DESIGN OF NET EJECTOR FOR SPACE DEBRIS CAPTURING

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ABSTRACT

Currently about 26,000 objects larger than 5 cm are tracked while orbiting near the Earth: the vast majority of this space debris is concentrated in the most useful Earth orbits; in particular, 79% are orbiting in Low Earth Orbit (LEO). In order to suppress collisions between existing space debris, removal is the only solution: NASA and ESA agree on the urgent need to remove 5-10 strategically chosen debris every year. One of the most promising technologies for space debris removal is the use of throw-nets to capture debris, followed by one or multiple deorbitation burns during which the debris is pulled with a tether.

Over the recent years, we have been studying technologies for Active Debris Removal (ADR) aimed at maturing net-capturing. In particular, this paper details the design of an ejector for capturing space debris with nets. We have also been developing a detailed high fidelity net dynamics simulator, to support and validate the ejector design. Following the design phase, an engineering model, to be used in a full-scale ground experiment, will be then manufactured, to further validate the system. In fact, the concept has already been validated at small scale on-board zero-G parabolic flights.

The net ejector, developed based on the experience matured thanks to the parabolic flight experiments, will be suitable for being installed in the chaser, based on one of the candidate platforms selected by ESA for a real ADR mission. The ejector design is based on a cool gas generator, which provides the compressed gas required to eject four bullets attached to the four corners of the net that is folded inside a container. Two ejectors shall be accommodated inside the chaser, in order to ensure redundancy in case of failure. The design has been supported by high fidelity dynamics simulations and validated for space applications by environmental tests in a thermal vacuum chamber. The presented work has been led by Stam under the ADR1EN project, funded from the European Union's Horizon 2020 research and innovation programme under grant agreement No 666758, through the SME Instrument.

1 INTRODUCTION

NASA Orbital Debris Quarterly News reported that as of January 2013, approximately 23,000 objects are tracked while orbiting near the Earth and, as of November 2015, 7,200 satellites have been launched into orbit, of which about 4,100 remained in space. Only a small fraction - about 1,100 - are still operational today. The rest are derelict debris objects that vary from minuscule particles to massive satellites and spent rocket upper stages.

Taking the loss of the ENVISAT satellite as an example, this satellite poses a considerable threat as space junk: the 26 m derelict is in an orbit where other space objects approach within 200 m of the satellite every year. An impact could generate a devastating chain reaction of debris collisions. The satellite is expected to stay in orbit for about 150 years until it eventually falls back into Earth's atmosphere and burns up. This situation generates an unacceptable risk for space infrastructures, space services and human lives, both in space and on Earth.

Although international agreements led to the adoption and implementation of mitigation strategies to limit the generation of new debris, long-term projections on the evolution of the space environment suggested that the number of objects in orbit could increase rapidly in the next 20-30 years, even in case of drastic, unrealistic measures such as an immediate and complete halt of launches and release activities [1].

Space debris is not spread uniformly through space, but is concentrated near the regions of space that are heavily used by satellites. For instance, LEO contains about 79% of the objects, whereas about 78% are debris, 15% are payload (operative and non-operative) and 7% are rocket bodies. In addition, this is the most problematic region in this regards, being used for most commercial satellites. In order to stabilize the space debris population, especially in LEO, NASA and ESA agree

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

that 5 to 10 objects shall be removed every year [2, 3]. Active debris removal can be more effective when the objects removed have high mass, high collision probabilities and high altitudes.

Studies [4] have been conducted to determine the characteristics of the debris fields around Earth. LEO was identified to have the highest chance of being congested, especially orbits with an inclination between 75° and 105°. Within LEO a number of objects have been identified which pose the biggest threat to the stability of the debris field.

The NORAD Catalog database [5] was analysed to identify the most crowded orbits and the most dangerous objects in LEO. First of all only abandoned intact spacecraft and spent rocket upper stages were considered. Then objects orbiting near polar regions were selected, as these are the most crowded orbits. Objects below 700 km were excluded from the selection process, mainly because they will most likely de-orbit within 25 years and thus follow the ESA requirements [6].

In the framework of the e.Deorbit mission, the ADR1EN project has a LEO debris removal mission as a specific target, with the design following the particular environment requirements.

General debris with a volume between 1 and 10 m^3 has been considered as the target debris for the ADR1EN project and 4 specific targets have been selected, consulting the NORAD Catalog database:

- 2 dead satellites: Alouette 1, SPOT 4
- 2 spent upper stage rocket bodies: Thor-Agena D, Ariane 42P

2 ADR MISSION

2.1 Mission Profile

We considered as a reference guideline the preliminary mission design performed by prime contractors within the ESA Clean Space e.Deorbit Phase A initiative [7, 8, 9] : this is designed to target orbiting debris in well-trafficked polar LEO orbits, between 800 km to 1,000 km altitude. At around 1,600 kg, e.Deorbit will be launched on ESA’s Vega rocket.

Considering the whole mission duration, a significant amount of time is spent for rendez-vous operations (tens of days) and only a little amount of time (days) for net ejection and debris capture operations. Because of this, our reference mission is considered a “Short Term” mission. The mission will have a total duration, from launch to re-entry, of around three months and can be divided in four main subsequent phases:

1. Launch
2. Rendez-vous
3. Target capture
4. Controlled re-entry

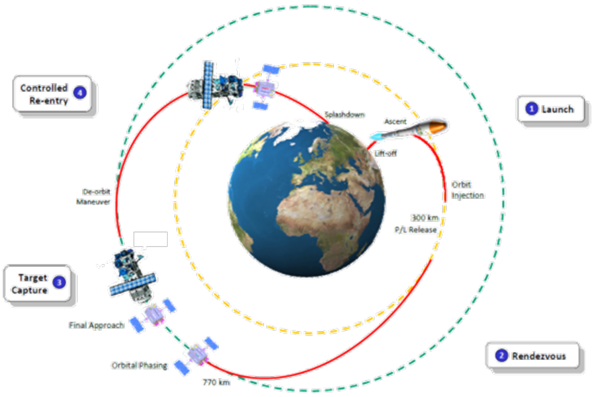

Figure 1. e.Deorbit mission phases (Credits: Thales Alenia Space).

