STEREOGRAPHIC SYSTEM FOR RECONSTRUCTION OF NET FLIGHT TRAJECTORY

Michał Dyrek[1], **Zuzanna Derda**[1], **and Wojciech Gołębiowski**[2]

[1]*OptiNav sp. z o.o., ul. Portowa 13b, 76-200 Słupsk, Poland, info@optinav.pl*
[2]*SKA Polska Sp. z o.o., al. Jerozolimskie 125/127 p. 508, 02-017 Warszawa, Poland, info@ska-polska.pl*

ABSTRACT

To support e.Deorbit mission simulator of deployable net system is being developed under ESA contract, by consortium of SKA Polska, OptiNav and Stam companies (project called ADRiNET). For simulation validation purposes experiments were performed in microgravity conditions, in parabolic flight. In the experiment prepacked, downscaled net breadboard is launched towards the satellite model. During its flight net develops, hits the target and wraps around the target. Experiment is repeated several times with varying net type and its velocity.

Simulator validation requires that each knot of the net is tracked in the experiment to allow digital reconstruction of knots trajectories with at least 100 Hz sampling. Two net types are used: 10x10 and 16x16 meshes (both about 1x1 m), so up to 289 knots are to be tracked regardless of their position in respect to satellite model. Net flight and in particular target entangling is a complex phenomenon with knot appearing at different sides of the target, parts of the net covering each other and frequent changing of their relative locations. It makes knots identification and tracking a very demanding task, both from hardware and software points of view, particularly taking into account parabolic flight conditions.

Experiment is recorded with four fast, color 4MP cameras, forming two stereographic sets for observing from two sides of the satellite. Optical axes of the sets are parallel to net flight direction.

For knot identification purposes net is colored in unique manner, so location of the knot within the net (in terms of row and column) may be determined regardless of net entanglement state.

The system is supported with OptiTraceTech - technology for detection and tracking of markers in 3D space, designed to measure coordinates, orientations and distances between points with one or more cameras. Specially designed markers help to precisely measure position and orientation of the target and net ejector.

For the reconstruction of knots trajectories dedicated analysis software was developed. Localization and identification of the knots on subsequent frames of the movie is performed automatically with manual supervision and set of automatic tools for manual operations support. Such approach speeds up the process of trajectories reconstruction from all of the recorded movies, it is reliable and resistant to automatic algorithms errors.

Whole the system proved to be reliable and efficient both in series of ground tests and parabolic flight experiment performed on board of Falcon-20 aircraft. Reconstructed trajectories from about 20 movies recorded in weightless conditions allowed for physical validation developed simulation tool for space debris capturing with deployable nets.

Key words: active debris removal, net, stereo vision, 3D reconstruction.

1. EXPERIMENT CONFIGURATION

Both the on ground and parabolic flight experiments were performed in the same set up of cameras, shooter and target. The visualisation of the experimental rig is presented on Fig. 1.

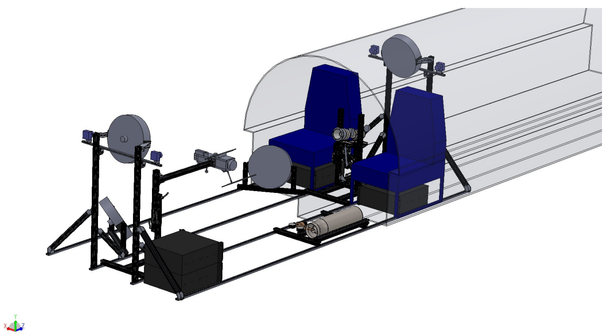

Figure 1. Experimental rig model

The camera used for experiments was Vieworks VC-4MC-C180EO-C. It has been chosen as meeting following requirements:

- high resolution (2048x2048),

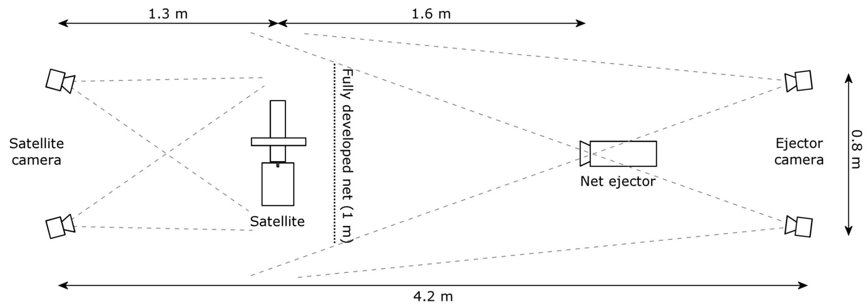

Figure 2. Working area in experimental set up (top view)

