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# TOWARDS A STANDARDIZED GRASPING AND REFUELLING ON-ORBIT SERVICING FOR GEO SPACECRAFT

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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. Endeffector and berthing fixtures are being designed in the range of few kilos and linear dimensions around 15cm. 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.

## I. 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.

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 and 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.

Note that OOS operations are not restricted to mechanical assistance (robotic or not) of a satellite in need, but include generally value-added tasks on orbit spacecraft, such as life extension or visual inspection tasks.

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

This paper is organized as follows: section I provides an introduction, section II introduces the ASSIST concept, section III provides a review on servicing/refuelling systems, section IV describes the foreseen scenarios, phases and operational modes, section V presents the ASSIST design while section VI describes the step-by-step refuelling operations, sections VII and VIII present the internal and external provisions respectively, section IX introduces the Kinematic and Dynamic simulator, section X shows the dynamic test set-up at NTUA air-bearing table facilities, section XI introduces the environmental test-setup at MOOG facilities and finally sections XII present the conclusions.

## II. 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 (as shown by next Fig. 1):

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



Fig. 1: ASSIST system (elements to be developed within this activity are in red). Source: ESA.

# III. <u>REVIEW OF SERVICING/REFUELLING</u> <u>SYSTEMS</u>

Since the beginning of the efforts for Satellite Servicing, it was apparent that OOS has the potentials not only to fix damaged systems, but to add value to existing satellites with tasks like satellite refuelling. However, although there were several plans during the last three decades, most of the planned autonomous

systems did not fly; indeed on the early years, and up until now, all OOS tasks took place either with combining EVAs with telemanipulated robots, or by using only telemanipulated robots, while fully autonomous efforts were strictly experimental. This seems natural as the design of reliable autonomous robotics systems achieved a high level of maturity especially the last decade. Nevertheless there is a strong trend between the major space agencies to achieve a considerable maturity on autonomous (or at least semiautonomous systems) in order to incorporate the use of robotic OOS in current technology roadmaps and future space missions.

Up until now the main application area for OOS was LEO. Indeed LEO offers some interesting types of satellites which require maintenance; however as a large number of significant satellite types such as telecommunication and meteorology ones are in GEO the interest on GEO servicing becomes larger.

Table 1 provides a comparison of some important OOS systems in LEO, the docking mode, type of end-effector and OOS task.

Mission	Docking Mode	End-effector
Canad- arm2	Specialized snare mechanism (Latching End-effector), also providing power/data signal transfer at both arm ends.	Latching End-effector or Dextre, docked on the free end of the manipulator.
Dextre	Specialized snare mechanism (Latching End-effector), also providing power/data signal transfer at both arm ends.	Two arms with ORU/Tool Changeout Mechanisms (socket wrench to torque bolts, retractable connector for power/signal connections), grippers, cameras and force/torque sensors.
JEMRMS	N/A	Small Fine Arm, for small item (e.g. ORU) handling.
ETS- VII	Handling tool with two large fingers, to grasp target appendages.	Gripper for medium size/weight equipment. Handling tool with two fingers and a fixed peg to handle small equipment and for peg- in-hole tasks.
Orbital Express (LEO	Three fingers that lock on an appropriately designed appendage on the target, after the manipulator has	Over-centre mechanism (Mousetrap) for target spacecraft probe capture and ORU replacement.

	grasped the target probe and aligned the two crafts.		
RRM	N/A	Wire Cutter Tool, Multifunction Tool (four capture/remove adapters for three distinct caps and one gas "plug"), Safety Cap Tool, Nozzle Tool (connects and opens/closes a satellite fuel valve).	
Table 1: OOS systems (LEO orbit).			

III.I Review of docking mechanisms similar to ASSIST

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 convenient 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 has the following phases during the docking procedure:

- A) 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.
- B) The probe enters the drogue, while on the same time a number of guiding pins (or similar mechanisms) allow the correction of small misalignments.
- C) 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).
- D) 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).
- E) Retraction of the probe to secure the "Soft-Docking" takes place and on the same time to bring the mating halves closer.

- F) "Hard-Dock" mechanisms start to operate now (again there can be active or passive mechanisms) such as latches or screws.
- G) Mating of data, fuel, gas etc. connections take place (almost at the same time with the Hard Docking).

