PROJECT FINAL REPORT

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4.1 Final Publishable Summary Report

4.1.1. Executive Summary

The EC FP7-SPACE Project PRoViScout (Planetary Robotics Vision Scout) aimed at demonstrating the feasibility of vision-based autonomous sample identification & selection as well as terrain hazard analysis for a long range rover scouting/exploration mission on a terrestrial planet along with the robotic elements required.

PRoViScout was intending to

- **Address and merge a representative set of sensors** to fulfil important scientific objectives and prove the general applicability to the approach in different mission scenarios.
- **Include** the **search for scientifically interesting targets** as an essential component for mission success **into the navigation chain by Autonomous Tasking**
- **Compile a PRoViScout Demonstrator** on a mobile platform that combines sensors, processing and locomotion on-board ready **for an integrated outdoor demonstration**.
- Integrate a **monitoring function** (PRoViM) to understand the behaviour of the system.
- **Demonstrate the feasibility of long-term vision-based scouting** making use of a representative outdoor test bed and the PRoViScout Demonstrator platform.

PRoViScout reached its objectives. A novel, autonomous exploration system was set-up and demonstrated within an external field trials campaign at the end of the project. Requirements from science and operations were collected and reported which lead to a set of candidate field trials sites and finally a decision to hold the trials on the Island of Tenerife. System design and interfaces were defined for the rover on-board system containing both scientific target detection and the rover navigation system. The system integration was realized in CORBA, which enabled end-to-end testing in the field, offering also simulation-based monitoring of all rover operations and displaying various elements of mission operations.

Whilst the full integrated chain containing of vision sensors and on-board rover software was successfully tested during the September 2012 Trials at Tenerife, complementary tests and verifications were conducted on a comprehensive set of sensors such as a Wide Angle Laser Imager (WALI), a hyperspectral stereo camera (HyperCam) and a newly developed 3D-Time-of-Flight (TOF) camera designed for medium range zoomable 3D & RGB signal capture at daylight.

The field trials at Tenerife were supported by images captured from a tethered aerobot, which were processed on-site into a medium resolution Digital Elevation Model (DEM) that was used for operations planning. At the end of the trial, the PRoViScout demonstrator platform autonomously ran an integrated outdoor demonstration containing vision based navigation, monitoring of actions & visualizing 3D scene, demonstrating science autonomy capabilities and combining science autonomy with navigation in a decision system.

The project and in particular the field trials were disseminated via the project web site www.proviscout.eu, and also (during the field trials) via a dedicated web site that gave on-line access to the activities during the trials (displaying the site via a web cam, and the software & simulated status of the rover and its instruments via different visualization modes). Various additional dissemination elements were published such as broadcast videos, press releases, and public as well as scientific articles and presentations at conferences, workshops and public events.

PRoViScout could successfully demonstrate a full chain of site mapping, missions / science planning, on-board mapping, path planning, navigation and Rover control, as well as science target selection coupled via a decision system to the navigation system, all integrated in a hardware framework consisting of a Rover (Idris by Aberystwyth University) and a stereo camera set-up with Pan-Tilt-Unit and RGB / multispectral capabilities. The whole set of elements necessary to assess the building blocks of a real planetary rover mission from the computer vision and science assessment point of view was complemented by aerobot images based mapping, and simulation integrated into the remote control scenario.

4.1.2. Project Context and Main Objectives

The search for traces of life – past or present – is at the centre of Europe's on-going planetary exploration programme. In the near future, robots with life science sensors will explore the surface of Mars and drill below its surface to look for signs of life.
The EC FP7-SPACE Project PRoViScout (Planetary Robotics Vision Scout) aimed at demonstrating the feasibility of vision-based autonomous sample identification & selection as well as terrain hazard analysis for a long range scouting/exploration mission on a terrestrial planet along with the robotic elements required. It has brought together major groups currently working on planetary robotic vision, leading experts in planetary surface operations, and experienced planetary scientists, consisting of research institutions all over Europe, NASA-JPL in the US, and the industrial stakeholders involved in mission design, vision, navigation and data exploitation for robotic space missions (Table 1), convening to a final end-to-end demonstration.

www.PRoViScout.eu © PRoViScout	▪ Joanneum Research (JR), Austria ▪ SciSys UK Ltd. (SSL), United Kingdom ▪ German Aerospace Center (DLR), Germany ▪ Aberystwyth University (AU), United Kingdom ▪ Czech Technical Unviversity (CTU), Czech Republic ▪ GMV (GMV), Spain ▪ University of Leicester (ULEIC), United Kingdom ▪ Swiss Center for Electronics and Microtechnology (CSEM / CH) ▪ TraSys (TRS), Belgium ▪ University College London (UCL), United Kingdom ▪ University of Strathclyde (UoS), United Kingdom ▪ Kings College London (KCL), United Kingdom

Table 1: PRoViScout Beneficiaries.

Robotic planetary space missions are unmanned missions performing in situ exploration of the surface and (if applicable) atmosphere for any planetary objects outside the Earth. Most such missions involve a means of mobility provided by either a surface vehicle (rover) or by aerial vehicles (balloons, aerobots etc.). Mobile systems are among the most critical of all space missions in requiring a rapid and robust on-site processing and preparation of imaging data to allow efficient operations for a **maximum use of their limited lifetime**. In future, the number and variety of such platforms will require more autonomy than is feasible today, particularly in the **autonomous on-site selection of and access to scientific and mission-strategic targets**. **PRoViScout** provides the building blocks on board of such future autonomous exploration systems in terms of robotics vision and decisions based thereupon. Populate a robotic vision on-board processing chain (PRoViSC) with representative components available at the proposing institutions, with minor adaptation and integration effort.

Its **main objectives** are summarized below:

- **Address and merge a representative set of sensors** (including a novel zoom 3D-Time-of-flight camera) to fulfil important scientific objectives and prove the general applicability to the approach in different mission scenarios.
- **Include** the **search for scientifically interesting targets** as an essential component for mission success **into the navigation chain by Autonomous Tasking** (Goal based planning and re-planning).
- **Compile a PRoViScout Demonstrator** on a mobile platform that combines sensors, processing and locomotion on-board ready **for an integrated outdoor demonstration**.
- Integrate a **monitoring function** (PRoViM) to understand the behaviour of the system.
- **Demonstrate the feasibility of long-term vision-based scouting** making use of a representative outdoor test bed and the PRoViScout Demonstrator platform.

4.1.3. Main Science & Technology Results / Foregrounds

4.1.3.1 Summary of Foreground

Within PRoViScout a **novel, autonomous planetary exploration system** was set-up and demonstrated within an external field test at the end of the project:

1. All **requirements from science and operational point of view** were collected and documented. This includes the definition of the target scenario planned for the field test during the final project phase (Figure 1).

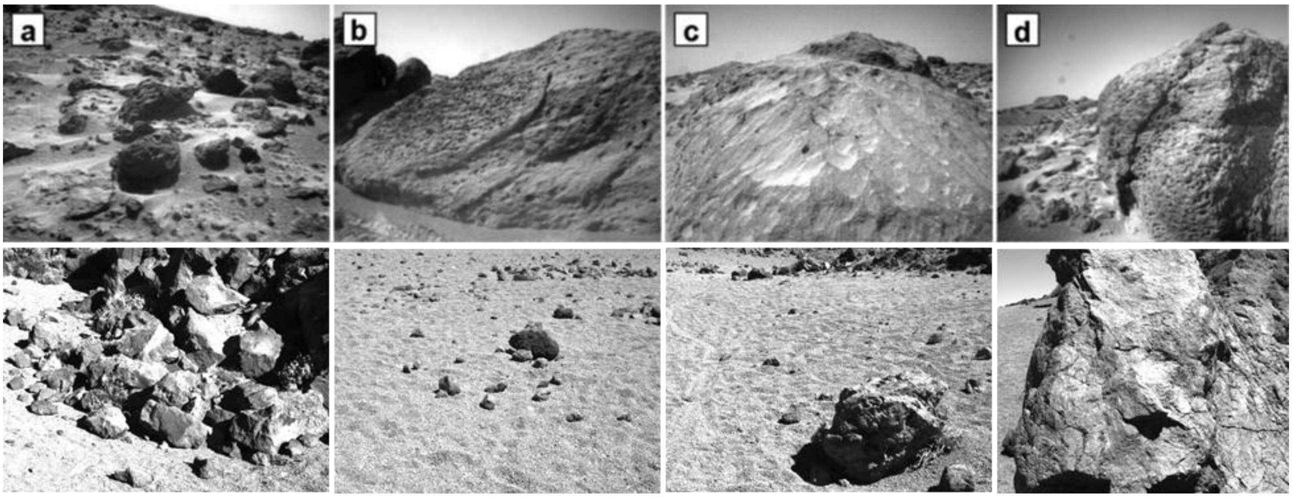


Figure 1: Top: Rocks at the Pathfinder landing site seen taken by the rover cameras. Bottom: Representative images taken from PRoViScout on-board cameras during final field trials.

