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A Standard Interconnect Benchmark for a European In-orbit Services, Manufacturing and Assembly (ISMA) Demonstrator

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Abstract

Growing space debris is an issue for which solutions are being sought, especially with the usage of space robotics. The topic ranges from disposal to sustainability. Modular robotic can be seen is a key factor to support sustainability in space. Within this framework, it is possible to combine modular components in such a way that, for example, a satellite can be created or in the event of malfunction, modules can be replaced without having to abandon the whole satellite. This reduces space debris. To connect the modules, standard interconnects (SIs) with multifunctional features, like to connect mechanically and transmit power and data, are required. In the operational grant (OG) PERIOD of the EU Horizon 2020 project PERASPERA, three existing SIs have been evaluated within a benchmarking concept to give a recommendation on the most suited one to be used in the orbital demonstration mission of PERIOD, as well as provide feedback for their future improvements.

Testing was conducted by the German Research Center for Artificial Intelligence GmbH (DFKI) as an independent body to neutrally evaluate the performance of SIs in relevant demonstration scenarios and in full transparency to consortium members. This paper describes the benchmark approach, methodology, test setup, execution, and recommendation path for what concerns the mechanical aspects of SIs. The approach can be extended and applied to future deployments of SIs in European and international space projects.
Keywords: Standard Interconnect, Interface, Orbital Robotics, Benchmark, Mechanical Test, Ontology

1. Introduction

Mankind's interest in continuing to use LEO for commercial and research purposes continues unabated [1]. There are many ideas and research approaches to avoid and reduce further space debris. The subject area is very extensive and goes from techniques for the collection of space debris to techniques for reusability.

For this purpose, modular robotics is used, which allows individual modular subcomponents to be combined with each other in such a way that new assemblies such as satellites are created. To be able to guarantee diverse functionality, the use of, so-called, multifunctional interfaces can help to connect subsystems with each other as required and be able to exchange them quickly in the event of malfunctions.

Multifunctional interfaces enable various features such as mechanical docking, transmission of power and data as well as liquids or heat transfer [2].

Existing multifunctional interfaces are for example Electromechanical Interface (EMI) from DFKI GmbH Robotics Innovation Center [3], HOTDOCK from Space Applications Services [4], iSSI® from iBOSS GmbH [5, 21], SIROM from SENER Aeroespacial [6] and ASSIST from ESA [7].

These interfaces allow (re)configuration of submodules (some can transfer liquid with built-in pipes and can be used for refuelling). Such possibility of (re)configuration moves In-Space Manufacturing and Assembly (ISMA) one step further. The ISMA processes can be realized with astronauts as it was done for the ISS and the repair of the Hubble telescope, but the harsh environment and the cost of human spaceflight increases the need for robotic ISMA and servicing missions [8].

The PERIOD [*] (PERASPERA In-Orbit Demonstration) project has the goal to demonstrate on the ISS key robotic technologies to enable ISMA and On-Orbit Servicing (OOS) applications. This includes in-orbit manufacturing of a modular spacecraft equipped with an antenna that is to be assembled in-orbit as well. The set-up can be seen in Fig 1 with two payload boxes, one equipped with the robotic system and one equipped with the satellite and reflector parts.

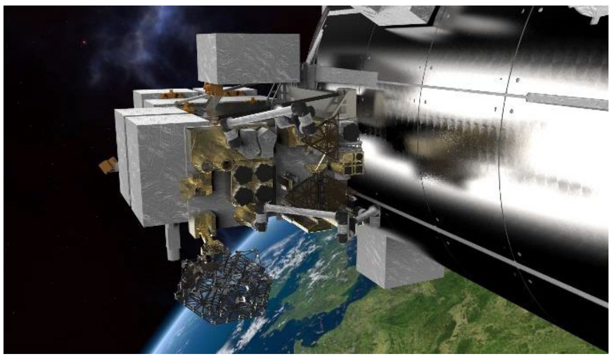

Fig. 1. The PERIOD Boxes mounted on the Bartolomeo platform outside of the Columbus module (credit: Airbus Defence and Space SAS).

The PERIOD project is one of the operational grants (OGs) of the third phase of the Horizon 2020 Space Strategic Research Cluster (SRC) on Space Robotics Technologies. Outcomes of previous OGs from the first and second call are implemented and further developed. PERIOD seeks to change the status quo by demonstrating an alternative to the traditional approach of manufacturing, assembling, and validating space hardware on the ground with direct in-orbit manufacturing and assembly using robotics, autonomy, and modularity [9].

The mission demonstration scenario considered by the SI benchmark consists of the manipulation by the in-orbit factory of a Payload Module (PLM) of a spacecraft, consisting of a 6U CubeSat form factor, with an aim for the latter to be attached to a Core Module (CRM) of the spacecraft, consisting of a 12U CubeSat form factor, via SIs.

An illustration of the fully assembled Client Satellite with the attached PLM and the built reflector dish is showed in Figure 2. The far-left unconnected cylinder is the passive back SI dedicated for the manipulator. The left middle cylinder is the passive PLM SI connected to the active CRM SI to form the connection between the two modules. A boom holding the manufactured reflector dish extends from the top of the PLM.

[*] https://period-h2020.eu/

The PLM will have two passive SIs mounted externally to it. One SI shall be positioned to interface with the CRM, and the other SI to interface with the Robotic Arm Manipulator of the in-orbit factory. During assembly, the manipulator will pick up the PLM with the manipulator's active end-effector attached to the back PLM's SI, and then move the PLM into position so that the front PLM's SI can attach to the CRM's active SI.

