On-Orbit-Servicing by "HERMES On-Orbit-Servicing System", Policy Robust Planning

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Certain timely "in-situ" help for satellites (on-Orbit Servicing or OOS) is more than desirable when problems arise. HERMES OOS defines a new and patented architecture based on a symbiotic philosophy with the client base and has established a policy robust planning. It starts on ground with a minimalistic approach for enabling refueling services on-orbit, since refueling is seen as the most promising OOS service. The necessary hardware for enabling the service is now available. It consists of a specially designed quick disconnect (QD) accessory, the HERMES QD. This QD can be fixed on top of any fill & drain valve, rendering the carrying satellites repeatedly refuelable without the need for any other modification. Such application of the HERMES QD on satellites will open a host of new opportunities that in aggregate we call the "HERMES Fuel-Trading System" (HFTS). The small (20 gram) HERMES QD can effectively eliminate the need for a dedicated tanker spacecraft since any spacecraft carrying the HERMES QD can also perform the function of the tanker spacecraft. Given the high initial costs for developing the infrastructure needed for OOS such simplification is currently considered indispensable.

I. Introduction

ON-ORBIT SERVICING (OOS) has received the "go" / "no-go" many times due to historical changes in national priorities, programmatic failures, or overambitious planning, despite the widely accepted view that certain timely "in-situ" help would be more than desirable when problems arise. HERMES OOS defines a new and patented architecture based on a symbiotic philosophy with the client base and has established a policy robust planning for immediate deployment. It starts with a minimalistic approach for enabling refueling services, since refueling is seen as the most promising OOS service[1-17]. The necessary hardware for enabling the service is now available. It consists of a specially designed quick disconnect (QD) accessory, the HERMES QD, which can be fixed on top of any fill & drain valve, rendering most satellites (depending on tank type) repeatedly refuelable without the need for any other modification. Such application of the HERMES QD on satellites before launch will open a host of new opportunities that in aggregate we call the "HERMES Fuel Trading System (HFTS)". The servicing system in the beginning will consist only of a single fuel-trading vehicle highly symbiotic to the client vehicle and also to other damaged but fuel carrying satellites. Later on a family of spacecrafts consisting of 5 distinct vehicles with complementary functionality is envisaged for the full deployment. At full deployment the system will be able to offer additional services such as high definition close-up inspection, corrective maintenance, as well as On-Orbit assembly. Transportation service within GEO, including inclined orbits, will also be available.

Figure 1. A UA delivers a KINITRON® to a client satellite under supervision of an EA.

Catalytic to achieving immediate and fast deployment is the simplicity of the envisaged QD solution. The small (20 gram) HERMES QD can effectively eliminate the need for a dedicated tanker spacecraft. Provided that it will be mounted on a significant number of spacecrafts it will enable propellant extraction from failed or overfed satellites for the replenishment of other satellites that are fit but short of propellant reserves.

Given the high initial costs for developing the infrastructure needed for OOS such simplification is considered indispensable at

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the moment. Adoption of the HERMES QD by the satellite operators community can pave the way for the HFTS regardless the sponsoring or not of OOS by national space agencies.

KOSMAS GEORING services Greece is poised to deliver the QD coupling at zero price given certain conditions. Other satellites (already on orbit) that cannot ingest additional propellant reserves can be served by a Kinitron®, mounted externally, thus having their own controlled tug to receive impulses on demand. This paper provides an extension of the functionality already presented[18,19].

II. The HERMES OOS Architecture

A. The Symbiotic nature

The core characteristic of the HERMES-OOS system is the design of each of the 5 constituting spacecraft elements under the objective of maximizing the reuse of materials and/or functionality of the satellites at GEO. Therefore drastic reduction is achieved on the absolute minimum of the functionality needed by the servicing vehicle(s).

Given the abundance of bandwidth on a telecom satellite, virtual presence of many tele-operators is possible with the mere introduction of video-capture apparatus on the servicing vehicle. The latter in some cases needs nothing but a feeder connection out of the star-tracker-camera-read-out electronics of the UA.

The captured video stream is then transmitted at low power (1-3 Watt) to the client satellite in proximity, and then, after being amplified, is retransmitted to ground based operators. This mode is so catalytic to efficiency as to multiply the link budget available to the servicing-vehicles by thousands of times and reducing the payload-power requirements by hundreds of times. Given the virtually unlimited bandwidth of a telecom satellite, virtual-presence of operators will establish a new norm in designing service operations.