The payload shall then be designed to resist full LEO environmental conditions during the target capture and controlled re-entry phases, expected to last about 2 weeks, with final burn in atmosphere.

2.2 Chaser Configuration

The PRIMA platform, developed by Thales Alenia Space Italy (TAS-I), was selected as the target chaser bus. In order to define the best accommodation for the ejector system, it has been designed to comply with the PRIMA thrust cone available internal space, maximum allowed payload and specific needs and platform constraint.

It was initially planned to equip the net ejector with two nets, in order to have a backup shot in case of failure of the first launch, together with an automatic reloading system, to be able to fire multiple targets within the same mission. However, this would be extremely complex, increasing the mass of the payload and most of all introducing a number of potential causes of failure. In order to optimize the system, by maximizing its cost-effectiveness, and to guarantee redundancy, it was then decided to have two identical ejectors and tether mechanisms, to be positioned inside the PRIMA thrust cone. Having two ejectors, tethers and nets inside the chaser will not only highly mitigate the risk of mission failure, but it will also open to the possibility of capturing multiple debris in a single mission. The allowed volume and maximum weight inside the chaser, though, are divided by half, resulting in an additional challenge for the ejection mechanism design.

The extremely challenging LEO environment makes it necessary for a specific set of requirements to be addressed during the mission definition. The main requirements impacting the ejector design were considered, in terms of: mass and volume, mechanical interface, thermal interface, power electrical interface, LEO environmental conditions. This is by no mean a complete list of all the requirements imposed on the system, but an overview of the main ones, that have been taken into account during the design stages. Other more specific requirements may be mission dependent and occur in a slight modification of the ADR1EN design that would not modify its functioning.

3 ADRiNET EJECTOR UPSCALING

The experience maturated throughout the ADRiNET project "Net parametric characterisation and parabolic test", developed within the ESA contract n. 4000109361/13/NL/RA and described in [9] and [11] built a solid background on the ejection mechanisms to throw nets. There, a pneumatic ejector was developed, which is briefly introduced here, as a starting point for the up-scaled ejector design. Then, a schematic view of the ejector is presented before proceeding into a more detailed description.

The ejector design was developed to be compliant with the deorbit mission requirements: this means compliance with LEO environment and deorbit manoeuvres and dimensions designed in order to fit two identical ejectors inside the available space on the chaser. The ejector has been designed in details, but no physical prototype manufacturing of this design is foreseen at the moment. This is because the prototype, being optimised for space application, would not be suitable for the full-scale ground tests that will be performed to validate the developed technology.

A second design will be then developed, derived directly from the first one, to be used for the ground tests. Due to the presence of gravity, the particularities of the test environment configuration and the possibility to use commercial components in place of space-proven ones, a few differences will be present between the two versions of the ejectors.

The old version of the ejector was based on a pneumatic working principle, with 4 identical bullets inserted inside 4 nozzles and shot by the release of compressed air, stored inside a gas tank. The net to capture the debris was folded and stored inside the ejector head and tied to the bullets at its corners. When the bullets were shot, the net was consequently ejected, moved by the higher mass of the four bullets.

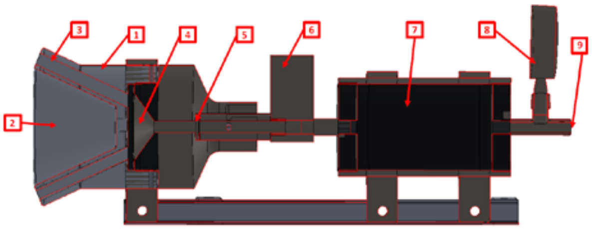

Figure 2. ADRiNET ejector schematic view.

Figure 2 shows a schematic view of the ADRiNET ejector main components:

1. Ejector head: made of Aluminium. Neodymium magnets are attached around cylindrical surface in order to prevent falling off the corner masses out of the nozzles.
2. Net container: a conical shape opened inside the ejector head in order to contain the folded net before the ejection.
3. Nozzles: four equal and symmetrical nozzles, used to eject the four bullets.
4. Gas distributor: here the compressed air coming from the tank is spread among the four nozzles.
5. Diaphragm: used to seal the hose in order to reduce the pressure.
6. Electrovalve: regulates the compressed air flow.
7. Gas tank: the compressed air is stored here.
8. Manometer: it is used to check when the pressure inside the gas tank reaches the desired value.
9. Compressed air inlet: an external tank is used to refill the ejector gas tank before every shoot.

A similar structure can be found in the up-scaled net ejector, with a few differences determined by the increased dimensions and the required resistance to the LEO environment. Figure 3 provides a general view of the ejector scheme.

