OPTIMIZATION OF TETHERED DE-ORBITATION OF SPENT UPPER STAGES: THE "MAILMAN" PROCESS

Christophe Bonnal[(1)] - Sophie Missonnier[(2)] – Bruno Malnar[(2)] – Matthieu Bullock[(2)]

[(1)] *CNES Launcher Directorate – 91023 Evry, France- christophe.bonnal@cnes.fr*
[(2)] *BERTIN Technologies, BP 284 – 78053 Saint Quentin-en-Yvelines, France- missonnier@bertin.fr*

ABSTRACT

Spent upper stages in highly inclined orbits represent a major threat for future evolution of orbital debris population: their lifetime in orbit is important and they are a major source of new debris following cascading effects of in-orbit collisions.

Active de-orbitation of these stages with conventional propulsion is costly energetically and appears not viable today; solutions based on electro-dynamic tethers also have limited efficiency for very high inclinations.

A concept based on passive momentum-transfer tethers is proposed. A chaser goes from stage N to stage N+1 using optimally the reaction induced by the tethered de-orbitation of stage N. Performing such optimal transfers at optimal time intervals enables to maximize the number of de-orbited upper stages for one given time period and size of the chaser.

The theoretical approach is based on an optimization with variable weighting factors. The numerical modeling and optimization algorithms are described. A simulation is given with a realistic batch of spent stages and old satellites extracted from the Two Line Element catalog. The corresponding expected overall performance is given and commented.

High level requirements of the chaser are described, and the critical aspects are identified; potential solutions are proposed leading to a short list of open points requiring additional R&D effort.

A global economical evaluation is also performed, leading to an assessment of the overall efficiency and attractiveness of this concept.

1. INTRODUCTION

1.1. Debris cascading effect in Low Earth highly inclined Orbits

One of the most critical zones in terms of debris proliferation around the Earth in the highly inclined Low Earth Orbits zone, either Polar Orbits or Sun Synchronous ones. These zones have been and still are extensively used since the early days of astronautics and present the highest debris concentrations around the Earth.

The spent upper-stages and old satellites left in these orbits represent a specific danger for future debris density evolution due to the cascading effect associated to collisions: experts have shown that Hyper Velocity Impacts may trigger the generation of debris masses more than 100 times larger than the impacting mass. Large intact stages and satellites, with masses in the range of several tons each, can therefore be seen as "nest" for future debris, as long as they remain in orbit.

These zones may even witness a kind of chain reaction effect: debris are regenerated by collisions or by explosions of large structures; unfortunately, at such high altitudes (≥ 800 km), residual atmosphere is so weak that there is only a very limited natural cleaning effect.

International regulations, widely agreed at IADC and UNCOPUOS levels, recommend to leave objects in LEO, after passivation, in orbits such that their remaining lifetime will be lower than 25 years.

It is therefore felt that dedicated efforts should be carried out in order to reduce the in-orbit lifetime of the already existing large debris, i.e. spent upper-stages and old satellites, in the region of highly inclined high altitude orbits.

1.2. Potential solutions for reducing the debris population in orbit

Numerous solutions have been studied in the past years, or still are, to remove these debris from orbit:

- Existing chasers:

The use of existing chasers either manned (US Shuttle, Russian Soyuz) or unmanned (Russian Progress) is unpractical due to limitations in accessible orbits: the high altitude Sun Synchronous Orbits are out of range of these vehicles; furthermore, the efficiency of their use is highly questionable, a mission costing several hundreds of M€ for a very limited number of de-orbited spacecrafts,

- ATV - HTV:

The use of the European ATV or the Japanese HTV (or any similar vehicle potentially developed in near future) is more credible: they can be launched towards any orbit, limited only by performance, and are by definition capable of performing rendez-vous. A dedicated berthing tool could enable the catching of unprepared large debris.

