AIRBUS DS VISION BASED NAVIGATION SOLUTIONS TESTED ON LIRIS EXPERIMENT DATA

A. Masson(1), C. Haskamp (2), I. Ahrns (2), R. Brochard(1), P. Duteis (1), K. Kanani(1), R. Delage(1)

(1) Airbus Defence and Space, 31 rue des cosmonautes, 31402 Toulouse Cedex, France, Email:aurore.masson@airbus.com
(2) Airbus Defence and Space, Airbus-Allee 1, 28199 Bremen, Germany, Email:ingo.ahrns@airbus.com

INTRODUCTION

The LIRIS Demonstrator is an experiment of vision based navigation sensors implemented on ATV-5 George Lemaître and activated during the approach phase with the International Space Station (ISS). Studies of non-cooperative rendezvous stress the need for a GNC based on image processing using LIDAR sensors and cameras.

The LIRIS Demonstrator is composed of two flight phases during the ATV-5 flight. The ISS fly-under is from about 70 to 8.8 km and the rendezvous with ISS is from 3.5 to 0km. The navigation sensors are composed of two infra-red cameras, one monochrome visible camera and a scanning LIDAR. LIRIS is separated in two experiments: the LIRIS-1 experiment proposed by SODERN which concerns the use of infra-red (IR) and visible (VIS) camera designed especially for non-cooperative rendezvous in space, and the LIRIS-2 experiment proposed by JenaOptronik and composed of a LIDAR Optical Head associated to an electronic which is interfaced with ATV and a recorder. This sensor provided full 3D scans of the approaching ISS between relative distances of 30m down to docking and relative position measurements starting at approximately 2.5km relative distances. In this paper we will present the results of the post-flight analysis of the cameras images and the scanning LIDAR data with specific emphasis on the relative pose-estimation providing a full six degree-of-freedom relative measurement.

The LIRIS flight database collects all the data coming from the sensors, with time synchronized and associated with a reference trajectory processed from telemetry issued from ATV navigation. This database contains also information on the sensors, like position, orientation and calibration laws. Beside the cameras in visible and LWIR spectrum, the LIRIS-2 experiment concentrated on the acquisition of scanning LIDAR data (i.e. a relatively dense 3D point cloud of relative 3D point measurements between the scanning LIDAR and the ISS as a target object).

In this paper, the main features of the LIRIS demonstration and sensors are presented. The Airbus Defence and Space Vision Based Navigation solutions are described. The test campaign results on LIRIS data are provided and preliminary performance as well as benchmarking on a LEON4 processor board will be given.

1 LIRIS FLIGHT DATA

The ATV-5 Georges Lemaître ascent flight took place from injection by Ariane 5 on July 29th 2014 until docking to the ISS on August 12th 2014. For the fly under, performed 4 days before the rendezvous, the ATV was positioned in Earth pointing mode by a slew manoeuver, and ATV front cone with LIRIS sensors is pointed toward the ISS. During the fly-under, a series of maneuvers maintain ATV in an orbit based on ATV GPS information processed on ground. The ATV rendezvous with ISS is composed of 2 phases, a far and a close rendezvous. The far rendezvous is from 30km to 250m performed with relative GPS between ATV and ISS. The close rendezvous is from 250m to docking and use a videometer to measure the ISS position and attitude.

1.1 Camera and LIRIS-1 experiment

The LIRIS-1 experiment proposed by SODERN combines two camera technologies: thermal infra-red and monochrome visible camera. The 2 IR cameras are redundant to mitigate the risk related to single event upsets and the VIS camera is used to compare IR and LIDAR images especially for the localisation of some ISS enlightened elements excepted during eclipse phases. Another advantage for the VIS camera is to present a better image quality with a higher image resolution of 1360x1024 pixels compared to the 640x480 pixels for the IR camera. All cameras have a recording cadence of 1 Hz with a total field-of-view of 58.6°x45.7° for IR cameras and 57.5°x44.9° for the VIS camera. The LIRIS-1 experiment is activated from 70km to 9km during the ISS fly-under and from 3.5km until docking during the rendezvous.

