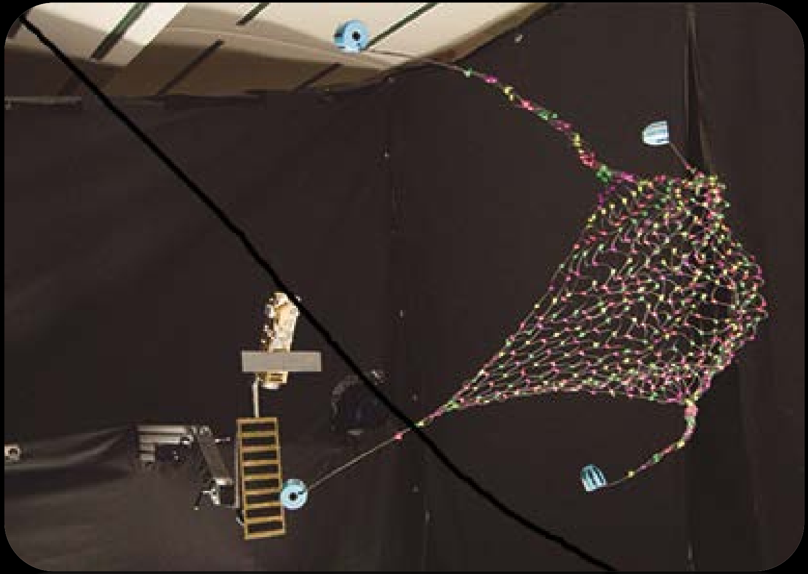
PATENDER

A NET-BASED EXPERIMENT AND POSSIBLE SOLUTION TO THE SPACE DEBRIS PROBLEM

Clean Space Industrial Days, October 25th 2017



INTRODUCTION & BACKGROUND

- Different aspects of debris objects and collisions challenging problem have been and are still under analysis by the different worldwide space agencies
- **A clear key issue is what 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

PATENDER (***Net parametric characterization and parabolic flight***) is an **ESA Clean Space Initiative project** developed by GMV/Univ. Milan/PRODINTEC whose objectives have been:

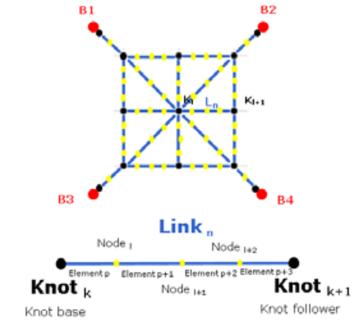
- Developing and validating a simulation tool for designing nets for capturing space debris via throw-nets
- Validating the simulator using experimental data generated by performing a set of experiments under microgravity conditions (achieved during a parabolic flight) and making a 3D reconstruction of the experiment images
- Use the validated simulator to analyse the deorbiting of the Envisat spacecraft using a throw-net

PATENDER THROW-NET SIMULATOR

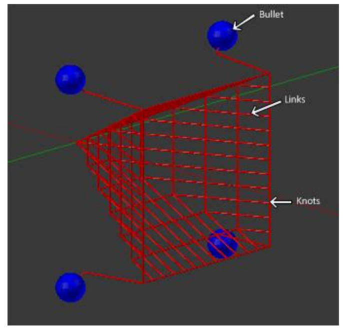
PATENDER simulator is able to perform simulations of large particle systems with **advanced 3D visualization capabilities**. The simulator is composed by 3 main elements:

- **Graphical User Interface (GUI):** based on Blender, allows the user to interact with the net configuration, environment and execution
  - Net configuration parameters (net type: planar, pyramidal, conical or user defined; net size; number of strings and rings, etc.)
  - Setting of propagation parameters
  - 3D visualization of the net deployment and of the target capture operation
  - Definition of the 3D view angle during the simulation
  - Plotting of the relative distance and relative speed measurements between any two net knots during the simulation
  - Plotting full state vector of any net knot or body (target or chaser) during the simulation
  - MonteCarlo simulations
  - Saving the the simulation visualization as video format and rendered images
  - Exporting the data obtained during the simulation to comma-separated values (CSV) and Matlab standard formats.
- **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 physics engine) and the contact dynamics algorithms