## III.II Review of non-space refuelling systems

Although the most interesting systems from where to get inspiration are used or designed to work in orbit, some useful idea for the ASSIST system can also be derived from non-spatial refuelling applications. These have been developed for a number of different domains. Next Table 2 provides a comparison among the refuelling systems analysed. When values are not directly available they are estimated by extraction from similar systems.

System	Vehicle	Max Fuel Rate GPM*	Complexity
Hose and probe	Manned ships	2200	Low
Probe and drogue	Unmanned ships	60	Medium
Nozzle and tank receiver	Cars	20	Low
Sealed nozzle and tank receiver	Trucks	300	Medium
Nozzle and tank receiver	Cars	N/A	Low
Flying boom	Aircrafts	1200	High
Drogue and probe	Aircrafts	N/A	High

Table 2: Refuelling system comparison of non-space applications. \* GPM = [gallons /min].

# III.III Validation of space refuelling systems

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 zerog environment accurately. For a robotic system to get tested however it is necessary to have enough experimental time with the lowest possible cost. Methods like parabolic flights and drop towers have limited time. Neutral buoyancy facilities like the one used for the Ranger Neutral Buoyancy Vehicle are highcost facilities, even though they allow a threedimensional representation of the systems [1]; however the inertia of the water is not compensated and the robotic systems must be water-proofed. HIL systems, like DLR's EPOS and GMV's Platform, allow threedimensional experimentation [2][3] 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 dynamic performance on tasks such as impacts, is questionable.

The air-bearing facilities give a good compromise: even though it is not possible to emulate the threedimensional motion, they can represent accurately a planar zero-g environment for significant durations [4].

The characteristics of an air-bearing facility are largely affected by the kind of tasks to be emulated. However the larger number of the existing facilities are 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 tip-over avoidance, control, etc.

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.

## IV. ASSIST SCENARIOS, PHASES AND OPERATIONAL MODES

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 manufacturers (see Table 3) has allowed highlighting more specific profiles for the required fuel categories and quantities.

Spacebus/Spacebus Neo (TAS)				
1000 kg MON/MMH	Combined mixture with averaged density of 1159 Kg/m3 implying 862L of liquids			
300 kg of Xenon				
Small GEO satellites (OHB)				
~500 kg of MON/MMH	Combined mixture for full chemical propulsion			
100 kg of MON/MMH	Combined plus 150 kg Xenon for hybrid			
200 Kg (typically Xenon)	For full-electric propulsion			
Space Tug missions (Airbus DS)				
200 Kg liquids	Chemical propulsion			
3000 Kg (typically Xenon)	Electrical propulsion			

Table 3: European Spacecraft Manufacturer fuel requirements on several platforms.

## IV.I Refuelling Phases

The proposed on-orbit servicing mission includes the following assumptions (see Fig. 2). The modes involved within the following phases are defined in the next paragraph:

• 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 10km) and a meter range (e.g 1.25m) (compatible within the maximum reach of the robotic arm mounted on the servicing S/C).

In this phase, the robotic arm is not used and the approach is entirely done by the servicing spacecraft bus by means of a suitable rendezvous sensor suite (with the aid of optical/radio markers on the serviced S/C).

At the end of this phase the following constraints must be met:

- the servicing S/C has adapted its movement performing a null relative movement with respect to the serviced S/C and
- the serviced S/C must be in a 3-axis stabilized configuration.
- 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. This phase shall start with nominally zero relative velocity between the servicing and the serviced target.

When the berthing phase is activated the serviced S/C must disable its actuators (to avoid unexpected relative movements bringing to collision with the servicing S/C) and the servicing S/C will be under

station keeping stationary conditions with respect to the serviced S/C. A 6-DOF robotic arm with a camera mounted on top of the arm tip (even within the end-effector fluid coupling plane) is assumed to be available, with an illumination source that provides 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.

- 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.
- The de-mating phase: the servicing operations have been concluded and the berthing mechanism unlocks the two spacecraft (passing through Harddock and Soft-dock Modes). The robotic arm safely retracts the end-effector within the approach frustum.

The system shall be designed so that all these operation 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.

# IV.I Refuelling Spacecraft Modes

The main modes that have been identified and their connections are shown in Fig. 2.



