ROBOTIC SYSTEM AND REFUELING MECHANICAL INTERFACE DESIGN FOR THE ITALIAN IN-ORBITING SERVICING DEMO MISSION

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ABSTRACT

In-orbit servicing (IOS) robotics is expected to lead to a paradigm shift in the space exploration and exploitation. Indeed, capabilities like in-orbit assembly, repairing, and refueling will enable life extension, performance upgrade, and reliability improvement of future/already flying space assets, possibly increasing benefit-cost ratio, and the construction of large structures, such as telescopes, stations, scientific outposts. Moreover, services like de-orbiting of decommissioned satellites, or re-orbiting/relocation of active satellites will improve the sustainability of the space. For all these reasons, the Italian Space Agency (ASI) recently awarded a contract for an In-Orbit Servicing demo mission to an Italian consortium led by Thales Alenia Space Italy, including Leonardo, Telespazio, Avio, D-Orbit, and other space companies. This paper focuses on two key subsystems of the IOS mission: the capture and refueling subsystems. In particular, the requirements and main challenges of the robotic system and the mechanical interface of the refueling system, which are under the responsibility of Leonardo, will be presented.

1. INTRODUCTION

Providing In-Orbit Services has been a long-term goal since the first conceptual studies in the early 1980s [1]. IOS activities, like active debris removal, refueling, maintenance, assembly, inspection, can bring a real paradigm shift in the use of the space. Indeed, they introduce new capabilities such as extending the life of flying space assets, constructing very large structure in orbit, re-using/reconfiguring already flying systems, which would result in a more sustainable exploitation of the space and savings in term of cost.

For all these reasons, in the last decades, agencies, companies, and academia have been investing considerable efforts in developing IOS technologies. The first demonstration mission was carried out in 1997 by JAXA with the Experimental Test Satellite VII (ETS-VII) in which autonomous rendezvous and docking, teleoperation and servicing tasks were verified [2]. Afterwards, in 2007, the Defense Advanced Research Project Agency (DARPA) launched the Orbital Express mission with the aim of testing autonomous servicing tasks (docking, refuelling, ORU replacement) [3]. Other two demo missions testing IOS technologies were the China’s Aolong-1 in 2016 and ELSA-d by Astroscale in 2021 [4]. Northrop Grumman launched in 2019 the Mission Extension Vechicle 1 (MEV-1), which was the first mission to extend the life of an already flying satellite in GEO, Intelsat 901. The MEV-1 reached the target satellite and performed the servicing tasks in 2020. Afterwards, another extension vehicle, the MEV-2, was launched by the same company in 2020 and successfully attached to the target satellite Intelsat 10-02 [5].

Currently, a number of IOS missions are planned to be launched in the next years: ESA-funded Clearspace-1[6], Robotic Servicing of Geosynchronous Satellites by DARPA[7], OSAM-1[8] and OSAM-2[9] by NASA, Mission Robotic Vehicle by Northrop Grumman[5]. Along with them, the Italian Space Agency (ASI) recently awarded a contract for an In-Orbit Servicing demo mission to an Italian consortium led by Thales Alenia Space Italy, including Leonardo, Avio, D-Orbit, and other companies. This initiative is framed within the In-Orbit Economy line of investments of the National Recovery and Resilience Plan (PNRR) presented by the Italian Government in the frame of the Next Generation EU programme. The IOS demo mission will be performed with two main space assets, the servicer which is the satellite capable of carrying the technologies to perform IOS services, and the target that is in charge to support the in-orbit validation of the technologies and functions enabling different IOS tasks: de-orbiting of a decommissioned satellite, re-orbiting/relocation and take-over of an active satellite (including repetition capability of the mating and detachment), refueling of an active satellite, repairing/refurbishment on-orbit of a satellite.This paper focuses on two of the key subsystems of the mission: the capture and refueling subsystems. In particular, the paper presents the main requirements and challenges in the design of the robotic system (subsystem of the capture system), and of the refueling system mechanical interface (subsystem of the refueling system), which are in charge of Leonardo.

The paper is organized as follows: in section 2 an overview of the Italian IOS demo mission is given; in section 3 and 4 the robotic system and the refueling mechanical interface are presented, including their requirements and main challenges; finally, in section 5, the content of the paper is summarized and future developments are discussed.