Nevertheless, the efficiency of such techniques is also questionable: the flight profile to adopt imposes that half the available ΔV is devoted to re-orbit the chaser after the de-orbitation boost. For instance, considering an ATV derived large chaser of 20 tons, including 10 tons propellant feeding a storable propulsion system, the de-orbitation capacity would be limited to 7 debris of 2 tons each. Paying some 300+ M€ to get rid of only 7 debris is not economically viable,

- De-orbitation propulsion kits:

Imagining a chaser dispensing small propulsive modules on the debris would roughly double the number of de-orbited debris, but would lead to a drastic increase of the overall cost,

- Electro-Dynamic Tethers:

EDT are promising solutions for future and are well studied throughout the world: ideas of adding a dedicated de-orbitation kit to an existing debris have been studied by Tether Unlimited, Inc with the Remora Remover™ concept in 1998 or more recently by Kibe et al. from JAXA with their Active Removal Systems. EDT nevertheless cause problems for SSO class of debris, their efficiency being limited for altitude higher than 1000 km and inclinations higher than 75°; their long time mechanical stability is also questionable; furthermore, even though they decrease significantly the lifetime in orbit of the debris, they increase its cross section leading to some doubts on the real efficiency of the system considering a criteria such as "probability of collision

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

over the orbital life-time"; last, their efficiency has never yet been demonstrated in orbit, the only experience so far (TSS-1R in 1996) being only a partial success.

1.3. Passive momentum transfer tethers

Passive tethers have been experienced numerous times in orbit so far: the SEDS-1 experiment, in 1993, demonstrated successfully the capability of de-orbiting an object from a mother satellite using a passive momentum transfer tether 20 km long. The principle consists in "forcing" two objects to follow trajectories imposed by the orbit of their centre of mass; when the tether is cut, the upper object raises its apogee as the lower one lowers its perigee.

The process can be improved if the unreeling of the tether is performed with a velocity such that the Coriolis effect bends the tether frontward up to 60°. This swinging tether effects adds a significant negative ΔV to the de-orbited object when the tether is cut at maximal tip velocity.

One demonstrates that when de-orbiting a mass small with respect to the Mother satellite mass, the perigee of the de-orbited mass can be lowered by an altitude equal to 14 times the length of the tether.

For instance, de-orbiting a spent stage with a large chaser from an 800 km altitude using a 30 km swinging tether would lower its perigee to 380 km, reducing the orbital lifetime from 200 to 3 years (typical values).

Ideas of using passive tethers to de-orbit debris have been published extensively since decades.

A very nice global demonstration is expected to be flown soon: the YES-2 experiment, led by Delta-Utec under ESA contract, will demonstrate the controlled de-orbitation of a re-entry capsule from a Russian Foton satellite, using a swinging tether (www.yes2.info).

This idea can even be improved, the chaser "jumping" from one debris to the following one thanks to swinging tethers. It is studied here under the nickname of the "Mailman" Process.

2. PRINCIPLE OF THE "MAILMAN" PROCESS

"In good old days in the French country-side, the Mailman, on his bicycle, had a hard time determining the best way to link all the houses he had to visit.

The optimal way was not the shortest in distance but the easiest effort-wise, function of the welcome received from the various houses he visited : depending on the coffee or the Calva he was offered and the time he had to rest, he had the courage to do the hardest legs of his trip first. His experience led him to choose a sequence depending on a global optimization with weighting factors associated to the visited houses".

This idea of an optimization with variable weighting factors depending on the targets can be applied to the de-orbitation of debris with passive tethers: a chaser goes from one debris N to the following one N+1 thanks to a maneuver greatly benefiting from the ΔV saved thanks to the use of the passive tether used to lower the orbital lifetime of the debris N.

By choosing properly the sequence of debris, the respective length of tethers used for each of them, and the proper waiting times necessary for RAAN shift, the number of lowered debris can be maximized for one given size of the chaser.

Three "tools" are used in the optimization process:

- First tool: the chaser propulsion system.

In this study, a standard chemical propulsion system is considered. This system may perform the necessary incremental velocity changes to bring the chaser to the appropriate orbit. It may be used to change the perigee and apogee of the orbit, the inclination angle, the RAAN and the final capture maneuvers.

- Second tool: the tether.

When the tether is cut, it lowers the perigee of the debris' orbit and increases the apogee of the chaser's orbit. The tether deployment length may be selected in order to reduce the amount of propellant necessary to move the satellite to the next debris. The tether length must however exceed the minimum one necessary to lower debris' orbit perigee such that the debris will de-orbit in an acceptable time period.

