INSIDeR, the Innovative Net & Space Inflatable structures for active Debris Removal

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ABSTRACT

Hundreds of thousands of debris are currently orbiting the Earth and their number is growing day by day because of scientific and commercial exploitation of space. Therefore, the need to perform Active Debris Removal (ADR) to stabilize the environmental effect and mitigate risks of a Kessler syndrome is real. To perform ADR, the idea proposed here is a new solution to safely deorbit space debris of various sizes using a capture system named INSIDeR, the Innovative Net & Space Inflatable structures for active Debris Removal.

INSIDeR is a patented concept, combining two key technologies:

- A net acting as capture system able to cope with large objects and to fit with different debris morphologies and tumbling rates
- Inflatable structures acting as deployment system ensuring control of the net movement, with a ring and two masts.

A deorbitation tether is used once the debris is captured to transmit the deorbiting loads.

This system relies on advantages of combining net and inflatable structures concepts, relative to:

- Adaptability to the debris target: adaptable to debris mass, size, and spin/tumbling rate
- Controllability during approach and damping of debris movement during coupling
- Adaptability to any ADR concept: INSIDeR is a kit box of about 50 cm edge that can be plugged on any system for mono or multi-debris removal chaser

This paper presents the results of the study to develop one version of the concept and assess its feasibility conducted by CT Ingénierie under an ITI for ESA.

More specifically, the paper first presents the concept in more details, with the context of use of such a technology and its advantages of flexibility and risk reduction. The architecture of the system and the sizing of the main elements are described. Then, the approach, capture and deorbitation scenarios with INSIDeR are presented, highlighting the differences with other ADR concepts. This includes a sensitivity analysis on several parameters, such as the approach speed. The requirements on the chaser platform, mainly in terms of deltaV and of manoeuvrability and attitude control, are also defined.

The capture sequence is also investigated, showing the results of the net capture simulation performed on ABAQUS software. These simulations have been performed to prove the feasibility of the concept and to identify the advantages of the net slow dynamic achievable with INSIDeR.

Eventually, the foreseen technology gaps and development roadmap are presented in this paper. It shows that each technology is individually already quite mature, which shortens the development roadmap of the system. The low maturity of this concept is at system level, at the interfaces between a tether, a net and inflatable structures, for this specific application. The conclusion discusses on the overall feasibility and on the future steps required to develop this technology.

1 CONTEXT

The idea is a new solution to safely deorbit space debris of various sizes using a new capture system named INSIDeR, Innovative Net & Space Inflatable structure for active Debris Removal.

INSIDeR is a patented concept combining two key technologies:

- High-strength flexible net acting as capture system able to cope with large objects and to fit with different debris morphology and tumbling rate;
- Inflatable structures acting as deployment system ensuring control and damping of debris movement.

A system based on the above mentioned key technologies offers technical and operational advantages relative to:

- Mission: INSIDeR can be used as capture kit able to fit on different ADR chaser concepts (mono-mission or multi-mission, chaser or mothership) enabling high controllability during capture and dumping

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sequence which will ensure full compatibility with a wide range of mission scenarios.

- Debris target: INSIDeR is scalable and adaptable to both small and large debris, light or heavy and robust to any object shape and attitude tumbling rate;
- Safety and reliability: INSIDeR capture sequence provide multiple Go/NoGo checkpoints as well as mission abort capability even after the net deployment in case of problem during the very last phase of target approaching;
- System development and qualification: INSIDeR is a simple, reliable and cost-effective solution which relies on an innovative combination of technologies relatively mature ensuring a limited qualification effort. This last point represents one of the main advantages of INSIDeR.

Fig 1. shows the concept of INSIDER.

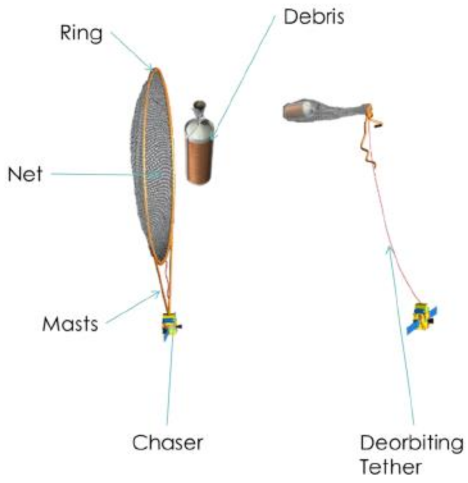

Figure 1: INSIDeR concept

The INSIDeR kit is made up of an inflatable structure, composed of two masts and a ring, a flexible net and a tether linking the capture system to the chaser. This tether is used to transmit the deorbitation loads after the capture

