DETAILED VALIDATION OF A THROW-NET SIMULATOR FOR ACTIVE DEBRIS REMOVAL AND ITS USE FOR CAPTURE OF THE ENVISAT SATELLITE

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ABSTRACT

Nowadays there is a general consensus among space agencies regarding the need to provide solutions for the problem of current debris in orbit. The PATENDER activity - *Net parametric characterization and parabolic flight)* - funded by the European Space Agency (ESA) under Clean Space initiative budget, was aiming at validating a simulation tool for designing nets for capturing space debris. This validation has been accomplished using experimental data generated performing a set of experiments under microgravity conditions achieved during a parabolic flight. Those experiments involved a scaled but representative net launched and capturing and wrapping a scaled satellite mock-up.
At a first change, the PATENDER Simulator has been validated from the comparison of the simulation data and the data obtained from the 3D reconstruction of the parabolic flight experiment images.
On a second step, the same has been also exercised to analyse the deorbiting of the Envisat spacecraft using a thrown-net.
This paper will introduce briefly the thrown-net simulator and will provide an overview of the validation campaign performed against the data extracted from the parabolic flight experiment. It will describe in details the simulations of the Envisat deorbiting and its corresponding lessons learned.

1. ACTIVE DEBRIS REMOVAL WITH THROWN-NET

Proliferation of space debris implies expensive and risky operations in some of our most valuable and thus exploited orbits such as LEO. More than 17000 objects are tracked by the US Space Surveillance network, of which less than 1.000 are operational spacecraft. More than 66% is from over 200 on-orbit fragmentations that have been recorded since 1961. These are assumed to have generated about 700.000 objects larger than 1 cm. To date there are 4 examples of collisions recorded. The space debris problem will be even worst in the near future as almost 1400 new satellites are expected to be launched in the next decade (Euroconsult forecast **¡Error! No se encuentra el origen de la referencia.**]).
Currently, the most of the worldwide space agencies and space industries identified as the potential major source for new debris the collisions among orbiting objects.
In order to identify the most suitable technical solutions to reduce the probability of in-orbit collision different aspects of this challenging problem have been and are still under analysis. Among those a clear key issue is the means to be used to physically catch the space debris with the aim of generating the successive safe deorbiting.
The use of throw-nets seems particularly promising for capturing objects in space in cases where grasping with a robotic arm will be difficult. This could be the case of targets with unpredictable spins and no suitable grasping points. From an operational point of view, the de-orbiting of an object with a throw-nets could be considered simpler because does not require complicated close-proximity guidance, navigation and control (GNC) loops. Additionally, even if maintain its complexity, a net is clearly a much simpler mechanisms than in case of a robotic capture. The flip-side causes difficulties in case of a net capture in the stabilisation of the stack post-capture.
Testability and simulations are critical aspects to be addressed in order to mature the throw-nets technology. For this purpose ESA has funded several activities to develop simulators that can accurately reproduce and consequently characterize the complex contact dynamics of a net wrapping around a tumbling body and, at the same time, such that they could be executed fast enough to perform statistical analysis. Additionally, these simulators were requested to be validated in an extensive campaign composed by a series of 0-g tests achieved during a parabolic flight sequence where a representative net must get deployed and accordingly capture a target mock-up.

2. OUTLINE OF PATENDER SIMULATOR

The thrown-net simulator framework developed within the PATENDER [1] activity is able to perform simulations of large particle systems with advanced 3D visualization capabilities.
The simulator is composed by three main elements:

- Graphical User Interface (GUI): It is based on Blender and allows the user to interact with the net configuration, environment and execution.
- Simulation Environment: Python scripts necessary for the configuration, execution of the simulator and exchange of data with the Net Models.

- Net Models: External application (developed using C++ language) containing the autocoded Matlab/Simulink dynamics propagator, the collision detection functions (based in the Bullet[1] physics engine) and the contact dynamics algorithms (Hippmann, 2003 **¡Error! No se encuentra el origen de la referencia.**]).

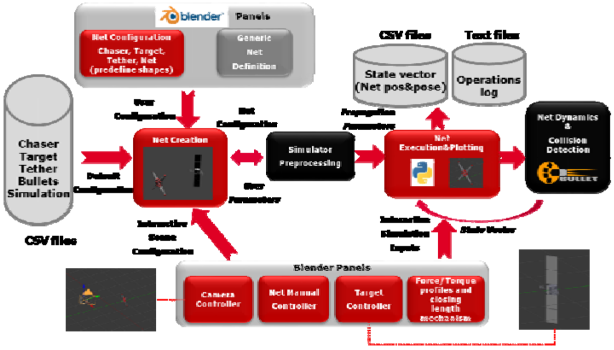


Fig. 1: PATENDER simulator architecture and data flow.

Through the GUI the user can perform the following operations: a) 3D visualization of the net deployment and of the target capture operation, b) define the 3D view angle during the simulation, c) plot relative distance and relative speed measurements between any two net knots during the simulation, d) plot full state vector of any net knot or body (target or chaser) during the simulation, e) save the simulation visualization as video format and rendered images and, f) export the data obtained during the simulation to comma-separated values (CSV) and Matlab standard formats.
The net configuration parameters (net type: planar, pyramidal, conical or user defined; net size; number of strings and rings, etc.) together with the propagation parameters (a set of configuration parameters for fast computing of the propagation algorithms) are loaded from dedicated csv file into the simulator. The dynamic propagator performs afterwards, the step-by-step simulation of the net deployment and wrapping and it communicates the computed state vectors at each time-step through the communication channels to the simulator.
The net knots and bullets are represented by spheres of different dimensions and the links as cylinders. Links are defined as any thread between two knots and are subdivided into intermediate nodes and elements (see Fig. 2) for a better representation of the net impact on the simulation target.