1.2 Scanning LIDAR and LIRIS-2 experiment

This scanning LIDAR was developed and integrated to the ATV-5 for the LIRIS-2 experiment by Jena-Optronik GmbH. This scanner was an early prototype of the next-generation scanning LIDAR for the relative measurement of non-cooperative targets. However, due

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

to safety limitations in the context of approaching a manned space-craft, the scanning LIDAR was not operated at its highest power-level and thus only provided data at a reasonable density for the last 30m. Furthermore, the field-of-view of the scanning LIDAR which is foreseen to be ranging between 1°x1° and 40°x40° degrees maximum was only controlled by a pre-defined timeline. Connected to this pre-defined field-of-view control also the scanning frequency and the scan-density varied according to a pre-defined scanning scheme. In the LIRIS-2 experiment, the LIDAR was switched on at a relative distance of approximately 2.5 km. Because of the power level constraints the LIDAR only provided a set of single measurements and no dense 3D-scan. This changed from distances of 30m and downwards. Also the scan duration changed with relative distances and varied between 120s for distances larger 300m, 16s for ranges between 100m and 300m, 4s for ranges between 100m and 30m, 1 Hz between 10m and 30m, and finally 3 Hz for ranges below 10m. According to this also the absolute number of scans varied with relative distance.

1.3 Intrinsic Calibration on sensors

Each camera has its own distortion calibration law estimated on-ground by SODERN and provided in the LIRIS database. The distortion is modelled with a 3rd order polynomial transforming coordinates in the detector frame to tangent coordinates in the camera frame.

During assembly, integration and testing (AIT) of the scanning LIDAR in Kourou at the ATV-5 spacecraft, only very limited time was available for the extrinsic calibration of the sensors. All sensors (i.e. the cameras and the scanning LIDAR) have been extrinsically calibrated with respect to a common calibration target consisting of the nominal ATV docking target-pattern consisting of seven retro-reflective corner-cubes. Measurements of these corner-cubes have then been used to estimate the alignment of the LIRIS sensors w.r.t. the main ATV space-craft. Due to the setup of the calibration body, it was not possible to have the target placed at varying locations in the field of view of the scanning LIDAR. Therefore a rather small target in one of the corners of the field-of view of the scanner had to be used. As discussed later in this paper, this type of extrinsic sensor calibration did not provide sufficiently high alignment accuracy. Further calibration efforts were undertaken by Jena-Optronik in order to remove distortion effects of the point-cloud and in order to provide accurate range measurements.

The orientation matrixes are obtained following the exploitation of a specific calibration test. The accuracy was estimated to be 0.5 deg for cameras and 1 deg for LIDAR but additional margins shall be considered for unknown uncertainties, therefore an extrinsic calibration was estimated from fly-under images as a bias correction.

1.4 Data quality

After receiving the scan data for the post-flight analysis, a first comparison between the geometry of the target model (here the ISS and especially the Russian service-module) based on the reference-data provided by the ATV's onboard docking-sensors (i.e. the videometer (VDM) [1] and the telegoniometer (TGM) [2] sensor also provided by Jena-Optronik. Both measurements are based on tracking a set of retro-reflective corner-cubes attached to the Russian service-module of the ISS. These measurements were taken as reference-data for comparison, well knowing that these measurements are not really ground-truth but the best information on the relative state between ATV-5 and the ISS available at that time.

A first glance at the data showed that especially for the last 30m relative distance the quality is quite good concerning density and false measurements. In principle, the 3D-point cloud provided by the 3D-LIDAR fit very well with the model of the ISS. Only at some portions of the target, the scanning LIDAR provided wrong measurements which tend to be too far away. These wrong measurements were mainly on the solar-panel of the Soyuz space-craft attached to the ISS at that time. Additionally, this test showed the first discrepancies between the scan data and the matching of the model based on the reference data. A range-dependent bias has been observed that could be well explained by an error suspicion on the sensor alignment.

1.5 Bias correction

Because of these observations, the full calibration process has been revisited and new efforts have been undertaken to improve the quality of the sensor alignment. After all a new improved alignment information has been provided by Jena-Optronik by matching the scan-data to the ISS model and comparison with the reference data. This comparison provided at the end an alignment-information that seems to be much better than the result of the extrinsic calibration during AIT in Kourou.

