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Towards a standardized grasping and refuelling on-orbit servicing for geo spacecraft

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ABSTRACT

Exploitation of space must benefit from the latest advances in robotics. On-orbit servicing is a clear candidate for the application of autonomous rendezvous and docking mechanisms. However, during the last three decades most of the trials took place combining extravehicular activities (EVAs) with telemanipulated robotic arms. The European Space Agency (ESA) considers that grasping and refuelling are promising near-mid-term capabilities that could be performed by servicing spacecraft. Minimal add-ons on spacecraft to enhance their serviceability may protect them for a changing future in which satellite servicing may become mainstream.

ESA aims to conceive and promote standard refuelling provisions that can be installed in present and future European commercial geostationary orbit (GEO) satellite platforms and scientific spacecraft. For this purpose ESA has started the ASSIST activity addressing the analysis, design and validation of internal provisions (such as modifications to fuel, gas, electrical and data architecture to allow servicing) and external provisions (such as integrated berthing fixtures with peripheral electrical, gas, liquid connectors, leak check systems and corresponding optical and radio markers for cooperative rendezvous and docking). This refuelling approach is being agreed with European industry (OHB, Thales Alenia Space) and expected to be consolidated with European commercial operators as a first step to become an international standard; this approach is also being considered for on-orbit servicing spacecraft, such as the SpaceTug, by Airbus DS.

This paper describes in detail the operational means, structure, geometry and accommodation of the system. Internal and external provisions will be designed with the minimum possible impact on the current architecture of GEO satellites without introducing additional risks in the development and commissioning of the satellite. End-effector and berthing fixtures are being designed in the range of few kilos and linear dimensions around 15 cm. A central mechanical part is expected to perform first a soft docking followed by a motorized retraction ending during a hard docking phase using aligning pins. Mating and de-mating will be exhaustively analysed to ensure robustness of operations. Leakage-free valves would allow for the transfer of fuel to the serviced spacecraft. The validation of the ASSIST system through dedicated environmental tests in a vacuum chamber together with dynamic testing using an air-bearing table will allow for the demonstration of concept feasibility and its suitability for becoming a standard of the on-orbit space industry.

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1. Introduction

The exploitation of space requires the establishment of both human and robotic presence. Towards this goal, various roadmaps indicate the need for the realization of a robotic orbital infrastructure for tasks such as satellite servicing, refuelling of space assets, orbital debris removal and construction of large assemblies on Earth or other planetary orbits. To this end, On-Orbit Servicing (OOS) plays a central role.

The history of servicing in space is not new; however the earlier approaches were inefficient. This was mainly due to the fact that initially satellites were built without taking into account serviceability. In the wider sense however, the docking operations of Gemini or Apollo can be regarded as a preliminary OOS function. As satellite technology became more mature and capabilities increased, the possibility of servicing satellites started attracting the interest of space agencies.

This provision of services in space is more and more an important factor in space exploitation and in maintaining the required space infrastructure. Through OOS operations a considerable reduction of operating costs for unmanned space assets such as navigation and geostationary communication satellite can be performed. The servicing of satellites in orbit includes many aspects of component assembly and equipment maintenance (both corrective and preventive), the replenishment of consumables and upgrade and repair capabilities.

The use of the OOS services can be considered in different phases of the space mission life cycle:

- Failure during the injection of the payload into the nominal target or transfer orbit. In most cases the satellite cannot accomplish this on its own; an orbit transfer vehicle could provide support.
- Necessity for support unfinished operations during the test and commissioning phase. Typical example can be incomplete deployment mechanism of solar arrays or of antenna dishes.
- Premature end of life of the satellite due to equipment obsolescence or wear.
- Extension of the expected duration of the satellite operative life through a refuelling of propellant tanks devoted to attitude/orbit control. This scenario will be the main subject of this ASSIST project and will be fully explored.

This activity is led by GMV (coordinator and dynamics simulator) together with MOOG (mechanical design, breadboard manufacturing and environmental testing), NTUA (air-bearing table dynamics and testing), DLR (contact dynamics), OHB (mission requirements and propulsion provisions) and TAS (mission requirements).

This paper is organized as follows: Section 1 provides an introduction, Section 2 introduces the ASSIST concept, Section 3 provides a review on servicing/refuelling systems, Section 4 describes the operational scenarios and phases, Section 5 presents the ASSIST design while Section 6 describes the step-by-step refuelling operations, Sections 7 and 8 present the internal and external provisions respectively, Section 9 introduces the Kinematic and Dynamic simulator, Section 10 shows the air-bearing test set-up, Section 11 describes the dynamic test cases and validation results and finally Sections 12 present the conclusions.

2. Assist concept overview

The ASSIST system is considered to be a set of servicing/refuelling provisions on a serviced GEO S/C and a set of provisions on the servicing S/C. They are decomposed into external and internal elements:

1. Internal: modifications to fuel, gas, electrical, data architecture to allow servicing in the GEO satellite.
2. External: integrated grasping/berthing fixtures with peripheral electrical, gas, liquid connectors, leak check systems, optical/radio markers for cooperative rendezvous. Hereafter they are described the main elements:

- The berthing fixture is referred to the mechanical interface, on the serviced spacecraft, connecting with the servicing counterpart.
- On the other side the end-effector is the mechanical interface installed on the servicing spacecraft (on the tip of a robotic arm) devoted to the connection with the berthing fixture.
- The part of the end-effector, that is foreseen to be the first to get connected with the berthing fixture, is called the capture probe. After such first contact a docking mechanism will perform the docking process.
- In a symmetric way the deeper part of the berthing fixture where the probe will touch is called drogue cavity.

Also, the following distinction between berthing and docking is adopted:

- Berthing involves the manoeuvring of the manipulator arm mounted on the servicing S/C to approach the end-effector to the berthing fixture of the serviced S/C until its capture probe gets in contact with the drogue cavity.
- Docking refers to the servicing S/C manoeuvres related to the engagement of mechanical couplings and solid contact is established with the berthing fixture of the serviced S/C is established.

3. Review of servicing/refuelling systems

The purpose of the ASSIST includes only the transfer of fuel and data, therefore the docking systems that enable the passing of humans (such as the system on-board the ISS) are interesting only in terms of analysis of their mechanisms but not for the docking procedure per se. In the case of transfer of fuel and data the probe-drogue system is the most appropriate in terms of simplicity and convenience. The analysis of the developed forces and torques is more straightforward and the footprint of the necessary mechanical dimensions is small in comparison with other docking mechanisms.