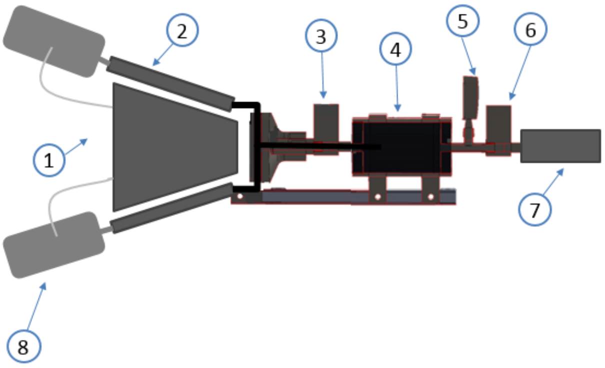

Figure 3. ADR1EN ejector schematic view.

The following list provides a more detailed view on new introduced components:

1. Net container
2. Bullet nozzles
3. Ejection and vacuum valves: an electrovalve controls the gas ejection, while a vacuum valve ensure that vacuum is present inside the nozzles before the shot.
4. Cold-gas tank: the tank is not filled on Earth, but directly in orbit thanks to a Cool Gas Generator (CGG).
5. Pressure sensor: it can control the pressure

level inside the tank and close the valve between CGG and tank when the desired value is reached.

6. Non-return valve: it makes sure that all the needed gas flows from the CGG to the tank.
7. Cool gas generator: keeps the gas in solid form during launch. When activated, a chemical reaction turns the gas volatile again and it fills the ejector tank.
8. Bullets.

It is worth noting that the tether mechanism is not present in this scheme, as it constitutes a standalone mechanism, separate from the ejector.

In the following sections, the detailed design of the space configuration ejector is discussed.

4 ADR1EN EJECTOR DESIGN

This section provides a detailed analysis of the ADR1EN ejector design process. First, the specific challenges of the LEO environment are discussed, in order to give and overview on the conditions the ejector has to sustain. Secondly, the upscaling process of the ADRiNET ejector is detailed.

Lastly, the complete ejector design is presented, with a focus on its structure and the components required, discussing their functioning and why they have been chosen, and the layout of the two ADR1EN systems (ejector, nets and tether mechanism) inside the chaser.

4.1 LEO Environment

Space is an extremely challenging environment, which requires a careful design and selection of each component, in order to resist the particular environmental condition.

LEO is characterized by high vacuum, microgravity, extremes of temperature, meteoroids, space debris, ionospheric plasma, and ultraviolet and ionizing radiation. Radiation levels are however lower than the ones experienced at higher altitudes. This, together with the relatively short duration of the deorbit mission, results in a lower impact of radiation on the ejector and the net when compared to other deep space missions.

Nonetheless, LEO is within the Earth’s magnetosphere, resulting in exposure to higher fluxes of ionizing radiation [12] when compared to Earth surface. The primary radiation sources are galactic cosmic rays (energetic particles from outside our solar system), particles trapped in the Earth’s magnetic field (the Van Allen Belts) and solar energetic particle events (solar flares). High-energy protons and heavy ions emanate from the Sun and elsewhere in the cosmos. Even higher energy secondary particles (protons, neutrons and heavy ions) are produced when the incoming radiation strikes an object in LEO.

The general characteristics of LEO can be summarized in the following table.

Table 1. LEO environment characteristics.

Temperature extremes	-65 to +150 °C
Thermal cycle time (orbit duration)	90 mins
Pressure (high vacuum)	10-700 nPa
Ionizing radiation	25-54 µSv/d
Ionospheric plasma	induced charge on polar orbits
UV radiation	100-200 nm
Atomic Oxygen	109 atoms/cm^3

4.2 Ejection Mechanism

Starting from the upscaling of the ADRiNET ejector, the main dimensions of the new ejector have been determined. Parameters such as the net container and nozzles dimensions, the required gas pressure and volume, etc. have been computed and will be detailed in the following sections.

A container for the net is necessary to keep the net safe and well folded until the moment of the launch. It has to be big enough to contain safely the whole net, without undesired compression that could compromise the correct net spread during the ejection phase.

For the ground tests, the following net types will be used, similar in structure but different in sizes:

- Net 1
    - Dimension: 15x15 m
    - Wire dimension: 1 mm
    - External mesh: 1.25x1.25 m
    - Internal mesh: 0.25x0.25 m
    - Internal area: 5x5 m
    - Mass: 590 g
- Net 2
    - Dimension: 9.6x9.6 m
    - Wire dimension: 1 mm
    - External mesh: 0.80x0.80 m
    - Internal mesh: 0.20x0.20 m
    - Internal area: 3.2x3.2 m
    - Mass: 430 g

It is worth noting that the choice of the specific dimensions of the container is dependent from other parameters, such as the length of the nozzles or the available space inside the chaser. For this reason, being the net container the biggest component of the ejector, the shape of the container was tuned during the design process, in order to allow 2 complete ejector systems to fit inside the chaser.

With the term ejection mechanism, we refer to the main components required for net ejection. In particular:

- Compressed gas tank
- Ejection valve
- Nozzles
- Bullets

The design of these components is strictly interconnected, since each one of them influences the others. Particular care has to be taken in the design process, in order to find a good compromise between small dimensions and good performances.

The ejector will have four rigid nozzles in the frontal part, each one dedicated to the ejection of one single bullet. The bullets will be partially inserted in the nozzles before the ejection, with the most part of their mass outside of the nozzles, in order to maintain the centre of gravity outside of the nozzle. This will help during the net shooting phase, since the net will be tied to the bullets on their centre of mass to avoid undesired rotations of the bullets during the fly. Moreover, having the bullet centre of gravity outside of the nozzle will avoid interference of the net with the bullets during the ejection.