2. The **System design** was developed. All **interfaces between the components** (rover, vision system, Hardware trade-offs, navigation system, decision module, execution control, and monitoring system) were defined, and the main functions as well as distributed and shared data were identified & documented in a design document (Figure 2).

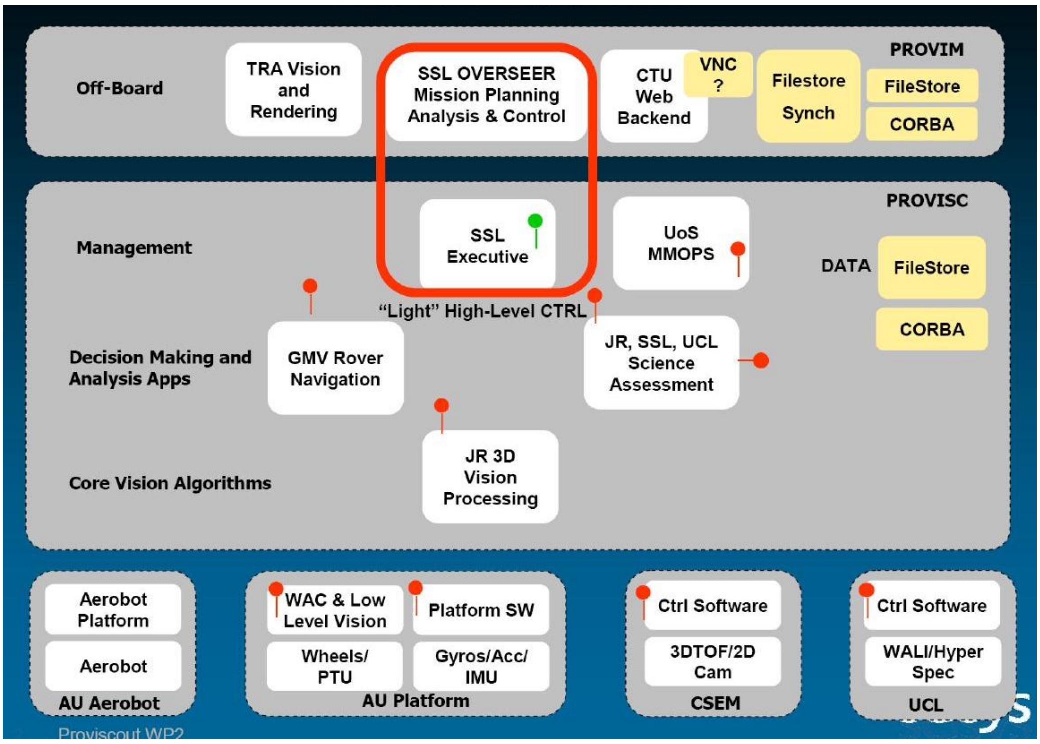


Figure 2: PRoViScout system & components design.

3. Candidate **field test sites** in Morocco, Tenerife, Wales and Iceland were investigated, assessed and discussed. Based on evaluating a set of selection criteria, **Minas de San José on Tenerife** was chosen as test site for the external field trials.
4. A set of reference targets (in terms of heterogeneous criteria like texture, color etc.) was defined and published in a **www catalogue of targets**.
5. The provided target data were used for **implementation, enhancement and verification of pattern recognition, learning, object detection and classification algorithms** to detect meaningful targets (like sediment layers, rocks etc.).
6. Based on the localization of potential science targets within a wide-angle camera (WAC) image, **pointing commands** (PTU, pan and tilt unit, angles) were produced to capture close-up images of those targets with a narrow-angle camera, or other imaging device (**APIC**, Automatic Pointing and Image Capture).
7. An approach to **distinguish between fluorescence of microorganisms and of host minerals** was established (Figure 3, left).
8. A new **3D-Time-of-Flight** (3D-TOF) camera was designed by CSEM being able to **zoom and integrate RGB high-resolution images**.
9. The following **components** were mechanically & electrically **integrated** into the **HW system**: rover and PTU, multispectral PanCam, High Resolution Camera (HRC), HyperCam and 3D-TOF.
10. The **software interfaces** of the following HW components were designed and realized using **CORBA**: rover and PTU, multispectral PanCam, HRC and 3D-TOF (the latter never having been tested in the full chain). No CORBA interface was implemented for the HyperCam.
11. **CORBA** was also used for the integration of the following **SW components** into **the SW framework** running **on-board** of the rover (**PRoViSC**): Vision Processing, Navigation, Science Assessment, Decision Module (MMOPS), Executive and Rover Control (Figure 2).
12. An **off-board SW component** (**PRoViM**) for monitoring and visualizing all rover operations / decisions etc. was implemented (Figure 2), both on-site and off-site via a www interface.
13. A **simulator**, modeling the elements of a robotized system and the morphology and the texture of its environment, was implemented in 3D (**3DROV**, Figure 3, right).

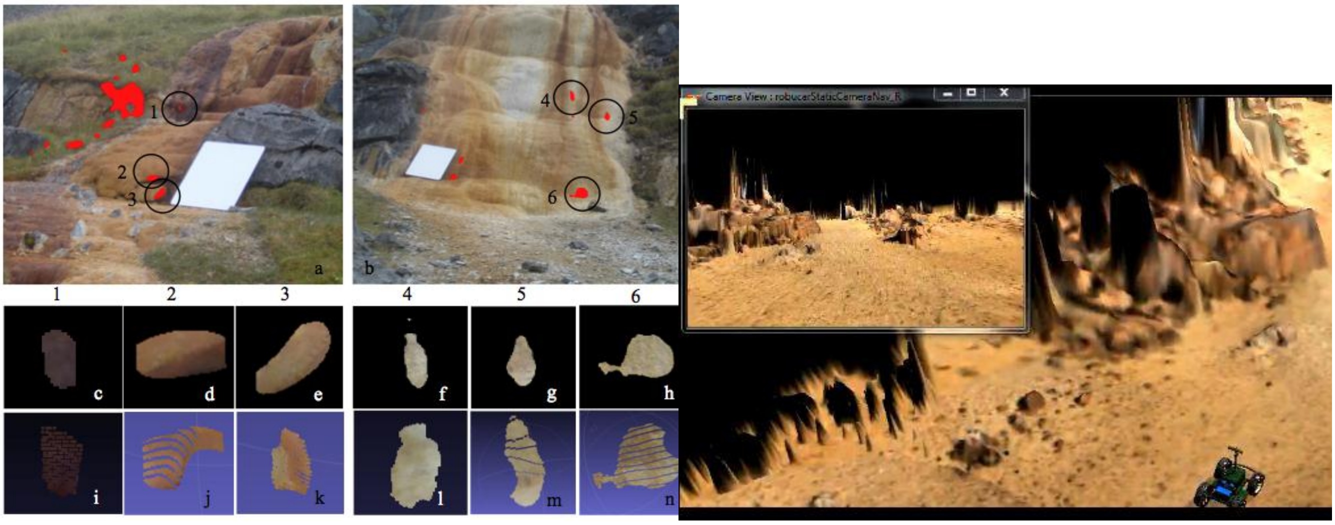


Figure 3: Left: a) NDVI (Normalized Difference Vegetation Index) feature samples 1-3 re-projected in 2D image; b) NDVI feature samples 4-6 re-projected in 2D image; c ~ h) Extracted 6 NDVI feature samples in 2D; i ~ n) Extracted 6 NDVI feature samples in 3D. Right: Screenshot of 3D simulator 3DROV showing the rover acting during final field test on Tenerife.