Fig. 2: Refuelling Modes High-level architecture for Serviced S/C (left) and Servicing S/C (right).

For the Servicing S/C:

- Rendezvous Mode (RVM-C): the approach of the servicing satellite is achieved thanks to the set of sensors and the actuators that allow the GNC subsystem to perform the rendezvous to the serviced S/C. When the distance reached by the servicing S/C is compatible with the berthing mode and the relative pose is stable (within some boundaries established in the performance requirements) the mode is switched to the BM-C mode. In case of fault events or by ground segment command the control can be passed to the Escape Mode (EM-C).
- Berthing Mode (BM-C): from the end of the Rendezvous Mode until the contact between the two ASSIST system halves (Soft-dock Mode) this mode brings the servicing S/C end-effector closer to the berthing fixture on the serviced S/C maintaining the relative position/velocity/attitude within values defined by the performance requirements. It ends when the probe on the tip of the end-effector enters the cavity drogue inside the serviced S/C. At this stage an unexpected event or a command from the ground segment can trigger to the Escape Mode.
- Escape Mode (EM-C): in case of contingency during the phases in which the involved spacecraft are not physically connected (RVM-C, BM-C) or after a fault in SDM-C (after the soft-dock mechanism has been confirmed to be released), this mode shall allow escaping from serviced S/C vicinities and reach a free drift and safe periodic closed trajectory.

- Soft-dock Mode (SDM-C): this is a transition mode between the phases in which the spacecraft are still detached and the moment of the first contact between them occurs. The mechanism to establish the soft connection is enabled to ensure the spacecraft do not drift away from each other. The servicing S/C will continue to maintain the relative conditions with respect to the serviced S/C and the relative movement will be performed exclusively by the robotic arm.
- Hard-dock Mode (HDM-C): once the soft contact has been confirmed a more stable connection is required and the Hard-dock Mode is commanded. During this mode all the servicing connections (mechanical, electrical) shall be engaged before the refuelling operations can start.
- Refuelling Mode (REM-C): the servicing operations like the passage of fuel/gas are performed. Both S/C operations concerning the attitude and orbital dynamics are controlled by the servicing S/C. In case of a problem a quick separation with the serviced S/C or a transfer to the Safe Mode is foreseen. In case a partial functionality of the robotic arm is maintained, a reversed process could bring the servicing S/C to gently disconnect to the serviced S/C through the HDM, SDM and EM modes. On the other hand if a major issue should disable some arm capability a direct switch to the Safe Mode could be preferred.
- Safe Mode (SM-C): in case of major issues during . the coupled phase a safe mode able to bring the servicing S/C in a safe configuration shall be considered. If possible a process of controlled disconnection of the involved spacecraft should be preferred and then a safe configuration could be selected. In case this monitored path is not possible the connection with the serviced S/C clearly does not allow an immediate steering of the chaser to reach the best possible Sun illumination (which is the usual process for contingency). In this latter case it should be decided whether it is possible to change the attitude of the jointed system (by means of the actuators of the servicing S/C) taking care of avoiding overload of the ASSIST system.

For the Serviced S/C:

- Nominal Mode (NM-T): the S/C is during its active life and it is perfectly controllable (apart from the possible degradation due to the age) and all its subsystems are fully operative. This is the starting point before switching to the Refuelling Mode.
- Refuelling Mode (REM-T): it can be considered as a sub-mode of the Nominal Mode with the active actuators disabled; the use of thrusters will be denied and the wheels will work at constant speed to avoid rude manoeuvres and uncontrolled

movement. In normal conditions the berthing, docking and refuelling operations by the servicing S/C will be performed while the servicing S/C is in this mode. In case some problem should arise during this phase the satellite should remain in this mode until the separation with the servicing S/C is confirmed and then the control should pass back to the Nominal Mode. The switch from this mode to the Safe Mode (SM-T) shall not be permitted in order to avoid dangerous conflicting commands of the two spacecrafts involved.

• Safe Mode (SM-T): this mode is usually dedicated to provide safe Sun orientation to survive to serious failure events while either the on-board system or the Ground Control Centre try the recovery of the mission. If the fault is recovered the control can switch again to the NM-T mode. The phase of approach or berthing of the servicing S/C shall be not permitted to avoid the obstruction of possible Sun sensors installed in the line of the approach.