In principle, a typical central docking system (APAS [1], LIDS [2], IBDM [3], ASPS [4] or DEOS BDM [5]) has the following phases during the docking procedure:

1. The controller of the active part (usually the part with the probe) aligns itself with the passive part (usually the part with the drogue) using some predefined markers as a guide.
2. The probe enters the drogue, while on the same time a number of guiding pins (or similar mechanisms) allow the correction of small misalignments.
3. As the most of the misalignments have been compensated the probe continues entering the drogue. Depending on whether the docking system is active or passive, a sensor to define the pass of a certain threshold or shock absorbers are used (or combination).
4. A mechanism which can perform a “Soft-Dock” is used to hold both mating systems on a loose connection. Usually this mechanism is a spring-loaded latch (passive systems) or a mechanism, which is extended around the probe forming a diameter larger than the tightest section of the drogue (active systems).
5. Retraction of the probe to secure the “Soft-Docking” takes place and on the same time to bring the mating halves closer. “Hard-Dock” mechanisms start to operate now (again there can be active or passive mechanisms) such as latches or screws.
6. Mating of data, fuel, gas etc. connections take place (almost at the same time with the Hard Docking).

All major space agencies turned into searching on how to mature the automated OOS with the extensive use of robotic systems. Up until now however, these autonomous robotic OOS mission are strictly experimental. OOS tasks are extremely challenging and specialized mechanisms and control algorithms must operate effectively in order to reduce the probability of errors. For this reason prior to launch, extensive theoretical but also experimental analysis is necessary. Since the theoretical development is relatively feasible, an issue that arises is the accuracy of the simulation results comparing to a real system in orbit. Human perception, due to gravity and friction, is certainly affected. Therefore is of outmost importance to have experimental facilities on Earth, which emulate the zero-g environment accurately. However to test a robotic system, it is necessary to have enough experimental time at the lowest possible cost. Methods like parabolic flights and drop towers provide limited time. Neutral buoyancy facilities like the one used for the Ranger Neutral Buoyancy Vehicle are high-cost facilities, even though they allow a three-dimensional representation of the systems [6]; however the inertia of the water is not compensated and the robotic systems must be waterproofed. HIL systems, like DLR's EPOS [7,8] and GMV's platform-art© [9], allow three-dimensional experimentation [10,11] but as they are based on the accuracy and the characteristics of both the manipulators and the software which models the zero-g environment, their complexity is higher.

The air-bearing facilities give a good compromise: even though it is not possible to emulate the three-dimensional motion, they can represent accurately a planar zero-g environment for significant durations [12]. The characteristics of an air-bearing facility are largely affected by the kind of tasks to be emulated. However the largest number of the existing facilities is dedicated to the motion of the base of a system without manipulator. By adding more DOF's by means of a robotic arm, the system tends to be more complicated and several parameters must be taken into account, such as coupled dynamics, dynamic singularities, tip-over avoidance and control [13–15].

Another issue to be considered is the sizing of the hovering systems, which can be reduced using modern electronics and embedded systems. However this size reduction is largely affected by the mechanical components and the tasks to be fulfilled. The use of some kind of gas (CO_2, N_2, air) in many ways imposes restrictions on minimum dimensions and this is a critical design driver. Finally the localization methods should also be carefully designed and adapted to the dimensions of both the robot systems as well as of the environment in which the emulator is located.

4. Operational scenarios and phases

In order to achieve the ASSIST requirements, a reference scenario has been defined at the beginning of the activity. The ASSIST system shall be compatible with:

- Large GEO telecom satellites (~4–6–8 Tn.)
- Small GEO telecom satellites (around 2.5–3.5 Tn.)

A survey performed among the most important European spacecraft manufacturer has allowed highlighting more specific profiles for the required fuel categories and quantities as listed hereafter:

- Spacebus/Spacebus Neo (TAS): 1000 kg of MON/MMH and 300 kg of Xenon.
- Small GEO satellites (OHB): ~500 kg of MON/MMH (chemical propulsion), 100 kg of MON/MMH +150 kg of Xenon (hybrid propulsion) and 200 kg (typically Xenon for full-electric propulsion).
- Space-tug (Airbus DS): 200 kg of MON/MMH and 3000 kg (typically Xenon).

4.1. The proposed on-orbit servicing mission includes the following phases

1. The rendezvous final/terminal phase, which begins when the servicing S/C detects the serviced S/C by its own sensing means and starts the relative navigation phase. For ASSIST we assume a distance of the S/Cs between few kilometres (e.g. below 10 km) and a meter range (e.g. 1.25 m) (compatible within the maximum reach of the robotic arm mounted on the servicing S/C).
2. The berthing phase, which is entirely operated by the robotic arm whose objective is to mate the servicing S/C end-effector part with the serviced S/C berthing fixture counterpart. The robotic arm should be equipped with an illumination source in order to provide a clear view of the markers placed on the berthing fixture mechanism.

   After the end-effector capture probe contacts the drogue cavity of the berthing fixture (Soft-dock Mode) a central mechanism will be retracted to ensure an initial soft docking. Later on a second phase of mechanical engagement using aligning pins will be performed ensuring a hard docking (Hard-dock Mode). This phase ends with a successful berthing/mating and subsequent connection of fuel, gas and electrical interfaces.
3. The servicing phase: the ASSIST system keeps the two spacecraft locked thanks to its mechanism. The refuelling takes place during this phase (Refuelling Mode). Servicing and serviced S/C actuators must not overload the ASSIST system interface: the ASSIST interface will be able to afford a maximum amount of forces and torques as defined per corresponding requirement.
4. The de-mating phase: the servicing operations have been concluded and the berthing mechanism unlocks the two spacecraft (passing through Hard-dock and Soft-dock Modes). The robotic arm safely retracts the end-effector within the approach frustum (0.15×0.15 m^2 in small base, 0.5 m height and 0.25×0.25 m^2 in large base).

The system shall be designed so that all these operations can be operated safely and in an autonomous way. For the design and development of the ASSIST system, the berthing phase is the one that will drive most of the requirements. As the development of the robotic arm and its control is out of the scope of this activity, it will be assumed that the robotic arm will be able to move its end-effector with highly accurate position control.

