1 ABSTRACT
This paper presents several on-going and recent activities within the European Space Agency (ESA) in the area of Vision-Based Navigation, using mainly cameras in the visible range, Infrared (IR) cameras and LIDARs. They aim at a variety of mission scenarios, comprising Active Debris Removal (ADR), Planetary Approach, Small Body Navigation, Rendezvous and Entry-Descent and Landing (EDL) in Low and High Dynamics.

Keywords: Vision-based navigation, model-based tracking, feature tracking, navigation camera systems, on-ground testing

2 INTRODUCTION
The current paper addresses the following projects in the context of the activities developed by European Space Agency (ESA) in the area of vision-based navigation:
- Image recognition and Processing for Navigation (IRPN) using cameras in the visible and the IR range alongside with LIDARs
- Navigation on a Chip, where a multi-mission flexible and reconfigurable Navigation Camera System (NCS) is designed and tested using a simplified breadboard set-up.
- Multispectral Camera for relative navigation, where a variety of algorithms are assessed in order to exploit the advantages of the information provided with a single camera (also designed within the project) in the different ranges of the visible spectrum, near UltraViolet (UV), Near-IR and thermal-IR.

3 IMAGE RECOGNITION AND PROCESSING FOR NAVIGATION (IRPN)

3.1 Objectives
The IRPN project aimed at the development and testing of a distributed vision-based navigation system for relative navigation between spacecrafts by means of different sensors like cameras in the visible or infrared spectrum, or scanning LIDARs. The chaser spacecraft carries the navigation sensors and approaches the target object down to few meters. The target object is the passive satellite ENVISAT which may be out of control, performing tumbling motions and which is uncooperative in the sense that it is not controlled and is not prepared for any kind of rendezvous techniques. The relative navigation w.r.t. the uncooperative target is not known a priori and there are no dedicated artificial fiducial visual markers for navigation purposes attached to ENVISAT that can be exploited by the navigation methods.

The IRPN system shall determine the relative position, attitude, velocities and angular rates of the target w.r.t. the chaser. The direct measurement of these properties is not possible. Instead, the chaser has to observe the target and estimate the kinematic states. In the context of the project different sensors are used for the rendezvous navigation, namely visual (VIS) cameras, thermal infrared (TIR) cameras and LIDAR. For the observation of the target the sensor data needs to be processed, the target’s pose is estimated and the target is tracked to predict its motion.

All IRP algorithms and the overall IRPN system have been tested extensively in different test environments: model-in-the-loop (MIL) and processor-in-the-loop (PIL) with synthetic (rendered) images. VIS and IR algorithms have been tested with real images with hardware-in-the-loop (HIL) using several mock-ups.
3.2 Mission definition and Reference scenarios

As depicted in Figure 2 the approach trajectory is defined by several holdpoints at distances of 100m, 50m and 2m (including a further holdpoint at 11m) in a direct approach (forced translation) towards the Centre of Mass (COM) of the target (Envisat).

In order to evaluate different illumination conditions and the robustness of the algorithms in the transitions from eclipse to Sun-light and vice versa, 8 sets of trajectories were initially considered with 60 Monte-Carlo runs each. They were executed with 7 sets with starting points distributed around the earth orbit (considering the orbit as it was in August 2014 with Mean Local Solar Time (MLST at ascending node) 10 PM), and one set starting in the expected orbit position in May 2020 with MLST at ascending node 6 PM (see Figure 3).

3.3 Camera Image Processing algorithms

The VIS Image Processing (IP) and the IR IRP algorithms use image data from visual (VIS) and infrared, or thermal infrared, (IR/TIR) cameras, respectively in order to estimate the target’s pose and to track it.

On the one hand, the pose is determined from the image data using the a priori known 3D model of the target. On the other hand, algorithms based on image keypoints allow the tracking of characteristic features on the target to improve the pose estimate when using an additional estimation filter.

Using a stereo camera setup enables searching for matches in the two stereo images to allow a triangulation and depth estimation for the corresponding object marks.

