VISION BASED NAVIGATION FOR PLANETARY EXPLORATION


As a passive system with a natural adaptation capacity to the environment, mimicking the human capacity for detecting hazards, vision-based navigation for space applications has been the subject of a sustained research effort in Europe for more than ten years. The “Navigation for Planetary Approach and Landing” (NPAL) ESA/EADS Astrium project paved the way for a new European autonomous vision based navigation system called VisNAV, aiming at a proof of concept, with an elegant breadboard realization, preparing for the next step to flight demonstration. This paper presents the consolidated design, and HW/SW architecture of the real time implementation. It also addresses the validation strategy from simulation, making extensive use of virtual scene generation through a realistic modeling environment, to in-flight demonstration experiment, as well as the achievable performances.

INTRODUCTION

Autonomous navigation is a key enabling technology for future planetary exploration mission. For planetary landers and rovers, as well as interplanetary navigation and rendez-vous, vision based navigation concepts, working on complex, potentially unstructured, scenes, appear as the most promising technology. The “Navigation for Planetary Approach and Landing” (NPAL) ESA/EADS Astrium project paved the way for a new European autonomous vision based navigation system called VisNAV. The target missions of VisNAV are Mars Sample Return (MSR) and lunar landing through the NEXT preparatory program, as well as asteroid landing (typ. Marco Polo in the ESA Cosmic Vision program).

In the frame of landing scenarios, VisNAV has the ambition to cover the descent and landing sequence towards an unknown, possibly hazardous terrain, taking the lander to a soft landing, controlling the dynamics to within 1 m/s of residual velocity at contact. Hazards above 10 cm of size are detected and avoided as well as slopes higher than 10°. The orientation of the vehicle in the local gravity field is monitored and controlled to a few degrees to limit the conservativeness of landing gear design. Both atmospheric and non atmospheric planetary bodies are considered.

VisNAV is based on feature points extraction and tracking. The continuous video stream is processed to extract motion observables, which are in turn combined with inertial navigation in a tight hybridization scheme, to provide for both an estimate of the relative motion with respect to ground, and at the same time reconstruction of the terrain through selected points of interest.

* EADS ASTRIUM, Toulouse, France.
**ESA ESTEC, Noordwijk, The Netherlands.
Initiated in 2001, the work program raised a major step in 2006 at the end of the development phase, concluding the design, HW/SW integration and validation of an elegant bread-board of VisNAV: the Vision Based Navigation Camera (VBNC). Since then a real-time experiment has been realized that allows demonstrating landing mission performances through terrestrial flight on the Precision Landing Ground Test Facility developed under ESA contract. First flight will occur in 2009 and demonstrate the navigation performances. In 2010, a second campaign will demonstrate hazard avoidance capabilities embedded in the Hazard Avoidance System Experiment (HASE). In parallel to the flight demonstration campaigns, an Engineering Model (EM) pre-development activity as already started aiming a space qualification in 2012. In this frame, alternative uses of VisNAV architecture are studied: rendez-vous and docking, interplanetary navigation, rover navigation. The multi-mission approach that is developed for VisNAV lies in the cost and risk reduction of the vision based technology development through commonality of means, tools and technological developments or validation. The VisNAV architecture thus relies on a modular design.

![Image](image1.png)

Figure 1. The VBNC (left), PLGTF NPAL experiment (centre) and PLGTF platform (right).

The VisNAV functional chain can be described as three successive main functions:

1. First of all, the image acquisition, performed by the camera. Besides the obvious function of sensor command and read-out, it is also in charge of other sub-functions, such as pixel correction.

2. Second the Image Processing, whose role is to process the large amount of information contained in the images and output a simple list of tracks (typically 200), to be fed to the navigation filter. It is implanted within the Feature Extraction Integrated Circuit (FEIC).

3. The navigation function itself, which mostly consists of a dedicated navigation Kalman filter.

A one-to-one association of these functions with pieces of hardware (namely Camera, FEIC, and On-Board Computer), is considered. Mastering the overall chain architecture is thus the key to globally optimize the hardware implementation choices.

This paper presents the consolidated design, and HW/SW architecture of the real time implementation of VisNAV. It also addresses the validation strategy from simulation, making extensive use of virtual scene generation through a realistic modeling environment, to in-flight demonstration experiment, as well as the achievable performances.
THE PLANETARY LANDING SCENARIO

The vision system has the ambition to cover the descent and landing sequence towards an unknown, possibly hazardous terrain, taking the lander to a soft landing, controlling the dynamics to within 1 m/s of residual velocity at contact. Hazards above 10 cm of size are detected and avoided. The orientation of the vehicle in the local gravity field is monitored and controlled to some degrees to limit the conservativeness of landing gear design. Both atmospheric and non-atmospheric planetary bodies are considered. Although the original activity was geared towards landing on a non-atmospheric planet (Mercury, Moon), the concept has been successfully tested also for the case of atmospheric planetary bodies (Mars) proving great robustness and flexibility.

