QUALIFICATION OF RESOURCE TRANSFER MECHANISMS AS PART OF INTERNATIONAL BERTHING AND DOCKING MECHANISM – HARD CAPTURE SYSTEM DEVELOPMENT

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ABSTRACT

The article highlights chosen aspects of design and testing campaigns of the Resource Transfer Umbilical mechanism, which are:

- Design description – challenges related with providing enough flexibility for compliance mechanisms and in the same time – enough stiffness to withstand operational loads and being subjected to mechanical loads environment
- Qualification test campaign - functional tests in ambient, as well as in extreme temperatures in vacuum, vibrations – both quasi-static and random, electrostatic discharge and life test
- Lessons learned – design evolution, reasons of significant design changes, materials selection of working pairs.

MISSION'S BACKGROUND

The International Berthing and Docking Mechanism (IBDM) is the European androgynous low impact docking mechanism that is capable of docking and berthing large and small spacecraft. The IBDM has been designed to be compatible with the International Docking System Standard (IDSS) and hence compatible with the ISS International Docking Adapters (IDA).

The IBDM could be used on different hosting vehicles, as well as and other space stations as the future Lunar Gateway DSG.

The IBDM comprises a Soft Capture Mechanism (SCS), and a structural mating system called the Hard Capture System (HCS):

- The function of the SCS is to ensure Spacecraft capture
- The function of the HCS is to create a rigid structural connection to allow for a pressurized passageway between the two spacecraft. It is also responsible for the service connections and the nominal and emergency separation functions.

The HCS main components are the following:

- HCS Tunnel Assembly: is a subassembly integrating the tunnel that provides the structural integrity for the whole assembly, the elastomer interface active seals, the alignment pins, and the Ready-to-Hook and Undocking-Complete sensors.
- HCS Hard Capture Hook System: is composed of twelve Hard Capture Hook Units which are independently driven by a Hook Driving Units on each. The motorgears drive the active hooks to the closed configuration to achieve structural mating and to provide seal compression and interface preload.
- Separation System Mechanism. The separators generate axial thrust force to push off the hosting vehicle from the ISS after the hooks opening manoeuvre. The torque is generated by a motorgear.
- Resource Transfer Umbilical. The umbilical connectors transfer power, data, and a ground safety wire between two docked vehicles. They are recessed below the docking mating plane during docking, and then are driven to mate after docking hard capture occurs by the Umbilical mechanisms. For undocking the connectors are driven to the unmated state prior to unlatching the hooks.
- MMOD Cover, a Micrometeoroids and Orbital Debris cover
- Thermal Control formed by an external MLI placed over the MMOD, and an active thermal heating circuit placed on the tunnel.

SENER Aeroespacial is responsible for provision of Hard Capture System, whereas SENER Poland develops the following mechanisms: Separators, Resource Transfer Umbilicals (RTU), Undocking Complete (UCS) and Ready-to-Hook (RTH) Sensors and Micrometeoroids and Orbital Debris (MMOD) cover.

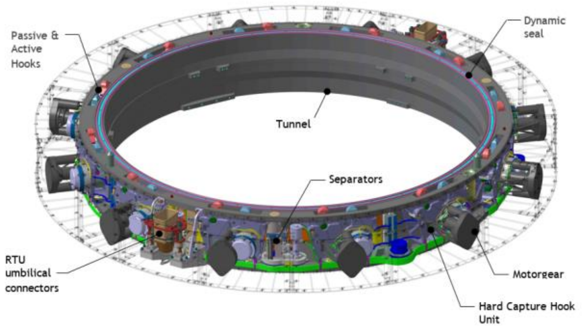

Figure 1. Hard Capture System main components (MMOD Cover outlined for clarity)

Although developing multiple mechanisms within the IBDM HCS project, in the paper, primary focus is put on Resource Transfer Umbilicals – a mechanism composed by a FRAM connector that transfer power, data and a grounding wire between two docked vehicles, and its motorisation mechanism. The FRAM connector is recessed below the docking mating plane during docking, and after docking, with hard capture confirmed, it is driven by the Umbilical mechanisms to mate with a similar mechanism on the other vehicle. The FRAM connectors are mounted on movable plates, which provide alignment features during mating and recentering function after disconnection. In current ISS IBDM HCS unit, there are two Resource Transfer Umbilicals – Plug and Receptacle and both of the units are androgynous – can work as passive or active units, depending on the command given.