In Fig. 2 the paths from the initial condition (RVM-C for the servicing S/C and NM-T for the serviced S/C) to the refuelling in nominal circumstances are shown as green arrows while the controlled escape steps from the coupled phase (REM-T/REM-C) to the safe configuration (SM-T and EM-C) are shown as blue arrows.

## V. 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 constrains the alignment problem to a single rotational axis which can be corrected for and, which is within the capabilities of 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 endeffector alignment pins to engage and centralise the whole system. The alignment pins have been arranged asymmetrically on the fluid plane so that the endeffector cannot be docked incorrectly.

Following subsections provide a detailed overview of the end-effector, berthing fixture and fluid couplings.

# V.I End-Effector

The end-effector is 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 preliminary design of the end-effector is shown in Fig. 3. 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 (serviced S/C). Included on the end-effector there are three couplings which connect to the berthing fixture half and seal with elastomeric O-rings.

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



Fig. 3: End-effector.

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. A keyed coupling between the stepper motor shaft and actuation shaft allows the actuation shaft to move towards the stepper motor as the pantograph expands and away from the motor as the pantograph contracts.

Both the collar and fluid plane mechanisms use a common lead screw which has a <sup>1</sup>/<sub>2</sub>" Trapezoidal 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, planetary gear box, two spur gears and a spline. The 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 (client spacecraft). The collar stepper motor to lead nut gear ratio is 42:1 which allows the application of high torque 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 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 2x guide pins attached to the shaft at a radial distance of 37mm 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 stepper motor to lead nut gear ratio is 166:1 and therefore a high torque can be applied to the nut, more than 5.1 Nm.

During the berthing procedure it is necessary to detect the axial force that is applied to the probe tip when it touches the drogue cavity. Locating a force sensor in the probe tip was explored but the small size of the probe tip and the difficultly associated with routing a wire made this impractical. Instead, a force sensor has been located at the base of the main shaft behind the lead nut radial bearing. This will detect the axial force applied to the tip.

Rotational positional encoders (optical) are installed on all stepper actuators so that the position during operations is known. In order to apply a torque to the lead nut at the end of the travel, missed steps will be detected and counted by the controller and based on the motor holding torque and gear ratio, the applied force can be controlled.

The selected material for the housings is Aluminium alloy. The selected material for all shafts, lead screws, gears and bearings is stainless steel. The pantograph actuation shaft carries high axial loads and it is desirable for this component to be flexible so that the probe tip moves axially under load. Titanium alloy is well suited for this component since it has a high yield stress but low young's modulus.

#### V.II Berthing Fixture

The berthing fixture provides the serviced S/C with one half of the grasping mechanism, which the servicer robotic arm end-effector docks with. This consists of a 'drogue' type arrangement which includes a central cavity into which the capture probe is inserted. 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 in the preliminary design. This allows a hybrid GEO platform (MMH, MON and Xenon) to be refuelled. The preliminary design of the berthing fixture is shown in Fig. 4.



Fig. 4: Berthing Fixture.

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 will be replaced with a blanking plate for chemical propulsion platforms without electric prolusion.

# V.III. Fluid Coupling

A sketch of the breadboard fluid coupling is shown in Fig. 5. The berthing fixture coupling half includes a valve which isolates the line and allows the end-effector coupling to be purged back to a catch tank on the servicer S/C. The valve is operated by a linear stepper actuator [1] which drives the valve actuation shaft [2], lifting the poppet [3] to open the valve.



Fig. 5: Mated Fluid Coupling with Valve Open.

The valve spring creates a preload on the seal which maintains a seal when a pressure differential of up to 2bar is applied. This allows the coupling to be pressurised prior to opening the valve so that a pressure

decay leak test can be carried out to ensure that the external leakage is within specification. The actuation shaft is keyed to the valve body so that when the actuator nut turns the shaft moves only axially and does not rotate.

There are two fluidic connections on the end-effector coupling as shown in Fig. 6. The first one is for the refuelling supply and the second is for purging and evacuation operations. The purge / evacuation tube fluid path passes through a side port and into the centre of the shaft [4]. The shaft is sealed to the valve body either side of the port using energised seals [5]. The refuelling supply pipe is connected nearer the outlet end of the coupling and the fluid flows to the client over the outside of the actuation shaft.



