FLEXIBLE CAPTURE DEVICES FOR MEDIUM TO LARGE DEBRIS ACTIVE REMOVAL: SIMULATIONS RESULTS TO DRIVE EXPERIMENTS

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ABSTRACT

The space debris removal and generation containment in Earth orbits is a well-known and urgent issue to be faced to mainly preserve the safety of the current and future active space systems.
From a removal system design point of view, the more the general purpose it is the more cost effective would be. On the other side, the more general purpose it is, the less effective it may turn to be.
In fact, a general-purpose removal system design should effectively intervene on objects completely different in configuration, materials and possibly in dimensions such as fragments, entire/parts-of dismissed satellites and third stages/fairing elements.
Moreover, elements to be managed do not cooperate and have a complex, free, not completely known dynamics.
Different techniques are being proposed in literature, starting from the classical robotic arm, dedicated to a narrow and specific class of debris which present parts the robotic arm can grasp to, up to action-reaction principle exploitation with no contact at all, such as gas plume impinging on the non-cooperative element to change its momentum.
The paper updates the work currently on going at Politecnico di Milano to design, characterize and test an in between solution: a net, shut from an active satellite, that embraces the debris element, closes around it and thanks to an active box, tethered connected with the net, drag it to the disposal position in space.
The problem has been deeply analysed to simulate at the best the net deployment, contact and closure dynamics on the target. Starting from their previous works results, the authors here add the critical discussion about the effectiveness of a planar net versus a 3D (either conical and pyramidal shape) net configuration solution according to the size, mass and configuration of the class of targets to be wrapped.
The already implemented numerical simulator, focused on driving the real device sizing and integration, has been upgraded by taking into account damping features of the thread materials to better match the available experimental results. The technology roadmap is under definition identifying the most urgent technologies to be tested.

1. INTRODUCTION

The space debris issue has become extremely relevant in the last years due to the high number of inactive flying objects in LEO, MEO and GEO, and effective solutions to remove such debris are currently under investigation as well as policies definition to properly manage the space vehicles end-of-life [1].
The Active Debris Removal (ADR) topic focuses on trading-off, designing and making operational mechanisms placed on board an active chaser that can rendezvous with and grapple an inert, tumbling, and non-cooperative target, to eventually change its dynamics either directly transferring it to a disposal orbit or providing a control device to be attached to the dead element to make it controlled up to disposal.
The main goal of Debris Collecting Net (D-CoNe) project, under development at Politecnico di Milano - Department of Aerospace Science & Technologies (PoliMi-DAST) since 2010, is to demonstrate the feasibility of disposing medium sized debris by means of a net device, connected, at its vertex, to the chaser satellite, through a tether.
A flexible ADR/servicing solution was also studied in the past by Astrium from a systemic point of view, as a part of the ROGER study [2], and it has recently been the topic of an ESA CDF study [3].
The D-CoNe net is cast by impulsively accelerating four flying weights, hereinafter named bullets, attached to the net mouth; then the relative trajectory of the bullets deploys the capture net gradually during the flying process, as shown in Fig. 1.