For the sake of simplicity only the final approach of a typical non-atmospheric landing scenario is presented here. The final approach starts as soon as full thrust is not required. The whole thrust capacity can be used to compensate for dispersions that occurred during the previous phase or for hazard avoidance maneuvers. The spacecraft attitude rate is likely to reach significant value. Similarly with atmospheric scenario but probably to a less extent, engine flares impact illumination conditions around the spacecraft, especially if thrust is activated. It may generate dust clouds as well. The final approach is also called Visual Guidance Phase (VGP). VGP is initialized when the Landing Site (LS) comes into visibility at a point called High Gate (HG). Hybrid navigation is fully operational at Visual guidance Phase Entry Point (VGPEP).

![Figure 2: Typical Lunar landing scenario](image)

CAMERA SIZING FOR LANDING

The VisNav camera design has to account for the specificities of autonomous landing. Currently, autonomous landing is constrained by high spacecraft dynamics and environment (illumination conditions, Sun elevation, albedo, terrain features, atmosphere, temperature, pressure and so on) that is very variable from one planet to another, from one landing sequence to another. The specifications that were retained for landing scenarios intend to cope with most scenarios (Mercury, Mars, Moon, and small bodies). Main design drivers are summarized in the following table:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Units</th>
<th>Range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winds</td>
<td>m/s</td>
<td>[0-30]</td>
<td>Wind directly affects the GNC performances. In particular, it is to be considered for horizontal velocity. Lateral Wind gusts up to 30 m/s have been experienced during MER EDL sequence.</td>
</tr>
<tr>
<td>Sun elevation</td>
<td>°</td>
<td>&gt;1,5</td>
<td>Potential landing sites on the Moon have been identified at South Pole, for their highly scientific interest. E.g. sun elevation is around 1.5° at Shackleton crater.</td>
</tr>
</tbody>
</table>
Dynamics °/s² <37 The maximum dynamics is driven by the high level of acceleration during retargeting maneuvers. Yaw/pitch angular acceleration up to 37°/s² must be considered. For the roll axis (optical axis), low dynamics are expected.

Field of view ° [50-70] The Field Of View sizing drives: the track length, the number of potential landing sites that are observed, the ground resolution for a fixed detector resolution.

Resolution m/pix. 2 (1.5 km) 0.15 (350 m) Resolution is mainly driven by Hazard Detection and Avoidance capability to detect slope higher than 10° and boulders with diameter greater than 50 cm.

Mass Kg <1 The mass is to be as small as possible.

Frequency Hz [10-20] Landing is characterized by high spacecraft dynamics and limited amount of time.

Table 1 – VBNC Design drivers

In addition the camera has to be robust to solar flux up to 15215 W/m² (Mercury case), radiations (prompt particle events) and presence of dust.

THE NAVIGATION ARCHITECTURE

Visual navigation is based on visual tracking of remarkable feature points. With a single measurement of a remarkable feature point, the point is known to lie along the line of sight vector, but the depth is unknown. Through hybridization with inertial measurements, tracking several points through a dynamic filter allows determining the depth as well as the states of the vehicle.

Navigation is an intrinsic hybridization scheme that allows a tight aiding between image processing and state estimation. The navigation functional architecture (Figure 3) is composed of 4 main functions:

- The navigation filter which provides the vehicle state estimation and feature points distance estimation. A continuous estimation of the mean plane fitting the last tracked feature points is provided and propagated in order to keep a minimal prediction capability even when all tracks simultaneously ends (after anomaly or fast retargeting maneuver).
- The camera aiding which provides feature point position estimation to the image processing and select the points to be tracked by the FEIC. Point selection logic is mainly based on Harris criteria (highest Harris weight preferred), but can be improved by selecting points in certain region of the image (for landing site distance estimation) or with good correlation properties. Feature points position prediction is based on a homography computed based on the state estimation.
- The feature point selection function which selects the feature points to include in the estimation among the 200 points tracked by the FEIC. In order to provide good state estimation, feature points shall be spread inside the field of view, not too close to the horizon (points at horizon do not contain much information about the distance to the plane), not too close one to the others (to provide different kind of information) and not too close to the edge (to avoid very short tracks).
The landing site position estimation which provides the landing site position estimation after an initial designation in one image.

**DEVELOPMENT AND VALIDATION LOGIC**

An incremental approach has been applied to the development and validation logic inducing the development at each step of simulation tools and framework.

1. Design tools have been developed based on image processing models to design and validate the navigation functions regarding performances and robustness. The image processing models were validated over simulated and real imagery. Image processing models for feature extraction and tracking are expressed in terms of number of extracted points, spatial distribution of points, repeatability, good and false match rates.