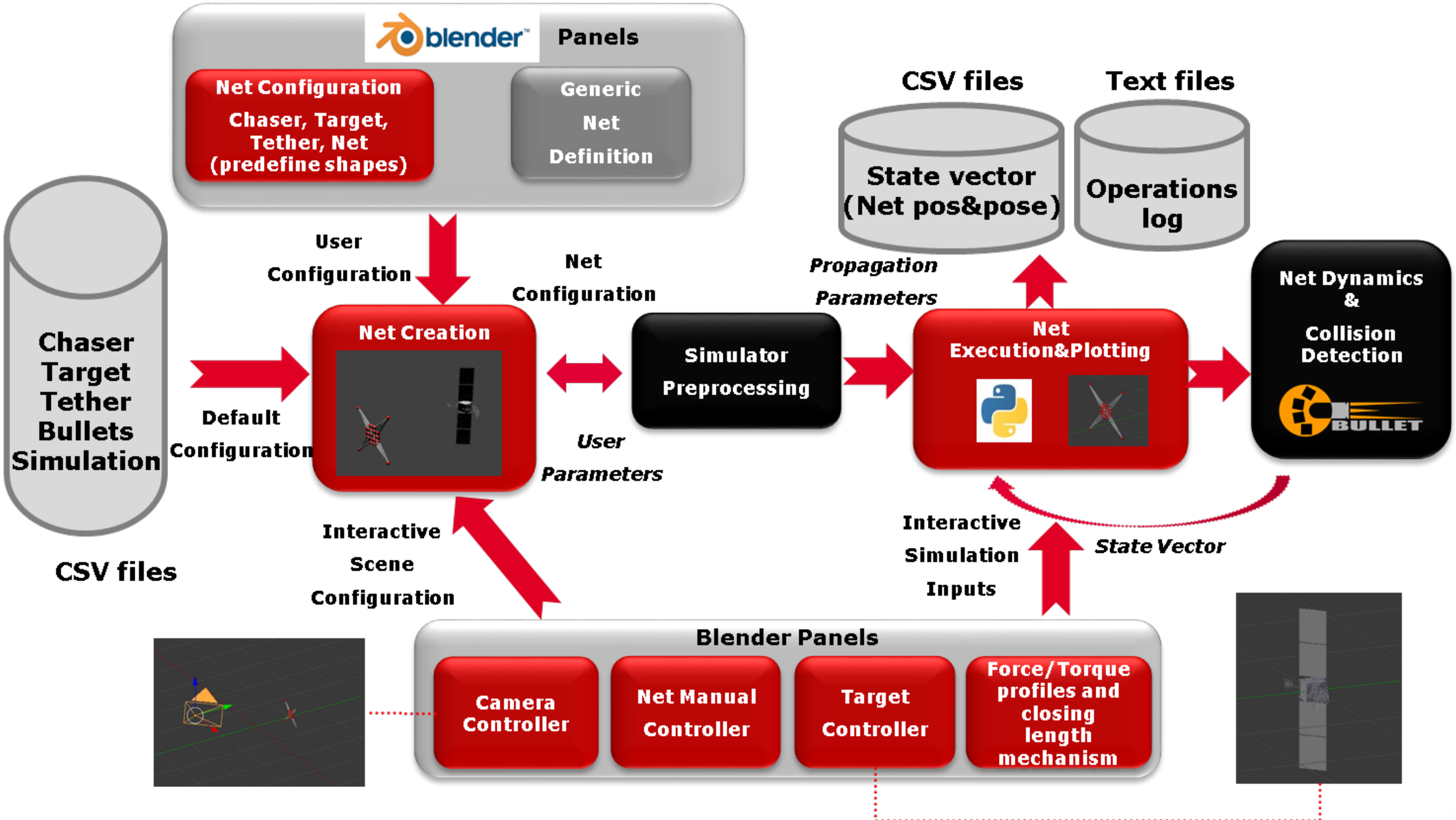
Net elements (knots, links, bullets and nodes) definition