14. A (mono-chromatic) **Aerobot** camera was set-up and mounted on a balloon. Image capturing tests were performed. Aerial images were used for DEM generation of the test site during the external test.
15. All integrated on-board **HW / SW components** were **tested** in a series of **lab tests**.
16. An integrated rover and instrument deployment was performed in a representative environment to **test science goals and performance**, and utility for sample targeting (**AMASE**, Arctic Mars Analogue Svalbard Expedition 2011).
17. The implemented 3D vision, science assessment and 3D reconstruction **algorithms were verified** by means of **applying them to PDS-archived MER imaging data** (Mars Exploration Rover).
18. An **Internal Test** including all integrated on- & off-board HW / SW components was performed.
19. A 10 days lasting **External Integrated Test** was planned, organized and performed in Minas de San José, a representative (Mars-like) landscape located in the caldera of Tenerife. During the first trial days, minor interface adaptions were implemented and all integrated components were tested on site The site was mapped using Aerobot images (including short-term generation of a digital elevation model – DEM – in the global coordinate frame).
20. At the end of the trial, **the PRoViScout demonstrator platform autonomously ran an integrated outdoor demonstration containing vision based navigation, monitoring of actions & visualizing 3D scene, demonstrating science autonomy capabilities and combining science autonomy with navigation in a decision system**.

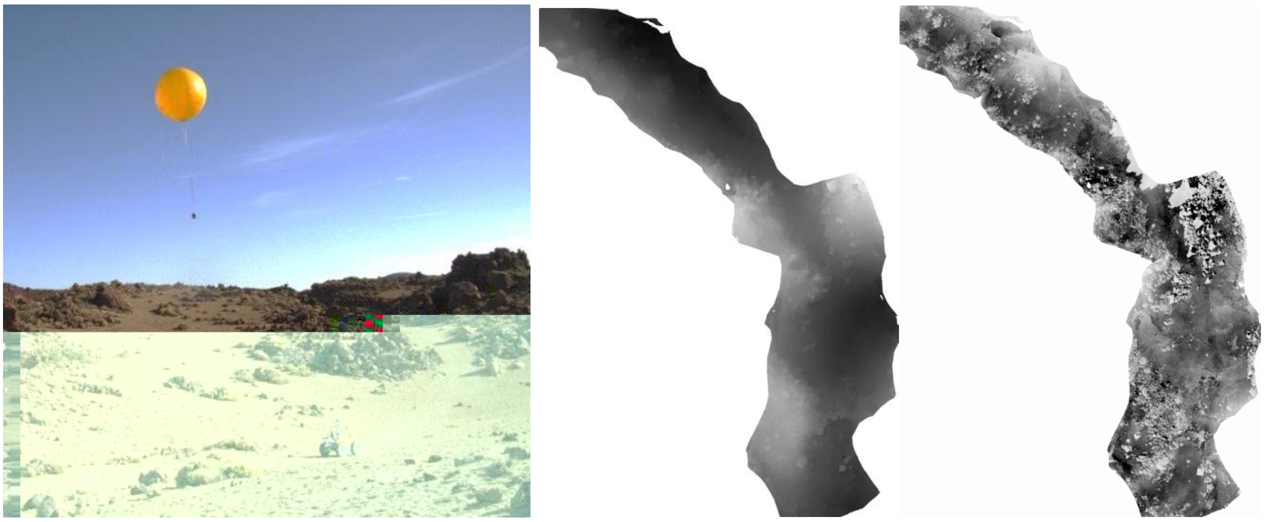


Figure 4: Left: Rover "Idris" with coupled aerobot acting on test site during final field test in Tenerife. Middle: Digital Elevation Model (DEM) of whole test site generated from aerobot images. Right: Corresponding ortho image.

21. A high **impact** could be reached by a set of **dissemination** activities such as a press day during the external field trial, the website incl. live streams during the field trial, scientific publications, presentations at conferences, a www target catalogue or student projects.

Within PRoViScout a **variety of results and foreground** could be achieved in the following areas of research and development: (1) missions, targets and system design, (2) science selection & science assessment, (3) vehicles & sensors, (4) on-board and off-board software, (5) system simulation and testing and (6) planning, organizing and performing an integrated external field test. More details about the named components are given below.

4.1.3.2 Missions, Targets & System Design

(a) Missions & Targets

At the beginning of the project, mission cases were collected for all relevant planetary surface missions and requirements were derived, taking into account the context of PRoViScout. The major result was the D2.4.1 Mission Requirements Document. It took into account the following objectives:

- Provide mission cases that represent possibilities
- Derive a number of requirements
- Identify realistic scenarios in analogue environments
- Define scientific objectives with success criteria
- Define different scenarios dependant on resources

The science assessments were reviewed and prioritise in terms of science and implementations, leading to a set of PRoViScout operational scenarios.

The **main objectives** were settled as:

- Applicable to a Martian analogue environment
- Navigation and localisation over 200m
- Identification of scientifically interesting targets
- Plan adaption depending on current situation

The **Concept objectives** were identified as follows:

- Making decisions more quickly, allowing a greater exploration activity
- Enable autonomous long range navigation and operations
- Enabling the detection and detailed capture of dynamic science events which would otherwise be missed
- Enabling a local science assessment of an area without compromising traverse schedules.

Further breakdown of the scenarios generated dependencies and chains, visualized in a scouting timeline, and a UML representation of a typical sequence of actions.
Finally, 33 scientific requirements were mapped to 56 functional requirements, broken down to the following components:

- PRoVIM Vision and Rendering
- PRoVIM Mission Planning, Analysis and Control
- PRoVIM Web
- PRoVISC Science Target Selection
- PRoVISC Vehicle Navigation
- PRoVISC Executive
- PRoVISC Planning
- PRoVISC Vision Processing
- Hardware: Rover and Aerobot

(b) System Design

From the gathered knowledge the system design was derived and summarized in the systems design document in terms of camera specifications and platform interface definitions. The GNC requirements & constraints were analysed and components were designed and modelled. A 3D-TOF processing prototype was generated and the design for a mapping cycle was elaborated. C++ interface discussions of Vision & Navigation core functions took place and pattern recognition use cases incl. examples were formulated. Overall Architectural Design raised a set of issues that were jointly discussed and resolved in major part.

After architectural design, system design and test analysis, the preparation and release of base system design documents (including ICDs) were distributed to relevant partners for their review, with aim of inclusion of inputs to be received into the final design. Based on this, architectural design, system design, code, and test analysis incorporating ICD inputs were received from consortium partners (including the relationships to the web interface, the GNC requirements and constraints, component design and modelling, and the specification of RGB/TOF sensor). Emphasis was also laid to the interface between vision processing and relevant visualization in PRoViM. The decided PRoViSC structure is displayed in Figure 5.

