Vision-based navigation experiment onboard the removedebris mission

Thomas Chabot, Keyvan Kanani, Alexandre Pollini, François Chaumette, Eric Marchand, Jason Forshaw

VISION-BASED NAVIGATION EXPERIMENT ONBOARD THE REMOVEDEBRIS MISSION

Thomas Chabot [(1)], Keyvan Kanani [(2)], Alexandre Pollini [(3)], François Chaumette [(4)], Eric Marchand [(5)], Jason Forshaw [(6)]

(1) Airbus Defence and Space, 31 rue des Cosmonautes 31402 Toulouse Cedex France, +33 5 6219 98 09, thomas.t.chabot@airbus.com
(2) Airbus Defence and Space, 31 rue des Cosmonautes 31402 Toulouse Cedex France, +33 5 6219 91 51, keyvan.kanani@airbus.com
(3) CSEM, Rue de l'Observatoire 58 2000 Neuchâtel Switzerland, +41 32 720 5965, alexandre.pollini@csem.ch
(4) INRIA Rennes Bretagne Atlantique, 263 Avenue du Général Leclerc 35700 Rennes France, +33 2 99 84 72 55, francois.chaumette@inria.fr
(5) Université de Rennes 1, IRISA, 263 Avenue du Général Leclerc 35700 Rennes France, +33 2 99 84 75 10, eric.marchand@irisa.fr
(6) Surrey Space Centre, University of Surrey Guildford GU2 7XH United Kingdom, +44 (0)1483 68 6307, j.forshaw@surrey.ac.uk

ABSTRACT

Airbus has been strongly involved in the design of Vision-Based Navigation (VBN) systems over the last years, with particular focus on applications such as planetary landing and orbital rendezvous. Based on this background and due to the increasing interest in Active Debris Removal (ADR), solutions for autonomous, vision-based navigation for non-cooperative rendezvous have been investigated. Dedicated image processing and navigation algorithms have been designed at Airbus and INRIA to meet this specific case, and some of them have already been tested over synthetic images and actual pictures of various spacecraft.

As the next step, a VBN experiment will be conducted onboard the upcoming RemoveDebris ADR demonstration mission. The RemoveDEBRIS mission, sponsored by the European Commission FP7 programme, started in 2013 and will launch to the International Space Station late 2017 from where it will be deployed to a 400km orbit. In addition to the VBN experiment, the mission will perform other ADR experiments such as net and harpoon capture and dragsail de-orbiting.

The VBN experiment will validate vision-based navigation equipment and algorithms, through ground-based processing of actual images acquired in flight of a debris mock-up target, in conditions fully representative of ADR. It will demonstrate state-of-the-art image processing and navigation algorithms based on actual flight data, acquired through three different but complementary sensors: two standard cameras, and a flash imaging LiDAR developed by CSEM, and validate a flash imaging LiDAR in flight.

1 Introduction

Orbital rendezvous in low Earth orbit has been mastered since the sixties, firstly initiated onboard US Gemini and Russian Soyuz spaceships, performed either manually or in an automated way. Orbital rendezvous subsequently became an essential technique in order to successfully assemble and service Earth-orbiting space stations and satellites, or perform lunar exploration. In the past few years, new mission concepts, and in particular Active Debris Removal (ADR), have led to the occurrence of new challenges regarding orbital rendezvous in general and relative navigation in particular.

For most rendezvous missions including ADR, navigation must be able to provide relative state estimates over a wide range of relative distances, from early detection until target capture. Depending on the specific rendezvous phase, these state estimates can be relative position and velocity only (3-DoF relative navigation), or relative position, velocity and attitude (6-DoF relative navigation). In the frame of ADR missions, the navigation function must also be robust to uncertainties regarding the target debris trajectory, its shape, rotation state, inertia characteristics, etc. The navigation function must be compatible with uncooperative targets, possibly tumbling and bearing no navigation aid whatsoever. Depending on the capture means, debris capture may require accurate relative attitude estimation. Finally, navigation must also fulfill new functions such as target identification, which consists of evaluating the target rotation state as well as reconstructing its shape if need be.

In order to address these challenges, several navigation solutions have been designed by Airbus and selected partners and will be described in this paper. Regarding 3-DoF relative navigation, a solution based on a passive, standard camera and innovative image processing algorithms (for LOS estimation at long distances and LOS plus range estimation at shorter distances) coupled with an Extended Kalman Filter (EKF) for navigation and relative states estimation has been proposed. At shorter ranges, two solutions for 6-DoF relative navigation have been proposed. The first one relies on an active flash imaging LiDAR, whose outputs are fused with Inertial Measurement Unit (IMU) and attitude sensing data in an EKF. The second solution relies on a passive standard camera and state-of-the-art image processing algorithms that provide pseudo-measurements, also fused with IMU and attitude sensing data in the navigation filter.

As a natural next step in order to prepare for future missions, these technologies are now foreseen to be demonstrated on actual space missions. The proposed navigation solutions will be implemented and demonstrated on the RemoveDebris demonstration mission. This mission is due for launch in late 2017 and will constitute the world's first demonstration of ADR to date. This demonstration will considerably raise the Technology Readiness Level (TRL) of the navigation solutions proposed by Airbus and demonstrate their performance and robustness in a flight context.

2 The RemoveDebris mission

RemoveDebris is a low cost mission (€15.2M) performing key active debris removal (ADR) technology demonstrations including the use of a net, a harpoon, vision-based navigation (VBN) and a dragsail in a realistic space operational environment. For the purposes of the mission CubeSats are ejected then used as targets instead of real space debris, which is an important step towards a fully operational ADR mission.

The project, led by the Surrey Space Centre, University of Surrey, consists of a consortium of 10 international partners including Airbus Germany, France and UK, and is co-funded by the European Commission in the framework of the FP7 programme. The mission proposed by the RemoveDebris project will be the world's first, and perhaps the most important demonstration of ADR to date, and the technologies that will be developed under the project have been strategically selected for their importance in future ADR activities.

The mission is targeting late 2017 for launch using the NanoRacks procurement service and via a SpaceX cargo launch to the International Space Station (ISS); from there, the satellite will be ejected and will start its main mission.

2.1 Main platform

An accommodation study of the main platform and its various payloads is shown below. The payload panel contains all the hardware for the demonstrations including: 2 x CubeSats, net, harpoon target assembly, VBN suite, dragsail. Multiple supervision cameras help record the experiments.

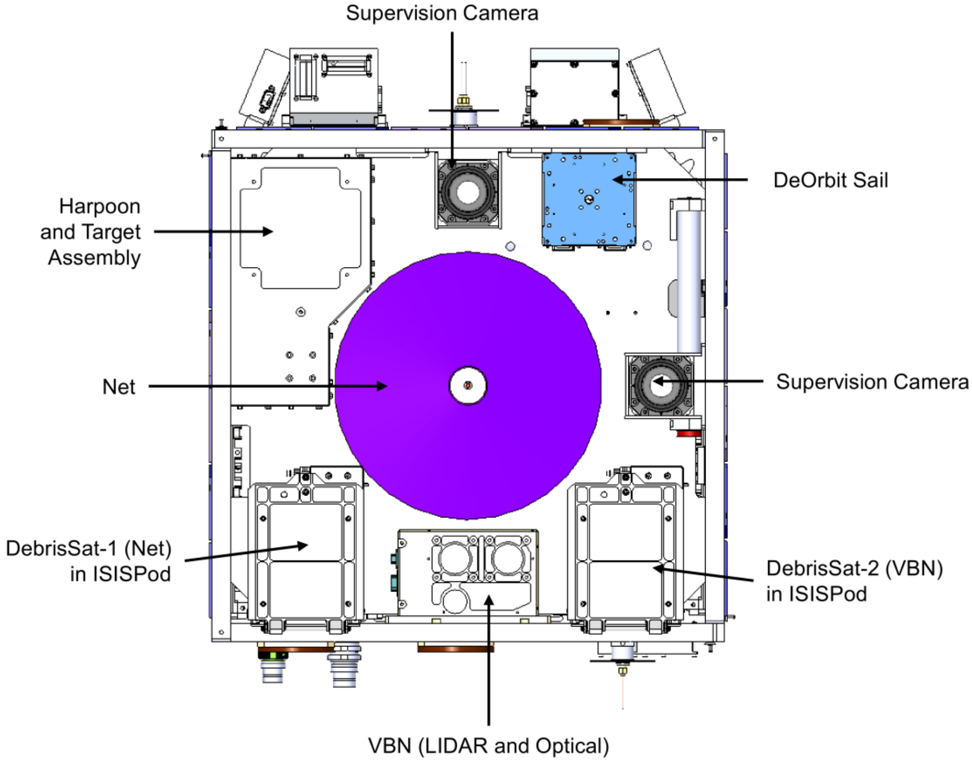


Figure 1: Main Platform (view on to payload panel) [1]

