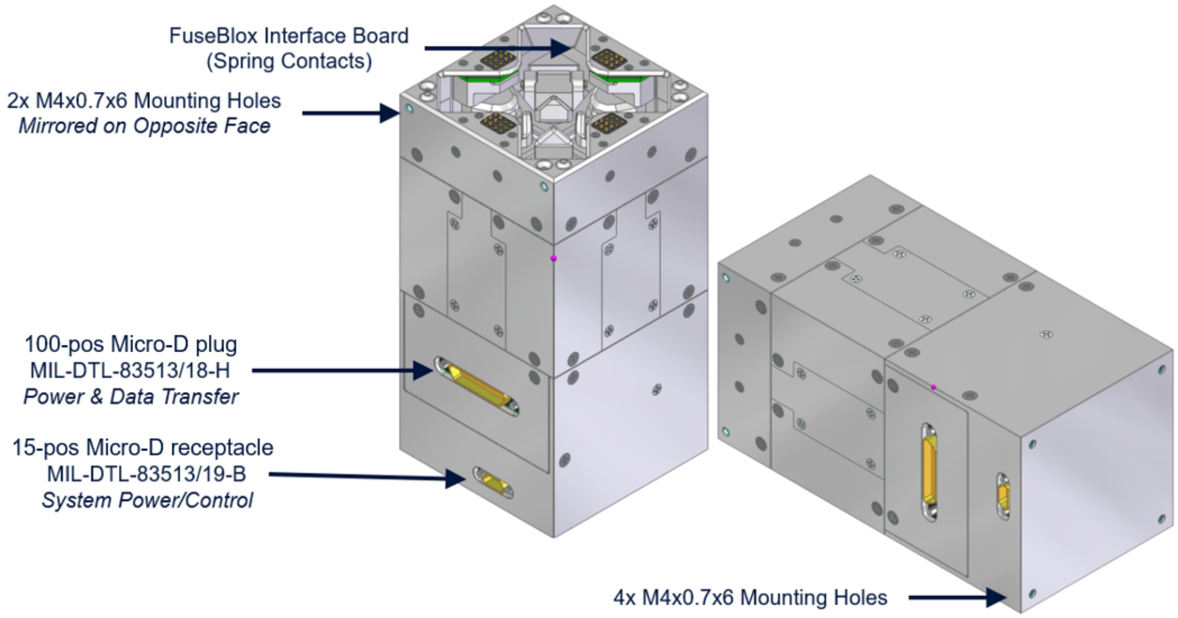


Figure 39 Overview of FuseBlox Mechanical, Electrical, and Data Interface features

The System/Power Control connector, J1, contains electrical power, CAN bus, and control discrete interfaces for the docking mechanism. The electrical power interface is 28 V DC nominal. The docking mechanism command and telemetry interfaces operates on a CAN bus. The system publishes standard telemetry at rates up to 100 Hz (if enabled), as well as on-demand telemetry for settings, faults, heater control, and versioning status. For development purposes, SpaceWorks has also developed a FuseBlox node in the Robotic Operating System 2 (ROS2) as an executable that can run on the host spacecraft computer. This node communicates with other nodes on the ROS network, which can be allowed data access and control of the FuseBlox connector system. FuseBlox connector functionality is exposed through a ROS2 topic for telemetry and several ROS2 services for commands. The interfaces are packaged separately for integration.

The Power & Data Transfer connector, J2, contains pass-through power and data transfer connections wired to the faceplate's spring probe interfaces. The connector provides the through power and data connections between two host spacecrafts. Rated power transfer should not nominally exceed 38.7V, 33.6A. The connector system uses TVS diodes to protect transfer power conductors against ESD events.

Figure 40 shows the pass-through connector pinout at the FuseBlox interface. The GIGE_* pins refer to 1000BASE-T Ethernet, also known as Gigabit Ethernet, with a nominal bitrate of 1 Gbps. There are two Base1000T links provided. 1553_* pins refer to MIL-STD-1553 with a nominal bitrate of 1 Mbps. There are four 1553 links provided. All communication links can be used simultaneously in any combination at full throughput, limited only by the two host spacecrafts’ capabilities.

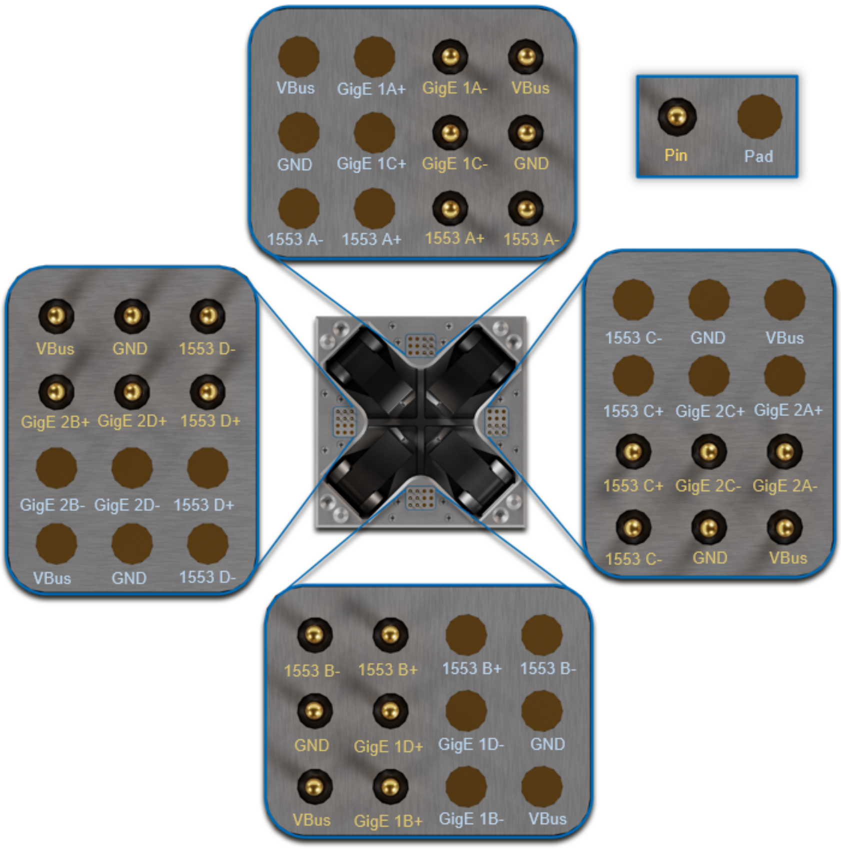


Figure 40 FuseBlox Pass-through connection pinout