ACTIVE DEBRIS REMOVAL AND SPACE DEBRIS MITIGATION USING HYBRID PROPULSION SOLUTIONS

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ABSTRACT

This paper presents the results of a study carried out in the frame of the ESA General Studies Programme (GSP), dealing with the feasibility of performing active debris removal by using a hybrid propulsion system embarked on the chaser spacecraft. While the study focuses mainly on the use of a hybrid rocket propulsion system on-board a chaser spacecraft that performs active debris removal, it also addresses the application of this innovative propulsion technology for debris mitigation purposes. Hybrid propulsion systems seem to be a promising alternative to conventional liquid propellant in-orbit propulsion systems, in terms of complexity, cost, operational advantages, whilst also offering the use of non-toxic propellants. The study has been carried out by Deimos Space, an Elecnor company, expert in mission analysis, and Nammo Raufoss, expert in hybrid propulsion.

1 INTRODUCTION

Hundreds of satellites populate the Earth-bounded orbits, and the number of satellites orbiting around the Earth is rapidly increasing. Among the objects in orbit around our planet, about 95% are classified as space debris. These debris objects are a threat as they can collide with the active satellites, in turn creating more debris objects and possibly even restricting access to important orbits such as the Sun-synchronous orbit (SSO) region. Several collisions have already occurred and the population of debris will keep growing if no measures are taken to mitigate the generation of space debris by implementing proper policies and mission design standards, as well as to remove space debris in the future. By removing existing objects from orbit, the risk of collisions can be greatly reduced and access to important orbits retained.

This paper presents the results of a 1-year study, funded by the ESA General Studies Programme (HYPSOS: Hybrid Propulsion Solutions for Space Debris Remediation Study), and dealing with investigating the feasibility of performing active debris removal (ADR) by means of hybrid propulsion solutions. While the study focuses mainly on the use of a hybrid rocket propulsion system on-board a dedicated chaser spacecraft that performs ADR, it also preliminarily addresses the application of this innovative propulsion technology for space debris mitigation (SDM) purposes.

Hybrid propulsion seems very promising to cope with the space debris problem, offering also a more environmentally friendly fuel. The hybrid propulsion system considered is based on 87.5% H2O2 as oxidizer. H2O2 in 87.5% concentration has a consolidated heritage as oxidizer in propulsion systems in Europe, with a Technology Readiness Level (TRL) of 9, and its handling and storing does not pose any hazard as such, if compatible materials are used and proper procedures and guidelines are followed. The combination of H2O2 and hydrocarbon-based fuels has the advantage of having very good performances in terms of theoretical specific impulse, competitive with many of the best candidates in hybrid propulsion. High concentration hydrogen peroxide has favourable characteristics because of: its high density, its storability at room temperature at ambient pressure and its possibility of being decomposed through a catalyst. The catalytic decomposition produces a gaseous oxidizing mixture of oxygen and water vapour at a temperature high enough to guarantee ignition. The motor is capable to self-sustain the combustion process at a wide range of operating conditions without the need of dedicated systems to control the combustion. This peculiarity is particularly beneficial when a synergy between different propulsive architectures is desirable: high concentration H2O2 can be used as propellant for monopropellant thrusters and in combination with a hybrid motor to provide a solution which covers a wider range of propulsive functions with a single propulsion architecture. The same oxidizer and pressurizer tanks and main fluid system components are used to drive all different kind of thrusters, both hybrid and mono-propellant.

The paper is organized as follows. In Section 2, a detailed survey is performed, in order to identify size-mass-altitude distribution of space objects belonging to ESA and EU from completed, on-going and future

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missions. Section 3 presents the active debris removal application. After a parametric sizing of orbital manoeuvres required for accomplishing a dedicated debris removal mission, the modelling of the Propulsion System (PS) is described, with the purpose of creating reliable and accurate tools to size and model the propulsion system and the appraisal of the PS, targeted at assessing the hybrid-based propulsion system for selected representative mission scenarios. The assessment, apart from the detailed sizing of the main components, includes a comparison with the corresponding conventional propulsion system and an indication of the TRL at component and system level. Section 4 tackles an outlook for SDM, with the goal of considering the adoption of hybrid propulsion system both as main engine embarked on future satellites and as a kit to be integrated on launchers upper stages to be compliant with End-of-Life (EoL) disposal policies. Finally, Section 5 contains the main conclusions of the paper.