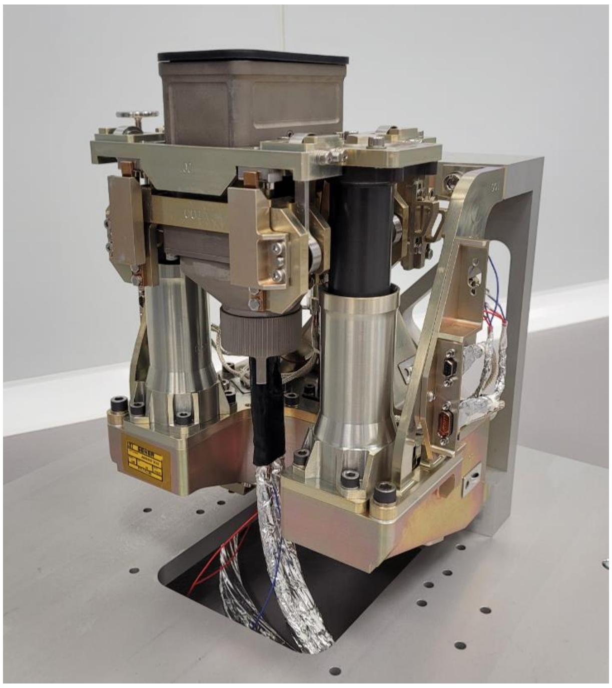

Figure 2. IBDM HCS RTU Plug mechanism

DESIGN DESCRIPTION

The RTU mechanism is composed of two similar mechanisms – RTU Plug and RTU Receptacle. Both of them have the same motorization part, including Tunnel interface structure, motorgears, and lead screws. The main differences between them are the main FRAM connectors' type (female versus male) and the type of compliance mechanisms. Both mechanisms need to provide particular misalignments compensations methods in six degrees of freedom in total.

Structure and motorization

The FRAM connectors are remotely extended and retracted with two symmetrically placed lead screws and driving nuts.

The transmission is achieved by a redundant BLDC motorgear, which in turn transmits the movement to the two mentioned lead screws through two symmetric spur gear trains. This mechanical link ensures the correct synchronization of the movement of both lead screws during the extension and retraction travels. As the lead screw – drive nut pair needed to be non-backdrivable and comply with motorization margin of 2, tests had been performed to verify if chosen material pair and thread design fulfils these requirements. The lead screw was manufactured in stainless steel 15-5PH (AMS-5659) and the drive nut in phosphor bronze UNSC51000 ASTM B139M. No additional lubrication was used.

The test was performed in mission representative conditions in thermal vacuum chamber. Results proved that the working pair to be non-backdrivable (self-locking under load) and the friction coefficient in a worst case (cold temperature and high vacuum) was 0.14 – 0.19.

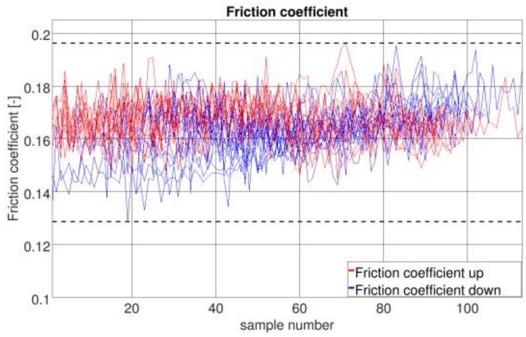

Figure 3. Friction coefficient of lead screw – driving nut pair in low temperature (-40°C), high vacuum (<0.1 Pa)

The power transmission chain composes of:

- BLDC motor, designed specifically for the mechanism's and mission's requirements,
- gear train - design is driven by several aspects: to provide an appropriate reduction ratio and torque transmission, and to leave a free volume in the central area for the FRAM harness. The resultant design that fulfils both space and ratio requirements contains 7 gears arranged in two symmetrical rows
- lead screws that provide linear movement of the bracket, to which connector is attached, supported by a set of bearings (both duplex and radial types)