2.2 Experimental demonstrations

The four demonstrations undertaken are as follows: (i) in the net experiment, a CubeSat (called DebrisSat-1) is ejected and a net is fired at the CubeSat, (ii) for the VBN experiment, another CubeSat (called DebrisSat-2) is ejected and data is collected from the VBN suite, the platform and the CubeSat, (iii) in the harpoon experiment, a harpoon is fired at a target plate which is extended away from the platform on a carbon fibre boom, (iv) the final experiment is the dragsail which will rapidly de-orbit the main platform on conclusion of the mission.

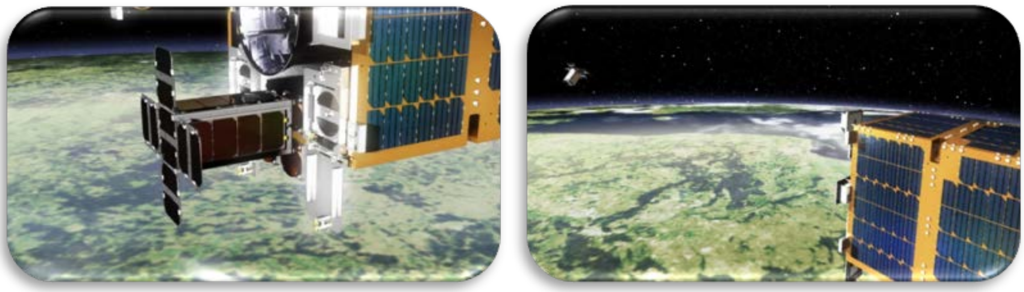


Figure 2: During the VBN demonstration, DebrisSat-2 is ejected from the main platform (left-hand side) and imagery is acquired while it drifts away (right-hand side)

In this paper concentration is given to the VBN suite which includes a standard 2D camera and a flash imaging LiDAR. It is also completed by an additional, 2D camera. The data and imagery collected from the various sources are downloaded to the ground and post-processed offline.

Further information about the mission concept, payload testing and operational timelines is available in [1], [2] and [3].

3 VBN demonstration

3.1 Introduction

The VBN demonstration will fulfil the following top-level objectives:

- Demonstrate state-of-the-art image processing and navigation algorithms based on actual flight data, acquired through three different but complementary sensors: two standard cameras, and a flash imaging LiDAR developed by CSEM,
- Validate a flash imaging LiDAR in flight, raising its system TRL to level 7-8

In order to fulfil these objectives, all the data acquired during the VBN experiment will be processed on the ground with innovative algorithms (e.g. 2D/3D and 3D/3D matching techniques detailed in §4.3) and specifically tuned navigation algorithms based on an EKF able to fuse data from different sensors (e.g. camera images and attitude sensing data).

During the VBN experiment image acquisition will be performed by the so-called VBN payload, which is an equipment specifically designed by CSEM in the frame of the RemoveDebris project, and which includes two different sensors: a standard camera, and a flash imaging LiDAR. The VBN payload, fully detailed in §3.2, is also completed by an additional, complementary 2D camera which is provided by SSTL.

GPS measurements from both target and chaser and onboard attitude estimation software will provide “ground truth” data against which the navigation algorithms outputs will be compared for validation and performance assessment. Post-processing activities will allow demonstration of performances of innovative 2D camera based navigation and 3D camera based navigation, allowing not only estimation of relative position and velocity but also relative attitude, one of the key drivers of successful capture of an uncooperative target.

In the following, the VBN payload and the VBN demonstration scenario are described in further details.

3.2 VBN payload

The role of the VBN payload is to capture standard color 2D and 3D images of debris and to transfer the data to the satellite. The times at which images have to be taken are programmed by the satellite on-board computer and transferred to the VBN payload as an array. The array's length is defined by the number of images to be taken in a given time window of the mission. It defines the sampling time of each image and its integration time. The VBN unit will acquire images in several time windows during the overall mission duration, especially during the harpoon and net deployments, and the release of the DebrisSat-1 and 2.

The VBN payload is developed by CSEM and is made of two vision-based sensors: a color camera and a flash imaging LiDAR. Both sensors are controlled by a supervision unit. Everything is integrated into a case sized 15 by 10 by 10 centimeters.

Figure 3: VBN payload proto-flight model (VBN PFM)

RemoveDebris is a unique chance to evaluate in-orbit ADR technologies. It is a low-cost mission with a budget only a small fraction of a larger scale, operational ADR mission. The main challenge in this context for CSEM was to develop and build a proto-flight model (PFM) based on a sensor concept for which very limited background and key components were available in Europe at the time of the project proposal in 2012. CSEM’s background was based on a flash LiDAR demonstrator made in 2009 in the frame of the Pseudo-Random Noise Continuous Wave Backscatter LiDAR Prototype project with ESA. Then, the European Commission granted the Flash Optical Sensor for Terrain Relative Robotic Navigation (FOSTERNAV) project that allowed to further develop the concept of flash imaging LiDAR hybridization with multiple operation modes and for several applications such as: landing, rendezvous and rover navigation. In the US, flash imaging LiDARs demonstrated their capabilities in the frame of the Autonomous Precision Landing and Hazard Detection and Avoidance Technology (ALHAT) program started in the early 2000’s. Now, second generation flash imaging LiDARs are used on several test platforms such as

MORPHEUS, a NASA project to develop a vertical takeoff and vertical landing test vehicle as well as an autonomous landing and hazard detection technology [4], and RAVEN, a technology module to be affixed outside the ISS to test technologies for autonomous rendezvous in space [5].

To some extent, the RAVEN approach is reproduced in the VBN payload: several vision-based sensors are integrated into a common housing. For comparison, RAVEN is composed of cameras in the visible and infrared spectral bands and a flash imaging LiDAR, whereas in the VBN payload, there are a flash imaging LiDAR and a camera in the visible spectral band.

The VBN payload is a hardware-software co-design, the main hardware components of which are: two vision detectors (a time-of-flight (TOF) detector and a half inch 3-Megapixel CMOS digital image detector), a VCSEL laser source at 805 nm, three micro-processors (supervision unit, LiDAR and camera management), one FPGA and two local memories of 2 GB each. The software is divided in four elements implemented in the three microprocessors and in the FPGA.

For RemoveDebris, raw data provided by the vision sensors are temporary stored in a local memory, then transferred to the satellite, and finally transmitted to Earth. Raw data contains very rich information from which different key figures can be extracted for autonomous navigation, such as: line of sight (LOS), distance, 3D geometry of the target and relative velocity.

Because of the limited budget, none of the selected VBN components were space qualified before the project started. Hence, a second challenge was to define a test plan compatible with the tight budget limitation but still enabling the assessment of the VBN functionalities and resistance to environmental constraints. Consequently, the test plan was elaborated in view of achieving the respective ultimate objectives for the functional and environmental tests while sparing some steps to be conducted in the frame of a more traditional approach. The ultimate objectives of both types of tests are:

- Test the VBN payload when programmed to capture 2000 LiDAR and 2000 camera images. This is the longest sequence foreseen for the mission.
- Assess if the VBN payload with its non-space qualified components will sustain the environmental conditions found in a one year LEO mission.