The capture sequence is divided into 6 phases. First, the structure will inflate in order to deploy the net. Once the deployment is confirmed, the chaser will perform the approach boost in order to obtain the right relative speed with respect to the target. Just before contact between the net and the debris, the masts will detached itself from the platform and deflate. Thanks to that, the structure will not prevent the net from wrapping the target and the chaser will not be subject to any stress during the capture. Finally, capture happens and once it is confirmed that the debris is captured and locked inside the net, the chaser can perform the deorbitation boost. This capture sequence is made of multiple Go/NoGo checkpoints that will ensure the safety of the mission. In addition, not having a rigid contact between the chaser and the target ensure that it won't generate additional debris in case of malfunction of the chaser mission or in case of a Collision Avoidance Manoeuvre (CAM).

The main innovation of INSIDeR concept relies on the fact to couple the two key technologies (inflatable structure and flexible net). Therefore, it is of prior importance to define and to specify the interfaces between these technologies. To do so, a Model-Based-System-Engineering has been built using the ARCADIA method. It helped to understand and quantify the impact of such a coupling at system level and to manage the technical specifications of each sub-systems. This approach is presented in the following section.

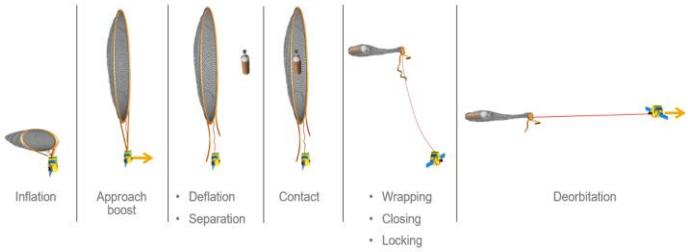

Figure 2: Capture sequence phases

2 MODEL-BASED-SYSTEM-ENGINEERING

The ARCADIA method presents four major steps:

- The Operational Analysis: the analysis of the environment in which our system will evolve.
- The System Analysis: the definition of our system needs.
- The Logical Analysis: the definition of abstract components that will compose our system.
- The Physical Analysis: the implementation of the previous design choices with real components.

The objectives of this paper is not to show the entire deployment of the Arcadia method on the INSIDeR project, but more the results it has provided and how MBSE and Capella have been the central method and tool for the project. Diagrams extracted from the designed model will be used in this paper as a way to illustrate several processes in the functioning of INSIDeR. Some of these diagrams have been simplified for more clarity.

The system functional analysis has been produced in order to understand what the INSIDeR kit was expected to perform. The diagram in **Erreur ! Source du renvoi introuvable.** shows all the functions of the system, and of its external actors (the functional exchanges are hidden for the sake of clarity):