- Third tool: the difference in the motion of the chaser and target created by orbit perturbations.

The most useful one is the difference is RAAN precession rates (RAAN precession being function of inclination and semi major axis); for the orbits considered here, it is in the order of 1°/day. Thanks to this phenomenon, one can wait until the RAAN of the orbits of chaser and target align.

A schematic example of such an operation is given in Fig.1.

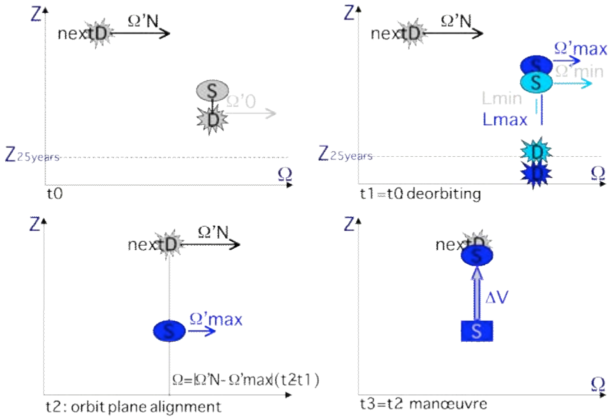

Figure 1. Schematic of the dual optimization using tether and waiting time

3. MODELLING

3.1. Hypotheses

- Chaser definition:

The preliminary evaluations presented here were made considering a typical full payload of the Ariane 5 launcher, including the expected improvements at the operational date, on highly inclined Low Earth Orbit, in the typical range of 20 tons; in principle, the chaser is somehow similar to the ATV developed by ESA. We considered an initial propellant mass of 10 tons. Of course, final de-orbitation of the chaser is taken into account.

- Debris population:

One of the main problem associated with debris is to know precisely when a spacecraft becomes a debris! The initial simulations were performed considering only the spent upper stages population; in a second phase, satellites launched more than 30 years ago were also included.

Debris located in Low Earth Orbits with perigees and apogees between 550 km and 1600 km are considered in this study. As shown in Fig.2, the debris are clustered around two inclination zones: polar and SSO.

Given the high cost of inclination corrections (~130 m/s for 1°), shifting inclination between 90° and 98° would

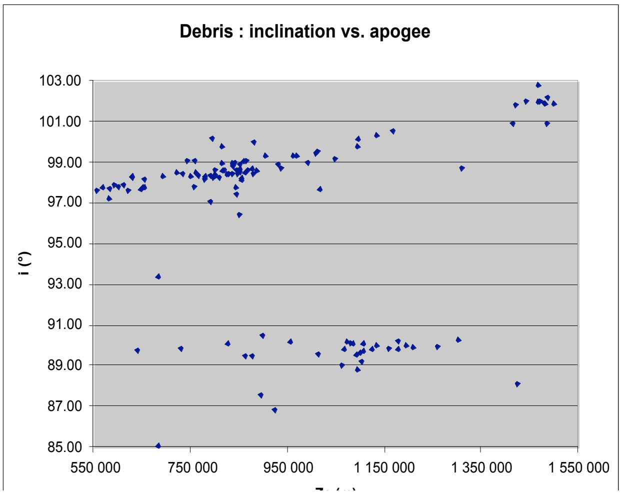

Figure 2. Debris population considered initially

spend more than 1000 m/s, which represents half of available propellant. For that reason we chose a priori to exclude the thirty or so debris which inclination is around 90°. We restrained our list to debris with inclination comprised between 95 and 103°. We also chose to keep only debris on circular or quasi-circular orbit, since apogee and perigee changes can be very costly in terms of propellant consumption. Our criterion is an eccentricity lower than 7.10^{-3}, which roughly means that apogee differs from perigee by less than 100 km.

The initial debris list includes 109 elements; a variant with 146 debris was also studied; a standard debris mass of 2 tons was assumed.

- Sequence constraints:

In order not to model in details the rendez-vous phase, it was assumed that a 20 m/s ΔV is required for the final phase of each rendez-vous, and that at least one week is required between two consecutive de-orbiting.

- Mission constraints:

Initial operating capability is assumed in 2015. The complete mission duration was chosen initially as 15 years; evaluation of the extension to 20 years was done.

