DOI: 10.13009/EUCASS2023-631
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

INSIDeR: Innovative Net & Space Inflatable structures for active Debris Removal

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Abstract

Because of the new space industry paradigm, consisting in sending constellations of commercial satellites, the number of objects in Low Earth Orbit (LEO) has increased drastically since 2020 and is expected to follow this trend in the coming years.
The INSIDeR solution is developed to tackle the issue raised by a large number of objects put into the same orbital region: the rise of debris number if spacecraft are not de-orbited properly or placed in graveyard orbits after their end-of-life, resulting in a greater risk of chain collisions that may prevent from using orbits of interest.
The INSIDeR solution is a kit one plugs on a space platform, which otherwise has its own mission. It could be on a satellite platform or an upper stage of a launcher, for instance. When the host spacecraft reaches its end-of-life, it will use the INSIDeR kit to capture a debris before performing a de-orbitation manoeuvre.
The kit depends on the host space vehicle for propulsion, attitude knowledge and control, telecommand, telemetry and tracking, thermal management and power generation. The debris capture relies on the combination of two key technologies: a flexible net deployed thanks to an inflatable structure, both previously folded inside the kit. The debris relative position and velocity along with its attitude are measured with a set of sensors inside the kit to ensure it is compliant with what the capture system can endure. A tether ensures a mechanical link between the net and the kit, and will be used once the capture is made to de-orbit the debris together with the satellite platform.
A ground demonstration of the inflation of the structure and deployment of the net, the debris capture and the net closing and locking mechanism is planned for autumn 2023.
The article presents the design constraints considered and the current design of the inflatable structure and the net. It also presents the mission analysis of a typical INSIDeR mission.
This project has been funded by the French government in the framework of "plan de Relance" and by the European Union in the framework of NextGenerationEU.

1. Introduction

The space market raises more and more interests and investments, particularly in the form of commercial constellation of telecommunication satellites. This growing interest leads to a number of consequences, among which the rapid rise of objects in low earth orbit. While some will be low enough to enter the atmosphere within 25 years after the end of their mission and therefore limit the risk of creating new debris that would stay in orbit for a long period of time, others will need deorbiting manoeuvres to limit the creation of space debris. It is important to note that if almost all satellites intend to comply with the French space operation act (FSOA) at launch, or at least follow the debris mitigation guidelines set by IADC, only 30% has effectively complied in the end during the last decade [1]. The issue of space debris is not news, but the recent space market growth encourages to tackle it quite quickly before orbits of interest become unusable.
The INSIDeR system has been designed to bring a solution to the debris situation, through active debris removal (ADR). It is a kit one puts on a space platform, such as a satellite or a launcher upper stage for instance, its mission starts when the host platform one ends, and is composed of 4 main phases: orbital manoeuvres to approach the target debris, characterisation of debris attitude and capture system deployment, debris capture, de-orbiting. The kit relies on the attitude and orbit control system (AOCS) of the host to get close to the debris and position properly relative to the debris. Once the debris characterized, a net is deployed thanks to an inflatable structure. The host then performs a final approach manoeuvre to get to the debris with a relative speed of few meters per second, and after the manoeuvre has

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been performed the net is separated from the inflatable structure, this way no mechanical coupling exists between the net and the host platform. At this point the net is linked to the kit thanks to a loose tether of around a hundred meters. Once contact has been made between the net and the debris, the net wraps around the debris and closes. The host can then perform the deorbiting manoeuvre.
The kit contains the net and the inflatable structure folded, the winded tether, a pressurized gas tank, sensors and actuators to ensure the capture mission can unfold, a power control and distribution unit (PCDU), a data management system. All subsystems are placed onto a support serving the purpose of a mechanical interface between the kit and the host platform. Everything is inside a truss structure and protected by multi-layer insulation (MLI).
The main advantages of the INSIDeR concept are its lightweight design, its scalability with respect to a wide range of debris shape and sizes, its genericity and the use of space-proven technologies and materials.
In the article the net and the inflatable structure designs are described, the mission analysis study is made to determine the required ΔV for the manoeuvres, in the end the overall kit is detailed.
This project was carried out in the purpose of having a ground demonstration for the net capture, the structure deployment and the scalability of the concept, considering a 50cm cubic shape for the target debris.

2. The capture system

2.1 The net

The net general shape is chosen to be circular, mainly to account for debris with spin rates, which are expected to be a large majority of debris, and marginally to have a generic system adapted to all shape of debris regardless of their shape. The net is made in Dyneema, as it is a space proven material (ProSEDS [2] mission for example) and commonly used, for instance for fishing nets or climbing ropes. This makes Dyneema a generic and mature material for INSIDeR application.
The net radius (r_f) was chosen considering the debris size (L_{deb}) and uncertainties (i) of the net positioning in the plane orthogonal to the orbit direction (called in the rest of the paper "x/y plane") using to the following formula:

$$r_f = L_{ref} + i \tag{1}$$

$$L_{ref} = 2 * L_{deb} \tag{2}$$

As stated in the introduction, $L_{deb} = 50cm$. The uncertainty of the net positioning depends mostly on the accuracy of sensors to determine with precision the relative position of the host platform with the debris and the actuators the host possesses to actually orient itself after computing the proper relative position from the sensors measurement. Sensors and actuators available on a given satellite platform vary among the different ones according to the main mission, orbit and size of such platforms, this is why a conservative value of $i = 1.5m$ has been considered, based on the uncertainty considered in [3].
It has to be noted at this point that the net radius influences strongly the overall mass and volume of the kit, and shall be reduced when the host platform for an actual mission is determined, considering the real positioning uncertainty it can provide.
The reference length (L_{ref}) is determined considering the net length it would take to completely wrap around the debris. This leads to a net of 5m diameter to catch a 50cm debris.