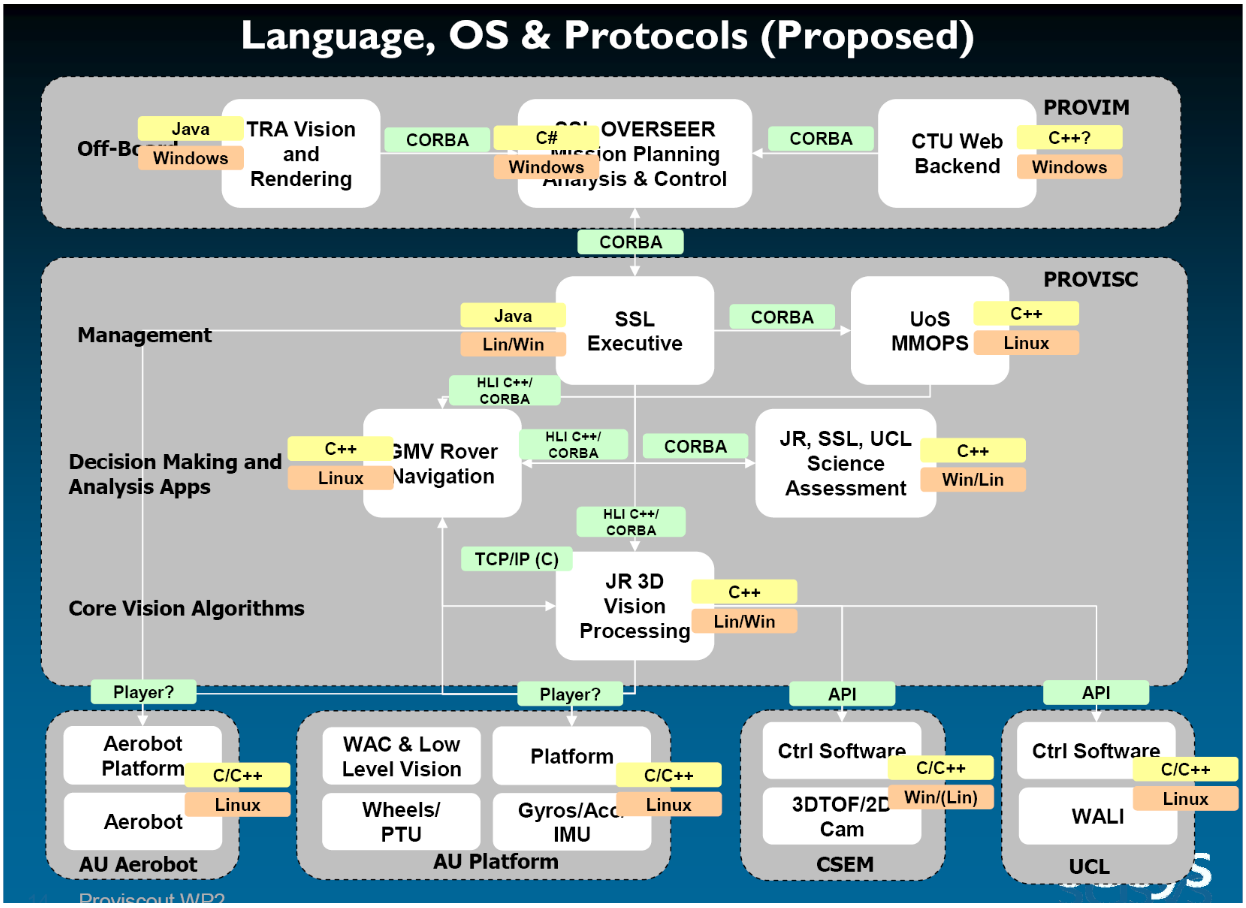


Figure 5: Proposed platforms and interactions in PRoViSC.

The interface for the request and return of information about the execution of tasks and their current status was formulated in discussions (Decision Module). The structure of example use-cases in order to identify the ways in which the Decision Module would interact with the choices offered to it was analysed and documented.

4.1.3.3 Science Target Selection & Assessment

A **representative set of test images for pattern recognition development** was prepared (three sets of test images - with three versions of each image: original, annotated, labelled). The data included data sets of original and annotated images from Svalbard and Iceland. Furthermore, test images from different terrestrial analogue environments that are representative for science targets on Mars (including labelled versions and masks) were prepared for simulation and testing purposes. An interactive web-based catalogue of test images (Deliverable D3.1.1) has been designed and implemented, making synergetic use of existing FP7-funded research infrastructure (i.e. the “Interiors and Surfaces” Node, operated by DLR in the context of Europlanet’s IDIS system.

An **Aerobot campaign** was performed in Aberystwyth in order to assess the viability of the aerobot images and potential for aerial science extraction.

A list of **candidate sites** for the external field test has been compiled. These sites were visited in June 2011 and the results presented at JPL MSL meeting in December 2011. Based on this information, Minas de San José on Tenerife has been chosen as test site for the external field trials.

The **fluorescence response** of different microbial and prebiotic molecular targets as well as the degradation of such a fluorescent signal by the UV and ionizing radiation environment of the Martian surface, have been characterized. A handheld fluorescence imaging instrument, a Wide-Angle Laser Imager (WALI), was developed. The specific objectives achieved are:

1. Full characterisation of the fluorescence response from different microbial and prebiotic target fluorophores by generating EEMs
2. Determination of the degradation of cyanobacterial fluorescent biosignatures by ionizing radiation on Mars
3. Determination of the degradation of prebiotic PAH fluorescent signal by solar UV on the surface of Mars
4. Design, construction, and testing of a handheld fluorescence imaging device, WALI.

The AU **Automatic Pointing and Image Capture** (APIC) software was developed and tested. The primary purpose of the AU APIC rover software is to locate potential science targets of interest in a wide-angle camera (WAC) image and then produce pointing commands (pan and tilt unit, PTU, angles) to capture close-up images of those targets with a narrow-angle camera, or other imaging device. Given an initial image or camera pointing direction APIC can, if required, run autonomously. The main aim of APIC is to help maximise the science data return from a rover exploration platform.

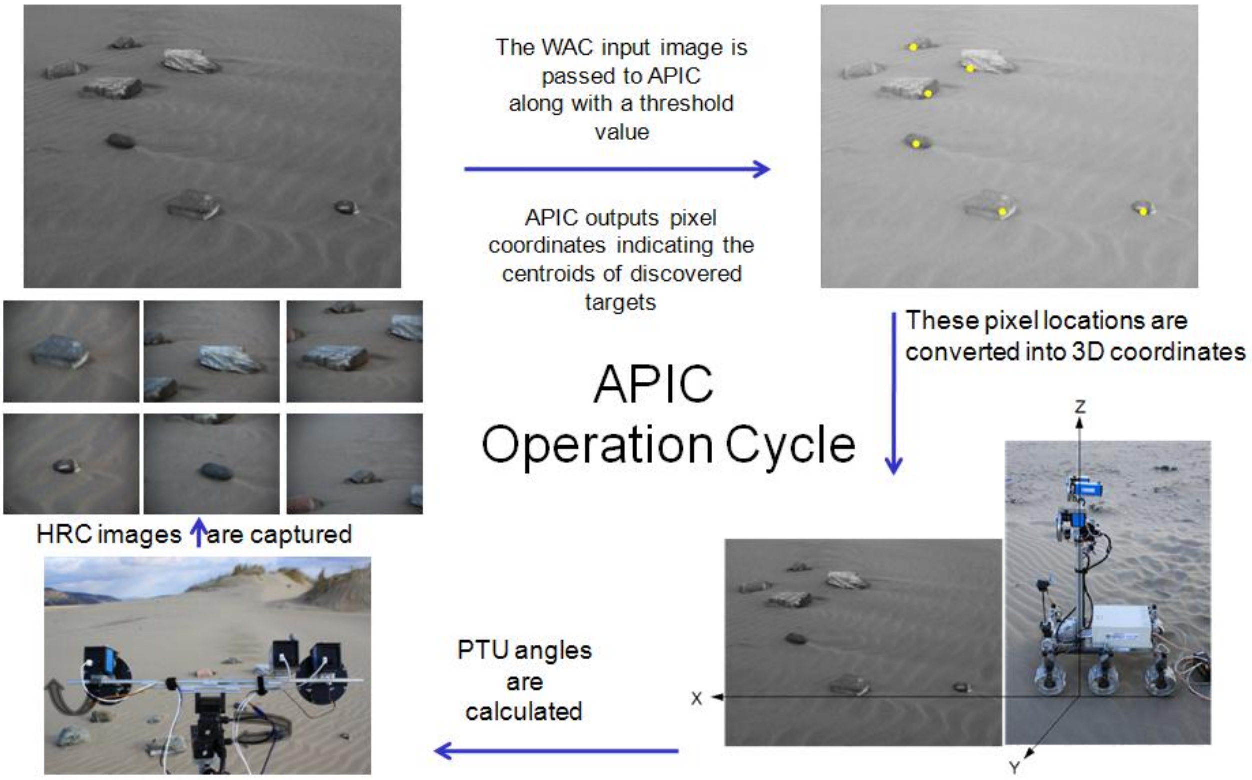


Figure 6: The autonomous APIC operation cycle. An image is captured using one of the AUPE-1 Wide Angle Cameras (WAC). This is processed by APIC to detect potential rock targets. The target pixel coordinates are converted to the PTU 3D coordinate frame, and the PTU is moved so that each target lies within the field of view of the AUPE-1 High Resolution Camera (HRC). The HRC captures close-up images of each target.