2. DEMO MISSION OVERVIEW

The Italian IOS demo mission includes two space assets, which will be launched together on a Low Earth Orbit (LEO):

- Servicer: a vehicle carrying the IOS technologies to be validated
- Target: a satellite to support the in-orbit validation of the IOS operations and technologies

The functions to be demonstrated by the IOS system can be subdivided in two subsets: near-future and mid-term-future functions. The former ones are deemed to be necessary in a near future in order to be able to capture and provide services to non-collaborative satellites (i.e., unprepared for servicing) which can be non-cooperative or cooperative satellites, (i.e., showing a tumbling motion or not). These functions are:

- Orbit transfer of the servicer to reach the orbit of the target
- Target tracking and inspection in both cooperative and non-cooperative scenarios
- Safe rendezvous and approach with the target in both cooperative and non-cooperative scenarios
- Target capture and rigidization of the servicer-target stack in both cooperative and non-cooperative scenarios
- In orbit services:
    - Attitude and Orbit Control System (AOCS) takeover: attitude and orbit control of the target satellite
    - Relocation of the target to another orbit
    - Disposal of the target at the end of life

Note that the capture of a non-collaborative satellite requires the exploitation of features common to different customer spacecraft. For this reason, the launch adapter ring (LAR) is selected as grasping feature in the mission. This is a reasonable choice already proposed and investigated in literature. In particular, the IOS system is required to be compatible with common European LAR size (e.g., 1194mm, 937mm).

The second subset of functions requires the target satellite to be collaborative, i.e., prepared for receiving services. It is indeed reasonable to imagine the use of standard or dedicated interface on future satellites in order to enable and facilitate the IOS activities. Therefore, in the demo mission, the target satellite will be equipped with specific interfaces in order to validate the following capabilities:

- Refueling of the target satellite tank(s)
- Refurbishment of the target satellite, i.e., Orbit Replaceable Units (ORUs) transfer

The target, that will be launched with the servicer, will belong to the small satellite class. However, the system design solution is required to be scalable and guarantee its applicability to targets of higher class of satellites, e.g. Cosmo Skymed and Sentinel satellites.

It is clear from the functions description that the IOS system shall comprise a capture and refueling subsystems. The former one is made up of a robotic system and a vision system, while the latter one is composed of a fluidic system and a mechanical interface. A suitable design of these subsystems is essential to accomplish the required IOS activities. In the following, the main requirements and design challenges of the robotic system and refueling mechanical interface, which are under the responsibility of Leonardo, will be discussed.

3. ROBOTIC SYSTEM

The robotic system is required to fulfil the following main functions:

- Perform a soft capture of the target using as grasping feature the LAR
- Dissipate the residual velocity between the target and the servicer (due to error in the synchronization)
- Drag the target towards the servicer
- Compensate residual misalignment between the servicer and the target
- Perform the hard berthing establishing a rigid connection between the satellites using the LAR of the target
- Perform the manipulation and transfer of an Orbital Replaceable Unit (ORU)

The accomplish them, the robotic system includes different active mechanisms:

- Robotic arm
- End effector (mounted on the arm)
- Berthing mechanism (mounted on the servicer)

In addition, the entire system shall be able to operate in the thermal and radiation environment of the LEO.

In the following paragraph, the main features of the robotic subsystems are discussed.

3.1. ROBOTIC ARM

The robotic arm is a central element of the mission since it is in charge of the most critical tasks of the capturing maneuver, along with the ORU manipulation. In particular, the arm shall fulfill the following functions:

- Place the end effector within a workspace compatible with the GNC limits and grasping performance of the end effector itself
- Dissipate possible residual motion between the target and the servicer (due to non-ideal servicer-target motion synchronization)
- Drag the captured target towards the hard berthing mechanism on the Servicer
- Perform ORU manipulation

To achieve these capabilities, the robotic arm is required to provide

- good positional accuracy for the capture phase and the ORU manipulation
- compliant behavior during contact situations in order to limit the interaction forces
- high dexterity
- good velocity performance to accurately track the moving grasping point

Another relevant requirement affecting significantly the design is the testability of the main operations of the robotic arm on Earth in 1-g environment. Considering the size of the arm, which for safety reason and GNC performance shall be longer than 2m, and the need of a certain stiffness (for structural and control performance), this requirement appears immediately challenging. Indeed, testability in the whole workspace would require an extreme oversizing of the actuators w.r.t. the need on orbit. Off-loading systems can be designed, but they are usually quite complex and could introduce additional disturbance not present during the real application. A good compromise could be the limitation of the testable workspace on ground. This solution would avoid excessive oversizing. On the other hand, the design of the tests and the integration require more effort since the robotic arm would not withstand its own weight in the entire workspace. Moreover, arm motion shall be designed in order to be always within the 1-g testable workspace.

The need of relatively high joint torques for 1-g testability and high velocity for grasping point tracking naturally pushes the design of the joints towards a single-stage solution rather than a two-stage one (typical of planetary robotics). In this regard, DEXARM [10], a robotic arm developed by Leonardo within an ESA contract, represents a strong heritage and reference for the IOS arm. The DEXARM joint is made up of the following components: a brushless motor, fail-safe active brake, harmonic drive as transmission, bearing system, motor absolute position sensor for commutation and velocity control, output absolute position sensor, output torque sensor for compliance control. Moreover, each joint is equipped with an electronic board driving the motor, acquiring the sensors and performing low level control. In DEXARM, local electronics has been selected rather than central electronics. This choice requires less harness along the arm and enables a more accurate measurement of the torque. On the other hand, it results in a hollow-shaft design of the joint, and, for a space application, in a more complex thermal design. Currently, this joint architecture coming from the DEXARM experience is considered as main reference and starting point for the IOS robotic arm design considering also the challenge timeline of the programme.