The final functional tests consist in executing a long sequence of image capture and transmission through the communication interface. For this purpose a ground support equipment (GSE) simulating the interface with the satellite has been prepared. The GSE is made of a hardware and a Python application. The hardware reproduces the SPI bus of the communication interface (2x 4 lines) at 6 Mbit/s with twice four LVDS signals face. The Python application implements the proprietary communication protocol elaborated on purpose for RemoveDebris. The software allows generating communication frames to test the whole set of commands and answers from the protocol.

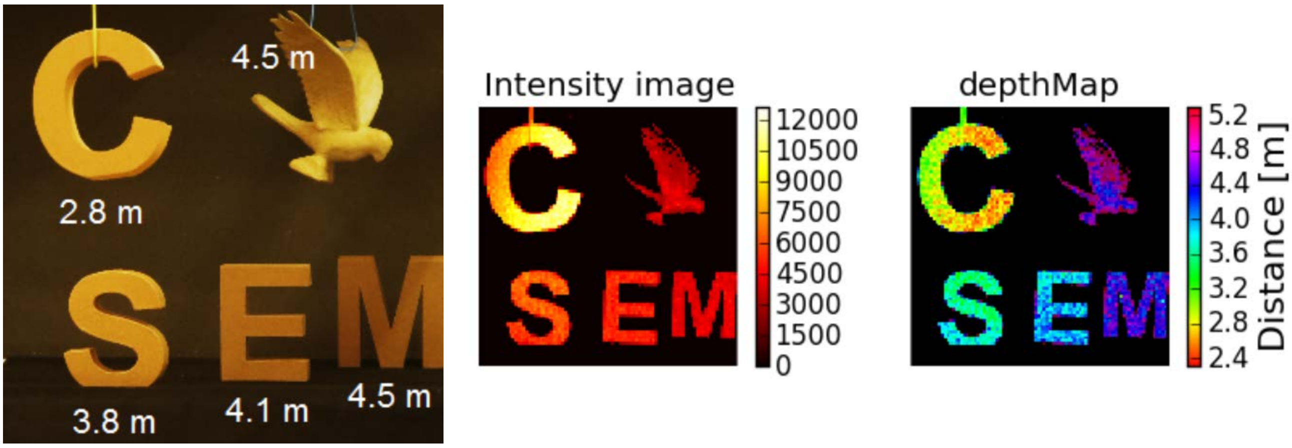


Figure 4: Example of target used for the functional test of the VBN payload with the classical 2D image generated by the camera on the left and both images generated by the LiDAR (intensity and depth map) on the right

The environmental tests present radiation, vibration and thermal aspects. The radiation aspect was addressed by design and analysis. A sufficiently thick housing made out of aluminum ensures protection of the VBN components against the expected level of radiation on LEO. The resistance to vibration and mechanical shock was verified by a series of random and sinusoidal tests. Random and sinusoidal tests were executed along the three axis with a success criteria defined as:

1. the first Eigenfrequency remains above 140 Hz,
2. between the start and the end of the vibration experiment, Eigenfrequencies do not shift by a value larger than 10%,
3. the amplitude variation of Eigenfrequencies remains below +/- 6 dB before and after vibration experiment,
4. the payload captures and transfers 100 LiDAR and 100 camera images before and after the test.

The VBN payload was successfully tested according to the criteria defined here above. The first Eigenfrequency is situated at 522 Hz along the y-axis direction.

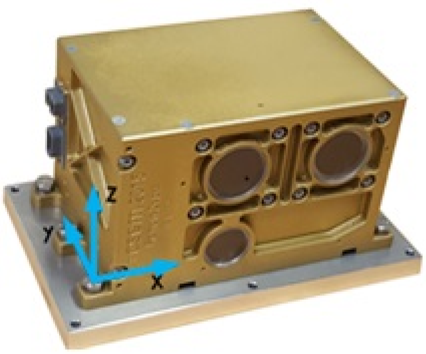
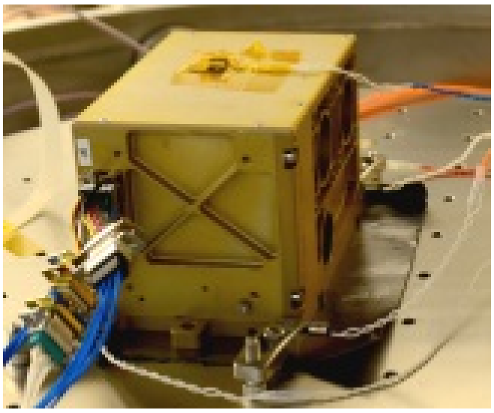
Random test parameters			Sinusoidal test parameters	
Frequency [Hz]	PSD [g^2/Hz]		Frequency [Hz]	Level [g]
20	0.200		20	0.5
40	0.350		40	11.6
70	0.080		70	11.6
500	0.080		500	0.5
2000	0.020		All axes	
Integrated Level	10.03 gRMS		Sweep rate [oct./min]	2
Duration	60 seconds	Definition of the axes		

Figure 5: Random and sinusoidal vibration tests parameters

The thermal aspect was validated with two series of tests made in an oven at ambient pressure, and in a thermal and vacuum chamber at 10^{-6} mbar. Three cycles were executed. For the first cycle, the VBN payload was tested before and after the cycle at ambient temperature, and was off during the thermal cycle. For the second cycle, the VBN payload was switched on at the minimum temperature and in operation until the end of the cycle. For the third cycle, it was switched on at the maximum temperature and operation until the end of the cycle.



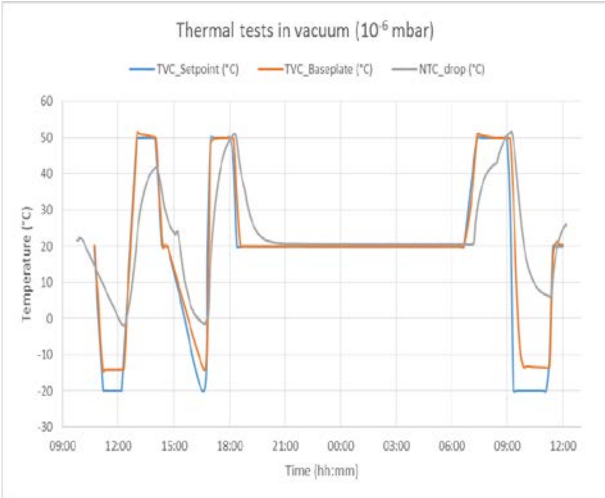


Figure 6: Thermal and vacuum test setup (left) and temperature monitoring in the VBN payload (grey line).

The environmental tests demonstrate the ability of the VBN payload to be operational in the conditions foreseen for the mission.

The VBN payload main features are summarized in the table below:

Table 1: VBN payload main features

Size [cm x cm x cm]	10 x 10 x 15
Mass [kg]	1.8
Average Power Consumption [W]	3.8
Peak Power Consumption [W]	5.2
Command and telemetry interface	2 redundant SPI x 4 LVDS lines
Proprietary protocol	
DC voltage [V]	20-36
Temperature range in operation [°C]	-20 to 50

Flash imaging LiDAR resolution	160 x 120
Flash imaging LiDAR half field-of-view [° x °]	8 x 6
Flash imaging LiDAR integration time [s]	0.0001 to 2.6
Flash imaging LiDAR image rate [Hz] (capture and storage in non-volatile memory)	0.2
Flash imaging LiDAR ADC resolution [bits]	12
Ranging accuracy [m]	0.02-0.08 at 20 m 0.4 at 100 m
Camera resolution	2048 x 1536
Camera field-of-view [° x °]	21 x 15
Camera integration time [s]	0.001 - 10
Camera image rate [Hz] (capture and storage in non-volatile memory)	0.1 (raw image)
Camera ADC resolution [bits]	10

3.3 VBN demonstration scenario

Demonstration needs and constraints

3D and 2D images will be captured over the three main experiments: over the net, VBN, and harpoon experiment. Following commissioning operations, images will already be acquired when the net CubeSat (DebrisSat-1) is released for preliminary checks, monitoring purposes, as well as a first collection of imagery data covering the net experiment. In a second step, the VBN demonstration itself will start, and will consist in capturing images of the VBN CubeSat (DebrisSat-2) from ejection until subpixellic distance is reached while ensuring that the widest range of visual configurations (in terms of distance to target, relative attitude, light conditions, background) is achieved. In a third step, images of the harpoon target assembly will be collected during the harpoon experiment in order to complete the set of VBN data. The following focuses on the second step, i.e. the definition of the VBN demonstration strictly speaking.