To allow the Navigation Function to estimate the target’s position, attitude, velocity and angular rate the Camera IRP determines the relative target pose w.r.t. the chaser. In addition to the image data, Optical Flow data can be used to predict the attitude of the pose of the target based on the in-image rotation and the recent pose estimate of the IRP algorithm. If estimates from the Navigation Function are available, this prediction is not necessary.

The pose estimation data comprises the 3D position of the target frame w.r.t. the chaser frame, the attitude of
the target w.r.t. the chaser frame using a quaternion and the uncertainty of this estimate using a covariance matrix.

The Camera IRP pose estimation comprises two steps, pose initialization and pose tracking. When no pose estimate from the Navigation Function is available, the pose tracking can only be started after the pose initialization has determined some first pose estimate.

### 3.3.1 Keypoint Tracking Algorithms

Distinctive keypoints in the image data are detected and tracked in an image series using the SURF algorithm ([RD02], [RD03] and [RD04]) to allow improving the motion estimate in a navigation filter. In addition to the image data Optical Flow data can be provided. It is used to avoid false keypoint matches in the tracking process. If estimates from the Navigation Function and from the Camera IRP pose estimation about the relative target pose (target body frame) w.r.t. the chaser (chaser body frame) are available, they are used to minimize the size of the image data to be processed and to predict the position of tracked keypoints.

The data of tracked keypoints comprises their image coordinates, image detection uncertainties, a unique ID for each keypoint, the 3D position w.r.t. the chaser frame and the uncertainty of this position. Furthermore, if keypoints are removed from the internal databases (if these keypoints have shown low quality), the IDs of the removed keypoints are given.

For keypoint tracking several strategies are pursued using the parallel tracking of different keypoint types. In the current implementation, SURF keypoints as well as line intersection points are detected in the image data. This enables not only to detect more keypoints in the image data, but to track keypoints that are suited to special conditions (relative motion of the target, size of structures of the target in the image, illumination of the target surface, background). The results of all tracking modules are fused in a final merging step.

### 3.3.2 Pose Initialization Algorithms

The pose initialization is comprised of several submodules which are executed consecutively. The pose initialization has the highest processing costs of all Camera IRP algorithms and is hence in the current implementation called at a maximal frequency of only 2 Hz.

The image data of both images of the stereo camera system is used to carry out a dense stereo reconstruction to estimate the distance to the target, implementing concepts from [RD05], [RD06] and [RD07]. The resulting Disparity Image is used to generate a set of hypotheses about the relative pose of the target w.r.t. the chaser body frame.

For all hypotheses the target CAD model is projected into the image to generate some search points which are used to search for edges in the image that correspond to lines on the target model. The distances between them are minimized to fit the target model to the current image data and on the basis of that to rate the quality of the corresponding hypothesis.

Finally, the rated hypotheses are registered in a simple pose initialization filter that manages the hypotheses of several time steps and determines the most probable target pose for the current time step to select the best hypothesis from the current set of pose hypotheses.

![Figure 5 Examples of Disparity Images generated using dense stereo reconstruction in realistic situations. (Upper row: Disparity Images, Lower row: corresponding image data)](image)

### 3.3.3 Pose Tracking Algorithms

The pose tracking is comprised of several submodules which are executed either consecutively or in parallel. Although the pose tracking is in general also possible if only the image data of one camera is processed, it has been shown that the processing of the image data of both cameras of the stereo camera system and the merging of both estimates result in more stable pose estimates, especially when the target is tumbling.

The pose tracking algorithms try to fit a CAD model of the target satellite to the image data. If no initial pose estimate is available or valid respectively, the pose tracking is not carried out. If one or more pose estimates are available (from Navigation Function, from pose initialization or from recent pose tracking) the best initial pose has to be chosen and (if from recent time steps) predicted for the current time step.

For the chosen pose estimate the target CAD model is projected to the image plane and search points are generated. Using these points, edges in the image data are detected that correspond to the lines of the target model. The distances between the edges and the lines are minimized to fit the target CAD model to the image data and hence the current target pose is determined.