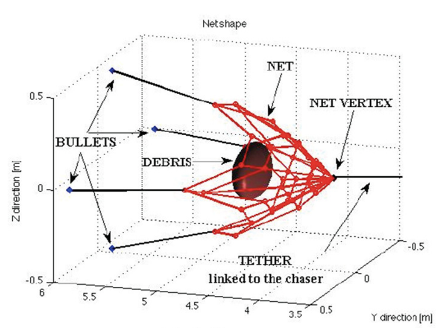


Figure 1. D-CoNe concept

Such a solution is safer than a contact-based mechanism, and applicable to a quite large class of differently shaped objects. By contrast with rigid capture mechanisms ([4], [5]), a flexible tether-net system allows a larger capture distance between the target and the chaser, lowering the collision occurrence chance; the conversion of a point-to-point capture into a surface-to-point capture, reducing both the capture precision requirements and the stress concentration; it is lightweight, with a quite limited volume demand on board, giving room for multiple captures and disposals within the same flight campaign. The high system deformability is the price to be paid: the system may be complex to control; critical oscillations may rise as rigid connection is no more provided between the target and the chaser; actual net-debris contact prediction is rough and the real contact forces distribution is actually unknown till the connection occurs; some critical operations (e.g. tether deployment) exist and failures management may reveal quite complex. To gain a robust design of the net-based solution attention must be paid in sizing the unfolding mechanism and to provide the mechanism with passive control that naturally leads the net to correctly open, hit the target and wrap it. To this end, modelling, numerical simulating and experimental testing are fundamental. To get the goal, firstly a simulator of the release and capture phase to drive the capture system design and sizing shaped at the best on the target catching goal is needed; secondly a test-bed must be implemented to accomplish experimental tests to deeply understand the dynamics and correctly refine the mechanism design. At PoliMi-DAST both the steps have been run through. The implemented simulator ([6]) has been currently refined by modelling the damping, by enlarging the set of net geometries, and by enlightening the computational burden. The new numerical results obtained on the deployment dynamics have still to be verified with a dedicated test campaign on the breadboard available at PoliMi-DAST.

2. THE SIMULATOR ENHANCEMENT

The aim of the implemented simulator stays in studying the net dynamics from the shot, through the debris wrapping up to the dead element pulling through the tether connection, to tune some configuration key elements in order to achieve the expected dynamics all over the capturing phase.

The simulator has recently been upgraded to deal with different net shapes, i.e. plane (square or rectangular), pyramidal or conical, and different debris objects, from conventional parallelepiped shapes representing satellites bodies to curved shapes, such as fairings and upper stages.

A tension signal can be injected into the net through its vertex to simulate active reel control; however the tether is supposed to be slack during casting, not to affect the natural motion and deployment dynamics of the net and not to exercise reaction forces on the chaser satellite during capture.

The simulator was also enhanced to take into account different initial conditions, corresponding to different folding strategies and canister shapes.

2.1. Modelling the flexibility

Modelling of systems composed by many flexible elements, such as webs and net, is tricky and computationally expensive, due to non-linearity and number of variables, especially when dealing with surface contact.

Several high order representations such as Assumed Modes Method (AMM) and Finite Element Method (FEM) exists to deal with flexible structures ([7] and [8]), however they are mainly applied in configurations with few flexible elements.

The choice of a lumped mass-spring model (Fig. 2), as also suggested in [9] and [10], allows a more convenient and flexible; nevertheless it requires a careful implementation to deal with constraints and high number of discretization elements.

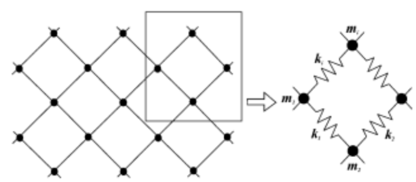


Figure 2. Net mesh modelling

Furthermore, if the mesh length is decreased, the spring stiffness increases and vice versa, being

$$k = \frac{EA}{l} \tag{1}$$

where E is the Young's modulus, A the thread cross section and l the mesh length. This effect needs to be taken into account in the discretization to avoid unphysical behaviour.

The analysis of the experimental results, obtained thanks to the testing campaign run with the breadboard implemented at PoliMi-DAST ([11], [12]) and comparison with simulation results showed that without damping, the elastic return is overestimated and the net doesn't achieve in simulation a complete and lasting deployment, as obtained through tests.

The net is discretized and modelled as a mesh of threads and points masses. The i-th knot dynamics is given by Eq. 2:

$$m_i \frac{d\boldsymbol{r_i}}{dt} = \sum_{j=1}^{N_T} \boldsymbol{T_{ij}} + \sum_{w=1}^{N_E} \boldsymbol{f_w} \tag{2}$$

where

- m_i is the concentrated mass of the i-th node,
- $\boldsymbol{r_i}$ is the absolute position of the i-th node
- N_T is the number of threads linked to the i-th knot;
- $\boldsymbol{T_{ij}}$ is the internal force vector, exercised through the rope tension by the j-th node on the i-th node;
- N_E is the number of external forces acting on the i-th node;
- f is the external force vector;

The ropes are massless elastic connections modelled with a spring-damper, active only under tension and not under compression. Eq. 3 gives tension on node i:

$$\boldsymbol{T_{ij}} = \begin{cases} (-k(r_{ij} - l) - d\,\dot{r}_{ij})\widehat{\boldsymbol{r_{ij}}} & if\, r_{ij} > l \\ 0 & if\, r_{ij} \leq l \end{cases} \quad (3)$$

where
- k is the stiffness and l the mesh length, as given by Eq. 1;
- d is the damping coefficient;
- r_{ij} and $\widehat{\boldsymbol{r_{ij}}}$ are respectively the magnitude and relative unity-magnitude direction of relative vector $\boldsymbol{r_{ij}}$
- $\dot{r}_{ij}$ is the relative velocity in the $\widehat{\boldsymbol{r_{ij}}}$ direction.