2 IMAGE PROCESSING FOR VISION BASED NAVIGATION

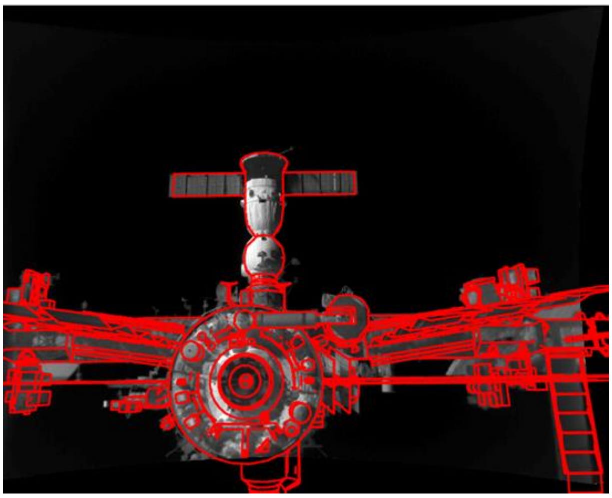
Airbus Defence and Space (ADS) has been working for many years on vision-based navigation solutions including target detection, target tracking and navigation filtering. Our image processing solutions are tested on LIRIS flight data to assess their performances on real images and are compared with the reference trajectory to make a post-flight analysis. The experiment covered the full range of rendezvous distances, the ISS starting as a point-like object in images, growing in the field of view and finally having it fully resolved in the sensor.

2.1 Camera-Based Pose-Estimation

The image processing (IP) is composed of detection and tracking modules working together in an automatic process loop [3]. As inputs, calibration data and an *a priori* 3D model of the ISS are used. They feed a navigation filter with LoS measurements at long range, and both position and attitude measurements at short range.

During the close-range rendezvous approach, when the ISS have a sufficient resolution, the IP detection module, based on gradient orientation, is activated. It is used to initialize the model-based tracking (MBT) which part relies on a non-linear minimization of the reprojection error [4]. MBT outputs the attitude and position of ISS in the camera frame. It works as follow. Salient edges from the ISS 3D model are extracted and projected on the camera image plane. A solver iterates then to find the best pose for which projected 3D model edges best match the image contours. The rest of the tracking sequence is made by a loop in which IP-tracking outputs are used to initialize the tracking for the next iteration until the end of the sequence. Figure 1 represents images from cameras and the MBT 2D-projection associated.

The IP algorithms are robust to occlusion, background and target rotation. For the LIRIS-1 experiment, the goal is to have an independent tracking working with image data only. MBT starts working when ISS has a minimum size in image around 60-100 pixels which corresponds to an approximated distance of 800 m from the camera.



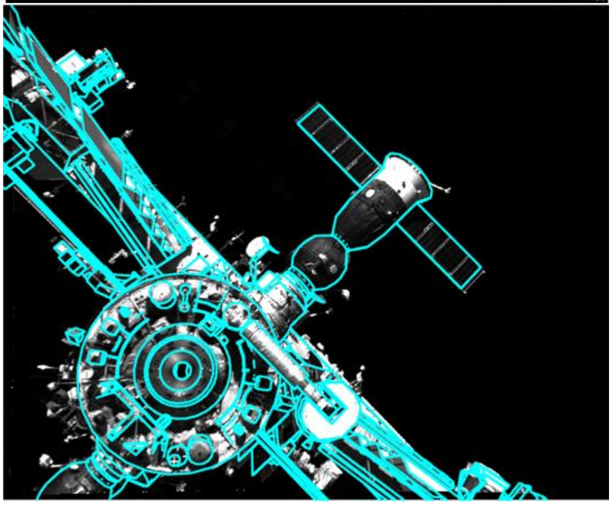


Figure 1. IR1, IR2 and VIS camera image with MBT 2D-projection in color (respectively red, green and blue). The ISS docking point is at a distance of 20 m from the ATV.

2.2 3D-LIDAR-Based Position-Estimation

For larger distances a relative position measurement between the approaching space-craft and the target space-craft is sufficient for the guidance and control (G&C) to bring the approaching space-craft closer to the target. Therefore, at larger distances a simple processing of the received measurements that just computes the geometrical center of all 3D-point measurements is sufficiently accurate to estimate a relative position. The processing is very simple and just applies centroid estimation.

The simple centroid estimation of course does not reflect the systematic deviation between the centroid of scanned 3D-points on the surface of the target space-craft and the actual reference system of the target space-craft. This difference normally results in a bias mainly along the boresight-direction. This bias has been estimated in simulations and taken as a constant corrective value. Using this very simple approach, relative position errors in the order of +/- 10m at 2.5km down to +/- 5m at 300m relative distances have been obtained.