- high frame rate (179 fps),
- presence of Bayer filter (color image),
- raw (non-mosaiced) data transfer for reduced transferred data amount

The set up consisted of four cameras grouped in two stereo pairs. The pairs was positioned at the edges of the rig, facing each other and observing the satellite from both sides. Optical axes of the cameras were parallel to net flight direction. To achieve optimal coverage of the experimental area, the cameras used lenses with different focal lengths. Ejector camera was equipped with 25 mm lens, which gives angle of view of 25 degrees; satellite camera - 16 mm (38 degrees). The appropriate distance between cameras in the stereo pair (stereo base) was determined experimentally by taking into account rig dimensions constraints, the blind area (triangular area between the cameras in a stereo pair, just in front of them, increasing with stereo base) and triangulation accuracy (increasing with stereo base). The resulting positioning of the cameras with relation to the ejector and the satellite is presented on Fig. 2. The spatial configuration of the equipement was also constrained by the size of aircraft. The tests were perfomed on Falcon-20, flights beeing organized by National Research Council in Ottawa. The restriction of space on board has been visualized on Fig. 1.

The experiment conditions imply use of strong light source. It was provided by 4 lamps - LED reflectors of 146 W, 10000 lumens each. They were positioned in a way to best illuminate the scene. To avoid light losses, floor and walls of the experimental section of the aircraft were covered with white material. Additional asset of the covering was that it provided uniform, contrastive background for a coloured net. The final setup from the point of view of cameras closer to the satelite model is presented on Fig. 3.

Exposure parameters used during the experiment were determined as a compromise between shutter time (which should be short to minimize motion blur of flying net), aperture (which should be small to provide large depth

Figure 3. View from cameras closer to the satelite model.

of field) and sensor gain (which should be small to minimize sensor noise). During the ground tests values of these parameters were established as:

$$t = 500\mu s$$

$$f = 4$$

$$gain = 9.12dB$$

All four cameras were synchronized by common trigger signal provided by square wave generator working with frequency of 175 Hz.

2. ACQUISITION

To ensure no data loss during the parabolic flight the needed calculations were performed and their results were verified during the on ground test. Requirements for proper data acquisition system were determined based on Falcon-20 parabolic flight cycle, and camera's parameters:

- The length of microgravity phase (parabola) during the experiment is about 20 seconds
- It was planned to perform up to 20 parabolas during single flight

- Each 0 g phase is preceeded and followed by 20 s of 2 g phase.
- Camera with resolution 2048x2048, acquiring data at 175 fps produces about 700 MB/s

Taking into account above values:

- Single recording (20 seconds long, 3500 frames) has size of 14 GB
- All 20 recordings (from single camera) have size of 280 GB
- Data rate at which camera produces the data is higher than maximum write speed of the fastest existing SSD drives

These facts make lossless data acquisition a challenging task. To achieve this goal each camera was connected (with Camera Link interface) with separate computer dedicated for data receiving and storing. Each of the computers was equipped with 32 GB of RAM memory and fast 300 GB SSD drive. The data from the camera was sent in real time to the computer, temporarily stored in large FIFO buffer in the memory and subsequently written to the disk. Additional, fifth computer was connected with acquisition computers through Ethernet network. It was used as acquisition console for controlling and monitoring acquisition on all cameras simultaneously (Fig. 4). Important design feature of the system was its ability to work with or without acquisition console - it could be connected and disconnected during the experiment without affecting acquisition process.

After the verification on ground the final hardware set up was as follows:

- 4 high speed color cameras (with Camera Link interface in Full configuration)
- 4 acquisition computers (connected to cameras)
- 1 acquisition console computer
- 1 Ethernet switch (connecting acquisition computers with acquisition console)
- Tunable fequency generator for triggering and synchronizing cameras.

During the whole experiment (2 days, 21 parabolas) about 1300 GB of data was collected and stored. The analysis was performed off-line. Fig. 5 shows example frame from the movie recorded during the experiment.

Figure 5. Frame from the Ejector camera (left) taken 1 second after the shot. This is the moment just before the net hits the satellite.

