DEBRIS REMOVAL MECHANISM BASED ON TETHERED NETS:
I-SAIRAS 2012

TURIN, ITALY
4-6 SEPTEMBER 2012

M.R.Lavagna [1], R.Armellin[1], A.Bombelli[1], R. Benvenuto[1], R.Carta [1]

[1] Politecnico di Milano, Via La Masa 34, 20156 Milano, Italia, lavagna@ero.polimi.it

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 an active 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 practically effective it may turn to be.

In fact, a general purpose removal system design should 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.

The paper presents the design, characterization and test-bed setting up of a possible general purpose solution: a net, shut from an active satellite that embraces the debris element, closes around it and drag it to the disposal position in space thanks to a tethered connection.

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, developed at Politecnico di Milano-Dipartimento di Ingegneria Aerospaziale (PoliMi-DIA), is to demonstrate the feasibility of disposing medium sized debris by means of a cone/pyramidal shaped net device, connected, at its vertex, to the chaser satellite, through a tether.

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 [2] [3], 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 net with passive control which naturally lead 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-DIA both the steps have been run through. A simulator has been implemented, discretizing the net with lumped masses, whose dynamics is affected by the gravitational acceleration and elasticity. The numerical results lead the set-up of the experimental model built to further validate the proposed capture system and to better understand its dynamics behaviour to finer tune its control.

Being the simulation of a micro-gravitational environment hardly achievable on ground, focus was on setting up a testing facility to characterize, validate and test the proposed active capture system simulating at the best the orbital operative conditions even in a 1g affected environment.

The device technical generalities are firstly presented; the mechanism crucial parts design dynamics numerical simulations and optimization process is then discussed.

Eventually the test-bed implementation and test campaigns are shown.

It is worth to underline that being the phenomenon very fast (few seconds), the Earth gravitational field does not influence the deployment dynamics, and thus a significant match between ground and microgravity tests is possible.

2. THE MECHANISM GENERALITIES

A conic\pyramidal shape has been imposed: although the class of trappable debris is limited with respect to a planar configuration, the net control becomes easier, both during the deployment and in capture configuration. During a rendezvous phase with the target, the net is folded in the chaser: at the correct distance, it is ejected and deployed by applying an impulse to four flying masses (or bullets) attached to the net mouth, represented by the cone\pyramid base: the relative position evolution in time of the bullets shall open the capture net gradually while approaching the debris, as shown in Fig. 1.

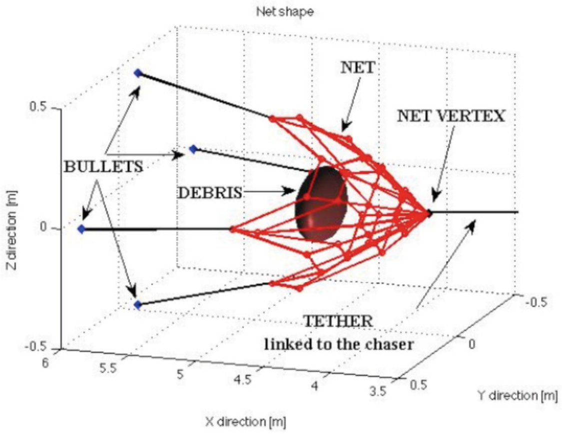

Figure 1. D-CoNe concept

The D-CoNe device must answer the following three tasks: to cast the net reliably with high accuracy in bullets velocity vectors, as they determine the uniform and correct net deployment; to make the net completely deployed before reaching the target; to make the net completely wrap the target just exploiting its natural dynamics.

The tether, connected to the pyramid vertex on one side, and to the chaser on the other, is left slack during the net deployment not to affect the natural motion and deployment of the net.

After capture, the tether connects the chaser and the wrapped debris: thanks to a tension control the disposal takes place, the tether is cut and the following debris hunt starts [4].

All that translates into the design of the bullets gun – given impulses and ejecting rails geometry - , the fine tune of the bullets masses, the design of a closing mechanism for the pyramid base, as soon as the target has been embraced, the net mesh, thickness and material definition.

Additional requirements include that the net shall fully deploy right before the target is reached, and the closure device shall guarantee the debris not to escape the net retaining effect.

To start consistently designing and finally implementing the system, a numerical analysis - based on a dedicated simulator - run first. As reported in the followings, numerical simulations provided the ratios between the bullets and net masses, the bullets initial velocity vectors (direction and modulus) to size the net shooting mechanism.

3. THE NUMERICAL ANALYSIS

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.