[1] Bullet Physics Library website: bulletphysics.org

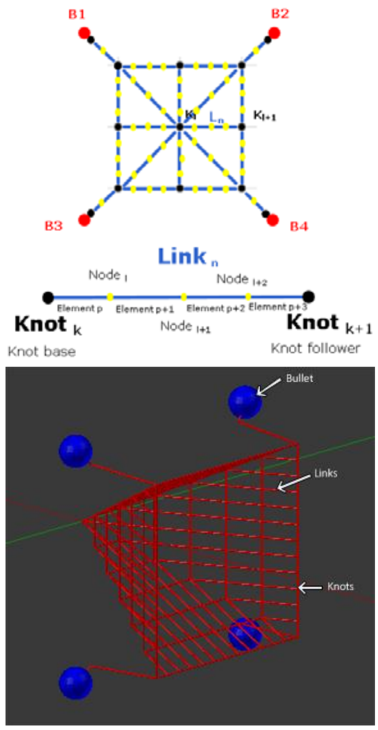


Fig. 2: Net elements (knots, links, bullets and nodes) definition (left) and Blender representation (right).

The tether, which connects the chaser with the net, is also modelled as a link, discretised into nodes and elements. Moreover, the user can choose at the beginning of the simulation the inclusion of an additional link (closing link) to ensure the capture of the target after initial wrapping.
The chaser and the target are imported as a CAD file at the initial position set by the user through the initial state vector. Moreover, the target can also be subject to actions such as scaling, change on the position, saving of the states and relocation the target at the saved position.
The PATENDER simulator has also the capability of running Monte Carlo simulations. This is carried out for a certain period (selected by the user) and avoids plotting in the Blender scene the evolution of the net, in order to speed up the simulation processing time. It has the advantage that given the setting of the simulation time, the user can run this function and save the state vector for different user parameters.

3. SIMULATOR VALIDATION

The PATENDER Simulator has been validated from the comparison of the simulation data and the data obtained from the 3D reconstruction of the parabolic flight experiment images [1]. The validation process was initially considered to be performed through the direct comparison between the positions of the simulated particles and the reconstructed particles. However, after the large experience and know-how acquired on the dynamics involved in the net wrapping process, the positions comparison approach is stated as insufficient since it is not considering enough information. After an intensive investigation of the process it has been clearly identified three phases with different physical characteristics: free-flight deployment (based on the net dynamics), initial wrapping and final wrapping (mostly dominated by chaotic collision process). [1]

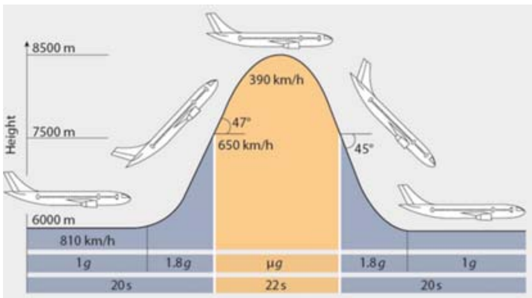
During the free-flight deployment, the direct comparison of the net positions is used for validation.

The net position comparison is not enough information for wrapping phases. The collision dynamic is governed by the chaos theory (slight differences before collision produce complete different results), and additional metrics are required. The comparison of the 3D moment features are the most appropriate metrics for the present scenario, since they are invariant for scale, rotations and translations.

The PATENDER simulator has been also exercised to analyse the deorbiting of the Envisat spacecraft using a thrown-net. This scenario distinguishes two phases: capture and burn (800N). We have proposed the use of square net of 40x40m with 4 bullets at the corners and Technora material with a link diameter of 1mm. During both phases a Montecarlo campaign was performed covering different initial conditions aiming to provide estimates of the full dynamics of this deorbiting process: likelihood of the net detachment, maximum linear velocities, angular rates and net elongations and maximum forces over the target surface and tensions transmitted to the chaser.

4. PARABOLIC FLIGH

The PATENDER experiment was flown on the Novespace 116th parabolic flight campaign (62nd ESA Parabolic Flight campaign, June 9th 2015) on board of an Airbus A310 aircraft. A typical Novespace parabolic flight is composed of 31 parabolas in a roller-coaster mode where six series of 5 parabolas are concatenated with short breaks of 1 minute and 45 seconds between them. Each parabola has a duration of ~22s with a microgravity maximum level of 0.05G and it is preceded and terminated by acceleration periods of 1.8G during 2-3s as shown in Fig. below. After each set of parabolas a long break of 5 to 8 minutes allow to perform minor adjustments of the on-board experiments.



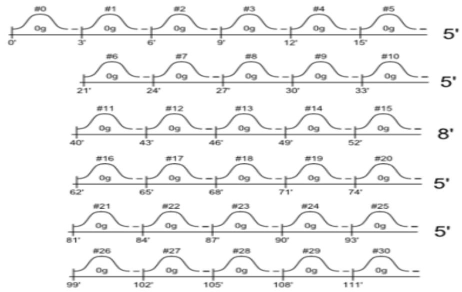


Fig. 3: Novespace parabola profile (left) and VP116 flight profile (right).

The PATENDER experiment within the parabolic flight was prepared with up to six nets (6) made of Technora, an aramid fibre well known for its high strength (Young Modulus of 7.3e10 Pa, density of 1390 kg/m^3 and threads diameter of 1mm) and approximate dimensions of 0.6x0.6m and 50g of mass. The net has a squared shape (folded net takes up 10x10x10cm) and each of its corners is attached to a massive bullet (200g, 5x5x5cm); its total mass is ~850g. The net is being hold in a container and deployed pneumatically by a launching system. After a horizontal motion of approximately 2m the net is fully deployed and wraps the satellite mock-up. The satellite mock-up is made of a rectangular block whose dimensions are 0.075x0.125x0.250m with an antenna array plate of 0.25x0.05m. Both the net and the target mock-up are representing a simplified capturing exercise of the Envisat satellite. This capture has been reproduced at a geometric scale of 1:40.

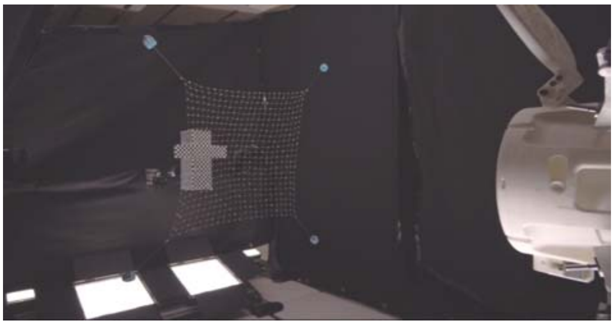


Fig. 4: Flight configuration and experiment integration on board Zero-G aircraft.