As detailed in Section 4.4, the net ejector design was supported by dynamics simulation software, developed during the ADRiNET project [10, 11, 13],improved and further developed during ADR1EN. The desired net and bullets velocity were computed, together with the nozzle ejection angle with respect to the ejector main axis, in order to obtain the complete net development just before hitting the target debris.

Table 2 provides a detailed view of the main parameters that were taken into account to obtain a correct and controlled shot of the net.

Table 2. Net and bullet ejection parameters.

ID	1	2
Net velocity	10 m/s	10 m/s
Bullets velocity	13 m/s	13 m/s
Net size	15x15 m	9.6x9.6 m
Bullet ejection angle	10.6°	7.1°
Net flight distance	50 m	50 m
Predicted full development distance	40 m	40 m
Predicted development time	3.1 s	3.1 s

Ground tests will be performed to validate the design and will help tune the values of these parameters, checking that everything works as expected during the net ejection phase. It is worth noting that the values reported in Table 2 are representative of a particular case mission, where the target debris is caught at 50 m distance from the chaser. Since the ejector is easily scalable for different missions, nozzle angles can be changed if the target is closer or further away from the chaser. On the other side, net velocity will remain fixed, since simulation have shown that 10 m/s is the best velocity at which the net should hit the target.

As it is visible from Table 2, an ejection velocity of 13 m/s is required for the bullets, in order to obtain a net velocity of 10 m/s. Being the ejector structured as a compressed gas ejection system, the velocity of the four bullets is dependent on the distance each bullet covers inside its nozzle. On Earth, the influence of the air friction would oppose to the bullet motion, with a force depending on the square of the bullet velocity: the higher the bullet velocity, the higher the air resistant force.

In space, though, having no external air acting on the bullet, it will constantly accelerate during the ejection. It is then possible to design the nozzle length and diameter as preferred, in order to obtain the desired bullet velocity, with no limitations.

A simple scheme of the gas tank and nozzle structure, as used in the ADR1EN ejector, is shown in Figure 4.

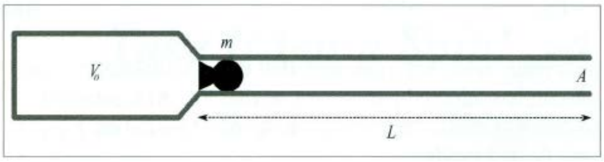

Figure 4. Simple scheme of the ejection system.

Theoretically, for a simple air-gun, the following formulas hold:

$$P(t)V(t) = P_0V_0 \tag{1}$$

Where P and V are the pressure and volume at time t and zero respectively.

When the ejector trigger is pulled and the compressed gas is free to expand, the bullet starts to move, increasing the volume occupied by the gas. In particular:

$$V(t) = V_0 + Ax(t) \tag{2}$$

Where A is the sectional area of the nozzle (that is the same area on the bullet, where the pressure is acting on) and $x(t)$ is the position of the bullet in the nozzle at time t $(0 \leq x(t) \leq L)$.

The force acting upon the bullet is:

$$F = AP(t) = m\ddot{x}(t) \tag{3}$$

Where m is the mass of the bullet.

Integrating this equation, it is possible to obtain the velocity of the bullet at the exit of the nozzle. The following equation holds:

$$v(L) = \sqrt{\frac{2}{m}\left[P_0 V_0 \ln\left(1 + \frac{AL}{V_0}\right) - fL\right]} \qquad (4)$$

Where f is the constant friction force between nozzle and bullet.

It is clear, then, how the velocity of the bullets at ejection depends on different parameters, in particular:

- Bullets mass: the general rule is that total mass of the bullets should be 4-10 times greater than mass of the net itself [13].
- Nozzle length: the longer the nozzle, the higher the ejection velocity.
- Nozzle diameter: the larger the nozzle, the higher pressure is required to shoot the bullets at a desired velocity.
- Gas tank pressure: the required pressure inside the tank depends on the desired ejection velocity and tank dimension (not too big to fit the chaser available space).

As said above, the desired bullets ejection velocity has been computed, through the dynamics simulator, as 13 m/s. This value can be obtained with different combinations of the previous four parameters. In the design process, different values have been considered, analysing the results in order to obtain a good compromise between dimensions (small space available inside the chaser), gas pressure (a value too high can give problems during valve selection) and normal litres of gas required (gas filling mechanism can produce a limited amount of gas). Table 3 reports the parameters values, as they appear in the ejector final design.

Table 3. Ejection parameters.

Parameter	**Value**
Desired ejection velocity	13 m/s
Tank volume	$2\cdot10^{-3}$ m^3
Tank volume	2 l
Bullet mass	1.1 kg
Nozzle diameter	30 mm
Nozzle length	160 mm
Cool gas generation needed	23.7 nl
Shooting temperature considered	20 °C
Pressure inside the tank before shooting	12 bar
Real ejection velocity (considering friction)	12.98 m/s

4.2.1 Ejection Gas Flow Rate

It has been discussed, in the previous section, the required pressure to obtain the desired bullet ejection velocity. Following this analysis, it is necessary to introduce in the mechanism a properly chosen electrovalve that will guarantee a fast opening and ensure a sufficient flow rate.

First of all, the ejector mechanism can be approximated to a system without an ejection valve, with the following assumptions:

- The gas is compressed inside the gas tank.
- There is vacuum inside the nozzles.
- The valve has instantaneous opening and can sustain any flow rate.
- No pressure loss is considered between the ejection valve and the exit of the nozzles. This means that flow rate at the exit of each nozzle is one fourth of the flow rate in the valve.