The whole design process has been driven by two main goals: minimize the kit size and mass. In addition, the hypothesis of a 4g acceleration for the deorbiting boost has been considered. A trade-off to determine the net mesh shape has been done to minimize the net mass. The following equations give the mass of a net for different net mesh geometry:

$$m_{f,t} = \rho_{dyn} \frac{c_{secu} * F_{thrust}}{L_{deb} * \sigma_{lim}} * \frac{4\sqrt{3}}{5} \pi {r_f}^2 \tag{3}$$

$$m_{f,s} = \rho_{dyn} \frac{c_{secu} * F_{thrust}}{L_{deb} * \sigma_{lim}} * 2\pi {r_f}^2 \tag{4}$$

$$m_{f,h} = \rho_{dyn} \frac{c_{secu} * F_{thrust}}{L_{deb} * \sigma_{lim}} * \frac{4}{3\sqrt{3}} \pi {r_f}^2 \tag{5}$$

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With $m_{f,t}$ the mass of a triangular net mesh, $m_{f,s}$ the mass for a square net mesh and $m_{f,h}$ the mass for a hexagonal net mesh, ρ_{dyn} the density of Dyneema, c_{secu} the mechanical security coefficient, F_{thrust} the thrust applied on the net for the deorbiting boost, σ_{lim} the yield strength of Dyneema, r_f the net radius and L_{deb} the debris size.
One can deduce that a hexagonal shape will be lighter than a triangular shape, which will be lighter than a square shape. Nevertheless, to ease the purchase of the net for the demonstration square mesh elements were considered for the design of the demonstrator.
One can observe that the net mass does not depend on the net threads thickness nor on the net mesh size, this is true only in the limit of manufacturability of the net material. For Dyneema, the net threads cannot be manufactured thinner than 12µm, beyond this limit the mass will depend on the net mesh size according to the following formulas:

$$m_{f,t} = \rho_{dyn} * \pi {r_{thread}}^2 * \frac{4\sqrt{3}\pi {r_f}^2}{L_{mesh}} \quad \textbf{(6)}$$

$$m_{f,s} = \rho_{dyn} * \pi {r_{thread}}^2 * \frac{4\pi {r_f}^2}{L_{mesh}} \quad \textbf{(7)}$$

$$m_{f,h} = \rho_{dyn} * \pi {r_{thread}}^2 * \frac{4\pi {r_f}^2}{\sqrt{3}L_{mesh}} \quad \textbf{(8)}$$

With r_{thre} the radius of net threads and L_{mesh} the length of a side of a mesh element. In this case the hexagonal shape remains the lightest option, followed by square shape, itself lighter than the triangular shape

The net characteristics are summarized in Table **1**, a picture of the net can be found in Figure **1**:

Table 1: Summary of net characteristics

	Value	**Unit**
Radius	2.5	m
Mesh shape	square	-
Mesh size	1	cm
Threads diameter	0.15	mm
Mass	420	g

2.2 The net closing and locking mechanisms

With a net designed to wrap around the debris, one must ensure the debris will not get out of the enclosed net right after the capture. There must be a system ensuring the net closes once the debris has been captured. The most important driver for this system design was to keep it as simple as possible.
An active solution has been quickly dismissed, because of the complexity it would bring to the system and the additional mass and energy it would require to have a safe and reliable system.
There has been some papers about passive net closing mechanisms, and a large majority of mechanisms relied on cables tightening the net perimeter, either thanks to the inertia of masses placed on cables ends or thanks to the deorbiting tether linked to the host platform. In the case of INSIDeR, the net cannot be mechanically coupled with the host during the capture, so the tether cannot tighten the closing mechanism.

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Therefore the net closing mechanism designed for INSIDeR net relies on cables, actually ribbons, going around the net perimeter, passing through the centre of the net and having masses of hundreds of grams attached at each end. Ribbons are linked to the net thanks to rings as depicted on Figure **1**. There are 6 ring guides per ribbon, 3 on each side. The choice of using ribbons instead of cables was driven by the possible locking mechanisms available for each solution. The locking mechanism for ribbons consists in a hollow cylindrical piece of plastic, with sharp teeth inside oriented towards one side, as one can see in Figure **3**. A ribbon going through such a piece can consequently move one way only, the one the teeth are pointing towards. These one-way ribbon guides are placed on the positions marked by a green dot on Figure **1**, there are 2 one-way guide per ribbon side for redundancy.

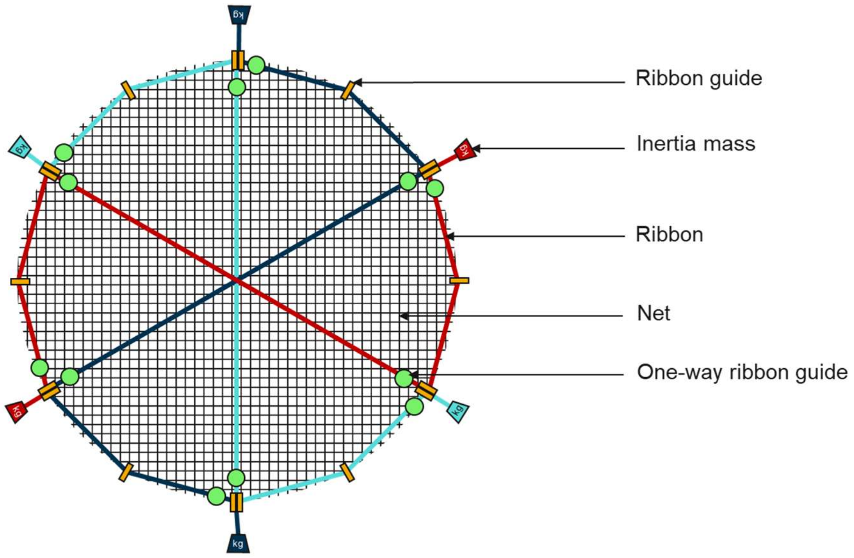

Figure 1: Net closing mechanism schematic

For clarification purposes, the net is represented in Figure **2** with only one ribbon mounted on, and the rings it passes through are represented in yellow while others are grey.