The team experienced a total of 7 failed launches due to non-simultaneous ejection of the four bullets. By reducing the number of friction rings on the bullet liners and increasing the initial velocity of the bullets it was not possible to increase the launching success rate up to a total of 23 parabolas (including 3 launches using a realistic Envisat mock-up). After the post-processing of the usable 20 parabolas, a total of 9 parabolas were selected for 3D reconstruction (5 parabolas were non-reconstructable and other 6 were having a reduced quality due to a very high launching speed not allowing to perform the 3D automatic reconstruction process).

A deployment and wrapping sequence is reported in

Fig. 5 below, as an example of successful capture, as visible from one of the front cameras.

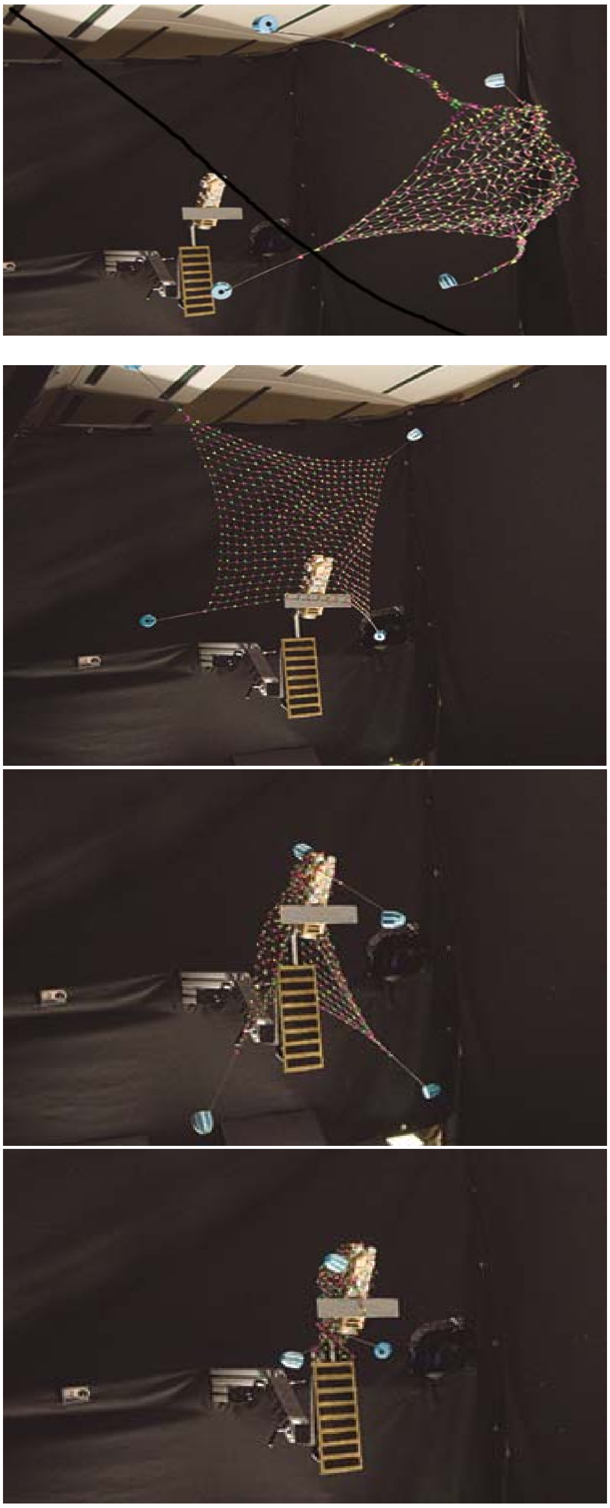


Fig. 5: Sequence of wrapping and capture of the Envisat satellite mock-up.

5. 3D RECONSTRUCTION SET-UP

Four Sony Nex-FS700RH cameras were recording all net launches at 60 fps in 4K resolution in order to allow the 3D reconstruction of the deployment and wrapping around the target.

The cameras have been placed as far as possible from each other to increase both the baseline (reconstruction accuracy) and the area that their field of view can cover with an acceptable resolution for reconstruction. They were placed in landscape configuration on top of the racks for stability purposes (e.g. to minimize their vibrations) and rotated around Z-axis of 45° and 35° for the front stereo-couple and the rear pair respectively. The focal length was set to 14 to reach the needed field of view; however such a wide angle requires finer calibration, especially at boundaries, to minimize distortions. The gain was set to 6, after saturation analysis; the iris aperture and focus were finally tuned to allow the correct depth of field. The shutter speed has been tuned to 1/1000s to limit blur as much as possible due to net motion, while keeping a sufficient amount of light.

Setting up a synthetic environment as the one presented in Fig. 6 and Fig. 7 has been proven to be very useful allowing a finer tuning of the camera settings in the experimental set-up.

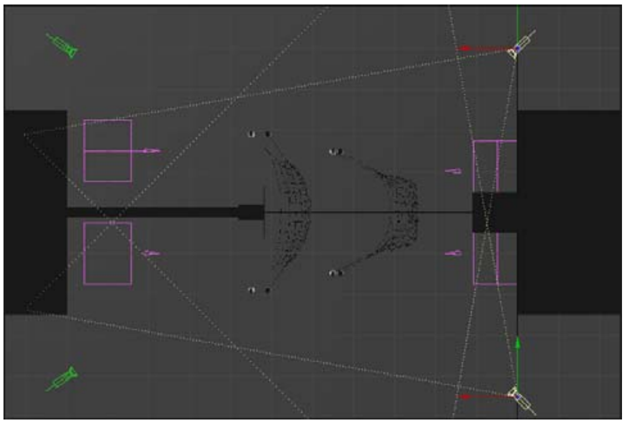


Fig. 6: Fields of view and stereo coverage – front stereo pair of cameras.

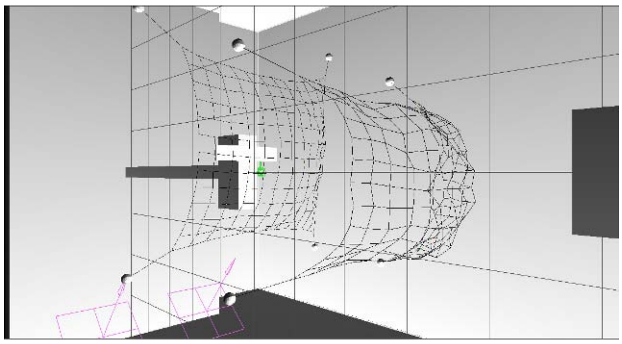


Fig.7: Net simulated deployment – front view.

