Design of an Interoperable Interface for In-Space Operations and Services of Modular Spacecraft

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Abstract

Current satellite designs are based on specific mission profiles, lacking the flexibility to adapt their capabilities, be repaired, or be refueled to extend their lifetime. In Europe, several companies are developing technologies to address this limitation and enable On-Orbit Servicing operations. Specifically, Space Application Services, Sener and iBOSS have developed Spacecraft Service Interfaces, respectively called HOTDOCK, SIROM and iSSI® that can be used to connect to satellite modules or Orbital Replacement Units, to build large structures in space, or to be equipped to robotic manipulators as end-effectors. These interfaces, in addition to providing a mechanical connection between two entities, also allow the transfer of data and power between them. Currently developed independently, none of these interfaces can operate with the others. This lack of interoperability does not allow a spacecraft equipped with an interface to be served by a spacecraft equipped with a different one, severely limiting cross-system compatibility and redundancy.

For this reason, the HORIZON EUROPE SPACE USB project aims to create a Common Passive Interface that is compatible with the three interfaces mentioned above. This new interoperable interface provides a mechanical connection and the exchange of data and electrical power with all three existing interfaces, without degrading performance or requiring substantial design modifications. This solution marks a critical step toward standardization in space, facilitating on-orbit servicing and promoting interoperability among different systems, thus enabling the emerging on-orbit robotic servicing market in Low Earth Orbit and Geostationary Orbit.

This paper describes the design processes and phases carried out within the SPACE USB activity. Starting from the analysis of the three existing interfaces, design priorities for each of them and the challenges that prevent interoperability between them have been identified and overcome. Different concepts were proposed and, subsequently, a trade-off analysis was conducted to choose the most viable, satisfying each individual constraint. Finally, a detailed design phase has been completed, and a laboratory implementation supported by a robotic testbed is planned by Q4 2025.

Keywords: Space, OOS, ISOS, Standard interconnects, Orbital Robotics

Acronyms/Abbreviations

Controller Area Network (CAN), Common Passive Interface (CPI), Geostationary Orbit (GEO), Light Fidelity (Lifi), Low Earth Orbit (LEO), On-Orbit Assembly (OOA), On-Orbit Servicing (OOS), Orbital Replacement Unit (ORU), Printed Circuit Board (PCB), Space Universal Serial Bus (SPACE USB), Spacecraft Standard Interconnect (SSI), Technology Readiness Level (TRL), Universal Standard Interface (USI).

1. Introduction

The current approach to satellite design is based on highly specialized solutions tailored to specific mission requirements. This strategy significantly limits the potential for satellite reuse in alternative missions and, in the event of malfunctions, often results in premature mission termination. Furthermore, the usual satellite's operational lifetime is strictly constrained by the amount of onboard fuel available at launch, making life extension difficult [1]. To address these limitations, several companies worldwide are developing technologies aimed at enabling On-Orbit Servicing (OOS) operations, as described in [2-3]. These technologies allow satellites to extend their operational life by replacing faulty components, upgrading to more advanced systems, or performing in-orbit refueling [4-5]. Another promising application is the On-Orbit Assembly (OOA) of large-scale structures, which would overcome the dimensional limitations imposed by launch vehicle fairings [6-7]. In detail, Space Application Services, Sener and iBOSS have developed Spacecraft Service Interfaces (SSI), respectively called HOTDOCK, SIROM and iSSI® that can be used both for the OOS-OOA operations and as end-effector of a robotic arm.

HOTDOCK [8] ensures mechanical coupling using 12 locking balls arranged in a 360° configuration and enables power and data transfer through connectors placed along its outer diameter. SIROM [9] establishes mechanical connection with three latches arranged in a 120° symmetric layout and transmits power and data via pogo pins located at the center of the interface. iSSI® [10] uses a bayonet mechanism for mechanical mating, provides electrical power through four pins pairs arranged in a 90° configuration, and transmits data via a central optical Gbit Lifi-interface. Additionally, both HOTDOCK and SIROM integrate a form fit alignment system to facilitate mating during docking operations, whereas iSSI® features a flat interface and does not include such alignment features in its basic configuration (but as an add-on). Direct interoperability among these interfaces is currently unfeasible due to significant differences in their mechanical and electrical architectures. The primary limitations arise from the mechanical symmetry configuration of each interface. Additionally, power and data transfer rely on three distinct technologies, each positioned at different radial locations, ultimately preventing system-level compatibility.