The servicing vehicle (see next subsection), which we call Utility Agent (UA), is designed with symbiotic philosophy wrt the client satellite. The video signal that is emanating from the UA for enabling teleoperation (at proximity operations) passes through the client spacecraft and gets amplified, so slashing the mass and power requirements of the telecommunication payload of the UA. The telecommand-telemetry stream of the client satellite can also convey CCSDS adhering commands to the UA at high power enabling further the miniaturization of the TT&C unit. Signals generated onboard the client satellite by solenoid valves and other components can be detected by appropriate sensors on the UA thus implementing a local interface of direct & fast communication between the client spacecraft and the UA. All these simplifications on the part of the UA allow the design of a small satellite with minimal power requirements. Solar cell panels consist of a skin only cover. No solar-array appendances are needed, therefore the UAs are safe against creating attitude control related challenges during maneuvers.

Another application of the symbiotic philosophy is the use of handicapped satellites on orbit for the extraction of fuel to feed fit but fuel-depleted satellites. Ideal donor satellites are new satellites (therefore full of propellants), which have encountered failure in a single processor or suffer severe power limitations due to battery or other power failures, rendering their commercial exploitation impractical.

Further application of the symbiotic principle is the potential use of satellites that are launched with direct-to-GEO injecting launchers. These satellites can be used as major carriers of propellants since their tanks have plenty of spare volume capacity with respect to their mission profile. We note for clarification that the satellites which are injected directly to GEO do not carry with them propellants for orbit raising maneuvers, which constitutes 80% of the volume of the propellant tanks.

B. The Elements

The elements of the complete HERMES OOS system at full deployment are five (Utility Base, Utility Agent, Escort Agent, Kinitron® and Orbit Raising Module). However, only a UA is necessary for starting up the operation. The remaining 4 elements enhance functionality and efficiency of operations. They are designed so that more difficult cases of servicing can be realized, such as serving satellites of current design that do not have the HERMES QD coupling, or future satellites that would be designed in a modular fashion consisting of an orbit raising module and the rest being a satellite with ion based station-keeping thrusters. A summary description of each of the elements follows. Further details for the Utility Agent follow in the section III ("The HERMES Fuel Trading System").

1. The Utility Agent

Is a small (150-200 kg) autonomous space vehicle equipped with a single robotic arm for connecting an "Agent-half coupling" to the F&D valves of propellant donating or receiving spacecraft, for further performing extraction or delivery of propellant. A version without the robotic arm would be capable to deliver Kinitrons® to client satellites. It will have capability to carry one or more Escort Agents when they will become available. Several versions are envisaged with variations in the carried accessories and propellant capacity.

2. The Utility Base

Is a large spacecraft designed for second-tier maintenance operations equipped with robotic manipulators. It is stationary at a convenient place at GEO and functions as a store place of resources and spares for UAs, EAs and Kinitrons® and as their parking place. Its exact configuration will be dictated by market forces.

3. The Escort Agent

Is a miniature (7-15 kg) highly compact free-floating inspector. It is usually carried by a UA for long trips and is deployed close to the inspection target. It can perform risk free close-up inspection and relays video feed with wireless technology to the UA. Its propulsion is based on heated-gas MEMS-technology based microthrusters.

4. The KINITRON®

Is a spacecraft having the role of a propulsion orbital replaceable unit (ORU) and can be carried by a UA for placement on a client satellite. Its function is to provide externally induced thrust. It is useful in cases where we cannot perform refueling. It comes in two versions as regards placement interfaces. One is designed for mounting on Apogee Engine nozzles and the other for mounting on a solar panel bracket. In both cases the composite thrust vector needs to be driven through the CoG of the client satellite. The Kinitron® is sized for performing station-keeping duties for about 8-10 Months and has 60-70 kg total mass.

5. The Orbit Raising module (ORM)

In the assumption that the future satellites will have two separate propulsion subsystems, one for Orbit Raising (chemical propellant based) and one for station keeping (ion engine based) there is high probability that future satellites will be constructed in a modular way. The ORMs will be specially designed to cater for docking of UAs and separation at GEO for further towing to a disposal place. This modular design and the availability of the towing service or ORM will result in timely elimination of the nonfunctional mass of a satellite (30%) when on orbit, without the risk of creation of debris.

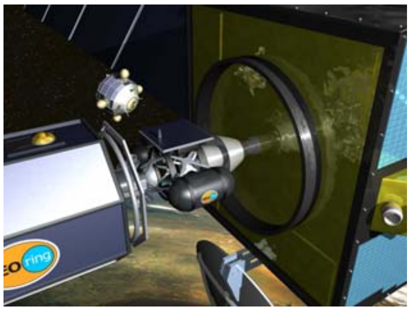

Figure 2. An Escort Agent inspects a delivery operation of a KINITRON® to a client satellite.

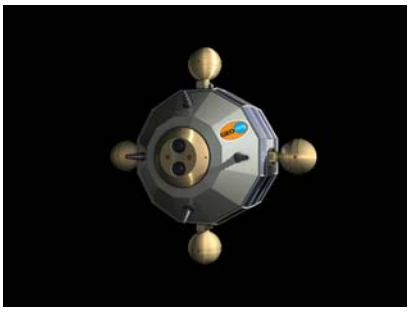

Figure 3. An Escort Agent.