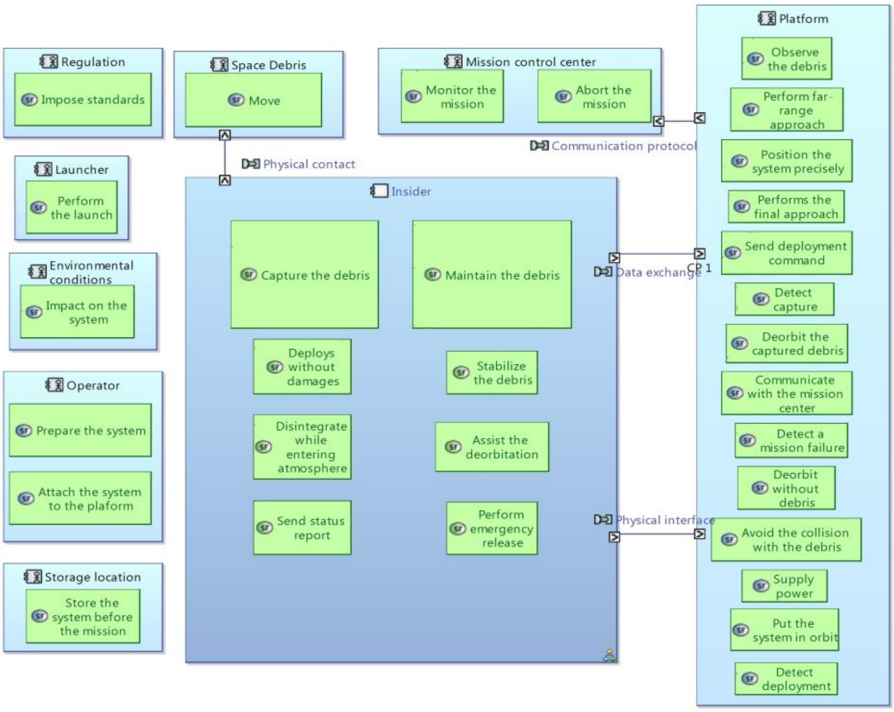

Figure 3: System functions

Within the INSIDeR box are all the system level functions that the INSIDeR system shall perform and that shall be translated into a more detailed functional architecture (Logical Analysis) and a components architecture (Physical Analysis). Around it, the external actors' boxes contain all the functions that are allocated to the entities that interact with INSIDeR during its lifetime. One can see that the platform owns many functions. In the business plan of INSIDeR, it has been decided and assumed that the INSIDeR kit is plugged on a chaser spacecraft. This spacecraft is capable of performing the "services" required for the capture and de-orbitation, such as the propulsive manoeuvers, the mid-range and close range observation of another space object or the communication with the ground.

The next step was the translation of system functions to lower level functions. A proper example of it, is the detailed definition of the functions to perform for a successful capture. The system function "Capture the debris" is detailed into more precise functions corresponding to what the system is expected to perform during the capture process. This is used to answer the question of *HOW* the capture is actually realised. The decisions on what type of capture, active of passive wrapping, the first definition of the contact speed range etc. are decided during this phase. This is shown in the functional diagram below, with in green the functions allocated to INSIDeR during the capture, while in blue the functions allocated to an external actor, either the chaser platform or a ground asset.

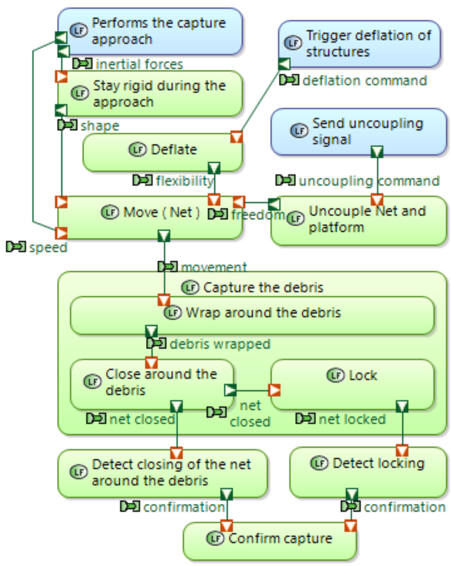

Figure 4: Functional analysis for the capture of the debris

This functional analysis is the beginning of the conceptualisation of the system. Indeed, several choices are made on how to achieve a system function, what actor is responsible for a given function etc… For instance, a major choice in the system is to actively *close around the debris* and passively *lock the net* when the debris is wrapped by the net. This choice has been made to ensure the system function *maintain the debris* during the different phases that follow the capture. Indeed, it has been shown by simulation that due to its spin, the debris risks to reopen the net and "escape" from it.

Performing this functional analysis also requires to parameterise the functions. This include for instance a duration for the deployment or a minimum safety distance for performing the final approach boost. The *close* and *lock* functions have also been parameterised: as the simulations showed a minimum time before the debris escapes from the net, a maximum time for closing this net has been set. Similarly, the force exerted on the net during the different phases following the capture have been assessed and the locking has been parameterised by the minimum force to be resisted. Moreover, the exchanges between functions are also modelled. They define what are the inputs required by the function to be performed and what are the outputs of the functions, used by other functions. This gives the opportunity to draw a concept of operation showing the sequence of event during INSIDeR entire operational lifetime. These functional exchanges are also shown in Figure 4.

A total of 48 functions have been allocated to INSIDeR. This gives the functional architecture of the system.

