TECHNOLOGY COMBINATION ANALYSIS TOOL (TCAT) FOR ACTIVE DEBRIS REMOVAL

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ABSTRACT

This paper present the work of the Swiss Space Center EPFL within the CNES-funded OTV-2 study. In order to find the most performant Active Debris Removal (ADR) mission architectures and technologies, a tool was developed in order to design and compare ADR spacecraft, and to plan ADR campaigns to remove large debris. Two types of architectures are considered to be efficient: the Chaser (single-debris spacecraft), the Mothership/Kits (multiple-debris spacecraft). Both are able to perform controlled re-entry.

The tool includes modules to optimise the launch dates and the order of capture, to design missions and spacecraft, and to select launch vehicles. The propulsion, power and structure subsystems are sized by the tool thanks to high-level parametric models whilst the other ones are defined by their mass and power consumption.

Final results are still under investigation by the consortium but two concrete examples of the tool's outputs are presented in the paper.

Key words: Orbital debris; system architectures; mission design; technology combination analysis tool.

1. INTRODUCTION

This paper presents the work accomplished during the CNES-funded OTV-2 project by a consortium led by Astrium. The goal of the study is to compare, rank and select mission architectures and technologies that are the most efficient, in terms of performance and cost, to perform active debris removal (ADR). The project includes a work package for technical analysis (performed by the Swiss Space Center), one for versatility analysis (performed by Surrey Space Technology Ltd.) and one for cost assessment (performed by Astrium). Once an architecture and the corresponding technologies will be chosen, a roadmap will be proposed as well as technology maturation strategies (performed by Bertin Technologies).

To evaluate the various mission architectures and to determine the characteristics of the spacecraft and the timeline required for an ADR campaign, the Swiss Space Center developed a technology combination analysis tool (TCAT). The outputs of the tool were used to define typical ADR spacecraft and to assess their cost.

The next section presents an overview of TCAT and of the combination of architectures and technologies that are studied during OTV-2. Then, the different modules are presented as well as the evaluation and design loops. Finally some example of the outputs the tool is able to provide are shown. An overview of the results and the main conclusions at this level of study (i.e. without the cost evaluation) are presented.

2. TOOL OVERVIEW

2.1. Objectives and capabilities

The main objective of TCAT is to compare system architectures for active debris removal (ADR). Given a pool of debris and a removal architecture (defined by the type of removing spacecraft, the types of propulsion and capture system, etc.), it can design all the spacecraft required to perform a whole de-orbiting campaign. All the systems will be optimised to remove specific debris but main trends can be extracted in order to select the most efficient architectures. In a second time, the results from TCAT can be used as baseline to design an efficient and versatile ADR spacecraft.

The development of TCAT started during a Master Thesis at MIT under the supervision of Prof. Olivier de Weck

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[1]. It is coded in MATLAB in a very modular manner so that each function or module can easily be replaced by a more performant one. The four main parts of the tool are: the debris database, the mission design modules, the spacecraft design modules and the launch vehicle selection modules.

2.2. Combinations

Three architecture are tackled by TCAT as shown in Figure 1.

- The Chaser, is able to rendezvous, capture and de-orbit only one debris. Several of them can be launched together.
- The Mothership (MS) can visit several targets and equip each of them with a de-orbiting Kit. The last debris is captured and de-orbited by the MS itself. It is assumed that a launch vehicle will contain only one MS and its Kits.
- The Shuttle can also visit several debris but they are de-orbited by the spacecraft itself, no kit is used. This architecture was rapidly discarded in its study due to its poor efficiency with conventional propul-

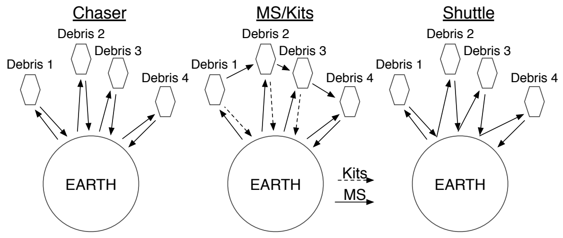

Figure 1. The three architectures that can be evaluated by TCAT

For each of the two first architectures several choices of technologies can be made. The first of them concerns the capture system which consists in either a flexible or a rigid link. In the first case, the ADR spacecraft shoots a net or a harpoon at the target and de-orbits it by pulling on a tether linking the spacecraft to the debris. In the second case, robotic arms and grasping mechanisms are used to attach the spacecraft to the debris. It was decided not to assess the performance of the robotic arm on a Chaser. The reason is that the cost of such a rigid link was assumed to be too high to be used on a single-debris system.