This lack of compatibility represents a major barrier to the widespread adoption of OOS technologies, as a satellite equipped with one interface cannot be serviced by a vehicle using another. To overcome this limitation, the HORIZON EUROPE SPACE USB project aims to develop a common passive interface (CPI) that is mechanically and functionally compatible with the existing European systems, thus enabling power and data transfer across different platforms.

The structure of this paper is as follows: Sec. 2 presents an overview of the CPI, while Sec. 3 and Sec. 4 details its mechanical and electrical architectures. Sec. 5 provides the CPI budgets and Sec. 6 illustrates the first assembled prototype. Sec. 7 finally provides a conclusion on the work achieved and presents perspectives on future activities.

2. System Overview

The CPI, illustrated in Figure 1, is a mechanical and electrical system without actively actuated components which enables mechanical, data and power connections of HOTDOCK, SIROM and iSSI® interconnects.

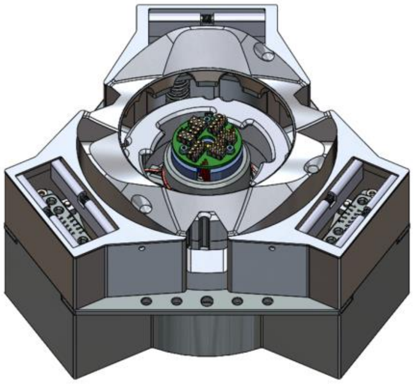

Figure 1: CPI 3D model overview.

The CPI mainly features:

- A shared mechanical body featuring a form fit and needed locking elements for the mechanical approach and coupling of the different interconnects.
- Electrical interfaces (internally and externally) to transfer data and power as function of the mated interconnect.
- A mounting structure and external connectors to mechanically and electrically interface with the host system.

3. Mechanical Architecture

The CPI's core structure consists of a cylindrical housing topped by a form-fit, which is designed to accommodate multiple coupling mechanisms while maintaining structural integrity and interoperability. The form fit of the CPI is composed of a set of alignment features enabling proper mating with HOTDOCK, SIROM and iSSI® active interconnects.

As illustrated in Figure 2, the CPI features:

- 6 flat surfaces, highlighted in orange, as part of 120° symmetry form fit for aligning HOTDOCK and SIROM
- 3 tapered holes, highlighted in yellow, on pattern 360°/4 for aligning iSSI®

Considering these features, the CPI combined the 90° and 120° symmetry provided by the active interconnects. In the current configuration the CPI allows 3 mechanical coupling positions for the HOTDOCK and SIROM and 4 mechanical coupling positions for iSSI®.

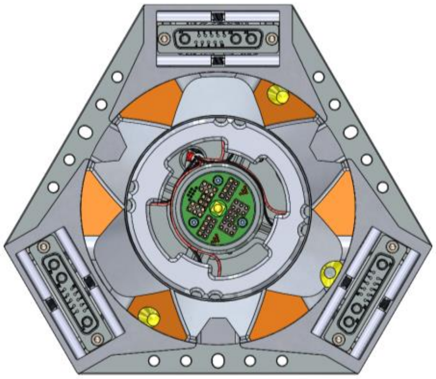

Figure 2: CPI alignment features: for HOTDOCK and SIROM in orange, for iSSI® in yellow.

The form fit has been designed and laboratory tested to maximize its attraction range when coupling with another similar form fit. Tests have been conducted with a compliant robotic arm for different misalignments and robotic configurations to identify confidence and uncertainty zones occurring from robot behavior. Figure 3 illustrates these laboratory results, obtained for a lateral misalignment of the robot with respect to the initial position [x,y]=[0,0]. The light yellow zone depicts the range of position around [0,0] where the confidence is high to enable the approach whereas the black zone depicts the position where the approach is impossible. The shading zone between the yellow and the black one depicts the zone of progressive non-confidence to enable the approach.