Net knots were colour-coded with fluorescent pigments using a 4-colour coding system (yellow, red, cyan and green) as reconstruction algorithms are based on colour-segmentation (as one of the simplest and robust methods to track elements at high speed). A uniform background was necessary as well as proper illumination: a LED-based illumination system was placed on the floor and was selected to meet parabolic flight safety constraints (heat, luminosity, operations and failures) and lighting conditions requirements, being very demanding with the needed resolution, frame rate and shutter speed.

Finally, two independent inertial measurement units (IMU) were synchronized with the system during microgravity tests to record acceleration profiles, as another key feature for the posterior model validation. The primary IMU was calibrated with the cameras position (having the secondary IMU as backup) in order to give as an output the accelerations and angular rate profiles in the master camera reference frame, being the reference frame for 3D reconstruction.

The 3D reconstructions procedure is based on the image processing for colour segmentation (to this end, net knots have been colour-coded with fluorescent pigments as previously mentioned), stereo matching of the segmented knot and iterative closest point (ICP) for time tracking of knots, as described in **¡Error! No se encuentra el origen de la referencia.**]**¡Error! No se encuentra el origen de la referencia.**]. The algorithms developed at Politecnico di Milano have been adapted for the specific features of this experiment and successfully tested on ground before the flight. An example of colour segmentation and knots localization is presented in Fig. 8 the first image is the result of raw file processing for white balance and gain correction, the second one is the yellow filter and the third one is the final binary image exploited by the reconstruction algorithm.

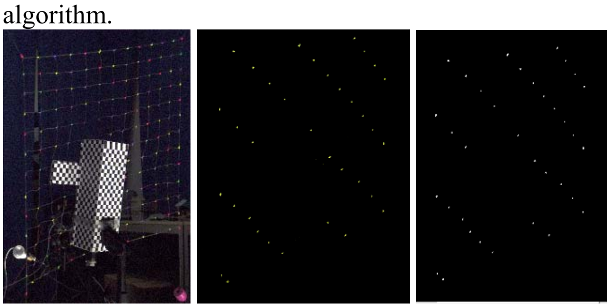


Fig. 8: Colour segmentation of yellow knots: processed image from raw, yellow filtering and final binary image.

The 3D reconstruction process of all the foreseen nine parabolas has been a laborious process performed between June 2015 and September 2016. In particular, in two of them (parabolas #27 and #30), the net is composed by a 24x24 knots mesh with a square shape of size 0.9x0.9m and in the remaining other seven parabolas (#10, #11, #16, #17, #18, #20 and #26) the mesh is 13x13 knots with a square shape size of 0.6x0.6m. For each parabola, they have been analysed and reconstructed 200 frames per camera (a total of 7200 images). The knots have been identified through the described semi-automatic algorithm and the bullets were manually identified for each frame.

Fig. 9 below presents the reconstruction of the net topology between two subsequent frames. All the points are correctly segmented by their colour and the stereo matching is accurate. From the comparison with the real images, a good correspondence can be observed.

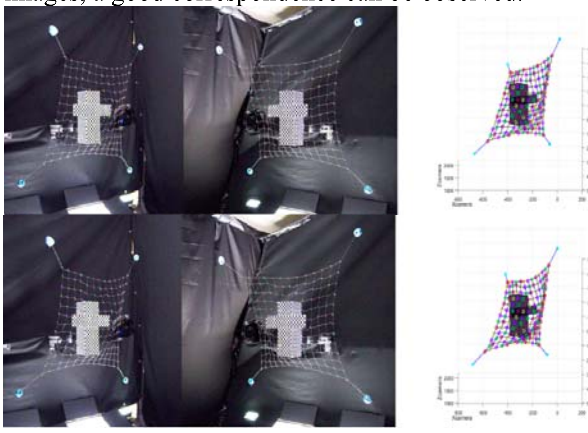


Fig. 9: 3D reconstruction of two subsequent frames.

A detailed view of the reconstruction applied process and obtained results might be found in [1].

6. THE ENVISAT DEORBITING SCENARIO [2]

As already addressed during the last phase of the PATENDER project, the developed and subsequently validated simulator has been exercised to analyse the deorbiting of the ESA’s Envisat spacecraft using a thrown-net.

This Envisat deorbiting scenario is characterized by the following characteristics:

Use of square net of 40x40m with 4 bullets at the corners and Technora material with a link diameter of 1mm. The discretized net-lumped model of the net considers 9102 DOF’s.

Use of a detailed Envisat 3D model. The Envisat mesh has been polished by simplifying the number of not-needed detailes and reducing the number of vertices and faces (vertices: from 17063 down to 1371; faces: from 10458 down to 2124). This simplification has an important positive impact over duration of the simulations (hours instead of days) while keeping the simulator accuracy.

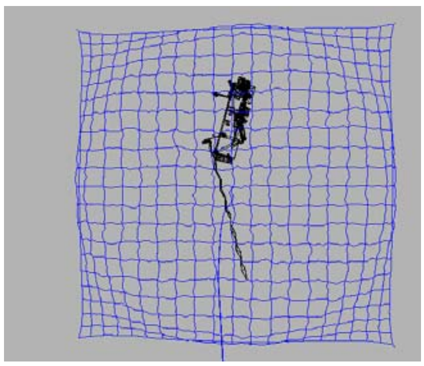


Fig. 10. Net deployment according to the defined parameterization

As agreed with ESA, the assumed scenario distinguishes two phases:

- Phase A: Capture phase. The chaser S/C is placed at a distance of 50m. The Envisat S/C is supposed to spin at a rate of 5deg/s (with a 90 deg. Angle between the spin axis and the reference axes). The precession rate is 0.15 deg/s. The chaser deploys (6s) the net launching the bullets with an initial velocity of [10 4 4] m/s. The net wraps (15s) Envisat and Envisat starts increasing its relative velocity from 0 to 2 m/s during 10 seconds. After reaching this velocity of 2m/s, the relative distance between chaser and Envisat is increased during 15.5 seconds up to 95m. Afterwards the chaser performs the tensioning applying a force of 2N during 20s.
- Phase B: Burn Phase: The wrapped Envisat is supposed to rotate initially at 2deg/s around the length axis aligned with the tether (all other rotations are negligible). The chaser S/C starts applying constantly a tensioning to the tether of 800N.