During dynamic testing it is assumed that the robotic arm does not articulate its joints (i.e. appendage-like configuration). In order to consider the flexibility typical of robotic arms another assumption is made: perturbations on an idealized rigid robotic arm induced by the flexibility of some of its parts are modelled as simple straight bending beams clamped to a rigid hub.

5. Assist design

The principal concept behind the ASSIST capture system is to allow for zero force capture to ensure that the target or client spacecraft are not pushed away from each other before a latching system can be deployed. Crucially the assembly allows for clamping of the two vehicles around a central axis before any further berthing processes take place. This constraints the alignment problem to a single rotational axis; the angular misalignments can be corrected by the robotic arm from the servicing S/C.

The end-effector includes a grasping mechanism, which consists of an expanding pantograph located at the end of a probe. The mating half on the client spacecraft consists of a 'drogue' type arrangement, which includes a central cavity into which the capture probe pantograph is inserted. The 'drogue' is part of the berthing fixture assembly, which includes fluid couplings and an electrical connector. The berthing fixture on the serviced S/C also includes three guide receptacles, which allow the end-effector alignment pins to engage and centralise the

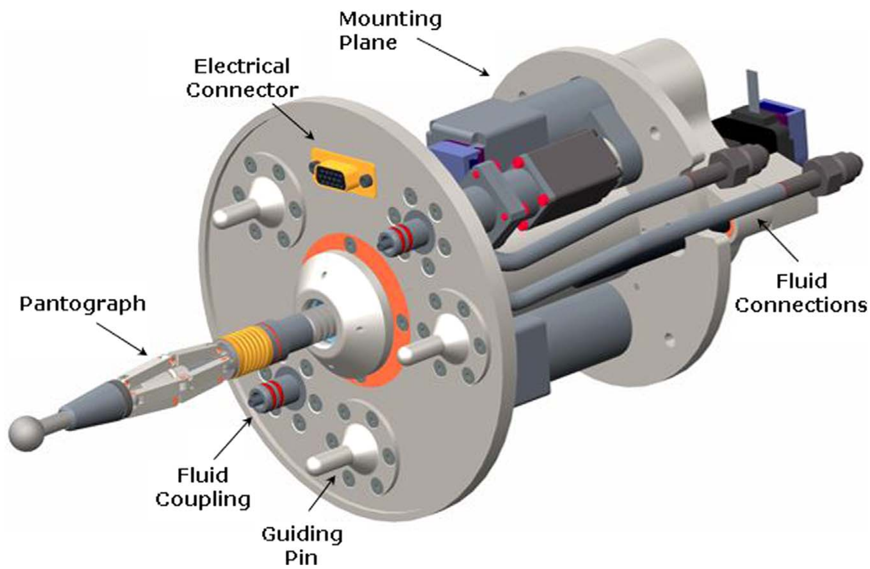

Fig. 1. End-effector.

whole system. The alignment pins have been arranged asymmetrically on the fluid plane so that the end-effector cannot be docked incorrectly. Following subsections provide a detailed overview of the end-effector, berthing fixture and fluid couplings.

6. End-effector

The end-effector (see Fig. 1) is foreseen to be attached to a robotic arm on the servicing S/C and includes the fluid and electrical connections and a grasping mechanism which docks with the berthing fixture on the serviced S/C.

The end-effector also includes one half of the fluid coupling and an actuation mechanism, which operates the valve in the client-berthing fixture half. Included on the end effector are three fluid couplings (fuel, oxidiser and xenon), which connect to the berthing fixture half and seal with elastomeric O-rings.

The alignment pins, fluid couplings and electrical connector are mounted on a plane referred to as the 'fluid plane'. When the system is docked, the 'fluid plane' on the servicer and serviced S/C has a compressive force between them, which is maintained during refuelling operations.

The end-effector finalizes in a probe tip actuated by a pantograph. The pantograph mechanism uses a central actuation shaft, which is driven from a stepper motor at the base of the end effector. A lead screw arrangement inside the main shaft transfers the stepper motor rotation to a linear motion. As the central actuation shaft retracts linearly, the probe pantograph expands (see Fig. 2). A ball/groove arrangement at the base of the pantograph allows the pantograph to rotate through the probe axis with low frictional torque while a large axial strength is maintained. The rotational degree of freedom allows the alignment pins to locate in the guides during docking. In addition to the ball/groove a thrust bearing has been introduced between the probe tip and the pantograph to reduce friction.

The end-effector has a fluidic plane with a collar that allows to ensure the final and hard docking process. Both the collar and fluid plane mechanisms use a common lead screw which has a 12 mm diameter by 2 mm pitch Trapezoidal (ISO) thread, chosen over ball lead screws to prevent back drive. Hence, once the collar or fluid plane has been transferred and the preload applied, the system is secured in place and the fluid pressure or external torque does not separate the fluid planes. Ball lead screws would require locking mechanisms to prevent back drive.

The collar is translated along the shaft using a lead nut (collar nut) on the main shaft, which is driven via a stepper motor, a planetary gearbox (27:1), two spur gears and a ball spline. The ball spline allows the rotational motion to be transferred to the lead nut whilst allowing it to move linearly with respect to the driving gear. Since the nut is rotating along the main shaft, the collar is attached to the nut using a radial bearing so that when it contacts the drogue throat it does not apply a torque to the berthing fixture (serviced S/C). The collar stepper motor to lead nut gear ratio is 42:1 which allows a high torque to be applied to the nut.

For the fluid plane translation, a second lead nut on the main shaft is driven via a stepper motor, a planetary gear box (100:1) and two spur gears. When the lead nut is driven, the fluid plane including the couplings translates along the main shaft towards the berthing fixture. The lead nut is supported on an angular bearing one side and a thrust bearing on the other. To constrain the main shaft rotational degree of freedom, it has an anti-rotation device attached to the back end. This consists of 2× guide pins attached to the shaft at a radial distance of 37 mm from the central axis, 180° opposite to one another. The pin axis is constrained to the housing using a plain bearing so that the shaft can move linearly but cannot rotate. The plain bearings must have a tolerance such that the maximum pin deflection (as a result of the torque through the main shaft) can be accommodated in the bearing clearance. Hence, the small rotational displacement is acceptable while the friction is reduced significantly.