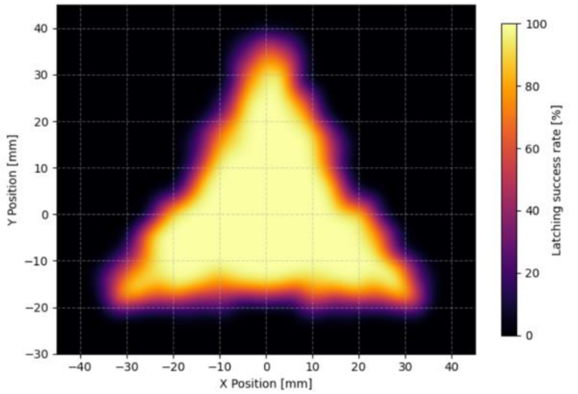

Figure 3 : Interpolated converging success rate heatmap of the CPI form fit.

The CPI locking functions consist of an aggregate of the locking technologies of SIROM, iSSI® and HOTDOCK, arranged in such a way that they are not conflicting with each other, but still enable the connection of the respective active interconnects.

As illustrated in Figure 4, the CPI features:

- 3 external pockets on pattern 360°/3 for hosting the active SIROM latches. These pockets have been designed to maximize the range of capture of the connection when dealing with capture before contact
- An internal locking race featuring 12 cavities on pattern 360°/12 for locking HOTDOCK.
- An internal and passive deployable piston featuring 4 wings for connecting the bayonet mechanism of iSSI®. This piston is actuated via a pin-driven mechanism (see section 2.1.4.3) which transitions from its retracted position (HOTDOCK/SIROM) to its engagement-ready configuration when iSSI® is aligned with the CPI.

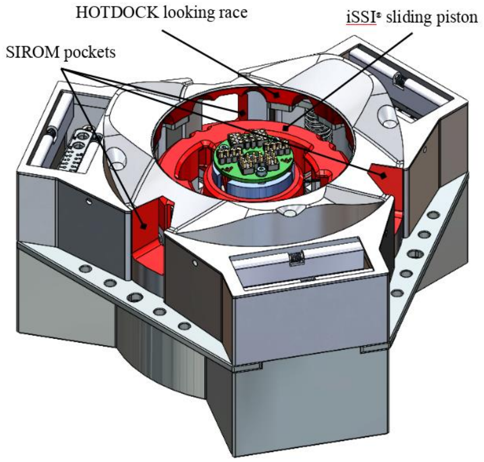

Figure 4: CPI mechanical interfaces (in red).

To deploy and retract the internal locking piston of the CPI, a spring-loaded bar mechanism, illustrated in Figure 5, has been implemented. The mechanism is driven by a sliding pin located in one of the tapered holes. The piston's movement is guided outside the cylinder of the central data and power interface module's mounting structure, featuring a small pin running in a dedicated groove to ensure controlled linear motion and actuation. A spring is integrated on the piston, connected to the backplate of the assembly, providing automatic retraction of the piston upon iSSI® decoupling, thereby restoring the interface to its default HOTDOCK/SIROM-compatible state, as illustrated in Figure 6.

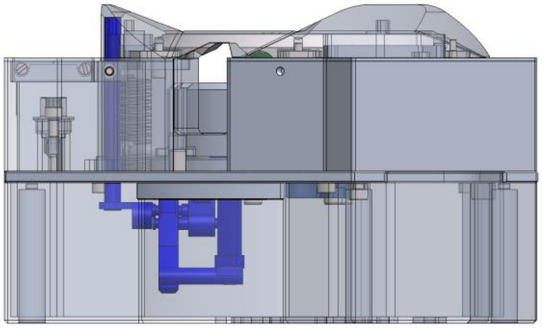

Figure 5: CPI internal piston driving mechanism (in blue). The harness and other components are either omitted or shown in transparent view for clarity.