The VBN demonstration scenario was defined in order to fulfill the following high-level needs:

- The demonstration scenario should allow to demonstrate different navigation techniques which are relevant for ADR ; this includes 3-DoF relative navigation and 6-DoF relative navigation, based on 2D images and 3D point cloud, used separately or combined,
- The demonstration scenario should be sufficiently representative of ADR rendezvous operations, meaning that images should be acquired from very close range (when target fills the cameras field of view) to subpixellic distance, and relative velocities should be similar to operational ADR missions typical approach scenarios,
- The demonstration scenario should demonstrate image processing algorithms performances and robustness to ADR conditions, meaning that images with different illumination conditions, with different backgrounds (i.e. dark background and Earth background), with still and spinning target should be acquired

In addition, it is expected that the total volume of acquired data should represent several 1000’s of images. However, several constraints coming from various levels (e.g. mission, platform, CubeSat) of this ambitious but low cost demonstration mission had also to be taken into consideration in order to design the VBN scenario. They include the following:

- No propulsion: the lack of propulsion system forbids the possibility for the main platform or the target to perform orbital maneuvers, meaning that the VBN scenario has to be such that all demonstration needs must be met with a single acquisition sequence.
- Open-loop pointing: considering that no operational sensor and corresponding GNC software could be flown onboard the mission to support real-time pointing of the payload boresight towards the flying targets, only open-loop pointing based on a priori knowledge of the target trajectory relatively to the main platform can be performed. This means that the VBN demonstration scenario has to be robust to various uncertainties. These include the platform attitude pointing performances, in the range of 5 deg (3σ), and the ejection accuracy, in the range of 20% (3σ) for the deployer ejection ΔV magnitude and 5 deg (3σ) for the deployer ejection ΔV direction accuracy.
- Collision concerns: the risk of collision between the main platform and DebrisSat-2 should

be minimized. This means that sufficient margins should be taken when designing the relative trajectory, in particular considering the level of uncertainties discussed just above.

- No star tracker: inertial attitude measurements are required in order to retrieve relative position and velocity in the LVLH frame from vision-based measurements obtained in camera frame. However, no star tracker will be available on the main platform, due to cost reasons. Inertial attitude measurements will instead be performed by taking pictures of star background with the VBN sensors, at a specific frequency and with the adapted exposure time.

VBN demonstration scenario definition

Due to the various constraints listed above, the ejection maneuver, which fully defines the VBN demonstration scenario, must be carefully defined in order to meet the demonstration needs in the most satisfactory manner. The magnitude of the ejection velocity has been selected at 2 cm/s, which is the minimum velocity which has been considered as reasonably achievable by the CubeSat deployer mechanism. The date and direction of ejection where then selected in order to:

- Minimize the relative drift between the main platform and DebrisSat-2, while keeping collision risk low enough,
- Minimize the risk of losing the target while in open-loop pointing,
- Maintain favorable observation conditions for the short range VBN algorithms, which leads to a Sun phase angle less than 45 deg (3σ) following separation and until the apparent size of the target is less than 50 pixels
- Ensure that the target could be acquired with both Earth and dark backgrounds

Trade-off analyses led to the selection of a direction of ejection close to the Y-bar axis (perpendicular to the orbital plane), with smaller components along the R-bar and V-bar axes sized in order to meet the previously listed illumination, relative drift, collision, and background criteria in a satisfactory manner. This direction of ejection leads to the trajectory which is illustrated hereafter on Figure 7:

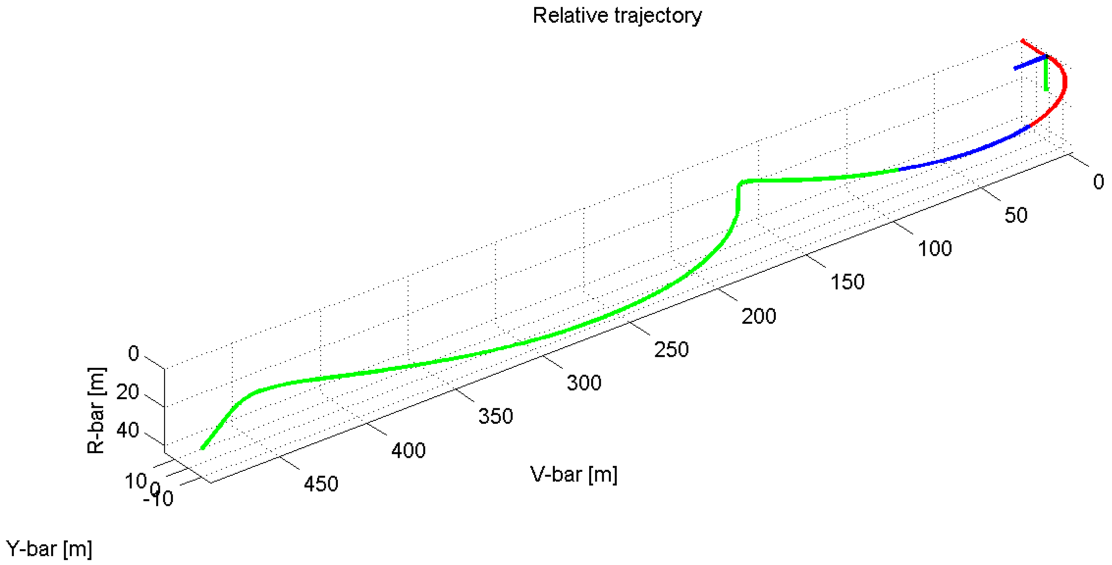


Figure 7: VBN scenario 4 phases on relative trajectory
(blind zone in black, close range in red, medium range in blue, far range in green)

As illustrated on Figure 7, the relative trajectory may be divided in four phases:

1. A **blind zone** phase following ejection, where DebrisSat-2 is too close to the main platform to be visible within the VBN sensors field of views
2. A **close range** phase, where DebrisSat-2 is extended within the VBN sensors field of view. This phase starts at the end of the blind zone phase and ends when DebrisSat-2 apparent size in the 2D camera detector array is around 50 pixels. Specific image processing algorithms may be used during this phase.
3. A **medium range** phase, where DebrisSat-2 is still resolved in the 2D camera field of view, but insufficiently to allow the image processing algorithms mentioned in the close range phase to operate with enough confidence. However, range estimation is still possible. This phase corresponds to a size in the detector field of view between 20 and 50 pixels.
4. A **far range** phase, where DebrisSat-2 is insufficiently extended in the camera field of view to enable range estimation. Only line-of-sight (LOS) to the target may be measured. This phase starts when the target is smaller than 20 pixels and continues until the end of the demonstration, covering at least 9 orbits.