2. VBNAT stands for Vision Based Navigation Tool. It is a Software in the loop (SIL) simulation tool. It includes a planetary scene generator as well as camera modeling in order to validate both IP prototypes and Navigation chain performances through open loop or closed loop Monte Carlo (MC) analysis.

3. Image processing prototypes served as a reference to validate performances of H/W coding within a dedicated H/W component: the Feature Extraction Integrated Circuit (FEIC). HW coded image processing prototype is used in the VBNAT tool to assess the end to end performances.

4. The FEIC was then integrated in a H/W in the loop (HIL) version of the VBNAT to perform closed loop HIL simulations.

5. The camera was subject to an independent development. Then the camera and the FEIC have been integrated within a single breadboard: the VBNC.

6. A real time experiment has been implemented and delivered that operates the VBNC for in-flight testing on an ESA unmanned air vehicle (UAV) platform: the Precision Landing Ground Test Facility (PLGTF). It integrates the VBNC and the navigation on-board computer (OBC).

7. The Hazard avoidance algorithms (subject to an independent development) are currently under integration into a real-time experiment for future flight onboard PLGTF.
Figure -4: An incremental approach has been applied to the development and validation logic.

From the very beginning of the development, this process has been implemented by an integrated team gathering competencies in the field of: GNC system analysis, Navigation design, Image processing and HW/SW co-design. This organization revealed efficient in the realization of such a complex technology with coupled algorithmic, robustness and performance issues.

**VBNC: an elegant breadboard of VisNAV**

The complete navigation solution has been developed and prototyped. An elegant breadboard of the camera has been assembled, that differs from the flight design mainly for the optics and some electronic components. Its compactness is affected in a limited manner by the use of commercial components (FPGA) instead of dedicated optimized implementations (ASICs).

Figure -5: VBNC camera breadboard exploded + assembly views
The elegant breadboard respects the flight design in most respect. The use of commercial optics and commercial grade components favors a demonstrator approach for testing on-ground and fine tuning.

<table>
<thead>
<tr>
<th>Camera Size</th>
<th>13 cm x 13 cm x 8 cm (baffle incl.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera mass budget</td>
<td>500 grs</td>
</tr>
<tr>
<td>Camera Power</td>
<td>2 W</td>
</tr>
<tr>
<td>Communication link</td>
<td>SpaceWire 100 Mbit/sec</td>
</tr>
<tr>
<td>Memory capacity</td>
<td>Up to 200 Feature Points and textures for tracking</td>
</tr>
</tbody>
</table>

Table 2 – VBNC Characteristics Summary

The breadboard is used to perform the complete proof-of-concept of the NPAL navigation solution. The breadboard is used in two configurations: either with direct picture acquisition on the Active Pixel Sensor (APS), or through electrical stimulation. An Electrical Stimulation Generator allows passing a complete video sequence in real time, shunting the detector to directly feed the camera memory.

**The Image processing chain**

To optimally support the navigation processing, the selection and definition of the image processing algorithms to be implemented is a crucial step. The main issue for vision based relative navigation lies in the selection of physical (fixed) points on the scene. These points should be relevant enough to support long term tracking along the landing sequence. Performances are driven by the robustness to the dynamic of the lander and scene appearance during the approach.

A major effort has been involved in the definition of objective criteria that could catch the intrinsic modeling of image processing algorithms. The main objective was to fit the exact behavior of the extraction and tracking algorithms in order to finely understand and decouple the main influences. Objective criteria were defined on the basis of navigation requirements.

The most relevant objective criteria for feature extraction revealed to be the spatial distribution of points, the distribution of relative accuracy and the repeatability between consecutive frames.

Extraction and tracking algorithms are based on the invariance of local feature points. As a consequence, algorithm design and validation must account for an exhaustive analysis of their behaviour with respect to distortion sources. In terms of kinematics distortions, we distinguish between (the following values are provided as an indication for planetary landing missions):

- **TXY** – motions parallel to image plan. Maximal expected translations are about 15 pixels. Maximum parallax effects are around 2/100° pixels.
- **RXY** – Rotations perpendicular to the optical axis. During S/C maneuvers (~50°/s ), they can reach 2.5°.
- **RZ** – Rotations around the optical axis. Expected to be lower than ~1°/s.
- **TZ** – Translation along the optical axis. The expected approaching rate (Vz/z) lies between 0 and 5%.

*RZ* and *TZ* are obviously the most disturbing effects regarding extraction and tracking performances.
For radiometric distortions:

- **FTM** – The modular transfer function at the Nyquist frequency (sampling frequency /2) is a common blurring measure. Contributors to FTM are: optic, detector, motion and micro vibrations. A coarse estimation gives a FTM lying between 0.13 and 0.2. It has an impact on the salience of points.