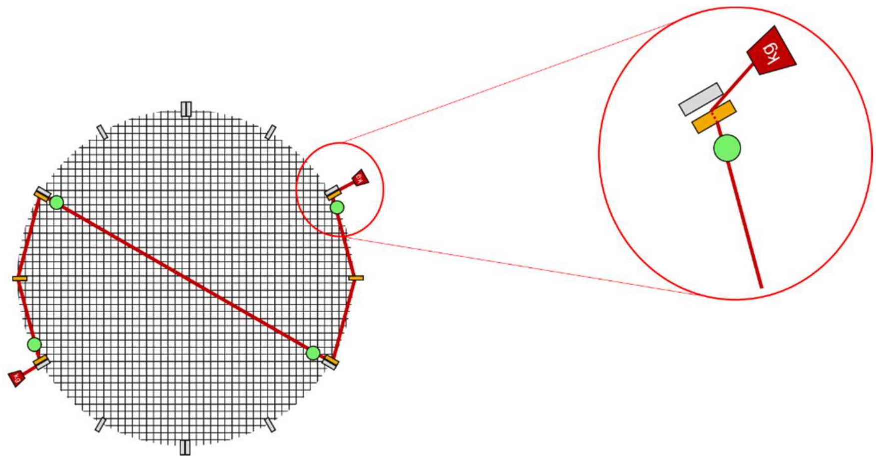

Figure 2: Focus on a net closing mechanism ribbon

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Figure 3: Example of a one-way ribbon guide

The one-way ribbon guides are linked to the net thanks to Dyneema threads as depicted in Figure **4**.

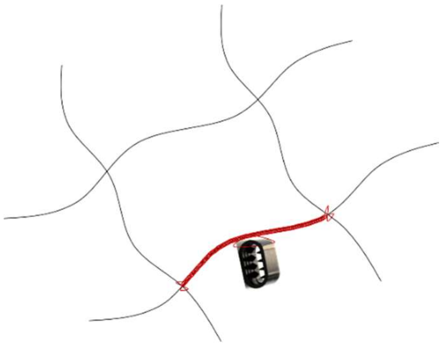
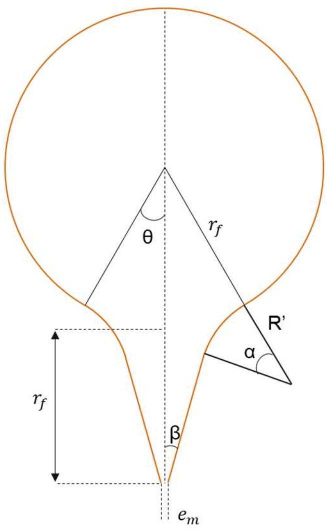


Figure 4: physical link schematic between a one-way ribbon guide and the net

3. The capture system deployment mechanism

3.1 The inflatable structure

The inflatable structure has the unique purpose of deploying the net properly. To do so, it has to survive in the space environment once deployed for several hours and survive inside a multi-layer insulation protected box for years before being deployed. The structure is also the subsystem that takes the most volume inside the kit, therefore it has to be designed with the constraints of minimizing its volume, in addition to limiting its mass as much as possible.
The inflatable structure geometry is obtained after a mass optimization of the kit, and is detailed in Figure **5**:



Parameter	Symbol	Value	Unit
Net radius	r_f	2,5	m
Aperture angle	θ	30	°
Curve radius	R'	1,452	m
Curve angle	α	45	°
Masts angle	β	15	°
Mast footprint	e_m	10	cm

Figure 5: Geometrical shape of the inflatable structure

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An arbitrary number of 6 contact points between the net and the inflatable structure has been chosen.
After looking at the inflatable antenna experiment [4] and making simulation over several orbits, the temperatures extremes met once the structure is deployed were outside the acceptable range for the materials looked into, ranging from -200°C to 120°C. This is why the structure is protected by 3 thermal insulation layers, to limit thermal exchanges, as it was the case for the deployable structure in [4].
The material was chosen after a trade-off between several pre-selected plastic materials: Kapton, Mylar and PEEK. To ensure the correct unfolding at the right time, the material is selected on the followings requirements:

- Operating temperature (-40°C / 120°C) ;
- UV Resistance (~48h unfolding) ;
- Creep (~20 years folding) ;
- Tensile Strength (Pressure 1.2bar) ;
- Density ;
- Acids resistance ;
- Space approved ;

The temperature is the most important requirement. The cold temperature affects the material on its rigidity. Indeed at -40°C all polymers become rigid and easy to break. The inflatable structure risk to rip during the unfolding.
When the inflatable structure will be deployed the sun will warm the polymer up to 120°C. The melting point and the Glass temperature of the polymer have to be lower than the operating temperature of the inflatable structure.
The folded structure will be stored for a maximum of 20 years. All polymers folded for a long-time creep. To be sure to have the right kinematic during the deployment, the polymer must have the lowest creep. A creep fold presents a risk to rip during the deployment.
The Pre-selected polymers have the following characteristics:

Table 2: Polymer characteristics

Material	Density g/cm^3	Young Modulus GPa	Elongation at break %	Tensile Strength MPa	Friction coefficient	Operating temperature °C	Thermal expansion coefficient x10^-6/K	Specific heat J/K*kg	Thermal conductivity W/m*K	UV Resistance	Creep	Acids Resistance
Kapton	1,42	2 - 3	8 - 70	70 - 150	0,42	-270 / 250	30 - 60	1090	0,10 - 0,35	Poor	Low	Poor
Kapton 30nm Alu	1,42	2 - 3	8 - 70	70 - 150	0,42	-270 / 250	30 - 60	1090	0,10 - 0,35	Poor	Low	Poor
Mylar (PET Biaxial)	1,3 - 1,4	2 - 4	-	190 - 260	0,2 - 0,4	- 40 / 115	20 - 80	1200 - 1350	0,15 - 0,40	Fair	High	Good
PEEK	1,2 - 1,3	3,7 - 4	50	70 - 100	0,18	- 40 / 250	40 - 108	1340	0,25	Fair	High	Good

The Mylar respects all requirements and was already used for ECHO 1 satellite and SPARTAN inflatable space antenna with success.