3. CALIBRATION

Calibration procedure used to determine geometrical relationship between cameras in stereo sets used a calibration plate presented on Fig. 6. The checker board was presented to both cameras at once around 15-20 times in various positions. The collected images were then automatically processed and the corners of the squares were detected and marked. Knowing the real dimensions of used checker pattern and having image coordinates of the detected points it was possible to create both: mathematical model of a single camera and a model of a stereo camera defined as a translation and rotation of right camera in respect to left one. Those models served later for triangulation purposes. The process of automatic detection of checker board pattern was implemented with use of camera calibration toolbox for Matlab [1].

Calibration was performed at the beginning and at the end of each flight. This process allowed to determine whether the cameras have been displaced in between the calibrations. The initial idea to calibrate the cameras during the flight in between the 0 g phases was abandoned due to the time needed for this process (the calibration required disassembling of the satellite model).

4. NET - NODES IDENTIFICATION

The net shall be represented as a set of knots that need to be unambiguously identified for tracking purpose. Each node is identified by a set of colors of it's adjacent edges. Several algorithms of net coloring have been taken into

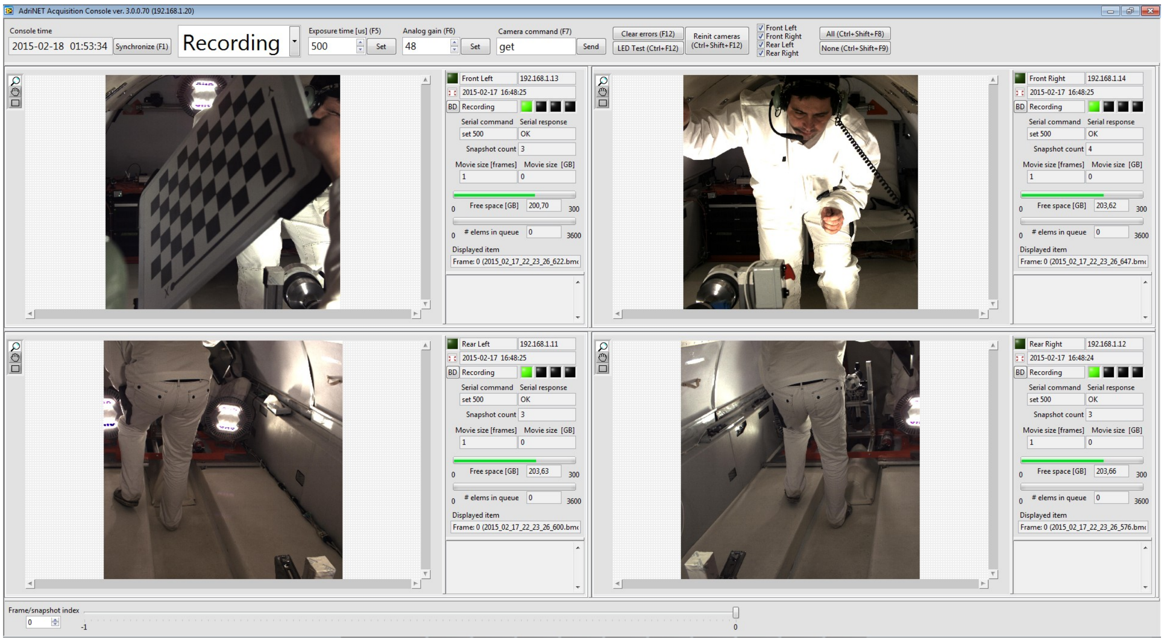

Figure 4. User interface of acquisition console application (during stereo calibration at the end of first day of experiments)

account from which one has been chosen as the most promising. Analysis complexity and color palette size were used as differentiating factors between proposed solutions. The chosen algorithm assigns one color for each edge (structure connecting two nodes). One node is then identified by a multiset of 2, 3 or 4 colors assigned to it's neighbor edges (edges that directly goes to/from the node). The algorithm's goal is to minimize the amount of colors used while preserving unambiguous marking of nodes. For the nets used in the experiment the 10x10 mesh was covered by 9 distinctive colors and 16x16 mesh with 11. The palette was chosen from 148 colors available for specific alcohol based markers. Alcohol based markers were chosen to minimize the effect of coloring on net rigidity and to provide maximum endurance and color intensity. The subset of 148 colors was calculated programmatically in a way to ensure maximum difference between the selected colors. The difference was calculated as an euclidean distance in 3D space defined by red, green, blue values. The pattern was generated by a dedicated software and all test nets were coloured according to it. The software ensured that there will be no repetition of color codes for any of the nodes in the net.