- FTM variations between successive acquisitions are due to motion blur and thus accelerations that are maximal during maneuvers (~40°/s²). A coarse estimate considers few % of FTM variations in worst cases.

- Random noise has two sources: detector noise (Gaussian with Signal to Noise Ratio ~70 to 110), dead pixels follow a uniform distribution over the image.

- Illumination conditions may vary according to the sun elevation, acquisition time adjustment optical transmission variations within the optical field of view (0-40%).

Performance analysis aimed at confronting an extensive review of feature point extraction and tracking algorithms to the various needs of the mission on the basis of objective criteria.

**The FEIC**

The FEIC FPGA was designed to receive 10-bit grey-scale mega-pixel images from the camera FPGA at a rate of 20 frames per second (20 Hz) via double-buffered image memory. While the FEIC is processing an image frame from one buffer the camera is writing to the other image buffer. The internal FEIC design consists of an interface to the image memory buffers which provides six different pixel streams to the rest of the chip. Two pixel streams (one for reading and one for writing) allow the OBC and test equipment to access the image memory directly via the FEIC controller and register file; two further pixels streams are provided to the feature extractor, one to the feature tracker and one to the list manager. A SpaceWire mini-router provides the external interface between the FPGA and the OBC. The top-level blocks of the FEIC are shown in Figure with arrows representing the main data paths. The off-chip arrows to the OBC and camera represent SpaceWire links.

The development of the FEIC was realized at University of Dundee. Such a large FPGA development, involving mathematical image processing algorithms, led to a careful and incremental design and validation process. This began with an implementation of the key feature extraction
and tracking algorithms using floating-point arithmetic in C++ followed by initial testing and performance evaluation. The result was a FEIC simulator program that would accept a sequence of images as input and perform automatic feature extraction and tracking using a simple controller to represent the OBC. It was tested over a large set of image sequences both real and synthetic that amount to about 400 test cases.

The next step was to produce a comparable C++ implementation using 32-bit and 64-bit integer arithmetic and to compare its behavior with the initial floating-point implementation on the test image sequences. Following the successful validation of the integer algorithms in the FEIC simulator, specific hardware feature extraction components were designed down to the register level. Each component was then implemented as a C++ thread designed to mirror the final hardware implementation. The results from C++ simulated hardware were continuously compared to the output of the reference image processing code to ensure the correspondence at all times.

After making any refinements to the design of the hardware component simulated in C++ to ensure that it behaved exactly like the “normal” integer C++ implementation the design was implemented in VHDL.

This process of designing hardware components, implementing them in the C++ simulator to validate the algorithmic/functional behavior and then implementing them in VHDL ensured that all the VHDL components behaved exactly like the original C++ implementations. The increment approach allowed the complete FEIC design to be constructed in small steps and its behavior to be continually tested throughout the development process. This design process is summarized in Figure -7.

**PANGU (Planet and Asteroid Natural scene Generation Utility)**

Landing a spacecraft on the surface of another body in the solar system is a difficult and hazardous undertaking. If a vision-guided lander system is to be used then the system needs to be thoroughly tested before being considered on realistic images obtained under different lighting conditions and from different positions and attitudes relative to the target landing site. As a result, the University of Dundee developed PANGU to generate detailed synthetic models of cratered planetary surfaces and to allow images to be generated from any position and under any light condition. The images are generated using OpenGL to leverage the powerful 3D rendering facilities of modern graphics cards. A TCP/IP interface allows clients to obtain images from specific locations and attitudes as well as performing back-projection queries to enable the
physical 3D location to be obtained for feature points extracted from synthetic images. This enables the navigation filters to be validated.

Although PANGU was initially developed to model the Moon and Mercury it has been developed further to provide models of asteroids and of Mars (including sand-filled craters). On the image generation side there have been improvements in the rendering speed and quality along with the addition of facilities such as RADAR and LIDAR instrument simulation. An example of an early Mars model is shown in Figure -8.

![Figure -8: a- NASA Spirit rover (top-left), NASA Viking lander (top-right), PANGU synthetic image (main). b- PANGU Hierarchical Model.](image)

A requirement of the NPAL study was to be able to view the synthetic model with a 70 degree field of view from high gate down to low gate. This required a model which was 500 km in size along each edge which could be viewed at the landing site with a grid resolution of 25 cm. With current technology it is not possible to construct and manipulate models of such size at such a high resolution. PANGU uses a hierarchical modeling technique based on a succession of 12 1024x1024 Digital Elevation Maps with increasing resolution at the centre. The resulting model can be viewed over a wide range of distances from the central landing site while using only 500 Mb of disk space and 1 Gb of RAM. An example is shown in Figure -8.