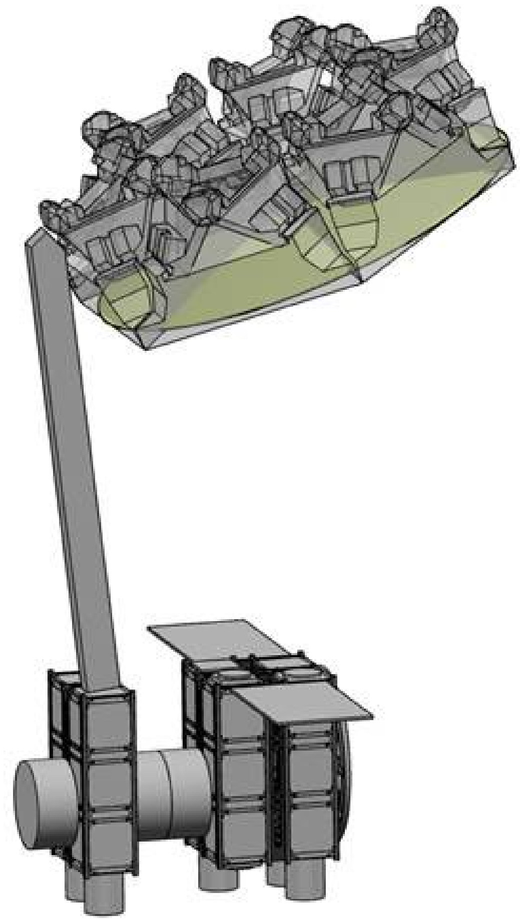

Fig. 2. CAD model of the fully assembled Client Satellite (credit: Airbus Defence and Space SAS).

Testing and verification of the SI connection will be performed while the Client Satellite is still at the factory. The tests must verify that the CRM can send power and telecommands through the SI to the PLM, that the PLM operates as expected after receiving the appropriate commands, and that the PLM can send back payload data to the CRM.

Once the Client Satellite is released into its own free-flying orbit and the commissioning phase is completed, payload operations will commence to acquire scientific measurements using the on-board experiment. Payload data will be downlinked using the high-bandwidth Payload Data Transmission (PDT) system, consisting of a Ka-Band Radio and antenna feeder on the CRM. The feeder will be pointed at a High Gain Antenna reflector dish. This reflector dish will be manufactured in the factory and attached to a mounting interface on the top of the PLM (note that this mounting interface is not an SI).

As already mentioned, several multifunctional interconnects exist in European space robotics, three of which are possible candidates for the in-orbit demonstration scenario in PERIOD: HOTDOCK, iSSI® and SIROM. These three interconnects have been tested within an SI Benchmark to evaluate which interconnect best meets the criteria of the demonstration scenario, as well as provide feedback for their future improvements.

This paper describes the SI Benchmark mechanical tests, the test setups, and the ontology conceived for the collection as well as evaluation of the obtained test results. Due to the existing confidentiality status of the test report, only selected evaluations are presented in this paper.

2. State of the art

This section contains a description of the state-of-the-art methods used for testing SIs or interfaces with similar purposes/functionalities relevant for the SI benchmark.

2.1 Payload exchange functional tests

SIROM was functionally tested at ADS Bremen within OG 5 activities. The demonstration was based on a robot payload exchange scenario involving the use of 4 SIROMs, and two active payload modules (APMs) (one APM with a payload camera and another dummy) [10].

2.2 Misalignment tests

The objective of the test was to evaluate the SIROM capabilities to mate SIs under different misalignments in all 6 degrees of freedom (DoF) (X, Y, Z translations and Roll, Pitch, Yaw rotations).

In this case an active SIROM is mounted as the end-effector of a UR10 robot while a passive SIROM is fixed to a workbench. The robot moves in position control mode to its target misaligned pose, then it switches to impedance control mode to behave compliantly and next, active SIROM is commanded to latch. During the latching, the gap, and misalignments between both SIROMs is self-corrected thanks to the latching system and guiding petals of the two interfaces.

2.3 Electrical tests

The purpose of the H2020 project entitled "European Robotic Orbital Support Services" (EROSS) is the mission and system design of a servicing spacecraft to perform rendezvous, capture and servicing of a client satellite, while validating this design with end-to-end ground experiments [11].

The functioning of the interface of the APM with its payload and with the robot end-effector, as well as that of the end-effector with the robot manipulator were successfully validated for what concerns the power transmission. Regarding data transfer, the demonstrations have proved that SI interface supports SpaceWire, Ethernet and CAN as data protocols.

Inside EROSS project, SIROM also demonstrated:

- SIROM control via CAN bus.
- High-speed data transfer via Ethernet.
- Regulated/ power transfer at 28V.

The electronics developed for EROSS project reached TRL 6 after a dedicated test campaign [6].

2.4 Orbital replacement unit (ORU) Exchange tests

Within the EROSS demonstration scenario were five SIROMs involved. One as the end-effector of the robotic arm, two on the ORU, and one on each satellite (client and servicer). The mission consists of the following steps:

1. Latching the robotic arm to the ORU on the servicer side.
2. Unlatching the ORU from the servicer satellite.
3. Transporting the ORU to the client side's SIROM interface using the robotic arm.
4. Latching the ORU to the client side.
5. Unlatching the robotic arm from the ORU.

An internal demonstration of an equivalent mission scenario preceded the EROSS demonstration with the only difference that not all building blocks of the project were included in it [12].