2.2. Net-debris contact modelling

Since the target and the chaser are supposed to fly in along track formation at capture occurrence, the relative velocity between the two bodies is supposed to be null.
The contact detection algorithm first checks whether the i-th mass is inside the target envelope or not and then refines the contact detection through the target mesh. This allows to save computational time while the net is not in contact with the target.
An impact algorithm has been implemented, based on the simple assumption that, being the knot far less massive than the target, the collision is almost inelastic. This algorithm is particularly light and efficient; on the other hand it asks for a dense net mesh.
A second algorithm has also been developed and it is currently under test: it is based on the elastic collision model ([13]): the normal force is computed as

$$F_n = (c\,s + b\,v_n)\,\boldsymbol{n} \quad (\mathbf{4})$$

where
- $\boldsymbol{n}$ is the surface outward normal vector
- c is the surface stiffness and b the damping coefficient
- v_n is the relative normal velocity between the two bodies.

This model is much computationally expensive than the former and needs precise tuning of coefficients c and b; nevertheless it allows taking into account tangential forces due to Coulomb friction as:

$$F_t = -(\mu\,F_n)\,\boldsymbol{t} \quad (\mathbf{5})$$

where μ is the friction coefficient and $\boldsymbol{t}$ the tangent unity-magnitude vector. Friction evaluation is fundamental to investigate the potential slippage of the net on the target after the grasp occurred.
The work on friction is currently on going and the algorithm is being tested.

2.3. Simulator results

Automatic coding features to accelerate the integration of the equations of motion have been added to the simulator, entirely developed in Matlab/Simulink environment. To turn from interpreted to compiled language significantly lowered the computational time up to at least a factor of three; still the solver features is one of the main drivers in the computational burden evaluation.
Simulation results allowed verifying that by introducing even a small damping ($d \approx 0.01 \div 0.1$), the elastic return of the net thread is contained and a better matching of the test campaign occurs: vertex oscillations in and out of bullets plane are reduced: the net acquires a better stretched and longer-lasting opened configuration, so at impact occurrence a bigger surface (for planar nets) or volume (for pyramidal nets) is available for capture. The damping coefficient tuning by means of the results of a material characterization test campaign has to be run.
In Fig. 3 a planar net to catch a 4x8x4 m^3 parallelepiped body is considered: the simulation results on the net deployment, impact and capture sequence are presented. The detailed net system characteristics are reported in the Tab. 1:

Net characteristics	
Net size (plane, square)	24 x 24 m^2
Net mass m_{net}	0.33 kg
Single bullet mass m_{bullet}	0.5 kg
Vertex mass m_{vertex}	0.15 kg
Bullet initial velocity V_0	3m/s
Bullet divergence angle from shooting axis α	40°

Table 1. Net characteristics of simulation example

The so far implemented model enhancements, focused on better fitting the real dynamics and on lightening the computational burden for fast running trade-off alternative designs: having a flexible tool is a key point to drive the breadboarding program and to support the experimental campaigns.

3. THE REMOVAL PHASE: THE TETHER CONTROL

The removal phase leans on the tether connection between the chaser and the net, wrapped on the target to

transfer the debris in the desired final orbit.
Therefore the loads on the tether are the main drivers of the design of this phase and the strongly depend on the tether control strategy, that is to be performed by the combination of the active reel control and chaser AOCS.
Among the potential strategies, just two have been investigated so far, because of their benefits in terms of either effectiveness or operations simplicity:

- pulling the target with fixed tether length, thanks to the chaser control authority;
- either releasing the cable and then cutting it, or exploiting the tether as an actuator thanks to the interaction with the electromagnetic environment it flies into as an electro-dynamic tether.

