Advancements in Satellite Docking Systems for In-Orbit Servicing: Addressing Challenges and Standardizing Technologies

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ABSTRACT

This paper covers the efforts of the AVS team to develop and standardize technologies for mechanical capture and secure in satellite docking systems and how this knowhow is leading to technical solutions that can meet a wide range of IOS operations. It also highlights the challenges associated with docking systems for in-orbit servicing. Furthermore, the paper includes a novel “actuator building block” for mechanical capture to enable interoperability and enhance competitiveness by reducing cost of development.

1. INTRODUCTION

Satellite docking systems play a crucial role in in-orbit servicing (IOS) missions, enabling the rendezvous, capture, and manipulation of satellites for various servicing tasks as satellite life extension, repair, upgrade, retrofit, repurpose and also de-orbit activities. However, there are several challenges associated with mechanical capture and securing, especially when dealing with both cooperative and uncooperative targets.

Efforts are being put in standardisation by agencies with roadmaps that co-exist with increasing independent commercial demand. Moreover, other private initiatives are focused on establishing unique use cases to support a range of applications covering Earth-orbit to deep space missions. Therefore, docking solution requirement vary from case to case. This may create a need for a variety of satellite docking solutions both for target satellites and service satellites.

ESA has taken the lead in coordinating efforts to establish common interfaces and protocols that enable interoperability among different docking systems. The aim is to facilitate collaboration among space agencies and commercial entities, reduce mission costs, and enhance mission success rates. This not only streamlines the process of integration but also could ensure the efficiency and reliability of docking operations. These enabling interfaces [1] shall:

- Ensure interoperability between spacecrafts from different countries and manufacturers
- Ensure the modularity of the interfaces to address different ranges of spacecrafts and missions
- Provide the ecosystem with efficient and proven interfaces (as COTS) to address new markets
- Define the good-enough set of guidelines and shared designs to foster both reluing on exixting solutions and propoting innovation and evolutions.

As a result, fostering standarisation, dissemination and adoption of the enabling interfaces is key to enable this ecosystem.

AVS has participated in some of the developments of various technologies that could be used to support the rendezvous and capture of both cooperative and uncooperative targets. These activities have been part of the effort ESA has conducted in order to standardise technologies: Clamping Mechanism for ADR, PRINCE, MICE, CAT,

By investigating different approaches, these projects have explored novel actuator architectures leading to an “Actuator Building Block” that is compatible with a variety of mission operations. The actuator building block can accommodate a wide range of both radial and axial capture distance. It is compatible with different type of client interfaces (prepared and non prepared) including different sizes of LARs. It can deal with a wide range of forces and torques as well as misalignments scenarios.

AVS approach is to use this actuator building block as the core of a different mechanical docking solutions by integrating it into the end effector or manipulator that will count with the interface needed in each case: two fingers, three fingers, addition of hydraulic, data or other interfaces

These advancements have the potential to enable docking between satellites of different sizes, shapes, and orientations, thereby expanding the scope of in-orbit servicing missions.

2. STATE OF THE ART

Missions focused on on-orbit servicing and active debris removal are gaining growing attention and interest. As concerns about space sustainability and the proliferation of space debris have intensified, in orbit operations have emerged as a practical solution to the Active Debris Demoval (ADR), repair malfunctioning ones, extend the operational lifespans of critical space assets or as a solution for the End-Of Life (EOL). Furthermore, technological advancements in space-related fields, such as autonomous rendezvous and docking, robotics, and remote servicing, have made IOS increasingly viable [1].

ESA's vision for future transport is to develop an ecosystem where an optimised fleet of reusable launchers injects payloads into high parking orbits, combined with a hub and spoke space logistics network to reach final orbits and provide transport support for in-orbit servicing [2].