2.5 Backdrive test

The objective of the test was to test the SIROM capabilities to mate an opposing SIROM under different robot backdrive conditions consisting of a robot resisting the latching between the two interfaces. These external forces may arise during the mating operation of SIROMs due to tiles mounting errors, robot control mode, forces induced by the compliant coupling between SI and tiles (used to avoid hyper-static stresses), etc.

The test case consists of the mating between an active SIROM towards a passive SIROM under a series of robot forces resisting the latching operation. Active SIROM is mounted as an end-effector of a UR10 robot while passive SIROM is fixed to a workbench. The robot moves in position control mode to a pose where active SIROM can latch (a few millimetres away from the passive SIROM), then the robot is commanded to perform a force or moment in each direction and finally the active SIROM is commanded to latch. During the latching, active SIROM's latches need to overcome the forces/moments exerted by the robot to be able to close the gap and correct the misalignment between the interfaces [13].

2.6 Mechanical Guidance and Diagonal Engagement

The form fit geometry of SI allows guiding the final approach of the interface before starting the mating process, with the support of a compliant robotic manipulator. The purpose of the test was to validate the capability of the HOTDOCK formfit to support self-alignment and accommodate different engagement angles with another device, as well as measure the range of attraction (distance and angles) ensuring the correct alignment.

The test setup consists of a robotic manipulator with one HOTDOCK attached as an end-effector, and another HOTDOCK attached to a fixed structure. The robotic manipulator is equipped with a force/torque sensor and can be operated in impedance mode.

The general procedure consists of first controlling the manipulator in position mode towards the initial position of the test, which is defined by a relative distance (in the connection plane) and orientation between the two HOTDOCKs. The manipulator controller is then switched to impedance mode and commanded to align the two SI, with a straight line motion (vertically, horizontally or in diagonal, as function of the setup configuration). Once the two HOTDOCKs are aligned (confirmed by the proximity detection), the mating process is initiated, which confirms their good alignment. This procedure is then repeated for different relative position and motion angles of the manipulator trajectory, which will create a map of attraction range and angle approach capabilities [4].

2.7 Spacecraft Modules and Payload Manipulation

HOTDOCK was tested in several projects relevant to future space mission concepts and involving the manipulation of spacecraft modules and payloads. This has been done through several ground laboratory demonstrators in MOSAR [14] and PULSAR [15] for orbital purpose, and in PRO-ACT [16] for planetary exploration.

All the demo setups involved a robotic manipulator, typically equipped with a HOTDOCK as an end-effector and different assets to be manipulated, including spacecraft modules, telescope tiles, or planetary in-situ components. The MOSAR demo setup is illustrated in Fig. 3.

Through these validations and demonstrations with these setups, several SI capabilities were demonstrated. These include:

- The use of the SI as an end-effector of the manipulator for operations with payloads, including mechanical manipulation (with the relevant load constraints) and data/power transmission to the payload.
- The use of the SI as an interconnection between assets to guarantee the mechanical integrity of the setup (e.g. assembly of mirror tiles) and the data/power/thermal connections.
- The capability to support single, double, and triple (diagonal) approach (cubic module shape) and simultaneous/sequential connections.
- The use of the SI telemetries with the setup controller to perform the operations.

Such setup also allows analysing the potential needs to enable the operation through the SI (e.g. required manipulator control mode operation and performances, as well as external visual servoing), as function of the selected SI.

Fig. 3. MOSAR test setup with HOTDOCK for demonstration of spacecraft modules manipulation.

2.8 Tests in orbit

The iSSI® is currently for more than six months in space for demonstration and qualification purposes.

In the course of the US mission the iSSI-FQE (iSSI® Flight Qualification Experiment) is beeing carried out by Skycorp Incorporated aboard the International Space Station (ISS) using iSEEP on the Japanese external platform KIBO. And is funded by US government sources. To date, long-term power and data transfer as well as ad-hoc testing of various coupling scenarios have been demonstrated successfully, while the mission is still on until December 2022. Current iSSI® TRL is 6 and is expected to reach TRL 7 or 8 by end 2022 [21].

3. PERIOD SI benchmark

The overall structure of the benchmark is divided into four categories: test requirements, the interconnects to be tested and the two primary test domains, the mechanical and electrical domains [17], as shown in the Fig. 4. In the following subsections, these four categories are described in more detail.

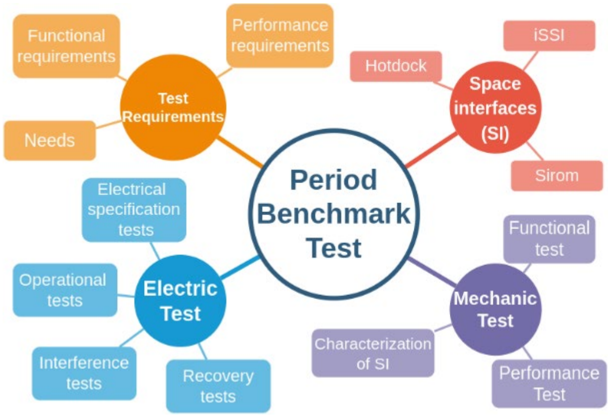

Fig. 4. The overall structure of the PERIOD benchmark for SI test.

3.1 Mechanical test methodology

From a mechanical point of view, a three-stage test structure was conceived. The first step of the benchmark tests involves characterization of SIs. The two other major steps were the functional and performance tests of the test samples.

To develop the SI Benchmark method, the process was conceived as shown in Fig. 5 starting from the ECSS-E-ST-10-03C testing standard [18] as well as the ECSS-E-HB-11A [19] guideline for the evaluation of a technology readiness level (TRL) of an element/subsystem/unit.