A simulator based on a first order massless tether model with linear control law ([14], [15]) has been implemented to predict tensions along the tether and identify the sizing requirements coming out from this phase.
A simulation result is shown below to clarify the output of such analysis and it refers to the first case where the captured target orbit is lowered by exploiting an electric thruster mounted on the chaser, the tether length being constant: this strategy allows less propellant mass on board and lower tensions on the tether if compared with chemical thrust; on the other hand power required by electric motors is high and the overall deorbiting effect is small. Tether reaction on both the bodies is accounted for in the model.
The capture is supposed to occur along the V-bar keeping a 10 m distance between the chaser and the target. The set of parameters is summarized in Tab.2:

Initial chaser orbit	Sun-synchronous i_0=98° H_0 = 800 km
Chaser mass m_{chaser}	2000 kg
Target mass m_{target}	1000 kg
Tether length l_T	12 m
Tether diameter dT	0.001 m
Tether Young's Modulus E_T	60 GPa
Thrust level T along V-bar	-0.01 N

Table 2. Deorbiting simulation parameters

Fig.4 shows the orbital radius of the two objects versus time: the radius magnitudes slowly decrease; oscillations are due to tether action; the distance is almost fixed and safety is guaranteed.

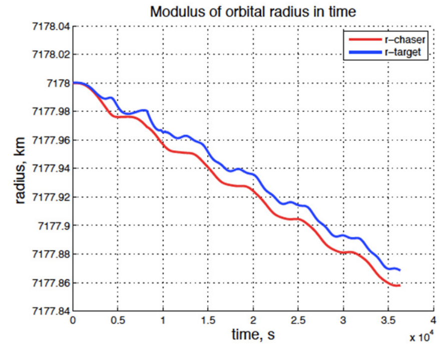


Figure 4. Evolution of chaser (red) and target (blue) orbital radius, low thrust application

Fig. 5 highlights the evolution of the tether tension during the disposal operations. A part from initial tugs, which need to be taken into account to size the system and strongly depend on tether and bodies physical and geometrical characteristics, the tension settles to a value close to zero in the second phase of deorbiting.

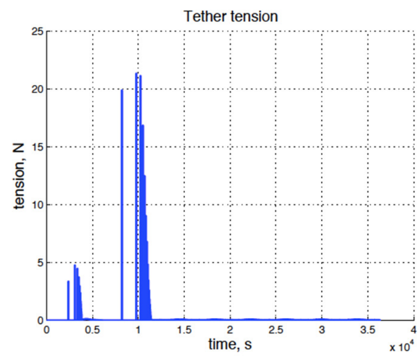
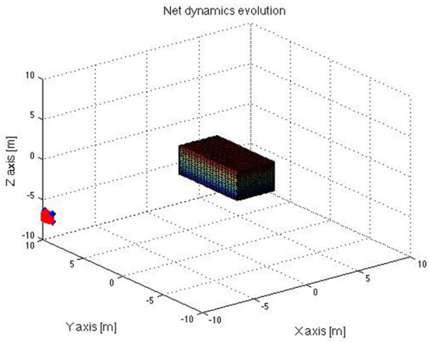
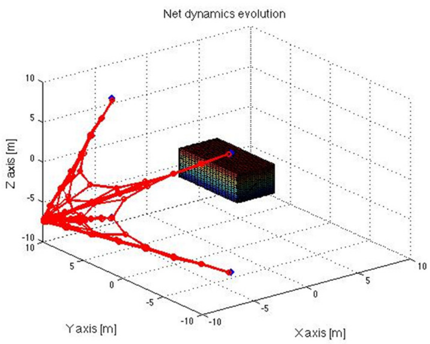


Figure 5. Tether tension during disposal with low thrust

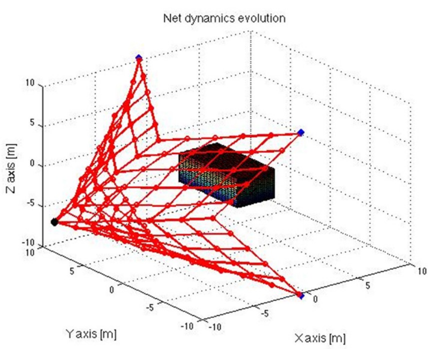
Work is currently on going to enhance these models by taking into account the tether dynamics and vibration control as well as the electro-dynamics effects, whenever an EDT (electro-dynamic tether) is considered.