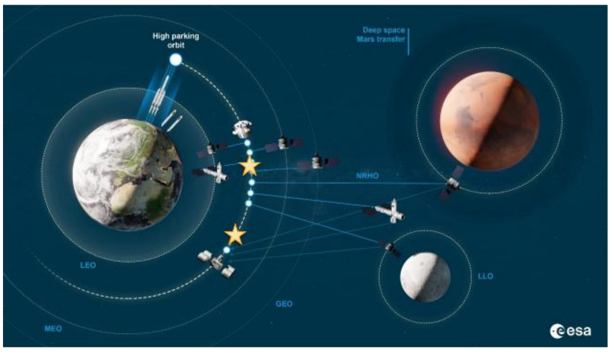

Figure 1: Hub & Spoke concept, injecting payloads with a reusable launcher and a network of in-space vehicles with reusable space-tugs []

This new space logistics ecosystem, designed to enhance space transportation and enable various in-space activities, relies on a network of interconnected In-Space Transportation Vehicles (ISTVs). These ISTVs will be equipped with standardized interfaces, ensuring compatibility and interoperability within the ecosystem.

A key enabler of these new capabilities is to mature the technology of in-orbit rendezvous and docking. Developing new standard interfaces for grappling, docking and System Interconnection between the ISTV and target, compatible with high thrust manoeuvrers for in-space transportation,

There have been numerous IOS missions conducted until now, categorized into two mayor segments: manned and unmanned [3]. Typically, unmanned missions involve docking with the client satellite, which is a critical operation for the mission. Two approaches can be taken in this operation, capture the target spacecraft by either the apogee engine or the Launch Adapter Ring (LAR). Several grippers have been developed for the capture of LAR.

3. TECHNOLOGIES DEVELOPED BY AVS

3.1. Clamping Mechanims for ADR missions, CLM

During this project, conducted under an ESA contract and in collaboration with OHB for requirement definition, AVS developed, produced, and tested a clamping mechanism, designed to reach up TRL 4. This mechanism was designed to capture the Launch Adapter Ring of the target spacecraft, following the initial capture performed by a robotic arm. Once captured, the clamping mechanism serves as a rigid structural link, capable of transferring significant de-orbit thrust loads for controlled re-entry into Earth's atmosphere.

Figure 2: CLM mechanism

The project started with the Envisat satellite as the target within the context of e-Deorbit developments, and was re-oriented following the mission cancellation to support on-going Cleanspace developments for Active Debris Removal, becoming one of the building blocks of the CAT system described below.

3.2. PRINCE, Pasive Mechanical and Rendezvous interface for capture after end-of-life.

The main objective of this activity was to design and verify up to TRL 3 a mechanical interface with integrated rendezvous / navigation aids (PRINCE) which enables the safe capture and removal of a non-operational/non-cooperative satellite for uncontrolled re-entry (i.e. no high thrust manoeuvres / loads as a results of controlled re-entry burns).

Within this activity leaded by GMV, AVS , designed, manufactured, assembled and tested the passive and active interfaces, including the navigation supports, and verified the capture process at GMV's platform Art facility.

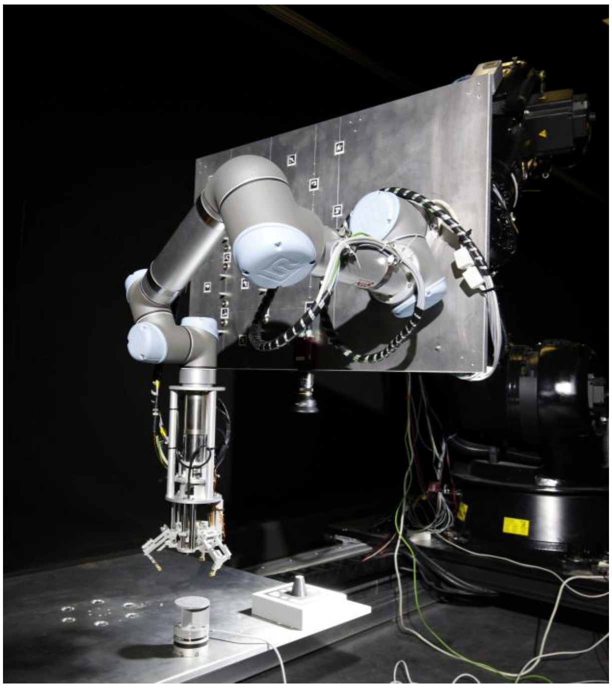

Figure 3: PRINCE testing

The passive interface is defined in the following section. The Gripper is the active mechanism in charge of MICE capture. It has 3 fingers, with a mixed rotational-linear motion to achieve maximum capture range in three axis. The mechanical capture & preloading mechanism is based on a D-drive implementation through the use of pivot rollers instead of linkages; the radial-to-axial Finger motion is provided with a single active DoF.