3.1. Modelling flexibility

The most challenging modelling aspect relates to the net representation: the Assumed Modes Method (AMM) is very effective in dealing with flexible structure modelling, taking advantage of shape functions to satisfy the boundary conditions and to decouple the in space from the in time variation aspects [5]. However, they are generally applied with quite simple configurations that include few flexible elements. With the coexistence of many flexible structures, the problem structuring requires an approach based on simpler methods, always capable of describing the phenomenon, but easier to handle.

Therefore a lumped mass approach has been here preferred: the actual net mesh is discretized and modelling ropes between knots as massless elastic connections, as shown in Fig.2. Springs between knots are active only in tension conditions: in compression situations they are deactivated.

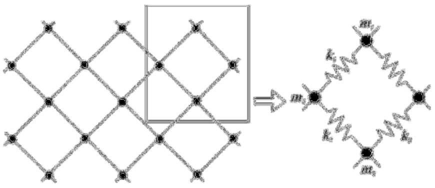

Figure 2. net mesh modelling

The i-th knot dynamics answers Eq.1:

$$m_i \frac{d\vec{r_i}}{dt} = \sum_{j=1}^{N_T} T_J + \sum_{w=1}^{N_E} f_w \qquad (1)$$

where:
N_T is the number of threads entering the i-th knot; Tj is the internal force exercised through the j-th rope tension; N_E is the number of external forces **f** acting on the i-th node.
Tension **T** is modelled through a Kelvin-Voigt viscoelastic model retaining only the pure elastic component (eq.2).

$$T = \begin{cases} EA\frac{\Delta l}{l_0} \text{ if } \Delta l>0 \\ 0 \text{ elsewhere} \end{cases} \qquad (2)$$

Where:
E is the material Young's modulus; A is the section area and l_0 is length at rest.
External forces **f** include either a constant gravity and the bullets aerodynamic drag, or the variable gravitational effects depending on the simulation refers to terrestrial or in orbit deployment respectively.
A local reference frame XYZ, centred in the net vertex, has been adopted to better monitor the behaviour of each lumped mass (Fig.3); the net is represented by 4 sections each containing 16 lumped masses, numbered sequentially from the first section near the vertex to the fourth section at the pyramid base, counterclockwise.

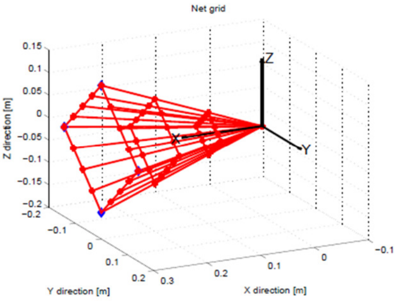

Figure 3. local reference frame

As already mentioned, initial impulses are imposed on the terminal bullets only, linked at the corner of section four, the pyramid base. Therefore the initial conditions in terms of bullets velocities orientation and intensity, and the bullet masses are crucial to symmetrically deploy the net along X.

3.2. Simulations to preliminary tune the mechanism

Simulations revealed that not to have the vertex overcoming the pyramidal section during the free motion after the initial bullets shot, a 10 times the i-th knot mass must be placed at the vertex; Fig.4 shows the bullets and sections displacement along time: the bullets start first, followed by section 4, the pyramid base and so on, up to the vertex that always follows all the net sections, correctly. It is worth to note the very short time (tenth of seconds) to gain the net full deployment, motivating, once more, the feasibility of experiments in 1g environment.

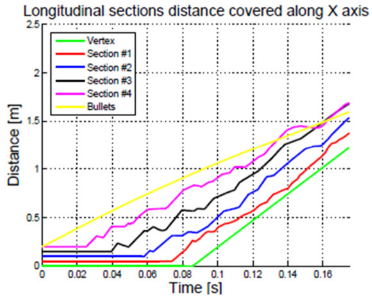

Figure 4. sections dynamics with weighted vertex

Tab.1 highlights the net geometrical and mechanical properties applied on the proposed simulation: D_{fin}, L_{fin} refer to the final height and side for the correctly deployed pyramid. Kevlar has been considered for the net ropes.