Starting from those simplifications, the following holds:

$$\frac{P_0}{\rho g} + \frac{{V_0}^2}{2g} = \frac{P_1}{\rho g} + \frac{{V_1}^2}{2g} \qquad (5)$$

Where P_0, P_1 and V_0, V_1 are the pressure and velocity before and after the valve respectively and ρ is the gas density at the operational temperature.

The flow rate is $Q = V_0 A_0 = V_1 A_1$, then we can obtain:

$$Q = \sqrt{2\frac{\left(\frac{P_0 - P_1}{\rho}\right)}{\left(\frac{1}{{A_1}^2} - \frac{1}{{A_0}^2}\right)}} \qquad (6)$$

Where A_1 is the nozzle sectional area and A_0 is the tank sectional area. For the sake of simplicity, ρ was considered as the mean value density between inside the gas tank and outside of the nozzles.

From Eq. 6, with the values in Table 3, the gas flow rate at ejection is $Q \cong 5\ m^3/h$.

The main electrovalve of the ejector has then been selected considering this value as a minimum requirement.

4.3 Final Ejector Design

Following the results and design constraints defined in the previous section, the complete design of the ADR1EN ejector has been carried on. In the following sections, the final design of the ejector is presented, discussing in details all its characteristics.

4.3.1 Overview

This section gives a general view of the working principle of the ejector, discussing how it is activated and how the gas moves from the pressure vessel to the nozzles, shooting the bullets. Figure 5 gives a schematic diagram view of the ejector main components.

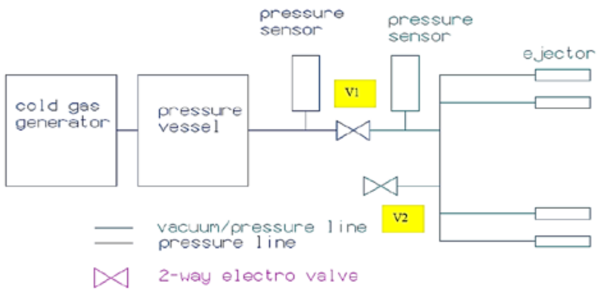

Figure 5. Ejector working scheme.

The working principle is the following:

- Starting condition: both valves V1 and V2 are closed, the net is folded inside the net container and the cover is positioned on top of the ejector, to keep the net and the bullets in place. The system is in orbit.
- Valve V2 is activated, in order to let air (any remaining from the launch) flow outside of the nozzle and generate vacuum.
- The pressure sensor after valve V1 is used to confirm that vacuum is obtained in the nozzles.
- Cold gas generator is activated. Gas flows inside the pressure vessel, until the desired pressure is obtained.
- Ejector cover is unlocked through the action of Frangibolts®.
- Ejector cover is opened. The cover sets both the net and the bullets free.
- Valve V1 is activated and the net is shot.

Following the ejector scheme proposed in Figure 3, the ejector design has been developed and the new components needed to guarantee space compliancy have been implemented.

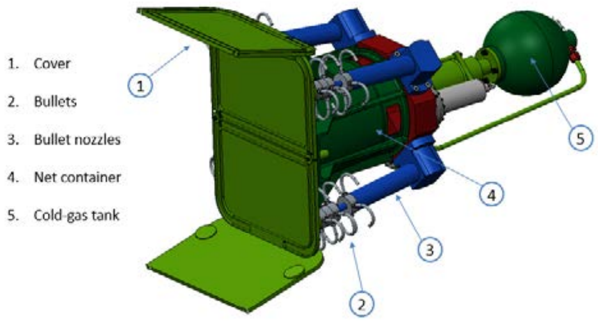

Figure 6. ADR1EN ejector front view.

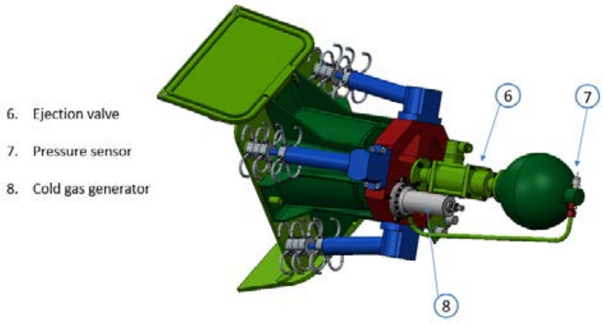

Figure 7. ADR1EN ejector rear view.

Figure 6 and Figure 7 show the final complete design of the ejector. It is worth noting that the ejector cover is shown in both “open” and “closed” configurations.

4.3.2 Cold Gas Generator

As already described in the previous sections, the choice of a cold gas generator (CGG) was made for the ejector design. In CGG, an alternative to traditional methods for storage of gas under pressure, the gas is chemically stored in a solid unpressurized form. That means that, while in rest, the grain is inert and will not decompose or deteriorate in time. This, combined with the fact that the gas compact dimensions when in solid form and that it will be produced at an ambient temperature, makes the cold gas technology an optimal choice for space missions.

The gas in solid form does not need any further intervention (e.g. fuel load) after integration and can be fired whenever it is needed by activating the gas generator, decomposing the solid charge and releasing the gas.

It is an innovative but mature technology, which has already seen implementations in space missions, usually for inflation and deployment purposes. Some implementation examples can be found in the Bigelow BEAM Technology Demonstrator Module, the Rosetta Lander Back-up Landing Gear Study, or the PROBA-2 mission [16].

Overall, the CGG technology has several advantages with respect to traditional gas storage methods:

- Lower volume than existing technology
- Flexibility in positioning
- Low maintenance
- More constant pressure profile
- Pressure profile adjustable through intelligent grain design
- Not pressurized if not initiated
- Inherently safe
- Long storability (gas cannot leak away).