Based on the specifications of the SIs provided by the vendors and the joint decision of the interdisciplinary project committee, the requirement bundles were first established. In addition, Korcut ontology was used to leverage ontology-based interdisciplinary experiences in robotics that helped to develop the test method.

Based on the developed test method, the mechanical and electrical benchmark tests were performed in the laboratory environment of the DFKI in Bremen. The evaluation criteria based on the Korcut ontology were created in parallel to the tests carried out. With the purpose of evaluating the test results according to different application scenarios, the PERIOD ontology was created.

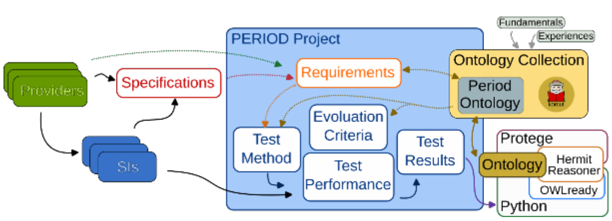

Fig. 5. The PERIOD SI benchmark test method development workflow.

3.2 Characterization of SIs

From the mechanical point of view, the first step of the benchmark tests involves the characterization of physical properties of SIs, as per the ECSS-E-ST-10-03C standard [18]. Several mechanical properties of the SIs were measured on the test samples (see Fig. 6). The values of the mechanical properties given by the SI providers were checked. For example, the dimensions of the active and passive SIs and the respective weights. Furthermore, the mechanical functions, in this case the locking mechanism, of every single SI were tested.

3.3 Functional tests of SIs

After the characterization step, the benchmark continued with functional tests that allowed to assess the correct functionality of the SIs. In the functional tests, the aim was to test how the respective SIs connect with each other mechanically. Specifically, an active and a passive SI were used here, and the process of mechanical connection was triggered with the respective software. A connection between two active SIs was also tested.

The mechanical benchmark test was performed with a 7-DoF robotic manipulator arm to test the interfaces in an orbital factory-like task. The interfaces were captured/latched in a variety of test cases to analyse capture sequences of SI with additional features, e.g., reception range or self-alignment capability. These tests were used to develop such robot docking scenarios and create a test procedure that was further optimized by establishing common test parameters for all three test objects.

3.4 Performance tests of SIs

The performance test was a repetition of the function tests with the difference that the specification values were used as test constraints instead of nominal values. According to the functional test experience, performance tests for mechanical testing purposes were carried out at the following three main points:

- Capture range
- Misalignment
- Contact retention

In addition, after a successful mechanical coupling sequence, every SI pair was also electrically tested to assess the functionality of the electrical connection and data transmission of the connected SIs.

So-called emergency cases were also tested, for example "release under load" as a representation of a worst-case situation.

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Fig. 6 In the context of the Project PERIOD with Benchmark tested SIs mounted on adapters from left to right: iSSI® active and passive with optional formfits [5], HOTDOCK active and passive [4] and SIROM active and passive [6]. The active type SI are in the back row and the passive SIs are in the front row.

3.5 Mechanical benchmark test setup

The relevant operational phases of the mission demonstration scenario that should be replicated by the SI benchmark consist out of the following:

1. Grappling of a payload module from the storage with the in-orbit factory manipulator, LOCARM, equipped with an SI.
2. Transfer of the payload module to the mating port (SI) of the client satellite.
3. Connection between the payload module and client satellite.
4. Disconnection of the manipulator from the payload module.
5. Utilities connection among payload module and client satellite (i.e. power and data).
6. Repetition of phases in reverse for reconfiguration of a client satellite.

Overall, the mechanical tests need to replicate two SIs being mechanically coupled together under certain circumstances. Since a manipulator arm is used in the PERIOD demonstration scenario, a manipulator arm was also used in the SI benchmark tests.

To get close to the demonstration scenario, a payload module was also used. The payload module corresponds to a 4 U CubeSat.

A commercial 7-DoF robot arm (KUKA iiwa 14 R820) was used as the primary element of the test setup for free movements of the test object in all three dimensions. Force and impedance control methods of the ROCK† based robot control framework were used in the realistic test scenarios to reconstruct them in a repeatable manner. In addition, the robot arm was used for sensor data acquisition. To increase the experimental space, a tilt and turn table was integrated into the experimental setup. The overall mechanical configuration of the test setup is illustrated in Fig. 7 and consists out of the KUKA arm mounted on the workbench, the active SI mounted on the end-effector of the robot and the 4 U payload module, with both passive SIs, connected with the active SI of the manipulator. At the bottom of the figure is the rotation and tilt table on which an active SI is fixed by an adapter.

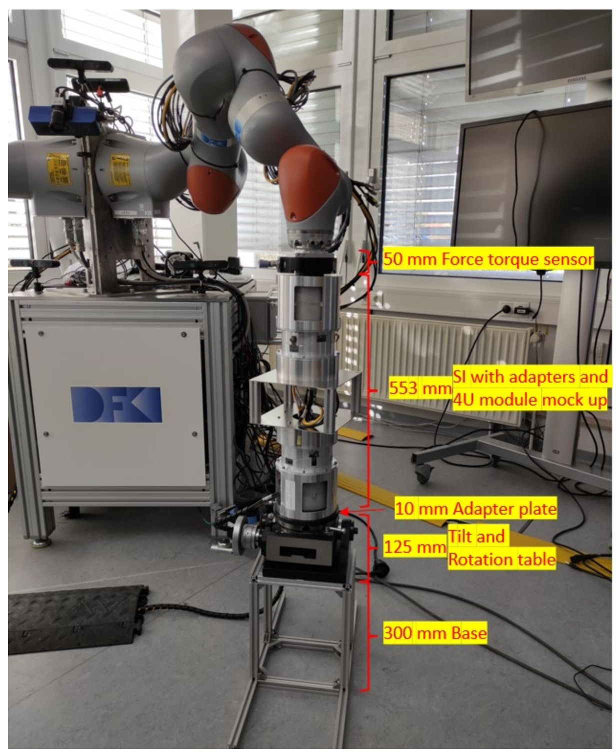

Fig. 7 Configuration and dimensions of the test setup.