Two contributors, with the supervision of ESA-ESTEC, have taken part in the development of the study: Deimos Space, expert in mission analysis and design, and Nammo Raufoss, expert in rocket propulsion.

2 DETAILED SURVEY ON EUROPEAN LEO MISSIONS

In order to identify a set of interesting spacecraft and their corresponding orbits to perform ADR and SDM, a detailed survey of European Low Earth Orbit (LEO) in-orbit spacecraft, under current design and planned future missions, has been performed. Because of liability reasons, only objects belonging to ESA, ESA member states and ESA cooperating states are considered. The information has been retrieved mainly from ESA DISCOS database [1] for in-orbit missions and mainly from eoPortal Satellite Missions Database [2].

A detailed survey identified 130 missions with mass greater than 10 kg to be potential objects of study for ADR and SDM analyses. The extracted information revealed that: satellite masses range from few kg to 7821 kg of EnviSat; 80% of the missions are in SSO, near SSO, polar or near-polar orbits; altitude ranges from almost 400 km to 1450 km and inclination between 20º and 100º.

Based on the main conclusions of this survey, the region defined by the SSO orbits between 350 and 850 km seems to be the most interesting for debris remediation and mitigation. The propulsion metrics retrieved considering SSO orbits allow designing a hybrid propulsion system suitable for the majority of LEO missions.

3 ACTIVE DEBRIS REMOVAL

In the active debris removal mission scenario, it is assumed that a dedicated satellite, the chaser, is sent to target/capture/de-orbit a single object in space. The chaser is then sized and instrumented to be fully independent once released by the carrier in its injection orbit. As stated by the scope of the study, the propulsion system is based on hybrid rocket technology.

Tab. 1 summarizes the propulsive functions to be covered by the propulsion system. Among the reported functions, targeting and de-orbiting are those requiring a high thrust level and thus the implementation of the full hybrid propulsion system. The other two functions require a lower authority but higher accuracy propulsion system: rendezvous and Reaction Control System (RCS) can be covered by utilizing the monopropellant operational mode possible with the hybrid technology considered in the present study.

Table 1: Propulsive functions and corresponding solutions assigned (HTPB = Hydroxyl Terminated PolyButadiene; HDPE = High Density PolyEthylene)

Function	Description	PS features
Targeting	To provide the thrust necessary to get into the proximity of the target → orbit altitude increase	Hybrid 87.5% H_2O_2-HTPB/HDPE
Rendezvous	To approach and capture the target → far, mid, close range maneuvering	Monopropellant 87.5% H_2O_2
De-orbiting	To provide the thrust necessary to de-orbit the target after rendezvous	Hybrid 87.5% H_2O_2-HTPB/HDPE
RCS	To provide attitude control during all the ballistic phases → non-deterministic maneuvers	Monopropellant 87.5% H_2O_2

It is considered that the carrier for such kind of missions is Vega [3] and it will impose the limitations on the maximum admissible chaser mass and envelope.

The target objects to be de-orbited considered in this study are in most cases satellites, which almost certainly have flexible appendages and deployed panels. These items represent points of weakness in the structure and thus impose strict requirements on debris remediation missions. A strict requirement in terms of maximum tolerated acceleration in order to prevent the risk of breaking down the target during re-entry is enforced to avoid producing additional debris. Several studies about debris mitigation and remediation mention this aspect but just a few give quantitative numbers; all the studies performed by ESA ([4] and [5]) consider a maximum tolerated acceleration on the debris of 0.04g during the de-orbiting phase.

The HYPSOS study has considered therefore this value as its reference for maximum tolerated acceleration, but assessing at the same time the benefit/impact on the propulsion system and overall chaser design of having a less stringent limitation.

3.1 Mission Scenario

Parametric ΔV needed for the propulsive phases of an active debris removal mission are computed in order to provide inputs for sizing the hybrid propulsion system embarked on the chaser spacecraft. When possible, results have been compared with the outcome of the ESA e.Deorbit Phase-A study ([4] and [6]) focused on EnviSat de-orbiting. For the ADR mission analysis, three different propulsive phases are studied. They are presented in the following sections.