Table 1. Net geometrical and mechanical properties

D_{in}-D_{fin}	[m]	0.2-1.0
L_{in}-L_{fin}	[m]	0.1-0.5
A	[m^2]	$7.8e^{-7}$
E	[N/m^2]	$20e^9$
ρ	[kg/m^3]	1440
mass	[kg]	0.135

3.3. Optimizing the system design

Although the parameters related to the system configuration which affect its dynamics are numerous, only a subset of them has been considered for optimization. In particular, those affecting the impulse given to the bullets: the bullets masses and their initial velocity vectors. A global optimisation technique has been preferred not to be affected by a wrong first guess assumption, critical aspect for local optimizer. The cost function expresses the quadratic difference between the actual net configuration once the vertex has reached a distance equal to the net stretched length D_{fin}, and the configuration the net would have in a fully deployed condition, as highlighted in eq.3:

$$J = \sum_{i=1}^{N_P} \left| P_i - \tilde{P}_i \right|^2 \qquad (3)$$

Where:
the J argument is the norm of the distance vector of the i-th node actual position from its ideal one.
The optimization settled on the following vector:

v_{bullet}=initial bullet velocity modulus =9 ms^{-1}
α_{bullet}= initial angular displacement of the v_{bullet} vector from X = 20 deg

$$\text{mass}_{\text{bullet}} = \text{each bullet mass} = 0{,}28 \text{ kg}$$

moving the search in the variable space defined in tab.2.

Table 2. optimization parameters imposed bounds

Parameter	LB	UB
divergence angle [deg]	1	45
velocity [m/s]	5	15
bullet's mass [kg]	0.1	2

A larger divergence would waste a significant part of the imposed impulse transversally, while a lower α would slow down the deployment phase; the bullets mass is a good compromise to make the imposed momentum significant for deployment while limiting the stress on the net ropes. With such a solution the bullets to net masses ratio is 1:8.

3.4. The closing mechanism

Once hitting the target and wrapping it, the net must keep trapped around the debris not to make it slip away during the disposal operations. A potentially effective and simple solution is to mount along the net final section perimeter four linear springs, and launching the device with the final section almost closed. Each vertex would thus be affected by the additional force contribution $\mathbf{F}_S$ given by Eq.4:

$$Fs = \sum_{i=1}^{2} k_i \,\Delta\mathrm{L_i} \tag{4}$$

where L_i is the actual distance between two vertexes.
The initial bullet velocity divergences αs open the net, as long as the related tension effect overcome the spring pulling force. Once this second effect prevails, the net tends to close again. By selecting the spring constant as a function of the target distance and the net geometry, an effective yet simple closure mechanism can be sized. Fig.5 depicts the trajectory of the four vertexes on the net pyramid base, with the properties given in tab.1. Results according to two different spring constants are reported for a terrestrial vertical launch: while weaker springs fail in closing the net base in the required distance (3.5 m), stiffer springs succeed.

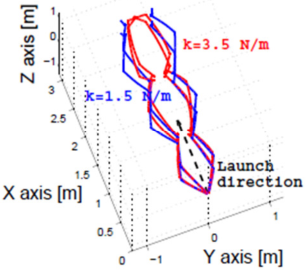

Figure 6: spring based closing mechanism effect on the deployment dynamics

The quasi-harmonic motion due to the instantaneous clashing bullet inertia and springs action is evident.

4. THE TESTBED SET-UP

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.

4.1. The net

A quadrangular mesh is selected, according to previous studies concerning space webs [6]: that topology revealed to be the optimum compromise between mass and stiffness. Square mesh has, in fact, the ability to withstand large shearing deformations without requiring creases in the material, which is an important characteristic for folding and packaging. The other important parameter to be set is the ratio between the square mesh dimension l and the net characteristic length D_{fin}: a good compromise in term of stiffness and mass turns out to be $k = l/D_{fin} \in [1; 5]\%$, moving toward the lower bound of the domain the more the L increases. However, this parameter shall be carefully chosen according to the mission and depending on debris features, not to let small parts of it slip away.
The net material selection has been driven by being very light, but strong and tough. A fundamental characteristic is for the net to be easily folded in the canister, so the material should be very flexible in bending. Tab.3 summarizes the features of the materials proposed in [6], which are consistent with properties reported in tab.1 applied to run the mechanism optimal sizing. Last but not least, the material must withstand the harsh space environment with limited degradation.

Table 3. net candidate materials properties

Material name	σ_u $[GPa]$	E $[GPa]$	ε_u $[\%]$	ρ $[\frac{g}{cm^3}]$
Zylon	5.8	180	3.5	1.54
Dyneema	3.7	116	3.8	0.97
Kevlar	3.6	130	2.8	1.44
Vectran	2.9	65	3.3	1.40

All those materials need a coating as they are heavily affected by the space environment, slightly increasing the overall mass. Only Dyneema can be thermo-welded, the others asking for knotting to get the net configuration.
For the ground test-bed, a hand made net of 1:5mm diameter Kevlar 49 braid has been exploited; the mesh is 5cm squared, pyramid shaped with the fourth section edge of 50cm and a D_{fin} = 1m, almost 0,150kg mass. The mass is about 0:150kg.