The mass optimization was then performed once the material and the general geometry were defined. It lead to the technical characteristics listed in Table **3**:

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Table 3: Inflatable structure technical characteristics

	Value	Unit
Internal radius	2	cm
MYLAR thickness	0.125	mm
Internal nominal pressure	1.015	bar
Burst pressure [a]	4.5	bar
Mass	500	g

[a]Burst pressure considering a security factor of 2

3.2 The inflating mechanism

The inflating mechanism is chosen as simple as possible. The inflation is done by gas expansion from a pressurized gas tank to the inflatable structure. The gas selected is Nitrogen as it is an inert gas and widely available on the market. The gas tank is made in aluminium, its size and the storage pressure were determined by the mass optimization. The storage tank is a sphere of 7.1 cm, storing nitrogen at 42 bar. The sphere wall are 2.15mm thin and the tank weighs 360g.
The gas is piped to a base (see Figure 6 and Figure **7**) that serves not only the purpose of interfacing the pneumatic pipes with the inflatable structure but also interfacing mechanically the inflatable structure with the INSIDeR kit. Nitrogen arrives through one hole per mast, to have a less chaotic inflation.

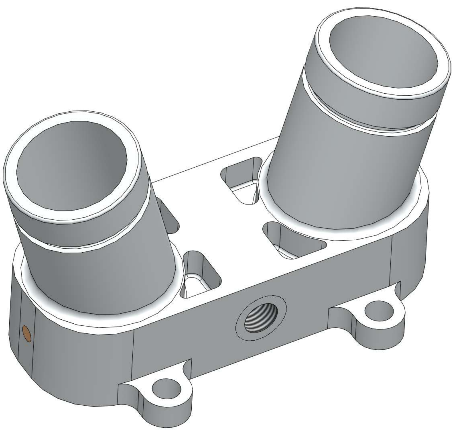

Figure 6: Inflatable structure base

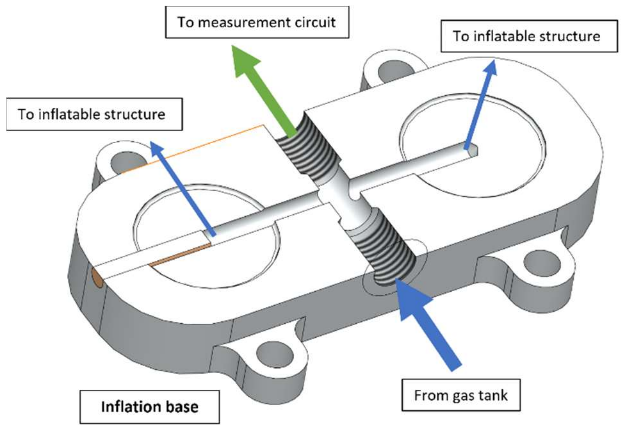

Figure 7: Inflatable structure base (cross-section)

When simulating the behaviour of the structure during inflation, it was found that the longer the inflation the lesser were the efforts transferred to the host platform. A trade-off between a short time of inflation and small efforts lead to an inflating time of approximately 70s, guarantying efforts of less than 50N. To ensure this inflating time only with gas expansion, the smallest diameter of gas conduit has been computed to be a hole of only 1 mm diameter. The law used to determine this time is described by equations **(9)** **(10)** and **(11)**:

$$\frac{P_0}{P_s} = (1+0.2)^{3.5} \approx 1.8929 \quad \textbf{(9)}$$

$$\dot{m}_{max} = \rho^* A^* v^* = P_0 A^* \sqrt{\frac{\gamma}{rT_0}(\frac{2}{\gamma+1})^{\frac{\gamma+1}{\gamma-1}}} \approx 0.6847 P_0 \frac{A^*}{\sqrt{rT_0}} \quad \textbf{(10)}$$

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$$t_{sub} = \frac{\ln\left(\frac{1.8929}{1.8929 + \frac{V_1}{V_0}}\right)}{-0.6847A^* \frac{\sqrt{rT_0}}{V_0}} \qquad \textbf{(11)}$$

With P_0 the pressure inside the tank, P_s the pressure inside the inflatable structure, equation **(9)** the shock condition at the throat, $\dot{m}_{max}$ the maximum mass flow rate in supersonic regime, ρ^* the density at the throat, A^* the throat area, v^* the gas velocity at the throat, γ the isentropic expansion factor, r the ratio of $\frac{R}{M}$ with R the ideal gas constant and M the Nitrogen molar mass, T_0 the temperature inside the tank, t_{sub} the time to reach a subsonic regime, V_0 and V_1 the volumes of the tank and the inflatable structure.

3.3 Deployment kinematic simulation

Understanding the deployment kinematics of the inflatable structure is crucial for ensuring successful mission outcomes. This section presents a series of simulations conducted to investigate the deployment of INSIDeR inflatable structure, with a specific focus on reaction forces on the satellite host to anticipate its manoeuvre.

The finite element model is built using plate elements with a mesh size of 5 mm (Figure 9-a). The simulation is run in two steps using explicit dynamics method in the 3DExperience platform. The first step, which is not analysed in this article for brevity reasons, simulates the folding process from the initial geometry into a compact state (Figure *8*), while the second step simulates the deployment through inflation following the pressure law shown in Figure 9-b.