3.1.1 Transfer to Target Orbit

Considering Vega [3] as baseline launcher, the best injection altitude that maximizes the chaser mass at the target orbit is selected by retrieving launcher performance, parameterizing the injection altitude and computing the ΔV necessary to acquire the target orbit. The transfer to the target orbit starts with the injection of the chaser spacecraft into an intermediate orbit called the injection orbit. This orbit has been chosen to be circular and coplanar with the target orbit in order to avoid highly consuming out-of-plane manoeuvres. In order to assess which injection altitude maximizes the mass placed into the target orbit, a range of altitudes from 300 km to 850 km has been considered. Starting from the injection orbit, the chaser spacecraft performs a Hohmann transfer for target orbit acquisition. Manoeuvres are assumed symmetrical with respect to the apsidal point, performed with tangential thrust and considering gravity losses.

The outcome of the parametric analysis, considering an average specific impulse (Isp) delivered by the hybrid propulsion of 300 s, showed that, in the case of the Vega launcher, the highest chaser mass at the target orbit is achieved when the injection altitude is the lowest possible (300 km) and orbital raising to target orbit is performed by the chaser itself. Total ΔV varies from about 40 m/s for 350 km target orbit altitude to 300 m/s for 850 km target orbit altitude.

3.1.2 Approach to Target

The proximity phase is necessary for proper approaching the target object. This phase typically starts from a distance of a few kilometres and ends at the vicinity of the target. The chaser is considered to perform a safe rendezvous and to mate with an uncooperative target. This phase analyses far and close rendezvous (refer to Fig. 1 for the rendezvous profile chosen).

Parametric analyses have been performed, varying both chaser mass between 1000 and 1550 kg and debris orbital altitude between 350 km and 850 km. Two monopropellant thrusters aligned with each body axis were assumed for RCS; a total of 12 thrusters, plus 12 for redundancy, of 20 N each are considered, with a delivered specific impulse of 150 s (expected for H2O2 monopropellant thrusters in this class) and a control frequency of 1 Hz.

The results showed that a high number of burns are required for station keeping and that ΔV mainly depends on the orbit altitude: lower orbits have faster relative dynamics and require more ΔV. Total ΔV for both far and close rendezvous can vary from 14 m/s to 18 m/s. In the study the maximum value has always been adopted.

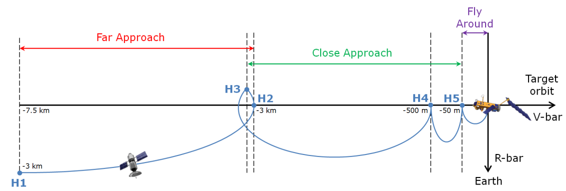

Figure 1: Graphical representation of the selected rendezvous profile

3.1.3 Controlled De-Orbit

The controlled re-entry consists in lowering the perigee to a given re-entry altitude (60 km in this study) such that the manoeuvre guarantees the impact of the stack formed by the debris and the chaser spacecraft over an unpopulated area in the South Pacific Ocean, not exceeding the casualty risk threshold imposed by the debris mitigation guidelines ([7]-[11]). One of the most relevant drivers in the controlled re-entry is the gravity loss: the higher the gravity losses, the bigger the ΔV, propellant mass and burning time required. For low thrust-to-mass ratios the number of manoeuvres drives the ΔV expenditure for the disposal phase: the higher the number of manoeuvres, the lower the gravity losses. A survey of feasible thrust and system mass combinations for hybrid propulsion has been carried out, together with multi-manoeuvre perigee lowering strategies, leading to the selection of solutions guaranteeing high-enough thrust-to-mass ratio to keep gravity losses negligible, while not exceeding maximum acceleration values. Initial orbit altitudes range from 350 km to 850 km. The perigee lowering strategies studied consider: 1 burn to lower the perigee at 60 km for direct re-entry; 2 burns to lower the perigee altitude to an intermediate value (200 km in this study); 3 burns to gradually lower the perigee down to 60 km. Thrust-to-mass ratio values considered, typical for hybrid propulsion system, range from 0.04 N/kg to 0.8 N/kg and propulsion system specific impulse is fixed to 300 s. The outcome of the analysis showed that, for the magnitude of the ΔV considered in the ADR scenario, thrust-to-mass ratios above 0.375 N/kg allow keeping the gravity losses below 1%. The thrust-to-mass ratios considered for the hybrid propulsion system in the present study are all above the limit where the gravity losses become negligible. In this case, the total ΔV does not depend on the perigee lowering strategy chosen and it varies from a minimum of 80 m/s starting from 350 km to a maximum of about 220 m/s starting from 850 km.