7. ENVISAT PARAMETERS AND CAD MODEL

In order to properly perform the collision detection and the contact dynamics a CAD model (mesh vertices and faces) of the Envisat satellite has been used within the simulator. The CAD model has been downloaded from celestiamotherlode.net and defined according to the real Envisat dimensions.

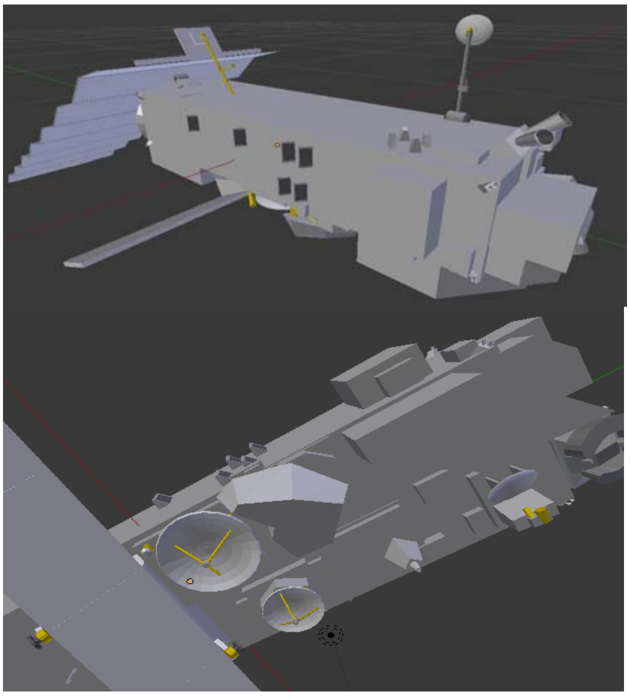


Fig. 11: Envisat CAD model from celestiamotherlode.net

However, the CAD model from celestiamotherlode is drawn through common operations (extrude faces, push/pull faces, duplicate objects…). The mesh defects are corrected, and the mesh shape is optimized in order to get the best performances of the PATENDER Simulator.

The solid objects are completed. See Fig. 12.

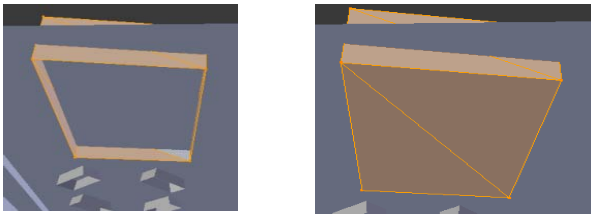


Fig. 12. Completing objects process

After completing the solid objects, the faces are triangulated. See Fig. 13.

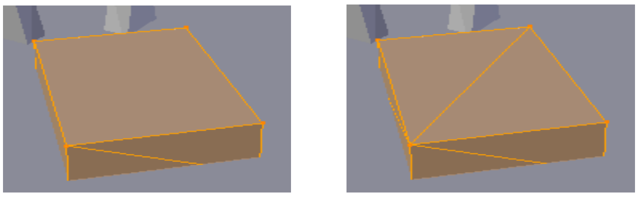


Fig. 13. Triangulating faces process

Duplicated vertices are removed. Automatic process available in Blender. 5378 vertices are removed.

Negligible details (usually included for texture proposes) are removed. See **¡Error! No se encuentra el origen de la referencia.** 14.

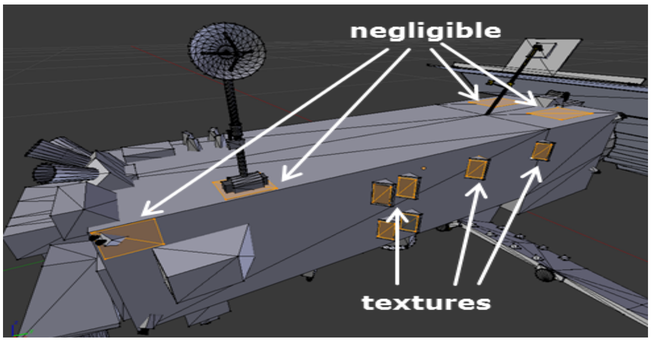


Fig. 14. Negligible details (usually included for texture proposes)

Cylinders and antenna dishes are simplified (complex shapes). See Fig. 15 and Fig. 16.

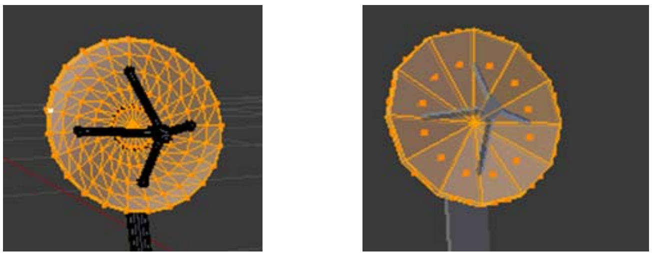


Fig. 15: Cylinders and antenna dishes simplification

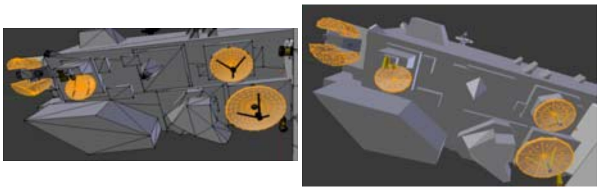


Fig. 16: Complex shapes simplification process

Details are pulled into the main body in order. If the objects are just adjacent (instead of pulling an object into the second one) the net can cross between them. See Fig. 17.

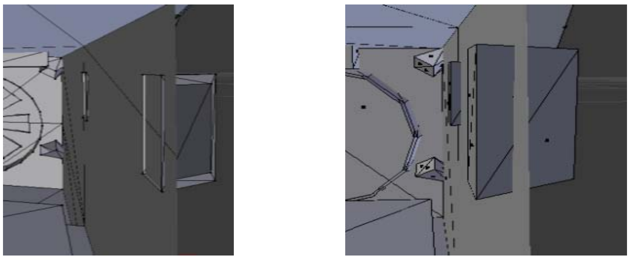


Fig. 17: Pulling details into main body process

Removed wrong vertices. See Fig. 18.