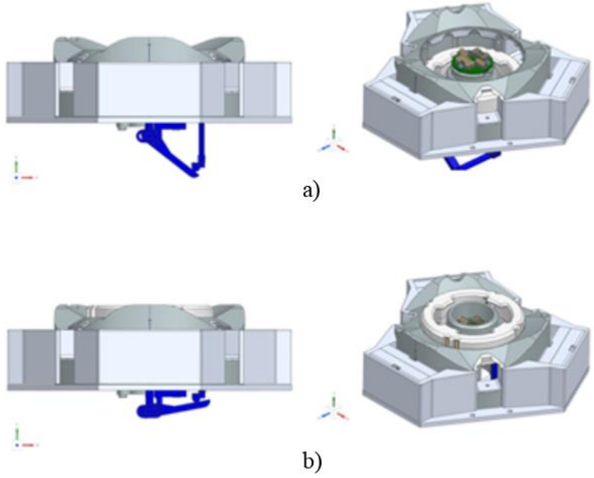

Figure 6: CPI internal piston driving mechanism functioning a) retracted (default position) b) extended when actuated by an iSSI® pin.

The CPI features a mechanical interface, as illustrated in Figure 7, which is composed of a mounting plate with long holes for alignment pins, through holes for attachment screws, and centering surfaces. Thus, several mounting configurations are available for integration into a system.

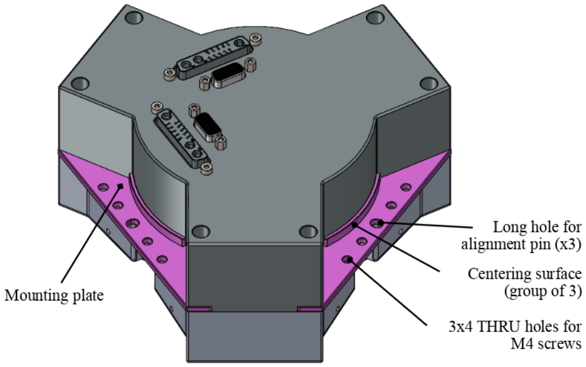

Figure 7: The CPI mechanical mounting interface and its centering features (in pink).

4. Electrical Architecture

The CPI data and power interfaces layout consists of a set of connectors and avionics from SIROM, iSSI® and HOTDOCK, arranged in such a way that they are not conflicting with each other, but still enable the connection of the respective data and power active interfaces.

As illustrated in Figure 8, the CPI features:

- 3 external DSUB 13W3 connectors covered with flaps for HOTDOCK power and data transfer
- 4 times 2 power races on the circumference of the internal sliding piston for iSSI® power transfer
- 1 internal PCB composed of spring loaded (pogo type) pins for SIROM power and data transfer, and a central optical interface for iSSI® data transfer

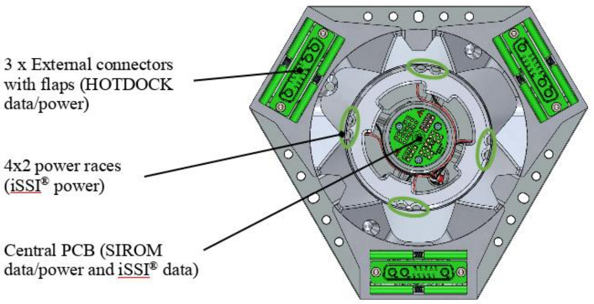

Figure 8: CPI data/power interface with respect to active interconnect.

The external data and power interfaces of the CPI are composed of a set of connectors split between the mentioned three different SSIs, as illustrated in Figure 9. These connectors are located on the back shell of the CPI. The back shell also contains the needed avionics, harnessing, and the piston mechanism.

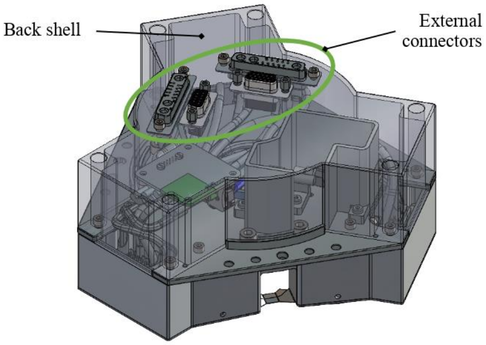

Figure 9: CPI external electrical interface and back shell configuration.