3.1.4 Delta-V Summary

A summary of the ΔV computed for some reference mission cases is presented in Tab. 2.

Table 2: ΔV summary for some reference cases

Target Name	Target Orbit [km]	Target Mass [kg]	ΔV Transfer to Target [m/s]	ΔV Approach to Target [m/s]	ΔV Controlled De-Orbit [m/s]
EarthCare	393	1860	53.2	18.1	95.2
Deimos-2	620	310	178.7	17.4	157.8
EnviSat	760	7821	253.0	17.0	193.1
MetOp-SG-A	817	3000	283.7	16.8	207.5

3.2 Hybrid Propulsion System Sizing

The hybrid-monopropellant propulsion system considered is based on 87.5% H_2O_2 as oxidizer and HTPB or HDPE as fuel and its architecture is presented in Fig. 2. As described in Tab. 1, the hybrid motor is responsible for targeting and de-orbiting, while the monopropellant part is responsible for rendezvous and for RCS.

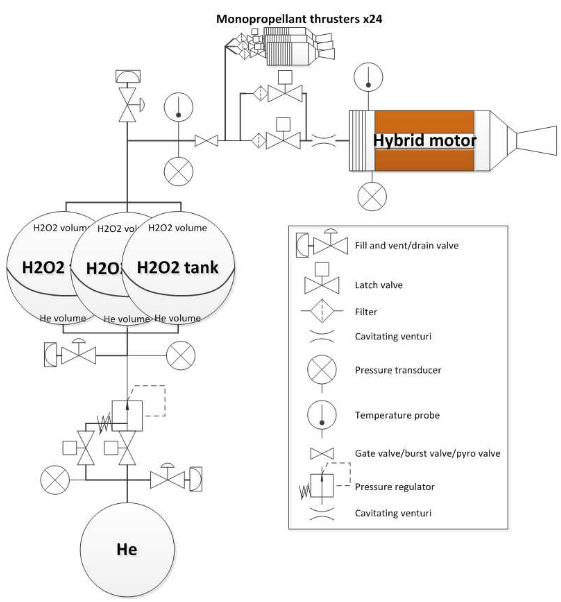

Figure 2: Hybrid propulsion system architecture

Parametric ΔV collected from the three propulsive phases with adequate margins has been considered to initially perform a simplified mass budget estimation, based on Tsiolkovsky rocket equation, in order to get an overview on the thrust class versus burning time required by each of the 130 mission scenarios retrieved in the mission survey. Starting from this information, a few interesting scenarios, spanning different ranges of thrust class and burning time, have been selected to perform a more detailed investigation. For this purpose, a complete and detailed performance model has been implemented with the aim of sizing in detail the hybrid propulsion system and predicting the temporal behaviour of the motor based on the requirements and assumptions.

All the main components of the propulsion system have been sized (mass and envelope of: oxidizer and pressurizing tanks, combustion chamber, nozzle) and the hybrid motor performance and behaviour have been assessed (propellants consumption and thrust profile).

In order to assess the hybrid propulsion system in a more thorough way, an additional goal of the HYPSOS study was to compare the hybrid propulsion system configurations considered for ADR with their corresponding conventional systems based on bi-propellant technology. For this purpose, a reliable sizing methodology of such bi-propellant system, when applied to the considered scenario, has been implemented as well.

3.2.1 Hybrid Propulsion System Detailed Sizing for Envisat

This scenario has been investigated because of its known interest in the European space community. ESA is already developing a dedicated mission to de-orbit this object through the study called "e.Deorbit" [4]. Envisat mass is estimated around 7900 kg and it flies at an altitude of about 760 km. The ΔV required for each phase of the chaser mission with corresponding margins and propulsion system involved are summarized in Tab. 3.