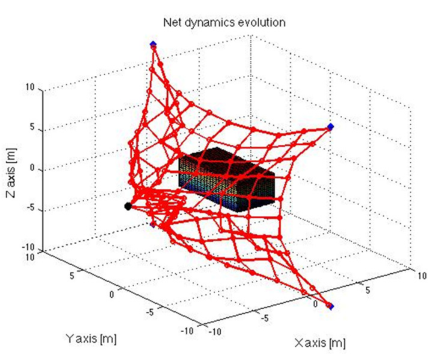
a) t = 0 s



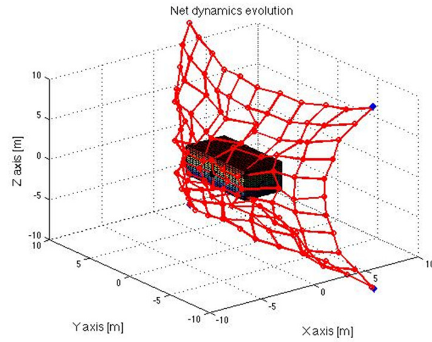
b) t = 5.32 s



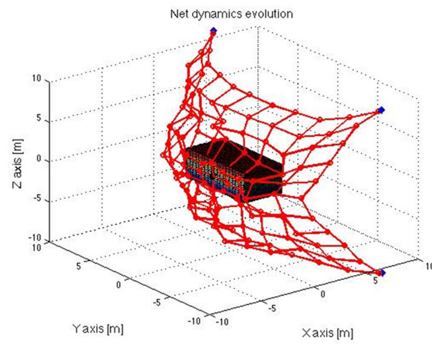
c) t = 7.24 s



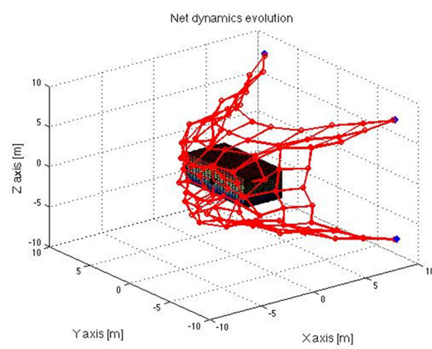
d) t = 9.13 s



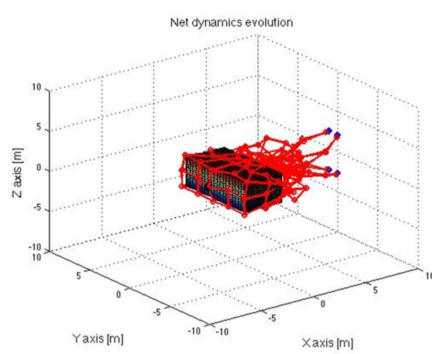
e) t = 11.21 s



f) t = 12.32



g) t = 13.8 s



h) t = 15 s

Figure 3. Simulation results: deployment and capture sequence

4. SIZING THE SYSTEM

The net-based capture is scalable, depending on the debris mass and significant length.
To design and size this system component the role of the numerical simulator outputs play a key role, providing a deep insight into the dynamics of the release, deployment, impact and closure phases, providing the net threads and tether tension evolution all over the time.
The net is stowed in a canister; the terminal bullets are positioned on barrels equipped with the ejection mechanism, as the initial impulse is given to the bullets only. The volume required to keep the net folded before release is minimal.
Depending on the overall design of the platform and the mission itself, the ejection mechanism can be either pneumatic or spring driven.
The pneumatic solution has a high TRL as it is designed as a pressurized system for propellant feeding. The pressure imposed on the bullets by the gas at the end of the barrels can be finely tuned thanks to the latch valve on the feeding line. This assures a good authority in controlling the balanced launch of the bullets, fundamental for the symmetric net deployment. This also assures a high initial velocity of the bullets, no matter what their mass is, by simply increasing tank pressure with practically no fallouts on the ejection system mass. To maximize the bullet ejection velocity is fundamental to minimize the net natural deviation during casting due to libration.
A spring driven mechanism can be the alternative to the pressurized system proposed above. In this latter configuration a dedicated pre-loaded element for each of the bullets to be ejected has to be provided. Precision and reliability are lowered although the system is simplified and enlightened. Moreover, the spring solution should be preferred whenever the bullet mass is small (i.e. for capture of targets up to 1 ton): the limited spring elastic coefficient turns to be an upper limit for the impulse imparted to the bullets for a correct net deployment.
Since the deployment dynamics are scalable, the investigated capture device represents a suitable and versatile tool regardless of the target sizes: in this way, medium/large pieces of debris can be captured.
Mass and sizes of net, bullets, tether, barrels and canister are affected by scaling the system. The pneumatic ejection mechanism is the same, being the pressure tuneable; however an optimized design of feeding lines may be envisaged for different system sizes. Also the reel system, control unit and sensors are not affected. Power is almost not affected by scaling.
For example for two different targets, the following masses are foreseen for a planar net configuration with 0.5 m mesh length, dragged by four bullets:

Debris mass [kg]	200	1000
Debris Maximum length [m]	2.3	3.9
Net mass [kg]	0.3	0.84
Bullets mass [kg]	4 x 0.45	4 x 1.27
Overall shooting mechanism and structure mass [kg]	12.83	13.09
Tether (100 m), reel and C.U. [kg]	2.4	2.4
Sensors and data handling [kg]	4.8	4.8
Total [kg]	22.13	26.21

Table 3. System mass budget for 200/1000 kg debris

Tab. 3 masses are 20% margined. Pressurized system is chosen, with Helium at 200 bar. The stereo cameras are supposed to be the sensors on the chaser to support the net release phase.
The net shape can be either pyramidal/conical or plane, although plane configuration is to be preferred for larger targets. In Figg. 6 and 88 two examples are represented, pyramidal and planar during deployment, for the capture of debris with a maximum size of 2 meters.

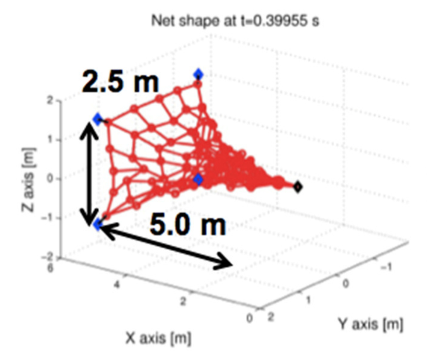


Figure 6. Pyramidal configuration for 2 m debris max length

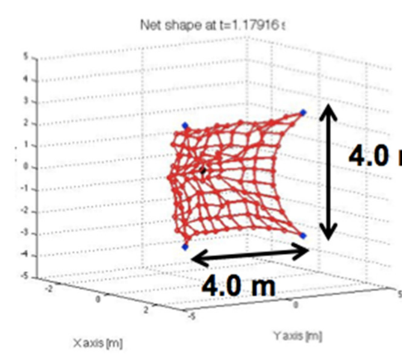


Figure 7. Planar configuration for 2m debris max length

Being the technology scalable and lightweight, an on board multi-installation strategy can be foreseen to perform multiple captures and disposals of several pieces of debris. The choice of a gas-based system easily opens the possibility to feed different shooters to answer redundancy requirements.

4.1. The large size debris capture scenario

The case of a large satellite recovery is treated here. The assumed debris features are:

- debris mass $M_{debris} = 8000$ kg;
- debris size 25 x 10 x 5 m^3 where a flexible appendage is considered to be at least half the debris size along its maximum length.

Because of the configuration and size, the net geometry has been selected to be planar. The net mass budget, represented in Fig. 9, is obtained by setting the single bullet mass equal to 10 kg and its initial velocity equal to 20 m/s. Anyone of the three net configurations presented in Fig. 9 is available in this way, changing its mesh length.

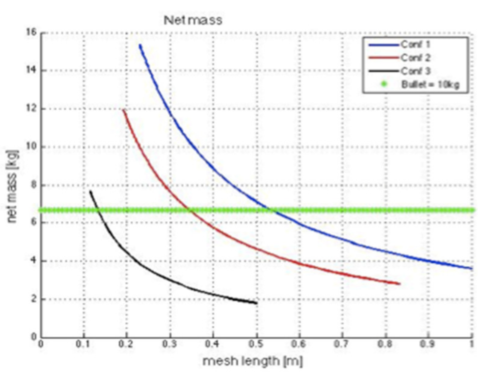


Figure 9. Net mass as function of mesh length, large debris scenario

The three configurations analysed are:

- Conf. 1 (blue): 36 x 36 m^2
- Conf. 2 (red): 30 x 26 m^2
- Conf. 3 (black): 18 x 18 m^2

The configuration choice strongly depends on the capture strategy, for example on the choice to capture the entire object or to leave outside particularly big flexible appendages, as in a "hot-dog" configuration.
Numerical simulations and sensitivity analysis are currently running to determine the most reliable configuration to deal with such large objects. Precise GN&C would be required for capture configurations where a limited debris area is to catch.
The system mass budget is reported in Tab. 4.