To ensure that all three SIs are tested under the same conditions, it was determined that the distances between the mating plates of the SIs to: a) the torque sensor and

† https://www.rock-robotics.org/

b) the rotation and tilt table shall be equal. Furthermore, the SIs are mounted on the payload module in such a way that the distance between the mating plates of the SIs shall be the same.

The following convention has been established:
The SI with the highest height dimensions was used as the basis for determining the distances. Fig. 8 shows the specified distances: 144 mm (from the mating plate to the rotation and tilt table and to the end effector respectively) and 265 mm from the mating plate to the mating plate when mounting the SIs on the payload module.

The dimensions of the whole test set up are shown in Fig. 7.

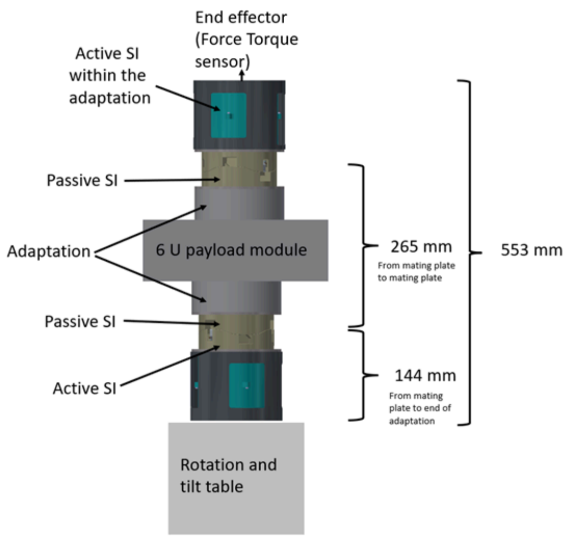

Fig. 8 Fixed distances of the test setup.

3.6 Mechanical benchmark test method

Since the considered SIs are all mechanically structured differently and have different working principles and specifications, even though some functions are similar, different operational ranges for the capture manoeuvre and type, or distance were considered. To ensure a consistent procedure as well as traceability of the selected test values, a logic has been developed that defines the way in which the test parameters for a particular test step are selected for capture range and/or misalignment tests.

Each planned test type was tested for two different configurations. First, the active SI is mounted on the robot manipulator arm and tested together with the corresponding passive SI, which is fixed relative to the ground. This passive SI is positioned on the rotation-tilt table via the payload module to which it is connected and the active SI to which it is connected via the other passive SI. This configuration is called a fixed payload mock-up (see Fig. 9).

Fig. 9 Test setup with fixed bottom payload module.

Alternatively, in another configuration where the payload is fixed to the robot manipulator arm, there is a passive SI at the end of the payload and an active SI mounted on a rotation-tilt unit placed on the ground (see Fig. 10).

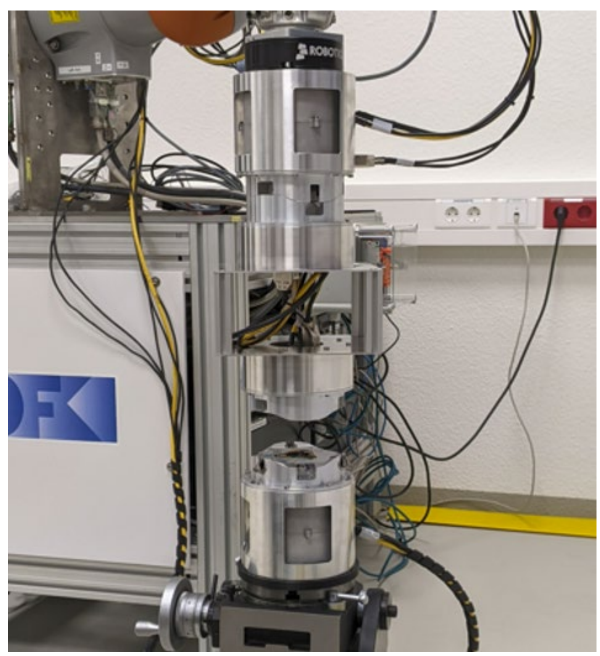

Fig. 10 Test setup with fixed payload module on the end-effector of the Kuka arm

In this way, the length of the robot manipulator arm in the end-effector is extended and the test is performed in more challenging conditions especially for the robot control. Various parameters also play a role in this, e.g., the size of the end-effector, the alignment values of the robot joints, the precise and accurate sensing of the forces generated in the positioning of the SIs during end effector grasping.

As shown in Fig. 11 the procedure starts with an initial state that is a manually alignment of the SIs for each test case to obtain a correct starting position. After storing the start values, the range parameters are determined in accordance with the specification limits of each SI as follows:

- If the test range is up to 3 mm or 2 degrees, it is checked in mm/degree steps using a normal method[‡].
- If the test range is larger, the test steps are repeated with halved values using a binary search method.
- The radial displacement rotation steps are checked from maximum rotation to zero, otherwise the rotation values are reduced.
- At the first successful docking by normal method or last successful docking for binary method, the data and power transmission are functionally tested.
- After successful docking, the tilt values (if possible) are tried using the same method but in reverse order (from 0 to a maximum value) until the worst case is determined.
- The last successful position is recognized as the limit of the specifications. For this position the data and power transmission related identification tests are repeated and tested for functionality.