5. Preliminary Budget

This section describes the estimated mass budget, dimensions and volumes, as well as power budget and data budget of the CPI.

5.1. Mass

Table 1: CPI TRL4 mass budget.

Item	Item mass [kg]
Structure	1.018
Locking features	0.167
Mechanisms	0.119
Connectors	0.100
Harnessing	0.283
System mass [kg]	**1.642**

Table 1 shows the estimated mass of CPI with 1.642 kg. The mass contains the structure, locking features, mechanism, connectors and harnessing.

5.2. Dimensions and Volume

The main outer dimensions and volume of the CPI is D190mmxH130mm and 0.004m^3 as shown in Figure 10.

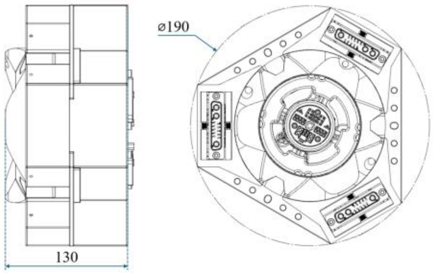

Figure 10: CPI outer dimensions (in mm).

5.3. Power

Table 2: CPI power budgets for coupled interfaces.

Interface	Voltage [V]	Current [A]	Power [W]
SIROM	100	10 (2.5A/contact)	1000
iSSI®	Up to 100	40	Up to 4000
HOTDOCK	Up to 100	Up to 40	Up to 4000

The CPI is designed to accommodate three different SSIs power interfaces. All three SSIs have different power budgets as shown in Table 2.

5.4. Data

Table 3: CPI data budgets for coupled interfaces.

Interface	Data Interface	Data rate
SIROM	Ethernet and CAN	1 Gbps (bidirectional with Ethernet) and 1 Mbps (with CAN)
iSSI®	Lifi Ethernet	900 Mbps
HOTDOCK	Ethernet or CAN	1 Gbps (bidirectional with Ethernet) or 1 Mbps (with CAN)

To cover the data transmission the CPI host three different data interfaces. All three have different transmission capabilities as shown in Table 3.

6. Prototyping

In the scope of the SPACE USB activities, a printed prototype version of the CPI has been produced based on the design introduced in above sections.

Figure 11: CPI 3D printed prototype.

Figure 11 depicts this final prototype where functions are highlighted per color: black for the structure, red for the locking features, and green and external connectors for the data/power connections.

7. Conclusions and Perspectives

The development of the Common Passive Interface within the SPACE USB project represents a significant advancement in addressing the current interoperability of European Spacecraft Service Interfaces, namely HOTDOCK, SIROM, and iSSI®. Through an iterative process, the CPI has been designed to enable mechanical coupling and support interoperable power and data transfer with the three different active interconnects. This milestone paves the way for achieving standardization for in-space servicing and assembly operations.

The CPI successfully consolidates multiple mechanical symmetries, data protocols, and power requirements into a single passive interface without compromising the functional integrity of the respective active interconnects. The laboratory testing of mechanical alignment, the implementation of a shared locking mechanism, and shared electrical interface demonstrate the feasibility of this unified approach.

Looking ahead, the next steps involve the fabrication of a TRL4-representative prototype and its integration within a robotic testbed for dynamic validation under representative operational conditions. These upcoming tests will assess mechanical robustness, repeatability, and electrical continuity across different mating configurations. Furthermore, scalability analysis might be envisaged to evaluate the CPI's application in various mission scenarios, including Low Earth Orbit satellite servicing and modular space station assembly in Geostationary Orbit.

In the long term, the CPI concept could serve as a foundational element for a universal standard interface (USI) in in-space servicing, fostering greater interoperability, mission flexibility, and system redundancy. This work thus lays the groundwork for a more sustainable, modular, and cooperative future in orbital infrastructure development and robotic operations.

Acknowledgements

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