The tethers considered for the study are standard SEDS type 30 km long; the influence of an increase in length was studied

3.2. Problem definition

The objective can be expressed with the following statement :

"Find the scenario in which a maximum number of debris are de-orbited for a given amount of propellant during a given time interval."

We can formulate our problem in this way:

Let $c(t)$ $(a_c(t), i_c(t), \Omega_c(t))$ the chaser orbit and D the list of d debris' orbits $(a_d, i_d, \Omega_d(t))$ with $i_d \in [90°, 180°]$,

Let $\Delta V(c,d,t)$ the velocity change needed to get $a_c(t) = a_d$ and $i_c(t) = i_d$, $d \in D$

Let $\Delta T(c,d,t)$ the waiting time needed to get $\Omega_c(t) = \Omega_d(t)$

We try to find a sequence of debris $d_0, d_1, d_2, \ldots, d_n$ successively tethered which solve:

$$\mathrm{Min} \sum \left(\alpha\, \Delta V(c, d_j, t) + \beta\, \Delta T(c, d_j, t) \right)$$

for $t \in [t_0, t_{max}]$

With $\sum \Delta V < \Delta V_{Max}$ and $\sum \Delta T < \Delta T_{Max}$

3.3. Problem resolution

Let i $(a_i, i_i, \Omega_i(t_i)) \in D$ a debris with a mass M_i tethered, at instant t_i, to the chaser c with a mass $M_c\ (t_i)$ with a tether L_i long.

Then after de-orbiting at $t_d = t_i + \delta t$,

$$a_c(t_d) = F(a_i, L_i) \approx a_i + 7\, L_i \,.\, M_i \,/\, (M_c\,(t_i) + M_i)$$

then $a_c(t_d) > a_c(t_i) \approx a_i$

$$a_i(t_d) \approx a_i - 7\, L_i \,.\, M_c\,(t_i) \,/\, (M_c\,(t_i) + M_i)$$

then $a_i(t_d) < a_i(t_i) \approx a_i$

Remarks: let P_i and A_i the perigee and the apogee of the debris i before de-orbiting:

$$P_i(t_d) \approx P_i - 14\, L_i \,.\, M_c\,(t_i) \,/\, (M_c\,(t_i) + M_i).$$

The life-time of the debris i will be reduced to less than 25 years if $P_i(t_d)$ is lowered to an altitude P_{min} function of A_i.

$$L_{min}(i) = (P_i - P_{min}(A_i)).(M_c(t_i) + M_i)/(14.M_c(t_i))$$

$i_c(t_d) = i_c(t_i) = i_i$

$\Omega'_c(t_d) = -9{,}97(R_\oplus / a_c(t_d))\text{^}3{,}5 \times \cos(i_c(t_d))$

then $\Omega'_c(t_d) < \Omega'_c(t_i) \approx \Omega'_i$ for $i_i \in [90°, 180°]$,

$\Omega'_c(t_d) = F(a_i, L_i) = -9{,}97(R_\oplus / F(L_i))\text{^}3{,}5 \times \cos(i_i)$

Let j $(a_j, i_j, \Omega_j(t)) \in D$ another debris and t_r such as $\Omega_c(t_r) = \Omega_j(t_r)$

$\Delta V(c,j)$ the velocity change needed to get $a_c(t_r) = a_j$ and $i_c(t_r) = i_j$, $\Delta V(c,j)$ is a function of $a_c(t_r)$, a_j, $i_c(t_r)$, i_j.

Now $a_c(t_r) = F_T(a_i, L_i)$ therefore $\Delta V(c,j)$ may express as a function of a_i and L_i

So, knowing the debris i where the chaser c is tethered, $\Delta V(c,j)$ may simplify into a function of L_i,

i.e. $\Delta V(c,j,) = F_V\,(L_i)$.

$\Delta T(c,j) = t_r - t_i$ the waiting time needed to get $\Omega_c(t_r) = \Omega_j(t_r)$ since c was tethered to the precedent debris i then $\Delta T(c,j) = t_r - t_d + t_d - t_i$ where t_d is the de-orbiting time.