The background evolution along the relative trajectory is shown hereafter on Figure 8 :

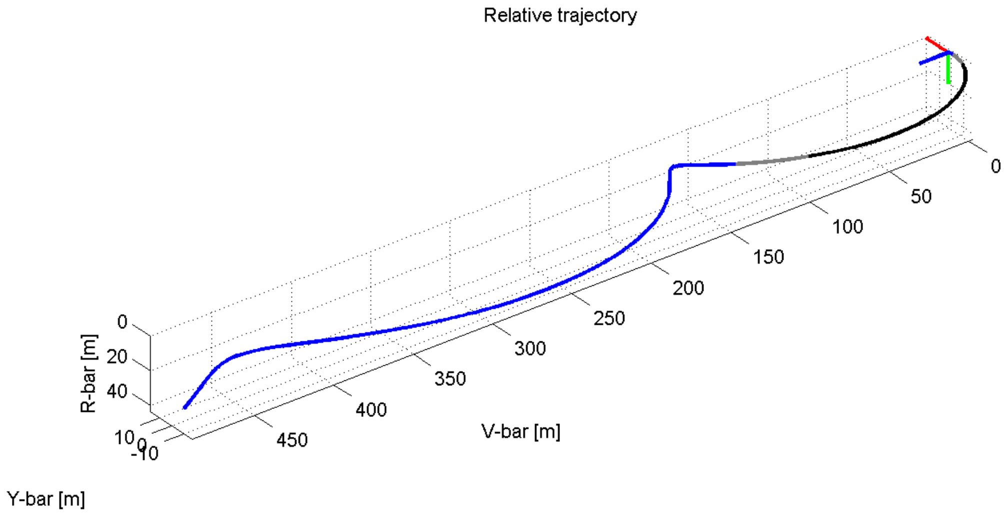


Figure 8: Background evolution along the relative trajectory

After a short duration with a dark background (barely visible on Figure 8 but lasting around 100s), the Earth enters the field of view of the camera (shown in grey) while the target is still in front of a dark background. The target then enters Earth background (shown in black, ~400s after ejection) and leaves it ~3000s after ejection. The Earth leaves the camera field of view after about 3500s.

Based on the resulting trajectory and the VBN sensors characteristics in terms of frame rate and data storage, a complete image acquisition sequence for the three sensors (flash imaging LiDAR, two standard cameras) was generated, cumulating a total of roughly 4500 images and approximately 5 GB of data.

Impact of dispersions

As mentioned before, the VBN scenario and relative trajectory are subject to a high level of dispersions due to platform attitude pointing performances, in the range of 5 deg (3σ), and ejection accuracy, in the range of 20% (3σ) for the deployer ejection ΔV magnitude and 5 deg (3σ) for the deployer ejection ΔV direction accuracy. The impacts of these uncertainties on the range and illumination conditions are illustrated on Figure 9 :

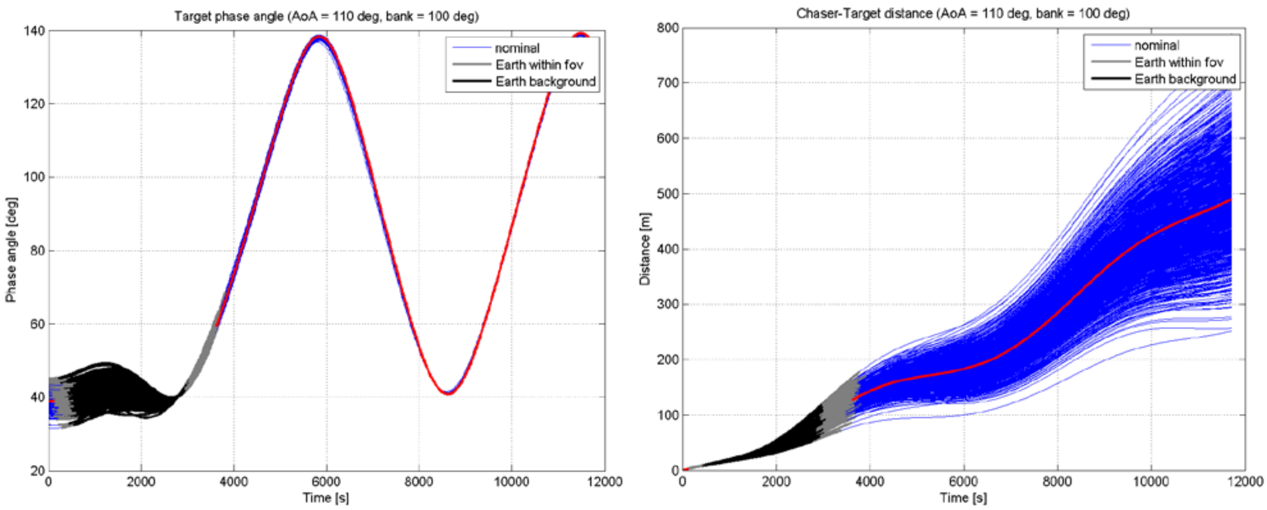


Figure 9: Impact of dispersions on illumination conditions (left-hand side) and range evolution (right-hand side)

Since only open-loop attitude pointing of the platform is possible, the most critical impact of dispersions at ejection relates to the angular error between the a priori and actual directions of DebrisSat-2. This angular error is illustrated on Figure 10.

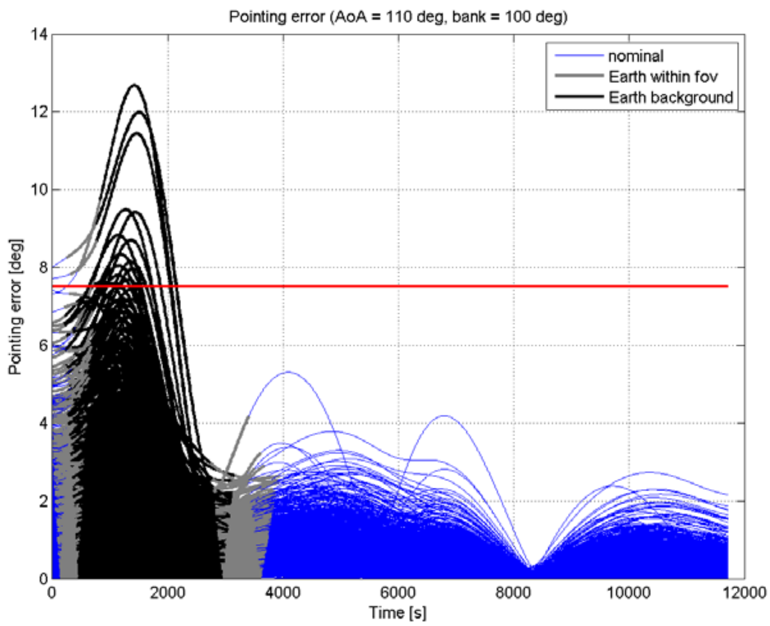


Figure 10: Angular dispersions

Figure 10 shows that DebrisSat-2 remains in the field of view of the cameras for the whole trajectory, except for a few cases where it exits the field of view for a finite duration. Over the whole trajectory, the success rate (i.e. probability that the target is within the cameras field of view at any given time) remains higher than 98.5% which was deemed acceptable.

4 VBN algorithms

4.1 Functional architecture

A standard functional architecture for orbital rendezvous VBN is shown hereafter on Figure 11. The sensors to be considered are typically a camera (or a flash imaging LiDAR), an IMU, and a star tracker. The image processing building block considered in this example is a model-based tracking algorithm (such as 2D/3D matching described in §4.3). The star tracker and the IMU outputs are combined by an attitude estimator in order to provide the best spacecraft inertial attitude estimate to the hybrid navigation filter, which computes the spacecraft states w.r.t its target. Note that the image processing building block may require aiding from the navigation filter.