C. The Patents

The enabling technologies of the above architecture are innovative and have been patented by a series of patents[20-21] and further pending patent applications. The concepts that have been patented include: the use of the client satellite to relay signals, use of client satellite to relay telecommands through the telemetry, use of the client satellite to relay telecommands through manifestation of execution of standard commands, a modular GEO spacecraft comprising an orbit raising module and an actuator arm for use on a spacecraft.

The breadth of the patented concepts covers the entire mission life of satellites. Some concepts are directly applicable to existing satellites requiring no modification, while others are applicable only to future satellites and they require radical redesign. However, one needs to retain that HERMES offers solutions both for the current satellites and to the future ones.

III. The HERMES Fuel Trading System

A. The requirements and the assumptions

The overall system requirements define a spartan system for performing fuel transfer between spacecrafts in Geosynchronous orbit through a single servicing vehicle, based on the use of the HERMES QD coupling and a policy robust plan of deployment. It is assumed that within 3-5 years from adoption of the coupling the penetration will reach 50 % and further that 4 satellites currying it would become candidate fuel donors after a failure on one of their non vital subsystems.

B. The Utility Agent

The service vehicle that we have coined “Utility Agent” has the designed capability of extracting propellants from propellant supplying spacecrafts (either failed satellites or new overfed satellites) and delivering them to satellites that are fit but depleted of propellants. It can also offer tug functionality but this is considered inefficient and of higher risk than fuel delivery. The control of multi-body dynamics, especially of satellites with deployed solar panels is deemed too challenging to start with and such transport mode has the disadvantage that it necessitates the use of the tug over prolonged durations plus the need for a return trip consuming further propellants and additional useful flight time.

The basic service will therefore be fuel transfer. However, limited inspection will also be available as a complementary service (albeit constrained by collision risk considerations, non specialized cameras and fuel penalties during maneuverings around the observation target). An Escort Agent shall be used for inspections at later stages of system deployment.

The mission profile of the UA includes the critical phase of rendezvous & docking which is facilitated by the use of the bandwidth of the client satellite for enabling the teleoperation. The UA needs to employ a robotic arm that will operate the "Agent-half coupling" for fixing it on the "Client-half coupling" of the client satellite.

C. The coupling

The need for a special coupling stems from the fact that each connection-disconnection cycle, as currently being performed on ground with the current type of available valves, entails a minimal but important leakage of propellant that is isolated in the closure between the recipient valve and the delivery hose valve. This leakage is in the range of 2cm^2 and necessitates the purge & decontamination-passivation process that is performed with the help of the apparatus of the filling-cart. However, in space such filling-cart would be impractical and any purging operation would be impossible if one considers the lack of separation walls and lack of decontamination-passivation equipment. Consequently any leaking during the disconnection process would constitute a highly harmful event dangerous both to the client satellite and to the servicing vehicle, given the need for presence of optics on UA (deposition contamination sensitive) and presence of gears (corrosion sensitive) for the mechanisms of the robotic arm and of the "Agent-half coupling" manipulator.

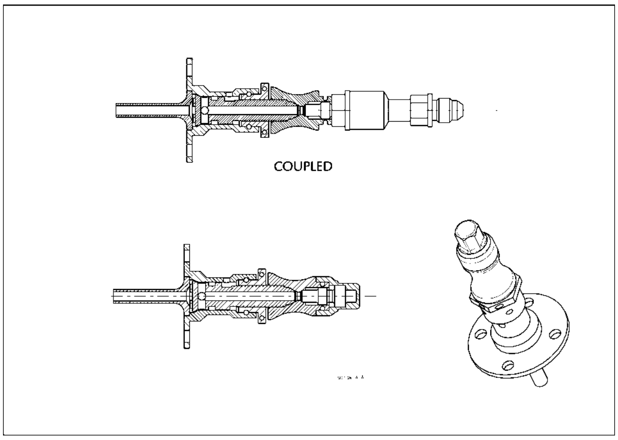

Figure 4. Coupling pair mounted on the F&D valve

The coupling consists of two halves, the "Client-half coupling" that is mounted on the client satellite, ideally before launch, and the "Agent-half coupling" that is to be carried by the UA.

The coupling that we have engineered serves as an add-on element for the valve of RTG-Aero-hydraulic, which adheres to the MIL standard[22] as regards connection interface. To this end investigation is under way wrt connecting to the F&D vales of others (EADS, Marotta, Moog …).

The basis of the design of the coupling is self-sealing-safety-coupling with zero-leakage-interface design. It is a threaded type, similar to the ones used by robotic manipulators inside nuclear stations or sub-sea operations. The pin-aligned type was avoided as it would currently penalize the Agent-half coupling with an unacceptable mass overhead. The respective alignment function will need to be performed by the robotic arm. The Agent-half coupling incorporates a rotary swivel joint.