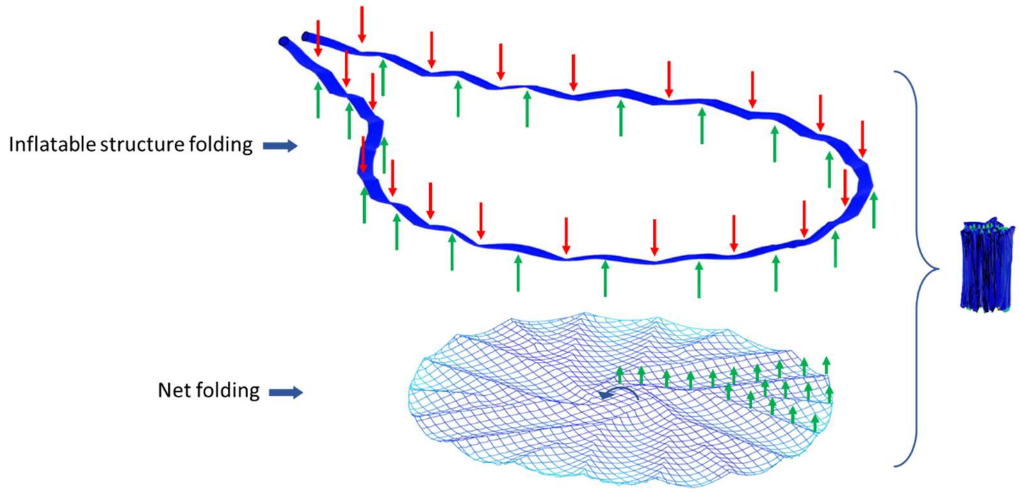
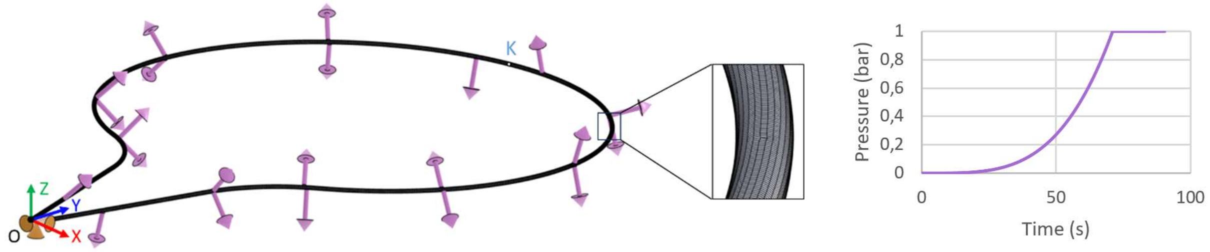


Figure 8: Folding schemes of the inflatable structure and the net

Many inflation scenarios have been tested in order to evaluate their impact on the reaction forces transmitted to the platform. In this article we analyse the scenario where the inflation takes 71 seconds to complete. Equation 11 allows incidentally estimating the orifice size to be used for the inflation base.



(a) (b)

Figure 9: Finite element model of the inflatable structure

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From a folded compact state, the deployment under exponentially varying pressure for 71 seconds exhibits chaotic kinematics during the first 30 seconds due to the release of the stored elastic energy before starting to stabilize horizontally and vertically (Figure 10 and Figure 11). It should be noted that this simulation does not take account of the net presence, which could reduce the chaotic kinematics at the beginning of the deployment.

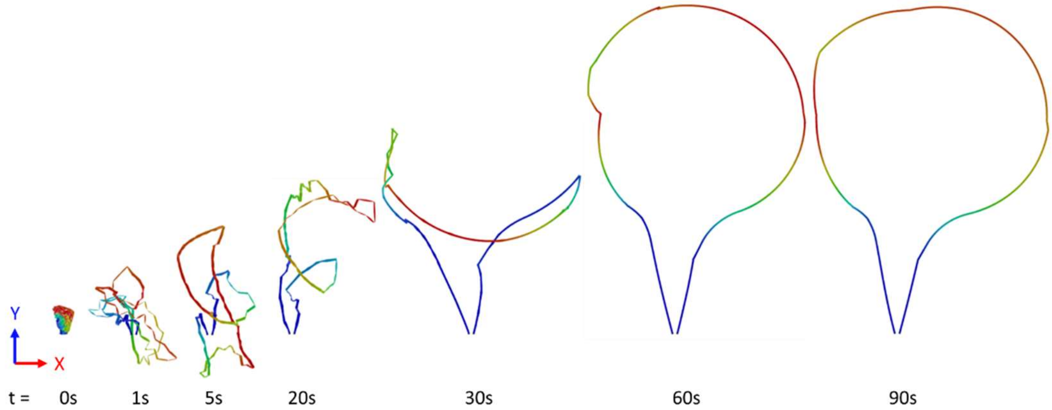

Figure 10: Deployment kinematics of the inflatable structure in the XY coordinates

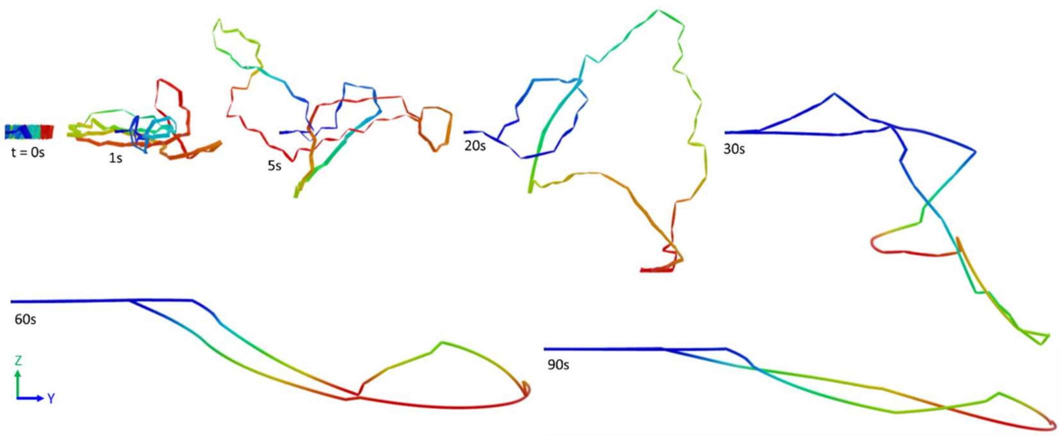

Figure 11: Deployment kinematics of the inflatable structure in the YZ coordinates

To quantify the stabilisation of the deployment kinematics, we plot the evolution of relative displacements of the point K in the inflatable structure along the 3 directions of the OXYZ reference frame (Figure 12). We observe that point K oscillates and dampens as the inflatable structure is pressurized which characterizes a stabilisation trend.