The second choice concerns the propulsion subsystem. The available technologies are bi-liquid, mono-liquid, solid, and electric systems. This subsystem can be separated in three different parts, each of which corresponds to a specific function:

- The **main** propulsion is used for the orbital changes. It is included on-board the Chasers and MS, but not on the Kits.
- The **AOCS** propulsion is used for the rendezvous and capture phases as well as to stabilise the target after capture. All types of spacecraft need such functions.
- The **de-orbit** propulsion is used to give the final burn to the target. All types of spacecraft need it, even the MS since it has to de-orbit the last debris.

By mixing the various propulsion and capture technologies, the following combinations were evaluated in TCAT:

- 1 type of Chaser using a bi-liquid system as main, AOCS and de-orbit propulsion, and a capture system with flexible link.
- 4 types of Kits: the propulsion can be either solid (de-orbit) and mono-liquid (AOCS) or fully bi-liquid, and the link can be either rigid or flexible.
- 8 types of MS: the propulsion can be either electric (main) and bi-liquid (AOCS and de-orbit) or fully bi-liquid, and each type of Kit can be used.

An important assumptions during the project was that the debris shall re-enter the atmosphere in a controlled manner. This leads to the need to have the de-orbiting boost performed by a high-thrust propulsion system, even when a low-thrust system is used for most of the orbital transfers. Another assumption was that the cost of a robotic arm was to high to be used on a Chaser as one or two arms need to be build for each debris. In the case of a MS/Kit architecture, where it is installed only on the main spacecraft, the cost in spread among multiple debris.

2.3. Campaign evaluation loop

A combination is defined by several inputs at different levels.

Debris inputs The first input is the pool of debris that has to be removed. It is a sub-group of the database of debris included in TCAT and it is described in the next section.

Mission-level inputs These includes the selection of one of the two architectures, and the number of debris that can be removed per launch. This last input is translated in the number of Chasers per launch and the number of Kits aboard a Mothership.

System-level inputs Finally, the types of propulsion and of capture system must be defined, as explained in the previous section.

For each combination, the loop presented in Figure 2 is executed by TCAT.

3. DEBRIS DATABASE

TCAT includes a database of 222 debris of interests for the OTV-2 study. They are separated in 3 inclinations regions (71°, 82° and SSO) and 3 classes of mass:

- ”Light debris” weight between 1400 and 2000 kg and are Cosmos and Meteor satellites, SL-8 and Ariane 4 rocket bodies and european and russian satellites in SSO.
- ”Medium debris” are Ariane 5 rocket bodies that weight around 4500 kg.
- ”Heavy debris” are SL-16 rocket bodies that weight around 9000 kg.

The database stores their orbital parameters (semi-major axis, inclination and right ascension of the ascending node (RAAN)) as well as their mass. The orbits are assumed to be circular and the only perturbation taken into account in TCAT is the RAAN drift due to the J_2 element

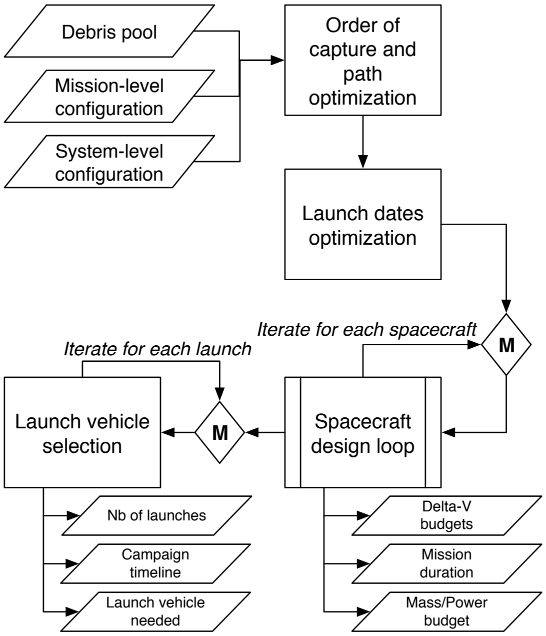

Figure 2. TCAT combination evaluation loop

4. MISSION DESIGN

4.1. Optimisation of path

In the case of a MS, when several debris must be visited, it is important to optimise the path between the debris in order to minimise propellant mass and mission duration. The optimisation is an adapted version of the well-known travelling salesman problem (TSP). In the original version, a unique traveller must visit a given number of cities once and only once and come back to its original point. The goal is to minimise the total distance travelled by the salesman. In the version used by TCAT, several salesmen (the MS) must visit a given number of cities (the targets). Each city must be visited once and only once and all the travellers must end their trip in a pre-determined city (a re-entry trajectory).