Now, we need to consider two cases:

1. If i is de-orbited right after it was tethered to c:

$t_i \approx t_d$ and $t_r - t_i \approx |\Omega_c(t_i) - \Omega_j(t_i)| \,/\, |\Omega'_c(t_d) - \Omega'_j|$

Now $\Omega'_c(t_d) = F_\Omega(a_i, L_i)$ therefore

$\Delta T(c,j) = |\Omega_c(t_i) - \Omega_j(t_i)| \,/\, |F_\Omega(a_i, L_i) - \Omega'_j|$

and $\Delta T(c,j,t_r)$ may express as a function of a_i, t_i and L_i

2. If i was de-orbited right before t_r :

$t_r \approx t_d$ and $t_r - t_i \approx |\Omega_c(t_i) - \Omega_j(t_i)| \,/\, |\Omega'_c(t_i) - \Omega'_j|$

Now $\Omega'_c(t_i) \approx \Omega'_i$ therefore

$\Delta T(c,j,t_r - t_i) = |\Omega_c(t_i) - \Omega_j(t_i)| \,/\, |\Omega'_i - \Omega'_j|$

and $\Delta T(c,j)$ may express as a function of a_i and t_i

So, knowing the debris i where the chaser c is tethered, $\Delta T(c,j)$ may simplify into a function of t_d and L_i , $\Delta T(c,j) = F_T(L_i, t_d)$

This can be solved with the following algorithm:

a. Choose the debris' list corresponding to a launching date of the mission, and an initial debris d_0 which the chaser is tethered to. $T(d_0) = 0$, $\Delta V(d_0) = 0$
   Choose ΔV_{max} and T_{max}

b. For i = 0 to n:

   b.1. For each d_j debris left in the list, solve:
   Cost (d_j) = Min $(\alpha(t).F_V(L_i) + \beta(t).F_\Omega(L_i,t_d))$
   over (L_i, t_d) with $L_i \in [L_{min}(i), L_{max}]$

   b.2. Find: Cost(d_c) = Min Cost(d_j)
   for all d_j debris left in the list

b.3. Calculate $\Delta V(d_c) = \Delta V(d_i) + F_V(L_i)$ and
$T(d_C) = T(d_i) + F_\Omega(L_i, t_d)$

b.4. If $\Delta V(d_C) < \Delta V_{max}$ and $T(d_C) < T_{max}$

Then $d_{i+1} = d_C$

Else Stop the mission

As we will see after, the following parameters have a strong influence on the results:

The choice of the initial debris d_0 is maybe the most influent but it can be performed easily before launching the mission by a test on all debris in the list,

- The choice of the launching date of the mission is important since it will have an impact on the size of debris' list,
- The choice of T_{max} gives more flexibility in debris' selection by allowing more waiting time to reduce the consumption,
- The choice of L_{max} gives more flexibility in debris selection by a larger choice of intermediate orbits for shortening waiting and reducing consumption,
- The choice of $\alpha(t)$ and $\beta(t)$ defines the meaning of selection criterion:

If $\alpha(t)=\alpha(N_{debris}/\Delta V_{max})$ and $\beta(t)=\beta(N_{debris}/T_{max})$ where N_{debris} is the number of expected de-orbited debris, it means that we allow a fixed quantity of propellant and a fixed waiting delay for each debris's de-orbited processing.

The choice of the value of α and β gives a weighting of the criteria:

$\alpha(t)= \alpha/(\Delta V_{max} - \Delta V(t))$ and $\beta(t) = \beta/(T_{max} - T(t))$ adapt the choice of the next debris selected according to the mission's advancement.

The choice of the value of α and β gives a weighting of the criteria. This option appears to be the best parameters set on our input data, with α=1 and β=1. It would be interesting to keep on working on this criterion definition to foresee and avoid dead ends.

3.4. Simulation results

- Sensitivity to the choice of first debris:

The total amount of debris de-orbited during a mission strongly varies according to the choice of initial debris. That is why we test all debris as starting point.

The options can be easily analyzed and the choice optimized before launching.

Fig. shows on vertical axis how many missions resulted in the score of corresponding abscissa, in terms of tethered debris.