The normal method is defined as a decrease in the radial displacement value of 1 mm and used either as a new hypotenuse value or as an axial value to create a new example test. Axial and hypotenuse range values were used to find various positions in planar directions on an interface surface for different experiments. The axial range is the maximum distance of test positions in x and y directions tried on the axes. The hypotenuse range is the hypotenuse displacement at a distance equal to the maximum axial distance. For this displacement, different x and y positions are calculated for different test positions in different directions. On the other hand, the binary method is used to set the new radial displacement value as half of the range to next limit and using this value either as a new hypotenuse value or as an axial value to create a new example test.

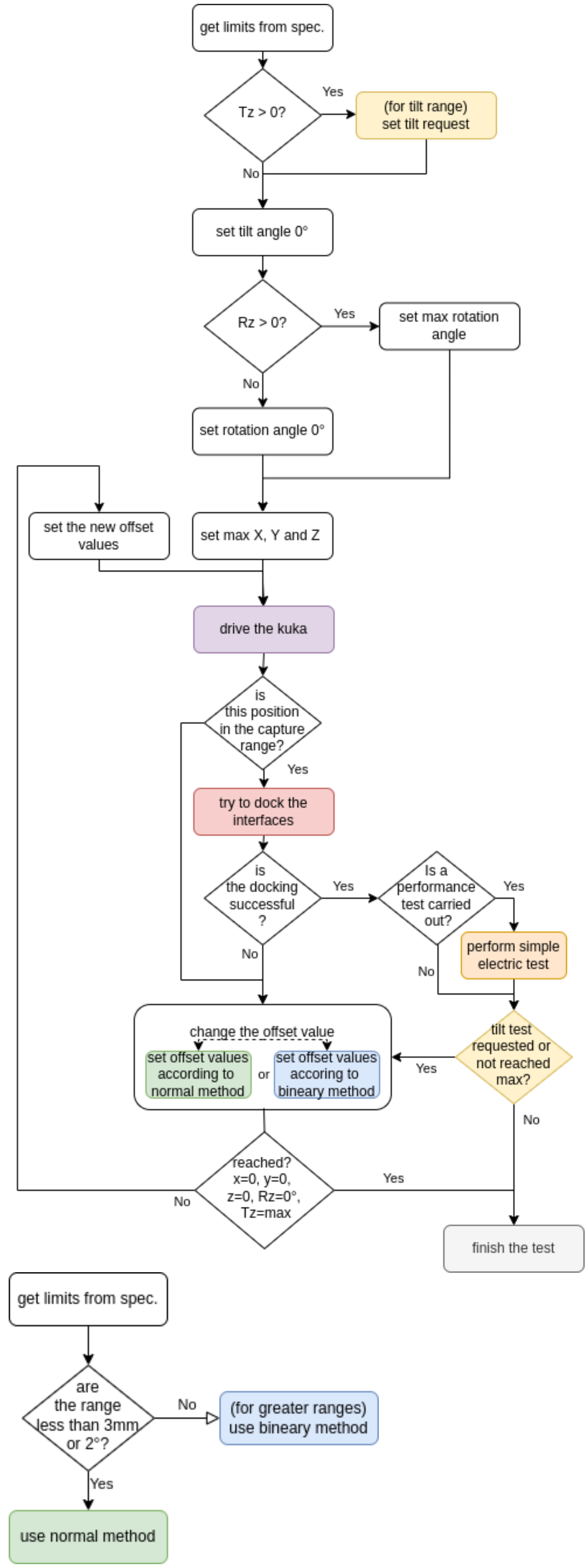

Fig. 11 Mechanical test procedure logic.

[‡] Continue reading for more details about the normal method.

4. Benchmark mechanical test results management and evaluation method

After the mechanical and electrical tests were completed, the evaluation took place. For this step, a methodology was developed based on various evaluation criteria from the Korcut ontology [17, 20].

In total four main aspects, namely the product, the physical, the mechanical design, and the mechanical test aspects (function and performance), as well as further 12 sub-criteria were used. The product aspect focuses on maturity, functionality, reliable design, and robustness, TRL level and stage of development of an SI. The physical aspect helps to evaluate the interfaces based on the physical parameters of the interface (comparison with the specified parameters and suitability for functionality), the temperature range of the interface for the intended purposes of the orbital factory. In addition, the aspect of mechanical design was used to evaluate the rotational symmetry of an interface and the capture and latching mechanism. The final part focused on the functionality and performance aspects (misalignment tolerance, capture range, and other parameters like e.g., release behaviour under load). Each main criterium is subdivided into at least four further sub-criteria to facilitate accurate and objective evaluation and comparison of SIs.

4.1 Evaluation method

This section describes in more detail the evaluation methodology that leads to the weighting of the test results of each SI.

As already mentioned, there are four main aspects which are further subdivided into individual sub-criteria, the so-called main criteria. The total sum of the weighted individual main criterion is always a maximum of 4 points. If a criterion is not completely fulfilled, points are deducted.

In some cases, if the SI has additional important features or functions compared to others that have given it great advantages, the points are gained.

The individual tables (Table 1 to 4) show from left to right main criterium, subdecision criterium and the maximum number of points that can be achieved or deducted in the subdecision criterium.