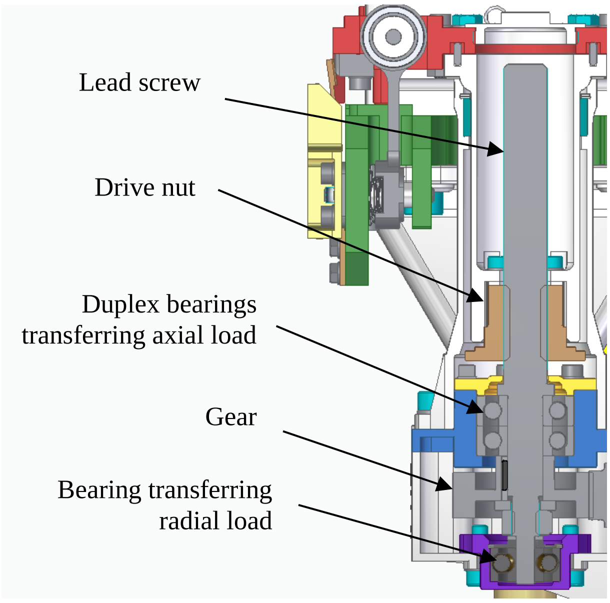

Figure 4. Cross section of lead screw – nut pair

Lead screws are placed inside enclosed tubes, which prevents contamination. Moreover, the tubes provide mechanical support to a plate when connector is retracted and hard end stop in case of switches failure.

Compliance mechanisms

One of the most important features of the RTU mechanisms is the capability to overcome potential misalignments during opposite connectors' engagement after docking. Apart from this, connectors need to return to their initial position after disengagement. For these reasons, FRAM connectors are fastened to an intermediate floating plate which is connected with the moving main plate. Both plug and receptacle connectors require different adjustment tolerances in plane. For that reason, the two RTU units are almost identical, except from the fact that they provide different alignment and recentering capabilities.

RTU Plug requires the capability to provide planar (normal to connector's centreline) and torsional misalignment compensation. The initial design of this mechanism assumed the usage of four flexural beams. Each of them was monolithic part which had constant square (1,25 mm x 1,25 mm) cross-section. At beams' ends there were two perpendicular holes for attaching to brackets. It did not allow for rotational movement, but thanks to such solution beams work as free-end beam, which reduces stresses and has lower stiffness.

The proposed solution comprised lateral compliance with a very high axial stiffness. Bending of all beams absorbed possible lateral misalignments as well as the rotational ones. This solution provided proper stiffness in vertical direction and did not buckle (analytically estimated buckling force for the whole assembly is approximately 1240 N when maximum possible axial force is 650N during demating of the connectors).

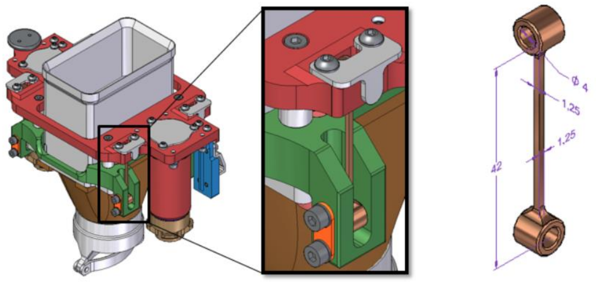

Figure 5. Initial concept of Plug compliance mechanism

Nevertheless, the described solution was prone to manufacturing flaws and there was high risk of flexible beams damage during launch, due to environmental loads. This risk could not have been accepted as this could lead to mission or even safety critical hazard.

Eventually, the compliance mechanism was completely redesigned to separate mechanical support of the connector from recentering and compliance function. In the end, mechanical support is provided by four links, that are equipped with spherical bearings and much higher cross section than the flexible beams in the initial concept. Recentering and compliance force is generated by eight leaf springs located around the FRAM connector. View on one of the links is presented below:

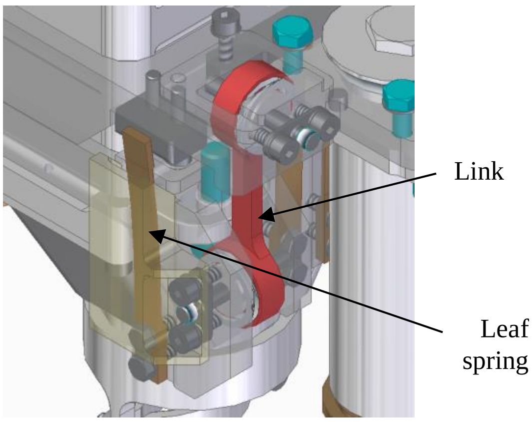

Figure 6. Final design of Plug's compliance mechanism

The proposed design proved to be working very well under environmental loads, achieving 85 Hz of first modal frequency.