Table 3: ΔV budget for Envisat

Mission Phase	ΔV [m/s]	Margin [%]	Propulsion System
Targeting	253	5	Hybrid
Rendezvous and RCS	18	100	H2O2 monopropellant
De-orbit	193	5	Hybrid

For this specific scenario, besides the hybrid propulsion system architecture with one single hybrid motor, an additional configuration has been investigated which makes use of multiple (smaller) hybrid motors working in parallel to deliver the thrust required to perform the orbital manoeuvres. The reason behind this choice has been to investigate a configuration exploiting the higher volumetric compactness of the smaller hybrid motors.

Tab. 4 summarizes the resulting mass of the propulsion system for the two different architectures respectively, in comparison with the corresponding bi-propellant system. For the single motor configuration, a mass saving of about 6.9% is achieved considering a hybrid PS. With respect to the single-motor configuration, the propulsion system with 3-motors is heavier but more compact, as can be confirmed by Fig. 3. It will allow for a more flexible architecture and ease the integration with the launch vehicle.

Table 4: Comparison of the hybrid propulsion system with the corresponding bi-propellant one for Envisat scenarios

	Hybrid single motor	Hybrid 3 motors	Bi-propellant
Propulsion system wet mass [kg]	844	899	907
Propulsion system dry mass [kg]	113	148	153
Propellant mass fraction	0.87	0.83	0.83

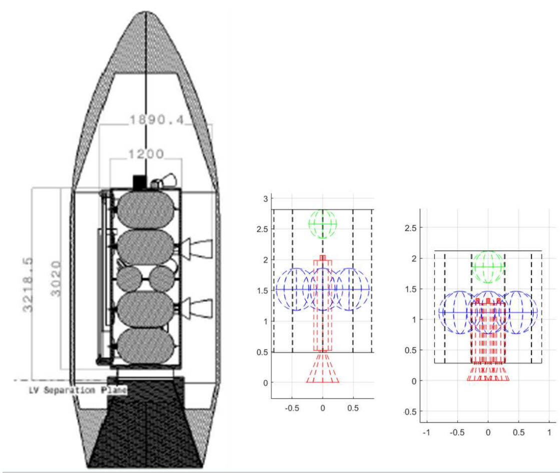

Figure 3: Comparison of the size between the e.Deorbit chaser, fitted in the Vega fairing (left), and the integrated PS architecture of HYPSOS, hybrid single motor (centre) and hybrid 3 motors (right)

4 OUTLOOK FOR DEBRIS MITIGATION

Adherence to the post-mission disposal guidelines is the absolute key driver for the environmental impact reduction and the new missions have to be designed in order to be able to autonomously and in a reliable way perform post-mission disposal at EoL, by means of:

- direct control re-entry, as already described;
- if the risk on ground is lower than 10^{-4}, uncontrolled re-entry in less than 25 years ([7] and [9]).

From a mission design point of view, the second option ensures the compliance with the space debris mitigation requirements for Earth observation missions, while minimizing the required propellant.

An exhaustive study has been carried out in order to determine whether a perigee-lowering manoeuvre is needed or not to comply with the 25 years rule for all the 130 missions selected in the first part of the study. In case it is needed, it is determined the highest (i.e. less costly) altitude onto which the spacecraft shall be manoeuvred in order to guarantee a safe uncontrolled decay within 25 years and the corresponding ΔV. Resulting ΔV needed have then been considered to size a dedicated hybrid propulsion de-orbiting kit for EoL disposal in future ESA missions.

The parametric uncontrolled re-entry analysis has been performed considering a range of starting orbit altitudes between 350 km and 850 km and ballistic coefficient between 10 kg/m2 and 180 kg/m2.

The results showed that for low target orbits (below 550 km), the re-entry is always performed without any manoeuvre. For those cases where a manoeuvre is needed, the perigee altitude decreases as the ballistic coefficient increases, so the amount of ΔV required increases. Besides, for a fixed ballistic coefficient, the perigee altitude decreases as the reference altitude of the orbit increases due to the fact that the higher the re-entry orbit, the less drag undergoes the spacecraft around the apogee.