The actual pose estimation process is carried out for each camera separately and therefore the two images are processed in parallel threads. At the end the respective pose estimates are merged to get a final pose estimate which is provided to the Navigation Function and to the keypoint tracking algorithms. However, it is possible to deactivate one of the tracking threads to only process one camera image.
The pose tracking algorithm is in general faster than all other Camera IRP algorithms. Assuming parallel threads for the processing of the two camera images the requirement for a frame rate of 10 Hz is easily reachable (at least on a powerful PC in the MIL set-up). The calculation time is almost independent of the size of the image. However, the calculation time rises if a higher number of edges is processed or if longer edges (or lines respectively) are visible on the target.

Figure 6 Examples of search lines for different distances to the target. (The length of search lines increases when the target gets closer)

3.4 LIDAR IRP Algorithms

The design of the LIDAR-based pose estimation consists of an architecture that uses a smart scanning LIDAR that will be able to control its field of view and its laser power level in order to achieve an optimal distribution of raw scan points over the surface of the target spacecraft ([RD08], [RD09] and [RD10]). The acquired scan points are then processed in order to estimate the relative position and attitude of the target spacecraft w.r.t. the LIDAR sensor.

For this purpose, three main steps are necessary: The field of view control, the pose-initialization and the pose-tracking.

After testing the LIDAR-based pose estimation in the IRPN project the most important observations were:

1. The role of the field of view control was more important than expected. A smart field of view control which really tries to distribute an optimal number of scan points on the target's surface provides much better results than simply approximating the field of view by a surrounding sphere.
2. Several sources of biases were identified. The bias of the LIDAR measurements and the differences between the assumed knowledge of the target geometry and the real target geometry lead to the main biases.
3. The viewing direction of the LIDAR towards the target geometry is very important and has a direct impact on the quality of the pose estimation results. It is clearly recommended to define the approach trajectory (including the consequences for the viewing directions) such that sufficient geometrical structures are visible in the field of view. If only planar or similar structures are visible in the field of view, not able to determine all requested degrees of freedom, a reduced pose estimation accuracy will be the result.

3.4.1 Field-of-View Control

The scanning LIDA by Jena-Optronik has a minimum field of view (FOV) of 1° x 1° up to a maximum of approximately 40° x 40°. The amplitudes of the scan pattern can be directly commanded and have a direct impact on the spatial distribution of the laser beams on the surface of the target object. This has direct influence on the data density and finally also on the pose estimation performance. The goal of the field of view control is an optimal setting of the viewing frustum such that the target is optimally covered.

For this purpose, two different methods are possible:

- The Distance-Driven FOV Control: As long as no sophisticated pose estimation result is available, only simple data processing can be used to control the FOV position and size. A candidate for such simple information is the position of the centroid which could have been determined already inside the LIDAR device with its own internal software. Using now the knowledge about the target dimensions in combination with the estimated centroid position allows one to place a sphere around the centroid of maximum target size. Then it can be assumed that the target object is inside the sphere. From these geometrical considerations the field of view can be defined as a function of distance to the centroid.

This approach was used in the IRPN project since the image generation was done offline before processing the LIDAR data.

- Scan-Driven FOV Control: The second method is driven by the full set of scan data and not only on an already condensed vector like the centroid. Here, the scan data can be analyzed (e.g. by looking at the minimum and maximum azimuth and elevation angles) in order to determine a minimum frustum around the point cloud. Then a better distribution on the 3D points can be ensured.

It is expected that this method would yield by far the better results.

Figure 7 Principle of automatic FOV control. Left: as a function of distance between sensor and centroid of 3D point cloud, right: as a function of the scan data

3.4.2 Pose initialization and Pose Tracking

The 3D LIDAR provides 3D point clouds which are independent from illumination conditions. The missing scale invariance of 2D template matching can be
compensated by using the knowledge about the range values measured by the 3D LIDAR. In case of complete view of the target object, even the full 3D position of the object can be defined by the position of the centroid of the 3D point cloud (at least for a specific attitude). Thus, only 3 degrees of freedom (i.e. the three angles of the attitude) are subject to a search in a multi-dimensional search space. This idea is behind the Template-Matching method.