In case of Receptacle RTU, there were no significant changes in the design since very beginning of the development. Receptacle needs to provide compliance in connectors' axial direction, as well as rotations around remaining two axes. The axial compliance is provided by four compression springs, which are mounted on screws. Screws are fastened through parts with spherical surface. The sphere is in contact with intermediate plate's conical socket (male sphere in female cone). Nuts are mounted to

a main plate by means of counter nuts, and their position on the plate can be adjusted to ensure proper fit into conical sockets in the intermediate plate. To reduce friction, conical sockets' surfaces are hard anodized and impregnated with PTFE. Screws and nuts are made of stainless steel.
In case of vertical misalignment between connectors plug side, the misalignment is compensated by spring's compression. Spherical surfaces on nuts provide possibility of enough angular motion.

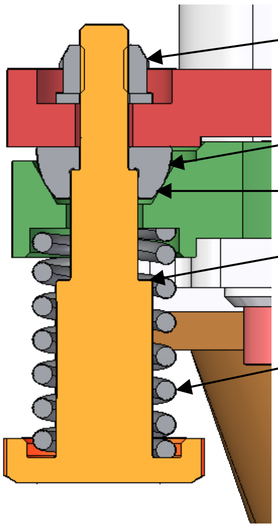

Figure 7. Receptacle's compliance mechanism

At the compliance of 5 mm total resistive force, for four, spring equals to 641 N. Total initial resistive force (displacement equals 0 mm) for all springs is 398 N. For the single spring, its rate equals to 12,14 N/mm.

QUALIFICATION TESTING CAMPAIGN

The goal of testing campaign is to prove the flight worthiness of the equipment on TRL 8. As part of qualification campaign following tests are conducted: physical measurements, functional tests in ambient conditions, life testing, vibrations, thermal vacuum cycling and functional test in extreme temperatures and finally the electrostatic discharge (ESD) susceptibility test.

Functional tests in ambient

For the functional tests, dedicated MGSE is manufactured. Designed jig allows to perform the test with one side of RTU active, while opposite side is passive. To avoid disassembly of RTU units during tests passive units of RTU (which will be later used on passive HCS) are used as passive side.

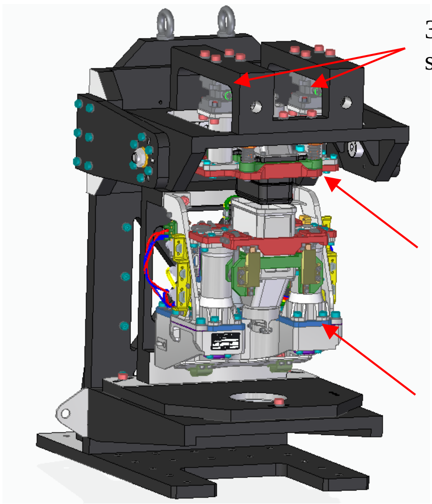

Figure 8. RTU functional test tool – general view

Functional tests composed of:

- Connectors' alignment check – performed in order to align connectors' nominal position to be sure that the misalignments will be introduced in relation to connector centerplanes.
- Nominal alignment insertion test – performed to verify correct functionality of RTU engagement with one side active and no linear or rotational misalignments applied. Afterwards, the plug was working as an active side of the connectors pair. Success criteria for this test is when connectors are engaged with final geometry required, insertion forces are within limits, engagement time below 300 seconds and all lines properly connected between connectors.
- Motorization margin verification – to prove motorization margin higher than 2, current was measured constantly during RTU operation. Nominal available current was 0,52A (28,0 VDC), hence success criteria was current consumption lower than 0,26A.
- Motor failure test – test performed to prove that mechanism can successfully mate with opposite side after electrical cut-off. While connectors are mating, power supply is switched off. After 30 seconds, power is restored and behaviour of mechanism is observed.
- Functional test with short-circuited motor windings – by design, each motor is a double winding motor, which means it has two stators in the same housing and shaft to provide redundancy. Goal of the test is to verify performance of mechanism, when short-circuit appears in one of the windings..
- Mechanical end-stops functionality – the nominal current limit for RTU driving unit is 0,52A as it is maximum value that power line can provide. In this test the active side is driven first to its mechanical hard end stop – both in retracted and in extended positions (position microswitches are disconnected

from controlling loop). When the hard stop is reached, the current is maintained for 20s.
- Identification of a misalignments combination, which results in highest in-plane forces generated by the compliance mechanism
- Axial compliance mechanism verification – measurement of axial force generated by the compression springs