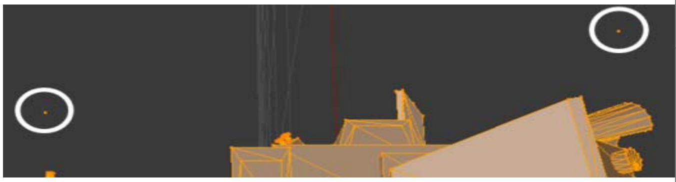


Fig. 18: Removing process of wrong vertices

Each object is defined as isolated mesh. It is useful for identifying mesh parts that can be broken during the wrapping or tensioning with the net. See Fig. 19.

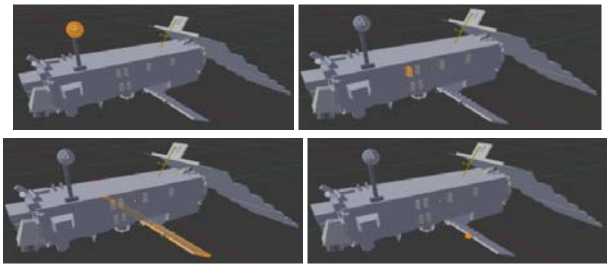


Fig. 19. Isolation process of each component

8. ENVISAT DEORBITING SIMULATIONS

In line with the defined mission scenario, the simulation of the Envisat deorbiting was also broken down in two main phases:

- Phase A. Capture-Stabilization-Tensioning
- Phase B. Burn

The Phase A and Phase B are performed following the sequence described by the below table (Tab. 1).

Sub-phase	Initial conditions	Time range
Phase A. Capture-Stabilization-Tensioning		
Deployment	The net deployment is the first part of the Capture phase. The target mesh, mass and inertia matrix described in section 7 are integrated into the simulator. The net parameters described in section **¡Error! No se encuentra el origen de la referencia.** are integrated into the simulator. The Target initial position is set to [50 0 0]. The Target initial angular rate is set to [0.0636, 0.0636, 0.] rad/s (5deg/s). The Target initial attitude is set to [0.0515, 0.1244,-0.3790,0.9155]. The bullets are launched with an initial velocity of [10 4 4] m/s.	[0 – 6] seconds
Wrapping	The net wrapping around the target is the second part of the Capture phase. The wrapping sub-phase starts at the end of the deployment sub-phase (the simulator state is loaded from previous sub-phase).	[6 – 21] seconds
Increase distance - Accelerated	The initial state is loaded from the end of the previous phase. The relative velocity between chaser and target is increased from 0 to 2 m/s during 10 seconds.	[21 – 31] seconds
Increase distance – Non Accelerated	The initial state is loaded from the end of the previous phase. The relative distance between chaser and target is increased during 15.5 seconds. The final relative distance is 95 meters and the final relative velocity is 2 m/s.	[31 – 46.5] seconds
Tensioning	The initial state is loaded from the end of the previous phase. The chaser thruster is enabled with a force of 2 N during 20 seconds.	[46.5 – 66.5] seconds
Phase B. Burn		
Burn	The Burning phase is started from an optimal wrapping (see section **¡Error! No se encuentra el origen de la referencia.**). Two initial states are considered: Wrapping Body+Solar Panel Wrapping Body The main Chaser thruster is activated with a force of 800N during 100 seconds.	[0 - 100] seconds

Tab.1: De-orbiting phases

A simulation campaign has been performed both for Phase A and Phase B.

For the phase A a total of 24 simulations were performed changing the initial rotation angle around X axis by an amount of 24deg. The following averaged values were computed and reported:

- Simulation (CPU) time
- Maximum target angular rate

- Maximum longitude/elongations for the net links, bullet links and tether link
- Maximum force over target surface
- Maximum tension transmitted to chaser

Regarding the phase B we have performed a total of 48 simulations. The percentage of successful captures of Envisat is 50.0% in the case of wrapping also the solar panel (out of 24 simulations) (Fig. 20 and Fig. 21). If we just capture the Envisat body such success rate increases up to the 62.5% (out of 24 simulations) (Fig. 22 and Fig. 23). We have computed the following averaged values:

- Simulation (CPU) time
- Maximum target linear velocity
- Maximum target angular rate
- Maximum longitude/elongations for the net links, bullet links and tether link
- Maximum force over target surface
- Maximum tension transmitted to chaser

The initial state for phase B is loaded from an optimal wrapping. The optimal wrapping is achieved starting from an optimal attitude of the target.