Blender representation



PATENDER THROW-NET SIMULATOR



SIMULATOR VALIDATION APPROACH

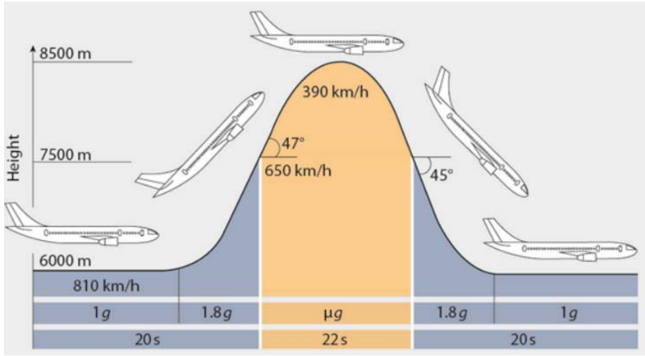
The validation has been made through comparison of the simulation data and the data obtained from the 3D reconstruction of net deployment/wrapping experiments images obtained from a parabolic flight test campaign.

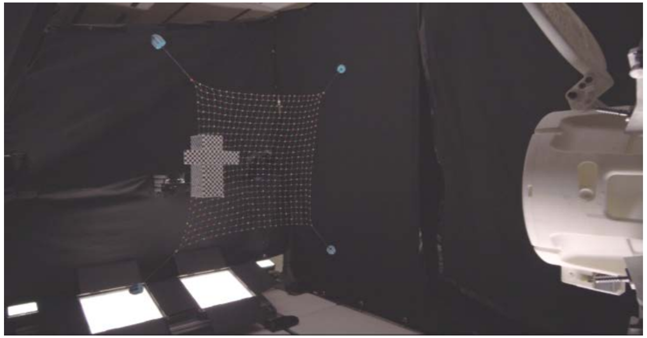
- The validation process was initially considered to be performed through the direct comparison between the positions of the simulated particles and the reconstructed particles
- However, after the large experience and know-how acquired on the dynamics involved in the net wrapping process, the positions comparison approach is stated as insufficient since it is not including 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
  - final wrapping (mostly dominated by chaotic collision process)
- During the free-flight deployment, the direct comparison of the net positions is used for validation
- During the wrapping, 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