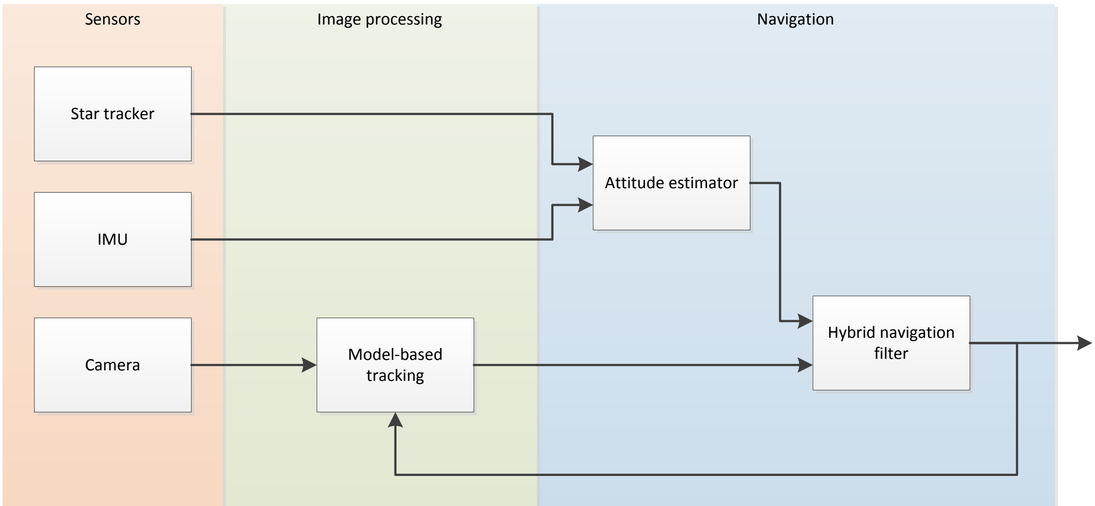


Figure 11: Vision-based navigation functional architecture for orbital rendezvous

For RemoveDebris, different image processing algorithms are to be considered. As discussed in §3.3 the relative trajectory may be divided in a close range phase, a medium range phase, and a far range phase. During the close range phase, the target is sufficiently resolved in the VBN cameras field of view so that relative attitude may be estimated and 6-DoF navigation be performed. The related image processing algorithms are described in §4.3. During the medium and far range phase, the target is too far for relative attitude to be estimated, and only 3-DoF navigation may be achieved. The related image processing algorithms are now discussed in §4.2. Navigation algorithms are described in §4.4.

4.2 Image processing for 3-DoF relative navigation

The measurement available for relative navigation evolves throughout the rendezvous phase. When target apparent size is smaller than 1 pixel, the centre of mass can be merged with the centre of brightness. The image processing algorithms task is to detect the target and to find its subpixelic location, which, due to low brightness, may be difficult to distinguish from the stellar background. The performances depend strongly on the target albedo, on the relative range and velocity. Relative navigation is then based on LOS measurements.

When the target extension in the field of view is larger than 1 pixel, simple image processing to find the barycenter of the target may be used. The illuminated pixel may be weighted depending on the target shape. Relative navigation is still based on LOS measurements.

Once the target is resolved, distance can be extracted, using knowledge of the target size and shape. For instance in the Mars Sample Return (MSR) case, which shows some commonalities with ADR missions including rendezvous and capture, the target is a spherical sample canister and the goal of image processing is to position a circle over the canister with the center located over the sample canister center of mass and a radius equal to the actual size of the sample canister in the camera image. During the MREP Camera ESA study [7], a trade-off including various image processing techniques has been performed by Airbus and Sodern, and led to the design of an algorithm based on Hough transform. The outputs of this algorithm are illustrated hereafter on Figure 12:

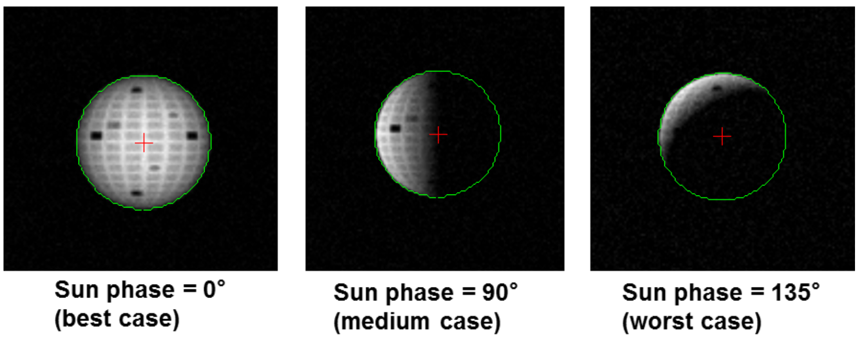


Figure 12: OS detection at close range for various illumination conditions [7]

Robustness and performance analyses over the last 100m have been performed with regard to Sun phase angle variations (illumination condition variations), range variations, the presence of Mars or Phobos in the field of view, the canister proper motion (up to 5 deg/s) and the occurrence of solar flare. Simulations have shown that the error in range measurement remains lower than 10% at 1σ and that LOS measurement error is lower than 0.01deg at 1σ.

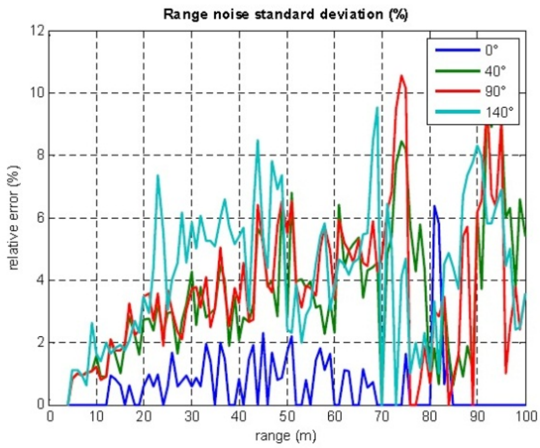


Figure 13: Robustness to range variations for various illumination cases [7]

Since MSR, a more generic solution, based on template matching has been developed by Airbus. Originally dedicated to asteroid, it can easily be adapted to satellite-like targets, as it can manage any target shape. Template matching has recently been tested in the frame of the FP7 NeoShield-2 project [12]. It will be used and tested on RemoveDebris images.

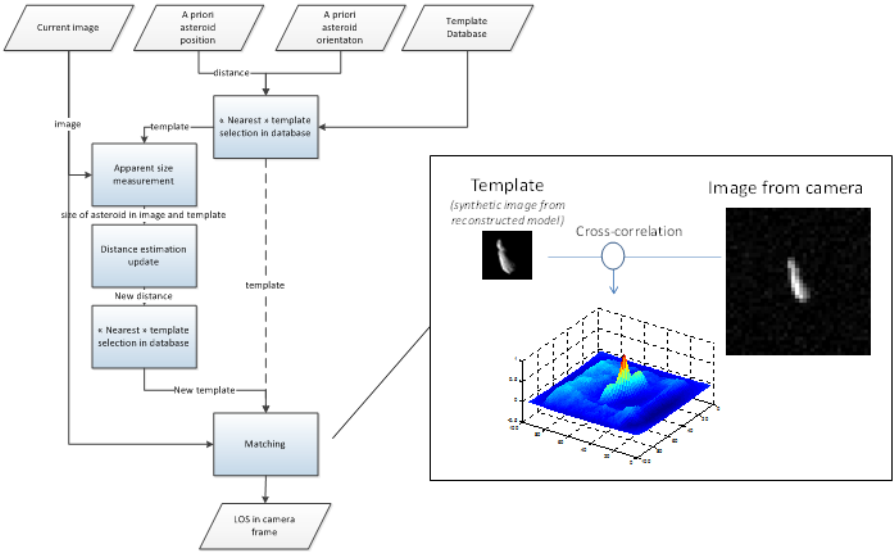


Figure 14: Template Matching principle [12]

4.3 Image processing for 6-DoF relative navigation and target identification

Two solutions for 6-DoF relative navigation have been investigated by Airbus in collaboration with INRIA, with sensors investigated under ESA or European Commission (FP7) studies. The first solution relies on the flash imaging LiDAR developed by CSEM in the frame of Fosternav and RemoveDebris - fused with IMU data in a navigation filter. The second solution relies on a passive, 2D camera and a state-of-the-art image processing that provides pseudo-measurements, also fused with IMU data in the navigation filter.

3D/3D matching

The first relative navigation solution relies on 3D pictures, provided by an active sensor, and a 3D model of the debris, either a priori known or estimated during the identification phase. 3D pictures are provided by state of the art 3D flash imaging LiDAR, developed in the frame of the FP7 projects Fosternav and RemoveDebris. The key components of flash imaging LiDAR are the laser illuminating the target and the receiver detector array. These two elements are operated in full synchronisation in order to generate three dimensional images of the target. The device determines either directly the time-of-flight (TOF) of photons with counters that started with optical pulse emission and stopped by the back-reflected signal or indirectly by measuring the phase difference between the modulated illuminating laser beam and the incoming back-reflected light per pixel.