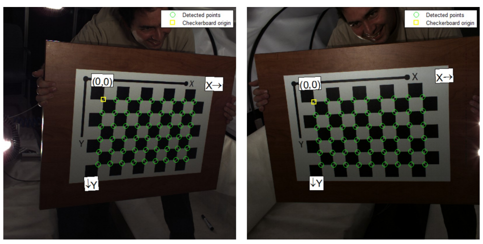

Figure 6. Frame from the calibration procedure, view from both of the cameras in one stereo set.

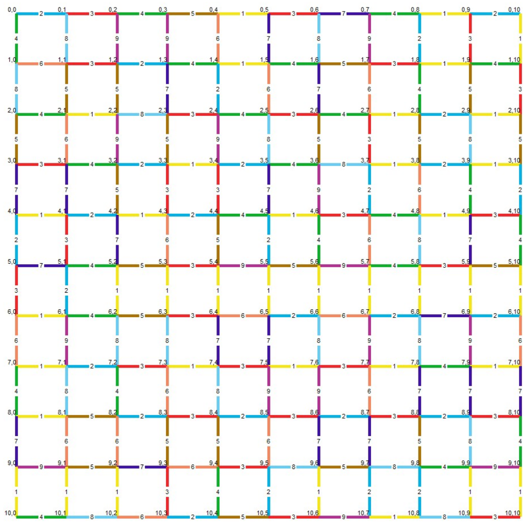

Figure 7. Net coloring scheme for 10x10 mesh (9 colors used)

5. NET - RECONSTRUCTION

The 3D reconstruction can be reduced to the problem of marking 2D position of net's nodes (on left and right image of the stereo pair), labelling them with grid coordinates on each frame of the experiment record and calculating their 3D positions using well known triangulation algorithm. During the tests with the application specially designed for this purpose (Fig. 9) it turned out that skilled user can achieve labeling speed of about 600 3D nodes per hour (1200 marked left/right points). Comparing this to the amount of data that needs to be processed leads to

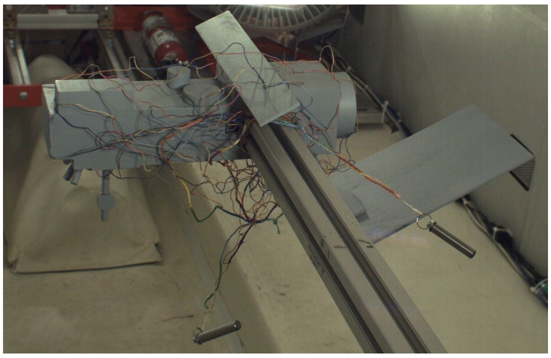

Figure 8. Need for a color code for knot identification is clearly visible at frames with net entangled around target.

unacceptable time estimations. On the other hand, full automation of the process is difficult to implement, especially on more complicated net configurations (post-launch, closing on debris). It is also associated with risk of mislabelling, what should be avoided at any cost. This is why automatic support for manual labeling turned out to be the most promising solution.

During a preprocessing step before the labeling some image processing operations are performed. The first step is foreground detection (separating pixels in which movement is present from background pixels) succeeded with color classification of foreground pixels using SVM based classifier. Color classification may be perceived as a special case of image demosaicing in which target color space is limited to a set of 9 or 11 colors used for coloring the net.

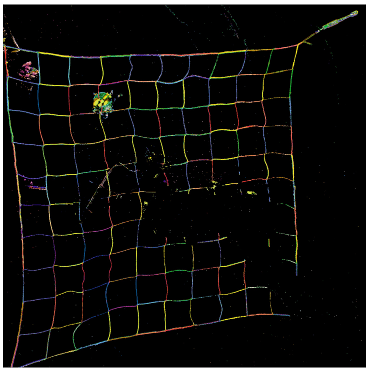

Figure 10. Results of color classification performed on foreground pixels (coloring scheme different than presented on Fig. 7)

Precomputed color classification results (Fig. 10) are used to support manual labeling. Few tools are available for the user to simplify this process by node localization, recognition and tracking. The feature that is especially valuable with regard to speeding up the labeling process is node tracking. After the node is marked and labelled on one frame, the tracking algorithm can propagate through subsequent/preceding frames and automatically localize this node using template matching. The template from current frame is localized in the next frame, new template is created from the localization results and the process is repeated. In the case when tracking algorithm fails to properly localize the node (and - in result - all following nodes), the user can manually correct node's position, however this is relatively rare situation. The measured accuracy of the tracking algorithm is about 95% which means that in 95 cases out of 100 the template taken from current frame is correctly located in subsequent frame. The result of the tracking algorithm is presented on (Fig. 11).