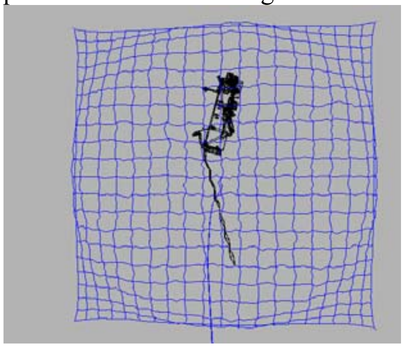


Fig. 20: Target attitude for optimal wrapping including Solar Panel

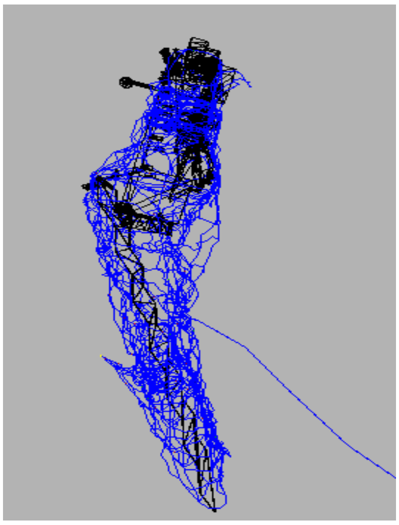


Fig. 21. Final state of the optimal wrapping including Solar Panel

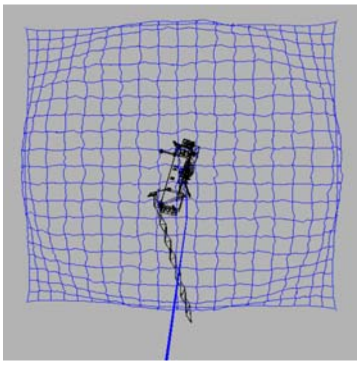


Fig. 22: Target attitude for optimal wrapping without solar panel

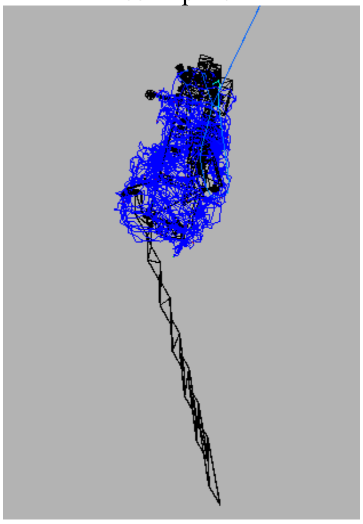


Fig. 23: Final state of the optimal wrapping without solar panel

9. RESULTS

9.1. PHASE A - STATISTICAL ANALYSIS

The statistical analysis of simulations performed for the Phase A are here below reported. They represent statistics (arithmetic mean, standard deviation, minimum and maximum) for all the successful captures of the Envisat.
The following averaged values have been computed:

- Simulation (CPU) time: ~4h (ranging from 2.4h up to 5.6h). The corresponding duration time of the simulation is 66.68s.-
- Maximum target angular rate: 48.4 deg/s. This angular rate is bigger than the initial angular rate of 5deg/s. This figure is considered acceptable even if the corresponding standard deviation is 62deg/s. They are some maximum values of 188deg/s that could imply a later detachment of the net during Phase B.
- Maximum net link longitude/elongation: 2.51/0.51m. This elongation is at the limit as it would imply that the links will break. The minimum net link diameter required is of 1.1mm (see below) instead of 1mm.

- Net link minimum diameter for avoiding breakage:
$$diameter_{req} = 0.001 \cdot \sqrt{\frac{2.51}{2.09}} = 0.001095\, meters$$
instead of 0.001m
- Maximum bullet link longitude/elongation: 0.59/0.09m. This elongation is at the limit as it would imply that the bullet links will break. The minimum bullet link diameter required is of 1.06mm (see below) instead of 1mm.
- Bullet link minimum diameter for avoiding breakage:
$$diameter_{req} = 0.001 \cdot \sqrt{\frac{0.59}{0.5235}} = 0.00106\, meters$$
instead of 0.001m
- Maximum tether longitude/elongation: 105.42/5.42m. This elongation is at the limit as it would imply that the tether will break. The minimum tether link diameter required is of 1.004mm (see below) instead of 1mm.
- Tether minimum diameter for avoiding breakage:
$$diameter_{req} = 0.002 \cdot \sqrt{\frac{105.42}{104.5}} = 0.001\,0044\, meters$$
instead of 0.002m
- Maximum force over target surface: 509 N. This force is a result of contact dynamics depending on the interpenetration.
- Maximum tension transmitted to chaser: 186 N. This figure is reasonable (below the force applied of 800N) and it should be taken into account within the design process of the chaser AOCS. In the case that it is considered from another location of the spacecraft the corresponding torques should be determined.

9.2. PHASE B - STATISTICAL ANALYSIS

The statistical analysis of simulations performed for the Phase B are reported. They represent statistics (arithmetic mean, standard deviation, minimum and maximum) for the successful and failed captures of the Envisat with and without the solar panel.

The successful captures of Envisat are 50.0% in the case of wrapping also the solar panel out of 24 simulations. If we just capture the Envisat body such success rate increases up to the 62.5% out of 24 simulations.

9.2.1. Successful Envisat Capture

In case of Successful Envisat Capture the following averaged values are computed:

- Simulation time: 12.8h (ranging from 6h up to 25h).
- Maximum target linear velocity: 5.2 m/s. This velocity is of similar order of magnitude than the initial relative velocity of 2m/s. It is considered acceptable.
- Maximum target angular rate: 145.4 deg/s. This angular rate is much bigger than the initial angular rate of 5deg/s. It was expected to reach a maximum value around 40 to 60 deg/s to be considered acceptable. A proper AOCS controller should be able to reduce such value to a lower figure.
- Maximum net link longitude/elongation: 3.13/1.13m. This elongation is at the limit as it would imply that the links will break. The minimum net link diameter required is of 1.2mm (see below) instead of 1mm.
- Net link minimum diameter for avoiding breakage:
$$diameter_{req} = 0.001 \cdot \sqrt{\frac{3.13}{2.09}} = 0.0012\, meters$$
instead of 0.001m
- Maximum bullet link longitude/elongation: 0.71/0.21m. This elongation is at the limit as it would imply that the bullet links will break. The minimum bullet link diameter required is of 1.16mm (see below) instead of 1mm.
- Bullet link minimum diameter for avoiding breakage:
$$diameter_{req} = 0.001 \cdot \sqrt{\frac{0.71}{0.5235}} = 0.00116\, meters$$
instead of 0.001m
- Maximum tether longitude/elongation: 122.64/22.64m. This elongation is at the limit as it would imply that the tether will break. The minimum tether link diameter required is of 1.08mm (see below) instead of 1mm.
- Tether minimum diameter for avoiding breakage:
$$diameter_{req} = 0.002 \cdot \sqrt{\frac{122.64}{104.5}} = 0.00108\, meters$$
instead of 0.002m
- Maximum force over target surface: 1055.83 N. This force is a result of contact dynamics depending on the interpenetration.
- Maximum tension transmitted to chaser: 542 N. This figure is reasonable (below the force applied of 800N) and it should be taken into account within the design process of the chaser AOCS. This maximum tension is applied from the Chaser COM and therefore torques are not generated by this force; in the case that it is considered from another location of the spacecraft the corresponding torques should be determined.
- It should be highlighted that simulations #29 and #43 are almost failing to capture the Envisat satellite as it is demonstrated by very high linear velocity (12.3m/s) at the end of the simulation (simulation #29) or angular rates (415 deg/s for simulation #43). In both cases it is annotated the averaged maximum value before starting the unwrapping phase.