2.3 3D-LIDAR-Based Pose-Estimation

The above mentioned method for the scanning-LIDAR based estimation of relative position just by centroid estimation the single measurements is of course not accurate enough for the last meters of the approach. Here, very accurate measurements in the order of centimeters are required. Furthermore, these measurements have to be precisely known with respect to a well-known reference system attached to the target space-craft. Therefore, another method is required that is based on the matching of a 3D model of the target space-craft and the acquired 3D point cloud. For the LIRIS 2 experiment, a tracking-algorithm [5] based on the family of iterative-closest point algorithm (ICP) [6] [7] has been applied.

2.3.1 Target Modelling

In order to match the 3D scan points with an expectation of the target space-craft one needs to have a good model of the target geometry. For this purpose, Airbus DS generated several versions of the target model that mainly differ in the level of complexity. The starting model had a total number of 2.8 mio. points and 4.6 mio. polygons. From this a smaller model of 13350 points and 13800 polygons has been made and this model has even been further reduced to 2800 points and 2600 polygons.

All models have been compared to the 3D scans of the scanning LIDAR but also to the camera images. Finally one had to admit that it was not possible to perfectly model the target for different reasons. First, not all the details of the target were available for the project team, second, some parts were no longer as built and provided differences due to possible damages. Examples for this observation are shown in figure 2.

The yellow points indicate points with larger discrepancies between scan and model. The next model shows the most important discrepancies. For instance, the Urthe-Cast camera could not be modelled and is missing in our model and thus represented by yellow scan points. The following figure shows the view from the camera in the visible spectrum for comparison.

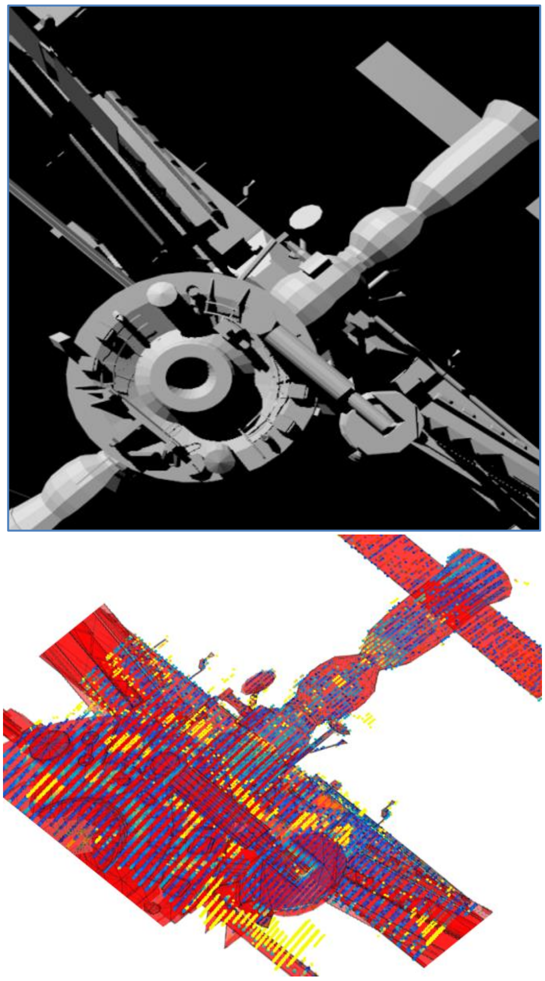


Figure 2. View of the larger model from simulated scanning LIDAR perspective (top) and overlay of target model and acquired scan: Point colors represent the distances between the closest patches of the target model (bottom).

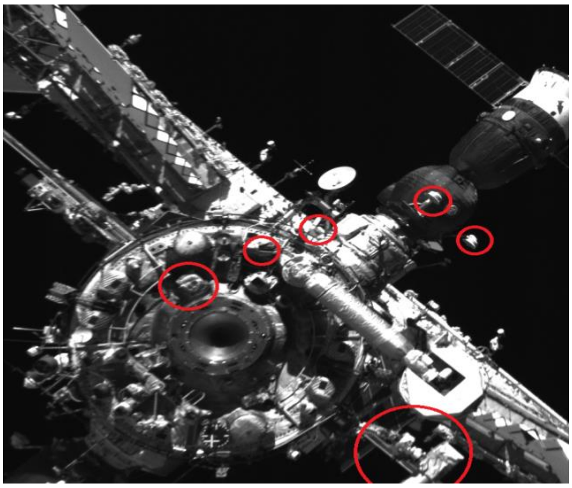


Figure 3. Camera image highlighting the areas of bad modelling of the target.