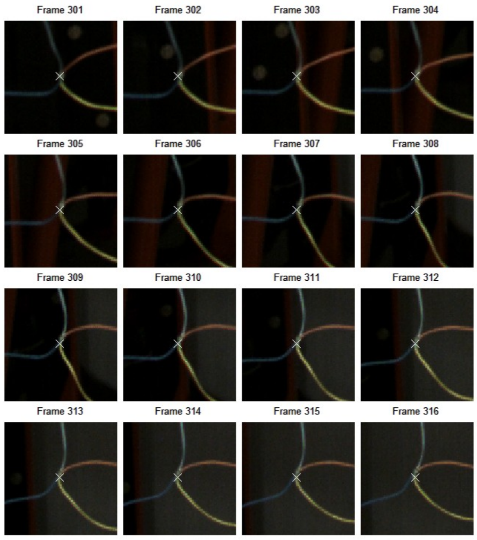

Figure 11. Results of automatic node tracking through 16 consecutive frames (node label: 6,6)

Using node tracking approach, labeling speed can be increased to about 3000 3D nodes per hour. The data labelling and net flight reconstruction is currently in progress.

6. OPTITRACE SYSTEM

OptiTraceTech is a technology developed by OptiNav for precise detection and tracking of specific markers in 3D space. For the purpose of this project it was used to determine the position and orientation of target (satellite model) and net ejector. The markers (see Fig. 12 were designed in a way, that a single marker is fully recognizable in the 3D space. The gray-scale pattern is used to code the ID of a marker (system provides 9 different markers) and to calculate it's position and orientation. In the system markers can be merged to represent objects. One object can be composed of two and more markers. It is defined by the relative distances and rotations of markers. Such objects may be used to unambiguously mark elements of 3D space or to define specific measurement tools. The marker and technology have patent pending.

Full working system consists of one or more camera, one or more objects and a PC. The acquisition module is not

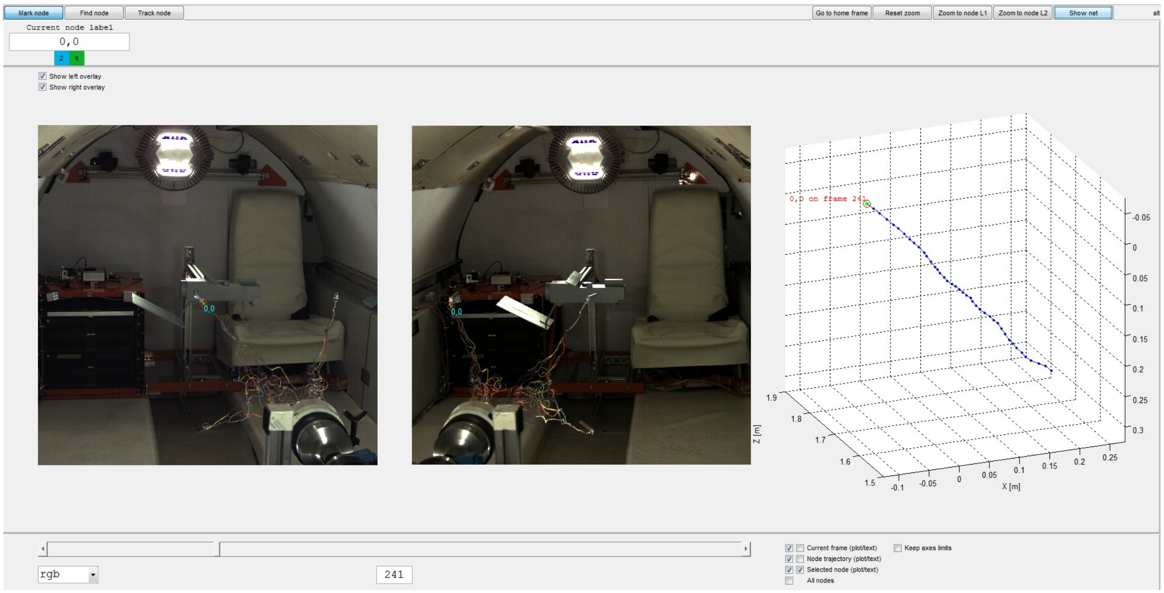

Figure 9. User interface of reconstruction application. The most of the window is taken by views from stereo camera and 3D visualisation of labelled nodes displaying trajectory of node 0,0