The **analysis and development of potential object definition and classification techniques**, incorporated into an image capture and processing application was performed; resulting in code and successful tests with sample data. A **science assessment and detection component**, which was ultimately tested in the presence of the reviewers on the test site in Tenerife, was developed. The Science Assessment and Response Agent (SARA) assesses images based on a set of fundamental operations and compares these against given scientific priorities for a particular Sol.

Final tests in Tenerife showed how the system extracted the required ROI in-situ which in turn triggered a science response see Figure 7.

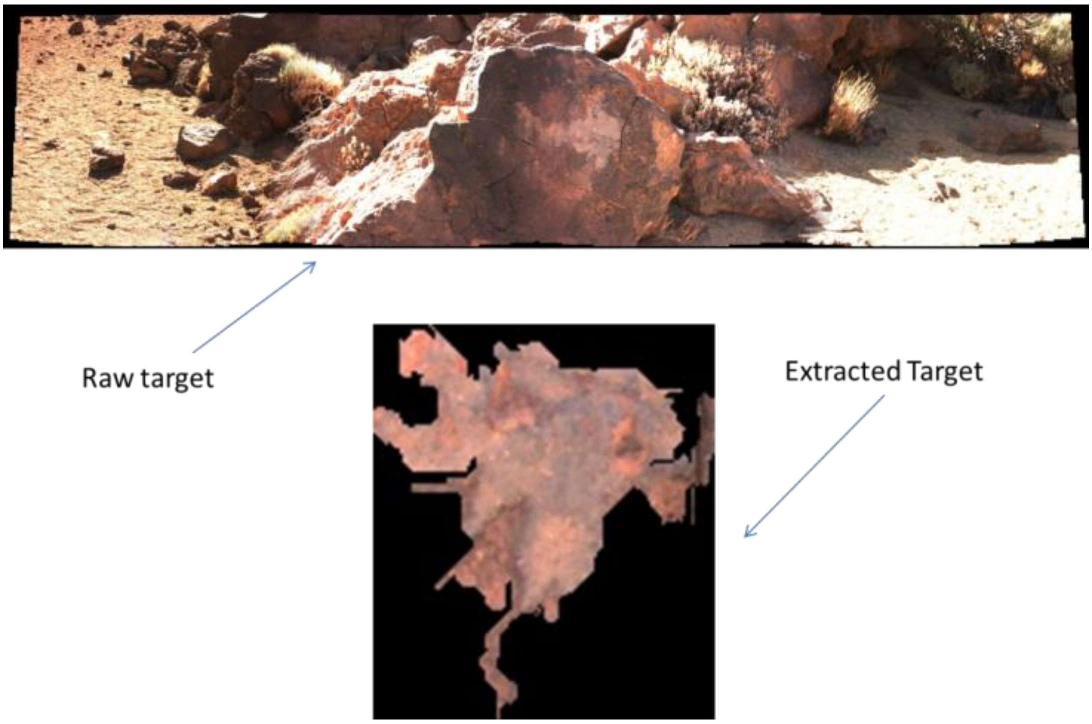


Figure 7: Results from Minas De San Jose showing a target Region of interest extracted by SARA.

Another pattern recognition agent that makes use of SIFT-based classification was developed as backup solution at JR. PRoViScout scientists were instructed for using the training component (Figure 8). Further tests with MER imagery (see also on Page 23) showed that the learning / classification approach is mature enough to distinguish between rocks and sediment layers. An option to include masks into the assessment was implemented, and a clustering prototype was integrated.

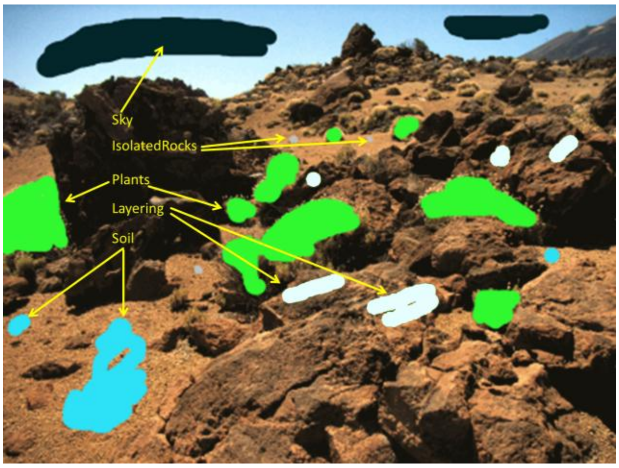


Figure 8: Part of instructions for training by scientists.

4.1.3.4 Vehicles & Sensors

(a) Tethered Aerobot

The AU aerobot is a tethered system, physically attached to an electric winch mounted on the Idris rover chassis. Once deployed, the rover is driven along a pre-selected route while the aerobot takes multiple overlapping images from above. The aerobot survey is a preliminary activity to allow area DEM generation prior to the main autonomous rover traverse. During the aerobot survey, the rover is manually driven and acts as a mobile anchor point for the aerobot. Once the aerobot survey is complete, the aerobot is hauled in and detached from the rover, in preparation for rover autonomous operation.

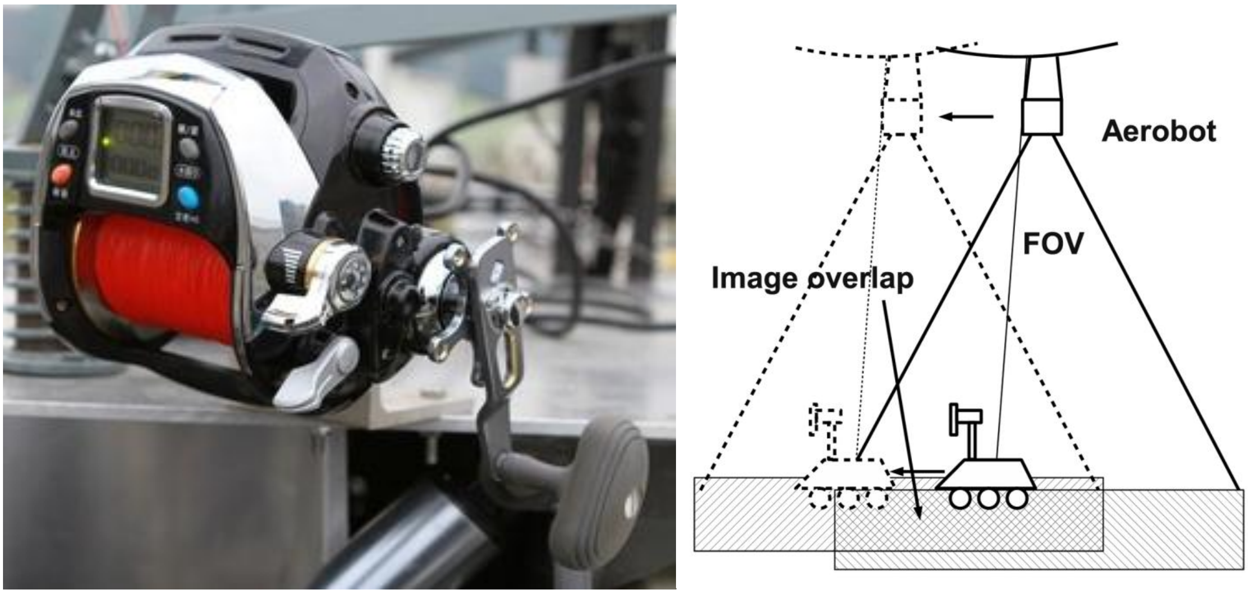


Figure 9: (Left) AU tethered aerobot rover winch mechanism. (Right) Diagram of tethered aerobot image capture with the overlap necessary for DEM generation.