2.3.2 Algorithmic Principles

The matching of the target geometry with the point cloud of the scan is performed by using the ICP algorithm. Here, we apply an ICP variant that matches scan points to the closest points on the model surface. The distances are calculated by computing the distance between a scan point and the closest point on a small triangular patch that models the target surface.

Beside the usage of point-to-patch comparison, the final performance of these type of algorithms is achieved by using specific weighting functions for the distances between points and surfaces, specific outlier rejection, as well as highly optimized distance computation between points and surfaces which applies as much as possible pre-computations in order to save computing time on the on-board computer.

3 RESULT ANALYSIS

For the result analysis, we focused on rendezvous sequence. The IP-tracking camera position and attitude estimation are presented without filtering or aiding from the navigation. The full 6DOF LIDAR-pose-estimation has been applied for close range rendezvous. For larger distances, the scan parameters were not optimally chosen for the pose-estimation and especially the scan density and scan frequency was not sufficiently good.

3.1 Ground truth correction using LIDAR Data

The relative position estimation based 3D-LIDAR scan-points has been performed for distances between 2.5km and 30m. Due to larger scan times at larger distances, the sampling is not homogeneous. Between 2.5km and 300m, only 11 scans have been acquired, at smaller distances, the number of scans increased. A bias obtained from simulations has been subtracted from the centroid computations. The finally achieved accuracy is below 10m-15m for distances up to 2.5km. At lower distances the error decreases down to 5m (e.g. at 300m relative distance).

3.2 Middle range Pose-Estimation

Concerning the middle range rendezvous, the ISS appeared with a sufficient resolution after 800 m of distance for cameras and the LIDAR scan data are enough separated down to 300m to ICP algorithms. The figure hereafter shows the position estimation with camera and LIDAR along the line of sight direction (X-axis) and lateral directions (Y-axis and Z-axis) comparing to the ground truth reference corrected by LIDAR data.

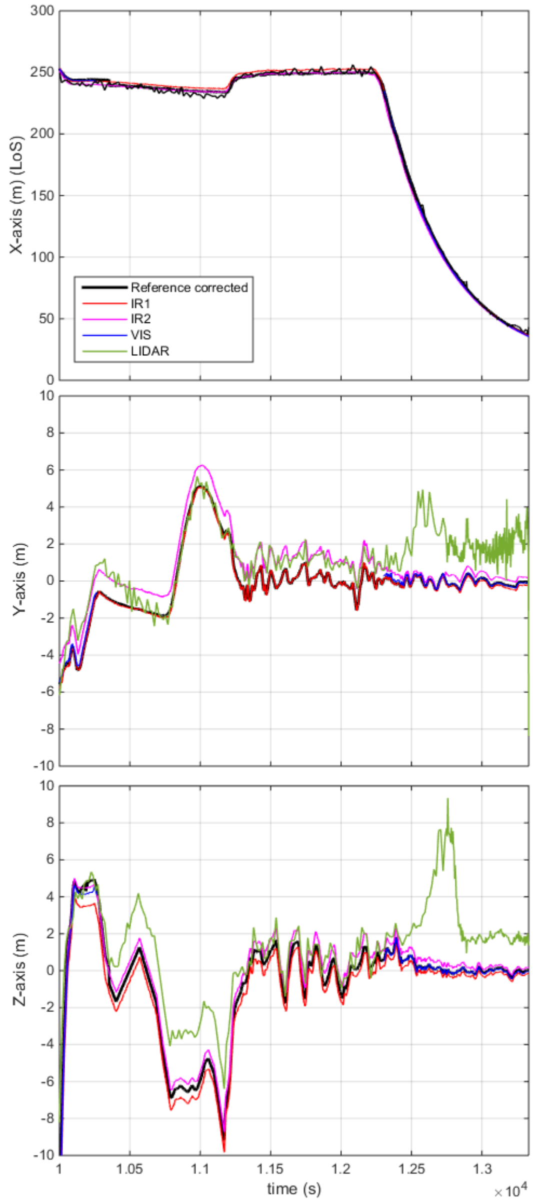


Figure 4. Camera and LIDAR Position estimation for middle-range rendezvous

3.3 Close range Pose-Estimation

Down to a distance of 30m, the ISS images are more detailed and the model-based tracking is much robust in that conditions. At the end, we can notice that some difference persists when we compare the sensors pose estimations. The extrinsic calibration of sensors can be one on the cause but not only because we notice differences in sensor quality when we compare infrared and visible cameras on many properties (resolution, sensor size, variation of PSF…). Other causes are possible to explain differences like the influence of the pairing of position and attitude or the existence of a local minimum in the MBT treatment.