**Camera Model**

PANGU uses a simple pin-hole camera modeling. The aim of the camera model is to transform the “perfect” images provided by PANGU into images that are representative of those generated with the specific navigation camera. The camera model implements the following effects:

- Kinematics: distortion rates, motion blur
- Geometric distortion and Optical/detector MTF
- Radiometric defects (PRNU, DSNU, dead pixels, PPE) and Noises (electronic/photonic)
- 3D parallax

About 400 sequences were generated to validate the end-to-end performances and sensitivity.
Covariance analysis

Sensors:

VBNAT

VBNAT is a multi-user facility environment gathering all developed functionalities for visual based navigation simulations.

Figure 9 – Functional description of the camera model.

Several tools and models have been developed in the frame of various VBNAT versions in order to store, visualize and post-process images and tracks. All these tools are Simulink blocks...
based on Matlab functions and S-functions. A part from the GNC functions, VBNAt integrates: a Sloshing model, a Parachute model, an Atmospheric perturbations model and an IMU model (Gyrometer scale factor, angular noise, bias, and random drift and Accelerometer scale factor, bias and noise).

The image generation process, using PANGU software, has been directly included within the VBNAT environment. The Simulink™ model send its request to PANGU for “image generation” through a TCP/IP interface to the computer where PANGU is running. PANGU uses the Digital Elevation Model (DEM) of the terrain and the Camera position and attitude to generate the images at the Camera frequency. It provides the image to the VBNAT environment.

A Covariance Analysis Facility has been added into VBNAT environment. This tool enables to perform two types of analysis:

- Inertial Navigation dispersions errors (taking into account initial estimation errors, IMU errors, Projection errors, and Gravity Field model errors),
- Dynamic dispersions (taking into account, initial dispersions, Boosts realization errors, Gravity Field model errors, Attitude Control errors).

VBNAT has been developed following an incremental approach, by a progressive upgrade of the simulation environment that is compatible with the overall development logic (Figure -4).

Performances

The end to tend validation gives a final overview of the major performance figures of merit of the navigation chain. The real time performances were obtained by feeding the VBNC with realistic images generated by PANGU and evaluating the behavior of the Navigation filter and the FEIC.

The following scenarios were evaluated:

- Mercury descent: corresponds to a non vertical approach with a small angle between the S/C velocity and the planet surface
- Lunar scenario is similar to the mercury one, including lunar features.
- Mars descent: is an almost vertical descent with an initial phase under parachute and the final phase without.
Figure 12 - Descent sequences are generated with virtual scenes at 20 Hz, on a Mars terrain in presence of boulders. Under parachute phase (left), under 3 axis control (right).

The following table presents a summary of the performances obtained on Lunar, Mercury and Mars scenarios with the Navigation Filter and the FEIC using real PANGU images.

<table>
<thead>
<tr>
<th></th>
<th>Moon</th>
<th>Mercury</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-track error (m/s)</td>
<td>NRT: 0.036</td>
<td>NRT: 0.22, RT: 0.282</td>
<td>NRT: 0.073, RT: 0.11</td>
</tr>
<tr>
<td>Along-track error (m/s)</td>
<td>NRT: 0.035</td>
<td>NRT: 1.83, RT: 3.55</td>
<td>NRT: 0.015, RT: 0.41</td>
</tr>
<tr>
<td>Distance to plane error (m)</td>
<td>NRT: 120</td>
<td>NRT: 115.5, RT: 138</td>
<td>NRT: 0.3, RT: 2</td>
</tr>
</tbody>
</table>

Table 3 : Worst case performances at touch down (NRT : Non Real Time, RT : Real Time)

Image processing functions revealed to be robust up to:
- 8° rotation n around the optical axis between frame that is 160°/s
- 20% approaching rate between frames
- Signal to noise ratio as small as 70

The end-to-end performances were obtained considering: 0.01° IMU/NavCam alignment error, 0.1%, camera scale factor error and 5ms measurement time tag error.

Sensitivity to IMU class has been evaluated that revealed a very low sensitivity of the final performances to gyro and accelerometer classes as well as a small dependency of the convergence time to the accelerometer class. The obtained performances are achieved with IMU as specified in the following table:

<table>
<thead>
<tr>
<th>Class</th>
<th>Comment</th>
<th>Gyro drift</th>
<th>Gyro scale factor</th>
<th>Accelero drift</th>
<th>Accelero scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Correct accelero + Mems/Sireus gyro (Class 3_3 accelero, Class 4 gyro)</td>
<td>20°/h</td>
<td>100 ppm</td>
<td>500 µg</td>
<td>1000 ppm</td>
</tr>
</tbody>
</table>
Implementation performances have been evaluated and validated through target measurements that demonstrate the capacity of a LEON processor to process the data according to a given amount of feature points (see Table 4) either optimally (primary) or sub-optimally (secondary). The sub-optimal integration of points allows a total parallelization of the implementation over several CPU if required.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>LEON</th>
<th>Virtual case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor rate</td>
<td>100MHz</td>
<td>2.5GHz</td>
</tr>
<tr>
<td>% of main CPU allocated to low frequency task</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>% of other CPU allocated to low frequency task</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>1 floating addition</td>
<td>25 cycles</td>
<td>25 cycles</td>
</tr>
<tr>
<td>1 floating multiplication</td>
<td>25 cycles</td>
<td>25 cycles</td>
</tr>
<tr>
<td>Camera frequency</td>
<td>20Hz</td>
<td>20Hz</td>
</tr>
<tr>
<td>Low frequency task</td>
<td>2Hz</td>
<td>2Hz</td>
</tr>
<tr>
<td>Examples of achievable filters</td>
<td>9 primary points (optimal filter)</td>
<td>32 primary points (optimal filter)</td>
</tr>
<tr>
<td></td>
<td>6 primary + 4 secondary points</td>
<td>10 primary + 104 secondary points</td>
</tr>
<tr>
<td></td>
<td>5 primary + 6 secondary points</td>
<td>6 primary + 184 secondary points</td>
</tr>
<tr>
<td></td>
<td>9 primary points on principal CPU + 7 secondary per additional CPU</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Real-time profiling results.

IN-FLIGHT TESTING: THE PLGTF EXPERIMENT

The NPAL project brought this vision-based technology to a TRL 4. In order to bring the technology to TRL 6, ESA initiated the “Precision Landing Ground Test Facility” (PLGTF) program on which the NPAL navigation system will be the first to be tested in 2009. PLGTF is based on an Unmanned Air Vehicle (UAV) and intents to simulate moon or Mars landing trajectory in the Morocco desert where terrain with Mars and moon representative morphology characteristic can be found. The test facility is currently under development.

Astrium has developed for the flight demonstration the NPAL experiment: The developments include the required flight hardware and software to support navigation algorithms execution as well as algorithms functional consolidation and tests to meet the maturity and robustness required by a flight demonstration.

The NPAL experiment has been delivered in April 2008 to prepare integration on the test facility. First flight tests are planned in spring 2009.

Real-time experiment Avionics development

The navigation algorithms have been implemented on a PC104+ system named Experiment Computing Box (ECB). The PC104+ technology has been selected for the flight hardware development as it offers the robustness (vibration, thermal) compactness (mass, envelop) and efficiency (power, computational) imposed by the flight experiment.

The ECB is built around the following components:

- A Pentium PC board (1.4GHz), running Linux, dedicated to the navigation algorithms
• An FPGA board (based on Xilinx Spartan module), used to handle the three equipments interfaces (Camera/FEIC, IMU, Time synchronization) at a minimal CPU cost, giving thus more processing time for navigation application. The FPGA interfaces with the camera through a Spacewire link and with IMU through a RS422 serial link.

In addition to the ECB core, a video-recorder has been developed to extend post flight analysis possibilities. The objective is, for instance, to allow off-line execution of the image processing algorithms on the stored images, to perform detailed analysis of the flight tests or to validate functional evolutions on real images. The video-recorder allows real-time storage of the full uncompressed video flux (100Mbits/s) onto a 16Gbyte flash disk, giving a 20mn recording capability.

A major advantage of the chosen architecture and design is its modularity. Additional CPU board can be integrated with minor effort on the ECB stack, to increase computation capacity and allow supplementary on-board processing. This functionality is currently exploited for the ESA “Hazard Avoidance System Experiment” project for which a dedicated CPU is added to implement Hazard Avoidance algorithms in real-time.

To be compatible with flight tests, the NPAL camera breadboard model was reinforced. The objective of the reinforcement was to ensure the camera can be operated without risk in the perturbed UAV vibration environment, while offering nominal measurement performance. The requirements taken into account are for vibration 1g sine 5-500Hz (operating) and for shocks 15g – 6ms (operating) and 30g – 11ms (survival). These requirements have been derived from the IMU operating domain. For PLGTF, the experiment base plate will be isolated from the UAV main body to ensure the equipments are operating within the specified domain.

Camera vibration and shock tests have been performed to verify that the reinforcement allows reaching the required accuracy. Two types of errors have been characterized: (i) The static error resulting from vibration and shocks by measuring the alignment of the camera bore axis before and after tests; (ii) the dynamics error during the vibration tests. This dynamic error was measured using a dedicated test structure on which was rigidly mounted a test pattern and the camera. Stability of the test structure was verified using accelerometers. Tests show good results in line with the needs (variations lower than half a pixel).