In the original problem, the distance to minimise is given in kilometres. In this version of the problem, the element $d_{i,j}$ of matrix of the distances D is given by

$$d_{i,j} = \Delta V_{i,j} \tag{1}$$

where $\Delta V_{i,j}$ is the ΔV required to go from the orbit of the target i that has the semi-major axis a_i, the inclination i_i and the RAAN Ω_i to the orbit of debris j, with a_j, i_j and Ω_j. The change of RAAN is performed actively in the same time as the change of inclination. The RAAN are taken as they are at Epoch 0 (Jan 1, 2023). In reality, the RAAN drift with time and the optimal path at Epoch 0 for a given MS may not be the same when the mission actually occurs. However, when the spacecraft is designed by TCAT (as explained later in this paper), the actual situation of the RAAN at launch and the drift during the mission are taken into account even though the path is the one decided in a static manner on an another date. This way the path may be sub-optimal but the spacecraft is designed for an actual mission.

4.2. Optimization of launch date

In order to make sure that the mission will not last too long and to be able to plan a whole removing campaign, a launch date has to be found for each launch. The best date to launch a single Mothership or several Chasers is assumed to be when the spread of the RAAN of all concerned debris is minimal. The algorithm used to find the optimal launch date is very simple. The RAAN spread is computed for each day within a given period of time. The day with the lowest spread is chosen as the launch date. The first date must be at least 3 months after the previous launch and the next launch opportunity is found within the next 3 months. This guarantees a launch every 3 months at most and every 6 months at least. Thus, a certain cadence can be achieved whilst keeping the availability of the launchers in mind.

5. SPACECRAFT DESIGN

5.1. Design loop

Each spacecraft is designed by TCAT by the design loop presented in Figure 3.

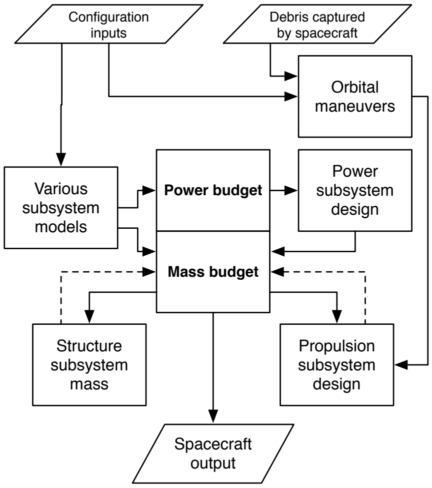

Figure 3. TCAT spacecraft design loop

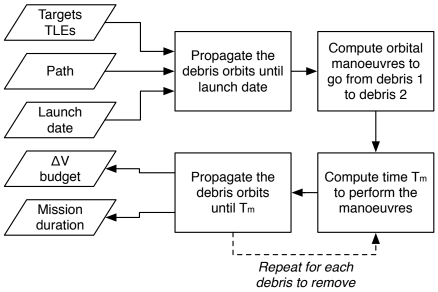

Figure 4. Orbital manoeuvres module in TCAT.

5.2. Orbital manoeuvres

Altitude and inclination changes The ΔVs for altitude and inclination changes are computed in very classic ways. In the case of high-thrust propulsion systems, Hohmann transfers are used. The boost at the perigee is used only for a change of semi-major axis whilst the apogee kick is used to change both the semi-major axis and the inclination at once. The duration of the transfers is assumed to be 50 minutes (half the orbital period on the transfer orbit) and the duration of the boost is limited to 20 % of the orbital period (around 20 minutes) to stay in the validity domain of the impulsive manoeuvre.