Fig. 6: End-effector Fluid Coupling Half.

For high pressure applications (greater than 24bar MEOP) the valve actuator on the servicer side is not required, the valve is designed to open under the pressure load. This increases the valve pressure drop but the increase in overall system pressure drop does not have a significant influence on the refuelling time.

The operating fluids will determine the fluid coupling materials. For the oxidiser coupling Kalrez 1045 is the heritage material which is used whereas for MMH, EPDM is used. For Xenon applications moog have qualified silicon which included long term swelling effects under pressure and also compression set and creep testing. The energised seals used on the actuation shaft will be PTFE which is compatible with oxidisers and fuels.

# VI. 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.

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 next Fig. 7.).



Fig. 7: Pantograph entering into the drogue cavity.

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. 8). The two spacecraft are now restrained in a 'soft' dock configuration.



Fig. 8: Pantograph deployed within the drogue.

6) Once the probe is expanded, the clamping collar is translated along the cylindrical section of the probe towards the drogue, 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.



Fig. 9: Pantograph deployed within the drogue.

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 for. 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 any minor misalignment is taken out by the guides. 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. 10) the servicing S/C can proceed with the process of re-fuelling the serviced S/C.



Fig. 10: Pantograph deployed within the drogue.

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. 11).



Fig. 11: Actuation valve moving the poppet.

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.

# VII. 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.

The standard chemical propulsion block diagram as depicted below 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.



Fig. 12: Generic Bi-Propellant Propulsion System.



Fig. 13: Refuelling Branch (MON side).

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.

The client spacecraft will require an additional refuelling mode. This mode can be considered as a submode of the Nominal Mode with the thrusters disabled and the wheels working at constant speed to avoid rude manoeuvres and uncontrolled movement. In the refuelling phase it is expected that the telecom payload will be off excepted TM/TC channels associated to omni-antennae. Therefore there is no need to keep an earth pointing at 0.1° and small rotation rates during refilling will be acceptable. In case some problem should arise during this phase the satellite will remain in this mode until the separation with the servicing spacecraft is confirmed.

Coordination of activities between the servicer and the satellite operator at the ground network is required in general during the refuelling procedure as both satellites have to be individually controlled (satellite mode change) and monitored. Thus, there will be no direct coupling between the servicing spacecraft and the client OBDH unit, to avoid any failure propagation. As an option a CAN bus will be included which has been selected as satellite bus for upcoming telecom platforms.

Filling the Xenon tanks in orbit is still considered a major task to solve. During filling the tanks usually heat up due to the Joule-Thompson-Effect. This heating can be easily compensated on ground by fans. In space the tanks are perfectly isolated by MLI against the environment and cooling would require a complex heat pipe system. Instead currently a liquid Xenon fuelling process is considered to keep temperatures in the client tank in the qualified range.

#### VIII. RENDEZ VOUS 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). In order to design them the rendezvous strategy has been studied and a trade-off has been performed for choosing the most appropriate sensor suite and the required targets.

The rendezvous in space can be categorized by the help/assist provided by the serviced S/C (target) to the approaching servicing S/C (chaser). From the lowest to the highest impact on the target S/C, we have:

- Non-cooperative rendezvous at all levels.
- Non-cooperative rendezvous at navigation level.
- Cooperative rendezvous at navigation level and at attitude control level.

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, so the simpler the navigation aids to be considered, the better.

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:

- A radio frequency (GNSS-like) sensor with radio emitter/repeater beacon mounted on the client S/C.
- 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.
- A vision camera on the servicing S/C, with or without aids mounted on the serviced S/C.

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 (50x30mm) separated a distance of 200mm and placed close to the ASSIST berthing fixture (see Fig. 14).



Fig. 14: Example of retro reflectors positioning on the large GEO docking face.

Regarding the berthing phase, a vision camera with at least 60° of vertical field-of-view and resolution of 1024x1024 pixels is envisaged. Within the approach frustrum (1.25m to 0.5m) 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 2x2cm and 2 square markers of 1x1cm) to assist the referred visual servoing process.



Fig. 15: Berthing fixture with 2D makers (left) and worst-case view at 0.5m distance (right).