The search for the remaining three rotational degrees of freedom can be solved by storing many different reference views in a database of small reference templates.

The initial search of the target attitude and position can then be performed by comparing all reference views of the model database with the small template generated from the most recent 3D LIDAR point cloud.

Figure 8 Generation of a small template from sinusoidal scan pattern provided by the 3D LIDAR and principle of comparison between generated template from the LIDAR scan and the previously generated templates of the model database

Once the initial pose has been determined by the pose-initialization step discussed before, the current scan data have to be matched to the geometry of the client object in order to update and refine the pose data. This algorithm applies the principle of the iterative closest point algorithm (ICP) from [RD11].

Figure 9 Matching of simulated scan data (blue points) with the planar patches of the satellite model (red surfaces)

3.5 Navigation Function

The Navigation Function (NAV) incorporates fusion and filtering of different local sensor level estimates (measurements). To allow the Navigation Function to estimate the target’s position, attitude, velocity and angular rate the Camera IRP determines the relative target pose w.r.t. the chaser and thus constitutes the last processing step of the IRPN processing chain. In addition to the image data, Optical Flow data can be used to predict the attitude of the pose of the target based on the in-image rotation and the recent pose estimate of the IRP algorithm. If estimates from the Navigation Function are available, this prediction is not necessary.

The pose estimation data comprises the 3D position of the target frame w.r.t. the chaser frame, the attitude of the target w.r.t. the chaser frame using a quaternion and the uncertainty of this estimate using a covariance matrix (see [RD12]). Furthermore, a coarse position estimation based on the mean of the dense stereo reconstruction is given. An additional output port makes it possible to provide the keypoint tracking of the following time step with a pose estimate even when the current time step’s image data does not allow determining a pose.

The Camera IRP pose estimation is divided into two parts, the pose initialization and the pose tracking. If no pose estimate from the Navigation Function is available, the pose tracking can only be started after the pose initialization has determined some first pose estimate.

The NAV module is divided in four main parts:

- NavControl
- Initialization
- Estimation
- Post-processing

Figure 10 Kinematic relations and NAV state vector elements
3.6 Model-In-the-Loop (MIL) tests and results

A MATLAB Simulink model has been developed in order to validate the IRPN algorithms using synthetically generated with the ASTOS camera simulator ([RD01]). The MIL contains the IRP algorithms and the Navigation Function as well as the different function blocks for reading the image and LIDAR data from hard disk, saving the test results to files, displaying the experiment data and controlling the experiment runs in an open-loop configuration.

3.7 Processor-In-the-Loop (PIL) tests and results

In the PIL facility not only the automatic code generation and compilation for an external hardware target was tested, but also the actual parallelization and the real time capability of the different elements of the IRPN system.

The same input data as in the MIL tests has been processed during the PIL tests. Hence, the same trajectories and the same image and LIDAR data was used. The PIL facility had to use this data, apply the IRPN algorithms in real time and store the calculation results afterwards for result analysis. All tests were performed on the Extended dSPACE System (see Figure 11).

Results of the MIL and PIL facilities are very similar (except for numerical errors). Examples are shown in Figure 12 and Figure 13 were the Visible and IR camera inputs are combined with the LIDAR measurements in order to obtain a more accurate solution.

3.8 Hardware-In-the-Loop (HIL) tests and results

In the HIL tests, real image sensors (VIS cameras + TIR cameras, no LIDAR) were used to generate real image data to test the IRP algorithms. The cameras were attached to the Spacecraft Rendezvous Simulator MiPOS (“Mini Proximity Operation Simulator”) of the Institute of Automation at Technische Universität Dresden (TUD) in order to simulate the approach of a chaser spacecraft to a target satellite (more details on the set-up are available in [RD14]). Two mock-ups of Envisat were used (at scale 1:25 and 1:5) for the different phases of the trajectory approach. During this image acquisition phase, the image data was saved to hard disk and only processed offline afterwards.

Results of the MIL and PIL facilities are very similar (except for numerical errors). Examples are shown in Figure 12 and Figure 13 were the Visible and IR camera inputs are combined with the LIDAR measurements in order to obtain a more accurate solution.