In the case of low-thrust propulsion systems, the Edelbaum equation is used. The thrust is assumed to be constant in the daylight and null during the eclipse. The transfer duration is assumed by Equation 2.

$$T_t = \frac{\Delta V}{F_{th}} \cdot \frac{1}{\bar{M}} \tag{2}$$

where $\bar{M}$ is the average of the masses before and after the transfer.

RAAN changes The path between the debris, in the case of a MS, is determined based on active change of RAAN for a situation at a given time. However, when it comes to actually design the mission of the spacecraft, the evolution of the RAAN is taken into account. The orbits are propagated by taking only the effect of the J_2 element of the Earth. Because the difference of RAAN between two orbits can be anywhere between 0 and 360°, the changes of RAAN can be performed in 3 different manners in TCAT:

- Passive: in this case the spacecraft stays on its initial orbit and waits for the natural drift to align its RAAN with the one of its next orbit. It is very efficient in terms of ΔV bun can take a lot of time, especially if the RAAN difference is big and the semi-major axes and inclinations of both orbits are very similar.
- Active: in this case, a boost is given to actively change the angle of the orbit. This is as quick as an equivalent change of inclination but can be very costly in ΔV (and therefore in propellant) if the RAAN difference is bigger than a few degrees.
- Semi-active: the spacecraft will perform a full Hohmann or Edelbaum transfer to change either its inclination, either its semi-major axis or both to go to an orbit which has a faster relative RAAN drift rate with its next orbit. This allows a transfer that is usually faster than the passive one and less consuming than the active one.

Although the semi-active change seems appealing, it is not always the best solution. Indeed, the choice of the right strategy will depend on the relative importance given to the time in one hand and to the ΔV in the other hand. In other terms: is it better to sacrifice time for propellant or the opposite? To answer this question a function to optimise is implemented in TCAT. It has the same form as the one presented in Equation 3

$$F = \alpha \cdot \Delta V + \beta \cdot T_t \cdot e^{\gamma T_t} \tag{3}$$

where ΔV and T_t are respectively the ΔV and the duration required for the full change of orbit (semi-major axis, inclination and RAAN). For each transfer, the three methods are compared by using this equation. The factors α, β and γ are still under investigation.

5.3. Subsystems models

Models are included in TCAT in order to assess the mass of the different subsystems. Three subsystems are designed by TCAT: the propulsion; the power and the structure. The other ones are pre-defined with constant mass and power consumptions during the different phases of the mission.

Propulsion The propulsion systems are designed based on the mass of propellant required to perform the mission. The models are based on flown systems data and internal studies performed by Astrium; they take the propellant mass as an input, as well as the propellant throughput per thrusters and the maximum acceleration that the system shall see to avoid break-ups, and return the dry mass of the subsystem as well as its power consumption and the number of thrusters.

The bi-propellant systems are the most complex, the mass of propellant is used to determine first the mass of the main tanks (for fuel and oxidiser) and the number of thrusters (based on the propellant throughput and the thrust level). The mass of the pressurant tanks depends on the mass of the main tanks. Because the architecture of the system is assumed to be the same from a spacecraft to the other, the mass of the pipes and of the drive electronics are assumed to be the same. The mass of the secondary structure, used to hold the propulsion subsystem) is assumed to be a constant fraction of the propellant mass.

The mono-propellant systems are simpler and used only for AOCS on the solid Kits. They are based on Astrium hardware and on data collected by TU Delft.

The solid propellant motors mass is interpolated from those of ATK's Star family [2].

The electric propulsion systems are based on the hardware of Smart-1 and a CNES study to use such equipment for ADR [3].

Power The power subsystem design is based on the power budget for the different spacecraft. The Chaser and the Mothership have conventional architectures with solar panels and secondary batteries. The solar panels are designed based on data from flown systems such as Astrium's 26-kW solar panels or the Smart-1 ones. The batteries are designed for the total duration required for the rendezvous and capture. During this critical phase, it is conservative to assume that the target will shadow the solar panels of the spacecraft, hence the system should rely only on stored power. A constant additional mass of is added to take the power management electronics (PME) into account.

The Kits are simpler and only use primary batteries without solar panels. The batteries are designed to last for the time required for the Kits to stabilise and de-orbit the debris.

Structure Based on data from existing spacecraft, the mass of the structure subsystems is assumed to be 30 % of the mass of all the other subsystems. In the case of the Mothership, the mass of the structure is also based on the wet masses of all the Kits aboard.