PARABOLIC FLIGHT

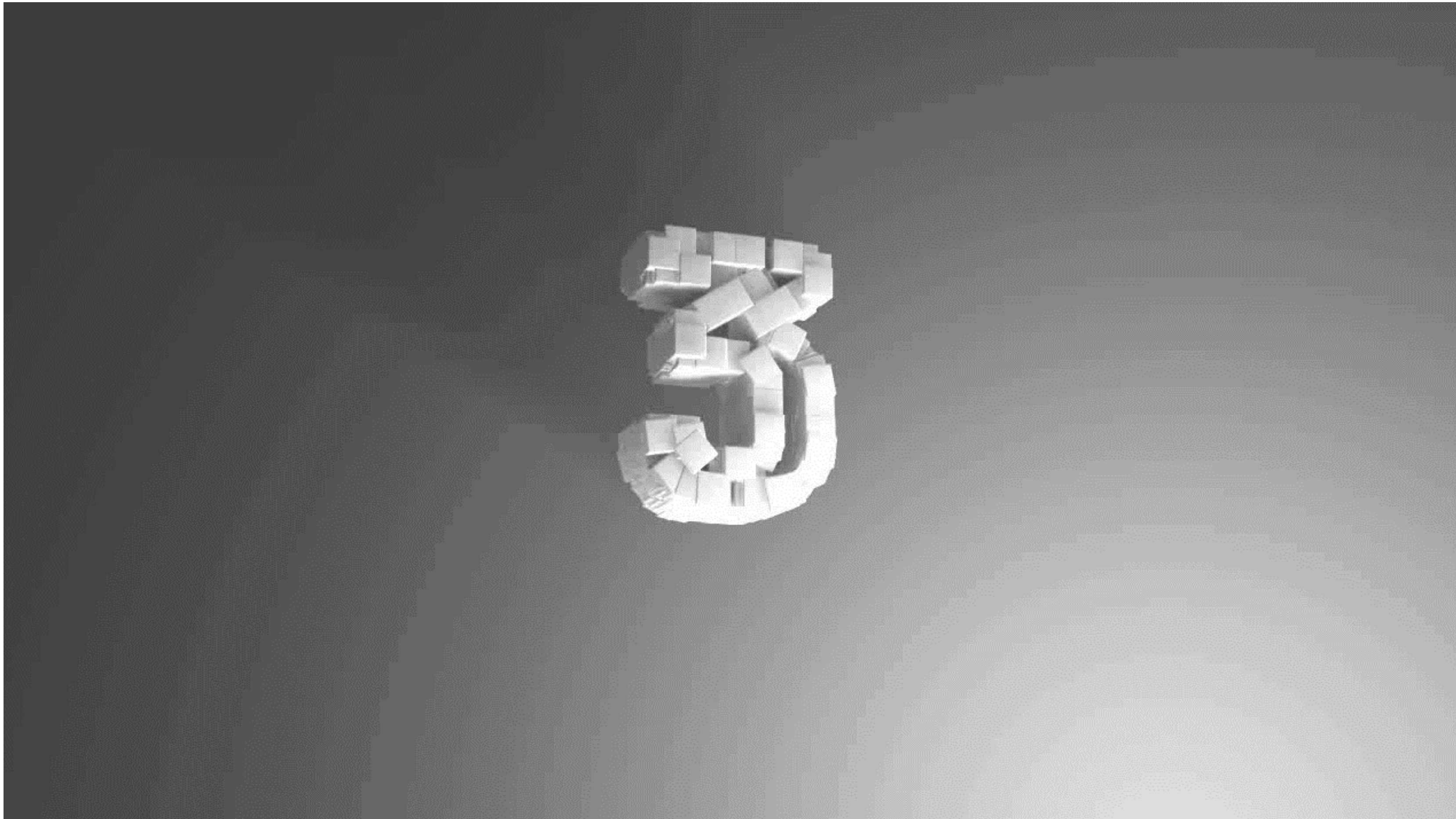
PATENDER experiment was flown on the Novespace 116th parabolic flight campaign (62nd ESA Parabolic Flight campaign, June 9th 2015) on board of an Airbus A310 aircraft

- 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
- After each set of parabolas a long break of 5 to 8 minutes allow to perform minor adjustments of the on-board experiments
- A scaling factor 1:40 has been used for the experiments
- Six nets (6) made of Technora (aramid fibre) with approximated dimensions of 0.6x0.6m and 50g of mass have been used.
- Folded net takes up 10x10x10cm and each of its corners is attached to a massive bullet (200g, 5x5x5cm) for a total mass of ~850g
- 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