**Ground tests**

A ground test campaign has been performed, after experiment development, allowing a first verification of the experiment behavior before helicopter flights. Static and dynamics tests on real 3D scene have been executed. For the dynamic tests, the experiment was mounted on a trolley.

The objectives of the dynamic tests were multiple: test of the feature point tracking capability, verification of the distortion compensation by the experiment software and, finally, verification of the landing navigation filter behavior. The tests show good results with velocity and position estimation by the navigation filter consistent with reality. The performance of the filter was nevertheless not quantified as no independent position or velocity measurements source/reference was available. The capability of the experiment to track feature point up to 15°/s2 acceleration was also demonstrated during the tests.

The following plots show the results of a dynamic test. The test consists in moving the camera toward a building wall, starting from 15m and a null velocity down to 8m. Pictures taken by the camera at the beginning and end of the scenario are shown below the plots. The test simulates a “landing” on the building, the navigation filter estimating its distance with respect to the building (red dashed curve) from the feature points estimated distances (blue curves).
This dynamic test demonstrates the capability of the navigation filter to correctly estimate relative position and velocity with no a priori knowledge. The observed behavior is the expected one. The final distance estimation is consistent with reality (8m) which confirms the nominal behavior of the overall chain.

![Graph showing points depth & distance to plane](image)

**Figure 13 - Ground tests results demonstrating nominal filter behaviour**

The developments undertaken in the frame of the NPAL experiment preparation have allowed improving the maturity of the NPAL navigation concept: Algorithms have been robustified, the required flight hardware and software developed and dynamic ground tests performed on real scene, showing promising results. The next step for validation is the flight demonstration of the experiment using a UAV as part of the PLGTF project. First flights are foreseen in spring 2009. Additional steps will be achieved in 2009/2010, with closed loop flight tests of Hazard Mapping and Hazard Avoidance functions through the “Hazard Avoidance System Experiment” project.

**ALTERNATIVE MISSIONS**

In parallel of these activities, ESA has initiated the “Multi-purpose Vision-Based Navigation Sensor Architecture Definition” project under Astrium lead. It aims at defining the architecture of the EM of a vision based camera core and navigation chain architecture that can be used, not only for landing, but also for other space applications such as autonomous rendezvous, interplanetary or rover navigation. The target missions are Mars Sample Return, Exomars, Lunar missions or asteroid sample mission. As part of this study the EM roadmap will be defined (industrial file available). The objective is to have a qualification model in 2012 and a flight model in 2013.

The multi-mission philosophy that is developed for VisNAV lies in the cost and risk reduction of the vision based technology development through commonality of means, tools and technological developments or validation. Parts of the VisNAV architecture can be obviously re-used (like the detection chain) or tuned (FEIC code, navigation filter) from an application to an other. The VisNAV architecture thus relies on a modular design.
Figure 14 – IP commonalities between missions.

**Rover missions**

A typical rover scenario consists in:

1. Locomotion objective detection from ground: Once images of the surroundings are acquired, and sent to Earth. Operators on ground process them and define a locomotion goal to reach; usually located several meters away, this is the locomotion objective.

2. Mapping: Images acquired by cameras are processed. They are corrected through a calibration procedure. Images are then matched and the Digital Elevation Map (DEM) of the surrounding area is built up.

3. Navigation: The navigation phase (the rover being still at rest) consists in building a risk map of the surroundings, providing every cells of the DEM with navigation scores, function of rover capabilities (maximal slope, possible rotation of rover, dimension). A sub-goal is then identified on the long way to the locomotion objective. The trajectory to the final target is therefore divided into several segments, depending on terrain features mainly (boulders, slopes). An optimal path is computed from the current segment to the next sub-goal.

4. Path execution: The path is sent to the path execution function. The rover starts moving. Typical velocity is on the order of 3 to 5 cm/s. A typical daily transverse is on the order of 100 meters.

5. Localization: In the meantime, the localization function is continuously performed on-board the rover’s computer. It basically consists in estimating the rover attitude and position with respect to a given set of coordinates (that is defined by Ground when the rover is at rest). The attitude and position are usually based on hybridization of IMU and visual odometry as well as wheel odometry. Typical localization needs are 1% for position and 1° after 100m.

A preliminary VisNAV assessment for rover localization has been done on the basis of sequences acquired on the CNES Mars yard to validate the image processing models (NPAL experiment embedded on Rover prototype). The conclusions are the following:

- Capability of the FEIC to detect and track 200 feature points in real time (10Hz readout frequency) in a mars representative environment.
- Good tracking efficiency of the implemented algorithms and robustness to the rover dynamics condition as well as the robustness of the image processing algorithms to distortion (long tracks).

- Simulated navigation performances are typically: 0.2% in position (estimation after 100m locomotion) and 0.5° after 360° circular trip.