Other subsystems The other subsystems include AOCS/GNC (attitude sensors and reaction wheels), avionics, thermal, telecom, the rendezvous sensors and the capture system. They are defined only by their mass and power needs and are completely independent of the mission or the other subsystems.

For instance, the rendezvous sensors assume a mass of 25 kg and a power consumption of 15 W. A harpoon or a net are represented by a mass of 20 kg and a power consumption quasi null since it is only instantaneous. The robotic arms, as defined in TCAT, weight 80 kg each and require 150 W while in motion.

Different margins and contingencies are included in TCAT as detailed in Table 1.

Table 1. Margins policy in TCAT

Parameters	Margin
ΔV	10 %
Propellant mass	10 %
Subsystem mass	20 %
System mass	20 %

The output of the spacecraft design loop are the ΔV, dry and wet mass and power budgets, the launch dates and the mission durations. At this point, each spacecraft is unique and designed specifically for its mission. The raw results from TCAT thus need to be studied to extract tendencies and design standard spacecraft.

6. DISPENSERS AND LAUNCH VEHICLE

In the case of the launch of multiple Chasers, the launch mass is not only the sum of the spacecraft's wet masses, it also includes the mass of the dispenser on which they will be attached. A model, based on actual data from the Galileo and Globalstar dispensers used in Soyuz [4], is included in TCAT and defines the mass of the dispenser as a function of the total mass of the satellites to launch. This is not a problem in the case of the MS since there is only one per launch vehicle.

The launch vehicle is chosen based on the launch mass. Three capabilities were assumed: 1350 (Vega), 4800 (Soyuz) and 15500 kg (Ariane 5). If an architecture is too heavy for any launch vehicle, it is discarded. For now, TCAT does not ensure the full use of the launcher's capabilities.

7. EXAMPLE OF OUTPUTS

7.1. Chaser outputs

In this first example, the goal is to remove 5 Light debris is SSO with a single launch of Chaser.

Table 2. Overview of the Chasers designed to remove 5 targets in SSO

Chaser	Delta-V	Sync time	Wet mass	Dry mass
1	417 m/s	0.0 years	660 kg	402 kg
2	442 m/s	0.7 years	672 kg	402 kg
3	358 m/s	1.2 years	670 kg	402 kg
4	298 m/s	2.2 years	596 kg	398 kg
5	342 m/s	1.9 years	656 kg	401 kg

The dispenser weights 516 kg, which leads to a total launch mass of 3770 kg. This is compatible with Soyuz, which would be filled at 78%.

In this example, 8000 kg (5 debris of 1600 kg each) can be de-orbited in just more than 2 years. This long time is due to the big RAAN spread of 83° at the time of launch. The problem with the debris in SSO is that their small number does not ensure that they will be grouped on a small RAAN spread.

The same combination but with 5 debris at 82° gives the results presented in Table 3.

Table 3. Overview of the Chasers designed to remove 5 targets at 82°

Chaser	Delta-V	Sync time	Wet mass	Dry mass
1	588 m/s	3.6 days	728 kg	406 kg
2	589 m/s	3.4 days	729 kg	406 kg
3	587 m/s	2.9 days	728 kg	406 kg
4	588 m/s	0.0 days	729 kg	406 kg
5	586 m/s	0.0 days	728 kg	406 kg

In this case, the RAAN spread is only of 3° and 7000 kg (5 debris of 1400 kg each) can be removed in less than a year.

A Chaser has to accomplish a typical ΔV between 400 and 600 m/s; its lifetime is strongly dependent on the RAAN spread at launch but will usually be shorter than 5 years. The power required by the subsystems is in the order of 400 W.

7.2. Mothership/Kits

In this example, the goal is to remove 20 Light debris at 82° (altitudes between 800 and 1000 km) with 6 MS. Each of them has a bi-liquid propulsion system as well as bi-liquid Kits. The capture is performed with a rigid link system. The campaign timeline is shown in Figure 5.

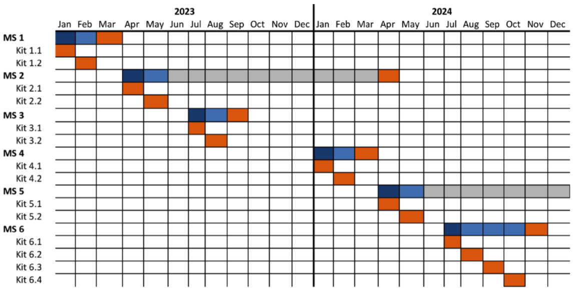

Figure 5. Example of removal campaign using 6 MS and 14 Kits. The dark blue marks indicate launches, the light blue ones represent rendezvous and capture phases, the orange ones are the re-entries of the debris and the grey ones are the phase when the MS is drifting whilst waiting for RAAN synchronisation.