Net mass [kg]	6.67
Bullets mass [kg]	4 x 10
Overall shooting mechanism and structure mass [kg]	16.58
Tether (100 m), reel and C.U. [kg]	2.7
Sensors and data handling [kg]	4.8
Total [kg]	70.75

Table 4. System mass budget for 8000 kg debris

5. THE BREADBOARD

The test-bed is composed of the net, the gun, the closing mechanism and the measuring sensors. All of them have being sized and realised in house, apart from the sensors, represented by high frame rate cameras [12].
The gun exploits a compressed gas system, easily tuneable (to achieve different initial velocities) and rechargeable, to shoot the bullets. Two nets are currently available at PoliMi-DAST: a nylon planar square net of 1.5 m (Fig. 9) and a Kevlar pyramidal net of 1 m height. Four spring reels braided with the net at its mouth are exploited to perform tests on capturing phases and closing mechanism. High-speed video recording stereo cameras are used to record phenomena and reconstruct the net 3D motion a posteriori (Fig. 11).
To refine the experimental breadboard, next steps involve

- testing different net shapes, sizes and materials to prove representativeness of experiments and simulations;
- improving the net gun by adding a mechanism to modify bullet initial divergence angle and by accelerating the reload process;

Figure 9. Experimental test bed

- testing different closure mechanisms with different spring stiffness and deeper characterize net dynamics during impact and closure;

- providing the test bed with a reel mechanism;
- improving the set of sensors and the test environment (markers and background) to achieve better precision in 3D reconstruction.

These measures taken, a deeper validation of the numerical simulator will follow, even in a 1g-affected environment, to robustly design and implement the breadboard in view of a parabolic flight campaign to test net deployment and capture phases in microgravity, as well as a reel and tether deployment test campaign, exploiting the low friction table available at PoliMi-DAST laboratories.
However, the abovementioned test environments confine, by their nature, the set of possible experiments and achievable conditions: only an In Orbit Demonstration (IOD) would definitively prove this technology as a whole and it would allow deploying full size nets. To realize an IOD payload, several developments and associated costs are still necessaries and mainly involve shooting mechanism technology, mechanism design as a whole self-contained payload box, sensors set, interfaces, GN&C algorithms development, reliability and redundancy.

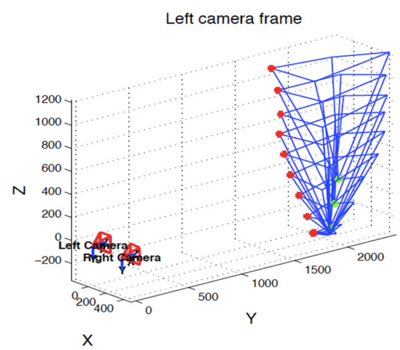


Figure 10. 3D reconstruction of pyramidal net deployment using stereo cameras

6. FINAL REMARKS

Active debris removal is a challenging task for an automatic space vehicle for different reasons dealing with proximity maneuvers, non-cooperative targets, orbit displacement. A tethered-net system could provide an effective solution to this challenge: the tethered-net device, as it is conceived, allows to capture medium/large size debris, to firmly and safely close around them, to perform disposal.
The state of the art of both the simulator and the test bed available at PoliMi-DAST has been briefly described, focusing on recent improvements and enhancements.
Experimental investigation has proven to be indispensable to validate and improve the numerical simulator and to reveal actual deployment dynamics and device characteristics. On the other hand the application of a validated numerical tool may support the design and efficiency of further experimental studies, improving the analysis of their results.
The simulator has recently been updated with damping and a more efficient contact detection algorithm; the work is currently focusing on modelling friction of the net on the canister and on the target, on modelling knot and joints flexibility, on modelling disposal phases with a higher order tether model and on reducing the overall computational time, that is still quite high for refined mesh. New results still need to be validated through tests. The experimental set up will be soon improved to test different net configurations, to acquire more flexibility; to increase precision in both casting and 3D reconstruction.

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