These multiple benefits were at the base of the choice of implementing such a technology in the ejector mechanism.

Looking at the ADR1EN ejector 3D view proposed in Figure 7, it can be seen how the CGG is positioned at the beginning of the ejector mechanism chain.

The ejection working procedure is the following:

- Initial condition: cold-gas tank (4) not pressurized, ejection valve (3) closed.
- Step 1: CGG (7) activated to pressurize cold-gas tank (4). A pressure sensor (5) monitors the CGG performance.
- Step 2: Ejection valve (3) is opened to eject the bullets (9) from their bullet nozzles (2), ejecting the capture net from the container (1).

It is clear, then, how the correct choice and sizing of a proper CGG is crucial for the whole mission success. The CGG has to correctly activate when required, fill the cold-gas tank with no gas loss and generate the correct pressure inside it, in order to guarantee the desired bullets velocity at the ejection.

For this reason, particular care has been taken in the key performance requirements definition for CGG:

- Amount of ambient temperature gas to be produced: 25 nl
- Target pressure cold-gas tank: 12 barA
- Operational/non-operational temperature ranges:
  - Non-operational: -35 to +55 °C
  - Operational (firing): -10 to +40 °C
- Maximum allowed dimensions: 480x200x200 mm (L x W x H).

Taking into account the performance requirements described above, a CGG developed by Moog Bradford and implemented in the PROBA-2 mission, has been selected. PROBA-2 is a Sun observatory mission, with the secondary objective of demonstrator for 11 technologies, among which the Cool Gas Generator Experiment (COGEX).

Up to date, three test firing have successfully been conducted (August 2011, October 2012, June 2016), showing a correct nominal performance of the CGG. The fourth and final CGG operation is planned for the end of 2018, to assess the correct behaviour of the system with on-orbit life of 9 years and post-delivery life of 13 years.

The COGEX CGG is a product commercially available and space proven, making it very well suited for this application.

4.3.3 Ejection Valve

Following the analysis performed on the gas flow rate at ejection, discussed in section 0, the ejection electrovalve has been selected. The final choice is the co-ax MK10 coaxial electrovalve.

Given a K_v coefficient of 2.5, the maximum allowed gas flow through the valve is computed as:

$$Q = K_v\sqrt{(P_1 - P_0)} = 35.75\ m^3/h \qquad (7)$$

As we can see, this value is much higher than the required value computed in section 0, therefore the selected valve can be successfully installed in the ejector. The valve is not space-proven, but the compliance with an ADR mission can be easily certified.

4.3.4 Net Container Cover

In order to avoid net exiting the container and bullets escaping from the nozzles during launch and orbit manoeuvres operations, a cover needs to be positioned on top of the ejector. The solution designed for the ADR1EN ejector makes use of a two opening doors mechanism, which allows a covering during launch and manoeuvres and a correct net ejection during the debris capture. Figure 8 shows the ejector cover in the two closed and open positions.

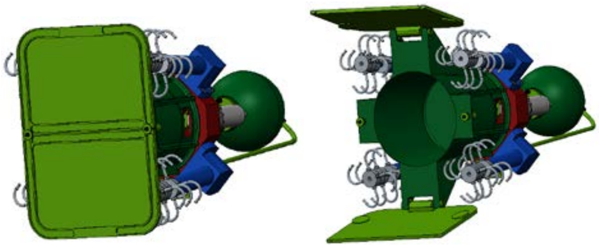

Figure 8. Net container cover in closed (left) and open (right) position.

The opening movement is guaranteed by two spring mechanisms, one for each door. In order to keep the cover closed before the net ejection, two Frangibolts are mounted at the cover sides and will be released a few seconds before the ejection.

The principle of operation of a Frangibolt mechanism is simple: a Shape Memory Alloy (SMA) cylinder elongates when heated up to fracture a bolt element thereby achieving separation of two or more components, in this case the ejector cover and net container. The Frangibolt actuator comprises of a cylinder of Nitinol (Nickel-Titanium) SMA and a specially designed (integrated) heater.

The selected Frangibolt for the ADR1EN project is the TiNi Aerospace FC2 actuator, which is suitable for applications that require up to 230 kg of load holding capability.

4.3.5 Two Ejectors Chaser Configuration

As discussed, two ejectors and tether mechanisms are foreseen inside the chaser, to provide redundancy to the mission, in case of one ejector failure, or to allow a multiple debris capture mission. The dimensions and masses of the ejector and tether mechanism have been designed in order to fit inside the chaser thrust cone and meet the maximum allowed payload requirement. Figure 9 shows the configuration of the two ejectors and tether mechanisms inside the chaser thrust cone.

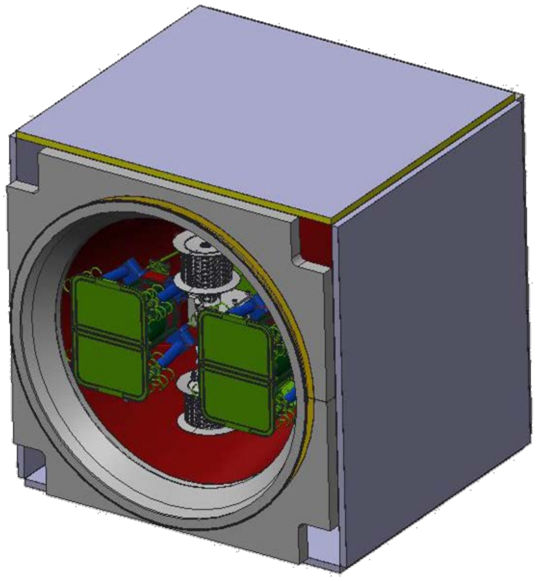

Figure 9. Payload configuration for the ADR1EN mission.