3.3. Mechanical Interface for Capture at End-of-Life MICE

This ESA activity, leaded by GMV with strong participation from AVS, continues the previous project PRINCE and raise the TRL of the passive interface up to 8. During this activity AVS studied of the inclusion of fine sensing capabilities, updated the design, manufactured the passive interface and carried out a qualification campaign.

The Passive I/F is the part to be embedded to future ESA Earth Observation satellites to allow its capture by a chaser robotic arm during a potential ADR mission. The purpose of MICE is to provide a mechanical interface to facilitate the capture of satellites after their End-of-Life. Its main characteristics are to be compatible with a long life (12.5 years) and a challenging environment, as this interface is meant to remain functional after satellite end-of-life, in uncontrolled environmental conditions.

The MICE dimensions allow it not to protrude from the LAR, while enabling capture in the presence of misalignments of ±20 mm and ±3º, being these the main drivers for its configuration.

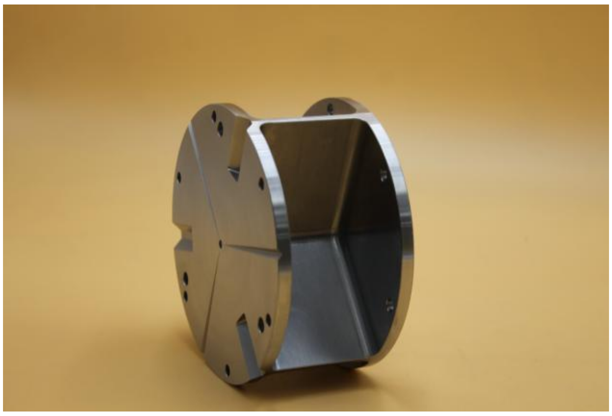

Figure 4*: MICE Passive interface*

MICE features enable the different functions required:

- Repeatable mounting on the Client satellite: guaranteed by the 6 screw holes at the Base plate and the alignment pin hole and groove. There are holes in the top plate to facilitate integration of the base plate screws during MICE mounting on the satellite (allows passing through the preload applying tool).
- Repeatable capture: MICE size has been dimensioned to guarantee compatibility with the range of misalignments defined. Fins are a key feature to guarantee that, despite the initial misalignments, the final captured position is always the same, providing contact surfaces which allow self-cantering of the Servicer. Contact grooves and pin holes also help to achieve a repeatable position at the end of the capture, complementing this function with load transmission through characterised surfaces (so that the contact stresses can be determined).
- Load transfer: As indicated above, contact grooves and pin holes have been included in MICE to guarantee a correct transfer of the loads transmitted by the Servicer side once the capture is completed. Fins and base plate and top plate have been defined

also to be compatible with the range of loads defined in the requirements.

As an interface between two independent systems, MICE has two interfaces itself, one with each of them:

- Interface with Client satellite: composed by 6 bolts and two holes for aligning pins to ensure the orientation during installation and to provide repeatability against potential in-plane thermomechanical strains.
- Interface with Service: as per the features described in the previous section (lateral fins, top grooves, lower face of upper flange).

3.4. CAT

AVS takes the role of mechanisms developer in this ESA activity, leaded by GMV, to develop a complete capture bay, including vision and control algorithms, for removal of satellites at end-of-life.