![Figure 15 – Results of feature extraction (left) and tracking (center) and rover experiment integration](image)

**Interplanetary navigation**

There are mainly three phases in an interplanetary mission scenario in which vision based navigation are of major interest: cruise phase, encounter phase and close phase.

**Cruise Phase**

During the cruise phase, maneuvers are performed occasionally. The navigation is done in an absolute manner, based on star mapping and asteroid detection for which ephemerides are a priori known. The target (planet or moon in the frame of Cosmic Vision) is not yet in visibility.

**Encounter Phase**

The target is in visibility, yet not resolved (it covers less than 10 pixels in size). LOS and position relative to the target are estimated on board while absolute navigation is still performed, notably through star mapping. Center of Brightness (COB) or even Center of Mass (COM) are estimated in function of Image Processing, knowledge of target geodesic, illumination phase and camera accuracy.

**Close Phase**

The target is fully resolved; its limb covers several pixels within the camera FOV. The navigation is done in a relative manner. The center of the target is estimated based on dark to bright transition and geodesic knowledge. Maneuvers for orbit correction can be done to optimize the slingshot effect or reach a particular point (to eject a probe or track a feature on ground).

Vision based solutions to interplanetary missions have been studied in the AutoNav project.

**Landing on small bodies**

The low-gravity conditions that prevail around small bodies allows using specific GNC techniques that are not usually applicable for planetary orbiting and landing, and impact the classical trades between autonomy and ground involvement. Naturally adapted to the navigation relatively
to a target, vision-based navigation techniques find an interesting application field for missions
towards small bodies as they offer an autonomous and efficient solution for interplanetary cruise
(target acquisition and tracking) and safe landing.

Current assessments of vision based navigation strategy for landing on small bodies are
mainly based on the Marco Polo project in the ESA Cosmic Vision program, which is a near earth
object sample return mission. Typical requirements of the overall GNC architecture are a landing
accuracy of 2 m around a predefined landing site. The major state to be observed by the vision
based navigation chain and controlled to meet the final landing requirements is the velocity direc-
tion with respect to terrain, which can be estimated using the matching of a few images at the
very beginning of the descent, just after the engaging boost.

Rendez-vous

More and more mission concepts rely on rendezvous techniques. Exploration missions toward
Mars and farther planets in the solar system with the return to Earth of sample soils as a goal, or
in orbit servicing mission to refuel or repair a satellite without mission interruption, to build large
structures or to clear dead satellites of an operational orbit towards a graveyard orbit are some of
them.

To answer the intrinsic risk of collision between the vehicles involved in the rendezvous and
flying at short distances, the reactivity is a key feature. The reactivity is not compatible with op-
erational constraints, such as communication availability, and speaks in favor of a high level of
autonomy of the rendezvous systems. The autonomy shall be understood as the on-board capacity
to plan or re-plan the mission to adapt to the different situations or the unanticipated ones. The
autonomy goes hand in hand with the capacity to analyze the situation and in particular a vision-
based navigation.

ESA and EADS Astrium are cooperating in the frame of HARVD, standing for High inte-
grated multi-range rendezvous control system and Autonomous Rendezvous and capture GNC
test facility. HARVD ambitious goal is to develop a highly autonomous and generic system for
rendezvous missions. It is designed to perform a rendezvous around any planet, on circular or
eccentric orbits, with an autonomous detection for any targets, i.e. cooperative or not, equipped or
not, for capture or docking and considering different propulsion configurations.

The VisNAV architecture is designed to handle such requirements: detect the target from
ranges as far as 1500 km, as well as to analyze the situation at closer range, for instance to iden-
tify the target and characterize its docking port orientation and motion.

Figure 1. Object recognition and matching
CONCLUSION

An ambitious research program was set to give Europe access to solutions in the field of vision based navigation for space applications. Key technology breakthroughs made this effort accessible, notably the evolution in the APS detectors, the capacity of the new generation LEON calculators. A long led effort in navigation design and real time implementation proved to be a major contributor of the technology development program.

The VisNAV camera exists at an elegant breadboard level. Its real time operation as well as performances on planetary landing scenarios are demonstrated. In-coming effort will focus on:

- The flight demonstration on PLGTF platform (2009) and integration of hazard avoidance functions (2009/2010)
- The confirmation of promising localization performances obtained on rover scenarios (2009)
- The upgrade of the architecture, up to an E(Q)M development, to account for alternative missions like landing on small bodies (2009-2012)

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- University of Dundee (UK): development of the PANGU tool and FEIC coding
- INETI (Portugal): Image processing expertise on feature extraction and tracking.
- Galileo Avionica (Italy): camera design and development
- Carlo Gavazzi Space (Italy): PLGTF platform integrator
- DEIMOS (Spain and Portugal): Hazard Avoidance functional design
- Katholieke Universiteit Leuven (Belgium): object recognition.

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