7. Berthing fixture

The berthing fixture (see Fig. 3) provides the serviced S/C with one half of the grasping mechanism, which the servicing robotic arm end effector docks with. This consists of a 'drogue' type arrangement, which includes a central cavity into which the capture probe enters during the docking operation. The provisions on the serviced S/C include three guide receptacles, which allow the alignment pins to engage and centralise the whole system. Note that the guide pins are positioned asymmetrically such that the docking cannot occur in the incorrect orientation, guaranteeing the correct pairing of the fluid couplings.

There are three fluid couplings and one electrical connector (ad-hoc DB-9 or alternatively the Souriau 8977 model [16]) in the proposed design. This allows a hybrid GEO platform (MMH, MON and Xenon) to be refuelled. The baseline design of the berthing fixture is to have common parts for both Small GEO and Large GEO platforms with the exception of the third fluid coupling, which will be used for Xenon refuelling. This coupling could be replaced with a blanking plate

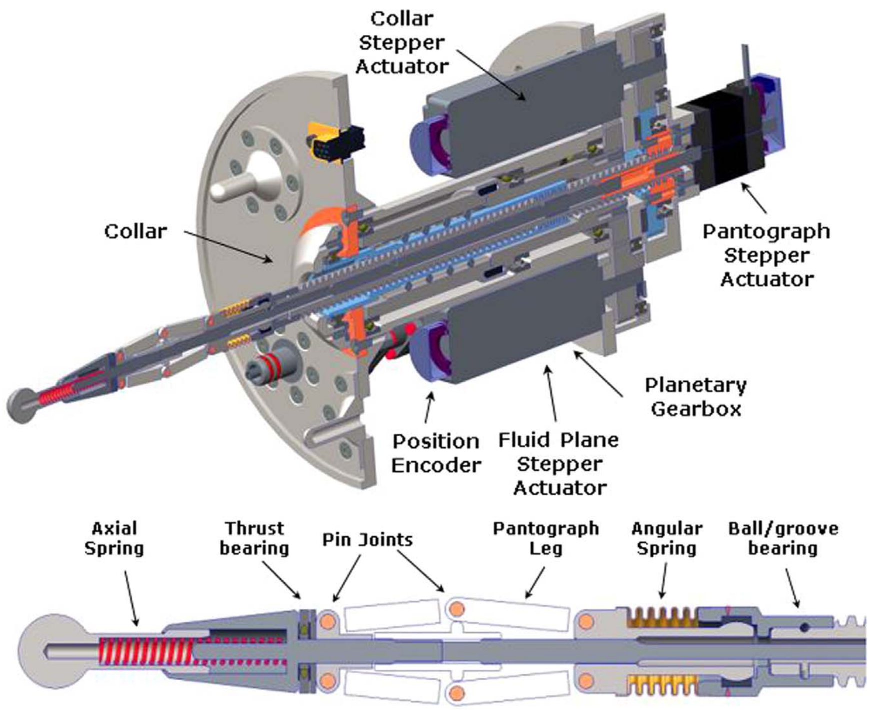

Fig. 2. 3D section of end-effector (top) and detailed probe-tip section with the pantograph mechanism (bottom).

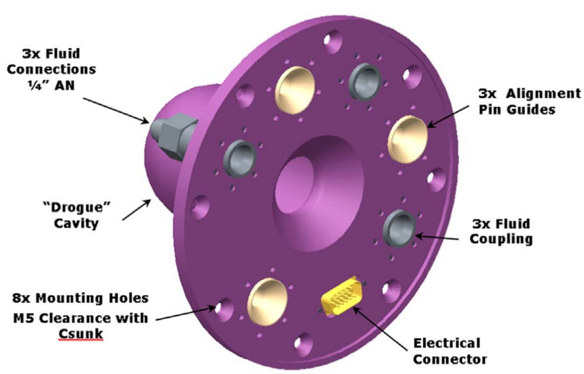

Fig. 3. Berthing Fixture.

whenever is not required.

8. Assist refuelling operations

The envisaged refuelling procedures can be decomposed into the following sequence of operations:

1) Berthing phase (up to approach frustum): Servicing S/C approaches serviced S/C using visual camera servoing.
2) The probe is aligned with the target satellite such that the centre of the probe is within the drogue's acceptance cone. The roll angle around the longitudinal axis is controlled via the robot arm to allow the alignment pins to be coarsely aligned with the alignment pin guides.
3) Berthing phase (approach frustum): Servicing S/C follows linear trajectory and end-effector tip enters into drogue cavity through the 'throat' (see Fig. 4. – left).
4) Once the probe is past the throat, the probe's force sensor is now activated and is waiting for a force to be applied at the spherical end of the drogue.
5) Upon contact with the spherical end of the drogue, the command is given to retract the end of the probe, keeping the remainder of the unit in position (see Fig. 4 – right). Both S/C are now restrained in a 'soft' dock configuration.
6) Once the probe is expanded, the clamping collar is translated along the cylindrical section of the probe towards the drogue (see Fig. 5 – left), thus making contact with the drogue throat, pulling the expanded probe and the collar together and trapping the drogue's throat. At this point a hard dock has been achieved and a firm grasp of the serviced S/C has occurred.
7) Check that the pins are still aligned with the guides. The capture process may have introduced a rotational misalignment (about the probes major axis), which needs to be corrected. To compensate, the fluid transfer plane is allowed to rotate around the central cylinder, the pantograph and collar have a rotational degree of freedom with respect to the main shaft.
8) The fluid transfer plane is translated towards the serviced S/C and the alignment pins will engage in the guides on the client half. The guides are tapered and hence they take out any minor misalignment. Once the pins have translated deep enough into the serviced S/C to engage with the parallel section of the guides, correct alignment will have been achieved. The fluid transfer plane continues to translate until it is firmly against the serviced S/C, which automatically connects the three fluid couplings. At this point (see Fig. 5 – right) the servicing S/C can proceed with the process of re-fuelling the serviced S/C.
9) Pressurise each fluid coupling with Nitrogen or Helium and monitor the pressure decay to determine the external leakage.
10) Actuate the 1st berthing fixture valve using the valve stepper actuator. The actuation shaft will move axially lifting the poppet (see Fig. 6 – left).
11) Fuel transfer (through operation of servicing and serviced spacecraft valves).
12) Once the client tank pressure reaches the target pressure the isolation valves on the refuelling branches are closed. The berthing fixture valve is isolated by operating the stepper actuator in reverse, retracting the actuation shaft and reseating the poppet onto the seat (see Fig. 6– right). Fluid coupling lines are purged.
13) Retract the fluid plane, collar and extend the pantograph. Undock