- Sensitivity to the maximum tether length:

Simulations have been performed with maximum tether lengths of 30 and 100 km. The following quantitative results have been obtained:

- for 100 km : 40 debris maximum can be tethered. Consumption is the stop criterion for the mission
- for 30 km : 32 debris maximum can be tethered. Consumption is the stop criterion for 60% of missions.

It is important to note that among the 109 debris to be de-orbited, the 30 km tether is not long enough to lower some of them to a suitable orbit (an orbit that will allow the debris to de-orbit within 25 years): only 64 debris can be correctly de-orbited with a 30 km tether (78 with a 50 km tether).

A length of 80 km is required to have the possibility of successfully de-orbiting all 109 debris.

On the other hand, even if life-time of such "high" orbits (altitude higher than 1400 km) cannot be shortened to 25 years, it is still interesting to reduce it.

A 100 km long tether allows for the de-orbiting of all debris on the list and also gives the maximum number options for selecting debris. One has a great number of options (where to place the chaser when the tether is cut) to shorten the waiting time and to reduce consumption. A 30 km long tether is not adequate to de-orbit all of the debris and the tether length is not found to be worth being optimized.

- Sensitivity to the maximum mission duration:

The extension of the maximum mission duration from 15 to 20 years enables the following results:

- 39 debris maximum can be tethered.
- The consumption is generally the stop criterion for the mission (57% consumption),

Qualitatively, it has been found that the increasing the mission duration gives more flexibility in debris' selection by allowing more waiting time to reduce consumption. It, of course, allows to continue missions previously stopped by time criterion.

- Sensitivity to the mission start date:

The influence of a late, but realistic, launch date in 2015 was assessed. For this case, the debris list is updated to take into account new debris (20 more rocket bodies randomly chosen among probable orbits) and satellites that have become "older than 30 years". The new list amounts to 146 debris.

The following quantitative results have be found:

- 40 debris maximum can be tethered
- Consumption stops 80% of the missions

Qualitatively, it has been found that the larger choice gives more flexibility in debris' selection.

- Sensitivity to a combination of these parameters:

Using simultaneously a maximum length of tether of 50 km, a maximum duration of mission of 20 years and a launch time in 2015 (using the list of 146 debris) gives of course excellent results:

- 44 debris at least can be tethered (68% mission de-orbit more than 30 debris).

Qualitatively, it has been found that The combination of larger choice in debris' selection and relaxed time-constraint leads to success. Dead-ends may remain blocking, even if they are less frequent since they benefit from the longer duration.

- Summary of the results:

The following Table 1. recalls the results obtained with different constraints:

- Conclusions for the modeling aspects:

Several aspects may be improved in the next phases:

. The maximum number of debris de-orbited during a mission may not be the best argument to determine preferable conditions, or to choose initial debris. One has, for instance, to maximize the robustness of these scenarios, taking into account uncertainties in orbital parameters at the beginning of the mission. It may be interesting to derive a guarantee level criterion that the started mission's final score will keep high enough.

. Work on debris' selection criteria, to foresee and avoid dead-ends is necessary in the following phases.

. And of course, a more realistic simulation taking into masses' ratio, to deal with heavier and higher debris first, while chasing satellite is heavy.

Mission's hypotheses	Maximum number of debris	More than 30 debris deorbited	Sensitivity results
Duration : 15 years Launch time : 2005 (63 R/B and 46 Satellites) Tether's Max length = 50 km	38 de-orbited	23%	
Duration : 15 years Launch time : 2005 (63 R/B and 46 Satellites) **Tether's Max length = 100 km**	40 de-orbited	32%	1 - Permits to de-orbit all tethered debris (~80 km is enough) 2 - Gives more flexibility in debris selection by a larger choice of intermediate orbits for shortening waiting or reducing consumption
Duration : 15 years Launch time : 2005 (63 R/B and 46 Satellites) **Tether's Max length = 30 km**	32 de-orbited	6%	Generally not enough to de-orbit tethered debris. The tether length is not worth optimising
Duration : 20 years Launch time : 2005 (63 R/B and 46 Satellites) Tether's Max length = 50 km	39 de-orbited	45%	Gives more flexibility in debris' selection by allowing more waiting time to reduce consumption
Duration : 15 years **Launch time : 2015 (83 R/B and 63 Satellites)** Tether's Max length = 50 km	40 de-orbited	49%	Gives more flexibility in debris' selection by a larger choice of debris
Duration : 20 years **Launch time : 2015 (83 R/B and 63 Satellites)** Tether's Max length = 50 km	**44 de-orbited**	68%	