Figure 11 Components of Extended PIL dSPACE System

Figure 12 Mean relative position error over all runs of scenario OCM_111 for VIS (x, y and z coordinate of target body frame w.r.t. chaser body frame; in m) and standard deviation (3-sigma-sleeve)

Figure 13 Mean relative position error over all runs of scenario OCM_014 for ALL IRPs with the Navigation solution (x, y and z coordinate of target body frame w.r.t. chaser body frame; in m) and standard deviation (3-sigma-sleeve)

Figure 14 The scale 1:25 mock-up seen with the VIS cameras (left) and the IR cameras (right) during an HIL experiment. The background had been cooled with water.
Initial problems were identified in the VIS image data for the IRP algorithms stemming from the narrow field of view of the VIS camera/lens resulting in seeing only a very small section of the ENVISAT satellite. Furthermore, the borders of the radiators sometimes were faded in a way that it was not possible to recognize the edges of the radiators. When this was corrected by taking a larger Field of View typical results were the ones shown in Figure 15.

Figure 15 Relative position error of run OCM_111_002 for VIS – close-range with new image data (x, y and z coordinate of target body frame w.r.t. chaser body frame; in m) and standard deviation (3-sigma-sleeve)

[RD14] also provides an extensive account of the difficulties of on-ground testing of Thermal Infrared cameras for use in space where scaling factors affecting also the thermal conductivities and emissivities, continuity of measurements (geometrical and thermal) between consecutive arcs and similar problems are relevant.

3.9 Conclusions and recommendations

The IRPN project was based on the idea to use a distributed vision based navigation system to allow a rendezvous approach of spacecraft ([RD13]). It has shown in different tests that a set of complementary sensors allows very well to estimate the relative pose with high quality. A LIDAR sensor allows a fast and accurate initialization and has a high accuracy for the distance estimation. Cameras (VIS / IR) allow for a good lateral estimation of the target object. However, the LIDAR is mainly suited for far-range and mid-range when the target object is completely covered by the adaptive LIDAR FOV. In the very close-range problems can appear if non-well-structured parts are in the FOV (i.e. only a planar surface). Camera sensors have a fixed resolution and therefore are only recommended if the target object is completely in the FOV. Hence, cameras are not well suited for far-range distances but still work well in close-range. In the mid-range camera sensors can improve the pose estimation, but it will be necessary to initialize the pose externally by other sensors (i.e. LIDAR).

The synthetic image data simulation was relying on the conventional computer graphics image generation pipeline with additional post-processing in order to take into account the different temperature along the orbit of the components on the surface. A complete model taking into account the underlying thermal process would be a more straightforward approach.

When comparing the results of the HIL facility with the ones obtained in the MIL/PIL it was also clear that small details (even at pixel level) have an impact when those images are fed into Image Processing algorithms. Thus the realism of the synthetically generated images from that point of view is a key factor to take into account when assessing to which extend the simulations performed are representative of (and thus useful for) real situations.

4 NAVIGATION ON A CHIP

4.1 Objectives

Based on the enormous amount of progress made in the areas of Star Trackers, Active Pixel Sensors, FPGAs and System on Chip design over the last ten years, ESA considered that these technologies were mature enough to be leveraged to produce a low cost, re-usable Navigation Camera system (NCS) that could be easily re-configurable from one mission scenario to another, with scenarios comprising Planetary Approach, Small Body Navigation, Rendezvous and Entry-Descent and Landing (EDL) in Low and High Dynamics. The objective of the Navigation on a Chip project ([RD18]) was to develop an efficient, compact and flexible hardware, firmware and software design for a future navigation camera system such that a single re-configurable hardware item can be used to meet the demands of the majority of the future optical navigation camera needs. This had to be done maximizing the synergy with Star Tracker developments in order to maintain low cost and a long-lasting product availability.