3.2. END EFFECTOR

The end effector is mounted at the tip of the robotic arm and its main function is the grasping of the target LAR. In particular, the geometry of the fingers shall be designed in such a way to be compatible with different LAR size (current baseline: LAR937 and targeting LAR1194). This is not an easy task since the LAR sections may be quite different and the design of the End Effector shall accommodate these differences to ensure sufficient contact points, and, consequently, a stable grasp.

Other important features of the end effector are the maximum opening width of the fingers and the grasping capability. Indeed, its design is required to be compatible with the overall positioning errors coming from the robotic arm, vision system, and GNC performance. Moreover, it is important that the closure motion of the end effector is sufficiently fast to avoid the target escape from the grasping workspace, especially in the non-cooperative scenario.

Finally, the end effector shall withstand the loads arising during the operations. Three different situations can be identified: the capture phase, the dragging towards the servicer, and the interaction with the other mechanisms (hard berthing, and, especially, the ORU). In the first case, the forces should be limited thanks to the free-floating dynamics of the target and the compliant behavior of the arm. However, it is a quite critical situation in which fault cases may result in uncontrolled collisions which shall be handled properly and require a robust design of the end effector. In the second situation, the sizing scenario is the non-cooperative one in which servicer and target have a tumbling motion generating centrifugal forces trying to separate the two satellites. Finally, during the interaction with the other mechanisms, and especially the ORU, the end effector shall withstand the loads due to peg-in-hole and engagement operations. All these load requirements translate in a certain robustness of the end effector and in a sufficient preload provided by its actuator/s. Trade-off between competing needs of relatively high velocity and preload is necessary in order to avoid too heavy mechanism, which would affect both the arm performance and the overall system mass (always critical in space application).

3.3. HARD BERTHING MECHANISM

The hard berthing mechanism is placed on the servicer and is in charge of rigidizing the servicer-target stack and withstanding the loads arising from de-tumbling, de-orbiting, and orbit transfer maneuvers.

As for the end effector, the requirement of compatibility with unprepared satellites naturally leads to the use of the target LAR as mechanical interface. Similarly, the system is required to work with different class of spacecraft, and thus its grasping system shall be able to adapt to both LAR937 and LAR1194, which may be different not only in the size of the diameter, but also in the shape of the cross section.

In order to guarantee a correct mating between servicer and target, an important aspect the design of the hard berthing mechanism shall take into account is the residual positioning error between the LAR and its interface due to inaccuracy of the arm, the end effector (non-ideal grasp), and vision system. If not properly considered, this may result in an impossibility to grasp the satellite or in a wrong distribution of the loads leading to failure. Therefore, it is essential to foresee a system to compensate this relative positioning errors.

Finally, the actuator/s and the structure of the hard berthing shall be sized considering the loads arising from the tumbling motion of the two satellites (in the non-cooperative scenario), the de-tumbling operation, the de-orbiting maneuver, the repetition of the berthing, and the orbit transfer maneuver for target relocation.

4. REFUELLING MECHANICAL INTERFACE

The refueling mechanical interface is part of the refueling system whose purpose is to demonstrate the feasibility of transferring a fluid between two spacecraft mated together. Along with the mechanical interface, the system includes the fluidic subsystem which is under the responsibility of D-Orbit and is not treated in this paper.

The refueling mechanical interface is made up of two parts, one mounted on the servicer and the other one mounted on the target. After the rigidization of the servicer-target stack, the refueling process will start triggered by the confirmation of the correct mating (provided by a dedicated sensor suite). The mechanical interface shall fulfill the following main functions:

- Maintain a sealed fluidic connection between the servicer and the target, ensuring a fluidic transfer between them
- Provide the sensors that allow to establish when the interface is ready to perform the fluidic transfer

In order to guarantee a reliable connection, minimizing leakage, it is important to compensate possible misalignments between the two parts and provide an efficient sealing system. This latter component, along with the structure, shall be designed to be compatible with the operative pressure range of the fluid and the maximum allowable flow rate. Another important aspect to be taken into account in designing the sealing system is the resistance to multiple mating/de-mating cycles which can deteriorate the system jeopardizing the performance.

Finally, the mechanical interface shall guarantee that no phase transition occurs during the fluid passage, and thus it is required to provide means to keep the temperature within a predefined range.

5. CONCLUSION

This paper provided an overview of the Italian In-Orbit Servicing demo mission. In particular, the attention has been focused on the requirements, high level input, and main challenges for the design of the robotic system and the refueling mechanical interface, part of the capture and refueling system, respectively. A proper design of these key subsystems has been identified as critical for the success of the demo mission. Currently, the program is approaching the system requirement review, and the preliminary design of the systems is under development. The preliminary design review is expected to be at the beginning of the next year.

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