The physical analysis, that defines the physical architecture, with the elements of INSIDeR and their interfaces, is done in parallel with the logical analysis. Indeed, to be able to provide inputs on the parameterisation of the functions, or to assess the feasibility of a concept choice, preliminary design of components or simulation are often required.

The functions defined in the functional analysis are then assigned to physical components of the system. This answers the question of *WHAT* is realising the functions. Sometimes, the logical functions are further detailed as they are realised by several physical components. The physical components are assembled in sub-systems and altogether produce the product breakdown shown in Figure 5. Note that this figure does not display the functions allocated to each components for diagram clarity.

Figure 5: Product Breakdown Structure of INSIDeR kit

Several functions can be joined together on the same elements if deemed efficient. This is the case for the *close* and *lock* functions that are both realised by the Roller. This is an assembly that includes a cable that is rolled by a spool, itself rotated by a motor while a clutch prevents the spool from unrolling itself. The concept is schematised in the Figure 6.

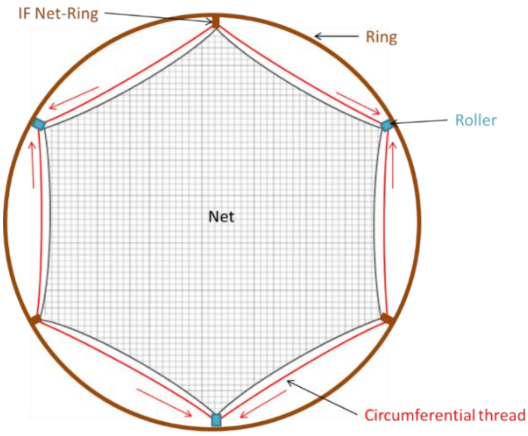

Figure 6: One example of closing system concept

While performing the physical product breakdown of INSIDeR and assigning functions to the different components, the functional exchanges have also been assigned to the physical interfaces between components. This "translation" from functional exchange to physical link is an essential tool for the identification of interfaces. Using Capella, it allowed to identify the interfaces themselves, their type and their criticality but also to assign a port for each end of the IF, ports that can then be conceptualised and designed. The interfaces between the components of the system are described in the diagram of Figure 7.

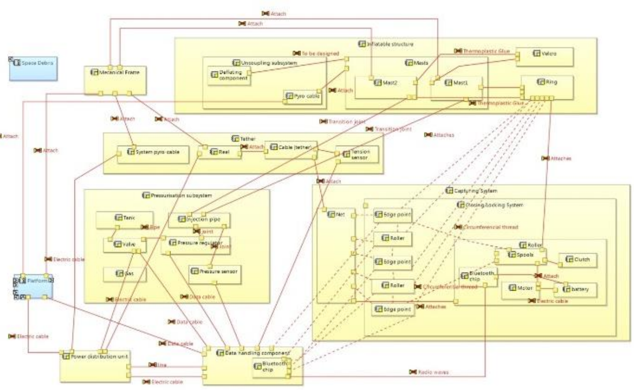

Figure 7: Interfaces

As the objective was to prove the feasibility, most of the mechanical interfaces that have been assessed as non-critical, have not been designed yet, and are labelled as 'Attach' on the diagram. On the other end, several IF have been flagged as critical and a preliminary solution that would ensure the feasibility of the system has been defined, such as the thermoplastic glue between the inflatable masts and the Velcro stripes to keep them folded.

Eventually, the model was also largely used to register and assign parameters resulting from the design analysis. For instance, Capella was used for budgeting the system. Indeed, a mass budget had to be defined and updated with the design outputs, in order to keep track of its total mass evolution and to ensure that the INSIDeR kit stays below the maximum mass requirement, 50kg. The use of Capella for this was to insert a mass parameter for each element of the architecture. The tool could automatically compute the total mass as well as compare the mass of each component with its target mass, defined in the preliminary phases of the project.

3 PRELIMINARY REQUIREMENTS AND REFERENCE TARGET

In order to start the design and the validation of the INSIDeR concept, a first set of preliminary requirements has been established with the European Space Agency. These specifications were made to define a reference debris target as well as some design rules. Some of these requirements are presented on Tab. 1.