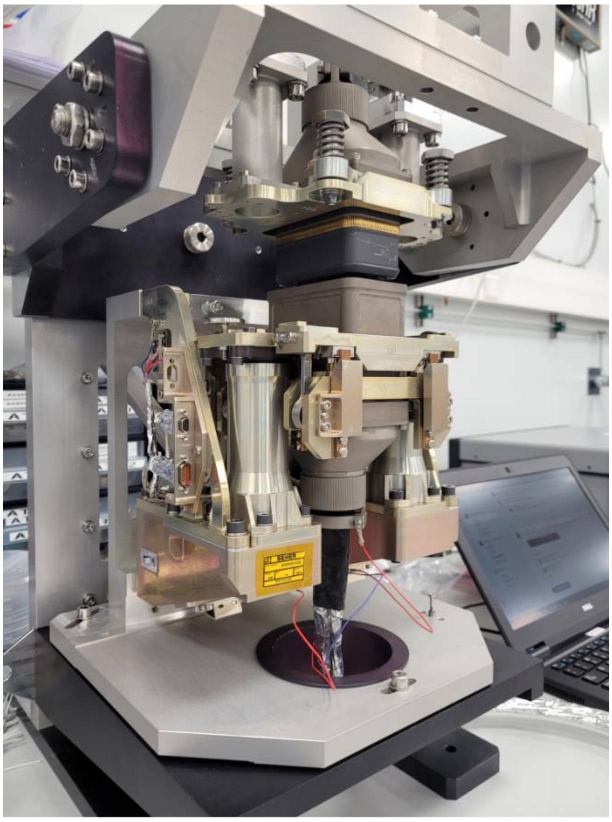

Figure 9. RTU during functional tests

Vibration tests

Both of the RTU units have been subjected to sine (quasi-static) and random vibrations. The equipment was mounted on shaker by using a dedicated vibration adaptor, which was designed in order to provide rigid interface avoiding the dynamic coupling in the lower range of frequency.

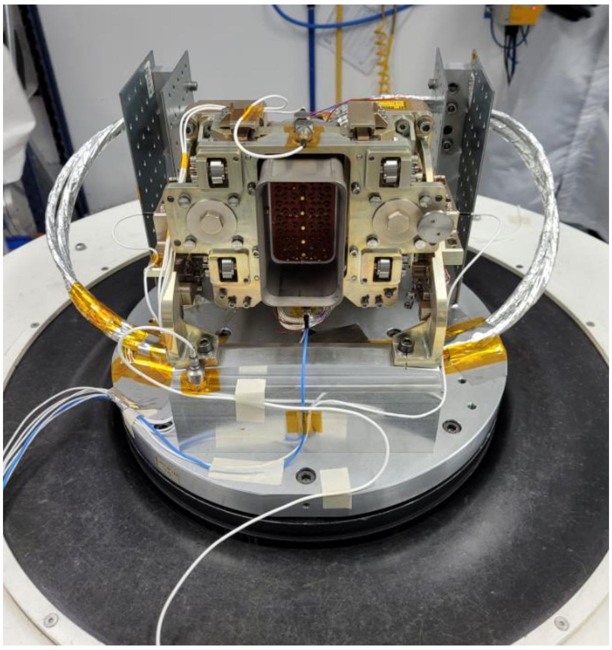

Figure 10. RTU Plug mounted on the shaker

First relevant modal frequencies of the mechanisms were as follows:
- RTU Plug: 85 Hz (in normal plane to the connector's axis)
- RTU Receptacle: 287 Hz (in normal plane to the connector's axis)

At the moment of paper preparation, RTU is undergoing Thermal Vacuum testing, in which complete functional testing will be performed, as well as remaining cycles of life test. Afterwards, RTU units will be subjected to ESD susceptibility, due to the presence of Hall sensors in motors, as well as to verify proper grounding of the main FRAM connectors. Outcome of the aforementioned tests to be presented during the oral presentation.

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