If either the altitude or the ballistic coefficient increases, the ΔV required increases too, reaching a maximum value of 119 m/s for a ballistic coefficient of 180 kg/m2 and an initial orbit altitude of 850 km. Compared with the controlled re-entry, this strategy is cheaper in terms of ΔV, but it requires more time.

Feasibility of performing post-mission disposal of future ESA missions in LEO and European upper stage rocket bodies in GTO by means of hybrid propulsion has been addressed.

A representative LEO mission scenario represented by the FLEX Earth Explorer has been chosen for a detailed sizing of the hybrid propulsion system for debris remediation by implementing an un-controlled re-entry strategy. While controlled re-entry is proposed for Ariane 5 upper stage de-orbiting from GTO.

4.1 Future ESA LEO Mission: FLEX

FLEX (FLuorescence EXplorer) has been chosen as the eighth Earth Explorer mission within ESA's Earth Observation Programme [12]. FLEX, slated for launch after 2020, will fly in formation with Sentinel-3 in a

SSO orbit at 815 km altitude. The FLEX propulsion subsystem will provide the necessary thrust for correction of launcher injection errors, formation flying acquisition with Sentinel-3, orbit maintenance for ground-track control at all latitudes (including a small ΔV allocation to cope with formation control in possible contingency situations), collision avoidance to avoid collision with space debris objects, End-of-Life disposal to comply with EoL guidelines. It will use a hydrazine system, with an assembly of four 1N thrusters, pressurized with helium and operated in blow-down mode. At the end of Phase B1, the estimated mass budget of hydrazine system and propellant sum up at about 80 kg. After 5 years (nominal mission phase + mission extension), the mission foresees as baseline scenario an in-plane manoeuvre to lower the orbit perigee to an altitude that guarantees safe uncontrolled decay within 25 years.

Deimos was involved in the FLEX Phase A/B1 study and the corresponding ΔV budget at the end of Phase B1 is summarized in Table 2. The ΔV for injection errors correction, collision avoidance and orbit maintenance are taken from Deimos FLEX Mission Analysis Report [13]. The ΔV for End-of-Life disposal to lower the perigee in order to guarantee re-entry into the atmosphere in less than 25 years was computed for FLEX in the frame of the HYPSOS study. The total ΔV to be delivered during FLEX lifetime is about 138 m/s and the minimum ΔV to be provided during orbit control is of 0.04 m/s.

The propulsion system should be the only one embarked on-board; this represents an appealing advantage if combined with the suitability of H2O2-based hybrids to operate synergistically with a H2O2 monopropellant system, the former being responsible of the EoL disposal manoeuvre while the latter provides the attitude control. Margins applied on top of the ideal ΔV are reported in Tab. 5.

Table 5: ΔV budget for FLEX mission

Mission Phase	ΔV [m/s]	Margin [%]	Propulsion System
Injection errors and formation acquisition ΔV	29.9	20	H2O2 monopropellant
Collision avoidance and orbit control ΔV	34.8	20	H2O2 monopropellant
EoL disposal ΔV	73.0	5	Hybrid
Total ΔV	137.7		

The resulting architecture of the propulsion system considered in this case is the one reported in Fig. 4.

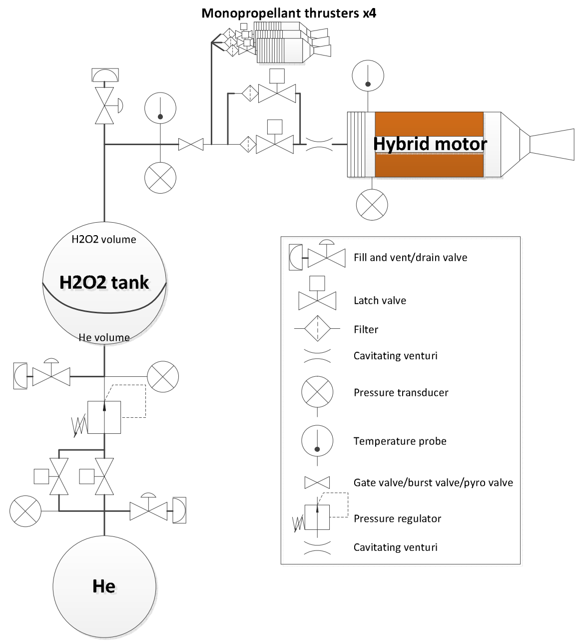

Figure 4: Fully independent hybrid propulsion system architecture for FLEX mission

Following the approach already adopted by ESA in preliminary sizing the propulsion system, [12], 4 monopropellant thrusters with nominal thrust of 1N each have been considered for the ACS.