In order to connect all the components in a single rigid body and then fix it to the chaser thrust cone, a specific aluminium structure has been designed. In compliance with the mission requirements, the structure will be fixed on the thrust cone using titanium bolts.

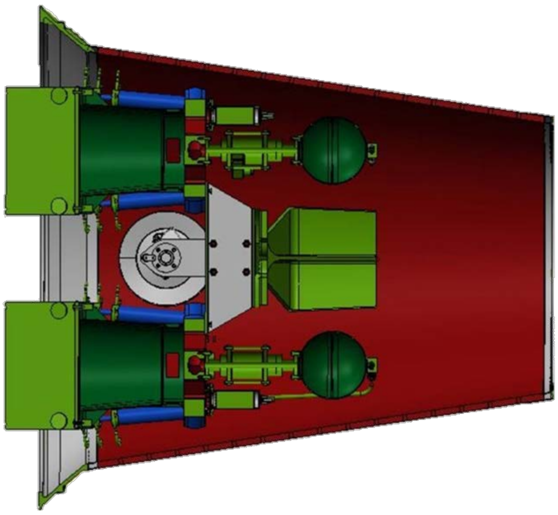

Figure 10. Section views of the payload configuration.

Figure 10 shows the components arrangement inside the thrust cone and the fixing aluminium structure.

It is well visible how all the components fit inside the thrust cone and no collision between the payload and the cone occurs, with a good safety margin. Only the ejector cover, when opened, exits the thrust cone, but this causes no problems since the chaser hold door will already be opened before the net ejection.

When comparing the space occupied by the two ejectors with the available space inside the PRIMA thrust cone, the length of the two ejectors is a little longer than the available space. This difference, though, is minimal and the ejector can fit with a small change in the positioning of the components inside the upper part of the thrust cone, which will allow gaining some space in the external part of the cone, where the ejector tanks are positioned. It is also worth noting that, due to the flexibility of the system, depending on the target mission, the dimension and shape of the gas tank can be easily modified in order to better fit the available space.

4.4 Dynamics Simulations Support

Simulations were used to verify and optimize the initial system design developed to meet the requirements. The software toolchain used for simulations was initially developed for ESA to support the e.Deorbit mission preparation and then validated within a parabolic flight experiment under microgravity conditions [10, 11]. The simulation tool has been improved and extended with further functionalities, needed to comply with the requirements of the ADR1EN project activities.

The simulator was a perfect tool for studying the advantages and disadvantages of certain ejection scenarios and which parameters influence the capture efficiency of net. Although simulation models are a simplified representation of real systems, it is enough to study certain phenomena – like energy balance – even better than in real experiments.

Simulation models with a large number of factors and parameters usually imply simulation campaigns with a large number of different scenarios, aimed at evaluating the impact of each one on the overall system performance. Even though some statistical techniques (e.g. factorial analysis) might be employed to reduce the number of scenarios, such simulation campaigns require a rigorous methodology to execute such large-scale experiments and, in particular, to analyse properly the large amount of results produced. The simulator developed and used within this framework allowed us to simulate a number of different scenarios without the need for such large simulation campaigns and long analysis of results.

The goals of the simulation campaign supporting the ejector upscaling and design are listed in the following:

- To study the ejection process to achieve the optimal net development paths and increase the capture efficiency.
- To estimate the ejection angle range useful for full-scale nets.
- To estimate the initial velocity range of the bullets. To identify the optimal initial momentum to be applied to achieve the best net development.
- To estimate inertia effect. To assess how the net mass slows down the motion of the bullets.
- To estimate the deviation of the bullet path from the ideal trajectory.
- To study the energy balance. To assess the amount of kinetic energy that is lost. To evaluate the level of energy dissipation due to material viscosity or internal friction.
- To analyse whether the nozzles configuration can provide a rotational speed to the net.
- To analyse which external forces need to be taken into consideration. To study possible issues during the ground test (air drag effects, weather, etc.).

4.4.1 Simulation Cases Definition

Because of the complexity of the ejector design, a large number of parameters and their combination influencing net ejection and flight had to be taken into consideration. Table 4 presents the ranges for the system parameters tested.

By combining bullet velocity, ejection angle, bullet mass and net size, we could create a large set of possible configurations and test the impact of these parameters on the behaviour of the system.

Table 4. Selected parameters tested.

Parameter	**Range**
Initial velocity	6 – 14 m/s
Angle	3 – 35 deg
Mass	0.327 - 3.744 kg
Size	9 – 15 m

Figure 11 shows the initial configuration of a simulation: it can be noted that it is not necessary to represent the complete chaser and ejector geometries. Instead, only the target debris, the bullets and the net packed into the container were modelled.

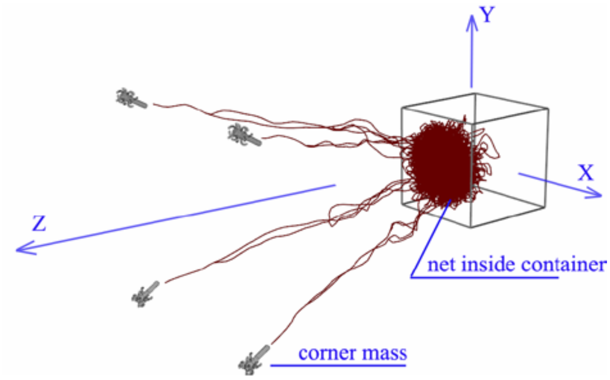

Figure 11. Simulation initial configuration.