## IX. <u>KINEMATIC AND DYNAMIC</u> <u>SIMULATOR</u>

The K&D simulator for the ASSIST project has been developed as a cooperative work among GMV, NTUA and DLR. An important item is to guarantee a shared input/output scheme for the Simulink model and a joint way to initialize the blocks with the scenario parameters. The framework used for the development of the simulator is GNCDE (Guidance Navigation and Control Development Environment) [8], 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. 17. 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 airbearing table setup under development at the NTUA facility, where these disturbances cannot be reproduced by the robotic models, and during proximity 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 modelisation 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.

During approach and docking of chaser and target satellite (see Fig. 16) the component pairs listed in Table 4 have to be considered in the contact dynamics model. Some of the component pairs are unique, some of them appear multiple times in the respective assemblies of the external provisions.

Chaser	Target	#
Pantograph	Drogue Cavity	1
Clamping Collar	Drogue Cavity	1
Alignment Pin	Alignment Hole	3
Fluid Coupling	Fluid Coupling	2
(male)	(female)	3

Table 4: Satellite Component Pairs to be considered in Contact Dynamics Model.



Fig. 16: Berthing Fixture (red) and End-Effector (green) during the final approach.



Fig. 17: ASSIST Simulator Architecture.

#### X. DYNAMIC TEST SET-UP

At the NTUA Control Systems Laboratory (CSL) an air-bearing facility has been developed for the purposes of the lab's academic research as well as for use in applied research projects ([5], [6]). The goal of the emulator is to be used as a testbed for studying the dynamics and control of space robots with or without manipulators, while performing On-Orbit Servicing (OOS) tasks, such as docking, berthing, assembly, passive object handling, etc. on a plane, see Fig. 18.(a). 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 eliminate as much as possible any residual vibrations from the environment. The larger part of the emulator is a granite table of extremely low flatness (flatness' mean value is about 5 µm) with side dimensions of 2.2m x 1.8m (about 4m<sup>2</sup> of surface in total). Robots with CO<sub>2</sub> tanks can float on the table using air bearings. More specifically installed air bearings lift the robots about 8-10µm – since the robots are fully autonomous, there are no external forces besides the robots' weight. The pressure from the CO<sub>2</sub> which flows from the air bearings cancel the effect of the weight thus providing essentially frictionless planar motion. Around the granite table a number of workstations are dedicated for telemetry and control of the floating robotic systems (see Fig. 18.(b)). These include a computer dedicated to the localization of the robots using an overhead industrial camera, computers for programming and control via Linux/ROS and/or Simulink Real Time and a computer necessary for the PhaseSpace MoCap system. In a separate room, a large CO<sub>2</sub> tank is installed which is used for replenishing the small CO<sub>2</sub> tanks which are installed in the robots.

The default setup of the CSL Space Emulator is comprised of two robots – one with the initial design (Cassiopeia) and one with a new design (Cepheus). Their dimensions and design allows the researchers to easily modify parts of the robots according to the required tasks. Both robots can translate using 3 or 4 pairs of thrusters and can rotate using either the thrusters or their reaction wheel. According to the required task, it is possible either to remove the current end-effector of the manipulator to install the appropriate tool or remove completely one or both manipulators, to directly install on the base any necessary equipment. Both robots are equipped with electronics, batteries, PC104 boards, servovalves, regulators, filters and motors.

For the purposes of the ASSIST project, Cepheus is being upgraded and a new robot is being designed. The design drivers for the required developments are a) the relative mass with respect to real systems scenarios b) the relative external dimensions with respect to real systems scenarios and c) the real-life refuelling scenarios to be emulated. In order for the robotic systems of the testbed to be dynamically equivalent to the real ones, a procedure to determine the scaling factors took place. This way it was concluded that Cepheus base will reach a diameter of 0.5m. The new robot for ASSIST which is under design will have rectangular shape with adjustable side length. Its top view will be square with sides of 0.45m, 0.5m, 0.6m and 0.7m depending on the scenario tested each time. Its height will be 0.43m (same as the other robots) and the system will be emulating a passive customer satellite which has depleted its fuel. To this end no servovalve or reaction wheel will be installed, but only the PC104 computer unit and electronics for the operation of the on-board sensors and the necessary CO<sub>2</sub> tank, filter and regulators for floating.