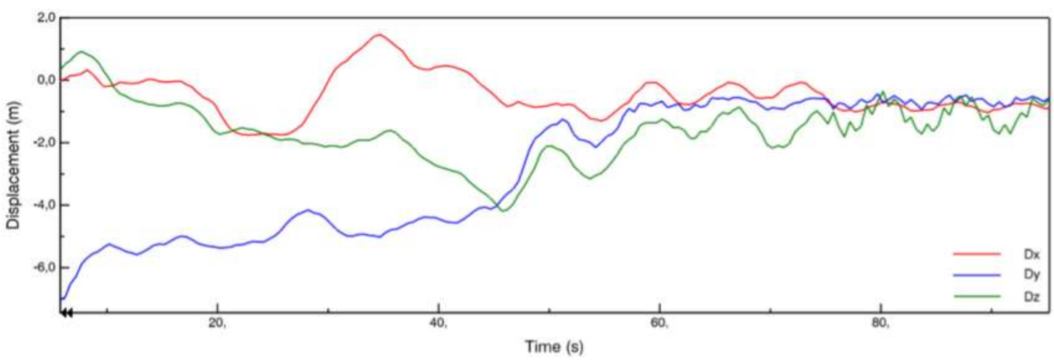

Figure 12: Relative displacement components of the point K (see Figure 9)

In terms of reaction forces on the platform during the deployment manoeuvre, we observe in the plot below an oscillatory behaviour of the 3 directions of the reference frame all while remaining below 50N force (Figure 13). We note that the reaction forces stay low during the 30 seconds corresponding to the initial chaotic step.

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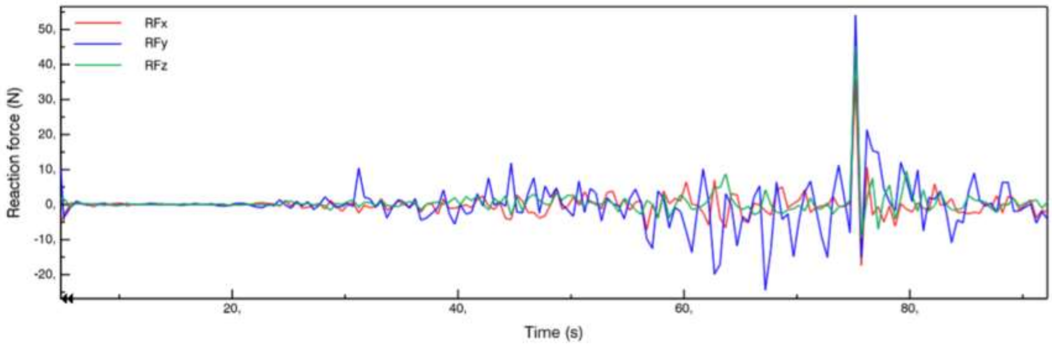

Figure 13: Reaction force components on the platform satellite

4. Mission analysis

4.1 Debris approach manœuvres and ΔV

The debris approach is similar to the one of the ATV doing a rendezvous with the international space station [5]. Once the host and the debris share the same orbital plane, the host performs a manoeuvre to do a Hohmann transfer between its orbit and the one of the debris. Once settling on the debris orbit, the host would have to perform small adjustment manoeuvres to ensure it is not drifting away from the orbit. Then, a phasing manoeuvre is performed to get to approximately 100m away from the debris. Once again small adjustment manoeuvres have to be made to ensure there is no drift between the host and the debris when the manoeuvre is done. At this stage the host relies on the INSIDeR kit to measure the relative position and velocity with the debris. The INSIDeR kit also characterizes the debris attitude and geometry to determine the capture feasibility along with the debris centre of gravity. With this information the host performs the final manoeuvre to capture the debris. Once the host is on a trajectory to capture the debris, the net is separated from the inflatable structure, this way the debris capture is made with no rigid mechanical link and the host will not suffer any effort from the capture.
It has to be noted that before performing each manoeuvre, except when on transfer orbits, the host checks it is on the predicted orbit and adjust its orbit parameters if not.
ΔV budget computations have been made for 3 separate debris capture missions, each for 3 different scenarios, and are summarized in Table **5**. The missions and scenarios are detailed in Table **4**.

Table 4: Detail of different missions and scenarios

	Description
Mission 1	Capture of a debris on the same orbit as the host
Mission 2	Capture of a debris on the same orbital plane as the host but on a different orbit. On a 1200km circular orbit for scenarios 1 and 2, on a 450km circular orbit for scenario 3
Mission 3	Capture of debris on a different orbit and on a different orbital plane, with a ΔV budget of 1km/s. Computation of maximum Δi to reach a 1200km circular orbit for scenario 1 and 2, a 450km circular orbit for scenario 3
Scenario 1	The host platform is a Venµs satellite [7] on a 720km sun-synchronous orbit
Scenario 2	The host platform is a SWARM satellite [8] in configuration A on a 450km sun-synchronous orbit
Scenario 3	The host platform is a OneWeb satellite [9] on a 1200km circular orbit

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Table 5: ΔV or Δi for the different missions and scenarios

	Scenario 1	Scenario 2	Scenario 3
Mission 1 (ΔV)	29 m/s	29 m/s	30 m/s
Mission 2 (ΔV)	245 m/s	370 m/s	392 m/s
Mission 3 (Δi)	7.5°	7.1°	7.1°

This study has been made to have orders of magnitude for given capture missions in terms of additional ΔV required to embed on host platform during design phases and an appreciation of which manoeuvres would be acceptable and which would not. Here, more than 1km/s of additional ΔV is considered unacceptable, which leads to the conclusion that the debris must be on an orbital plane close to the one of the host and in the same orbital region.