This project integrates all the previous developments to verify its operation as part of the same system. The Capture Bay is a complex robotic assembly to be integrated at the servicer satellite, composed by the Gripper to grasp MICE interface for the initial capture of the target, developed at PRINCE activity, a hexapod developed by AVS to enable the Gripper’s position fine adjustment during capture, three units of the Clamping mechanism for the capture of the Client's LAR (Launch Adapter Ring) developed at CLM activity, leaded by AVS, a Navigation and G&C system and the control boards.

The client satellite will integrate a client bay to facilitate the capture, composed by the Passive interface from MICE project, a Visual navigation aid and the Client LAR.

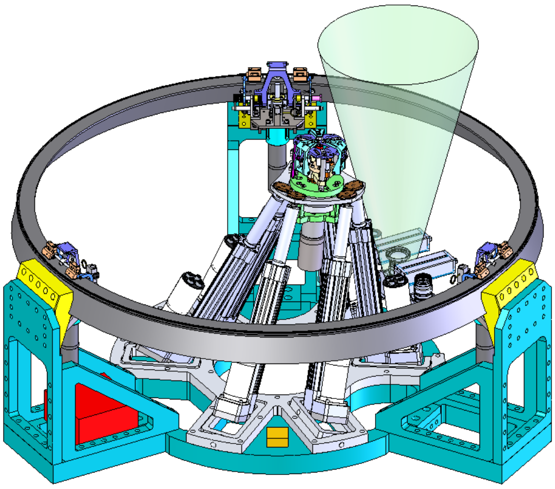

Figure 5: CAT robotic assembly.

3.5. ASSIST

The ASSIST activity leaded by GMV, establishes a standard (International Intersatellite Fuel Transfer System Standard IIFTSS) docking interface definition enabling on-orbit operations for grasping and refuelling geostationary spacecraft.

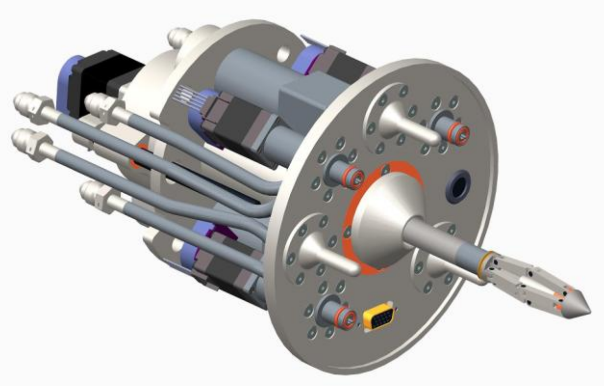

Figure 6: ASSIST Docking system

ASSIS consists of two main components: an end-effector on the chaser satellite's robotic arm and a berthing fixture on the target satellite. It aims for zero-force capture to prevent separation before latching. The docking process involves clamping both spacecraft along a central axis, simplifying alignment correction with the chaser satellite's robotic arm.

The end-effector has a grasping mechanism with an expanding pantograph at its probe's end. The target spacecraft's mating component, known as a 'drogue,' includes a central cavity where the capture probe's pantograph fits. This 'drogue' is part of the berthing fixture, which also contains fluid couplings and an electrical connector.

The target spacecraft's berthing fixture features three guide receptacles to engage and centralize the end-effector alignment pins. These pins are strategically placed asymmetrically on the fluid plane to prevent incorrect docking.

4. STANDARIZATION CHALLENGES

There are a number of challenges regarding the standardization of these type of interfaces.

Some of them are related with technical aspects of the operations needed, such as the need to accommodate large temperature gradients or the robustness against ESD discharges. However, even when some of the ‘topics’ are commonly shared, the ‘levels’ can vary widely depending on the scenario. Specific examples are the detrimental effects of radiation, with significant differences between LEO and GEO satellites (especially for long term exposure of potential dedicated interfaces at the client end) or the potentially large variations in mechanical efforts to be transmitted depending on the type of propulsion used by the Servicer (e.g. chemical vs. electrical) or even the type of intended services (station-keeping vs. refuelling).

Another significant aspect to be considered is the current platform status and the expected evolution, which impacts the potentially provided services. Currently flying satellites are in general ‘un-prepared’ for IOS, so existing interfaces must be used and some functionalities (refuelling, data/power transfer) are out of the table; to date, the missions conducted have been designed with an ad hoc docking system tailored to the particular mission.