Regarding image processing, many publications on 3D cloud matching are available [8][9]. It is typically model-based, as it aims to match the 3D model of the debris with the 3D point cloud provided by the camera. Many algorithms have been developed in the computer vision domain to solve this problem, but for different applications such as search in 3D database or object recognition. The relative navigation solution therefore consists of a 3D camera that provides 3D pictures to image processing for matching with a known model. As there is always an ambiguity between pure rotation and translation of the target within FOV, fusion of IMU data within the navigation filter is needed. As a result, reliable estimation of relative position, velocity and attitude are provided by the proposed navigation solution.

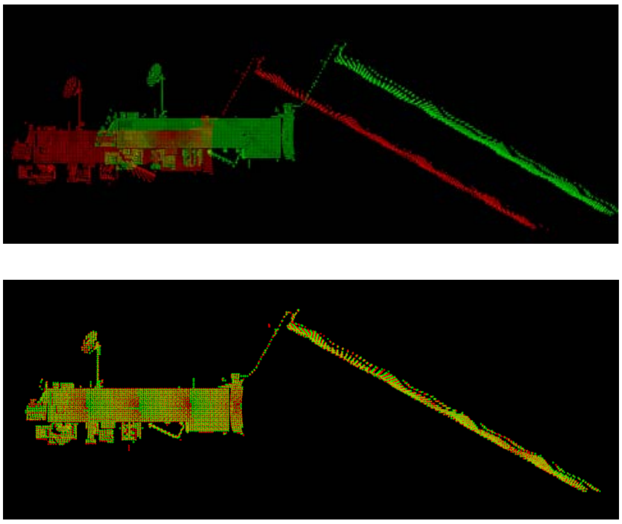


Figure 15: Example of 3D/3D matching algorithm. Matching 3D point cloud (depth map) with a priori known 3D model using ICP algorithm.

2D/3D matching

One of the solutions investigated by Airbus in collaboration with INRIA relies on 2D pictures, post processed to match a 3D model of the target. It can only be used when the 3D model of the debris is a priori known or estimated during identification. Similar to 3D/3D matching, it can provide estimation of relative position and attitude, necessary conditions for successful capture. Such an approach is divided into two steps: initialization and tracking.

Initialization

Initialization aims at detecting the target in an image sequence and at providing the tracking with an initial guess of the target pose, without any prior information on the pose. It consists of matching (detection/matching stage) the image contours with a database of views built during the identification phase. This initialization is done stepwise.

Identification learning : a hierarchical model view graph leading to prototype views of the model is built. Each node of the view graph contains an image projection of the target contours at a particular point of view. The points of view are sampled on a sphere. The sampling of the views is optimized to limit the memory size of the database and to ensure the whole coverage of the space of possible views.

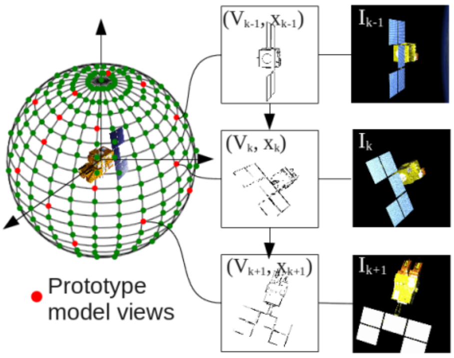


Figure 16: Principle of initialization. Several views on a sphere are selected to produce prototype views stored in a hierarchical model view graph. Target is then extracted by segmentation and matched over successive frames with closest prototype [10].

Online target detection : silhouette of the target is extracted in the image using bilayer segmentation techniques. This method consists in minimizing an energy function combining motion and color, along with time and space priors. It allows distinguishing the foreground shape from the background and has the advantage of being real-time.

Online matching and pose initialization : the view graph is then explored to find the prototype view whose contours correspond the most to the extracted silhouette. It considers both distance and orientation of edges to match: once the closest prototype view is found, its associated pose is considered as initialization of the target pose. The matching stage can be rather time consuming. To cope with real time constraints, a Bayesian framework is set to spread the initialization over several images (time domain initialization). It enables to provide an up to date pose initialization to the GNC system.

Tracking

Once the target has been detected in the image, and its pose has been initialized, a frame to frame edge tracking is performed. Like initialization, tracking is then 3D model based. It aims at finding the target pose which makes the best match of the projection of the 3D model with the image edges. Tracking and pose estimation are thus simultaneous. Unlike initialization, edge matching is local. As a consequence, tracking runs in real time but is less robust to high differences between edges, meaning that the predicted target pose shall be close enough (a few pixels) to the actual one.

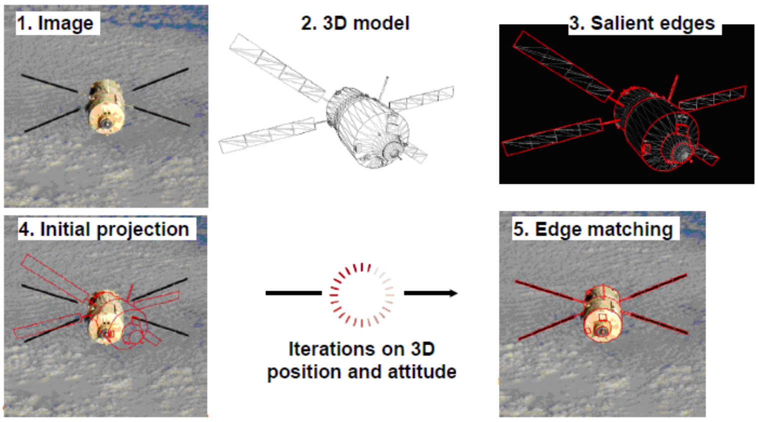


Figure 17: Principle of tracking. Tracking is performed using a frame (1) and the 3D model of the target (2). The salient edges of the target are extracted (3) and projected into image (4), given an initial pose. Pose is iteratively refined to make projection edges match with image edges (5).

Edge-based tracking can be combined with other modalities, such as color (local histograms describing the local distribution of colors or gray levels on each side of the projected edge) and texture-based features (Kanade-Lucas-Tomasi features), thus increasing the robustness of the tracker [11]. The tracking algorithm has been successfully validated on real images, as shown on Figure 17 and Figure 18.

Figure 18: Example of tracking on real images of Soyouz (from [10])

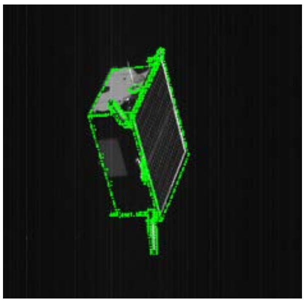


Figure 19: Example of tracking result on TANGO satellite (PRISMA mission)

4.4 Navigation algorithms

The vision based navigation solution presented in this paper for rendezvous is based on image processing measurements hybridization with inertial measurements. This results in a simple yet efficient design, where the core hybrid navigation Extended Kalman Filter (EKF) is able to receive visual measurements from various sensors or image processing algorithms.

The main component of the navigation consists of an Extended Kalman Filter. This filter has been developed by Airbus as a generic filter based on sensor models [6]. The filter core is the same: only the processed measurements change. The navigation is based on LOS measurement for far range, on LOS and range measurements for medium range, and on relative position and attitude measurements for close range.