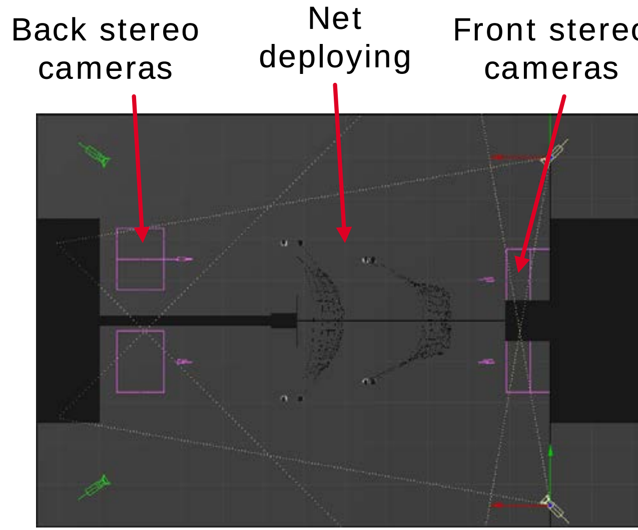
PARABOLIC FLIGHT: VIDEO

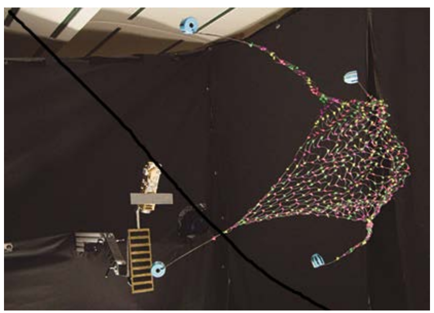


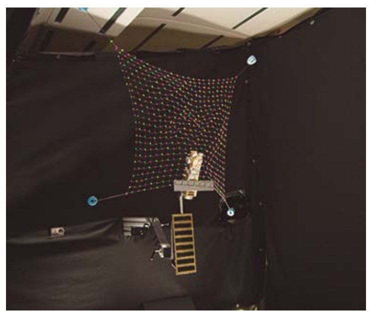
PARABOLIC EXPERIMENT RESULTS

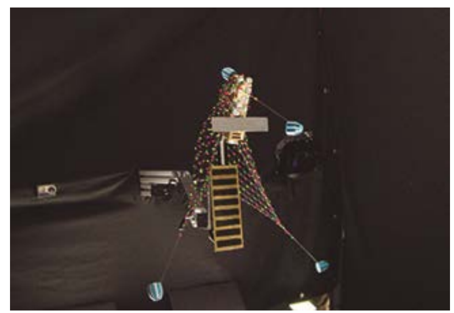
Main experiment facts:

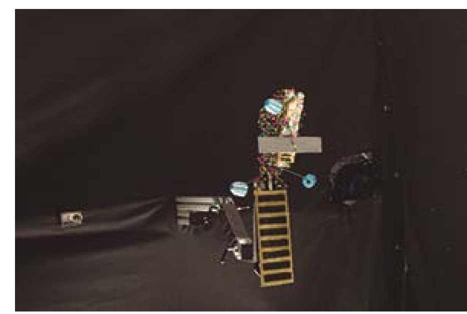
- 23 successful captures, including 3 net launches using a realistic Envisat mock-up
- 7 failed captures (due to non-simultaneous ejection of the four corner bullets)
- 9 successful parabolas selected for 3D image reconstruction
  - Two stereo pairs of cameras used during the tests, one pair in the front, another in in the back. Shutter speed=0.001 sec. 60 frames per second. 4 Kpixels.
  - Some snapshot images corresponding to a successful test case (including deployment a wrapping) is shown











3D IMAGES 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 using a 4-colour coding system (yellow, red, cyan and green), stereo matching of the segmented knot and iterative closest point (ICP) for time tracking of knots

- Colour segmentation of yellow knots: processed image from raw, yellow filtering and final binary image

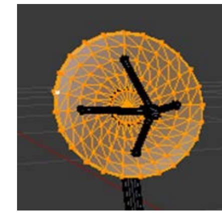
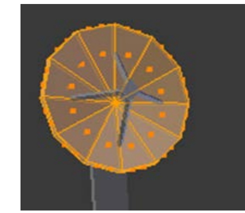
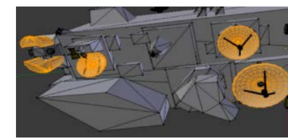
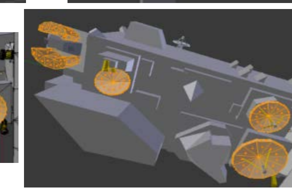
- An IMU has been synchronized with the system during microgravity tests to record acceleration profiles, as another key feature for the posterior model validation

- 200 images per camera and per parabola have been processed, for a total of 7200 processed images with a semi-automatic processing algorithm

ENVISAT DEORBITING SCENARIO

Main ENVISAT scenario 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 model considers 9102 DOF's
- A simplification of the ENVISAT CAD model has allows to reduce the simulation time from days to hours while keeping the simulator accuracy
  - vertices: from 17063 down to 1371
  - faces: from 10458 down to 2124

- 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 2m/s velocity, 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.