For the localization of the robots on the granite table three different systems are used. Each robot has a number of optical sensors installed (2 or 3 depending on experiments' requirements), which give the relative position of the corresponding robot base – they are installed on the bottom section of each robot and have similar operation principle as the computer mice. Although these sensors operate at high frequencies, they accumulate error due to drift. For this reason, LEDs on top of each robot are detected by an overhead camera, located above the centre point of the granite table. An external computer calculates the position and orientation of each robot with higher accuracy from the optical sensors, but with slower frequency. By fusing the data

of the information gathered 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 industrial Phasespace MoCap system. A Fastec HiSpec low light high speed camera can be used also to capture the moment of impact for off-line analysis.

For measuring the produced forces and torques during impacts, the CSL will mount on the robots the HPS In-house force sensors which are 6-axis force/torque sensors with integrated electronics (see Fig. 19). The sensors' precision is 1/1000 of full scale and resolution 1/4095 of full scale with current electronics. Its full scale of measurement is between 50N to several kN. One of the advantages of this sensor is that it allows, to a reasonable extend, to be modified easily in order to get integrated in the docking mechanism [7]. For their calibration industrial ATI Force/Torque sensors will be used.



Fig. 19: HPS In-house force sensors: (a) CAD Drawing (b) Prototype.

The CSL Space Emulator can use various OS (Windows, Linux, etc). However the advantages of Robotic Operating System (ROS) were acknowledged and currently all robotic systems as well as their communications with the workstations use ROS (see Fig. 20). The implementation of ROS modules is at the last phase of its development and currently the localization subsystems are already integrated using ROS technology.



Fig. 20: ROS implementation at the NTUA-CSL Space Emulator.

# XI. ENVIRONMENTAL TEST SET-UP

Environmental testing is aimed at demonstrating the docking procedure, fuel transfer and undocking in a representative thermal vacuum environment. Functional testing will also be performed to understand the performance at the extremes of temperature. A breadboard model shall be manufactured for the thermal vacuum testing.

The end-effector will be mounted on a linear slide assembly inside the vacuum chamber so that the robotic arm (or spacecraft translation) can be simulated. The first part of the docking process is the translation of the end-effector probe into the drogue throat using the linear slide. When the probe tip touches the back of the drogue, the signal from the force sensor exceeds a limit value set in the controller and the translation is halted (no further steps are sent to the actuator). The linear slide assembly is shown in Fig. 21.

The berthing fixture is rigidly mounted to the support structure but can be set at a rotational offset with respect to the end-effector axis of up to  $20^{\circ}$ . For the thermal testing, a rotational offset of  $20^{\circ}$  will be used to demonstrate the docking with a worst case misalignment.

The end-effector is located on a spring cage assembly which is sized to allow for lateral and axial displacements which compensates any miss alignment with respect to the berthing fixture. During the berthing procedure, when the fluid plane transfers to the berthing fixture, the linear slide is also driven such that the outer cage moves with the end-effector. In a flight system the spacecraft would be free to move during the fluid plane transfer.



Fig. 21: Environmental Test Setup for ASSIST validation.

The springs are sized so that a torque is applied to the end-effector when the angular misalignment  $(20^\circ)$  is corrected. The force is representative of a torque applied by the spacecraft AOCS.

A dedicated fluid rig will be used for the thermal vacuum testing which includes a thermal fluid loop to condition the hardware at the required temperature, between 5°C and 60°C. The rig also provides a high pressure liquid and gas pressurisation system for liquid transfer simulations and leakage testing.

# XII. 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, which are most likely the client candidates for a refuelling service. These internal provisions are intending to impose the minimum possible impact on the current architecture of GEO satellite and minimum additional risks in its comissioning.

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 endeffector 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 [8] has been used to generate a cooperative Kinematic and Dynamic simulator, obtained integrating the contributions of GMV/NTUA/DLR.

Within this activity, a breadboard of the end-effector and berthing fixture will be tested under environmental (vacuum chamber) and dynamic tests (air-bearing table) in order to validate the design of the berthing mechanism and the inter-spacecraft connections.

Finally, the activity aims at proposing a refuelling European standard, 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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