(b) Rover

Different to the initial plan, AU and the PRoViScout Consortium decided to use a larger – more robust – rover for final field testing, based on platform mobility tests and mass & momentum considerations. In March 2011 a decision was taken towards the Idris Rover (Figure 10).

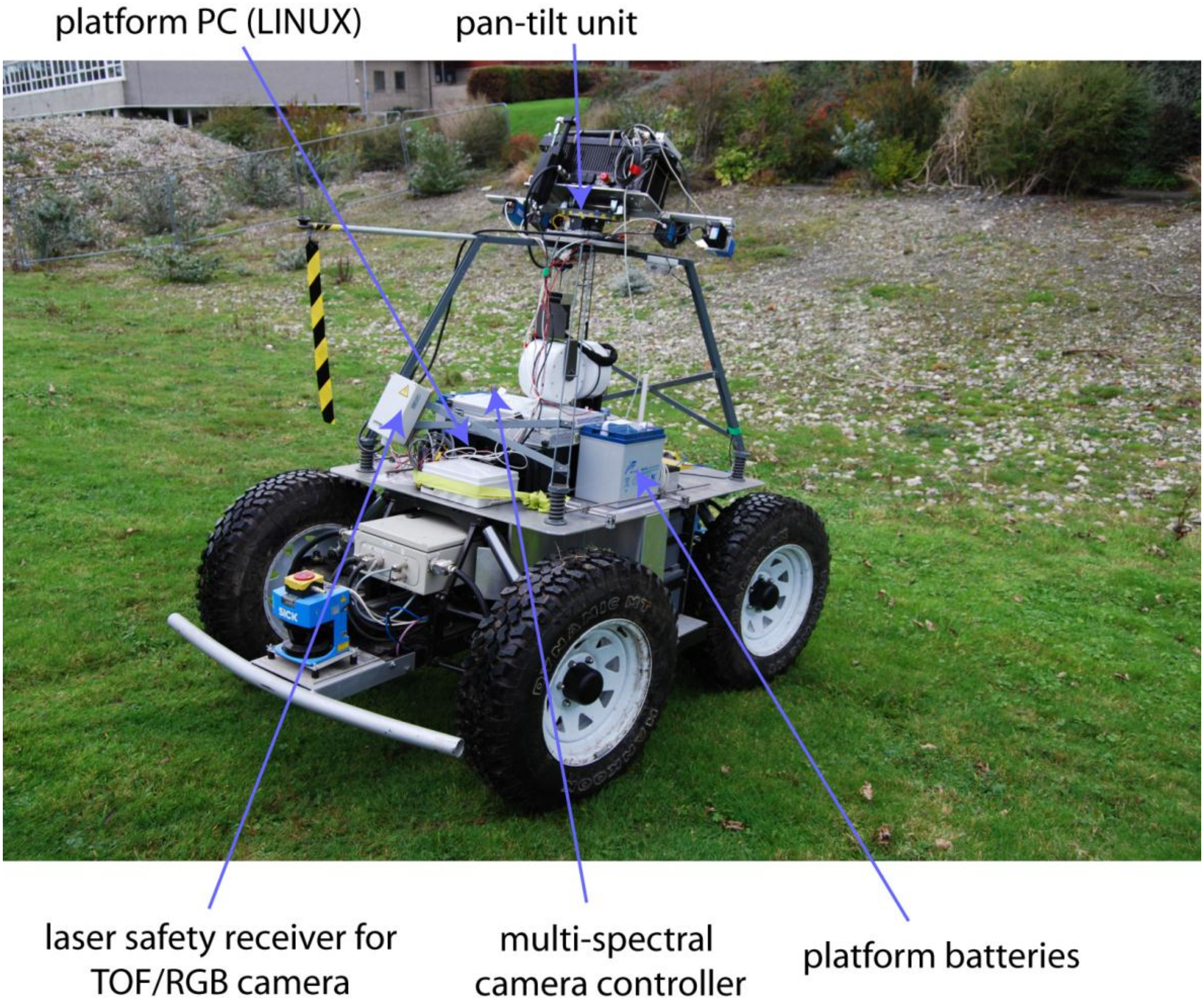


Figure 10: Rear view of the AU Idris rover during the first integration week at AU; visible are the heavy-duty PTU, the (black) platform PC underneath the aluminium case of the multi-spectral camera (AUPE-1) controller, the laser safety receiver of the 3D-TOF camera, and one of the platform batteries used to power the cameras and platform PC.

A heavy-duty pan and tilt unit was designed and built to house the PRoViScout cameras. These sensors included the TOF/RGB camera (CSEM), the two hyper-spectral cameras (UCL), and the (AUPE) stereo multi-spectral cameras (AU). Integration and testing of these cameras with the new heavy-duty pan and tilt unit took place during a variety of laboratory and integration tests.

(c) Sensors

<u>The TOF/RGB Camera</u>

The PRoViScout camera developed by the CSEM is equipped with a RGB camera and a time-of-flight (TOF) camera sharing the same lens to measure co-registered color images and range maps. The RGB/TOF camera is equipped with a zoom lens and a zoomable high-power laser illumination to improve the depth information at higher zoom levels of the camera. In the first project period the camera has been developed and assembled. In the second project period, the TOF/RGB camera has been further developed in three steps: (a) Optimization of the status quo after period 1, (b) Calibration and (c) Testing. During the internal integration campaign the camera switched off at an integration time exceeding 27ms. Time and budget were not sufficient to detect and fix the cause of this problem. Thus, the TOF/RGB camera did not join the external field test in Tenerife.

Multi-spectral Panoramic Camera and Aerobot Camera

The new **AUPE-2** camera hardware comprised 5 MegaPixel, 14 bit, GigE cameras and improved optics for each of the WACs, and a 1.3 MegaPixel, 14 bit GigE camera with an RGB filter wheel for the HRC. All of the cameras now have very high quality lenses. We serviced the WAC filters to replace any faulty filters, and the AUPE-1 suitcase-based PC-server was replaced with a FitPC to minimise (volume, mass, and power) the associated image capture (server) computer. The new cameras meant that we could bin etc. and extract 1024 x 1024 images when emulating the ExoMars PanCam, for example. The upgraded detectors, optics and 14 bit A/Ds meant that we had significantly better science cameras when compared to the old 1024 x 768, 8-bit cameras. We also lost the FireWire interface and reduced the overall mass and complexity of AUPE-2 for field trial deployment. The AUPE-2 system was used extensively during the Tenerife field trails, and proved to be an invaluable data source for the PRoViSC software modules.

The AU **aerobot's primary sensor** is a 5 Mega-pixel monochrome camera. Images are captured by the camera and stored on-board the aerobot for later retrieval. The aerobot also has an Inertial Measurement Unit (IMU) to measure its orientation in roll, pitch & yaw and a Global Positioning System (GPS) to measure absolute position and altitude. Note that neither of these systems are high-accuracy, and provide only an estimate of attitude to constrain image registration and DEM reconstruction. Operation of the AU aerobot is coordinated by an embedded Linux computer. The camera used in the current version of the AU aerobot is a Prosilica GC2450. This camera has a Sony ICX625 monochrome CCD sensor with a resolution of 2448x2050 (5 Mpixels) and a gigabit (1000 Mbps) ethernet interface. It is capable of imaging up to 15 frames per second at full sensor resolution with 8 or 12 bit pixel data. The camera allows operation modes such as single or triggered frame capture and supports configurable auto-exposure and auto-gain algorithms. Image sub-framing and pixel binning are also possible.