ENVISAT DEORBITING SCENARIO RESULTS

Phase A: Capture-Stabilization-Tensioning phase

- 24 simulations (changing the initial rotation angle around X axis by an amount of 24deg). CPU time: average 4 hours for 67 second simulation.
  - 50.0% success in the case of wrapping also the solar panel
  - 62.5% success if we just capture the Envisat body
- Averaged ENVISAT angular rotation at the end of the phase: 48.4 deg/s
  - Some maximum values of 188deg/s ENVISAT rotation as consequence of the net wrapping have been observed. This could imply a later detachment of the net during Phase B.
- Maximum net link longitude/elongation: 2.51/0.51m
  - This is at the limit of the material properties ➔ 1 mm link diameter shall be increased to 1.1-1.2 mm

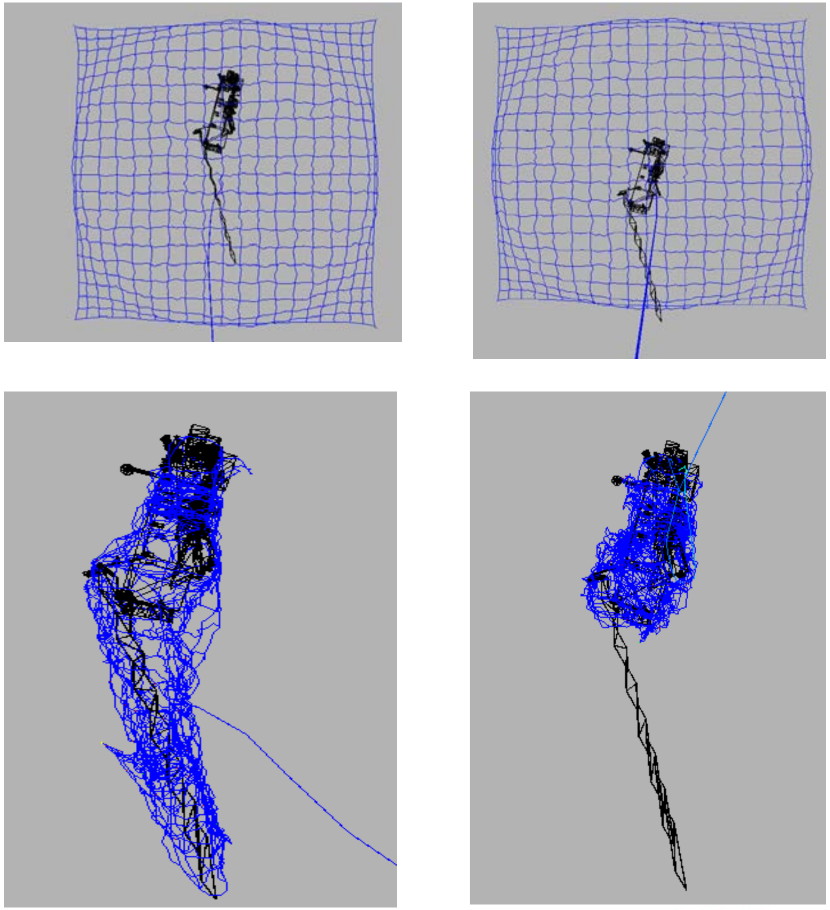
Phase B: Burn phase

- 48 simulations (starting from ideal wrapping conditions). CPU time: average 12.8 hours.
- Successful simulations:
  - Maximum target linear velocity: 5.2 m/s (similar order of magnitude than the initial relative velocity of 2m/s)
  - Maximum target angular rate: 145.4 deg/s (much higher than expected 40-60 deg/s ➔ higher demands over chaser AOCS)
  - Net link/bullet link longitude/elongation: on the structural limit ➔ increase the link diameter from 1 mm to 1.1-1.2 mm
- Failed simulations:
  - Maximum target angular rate: 215.6 deg/s
  - Detachment time: 149s

CONCLUSIONS

Main conclusions:

- A validated throw-net simulator has been developed
- Validation has been done using micro-gravity experimental results, including semi-automatic 3D images reconstruction
- The simulator has been used for a quick throw-net design case for ENVISAT scenario:
  - The first design has demonstrated the validity of the simulator as design supporting tool
  - The results of the first design are a good starting point for deeper studies
  - Still many uncertainties over the ENVISAT capture scenario through net ➔ extensive and exhaustive analysis should follow in the future



THANK YOU