A trade-off has been performed between the two new image sensors under development in parallel by ESA (HAS3 and Faint Star, both intended to work in the visible range). HAS3 targeted high performance, low noise and snapshot shutter operation, while Faint Star implements logic on-chip for image (rolling shutter) sequencing, readout, background removal and some functions dedicated to Star Trackers.

The activity prepared an architecture for a versatile multi-mission navigation camera suitin most of the needs with high level of integration, including a preliminary design and the implementation and testing of the potentially most critical aspects on a breadboard.
The needs in terms of configurability, HW/SW architecture (FPGA, CPU, memories, buses) were also identified. The designed Navigation Camera provides a versatile system that can be used in a variety of scenarios and phases within a mission, taking advantage of the synergies with previous developments in ESA.

### 4.2 Optical Requirements and trade-off

The analysis performed in the mission scenarios that are expected to be covered by the Navigation Camera System was based on the experience with previous representative missions of each them ([RD15], [RD16] and [RD17]). Results are summarized in Table 1 and Table 2, shown graphically in Figure 16, where three distinct optic design areas can be clearly identified covering groups of mission scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Overview A</th>
<th>Overview B</th>
<th>Overview C</th>
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<td>Small Body Navigation</td>
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<td>Planetary Approach</td>
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Figure 16 Visualization of requested optics parameter for the different applications (Mars Sample Return (MSR), Planetary approach, Descent and Landing (D&L) in Low and High Dynamics and Rendezvous (Rnd)).

### 4.3 Optical Design

The design of optics A is based on a Schmidt-Cassegrain variant. The optical design falls into three elements plus detector. The front lens is used twice, i.e. it is refractive at the outer part and reflective at the inner part, the second lens is simultaneously the first mirror (Mangin mirror) and the third lens is used as field lens. All surfaces are spherical except the front side of the first lens which is aspherical. All lenses are made of the same material: quartz glass.

Design of optics A is complemented with the baffle in Figure 18.
The design of optics B is based on an Aenar achromat derivative and is similar to the APS star tracker optics. The optical design falls into four lenses plus detector. Front side of first as well as last lens is aspherical. All lenses are made of the radiation hard material: BK7G18 and SF6G05. The stop position is in front of the first lens, thus it can be easily accessed for replacement of different diaphragms of fixed diameter on ground.

4.4 Preliminary Design and Interface
Definition of the Electronic Box

The following components were considered for the Digital Processing Unit (DPU):

- FPGA (Microsemi RTG4 or Xilinx Virtex5, where a trade-off was performed in terms of reconfigurability, radiation hardness, SEL immunity, memory resource, etc), Clock Chip (96 MHz) – (FPGA footprint differs)
- Reset/Supervisory/Watchdog circuitry
- SRAM (up to 60MBit for image correction coefficients)
- 2x SRAM (up to 40MBit for image buffer); SDRAM (up to 2.5GBit); EEPROM (up to 64GBit)
- Memory Bus Driver (as an option), 5x independent Memory Controllers
- Core power supply for FPGA generated on DPU; power monitoring circuitry
- SpaceWire Transceiver for Heads; two channels per head for high bandwidth
- SpaceWire Interface to S/C, Test; JTAG-IF allowing access to FPGA and LEON3 DSU
- SDRAM and EEPROM used exclusively by LEON3 Soft-Processor
- Single high density MHD-052 board-to-board connector to connect IFU PCB
• Single connector solution (MDM) for optical heads including Power, Reset and TEC signals

4.5 Navigation Camera Design in comparison to Star tracker Design

The star tracker application (for which sensors and techniques are considered in this Navigation Camera System) can be a subset of the navigation camera algorithms. The electronics design of the navigation camera includes much more memory environment and processing capability than a standard star tracker. The star tracker software algorithms can be held in the code RAM area. An FPGA hardware reconfiguration of the preprocessing architecture is not necessary. The convolution operators and kernels can be arranged in the processing sequence from frame to frame by the multiplexer field.