Table 1: Selected preliminary requirements

Requirements	Priority
Debris type	Mega constellation SC
Debris max spin	5°/s
Apogee max altitude	1200km
Maximum Relative Position Knowledge Error	1,5m y/z; 5m x
Maximum Relative Position Error	1,5m y/z; 5m x
Max approach speed	2m/s
Minimum opening of the net during capture process	95% of net diameter
Net margin around the debris contact point	2 x debris ref size
Max debris holding duration after capture	few minutes

To define the reference target, a sensitivity analysis on the system mass has been conducted with different kind of debris, from a cubesat to a launcher upper stage like the Ariane 4 H10. The results of this analysis is presented on Tab. 2.

Table 2: Sensitivity Analysis

Debris	**Cubesat**	**Parasol**	**Jason**	**Helios**	**H10**	**Envisat**
Net mass	0.05	1.0	6.0	7.9	9.8	230
Ring mass	0.1	0.9	13.5	11.8	13.4	1 005
Masts mass	0.07	0.5	8.6	7.5	8.5	636
Gas	0.01	0.1	1.4	1.2	1.4	107
Tether	0.02	0.1	1.8	3.8	0.2	7
Others	1	3	5	5	5	15
Total mass	1.25	5.6	36.3	37.2	38.3	2 000

An important mass threshold has been noticed for the system mass between a Parasol-like satellite and an upper stage. Even if a system mass of less than 50kg is acceptable, it has been decided, in accordance with ESA, to focus the design of the system on a OneWeb-like satellite (200 kg). First of all because it appears to be the most suitable target with respect to the system mass, but also because it matches the expected evolution of the NewSpace sector, with a growing number of constellation, and thus debris, planned in a near future. This system can scope with targets in the range of 100 to 1 000kg. The reference target is therefore a OneWeb-like satellite, which is around 200 kg and is a one metre cube with two 2 meters long solar panels.

4 MISSION ANALYSIS

An important part of the study led in the scope of this ITI was to assess the feasibility of the approach and deorbitation phases. This analysis has been conducted considering a typical ADR platform, using classical propulsion unit and GNC system.

The reference for approach and contact in Europe is the ATV (Automated Transfer Vehicle) approach and most debris capture systems use this approach according to literature. This approach has therefore been selected for the INSIDeR concept.

The ATV-based approach is divided into 5 phases:

- The launch, which is not studied in the scope of INSIDeR;
- The phasing, aiming at reducing the orbital phase angle between the chaser and the target;
- The homing transfer;
- A closing which is the acquisition of the final approach line;
- And a final approach.

This last phase is the fundamental difference between the INSIDeR and the ATV approach.

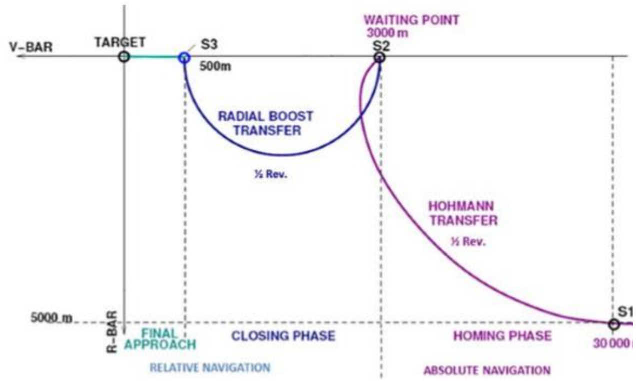

Figure 8: ATV approach

The strategy is to wait at S4 point to characterize debris attitude. Once the GO for deployment is received, the structure and the net can be deployed. As this point is stable (meaning no relative speed between the target and the chaser) the system can check the good deployment of the system before the final GO for capture.

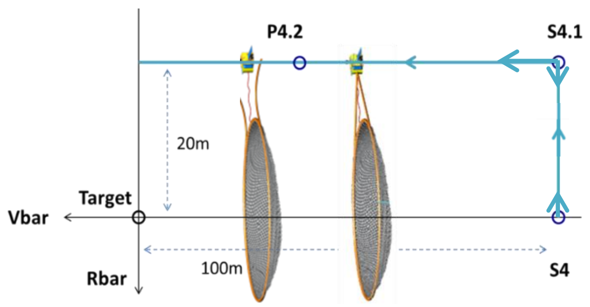

Figure 9: INSIDeR Final approach

An intermediate boost needs to be performed in order to align the target with the centre of the net as the centre of gravity has moved due to the system deployment. The chaser will then go through S4.1 point (Fig. 9) and once it is confirmed that the net and the target are aligned, the final GO is sent and the capture can happen with the deflation and separation of the structure just before contact. Thanks to this sequence, a Collision Avoidance Manoeuvre (C.A.M) can be performed at any time, even with a separated structure thanks to the tether.