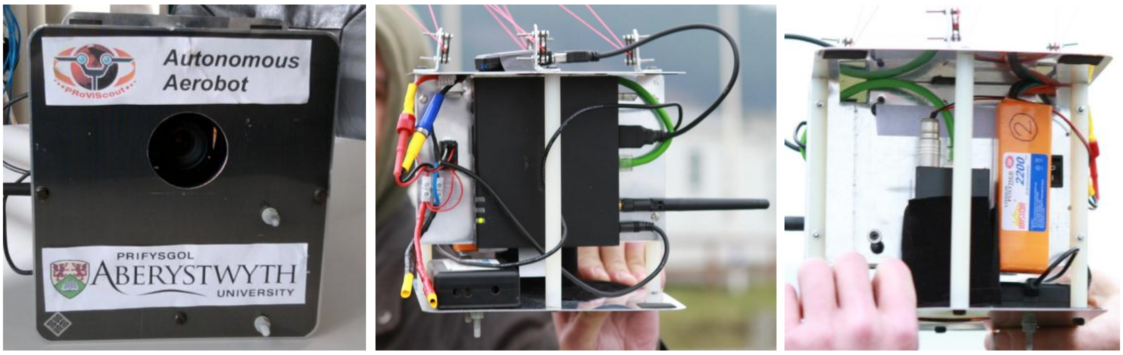


Figure 11: AU tethered aerobot. (Left) Bottom face with camera aperture. (Middle) Control PC, IMU and GPS. (Right) Camera and battery pack.

WALI

It was proposed that the on-board rover system consist of the Camera + Hyperspectral Imager based on use of LCTF technology (i.e. HC-1) for obtaining hyperspectral images of rock face targets. WALI-A (tripod mounted) would then be employed for UV laser induced fluorescent observations using the Sigma camera and a specially designed baffle (to house and isolate the UV LED emission) during the day. White LEDs were included in the baffle to allow context images to be captured. This also meant that WALI-A could be employed for fieldwork with or without the rover.

The WALI A system retains the original Fovean Sigma DSLR imaging system. The camera is securely attached to a metal frame, also bearing a light-tight black-out tube. The DLSR is zoomed in to its fullest extent, and thus the lens forms a light-tight seal with the circular opening in the black-out tube. Arranged around the lens on the closed end of the tube are both white LEDs and 365nm UV LEDs. These are powered by a removable battery pack mounted on the frame, and the white-light and UV sources are switch-operated independently. In the interests of safety, a warning indicator LED, sited on the outside of the black-out tube to be visible whilst operating the camera, shows when the UV LEDs are on (Figure 12).

Figure 12: Side view (left) and "Down the barrel" view (middle) of the second version of WALI showing the white LEDs. The light-tight barrel obviates the need for a blackout tent. Right: Field testing of WALI 2 on photosynthetically-colonised rock surfaces in Tunbridge Wells.

HyperCam

The MSSL hyperspectral camera (HyperCam1 or HC1) is a small camera mounted on the PTU. HC1 consists of two BlueFox CMOS cameras and attached liquid crystal tuneable filters (LCTF) to acquire narrow band multispectral images. Since HC1 uses available light it is entirely passive. HC1 took part in both the PRoVisG and PRoViScout Tenerife field trials (in September 2011 and 2012 respectively). However, the design was modified for the 2012 trial with the EMCCD camera replaced by two BlueFox CMOS cameras (with auto exposure capability) allowing both LCTF's to be used simultaneously.

Figure 13: HyperCam optical head composed of Blue Fox CMOS camera, C-mount lens and LCTF (adapter but not stray light baffle shown); on top of SNIR & VIS control electronics boxes.

The HyperCam was operated wirelessly by remote desktop sharing to allow the operator to interact through the LabView™ based control software.

The named **components,** except WALI, were mechanically & electrically **integrated** into the **HW system**.

4.1.3.5 On-Board and Off-Board Software

(a) On-Board Software

The SW framework running **on-board** of the rover (**PRoViSC**) enables the operational vision-based navigation and control of the rover for an end-to-end demonstration.

The **software interfaces** of the following **HW components** were defined in the system design process and realized using **CORBA**: rover and PTU, multispectral PanCam, HRC and 3D-TOF (never having been tested). No CORBA interface was implemented for the HyperCam.

CORBA was also used for the integration of the following **SW components** into PRoViSC: **Executive**, **Decision Module** (MMOPS), **Science Assessment, Navigation**, **Vision Processing** and **Rover Control** (Figure 2).

Executive

The Executive had two main purposes in PRoViScout:

- Act as an interface between the PROVIM and Rover. This includes providing status/monitoring information such as rover position and timeline status to PROVIM, and receiving plans and science templates from Overseer and forwarding these to MMOPS for possible insertion into the plan.
- Maintain a model of the onboard plan as prescribed by MMOPS and execute this at appropriate times

Tasks that can be executed by the executive include:

- Navigation/Traverse
- Acquire RGB - using 3D TOF's RGB camera
- Science Assessment (RGB) - assessment of science from RGB image data
- Acquire High Resolution Image
- Acquire WAC Image
- Acquire 3D TOF
- Replan

Decision Module (MMOPS)

MMOPS relies upon to update and ensure the consistency of the mission timeline. In addition to receiving an initial plan, it receives requests to add navigation tasks and science opportunities to the timeline. Before doing so it ensures that there are enough resources (time, power, memory) for continued operation using static and dynamic information. Timeline validation and repairing (as required) also occurs periodically to ensure correct operation of the rover. Depending on the type of sub plan currently executing, task failures/overruns are treated differently. For example, if a science opportunity sub plan fails, this is simply removed and execution continues as normal. If a navigation task fails it is possible to recover if there is a task overrun and there is no restriction on time. Any changes made to the plan are passed on to the Executive for execution.

Science Assessment

In order to fulfil science autonomy requirements, a number of Science Assessment components are available to analyse images taken using cameras on-board the rover. Although these have implemented a different set of algorithms, these all need to identify features such as structural layering, compositional layering, cross bedding and slumped structures. As part of the science assessment tasks, the science assessment component uses a DEM to determine the location of a target in 3D space, and determine the most appropriate coarse waypoint from which to perform the next level of science.

Navigation

The Navigation component is in charge of instructing the Platform to move the rover from one location to another. This typically involves taking WAC images, constructing a DEM and combining this with mechanical odometry and IMU readings to determine current location and produce a series of internal waypoints required to traverse to the destination.

Vision Processing

Vision Processing provides a set of utilities to perform various functions involving imagery, including:

- Image acquisition (e.g. 3DTOF, RGB, WAC, WALI)
- Construction of a panoramic image from the WAC
- Reconstruction of stereo imagery from WAC and ACAM
- Generation of hazard and slope maps from DEM
- Calculation of visual odometry for use in the navigation component
- Maintenance of a global map

Rover Control

In its simplest form, the Rover Platform component provides an abstraction to the low level functionality specific to the platform. This includes access to:

- A Pan/Tilt unit mounted on the mast
- A Wide Angle Camera system, comprised of two cameras with R, G, B filters. 12 geology filters are also provided and spread between cameras (i.e. 6 geo filters per camera). Nominally full 360x180 panoramic produced on all available wavelengths taken at each coarse waypoint, although possible to specify more limited angles and only in RGB
- A 3D Time of Flight camera with RGB capabilities - nominally full 360x180 panoramic taken at each navigation step, although possible to specify more limited angles, zoom and RGB/3DTOF only
- The Locomotion subsystem
- (Potentially) A Hyper Spectral Imager (not realized within PRoViScout).