The star catalogue for the optics B with 25deg FoV will have a size of <100kByte. Due to the smaller FoV of optics design option A the star catalogue will claim < 3Mbyte. This can be well implemented in the memory environment of the navigation camera system. For functional reason the star tracker application shall be already loaded in the code RAM area to be enabled quickly from frame to frame. This makes particularly sense when observing a bright resolved object with stars around. In order to image the bright object surface within the dynamics range of the ADC we need to select a very short exposure time. This does not allow to see a sufficient number of stars. Just before and/or after this short exposure frame for bright object processing we can set star tracker-like exposure cycles (e.g. 100ms).

With this measure the bright object photometry can be directly linked to the inertial frame despite the very high dynamics in the scenery. The same procedure is applicable when searching very faint objects (comet, sample container, etc.). Here the exposure time might be too high for a star tracking cycle. The science frame with long exposure time can be surrounded by standard star tracker frames for the inertial frame transformation of the science data.

4.6 Breadboard Design and Testing

For the actual Breadboard design conventional optics (with representative optical properties, i.e. focal length, etc) were used alongside the development kit for the HAS-3 sensor.

A preliminary implementation of the image processing algorithms was tested in order to show the effectiveness of the set-up for the planetary approach scenario (considered as part of the night sky test in Figure 24) and small-body body navigation (Figure 25 and Figure 26) using synthetic images produce by PANGU (Planetary and Asteroid Natural Scene Generation Utility, [RD19], [RD20] and [RD21] with videos showing the capabilities of the tool).
5 MULTISPECTRAL CAMERA FOR RELATIVE NAVIGATION

5.1 Objectives

Two parallel activities have been set up with the following objectives:

- To make an assessment in a bottom-up approach, of the potential use of the combination of visible, IR, and UV wavelengths for navigation sensing, identifying the most promising technologies and analyzing their impact at system level.
- To review existing space-qualified detectors technology which could be used for such purpose and their response in the identified spectral bands.
- To provide an architecture and a preliminary design of a Multispectral Sensing Device (MSD)

5.2 Background

The emergence of new applications, such as debris removal, assembly in orbit, asteroid exploration and exploitation, in-orbit servicing, and planetary flybys open a new window for the investigation of the use of spectral bands on each side of the visible spectrum for navigation purpose. An IR camera is for example considered as a promising candidate navigation sensor for future de-orbiting missions; such a sensor was flown as experiment on the ATV-5.

The advantage of multispectral and hyperspectral imaging over conventional single wavelengths imaging is that the spatial relationships among the different wavelengths sensed in a neighbourhood of the centroid of a target allow very accurate classification of the features of the image. Another advantage is that hyperspectral imaging is very robust to single wavelength shadowing and information gaps during the establishment of a navigation solution. The disadvantages are high cost and complexity.

Multispectral and hyperspectral scanning use the principle of obtaining information from a large portion of the spectrum that any given object provides as unique spectral signature. Astronomical payloads use multispectral and hyperspectral imaging to determine a spatially-resolved spectral image. Having a spectrum for each pixel scanned allows more data to be obtained. Multispectral and hyperspectral sensors collect information as a set of images where each image represents a range of the electromagnetic spectrum. These images are then combined and form a hyperspectral data set for processing and analysis. Hyperspectral imaging uses narrow spectral bands over a continuous spectral range to produce the spectra of all pixels in the scene. Multispectral and hyperspectral imaging that includes infrared bands may need cooling technologies and hence are complex and expensive.

5.3 Motivation and Mission Scenarios

Multi-spectral imaging can lead to significant improvements of space navigation systems. During the activities of this project a navigation solution has been assessed that combines multiple Visible and Near IR (VNIR) spectral channels and a Thermal Infrared (TIR) spectral channel. This leads to a more robust navigation solution compared to conventional systems detecting only in the visible range:

- Navigation can be performed also if the Sun is in eclipse by detecting the thermal radiation.
- Specific wavelengths dependent features can be identified by a finer sampling of the VNIR spectrum.

Possible applications of such a multi-multi-spectral device (MSD) are:

- Non-cooperative rendezvous (debris detection and removal scenario)
- Cooperative rendezvous: relative navigation between two cooperating space vehicles (docking to the ISS scenario)
- Descent and landing on an asteroid
- Planetary fly-by
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