4. CONCEPT OF THE CHASER

4.1. Identification of the target

Since the targets are exclusively integer spacecrafts (spent upper stages or old satellites), we can assume that their geometrical definition is perfectly well known. Some minor discrepancies may occur between theoretical modeling and practical, such as residual propellants, tilting of the main engine or slight wear of surfaces (thermal protections), but these side effects may be considered as secondary.

The complete identification of the target may therefore be performed thanks to stereoscopic vision of the target, and comparison with the theoretical figure.

Kibe et al. showed the efficiency of such an identification as a function of the lighting conditions, and even performed simulations on ground.

4.2. Tumbling

If the target is tumbling with a high energy, it may prevent a proper rendez-vous and berthing. Flat spin can generally be encountered when a stage is left in orbit with a spin along an axis not presenting the highest inertia and with an important quantity of residual propellants; a divergence of nutation may then be encountered, leading to a stable flat spin.

Hopefully, this combination is not very frequent: we believe for instance that only some 10% of the spent Ariane 4 upper stages are currently in flat spin, and none of the Ariane 5 one.

This tumbling may probably be detected in advance thanks to ground optical or radar observations: flash or variable RCS

In addition, Kibe et al. explained that thanks to the help of a robotic arm, a low energy tumbling motion may be countered using properly small interactions on the target.

A very similar idea was studied by TRW in the 80’s with the version of the OMV aimed at recovering hazardous payloads.

It is however recommended to consider that typically 20% of the target population will be disregarded before the selection of the next target, and that a remaining 10% population may not be caught once on location.

4.3. Interfaces between chaser and target

Two robotic arms may be used for the attachment of the tether to the target:

- The first one will catch the target on a pre-planned location thanks to an ad-hoc grapple; it may also be used to stop the remaining movement of the target
- The second one will be used to install the tether in its location on the chaser. It is proposed to use a stinger-like interface, expanding structure or even fast-curing foam, expanding in the combustion chamber of the main propulsion of the target. If properly realized, it will guarantee that the tether will be aligned with the center of gravity of the target. This is important for the initial deployment phase to avoid erratic, un-damped movements

4.4. General description of the chaser

The chaser concept may easily be drafted considering sub-systems already existing on ATV, qualified for the Japanese ETS-7 automatic rendez-vous demonstration in 1997, or just based on the enormous experience gathered by Russia with Progress docking to various Stations.

The major features would be the following:

- Dual mode main propulsion MON-MMH or LOX-Methanol (if storage of LOX during decades is practical),
- 6 DOF redunded Attitude Control System based on the same propellant couple, used for final rendez-vous,
- two or three cameras enabling stereoscopic reconnaissance of the target, maybe coupled with flood-lights,
- Solar-Generators coupled with batteries enabling proper functioning in sunny phases as well as during eclipses,
- two robotic arms, one used to catch the target, one used to install the stinger inside the target nozzle and to provide the separation ΔV,
- telecom to the ground: the most critical phases may require to be performed under real-time monitoring, or maybe even remote-controlling from ground,
- classical GNC, potentially with GPS, as already used on ATV,

The payload itself would consist in a rack of 37 tether canisters similar in principle to those used for the SEDS experiments, arranged following an hexagonal pattern; then, the maximal distance between any canister and the axis of the chaser is less than 1 m.

The servitudes used for the tether deployment would be common to all tethers (brake, tension measurement, cutter) and the robotic arm would just go and fetch one tether tip after another.

This solution of multiple tethers is felt much more robust than considering the reeling back of a reusable tether.

4.5. Open points

Obviously, there are thousands of aspects to verify and demonstrate before confirming the interest of such a concept.