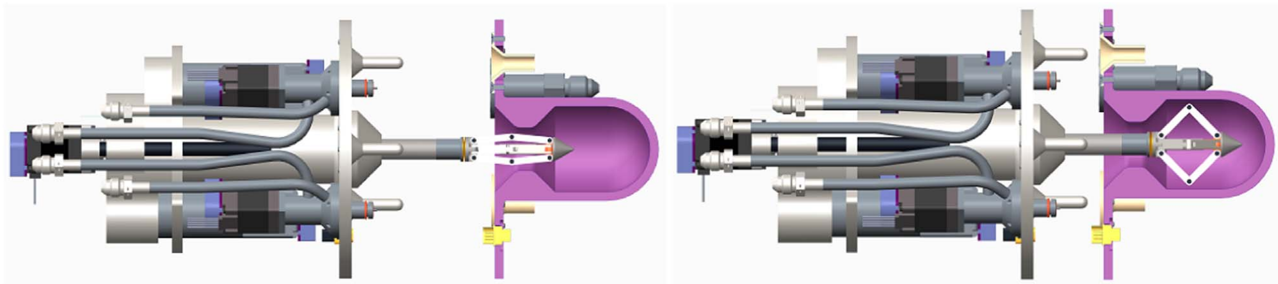

Fig. 4. Pantograph getting introduced into the drogue cavity: initial entrance (left) and deployment (right).

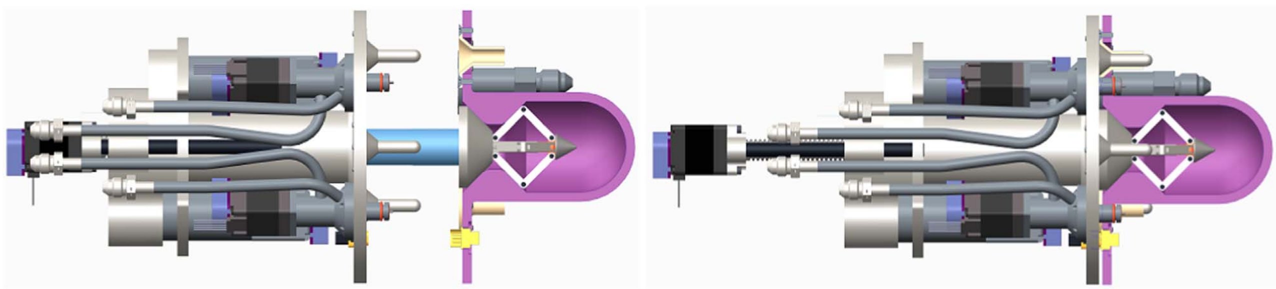

Fig. 5. Pantograph deployed within the drogue: clamping collar attachment (left) and final hard docking (right).

the ASSIST system by retracting the probe from the drogue using the robotic arm until exiting drogue cavity.

9. Internal provisions

The internal provisions are designed with the minimum possible impact on the current architecture of GEO satellites, so that accommodating them in future satellites will not be seen as a major complication (both technical and in terms of costs), nor will it introduce additional risks in the development and commissioning of the satellite.

As depicted in Fig. 7, the standard chemical propulsion block diagram can be extended by a small branch including a pyro-valve, a solenoid or latch valve and the berthing fixture with an internal isolation valve. For a bipropellant system two of these branches are required.

This simple design is also applicable for electric propulsion with the small change that the pyro-valve will be exchanged with a normal latch or solenoid valve and the additional test port (FDV) can be skipped. All selected components use standard interfaces (e.g. 28 V valve interface) available on GEO communication satellites due to the existing propulsion system needs.

10. Rendezvous external provisions

The rendezvous provisions are the external provisions of the ASSIST system, which are needed for the rendezvous and berthing sensors proper working. They consist in targets and markers to be added to the target satellite (GEO). The ASSIST system strategy consists in a cooperative rendezvous, with the serviced S/C controlled in attitude, and has the goal of minimizing the impact on the serviced S/C for both internal and external provisions by using as simple navigation aids as possible. Cooperative Rendezvous in space can be done with the use of a whole range of different sensors. In case of ASSIST, the main consideration is that the target spacecraft is an active satellite in the GEO orbit, whose orbit is precisely known, therefore no long-range sensor is needed on-board the servicing S/C, which can travel up to kilometre-range proximities of the target serviced S/C with the only help of ground tracking, as done by the ATV when docking to the ISS.

Once arrived to the region of few kilometres of relative distance there is the need of using relative sensors; a trade-off between the following sensors has been performed:

1. A radio frequency (GNSS-like) sensor with radio emitter/repeater beacon mounted on the client S/C.
2. A LIDAR (LIght Detection And Ranging) sensor on the servicing S/C with or without aids mounted on the client, such as retro-reflectors arranged in specific geometries.
3. A vision camera on the servicing S/C, with or without aids mounted on the serviced S/C.

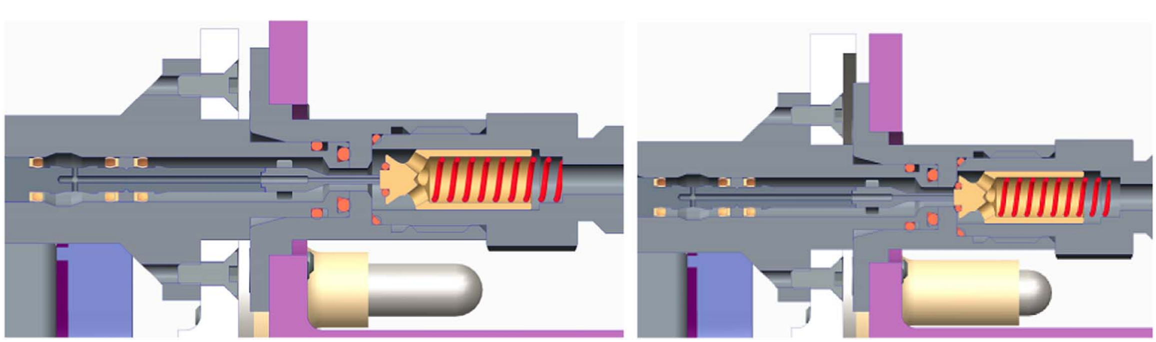

Fig. 6. Actuation valve actuating (left) and releasing (right) the poppet.