Tab. 6 summarizes the overall characteristics of the hybrid PS for FLEX.

Table 6: Main results for the hybrid propulsion system of FLEX

Consumed propellant, monopropellant [kg]	48	Propulsion system wet mass [kg]	86
Consumed propellant, hybrid [kg]	24	Propulsion system dry mass [kg]	15
Burning time [s]	200	Oxidizer tank capacity [l]	52
Peak thrust [N]	340	Pressurizing gas tank capacity [l]	8
Peak acceleration [m/s^2]	0.4		

4.2 Upper Stage: Ariane-5 ECA

Among all the scenarios considered for space debris mitigation, upper stages disposal provides a very interesting scenario for space debris mitigation, where H2O2-based hybrid propulsion system could represent the best compromise between performance and complexity/costs. Upper stages are geometrically simple bodies, sized to withstand severe thermomechanical loads at launch and separation; as such, they do not impose any requirement on maximum tolerated acceleration during de-orbiting as stringent as the one applicable to satellite. This in turns gives more flexibility and freedom for designing the propulsion system since it allows for a quite sharp and short manoeuvre, without demanding requirements associated to slow and long duration actuations. The manoeuvre is performed at beginning of life that is a few hours after launch and this removes all the issues and complexity associated to guaranteeing long reliability of the propulsion system in space, in particular in storing on board the propellants without affecting the performance. A single burn is needed, meaning that no restart capability is required for the propulsion system, thus preventing it from being subjected to thermal cycling and lowering risk of failures due to multiple actuation of the valves.

The current European launchers are: Vega, Soyuz and Ariane5. Vega [3] and Soyuz [14] already comply with the ESA space debris mitigation policies, with the upper stage performing a last burn to re-enter into the atmosphere after releasing the payload. Ariane 5 upper stage, instead, lacks of fuel to perform re-entry. Not even the next generation European launcher, Ariane 6, seems to implement the policy, at least based on the information publically available. This section focuses on proposing strategies to de-orbit Ariane 5 upper stage from Geostationary Transfer Orbit (GTO) exploiting hybrid propulsion technologies.

The initial orbital parameters of the GTO orbit reached by the upper stage of Ariane 5 ECA (Evolution Cryotechnique type A) are 35943 km apogee altitude and 250 km perigee altitude [15]. The optimised controlled re-entry performed lowering the perigee of the spacecraft from 250 km to 60 km will require a ΔV of 20 m/s, including gravity losses. The de-orbiting system will have to carry a maximum host mass of 6335 kg.

The architecture of the propulsion system considered in this case is shown in Fig. 5. Respect to the architectures conceived for ADR, the present one results quite simplified because only the de-orbiting phase has to be taken into account.

Tab. 7 summarizes the overall characteristics of the manoeuvre performed by the hybrid propulsion system for the considered scenario.

Because of integration benefits, a configuration with 2 hybrid motor has been selected in the end as the most favourable, allowing for axis-symmetric mounting and providing an easier vectoring of the thrust through the centre of gravity of the upper stage.

Taking into account the geometry and components distribution on the upper stage, the configuration of the propulsion system with 2 hybrid motors and two tanks is the most favourable. The motors can be mounted diametrically opposed with each one its tank in the vicinity, either at the bottom or at the top end of the upper stage fairing, being fixed at its inner surface. It is recommended that the motors are integrated in the upper stage with the nozzle divergent hung outward of the envelope for a most effective and safe manoeuvre.