Among the most critical aspects:

- A swinging tether may have a limitation in its length due to the deployment time. Standard values show that a swinging tether of 20 km may be deployed in 90 minutes, say one orbital period. The risk of encountering strong perturbations due to the dynamics of the tether increase drastically when this duration increases.
- Nominally, the de-orbited debris remains attached with the full length of its tether during its remaining life-time: this is obviously unacceptable, since it increases strongly the collision risk with other satellites. The idea of finding a tether material sensitive to UV, thus "melting" when exposed to the sun, has been studied by Delta-Utec but with no decisive conclusions. Maybe one could then imagine a way of polluting the tether just before its deployment thanks to a chemical reaction taking place in its container… Nevertheless, some R&D effort is required in tis domain.

Some potential improvements have also been identified:

- It is felt today that considering a dry mass of 10 tons for the chaser, for 10 tons propellant, is far to conservative. More precise figures derived from the ATV for instance show that the dry mass could be lowered by a factor of 2 and lead to an increase in propellant mass.
- Since the chaser has to perform a very long mission, it will be equipped with large Solar Generators; it is therefore interesting to consider the use of additional electrical propulsion (Hall effect engines for instance) to optimize the large transfers from the higher altitudes to the lower ones, including the final de-orbitation.

5. PROGRAMMATICS ASPECTS

A very preliminary evaluation of the programmatics aspects can be attempted:

- The early consolidation study phases could require 3 years during which proof of interest and proof of feasibility would be performed. It is mainly during this period that the R&D relative to the tether material shall be performed,
- The development would typically take 7 years, which is relatively short, considering all the already existing technologies and hardware,
- The manufacturing could be shared between various countries, under an international cooperation agreement reflecting the existing knowledge on similar topics,
- Considering "Western" figures, the development and manufacturing of the Chaser could cost some 250 M€ (no new development on engines, telecoms, aso…),
- Its launch with one of the large available "Western" modern launcher could require some 100 M€,
- The operations during the complete lifetime will also be expensive: considering a network of existing control-centers coordinated by a dedicated one, 50 people full time during 20 years would lead to roughly 150 M€

The grand total mission cost would therefore be in the range of 500 M€ to de-orbit maybe 50 spent stages and satellites… Is 10 M€ / debris an attractive value ? Maybe not.

On the opposite, reconsidering the above figures in a worldwide cooperation scheme, where each space faring country would take a significant share (launch by China, development in Russia, Integration in Europe, Propulsion from India, Structures from Ukraine, Robotics from Japan, Control from USA…) could decrease these figures by a factor 5 or more.

Then, leaving a clean space to our children in a joint worldwide effort, spending a couple of M€ per debris, could be worth it on every aspect, technical, economical and political (IADC-Sat ?).

6. RECOMMENDATIONS

The "Mailman" process described here, based on optimisation with variable weighting factors, could enable the reduction in lifetime to less than 25 years of up to 50 large debris, spent-stages of dead satellites, for one single Chaser mission, considering only in-flight demonstrated techniques.

It is first recommended to check with the ad-hoc specialists whether the idea does present any interest ! Simulations are necessary, led for instance by IADC WG2, in order to compare long term evolutions of the SSO zone with and without the progressive removal of 50 large spent stages and satellites.

If this action turns out to be positive, it is recommended to task an international working group, maybe sub-part of IADC WG4, to lead industrial studies aimed at reaching the overall proof of feasibility.

Last, it is proposed to identify in which frame such a development in worldwide cooperation could be proposed: it could be tasked by IADC SG, with ad-hoc Terms of Reference, or performed through a UNCOPUOS led initiative.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the work done in the early phases by Fanny Pille, Erwan Kervendal and Amélie Sergent, students from the French engineer school ESTACA.

The authors wish to thank their colleague Jacques Borromée (Hynov) for his precious help and advises, mainly on theoretical aspects.

ACRONYMS

ATV	Automated Transfer Vehicle
DOF	Degree Of Freedom
EDT	Electro Dynamic Tether
GNC	Guidance, Navigation and Control
HTV	H-II Transfer Vehicle
IADC	Inter-Agency Space Debris Coordination Committee
LEO	Low Earth Orbit
RAAN	Right Ascension of Ascending Node
RCS	Reaction Control System
R&D	Research & Development
SSO	Sun Synchronous Orbit
UNCOPUOS	United Nations Committee for Peaceful Use of Outer Space

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