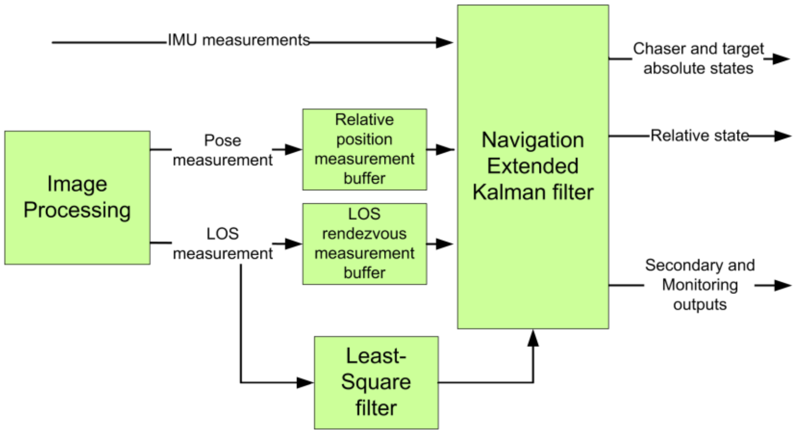


Figure 20: Navigation filter architecture

The navigation filter architecture is designed to be versatile enough in order to be compatible with a whole rendezvous mission, from far range detection to capture. It is composed of the main EKF and its measurement buffers, together with a Least-Square filter designed to handle large initial dispersions which may be incompatible with the relative motion linearization assumptions used by the EKF. Although not strictly needed for ADR missions where good initial estimates of the target orbit around the Earth may be provided from ground observation means, this Least-Square filter is also part of the generic rendezvous navigation solution since it is needed for rendezvous missions where the target orbit is poorly known, such as Mars Sample Return for instance.

4.5 Simulation results

Simulation tools were used in order to support the definition of the VBN demonstration scenario as well as to perform a preliminary validation of the navigation algorithms. Synthetic images were produced with a high level of fidelity by a rendering tool developed internally at Airbus and called SurRender.

SurRender is an image simulation software developed since 2011 by Airbus and dedicated to space scene modelling:

- It handles various space objects such as planets, asteroids, and spacecraft.
- It is optimized for space scenes: it handles solar-system sized scenes without precision loss and optimizes the raytracing process to explicitly target objects.
- It produces physically accurate images with quantitative radiometric values, expressed in physical units (irradiance value per pixel in $W.m^{-2}$, or spectral irradiance in $W.m^{-2}.Hz^{-1}$).
- It performs complete sensor modelling, including PSF, distortion, motion blur, electronic noises, rolling shutter, and other low-level detector effects

Based on the relative trajectory described in §3.3 and on the selected illumination conditions, images corresponding to the whole VBN demonstration scenario could be generated by SurRender. Examples of these images for various dates along the trajectory, indicating the available measurements and the corresponding image processing algorithms are shown on Figure 20 :

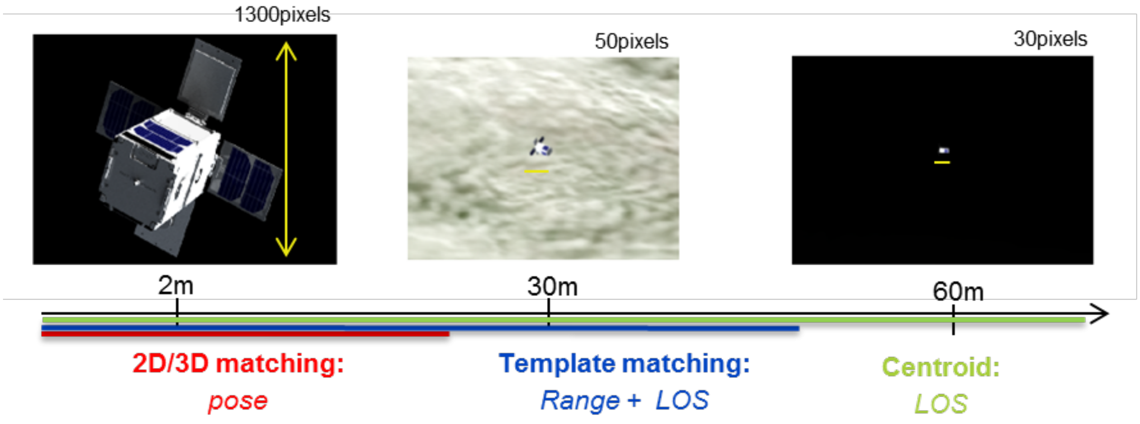


Figure 21: Images sequence provided by Surrender and associated measurements

Image processing algorithms corresponding to the different phases of the VBN scenario were then applied on the simulated images. For instance, the application of the 2D/3D matching algorithm at the start of the scenario is illustrated on Figure 21 hereafter:

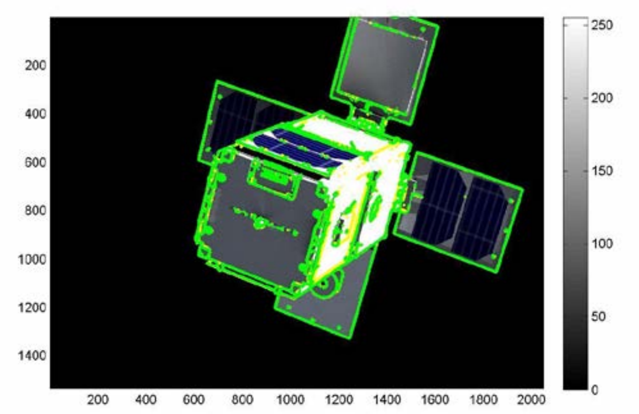


Figure 22: Application of 2D/3D matching for close range rendezvous

Measurements from the image processing algorithms were processed within the navigation filter described in §4.4. Preliminary results showing the errors on relative position estimation over the first 25m of the relative trajectory are provided in Figure 22, showing the correct performances of the image processing algorithm (2D/3D matching in this case) and the added-value of the navigation filter. The relative error on range remains less than 0.4% over the first 25m, i.e. when the target covers at least 50 pixels.

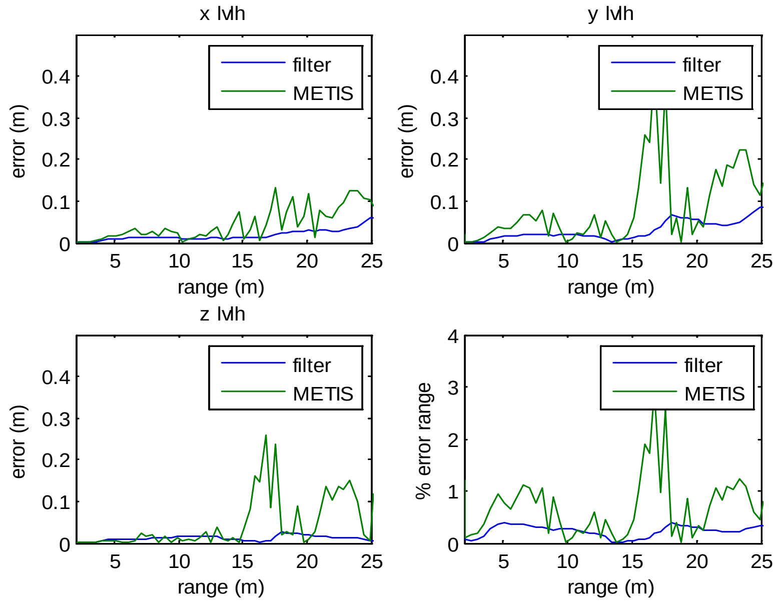


Figure 23: Errors on relative position estimation
(with "METIS" image processing only in green, after filtering in blue)

5 Conclusion

The RemoveDebris demonstration mission, including various ADR technology experiments, is now on track for a launch late 2017. Among others, it will include the Vision-Based Navigation demonstration composed of 3 sensors (an innovative flash imaging LiDAR and two standard cameras), a flying CubeSat target as well as navigation and image processing algorithms which will be used to process on ground the images and data acquired in flight. The proposed navigation and image processing algorithms offer navigation solutions that cover the full spectrum of relative navigation needs (including both 3-DoF and 6-DoF relative navigation) for Active Debris Removal, one of the most demanding orbital rendezvous mission concepts.

Simulation campaigns in high-fidelity simulation environments have been performed, validating the proposed VBN demonstration scenario as well as the image processing and navigation algorithms on synthetic images. The proposed navigation solutions will soon be validated on flight images acquired during the actual VBN demonstration. This demonstration will considerably raise the Technology Readiness Level (TRL) of the navigation solutions proposed by Airbus and demonstrate their performance and robustness in a flight context, paving the way towards the appropriate level of maturity for flight operations on future operational missions.

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