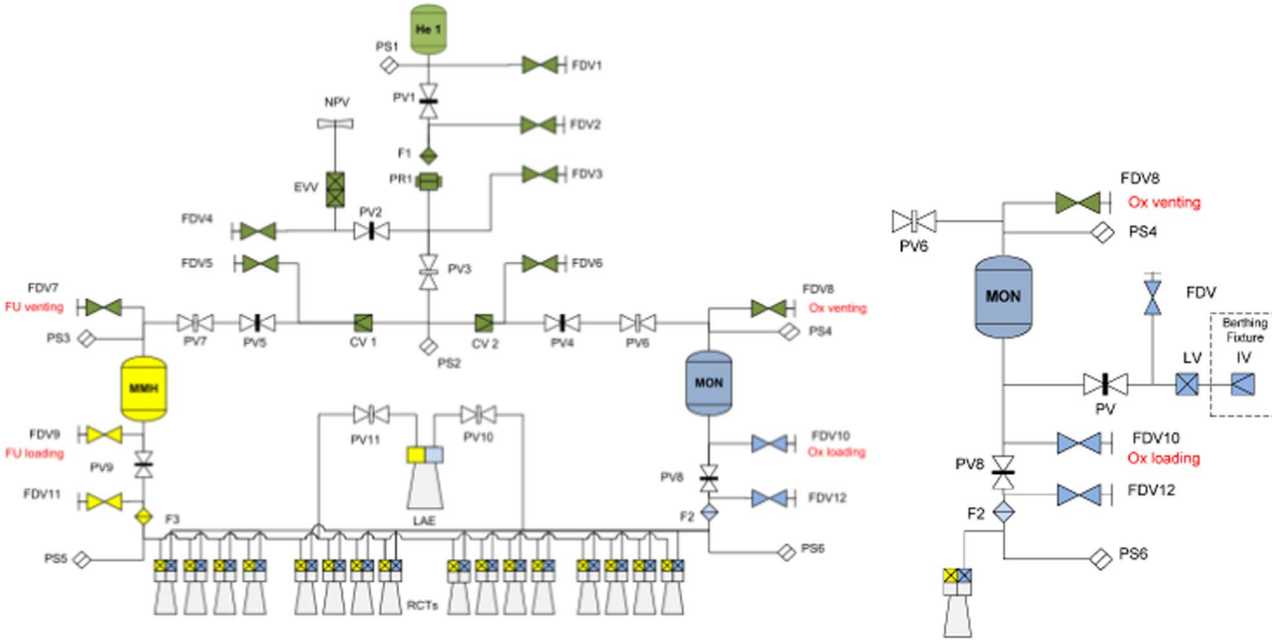

Fig. 7. Generic Bi-propellant propulsion system (left) and MON-refuelling branch (right).

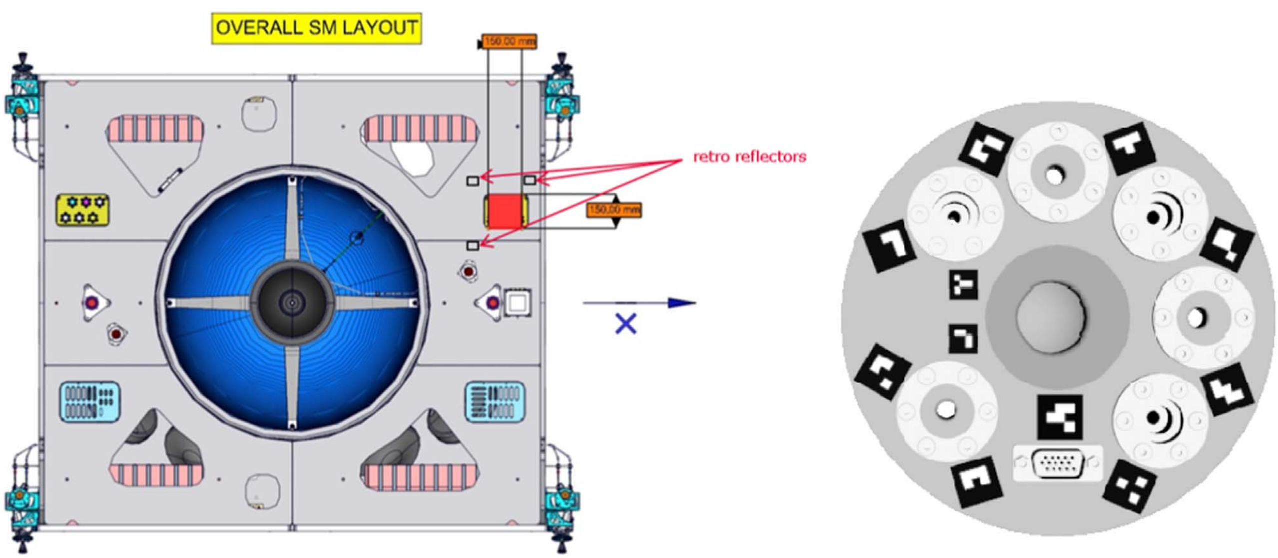

Fig. 8. Example of retro reflectors positioning on the large GEO docking face (left) and visual markers on the berthing fixture (right).

The winner of the trade-off is a scanning LIDAR with the use of retro-reflectors on the serviced S/C as it presents the following advantages: robust to lighting conditions, very high accuracy in range, LOS and attitude and extended operating range. Taking into account that the retro reflectors to be placed on the serviced S/C shall allow both long range (up to 5 km) and short range operations, and that the modifications to the GEO satellite shall be minimized, the proposed solution is a set of three reflectors foils (50×30 mm) separated a distance of 200 mm and placed close to the ASSIST berthing fixture (see Fig. 8).

Regarding the berthing phase, a vision camera with at least 60° of vertical field-of-view and resolution of 1024×1024 pixels is envisaged. Within the approach frustum (1.25–0.5 m) the robotic arm will perform a visual servoing manoeuvre of the end-effector with the aid of the camera mounted on the fluidic plane. Several 2D markers will be placed over the berthing fixture (9 square markers of 2×2 cm and 2 square markers of 1×1 cm) to assist the referred visual servoing process.