4.2 De-orbiting manoeuvres and ΔV

Once the debris captured and secured inside the closed net, it is linked to the kit thanks to the de-orbiting tether. To perform the de-orbiting manoeuvre it is mandatory to tension the cable. A de-orbiting manoeuvre performed without a taut tether can lead to an elastic deformation catapulting the debris into the host platform, or can lead to the tether break, leaving the debris behind in addition to potentially forming new debris. Different thrust profiles to tighten the tether are explored in [6]. This paper studies the influence of thrust profile shape on the tether tautening considering different thrust system and thrust control abilities of a tug towing a debris thanks to a cable. According to this article it is possible to accommodate such a configuration while placing the tug and debris on a re-entry orbit. The less constraining method to consider for the design phase of INSIDeR kit seems to be an impulsive thrust profile, as it would greatly reduce the choice of host platforms to exclude the ones featuring only an on/off thrust.
The actual thrust profile would have to be determined for each mission. In a similar way than the debris approach manoeuvres, the required ΔV is computed for the 9 mission/scenario combinations (see Table **6**). These computations are made considering and maximum de-orbiting time of 25 years, and are made thanks to the OPERA software made available for free by CNES.

Table 6: De-orbiting ΔV for the different scenarios

	5 years re-entry	10 years re-entry	20 years re-entry
Venµs (720km)	96 m/s	87 m/s	62 m/s
Venµs (1200km)	240 m/s	232 m/s	221 m/s
SWARM (450km)	2 m/s	0 m/s	0 m/s
SWARM (1200km)	242 m/s	233 m/s	199 m/s
OneWeb (450km)	6 m/s	0 m/s	0 m/s
OneWeb (1200km)	247 m/s	239 m/s	214 m/s

In the end, the extra cost for each mission/scenario combination is the relevant value of interest and would be computed considering the difference between the ΔV the complete INSIDeR mission requires and the ΔV the host would require without hosting an INSIDeR kit. In our case, the Venµs spacecraft has a manoeuvre planned to go down to 410km altitude orbit for the last phase of its mission, this manoeuvre can be considered a de-orbiting manoeuvre and would require a ΔV of 170m/s approximately, the SWARM satellite is low enough to be de-orbited naturally within 25 years after the end of its mission, so no manoeuvre is required to de-orbit it, and a OneWeb spacecraft would require approximately 210m/s according to OPERA computations, in accordance with [10].

DOI: 10.13009/EUCASS2023-631

5. The INSIDeR kit

To perform the debris capture, some functions not available on all host platform have to be ensured by the INSIDeR kit, along with all functions necessary for the correct functioning of the kit. The kit has been designed to get approximated power and mass budget values, along with dimensions of the entire kit. To do so components-off-the-shelf (COTS) sensors and actuators were selected (see Table **7**), space-proven materials have been considered for the structures and the thermal insulation, and the CAD of the kit has been made to place the components inside the kit following basic design rules such as keeping hot components away from each other, or limiting electromagnetic interactions (See Figure **14**). The kit components arrangement inside the kit does not come from any optimisation process and should therefore be improved in future works to limit the kit volume as much as possible.

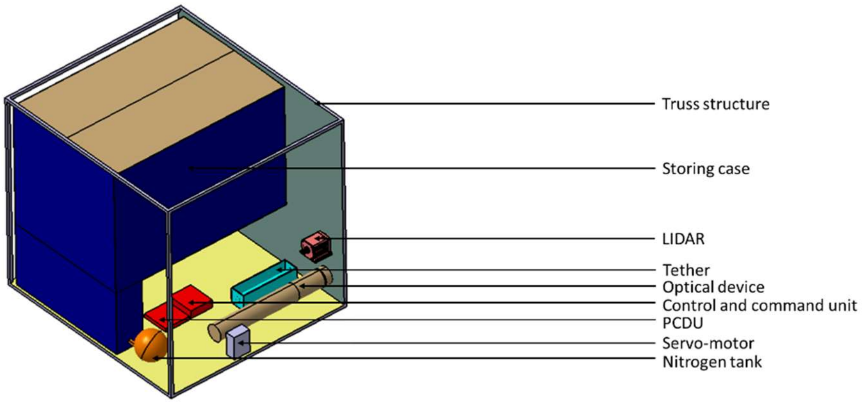

Figure 14: INSIDeR kit schematic

The inflatable structure and the net are folded in a container. The container has an actuated opening so the structure and net can be freed when needed. The inflatable structure is fixed on a base, which serves the purpose of mechanical interface with the kit along with the purpose of pneumatic interface with the inflating mechanism. The gas tank is linked to the base with pipes separated by an actuated valve, to be able to inflate the structure when needed. It also features a pressure sensor to monitor the inflation status, as is the inflatable structure. The net is linked to a 100m de-orbiting tether that is the mechanical interface between the net and the kit once the capture is done. All these components are fixed on a plate and enclosed inside a truss structure wrapped in multi-layer insulation. The truss structure is actually made out of 2 orthogonal plates in addition to trusses. The other plate hosts a LIDAR sensor and actuator and an optical infrared sensor to characterize the debris shape, relative position and relative speed before the final approach manoeuvre.