Once the capture is confirmed, the chaser has to deorbit the whole system.

Three different strategies have been analysed for the re-entry:

- An uncontrolled re-entry,
- A single burn deorbitation,
- A multi burns deorbitation.

For the uncontrolled re-entry, the feasibility depends on the debris atmospheric destruction process and on the residual casualty risk. Moreover, this strategy would mean that the debris would stay in orbit for years. Its presence stays a concern in term of collision risk. Particularly, the debris after the manoeuvre will cross the ISS orbit or orbits used by other constellations and this might be damageable to the entire space sector. In conclusion, uncontrolled re-entry is not recommended even if feasible.

Concerning the single burn strategy, drawbacks that were stressed out by many studies on the ENVISAT are ignored considering that the debris mass is much smaller for OneWeb type debris. Mainly, lighter debris allows for a smaller thrust and burn duration during the deorbiting. The positive consequences are several: negligible losses due to finite burn, reduced heat flux on the tether and reduced tether entanglement risk. The analysis shows that only 90N of thrust is necessary to neglect the loss due to finite burn, so 90N will be taken as the requirement for minimum thrust for the chaser platform which gives the required thrust range for the platform: $90 < T_{burn} < 800N$. A 400N thrust level is used as baseline. Finally, with margin and with the assumptions given before, the total deorbiting ΔV is 350m/s (applied to the debris-chaser system). A more detailed study is needed on the manoeuvre dispersions induced by the tethered system and on their implication on the platform controllability requirements.

Concerning the multi burns strategy, the main disadvantages compared to the single burn are the complexity, the post burn controllability and risks, and a higher total ΔV. With the margins and the assumptions given before, the total deorbiting ΔV for the multi burns strategy is 378m/s (applied to the debris-chaser system), so larger than the single burn. Multi burns strategy has been chosen by many other ADR missions for deorbiting bigger debris, so the strategy is assumed feasible but in the INSIDeR case presents more constraints than the single burn.

To conclude on the deorbitation strategy, the single burn option is seen has the best option within the 3, provided that the controllability of the tethered system is proven by further analysis. This choice is mainly led by the simplicity of operation and the smaller ΔV required for the single burn strategy. Eventually, these results have been obtained using OneWeb spacecraft as debris and are valid for light debris. Options for larger heavier debris shall be analysed in the future and they might lead to different conclusions concerning both options.

5 DESIGN OF THE CAPTURE SYSTEM

To ensure the feasibility of a capture using a slow dynamic net, meaning with a low relative speed with respect to the debris, two studies were of prior importance.

First, it was necessary to size the net to ensure that it is large enough to naturally wrap the debris, whatever its shape or attitude, and that considering all potential positioning errors. The contributors to these error have been identified in the requirements of INSIDeR and are the following:

- Relative Position Error: the chaser might not be able to position itself exactly at the correct Rbar distance to the target due to manoeuvres precision. The requirement for this error is fixed to 1,5m maximum.
- Relative Position Knowledge error: the chaser knows the relative Rbar distance with certain accuracy, due to the precision of the on-board instrument(s). The requirement for this error is fixed to 1,5m maximum.
- Structures shape error: the inflatable structures might not have their theoretical shape. The requirement on the inflatable structure is that the opening of the net stays over 95% of the net diameter at all time. This gives a position error of the net centre that can be approximated to 5% of the net diameter in Rbar.

The position error is the arithmetical sum of these 3 errors (which leads to a conservative approach).

Moreover, the net meshes have been sized to ensure that links can bear the deorbitation loads and not to lose the debris during re-entry. This phase has been seen as the dimensioning phase for the net. Indeed, the other tension that will apply to the net is during the capture, when the debris enters in contact with the net. In this situation, the net being free floating, the only force acting on the net is its own inertia during acceleration. The contact speed is low (in the range of 5m/s, plus the debris tumbling rate) and the net is very flexible, so the acceleration forces applied to the net will probably be low.

The material used for this net is the Dyneema, which has already been used in the space sector.