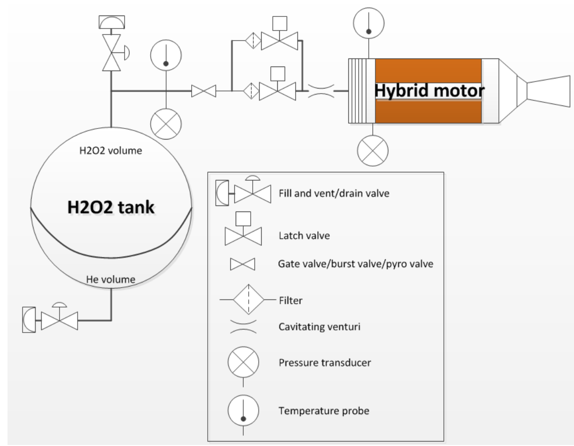

Figure 5: Hybrid propulsion system architecture for upper stage post-mission disposal

Table 7: Main results for the orbit lowering manoeuvre applied to Ariane-5 ECA

Consumed propellant [kg]	49	Propulsion system wet mass [kg]	81
Burning time [s]	24	Propulsion system dry mass [kg]	33
Peak thrust [N]	3189x2	Oxidizer tank capacity [l]	117
Peak acceleration [m/s^2]	0.98		

Fig. 6 is a 3D view of the system with 2 hybrid motors and one tank and its overall envelope. As an example, Fig. 7, shows a possible location of the components at the top of the fairing of the upper stage.

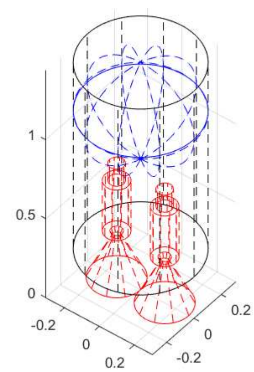

Figure 6: 3D view of hybrid propulsion system main components accommodation (measures in meters)

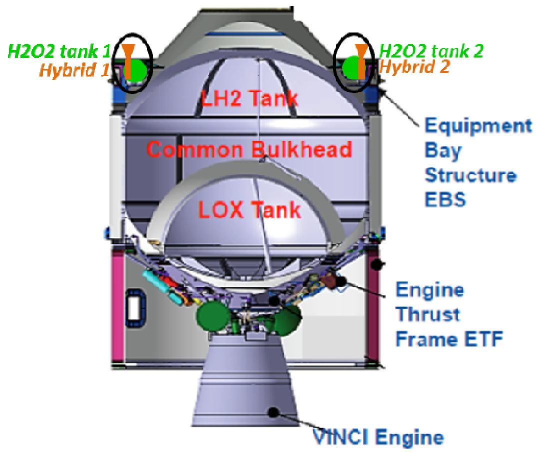

Figure 7: Ariane 5 upper stage, section view schematic with possible locations of the hybrid PS for de-orbiting (sketch on scale)

5 CONCLUSIONS

Nammo and Deimos worked together in a 1-year project funded under ESA-GSP with the goal to investigate the implementation of a propulsion system based on hybrid rocket technology for active debris remediation missions. Promising results have been obtained thanks to the simplicity and intrinsic safety of hybrids, whilst offering competitive performances.

Extensive mission survey has been performed on ESA/EU missions to retrieve debris dispersion and masses. ΔV analysis for the main propulsive phases has been carried out and contributions for targeting, de-orbiting and rendezvous have been calculated for each scenario.

Modelling tools have been implemented to assess, first preliminary on all the scenarios and then in detail on selected scenarios, the hybrid propulsion system. Size and mass of the main components as well as time evolution of the propulsion system are computed. A modelling tool has been implemented to assess the corresponding bi-propellant propulsion system for each scenario, in order to compare the two systems. In general, it has been observed that a hybrid-propulsion-based system benefits of a simpler architecture with a lighter impact in terms of wet mass.

TRL and delta-development of the main technologies included in the hybrid propulsion system have been evaluated. Projects are already on-going in Europe for developing and qualifying the key technologies of the system and the results achieved so far allow assigning a TRL6 at component level to all of them.

Finally the outcomes of the study have been used to outlook at future ESA missions potentially requiring debris disposal kits based on hybrid propulsion.

6 ACKNOWLEDGMENTS

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