- Tensile tests to characterize the strength performance of net threads have been run.

4.2. The gun

The gun design has been driven by the need to guarantee the simultaneous ejection of the four bullets and the will of making their initial velocities tuneable to run different tests.

Those requirements led to exploit a gas expansion to get the initial impulse for the net deployment. As a consequence, the gas pressure became a sizing quantity, together with the bullets mass and emission velocities (Eq.5):

$$v_{ini-bullet} = I_{bullet} = \int P \cdot A \cdot dt \qquad (5)$$

Where:

P is the gas pressure in each shooting channel, and A the shooting channel section area.

Fig.7 highlights the shooting device, made of three main parts: a rectangular pressure chamber – which is the gun base -, a trigger and a quadripartite shooter.

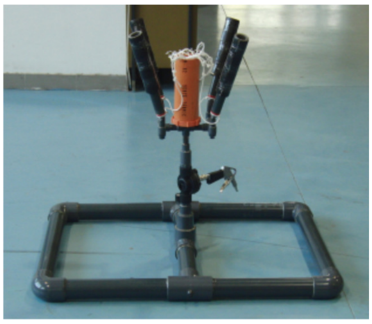

Figure 7: the shooting mechanism

The size of the pressure chamber comes firstly from the need to be a stationary high-pressure tank for the whole device, secondly from the need to provide both on ground stability and device symmetry. The chamber is charged a common Shrader valve while the pressure level is monitored thanks to a manometer.

The shooter is just above the chamber; it transfers the compressed air from the chamber to four pipes into which the bullets are placed, to give them the correct impulse to move and drag the net, initially folded in the ad-hoc orange, centrally located, canister. The four pipes constitute the gun barrels, tilted 20 deg apart the vertical as requested by the optimal design on initial conditions.

The trigger device consists of a modified solenoid valve on which a manual air tap is mounted. The valve modification makes it manually tuneable: the solenoid has been removed and the orifice has been filled and sealed with epoxy resin. A hole has been made in the valve cap in order to screw in a metal nipple, this creates the handy interface through which assemble a manual one way valve (tap) that works as a trigger. Pressure moves in the 3 -15 bars range.

Such a gun can be easily implemented on board, taking advantage of the propulsion unit that typically offers pressurised gases for chamber feeding.

A pressure driven gun offers high precision in firing synchronism and impulses direction and magnitude, properties difficult to be gained with pyrotechnics actuators, solid motors or spring actuators.

4.3. The bullets

The bullets mass plays a fundamental role in assuring a correct net deployment. More, they must fit the barrels and must be very well balanced to precisely catch the momentum transferred by the gas with no parasitic torque. Being the current a test-bed, variable mass is foreseen to run different experiments. This is obtained thanks to concentrated masses added on the bullets top. The single bullet mass is 0.23 kg.

4.4. The closing mechanism

As mentioned in 2.4 a spring based mechanism has been here preferred to close the net around the target as soon as the contact occurred.

Therefore, in the test-bed four spring driven reels are mounted at the section four, just at the bullets connection points. Those torsional springs rewind threads aligned with the pyramid base edge, to accomplish the pyramid base vertexes to come closer to each other's up to the net closure.

The bullets mass, initial velocity and the springs stiffness determine the distance needed to deploy the net and close it back. This sets up the required distance from the target the net realising must start. Once the net, the bullets, and the initial impulses are sized, the spring stiffness selection tunes the correct distance for the target to be, to let the capturing process properly working.

Fig.8 shows snapshot of a capturing sequence, highlighting the prevalence of the bullets divergence first, to properly deploy the net, followed by the spring elastic prevalence afterwards, that provokes the net closure around the target.