11. Kinematic and dynamic simulator

The K&D simulator for the ASSIST project has been developed using the GNCDE (Guidance Navigation and Control Development Environment) simulator [22], a software providing a set of useful tools for a complete analysis and development of a GNC system but can be also used to handle the initial phases of the development of a simulator. A first architecture of the simulator can be found in Fig. 9. The simulator can be decomposed at high-level into the following groups:

1. Disturbances: the forces and torques perturbing the motion of the S/C will be taken into account in this block (fuel sloshing and arm flexibility). Other sources of real orbital/orientation perturbations (Solar Radiation Pressure, Luni/Solar acceleration, oblateness of the Earth) have been intentionally disabled to align the outputs from the simulation with the expected results from the air-bearing table setup under development at the NTUA facility, where these disturbances cannot be reproduced by the robotic models, and during proximity

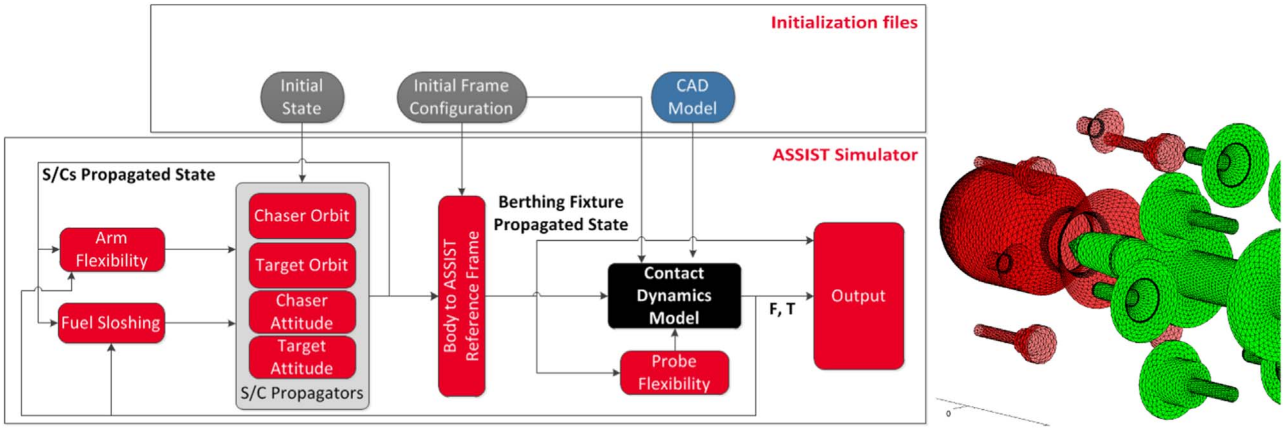

Fig. 9. ASSIST Simulator Architecture (left) and simulation of the docking (right).

OOS operations they do not play important role.
2. S/C propagators: orbit and attitude of the involved satellites. The output of these blocks should be in body reference frame.
3. Transformation of reference frames.
4. Contact Dynamics Model in charge of computing the Forces/Torques involved during the connection.
5. Shock attenuator to avoid unwished rebound phenomena at the moment of the first contact between the tip of the probe and a surface of the berthing fixture.

The contact dynamics model (including the modelling of a linear and angular spring-damper mechanism) extends the overall system simulator performance by the ability to consider forces and torques caused by physical contact of chaser and target satellite component surfaces. The computed contact forces and torques are fed back into the satellite systems' equations of motion in order to enhance the fidelity of motion prediction and system verification capabilities.

12. Air-bearing test set-up

At the NTUA Control Systems Laboratory (CSL), an air-bearing facility [17,18], has been developed for the purposes of the lab's academic research as well as for use in applied research projects [19,20,21]. Its default setup consists of a granite table, two floating robots, workstations and other peripheral devices required for the operation.

The emulator is located at the basement lab of the CSL in order to minimize residual vibrations from the environment. The larger part of the emulator is a granite table of extremely low flatness (maximum error is about 5 μm) with side dimensions of 2.2 m × 1.8 m (about 4 m^2 of surface in total). Robots with CO2 tanks can float on the table using air bearings that lift the robots to about 8–10 μm, i.e. higher than any table peak. Therefore, the robots moves with practically zero friction. In addition, since they are fully autonomous, no external forces except for the robots' weight are applied, and the robots move on the table as if they were in a zero-gravity environment.

The default setup of the CSL Space Emulator is comprised of two robots, the Cepheus (chaser) and the Cassiopeia (target). Both translate using 3 or 4 pairs of thrusters and rotate using either the thrusters or their reaction wheel or both. Cepheus robot has a diameter of 0.5 m and weight adjustable between 18 and 24 kg. Cassiopeia has adjustable side length (0.45 m, 0.6 m and 0.7 m) and adjustable weight between 11 and 24 kg.

For the localization of the robots on the granite table three different systems are used. Each robot is equipped with 2 or 3 base-installed optical sensors, operating as those in optical computer mice, and providing relative base displacements. Although these sensors provide feedback at high frequency, they accumulate error due to occasional drift. For this reason, an overhead camera located above the centre point of the granite table, detects LEDs on top of each robot. An external computer calculates the absolute position and orientation of each robot, but at a lower frequency compared to the optical sensors. By fusing the feedback from both the optical sensors and the camera, the position and orientation of the robots are determined and can be compared (during calibration) with an commercial Phasespace MoCap system. A Fastec HiSpec low light high-speed camera can be used to capture the moment of impact for off-line analysis.

13. Dynamic testing cases and validation results

The CSL Space Emulator has been used to perform a set of test cases aiming to validate the ASSIST K & D simulator, see Fig. 10. During those tests the berthing probe-drogue mechanism was tested in terms of contact forces, proper insertion of the probe in the drogue inner cavity, and time in which the probe tip and the pantograph remain inside the cavity, before they (if they ever) bounce off the cavity.