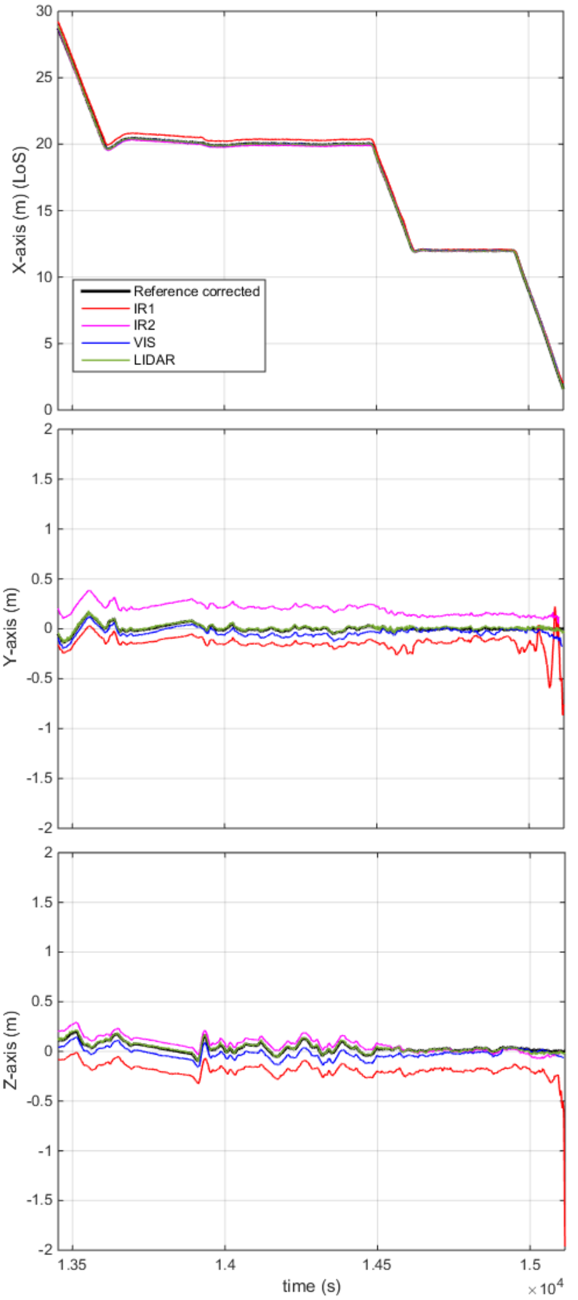


Figure 5. Camera and LIDAR Position estimation for close-range rendezvous

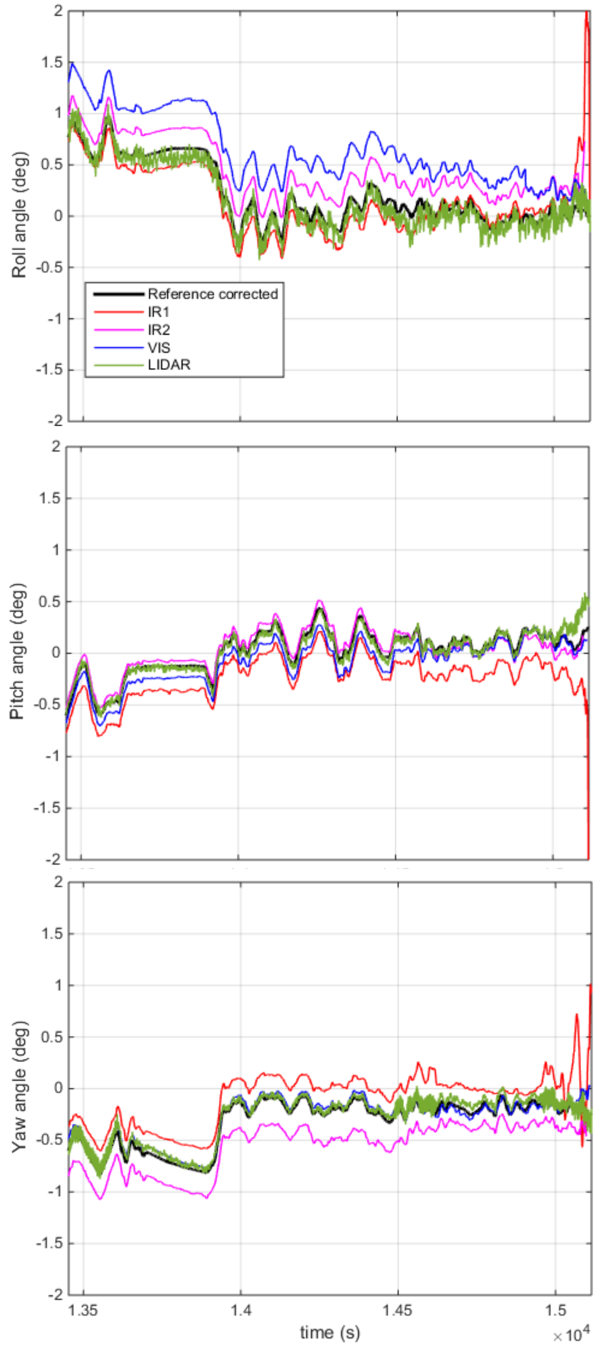


Figure 6. Camera and LIDAR attitude estimation for close-range rendezvous. Angles are represented in Euler convention.

The following sequence shows the matching between the LIDAR-scan points and the target model. The false color representation of the scan points indicates distances between the model and the scan points. The yellow points represent the points with largest distances mostly showing not modelled parts of the ISS. The relative distances for the different figures range from 27m, 10m, 5m down to 0m (docking).