Tests were performed, for example, keeping the ejection velocity, while modifying the ejection angle (Figure 12).

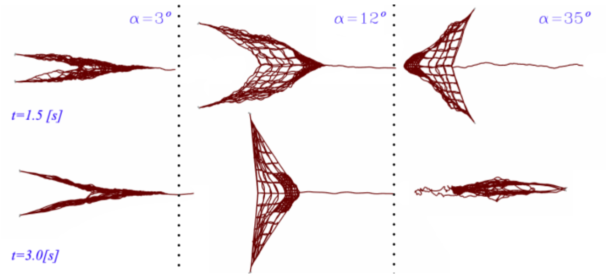

Figure 12. Three cases with different ejection angles.

Another set of tests was performed for different types of net (Figure 13).

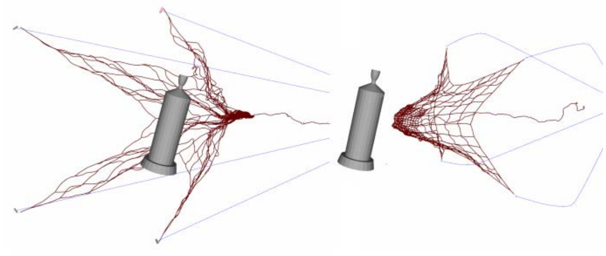

Figure 13. Too small (left) or too large ejection angle.

The net capturing effectiveness was checked not only for the nominal designed nets and capturing process parameters, but was also extrapolated. For this reason the conclusions obtained from these simulations can be useful for system design in the future.

The simulation results provided an important support for the ejector design.

Thanks to this approach it was possible to obtain a reliable ejector design, as described in Section 4.3.

4.5 Environmental Tests

Environmental tests were performed on the ejector components, through Thermal Vacuum Cycling Test (TVCT). The TVCT consisted in a thermal cycling of part of the ejector assembly, comprising some of the components, mechanisms and materials. Temperature were in the range -20 °C to 50 °C and the pressure was below 10^{-4} mbar. The temperature extremes were defined in accordance with thermal simulations performed of the PRIMA thruster cone.

Since in the ADR mission the net would remain folded in the container until the moment of ejection, it was decided not to perform mechanical tests in the TVCT, as these would not be representative of a real situation. Each net was then packed inside its container and, in this configuration, exposed to thermal vacuum cycles.

The thermal cycling was performed in the PESCha (Planetary Environment Simulation Chamber) chamber (Figure 14) at Thales Alenia Space Italy premises in Turin.

Figure 14. PESCha facility (Credits: Thales Alenia Space Italy).

The objective of the TVCT was to have the ADR1EN payload exposed to representative low pressure and variable temperatures cycling between two extremes, in agreement with ECSS Space Environment Testing [15]. For this purpose, the following steps were performed:

1. Vacuum Thermal Cleaning

A prolonged vacuum and warm period devoted to the "cleaning" of the hardware in the chamber, to limit potential contamination of the facility.

2. Tuning step

Devoted to tune the process parameters, in order to obtain the defined temperature profile on the reference point.

3. Thermal Vacuum Cycling

With thermal cycles performed on the mechanisms and components.

The minimum and maximum temperatures, T_{min} and T_{max}, the dwell time duration and the pressure levels were selected with a worst case approach:

- T_{min} = (-20±2) °C with an additional conservative delta margin during the dwell time of -1 °C.
- T_{max} = (50±2) °C with an additional conservative delta margin during the dwell time of +1 °C.
- Dwell time with a minimum duration of 3 hours.
- Pressure inside the thermal vacuum chamber below 10^{-4} mbar for the operative duration of the test (pressure level to be reached before starting the representative thermal cycles).

At the end of the TVCT, visual inspections was also performed, by means of Leica DMI3000 B optical microscope, on specimens submitted and not submitted to the TVC testing, to assess any modification in the materials structure.

Based on the test results the TVCT was considered fully successful, and the tested components can be considered to be suitable for being used in an ADR mission.

5 CONCLUSIONS

The design of the ADR1EN ejector, carried-out scaling up the small-scale ejector developed within the ESA ADRiNET project, was presented in details in this paper.

First, an overview of an ADR mission was provided, defining its profile and phases. Then, the chaser configuration, based on the PRIMA platform developed by TAS-I, was considered. These, together with the environmental requirements, composed the complete requirements set for the design of the ADR1EN ejector. Finally, the simulation and environmental testing activities, to support the ejector design phases, were discussed.

The experience matured within the ADRiNET project served as a base to up-scale that design, while complying with the identified requirements. The conceptual design of the ejector was initially defined, identifying the main components of the system and dimensioning each one, on the base of the system requirements. Then the detailed design of the ejector was performed, defining its functional scheme, its working principle, the components and sub-systems. The ejector design is based on a cool gas generator providing the compressed gas to eject four bullets attached to the net, folded inside a container. Two ejectors will be accommodated inside the thruster cone of the chaser, in order to ensure redundancy in case of ejection failure.

The design was supported by dynamics simulations, to assess the influence of functional parameters on the system, and environmental tests in TVCT.

The ejector design here presented is therefore a strong potential candidate for an ADR mission.

6 ACKNOWLEGMENTS

The ejector design was performed under the ADR1EN project, that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 666758, through the SME Instrument, by a consortium composed of Stam (Italy), SKA Polska (Poland) and OptiNav (Poland).

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