Newly launched platforms will be able to be served on the basis of their featuring interfaces, for which there are not clear standards as of today. However, different satellites may require different requirements depending on shapes, sizes, interfaces and intended services.

On top of that, on-going efforts by the agencies to tackle the orbital debris issue, which may comprise the addition of specific interfaces to enable Active Debris Removal missions (at least in agency-funded missions) are also to be leveraged the commercial market interests on life-extension, potential reduction of costs by relying on Servicers for orbit transfer operations, etc.

As a result, achieving standardization is complex and requires extensive collaboration among space agencies, satellite manufacturers, and industry stakeholders to develop flexible and interoperable docking systems that can accommodate the diverse needs of different missions.

AVS is actively working on the development and promotion of standardized docking systems, creating docking interfaces and mechanisms that can be adopted as industry standards. AVS's efforts include the design, testing, and validation of docking systems like MICE and ASSIST to establish common interfaces that can be used across multiple missions and spacecraft.

By supporting the establishment of these standardized docking systems, AVS aims to streamline IOS operations and reduce the lack of flexibility associated with ad hoc docking solutions. This approach facilitates interoperability between different missions and spacecraft, promoting cost efficiency and mission flexibility. AVS's work in this area represents a collaborative effort with industry partners and space agencies to create a common framework for docking technology in the space industry.

5. DEVELOPMENT OF AN ACTUATOR BUILDING BLOCK

In order to address the wide variability of requirements and to reduce the development costs of the potential solutions, AVS is leveraging the knowledge gained from previous projects to generate an actuator building block to enables interoperability, modularity and standardisation while keeping a degree of flexibility to meet specific the mission requirements.

The first step pertains the identification of common needs of the mechanical interfaces, irrespective of the level of functionality required for them. It comprises aspects such as performing a soft-capture before rigidisation (or ‘hard capture’) of the mechanical connection, the compatibility with several docking attempts (with its associated tribological challenges) and the capability to disengage safely.

The capability to compensate misalignments can vary significantly depending on the scenario (direct docking vs. compliant robotic arm, cooperative vs. un-cooperative, etc.), and likely become a main driver of the actuator architecture (trade-off between working volume, stiffness, operation speed, etc.). In any case, it is clear that a suitable mechanical connections must be established before engaging electrical and/or fluidic connections, with a complementary trade-off regarding the use of the very mechanical approach motion to set the connections or the implementation of dedicated degrees of freedom to this end (both with different impacts on the reliability of the operations).

From an architectural point of view, there also a number of trade-offs to be performed, mainly related with the degree of integration of the different functions. Namely, it is clear that the mechanical connection is always a required function (e.g. both for ADR missions and as a first step of IOS), but the implementation of all the functionalities in a single mechanism or the distribution of functions across several components is a key aspect.

Using a ‘multi-point’ connection simplifies each of the connections and reduces the mechanical loads, but is less versatile in terms of size scalability (e.g. different LAR sizes) and may feature more mass than a ‘single-point’ actuator (despite the need to be more robust in itself). Potential ‘hybrid’ solutions (e.g. with complementary passive ‘pads’ to provide additional load paths are also under assessment). The use of a ‘single-point’ interface for all the functions reduces also the impact on the client platform, but is more challenging to implement at actuator level.

These on-going trade-offs are supported by AVS experience and updated with the results of on-going activities, and by dedicated models and analyses to support the decisions, so that particular sets of requirements can be quickly assessed and existing developments re-accommodated to the new demands.

6. CONCLUSION

The paper describes AVS´s team efforts to develop and standardize technologies for mechanical capture and secure in satellite docking systems and how this knowhow is leading to technical solutions that can meet a wide range of IOS operations. It is difficult to provide definitive ‘answers’ to such open questions, but AVS is in a position to support the on-going developments and to provide quick solutions to the challenges ahead.

7. REFERENCES

[1] Enabling a European In-Space Transportation ecosystem

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