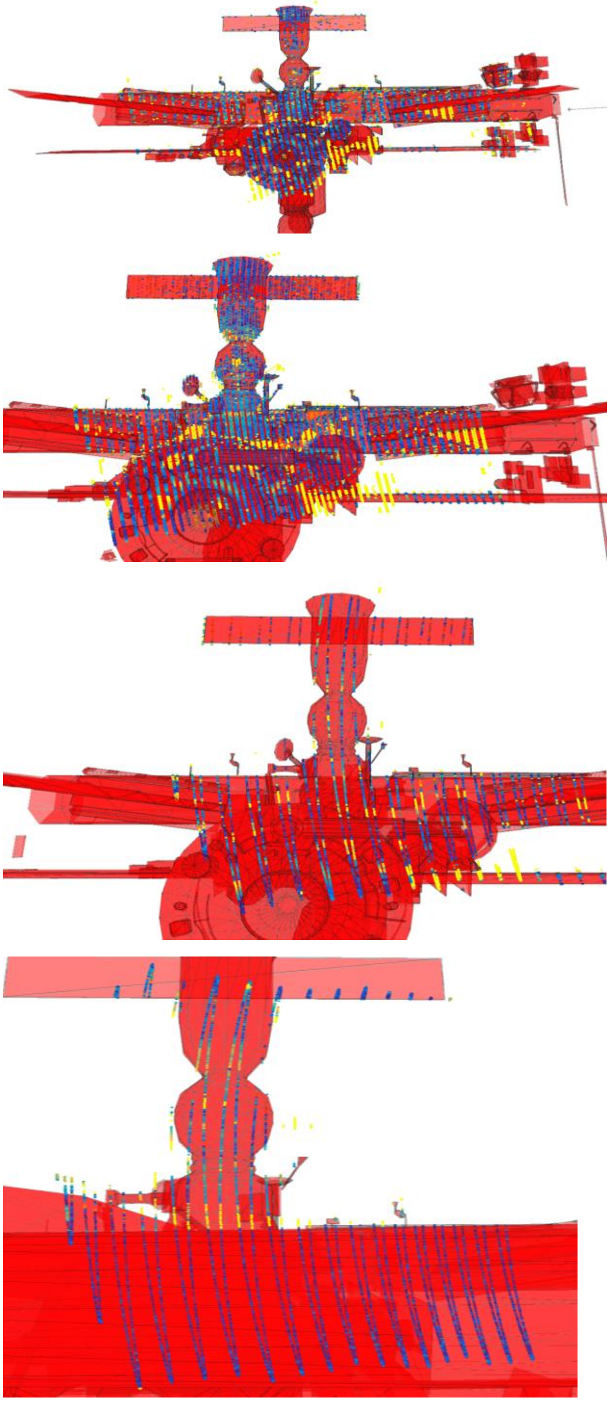


Figure 7. Overlays of scan and model for several ranges

3.3.1 CPU Load of 3D-LIDAR-Based Pose-Estimation

Beside the camera-based pose-estimation, the LIDAR-based pose-estimation is computationally expensive - at least for a typical on-board computer for space-crafts. In order to test the feasibility of the algorithm on recently developed on-board computers, the LIDAR-based pose-estimation has been implemented on a state-of-the art LEON4 processor which has 4 cores. For the tests, an evaluation board by Gaisler Aeroflex has been used. The algorithm has been implemented for one single core of the LEON4. For the test purposes, the model of the target has been compiled into the software and also a typical point cloud from the LIRIS data set has been compiled into the source-code, i.e. no real interfacing e.g. via a space-wire interface has been done yet.

Based on this setup, the LIDAR-based pose-estimation could be run at a frame rate of approximately 3 Hz. This is in good accordance to the maximum scan frequency of the LIDAR itself which provides reasonable spatial resolution distributed over a field of view of 40°x40° also at approximately 3 Hz. Although these tests are not finished yet and real interfaces are still missing, the results are very promising and indicate that such kind of algorithm might be hosted on a single core of a LEON4 processor.

CONCLUSION

The LIRIS Demonstrator was a successful study for non-cooperative rendezvous in space. It enabled to acquire many data with LIDAR and cameras, and thus to confront IP algorithms to real space conditions. It enabled also to assess IP robustness and performances, even if this assessment has been a bit tricky, due to the too low accuracy of reference trajectory, especially at very close distance. To cope with this, the reference has been corrected by using LIDAR data, but calibration residuals are probably still present and perturb analysis of image processing results. Quantitative performance assessment of IP solutions has thus to be taken carefully.