Using classical engineering design rules, and considering a OneWeb satellite as target, the net diameter has been set to 21.5m with a mesh size of 33cm, and links are 1mm diameter.

Secondly, the capture process has been studied in details, modelling all links and nodes on a finite element software, to be sure that the capture was possible with a very low relative speed net. It appeared that the net always wrap the debris whatever its attitude. These simulations pointed out the need of a specific mechanism that will not only help to close the net, but also lock it in order to keep the target trapped. The first considered solution for this mechanism is to use three motorized spools linked to the net circumference using clutches to lock it.

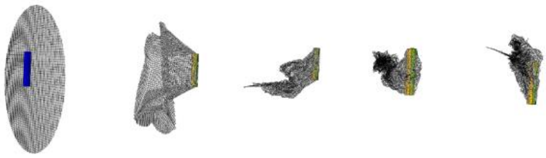

Figure 10: Wrapping simulation results

For this design of the capture system (net plus closing mechanism), the total estimated mass is 2.2kg.

6 INFLATABLE STRUCUTURE

6.1 Design of the structure

The main criterion that drove the design of the structure was the “opening” criterion. The opening is the projection of the deflected structure on the chaser normal axis. This opening needs to be at minimum 95% of the net diameter. This criterion limits the acceptable deflection of the structure, and thus, its stiffness.

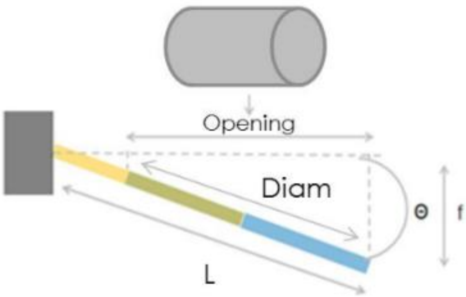

Figure 11: "Opening" description

The opening has been computed with different radius for the structure and different internal pressures, using modified Timoshenko theory by adding the effect of the pressure on the flexural rigidity and the shear strength

[1].

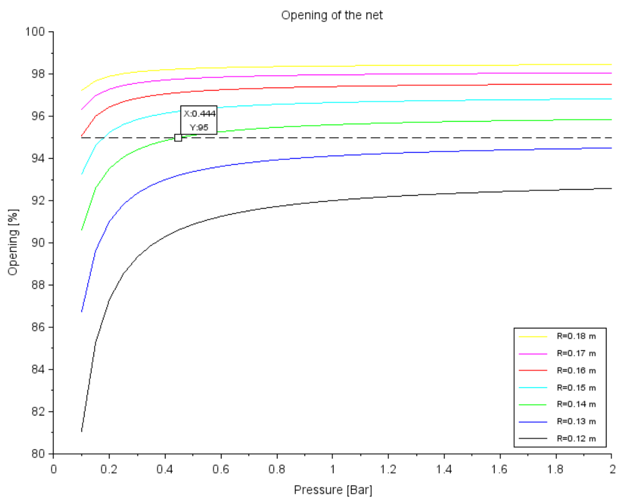

Figure 12: "Opening" wrt structure radius and pressure

One can note on Fig. 12 that the radius of the structure has the most important effect on the structure deflection. The radius has been set to 0.14m with an internal pressure of 0.45 bars. The thickness has been computed to withstand the internal pressure. The total mass of the deployable structure (ring + masts) has been evaluated at 20.1kg.

6.2 Folding pattern and deployment

The packing method is a critical component of the inflatable structures design. It determines, among others, the loads transmitted to the spacecraft during the deployment, as well as the strain energy stored in the stowed configuration; which affect the initial dynamics of the deployment. Moreover, the packing method still exerts its influence through residual creases, stresses, or material cracking at fold lines and vertices [2]. Several methods of packing and deployment control mechanisms have been successfully demonstrated in laboratory environment.