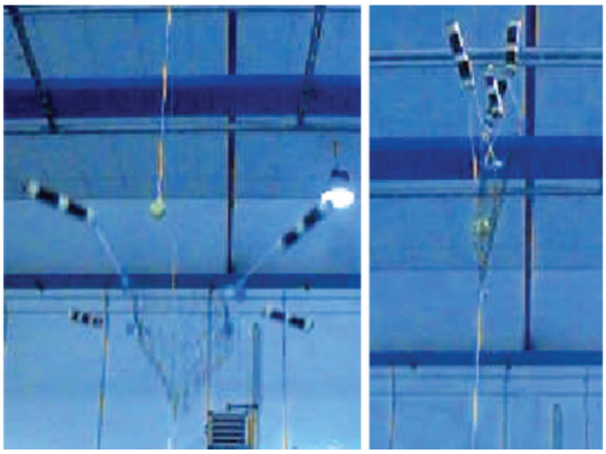

Figure 8: capture and closing experimental sequence

4.5. The measuring sensors

No sensors such as accelerometers or strain gauges can be mounted on the net without modifying its dynamics; it is then mandatory to use video imaging as main measurement technique.
Being the evolution of the system very fast – the whole deployment occurs in less than 1 s -, the dynamics evolution is filmed by high-speed cameras (500 to 1000 fps): displacements, time intervals and velocities of pre-marked points on the net can be computed.
Whenever using high-speed cameras are exploited, intense light conditions must occur, on a contrasting background.
The number of sensors strongly depends on the test to be run: whenever the bullets velocity relation with the chamber pressure wants to be identified a single camera suffices; whenever the net deployment is investigated two synchronized camera, orthogonally placed - one to the other - are used, to make the 3D reconstruction possible.

5. PRELIMINARY TEST RESULTS

The first test campaign was focused on checking for the gun effectiveness and pressure-initial bullets dynamics conditions. To this end, shots with different charging pressure occurred and the correspondent bullets initial velocity has been measured. Results are reported in fig.9, according to different bullet mass. The relationship turned out to be quasi linear.

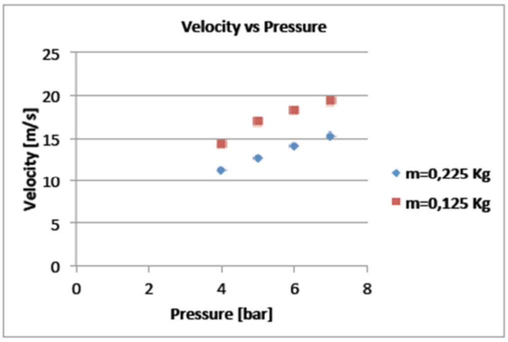

Figure 9: bullets initial velocity versus pressure changes: experimental results

The test campaign is now focused on identifying the optimized Kevlar net dynamic behaviour by varying the initial impulse: bullets mass and chamber pressure are varied in the [0:125; 0; 225] kg and in the [4; 5; 6; 7] bar ranges respectively.
Those tests serve also to validate the dynamic model implemented in the simulator. It is confirmed that the initial acceleration is so high and the system evolves so rapidly that the gravity, which can anyway be included in the model, can be neglected during the first phase of deployment: it was demonstrated], as part of the project, that gravity doesn't influence the dynamic behaviour at least for the first $2D_{fin}$ covered by the net, making the terrestrial testing significant event if not substitutive of an exhaustive low gravity environment testing campaign.

6. FINAL REMARKS

The D-Cone project has been here briefly presented.
The coordination of numerical simulations with preliminary experimental testing allowed verifying the correctness of the assumptions made in the modelling process. Moreover, the feasibility of a net based device for objects capturing has been confirmed.
Numerical results highlighted that a 0,3 m target can be trapped by a 1m length net, starting the deployment process no farer than 5m.
Although the experiments run all on Earth, under 1g environment, the deployment phase is so fast and the initial impulses definitely larger than the gravitational attraction that those test are equally faithful of the in space deployment process.
Next steps include the simulator refinement according to further experimental campaigns, the test-bed implementation refinement and, if possible, the microgravity testing with parabolic flights. The test-bed is easily scalable to a smaller volume envelope, to fit the secure flight constraints.

7. REFERENCES

1. Liou J. C.(2009): A sensitivity study of the effectiveness of active debris removal in LEO, *Acta Astronautica*, 64(2-3):236-243.
2. Hobbs S.(2010): Debris removal from low Earth orbit DR LEO. Cranfield University, College of Aeronautics Report 1001.
3. Nishida S., Yoshikawa T.(2003): Space debris capture by a compliance controlled robot. National aerospace laboratory of Japan, Proceeding of the 2003 IEEE/ASME.
4. Bonnal C. (2005), Un projet innovant contre la pollution orbitale. Online at http://www.cnes.fr/web/CNES-fr/3767-un-projet-innovant-contre-la-pollutionorbitale.php (as of May 2012).
5. Junkins, J.L. and Kim Y.(1993): Introduction to Dynamics and Control of Flexible Structures *AIAA Education Series*, New York.
6. Tibert G., G¨ardsback M.(2007): ESA Space Webs Final Report. KTH Engineering Sciences, Royal Institute of Technology, Stockholm, Sweden, Ariadna Contract: 19702/06/NL/HE