For far and middle range rendezvous, the position and attitude estimation from camera tracking are correct, the LIDAR algorithms have lower performance for position estimation, mainly due to the few number of available scans. For close range rendezvous, the accuracy of pose estimation of all sensors increases. Many details can be resolved on sensors and the LIDAR scan mode was optimized to upgrade the resolution. Infrared cameras provide less accurate pose estimation than LiDAR and VIS, probably due to their lower resolution, blur in image at close distance and extrinsic calibration errors.

LIRIS experiments have provided a unique set of data to increase validation and maturation of camera and LiDAR based navigation solutions. It makes us confident in their ability to be used as rendezvous sensors for future rendezvous missions, with uncollaborative or collaborative targets. LIRIS has also provided a useful feedback for future missions and experiments which should pay a special attention on sensor calibration and target 3D model reliability. Finally, LIRIS should be considered as a first step in rendezvous in-orbit demonstration, and more in-orbit experiments still need to be performed to complete present study and to improve visions based navigation performance assessment.

REFERENCES

1. G. Casonato, G. B. Palmerini. Visual Techniques Applied to the ATV/ISS Rendezvous Monitoring. In Proc. Of Aerospace Conference, 2004. Vol. 1, Big Sky, USA, April 2004.
2. Y. Roux, P. Da Cunha. The GNC Measurement System for the Automated Transfer Vehicle. In Proc. of the ISSFD conference, 2004.
3. X. A. Yol, E. Marchand, F. Chaumette, K. Kanani, T. Chabot. Vision-based navigation in low earth orbit. Int. Symp. on Artificial Intelligence, Robotics and Automation in Space, i-SAIRAS'16, Beijing, China, Jun 2016.
4. E. Marchand, H. Uchiyama, F. Spindler. Pose estimation for augmented reality: a hands-on survey. *IEEE T-VCG*, 2016.
5. F. M. Kolb, M. Windmüller et al., The LIRIS-2 3D-Imaging LIDAR on ATV-5, In Proc. Of the 39 Annual AAS Guidance, Navigation and Control Conference, pp. 1023-1028, Breckenridge Colorado, USA, Feb. 5-10, 2016.
6. B. Mädiger, J. Sommer, I. Ahrns. RTES: Robotic Technologies for Space-Debris Removal. In Proc. Of i-SAIRAS 2014, Montreal, 2014.
7. Besl, P. and McKay, N. A Method for Registration of 3-D Shapes. Trans. PAMI, Vol. 14, No. 2, 1992.