Past experiments such as the “Inflatable Antenna Experiment” (IAE) conducted by L’Garde and NASA [3] have shown the importance of a controlled deployment in order to limit impulse forces and moments imparted to the spacecraft. During the IAE flight, the inflatable structure was supposed to be kicked off the parent spacecraft (Spartan spacecraft) by a loaded kick plate once the outer doors were verified open. Unfortunately, the structure went out of the spacecraft immediately after the opening of the door and the kick plate had no effect on it. This phenomenon was attributed to residual gas within the structure and the stress in the membrane due to the packing. The loss of this impulse force made the deployment uncontrolled and the Spartan spacecraft was pitched in various directions and the AOCS had to counter the efforts and to stabilize the platform. This experiment demonstrated that significant impulse forces could be imparted to the platform. Thus, an unpredicted behaviour could oversize the attitude control system. Therefore, it is important to control the deployment of an inflatable structure. It also shown the robustness of inflatable structures as it eventually deployed to its proper configuration [3]. There is no particular ways to package space inflatable structures to achieve the optimum results [4]. The reference [2] have conducted a review of inflatables structures packing methods. They highlighted different patterns of folding such as the “coiling and wrapping” and the “Z-folding”. At this point of the study, and regarding our knowledge of inflatable structures, the folding pattern cannot be precisely established. This study has to be led in a later phase with a specific knowledge. However, it has not been estimated as a showstopper regarding past experiments, and in particular, the IAE, which successfully completed its deployment despite its uncontrollability and unpredicted behaviour.

7 DEVELOPMENT ROADMAP

A maturity roadmap has been established in order to consolidate the proof of concept and validate INSIDeR performances. An important advantage of this concept is that main technologies can be qualified via ground tests which will significantly reduce costs. Eight tests have been planned within three years. Only three of these tests are planned on a specific space-related environment like a zero-G flight. Hereafter is the list of expected tests:

- Ground tests:
    - Deorbitation: loads apply on the assembly
    - Inflation: Deployment/deflation sequence of the structure
    - Capture: Closing sequence static test
    - Mechanical: Static vibration tests of the kit
    - Electronic: Breadboard test of the electronic components
- Zero-G tests:
    - Inflation: scaled down deployment and deflation test
    - Capture: Scaled down capture sequence (similar to Adrinet and Patender)
- Space Environment test:
    - Only at component/material level

It is expected that all subsystems can reach a Technological Readiness Level (TRL) of 5 or 6 within these three years. The schedule of the foreseen tests is presented in Fig. 13.

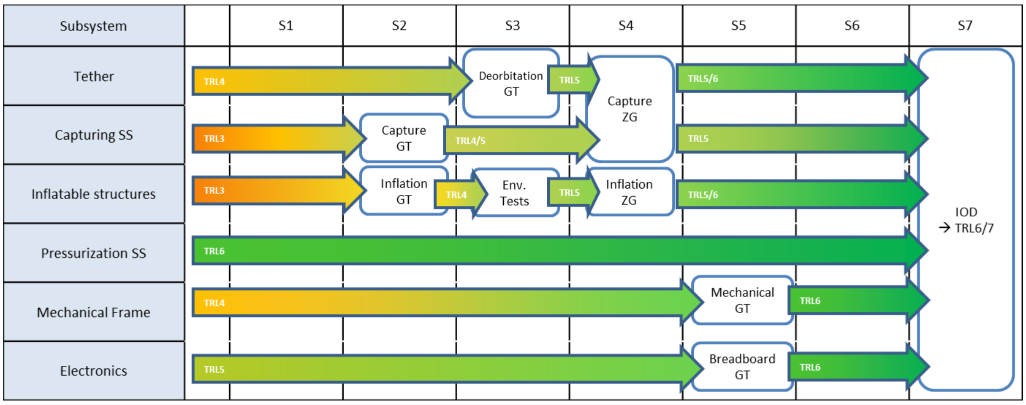

Figure 13: Development Roadmap

8 CONCLUSION

INSIDeR is an innovative and reliable solution to perform active debris removal. Its feasibility has been proven through this ITI activity. A debris capture with a low-speed net is possible, which allows time to control and secure the operations, and the use of an inflatable structure to deploy and control the net during the approach manoeuvre is feasible. This concept can scope with a large range of debris shape, mass and attitude.

The tests necessary to raise the TRL to 6 have been assessed, along with a development roadmap.

Some potential partners have been identified and they will be contacted in future development phases. The objective is to build a consortium of partners and suppliers to combine knowledge and experience on the key technologies of INSIDeR, which is necessary for this kind of multi-disciplinary innovative project.

This partnership is part of the business plan developed in the scope of the ITI. Globally, the business plan shows the economic viability of the project. With realistic hypotheses and simple market analysis, profitability can be achievable within three years with a unit price in the range of 100/200 k€.

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