4.1.1 Product aspects

Table 1 shows the main and subdecision criteria for product aspects of the SIs. The subdecision criteria of "Maturity" consider the envelope and components of the SIs, for example, whether an SI is a mature product or still rather in the development stage. Accordingly, the points are awarded and thus a weighting is achieved.

"Operability" was used to determine if the SI was fully functional or if there were any parts missing from the overall function.

The item "Reliable & robust design" was used to check whether the SI and its component are robust or reliable enough to withstand all test procedures.

The respective TRLs of the submitted SI versions were reviewed and weighted accordingly.

Table 1. Main and subdecision criteria of product aspects.

Main criterium	Subdecision criterium	Max point
Maturity	"Off-the-shelve" product quality	4
	Engineering sample (limited quality)	-1
	Missing part - functionality	-1
	Malfunction - Failure	-1
	Other positive points	1
Operability	Operability	4
	Limited operability: faulty design	-1
	Limited operability: missing part	-1
	Limited operability: other issues	-1
	Other positive points	1
Reliable & robust design	System is (fully) reliable & robust	4
	Problems with reliability (not suitable for all test cases)	-1
	Problems with robustness (damage during normal operation may occurs)	-1
	Other problems (under dimensioned, reduced protection, etc.)	-1
	Other positive points	1
TRL	TRL 6 or more	4
	TRL 5	3
	TRL 4	2
	TRL 3	1
	less	0
	w/ no changes (0)	0
	w/ minor changes (-1)	-1
	w/ major changes (-2)	-2
	w/ different version (-3)	-3
	TRA is traceable and based on laboratory tests (+1)	1

4.1.2 Physical aspects

The physical aspects, detailed in Table 2, include checking the dimensions and mass of the SIs to see if they match the manufacturer's specifications and meet the project requirements, as well as whether the operational temperature range is sufficient for orbital and terrestrial applications and how it compares to the other SIs.

Table 2. Main and subdecision criteria of physical aspects

Main criterium	Subdecision criterium	Max point
Physical parameters	Envelope (LxWxH)	2
	Mass	2
Temperature range	(fully) Suitable for orbit environment (assuming operational range of -40 to 70 °C)	4
	(only) Suitable for tests on Earth	-1
	Compared with other interfaces (not the best)	-2
	Other positive points	1

4.1.3 Mechanical design aspects

The focus on checking the mechanical design, as shown in Table 3, is mainly on the docking mechanism, how many docking orientations there are (90° or 120° symmetry) and the design of the latching mechanism (whether it is "protected" or can it break during docking or damage other parts of the SI).

When checking the docking characteristics, the focus was to determine: if a capture before docking is possible, if robot force is required for the docking process, if pulling capability is available and how much time is needed for the docking or undocking process.

Table 3. Main and subdecision criteria of mechanical design aspects

Main criterium	Subdecision criterium	Max point
Rotational symmetry	90°/120° symmetry	4
Latching mechanism	No moving part outside the envelope	4
	One or more moving parts (outside the envelope)	-1
	Latching parts can be damaged	-1
	Latching parts can damage other parts of SI	-1
	Other positive points	1
Docking characteristics	Capture before contact	1
	No robot force required for docking	1
	Pulling capability	1
	(un)Docking sequence duration (<2s: (1);<5s: (0.75); <8s: (0.50), <12s: (0.25) , >20s: (0)	1
	Other positive points	1

4.1.4 Functional & performance aspects

A particularly noteworthy point was the functional and performance aspects, as shown in Table 4. Here, the main mechanical properties of the SIs were tested, which mainly include the misalignment tolerance in axial, radial and angular direction during the docking process.

Under "other characteristics", fail safe release was evaluated, among other things. Here, two active SIs were at first coupled with each other. Then, it was simulated that one SI is no longer able to decouple in order to check whether a mechanism is available on the counterpart SI to decouple the stack.

In release under load the SIs were tested how they deal with unexpected situations and whether they can be decoupled under load conditions.

Further points were awarded when the SIs are able to maintain contact retention under external torque and capture under backdrive of a manipulator.

Table 4. Main and subdecision criteria of functional and performance aspects

Main criterium	Subdecision criterium	Max point
Misalignment tolerance	Radial misalignment	1
	Angular misalignment	1
	Overall misalignment capability	1
	Other positive points	1
Capture range	Axial capture range	1
	Radial capture range	1
	Angular capture range	1
	Overall capture range	1
	Additional positive points	1
Other characteristics	Fail safe release (when coupling two active interfaces)	1
	Release under load	1
	Contact retention under external torque	1
	Capture under backdrive of manipulator	1

4.2 PERIOD Ontology

The PERIOD mechanical tests as well as the electrical tests [14] showed that the interfaces are quite different depending on the functionality and the evaluation criteria. Comparing these variations based on a fixed criterion and selecting or not selecting an interface accordingly can eliminate an interface with some critical additional features. However, this eliminated interface and its features may be the key to a specific task that can be selected in the future. As a result of these tests, it became clear that we need a solution that on the one hand can represent all SI features, and on the other hand can save and share rich test results in a standardized way as well as query them to find the appropriate interface based on needed task parameters. Therefore, the PERIOD ontology has been developed as part of the Korcut ontology families, to provide a generic SI model semantically and share test results in a rich and uniform way. Additionally, it supports dynamic querying and reasoning in terms of decision traceability for different orbital mission requirements and matching SI. Given its ability to contain a wealth of data that go beyond a simple table, the PERIOD ontology can be seen as a complement and extension of the previously described benchmark evaluation method.