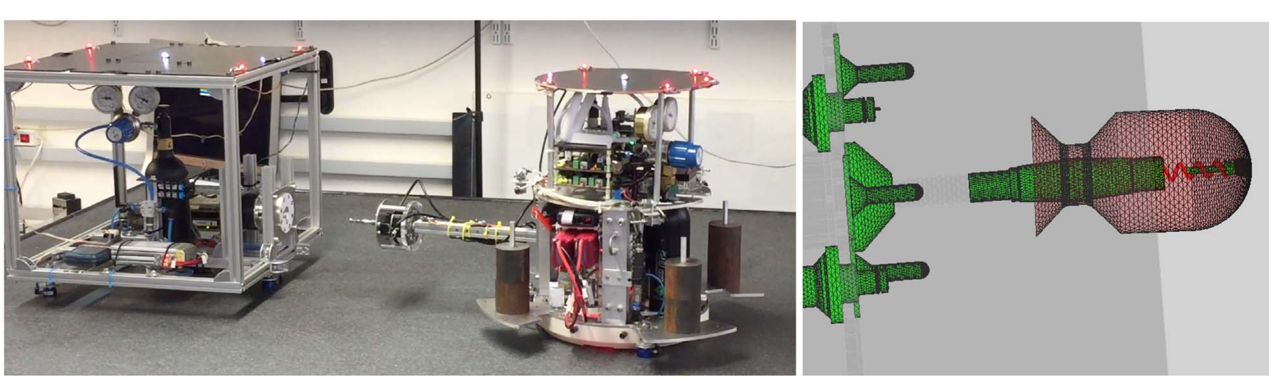

Fig. 10. NTUA CSL Target and Chaser robots (left) and corresponding K & D simulation (right).

A total of 50 test cases (5 scenarios × 10 impact conditions) were selected. The five proposed scenarios were determined taking into account different combinations of low and high mass for the chaser and target robots (low/low, low/medium, high/low, high/medium and high/high masses for both robots). The impact conditions were a combination of different angular misalignments (aligned axis and ± 11.3° tilted angles), lateral displacements (centred vs. 2 cm off-centred trajectories) and initial velocities (5 and 10 mm/s).

The ASSIST simulator has been able to reproduce the dynamic testing results; from this cross-validation we are deriving the following conclusions:

1. The chaser/target position and velocity are very accurate (error in position of 1 cm and in velocity of 0.5 mm/s) within the simulator up to around the 37% of the total simulated time of 23 s (meaning the first 8.5 s). In all cases within such representative part of the simulation the end-effector was able to enter within the drogue cavity. Doubling such evaluation criteria (position/velocity errors of 2 cm and 1 mm/s) it has been shown that the simulator is able to cover up to the 60% of the duration of the simulated time.
2. The chaser/target attitude is highly accurate (error in attitude of 1 deg) within the simulator up to around the 34/45% of the total simulated time. If we increase the maximum attitude error up to 2 deg the simulator is able to cover the 62% of the total simulated time (the 1-sigma deviation standard allows to cover up to the 100% of the total simulated time).
3. The pantograph stays within the drogue cavity an average of 1.7 s (between a minimum of 0.3 s and a maximum of 4.7 s and with a standard deviation of 0.8 s). This average of 1.7 s is a very reasonable time duration for the deployment of the pantograph mechanism. This pantograph deployment phase happens within the mentioned first accurate phase of 8.5 s
4. A small percentage (15%) of the performed tests cases were showing that the probe tip was not able to enter into the drogue cavity. Our explanation is that such test cases were executed within the air-bearing table with initial conditions not compliant with the foreseen scenario (e.g. trajectories slightly overcoming maximum inclination; impact speed above the maximum allowed relative velocity).

   Following the validation of the K & D Simulator, an exercise was performed of using the simulator according to the GEO scenario conditions, allowing demonstration of the validity of the ASSIST concept. In this direction we have performed a Monte Carlo campaign corresponding to the proposed GEO scenario: ± 5 deg. of maximum initial angular displacement, 2 cm of maximum initial linear displacement and 0.018 m/s (0.01 m/s lateral and 0.015 m/s axial) of maximum initial approach velocity. Two other restrictions were derived from the manufacturing process (maximum torque on the pantograph of 3.56 Nm and maximum axial load of 900 N).

   From the results of the Monte Carlo campaign we have identified the following performances:
5. The maximum angular deflection of the pantograph due to the lateral/angular flexibility is 9.55 [deg].
6. The maximum torque over the pantograph is about 1.93 [Nm] (below maximum admissible torque of 3.56 Nm).
7. The maximum linear compression of the probe tip due to the axial spring is 0.014 [m].
8. The maximum axial force supported by the pantograph is 131 [N] (below maximum admissible load of 900 N).
9. The minimum computed time for the pantograph deployment is 2 [s]. This duration is considered enough to allow the mechanical actuation of the pantograph mechanism.

14. Conclusions

This paper has presented the ASSIST system composed by the internal and external provision of a servicing/refuelling system for GEO satellites. The design of the internal provision has been performed taken into account the characteristics of current and foreseeable GEO telecommunication satellites. These internal provisions are intending to impose the minimum possible impact on the current architecture of GEO satellite and minimum additional risks in its commissioning. The same applies to the external provision (berthing fixture) of the client GEO satellite, which will have to be designed seeking a minimum impact (in terms of mass, volume and complexity) in order to have a chance to be adopted by the industry, while also being able to provide flexibility in terms of the type of servicing they will enable.

The ASSIST system also includes the servicer side of the external provision (*end*-effector). This end-effector is supposed to be mounted on the tip of a robotic arm. A camera system is envisaged to support the final berthing phase while a LIDAR sensor is assumed to be used during the previous rendezvous phase.

To reproduce the scenario where the ASSIST system is supposed to operate and simulate the terminal phases of the analysed berthing/docking mission, the GNCDE Tool [22] has been used to generate a cooperative Kinematic and Dynamic simulator. Within this activity, a breadboard of the end-effector and berthing fixture has been tested (dynamic tests on an air-bearing table) in order to validate the design of the berthing mechanism. We can assess that the ASSIST design behaves properly under the defined GEO scenario conditions: the probe tip is flexible enough to be linearly and laterally deflected; such lateral flexibility allows to enter the probe tip within the drogue mechanism a certain amount of time enough to deploy the pantograph mechanism and finalize successfully the soft-docking phase. The maximum axial loads and torques afforded by the probe tip (as the weakest part of the design) are below the maximum values determined from the ASSIST design.

Finally, the activity aims at proposing a refuelling European standard (similar to the International Docking Standard [23]), based on the results of this project, to be agreed with all relevant European actors. Major European large system integrators (LSI's) are already following this activity, providing his feedback and encouraging its definition.

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