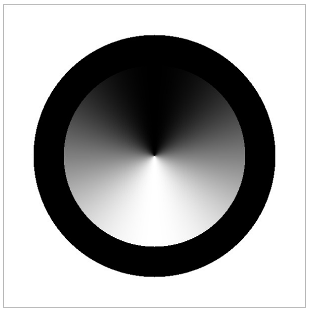

Figure 12. An exemplary marker

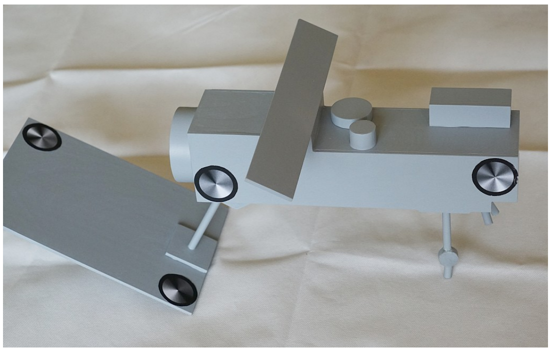

Figure 13. Envisat model with markers for position and orientation determination

a part of the system so the choice of vision hardware is unlimited what was an advantage in this case.

The accuracy of the OptiTrace system depends on several parameters what allows user to choose between high performance and low costs. The most important part is the precision of lenses and camera construction that result in the distortions on images. This is compensated by the proper internal calibration, but the effectiveness of this process influences the resulting accuracy. The other components that can enhance it are:

- larger marker sizes,
- higher camera resolution,
- more markers composing one object,
- proper light settings,
- more cameras in system.

First the satellite model and net ejector were marked with two different objects composed of three markers. One pair of the cameras at a time was used to acquire images of the scene. Then the images were processed by the system giving the coordinates of the objects attached to satellite and ejector. This process was repeated on the second set of cameras. The objects were kept in position between two acquisitions. The images were then again processed. The coordinates obtained for each pair were used to define the distances between the cameras, model and ejector. The second step was to define the relative orientation of satellite and ejector. Several clue points were identified by one of nine markers. The acquisition was performed separately for the satellite and the ejector. Nine points were collected to represent the orientation of those objects in 3D scene.

7. CONCLUSIONS

There were many obstacles expected for the on board tests both of technical and human factor origins: ac-

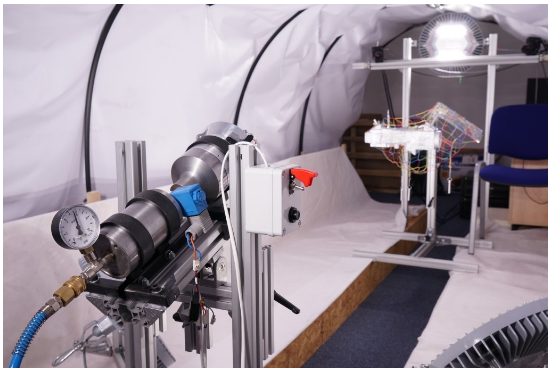

Figure 14. Falcon-20 cabin mock-up with experiment and cameras installed

tual light conditions in the cabin, potential problems with hardware, limited depth of field, unknown net behaviour in 0g, etc. In order to identify potential problems and find countermeasures a mock-up of Falcon-20 cabin was built (Fig. 14)and the tests were performed inside. These ground tests allowed to find the most optimal configuration for the hardware, overcome all the impediments and train the experimenters properly. The team was additionally trained in centrifuge in order to prepare them to parabolic flight conditions and frequent changes of gravitational acceleration.

Despite the spatial restrictions and high requirements for the acquisition rate and camera's resolution the experiment proved to be a success. The precalculated parameters for the hardware and the assumed set up fit perfectly into the needs of the experiment. The collected data has been processed and analyzed. Special software proved to be necessary as an assistance in the 3D reconstruction to reduce the processing time. The so obtained results allowed for digital reconstruction of knots trajectories, used later for the validation of net simulator.

The follow-up of the presented work is ADR1EN project (First European System for Active Debris Removal with Nets) funded within Horizon 2020. Its goal is to procure full scale functional breadboards of the net and ejector for the selected debris removal mission target. The optimal net will be designed using described validated simulator.

REFERENCES

[1] Bouguet J.-Y., 2013 , Camera Calibration Toolbox for Matlab, `http://www.vision.caltech.edu/bouguetj/calib_doc/index.html`