Figure 5. The HERMES QD coupling (life size).

D. The coupling manipulator

All fill & drain valves are manually operated, and there is need for incorporating mechanized use of them on the coupling manipulator or to have an additional manipulator perform this function. The ideal configuration depends entirely on the valve type.

For handling the RTG-Aero-hydraulic valve a coupling manipulator has been designed for automated testing of the coupling in a Thermal-Vacuum chamber and incorporates both functions, the connection/disconnection of the coupling and the opening/closing of the valve.

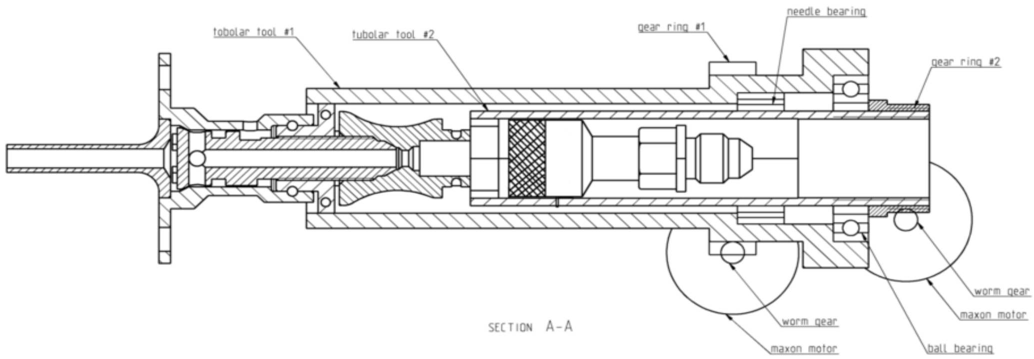

Figure 6. The mechanized manipulator to operate the couplings and the F&D valve.

E. The mission scenarios

Certain fuel transfer scenarios on-orbit are envisaged that make the deployment of the coupling a priority.

1. Extracting fuel from a damaged satellite

Total-loss-failure events in the last decade include at least 15 satellites that have had a type of failure that renders the satellites commercially a total loss, but still in a condition that would enable defueling to take place (temperature under control, attitude under control, one transponder functioning). These are the ideal candidates for initial low risk defueling operations.

2. Extracting fuel from overfed satellite

Satellites that are launched directly to GEO could be overfed wrt propellants & pressurant gas they carry with them. Satellites that are launched in this way they normally carry only the amount of propellant that is required for station keeping which is 20% of the useful volume of the propellant tanks. Topping up a single satellite that goes directly to GEO would mean it would carry a surplus propellant load equivalent to the propellant budget of 4 satellites of the same size.

3. Extracting fuel from Upper stages.

Due to potential concerns wrt approaching new assets of high value on orbit (scenario E.2) an alternative way would be to get the propellant from the upper stage that is anyhow a disposable item.

4. Extracting safety margin fuel.

Launch injection at GTO/GEO, is always very hard to predict accurately as it is dependent on co-passenger mass, date of the year, and performance of the launcher. Further the GTO to GEO transfer depends on the performance of the satellite. These uncertainties mean technically that a fuel margin would be the right mitigation solution. However, financially, such a solution would entail a sizeable cost. Recovery of this cost would be on a very distant point in time (after 12 years) on the condition that the satellite would still be operational and that it would still have a market. Such a distant eventuality deters operators to opt for a sizeable margin wrt propellants. However if they would also have the choice to sell on-orbit the excess fuel, which would be unlikely to be needed, they would opt for such a margin. Certainly this proposition will not find many advocates before we record significant evidence of successful defueling/refueling operations. However, as many other options exist for performing such demonstrations we believe this milestone will arrive soon. This scenario highlights the universality of fuel delivery options and the unnecessary nature of a dedicated tanker spacecraft.

5. Passivation of spacecraft

The recommended practice to passivate spacecrafts[23] is potentially an additional source of propellant and especially of pressurant gas, given the uncertainties of these resources at the end of their operation. Likewise, they can serve as temporary storage vessels in case the primary propellant holding vessels would need to be emptied fast (degradation of power subsystem, risk or losing also the spare processor, …). Therefore the recommended practice of passivating spacecraft may need to be selectively revisited.

IV. Conclusion

Tanker spacecraft is not a necessity for providing refueling services. Plenty of options based on the HERMES QD are possible as described by the "HERMES fuel trading system". Passivation practice on spacecraft in the future might need to be selectively revisited for converting old spacecraft to temporary tankers.

Acknowledgments

Author thanks RTG Aero-hydraulic for the provision of F&D valve samples, designs and engineering advice on fluid & pressurant gas issues of their propulsion components.

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