The use of sensors and actuators has been detailed according to each mission phase, starting at the point where the chaser is on the same orbit as the debris and approximately 100m from it, before the final approach manoeuvre. This gives the power budget of 53W needed during the most demanding phases (see Figure **15**). A margin of 15% has been considered for the power consumption of all components.

DOI: 10.13009/EUCASS2023-631

Table 7 : INSIDeR kit power budget

	Quantity	Reference	Power [W]	Total power [W]	Total power with 15% margin [W]
Pressure sensor	2	PRECISION Pressure Transducer / Transmitter AST20HA	0,56	1,12	1,29
Optical sensor	1	Boson Plus 640, sans objectif : sans obturateur	5	5	5,75
Stepper motor	2	Stepper Motors Series AM2224	3	6	6,9
Angular position sensor	1	CP / CCP - Modèle CP 2F (ou CP-2 FB)	1	1	1,15
Strength sensor	1	FL025U(C)-2SGKT, Universal Load Cells	0,70	0,70	0,81
Temperature sensor	2	PW0K1.216.7W.A.007 Platinum sensor with wires	7	14	16,1
Hold down and release mechanism	1	NEA® Model 9040 Miniature	16,2	16,2	18,63
Electro-valve	1	IEPA1211241H solenoid valve	5	5	5,75
LiDAR	1	NCDT ILR2250-100	1,5	1,5	1,73
Power control and distribution unit	1	GOMSpace NanoPower PDU-200	0,6	0,6	0,69
Control and command unit	1	GOMSpace Nano-Mind A3200 CDHS	0,9	0,9	1,04

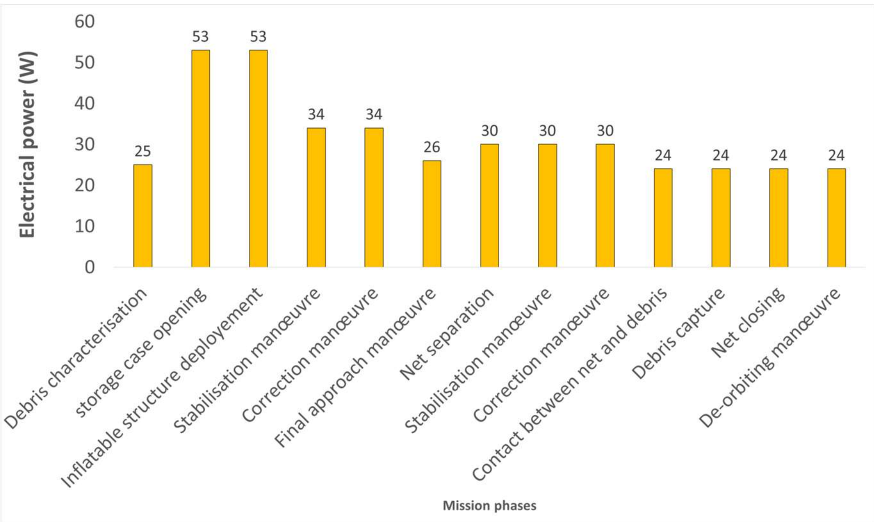

Figure 15 : INSIDeR kit power consumption according to the capture mission phases

DOI: 10.13009/EUCASS2023-631

Concerning the mass budget, no mass optimization of structures has been made, so it is expected to be able to reduce the kit mass significantly. The mass budget breakdown is detailed in Table **8**. With margin for now the kit weighs less than 15kg, with the aim of bringing this weight below 10kg after the structure mass optimization.

Table 8: INSIDeR kit mass budget

Component	**Material**	**Mass [g]**
UNITS		
Power control and distribution unit	see Table **7**	65,55
Command and control unit	see Table **7**	27,6
SENSORS		
Pressure sensor	see Table **7**	207
Optical sensor	see Table **7**	7,5
Angular position sensor	see Table **7**	113,85
Strength sensor	see Table **7**	313,03
Temperature sensor	see Table **7**	0,23
ACTUATORS		
Hold down and release mechanism	see Table **7**	31,28
Optics steppermotor	see Table **7**	287.5
Electrovalve	see Table **7**	5,75
INFLATABLE STRUCTURE		
Inflatable structure	Mylar	531,3
Thermal protection	MLI	289,8
Closing net mechanism	-	920
Net	Dyneema	437
INFLATING MECHANISM		
Gas storage tank	Aluminium	414
Pressurisation gas	Nitrogen	33,925
Residual gas	Nitrogen	1,98122
Base	Aluminium	1150
STRUCTURE		
Storing case	MYLAR	2814,05
Truss structure	Aluminium	5629,365
Thermal protection	MLI	123,74
OTHER		
LiDAR	see Table **7**	304,75
De-orbiting tether	Dyneema	788,9
Tether storing case	TBD	TBD
TOTAL WITHOUT STRUCTURE [kg]		**6**
TOTAL WITH STRUCTURE [kg]		**14,6**

The main downside of such a solution is its dimensions. The inflatable structure, while lightweight, takes a lot of space. The analytic computation of the kit dimension, taking into account the imperfection of the structure and net folding, is 73x67x68cm^3, or 333L. The inflatable structure and the net account for more than 40% of that volume. With a compact placement of components inside the kit this value could be lowered, with the absolute limit being the combined volume of all components.

6. Conclusion

The next step for INSIDeR design is a series of demonstration during the 2023 summer, to study the inflatable structure deployment, the net capture and closing mechanism, and the scalability of these systems.

DOI: 10.13009/EUCASS2023-631

For the inflatable structure the team will look at the deployment kinematic and the accordance with simulations, along with the pressure evolution during the structure inflation and the mechanical efforts transmitted to the host platform when deploying.
For the net only the kinematic will be studied, and the net closing mechanism will be implemented to get a proof of concept. The scalability of systems will be studied through 2 separate demonstration campaign, with systems of 2 different sizes.

After demonstrating the main systems for debris capture, an in-orbit demonstration is next logic step before making INSIDeR kit commercially available.

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