5. Results examples

Due to the confidential nature of the benchmark and its evaluation, only selected results are shown in this paper for illustration purpose only. In agreement with iBOSS GmbH some results of the evaluation of the iSSI® are presented here. It should be noted that the results refer to the existing versions of the iSSI® submitted for the SI benchmark.

Table 5 shows the main criterium operability. The maximum points were almost reached. From an operability point of view, the iSSI® could be tested only partially, leading to the sum 3 for operability. Reason for this was an incompatibility of available formfits due to parallel iSSI® version upgrade.

Table 5. Evaluation of operability of the iSSI®.

Main criterium	Subdecision criterium	Calculation	SUM
Operability	Operability	4	3
	Limited operability: faulty design	0	
	Limited operability: missing part	-1	
	Limited operability: other issues	0	
	Other positive points	0	

Another main criterium from product aspect (section 4.1.1.) is a reliable and robust design illustrated in Table 6. During tests and without any apparent cause, a data transmission lens came off of one iSSI®, an ad-hoc identified production Total Quality Management (TQM) issue on the supply side. For this reason, there was a point deduction of one point from the maximum achievable score of 4.

Table 6. Evaluation of reliable & robust design of iSSI®.

Main criterium	Subdecision criterium	Calculation	SUM
Reliable & robust design	System is (fully) reliable & robust	4	3
	Problems with reliability (not suitable for all test cases)	0	
	Problems with robustness (damage during normal operation may occurs)	0	
	Other problems (under dimensioned, reduced protection, etc.)	-1	
	Other positive points	0	

An excerpt from the mechanical design aspect, as described in subsection 4.1.3, of the main criterium latching mechanism shows that a point deduction was also made here, see Table 7.

Moving parts outside the envelope may be unsafe and in case of failure might impede docking. iSSI® has a bayonet latching mechanism that moves out of the SI in to opposing SI to lock it. If the locking mechanism has a shape that collides with another object during capturing or positioning/alignment, it can damage itself.

Table 7. Evaluation of latching mechanism of the iSSI®.

Main criterium	Subdecision criterium	Calculation	SUM
Latching mechanism	No moving part outside the envelope	4	3
	One or more moving parts (outside the envelope)	0	
	Latching parts can be damaged	-1	
	Latching parts can damage other parts of SI	0	
	Other positive points	0	

One result of the main criterium "Other characteristics" of the main aspect "Functional & performance aspect", described in subsection 4.1.4, shows that there are also not only full points or no points, but also gradations of points, as detailed in Table 8. Some subdecision aspects require a percentage weighting.

In the present case in "capture under backdrive of manipulator", the capture was successfully tested till 14 N of measured backdrive axial force. Testing of higher backdrive forces was confined due to the limited capture range of the SI and limitations of the test method conceived. Given the non-existent specification value of this parameter by the provider the characteristic of the SI was awarded 0.75 points from a maximum of 1 point.

Table 8. Evaluation of other characteristics of the iSSI®.

Main criterium	Subdecision criterium	Calculation	SUM
Other characteristics	Fail safe release (when coupling two active interfaces)	0	2,75
	Release under load	1	
	Contact retention under external torque	1	
	Capture under backdrive of manipulator	0,75	

From the overall results the main strengths of the iSSI® are its flat surface design functional modularity and the option to use a formfit as an add on if needed depending on the use cases and requirements.

6. Conclusions

In this paper, the PERIOD benchmark mechanical test method developed to differentiate SIs is introduced. The testing is a three-step process that introduces SI mechanical properties for structured characterisation, functional and performance characters based on application-oriented ontology-based 24 criteria. The PERIOD Benchmark for mechanical test has been performed for three European interconnects (HOTDOCK, iSSI®, SIROM) totalling 376 test cases. Since the SIs are not directly comparable to each other, due to their different functionalities and components, the PERIOD ontology as a part of Korcut ontology family was crated and used in this work to generate a concept model of SI, to share benchmark mechanical test results and compare them in a consistent and a standardized way.

A first analysis showed that each SI is applicable, provided that it is adapted according to the required application scenario. For use in orbital mission scenarios, all three SIs are applicable, provided the installed components are space qualified. Among all the tested interconnects iSSI® is currently the first multifunctional interconnect that has been tested in space environment aboard the ISS. But this newer version was not the version sent to DFKI for the benchmark tests.

With the help of the achieved evaluation, it was also possible to point out improvement possibilities, so that every SI provider has advantages from the SI benchmark to improve his SI for future orbital missions. This possibility also existed during the test phase, so that the currently available results may no longer apply in part because the improvement process has been initiated.

The setup of the SI benchmark and the developed ontology is/can be used as a basis for the development of standards within the European Operation Framework (EOF).

In agreement with iBOSS GmbH section 5 highlights few examples of results of the evaluation of the iSSI® to show the methodology employed for the evaluation. As already mentioned, the three SIs are not directly comparable. The iSSI® design differentiates with its key feature: the flat surface design functional modularity and the option to use a formfit as an add on if needed. HOTDOCK and SIROM have integrated formfits whereas iSSI has a formfit as an add on module. In addition, it can be mentioned that the active iSSI® has an extra electronics box while active HOTDOCK and active SIROM are compact envelopes that contain everything.

For future operations in complex orbital missions, where for example modules are to be coupled with the aid of one of the three interconnects, corresponding suggestions for improvement have already been communicated to the respective Si providers. Since all three tested SIs are already working promisingly, it can be assumed that they will be used in European space robotics sooner than later. Choosing one SI over the other will depend on the specific functionalities needed by a mission scenario.

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