In this example, 8 debris (11.2 tons) can be removed within the first year and 11 (15.4 tons) during the next one. The 2-Kit MS are launched with Soyuz and the 4-Kit one with Ariane 5. The last debris is removed only after 6 years due to the long time the second MS has to wait before RAAN synchronisation. In most of the cases, active RAAN changes can be performed and thus the mission durations can be reduced. This is however not always the case as shown in Figure 6.

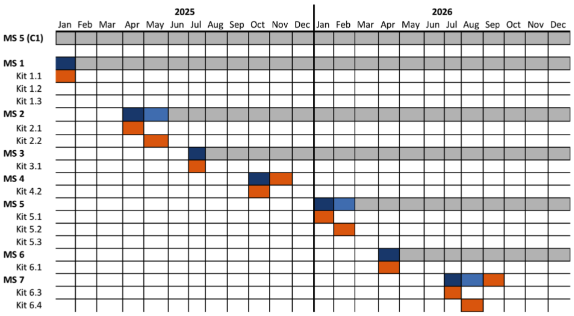

Figure 6. Example of removal campaign using 7 MS and 13 Kits. In this case, most of the MS use passive or semi-active RAAN changes, which take more time than active changes.

In this campaign, due to larger RAAN differences, the active transfers are usually not possible. This reduce the number of debris removed per year to only 6 (8.4 tons). All spacecraft are launched with Soyuz.

The Kits used for this campaigns weights less than 500 kg (wet mass) which is comparable to the mass of a Chaser, they have to provide a ΔV of less than 300 m/s. The Mothership is a much heavier system with a dry mass between 900 kg (1 Kit) and 1600 kg (4 Kits). The propellant maximum capacity is between 450 and 2600 kg. This spread of the masses shows that several categories of Mothership are required.

In these example, the typical power consumption of the Kits is less than 120 W and the one of the MS is around 600 W.

8. RESULTS AND CONCLUSION

The results are still under evaluation by the consortium. The results will include the typical dry masses and propellant capabilities of each type of ADR spacecraft; the achievable removing cadence (in debris per year) as well as the cost per debris and the cost per mass removed.

The final conclusion of the OTV-2 study will come with the results from the cost analysis. However, some trends can be extracted from the outputs of TCAT. First of all, it is interesting to note that the differences between the Chasers and the Kits in terms of mass are very small. It is thus likely that multiple Chasers stacked in a launch vehicle is an attractive option. The Chaser is also appealing due to its parallel functioning which can be faster than what is achievable by the MS, which is a serial process. The risks seem to be lower as well since a failure of one Chaser does not impact the mission of the others. However other selection criteria will be taken into account in the technical/economical evaluation, which may lead to different conclusions.

During the analysis, the RAAN spread quickly became a major driver in the mission duration. It is very important to optimise the path between the debris and the launch dates whilst taking into account the RAAN spread and its variation over time. Within the mission design module, a cost function allow to optimise the strategy by choosing between active, passive and semi-active changes. A future version of TCAT is planned to ensure that the drift orbit, in the case of a semi-active change, is optimised as well.

Regarding the method of capture, the impact at high level is very low. Each method has pros and cons but only a finer and deeper analysis will lead to the selection of one over the other.

The choice of the propulsion system seems a little bit more obvious. With ΔV in the order of magnitude of less than 3 km/s, the gain in terms of propellant mass, due to the higher Isp of the electric systems, is not sufficient to compensate the large power subsystem required to supply them. Moreover, the fact that a bi-liquid system must be added to the electric one in order to ensure a controlled re-entry increases the mass and the complexity of the system. In this case, the bi-propellant propulsion, which also allows shorter transfer durations, seems to be a better option. For the de-orbiting function, the bi-propellant system looks once again to be the best solution because it is easier to control than a system with solid propulsion.

Once again, these are only technical conclusions based on TCAT results. The cost analysis will add another level to the trade-off and will lead to the final ranking of the architectures.

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