9.2.1. Failed Envisat Capture

In case of failed Envisat captures during Phase B. the following averaged values are computed:

- Simulation time: 12.5h (ranging from 4h up to 25h). This simulation time is similar to the successful captures (also 12.8h of average).
- Maximum target linear velocity: 5.4 m/s. This velocity is of similar order of magnitude than the initial relative velocity of 2m/s and only a little bit above the maximum linear velocity of the successful captures (5.2m/s). It is considered acceptable.
- Maximum target angular rate: 215.6 deg/s. This angular rate is much bigger than the initial angular rate of 5deg/s. It is not considered acceptable.
- Maximum force over target surface (before detachment): 573.6 N. This figure is reasonable (below the force applied of 800N) and it should be taken into account within the design process of the chaser AOCS. It is slightly bigger than the averaged maximum force of 542 N from the successful captures. In the case that it is considered from another location of the spacecraft the corresponding torques should be determined.
- Detachment time: 149s.
- While comparing the statistics of the successful Envisat capture during Phase B differentiating between simulations with and without solar panel, it is observed that that averaged values are always much bigger in the cases without the solar panel (29% for the linear velocity, 131% for the angular rate and 34% for the maximum tensions). The simulations without the solar panel last approximately double time than the simulations with the solar panel.

10. CONCLUSIONS, DISCUSSIONS AND FUTURE WORK

Concerning both phases of capturing and burning following conclusions are derived:

- The likelihood of net detachment could be reduced by including a closing link mechanism. This mechanism should ensure a robust capture of the net avoiding its disentanglement.
- It is required to increase the diameter of the net link (not only the internal threads but also the tether and the bullet links) from 1mm up to 1.2mm.
- They are observed very high maximum angular rates (up to 647deg/s) while the mean maximum value is 180 deg (still high but it could be reduced with an ad-hoc tensioning controller).
- The burning phase is considered to define an excessive and instantaneous increment of tension (from 2N to 800N). Such increment should be more gradual in order to get the net accommodated to the shape of the Envisat and allow to distribute the forces across all other net links. In this manner it is foreseen that the angular rates should be reduced to more acceptable values (below 100deg/s).
- The transmitted force of 800N produces during the first instants an elongation of the tether (it was initially tensioned only by 2N). Whenever all segments of the tether are tensioned at 800N, the target acquires a relative velocity with respect the chaser. As consequence of this generated relative velocity, the tether will be elongated more than expected in order to reduce such relative velocity and keep the overall energy of the system (the kinematic energy is transformed into potential energy of the net elongation). These high forces will produce unacceptable torques when the target is rotated from the initial attitude, and hence the angular rates are drastically increased.
- Almost all of the simulations shows the dynamics of a typical equivalent spring-damper system with four instants of maximum elongation of the tether (t=88.6, 112.3, 134,5 and 157.5s). In some cases there are five of six peaks (happening last ones during last moments of the tensioning).

Next Fig. 24 shows an example of good/bad wrappings of Envisat. In the good case the tension graph shows the shape of a parabola and no angular rates are generated. In the bad cases the tension graphs is much noisier and it does not represent a parabola; instead of that some damping energy is transformed into angular rotations of the target.

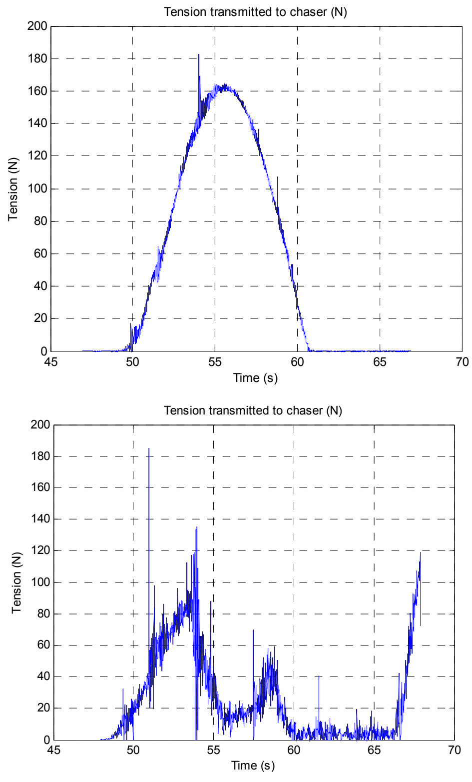
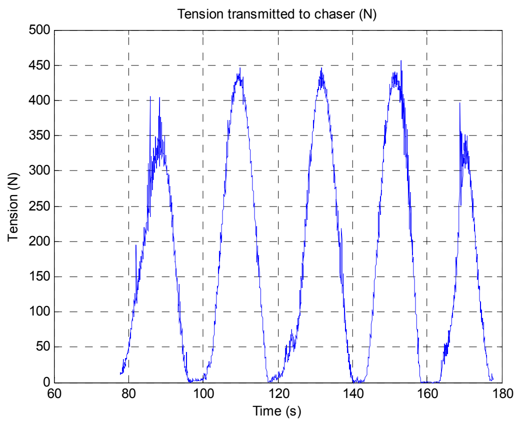


Fig. 24: Final state of the optimal wrapping without solar panel

- Next Fig. 25 shows again a good/bad behavior during the phase B of the tension transmitted to the chaser. In the good case they are shown clear oscillations of the tensions of similar magnitude and the corresponding angular rate of the target is almost kept constant. In the bad case after the first oscillation they appear angular rates on the target and the tensions start increasing over the time.



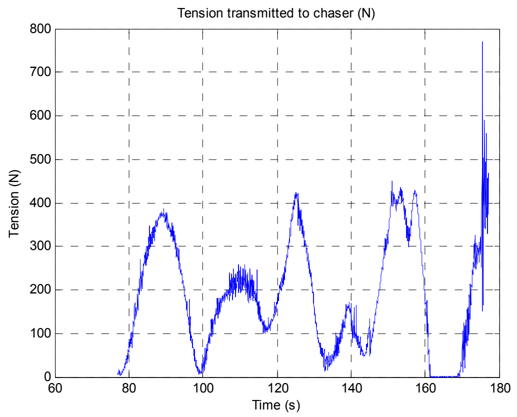


Fig. 25: Tensions transmitted to chaser for Phase B #10 (top) and #28 (bottom).

11. ABBREVIATIONS AND ACRONYMS

- PATENDER: Net parametric characterization and parabolic flight
- ESA: European Space Agency
- LEO: Low Earth Orbit
- GUI: Graphical User Interface
- GNC: Guidance, Navigation and Control
- CSV: Comma-Separated Values
- IMU: Inertial Measurement Units

12. REFERENCES

12.1. References

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