Figure 14: Vision DEM product (left), hazard map (middle) and navigation map (right)

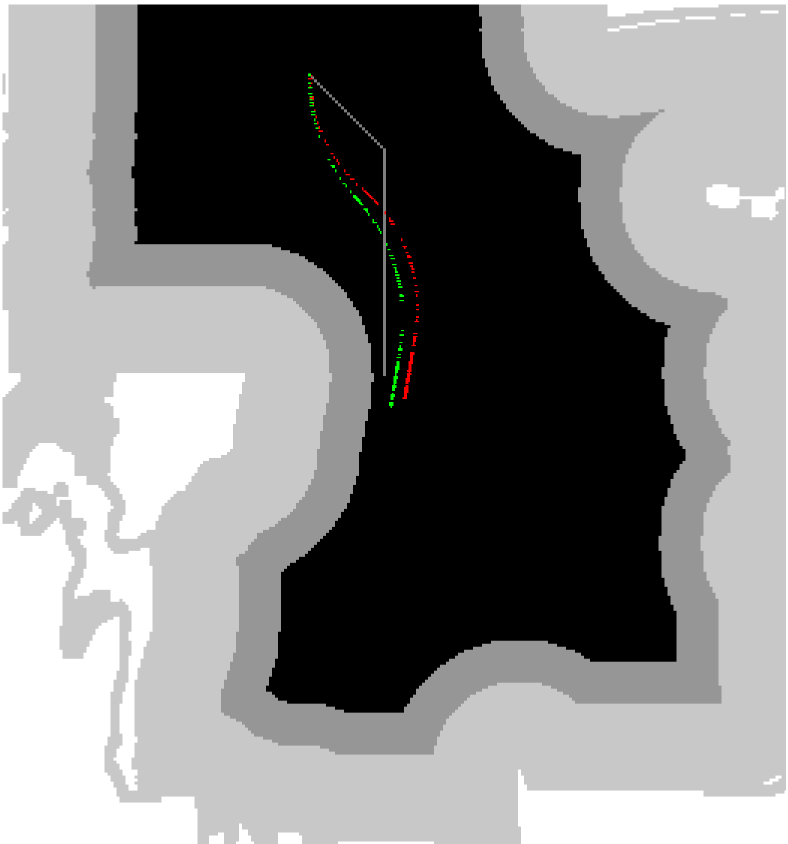


Figure 15: Navigation map with executed trajectory (green), Kalman trajectory (red) and path-planning solution (grey).

(b) Off-Board Software (Monitoring & Control)

An **off-board SW framework** (**PRoViM**) for monitoring and visualizing all rover operations / decisions etc. during a running mission was implemented and tested (Figure 2). This Software framework consists of three parts: Overseer, vision & Rendering (3DROV) and WWW Interface.

Overseer

The Overseer was directly communicating with the on-board Executive. It was responsible for the planning of the rover tasks and the visualisation ot task timeline's and the rover's progress.

Vision and Rendering

The simulator, modeling the elements of a robotized system and the morphology and the texture of its environment, was implemented in 3D (**3DROV**, Figure 3, right). The 3D Robotic Visualisation and Rendering function mainly includes:

a) The 3D Scene Rendering module that renders in a photo-realistic virtual scene the real or the simulated rover and its surrounding environment. It visualises also additional items such as 'targets', Activities glyphs and image overlays and allows the animation of all modelled mechanisms.
b) The Rover S/S's Movement Control that supports the specification of 'targets' to be reached be the rover mechanisms (Locomotion, Mast, …) and allows the rehearsal of motions of mechanisms.
c) The Data Monitoring that allows animating the robotic system in the synthetic scene, displaying on-line in 3D and analysing downloaded or simulated data

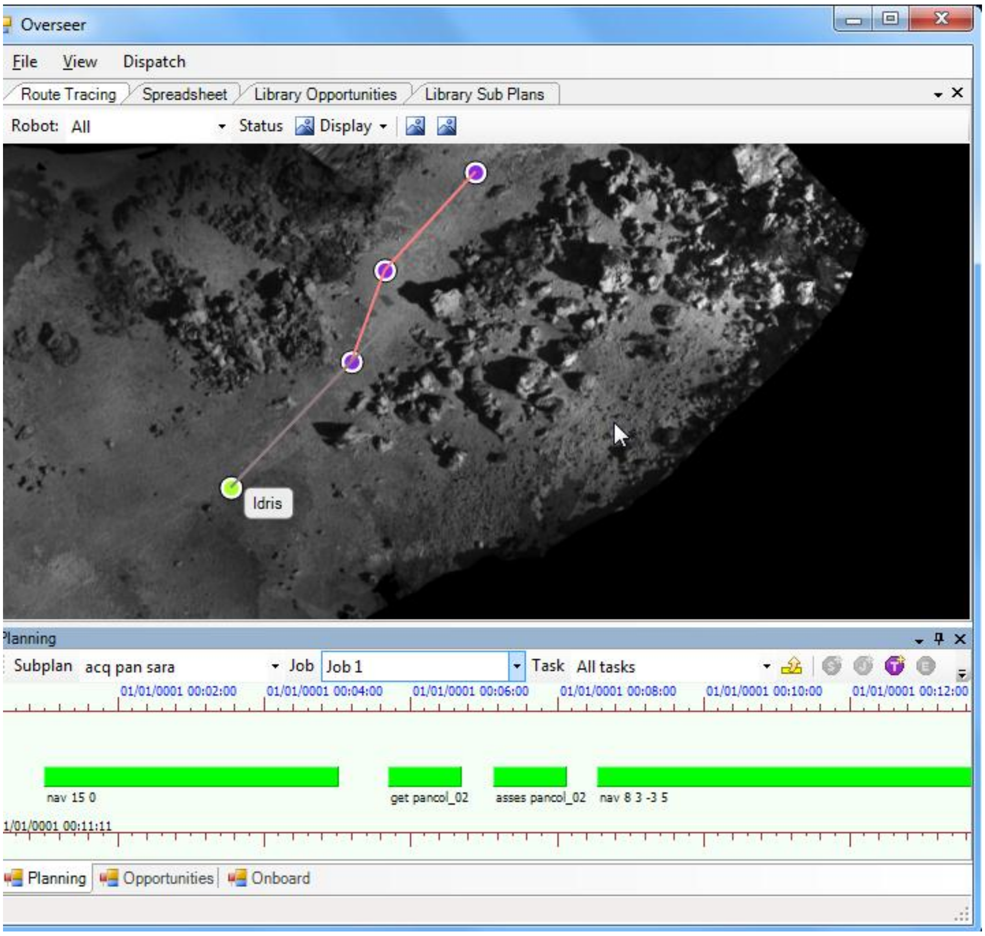


Figure 16: Screenshot Overseer taken during Field Test on Tenerife.

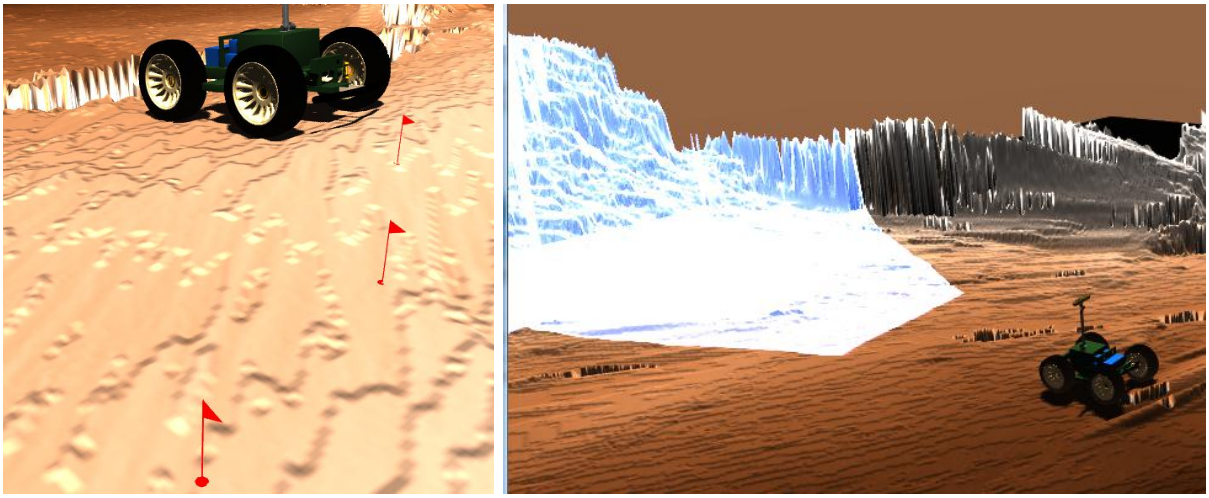


Figure 17: Screenshots 3DROV.

WWW Backend

A **web based system** for monitoring and visualisation of experimental missions providing a unified www presentation of the status of a mission was developed. The system was designed to support remote missions connected over only a slow, e.g. sattelite, network. Activity in the mission control centre, path planning, simulation and monitoring) and in the field (web cam) were transmitted over a satellite link to a CTU server and transformed into a live video feed at http://cmp.felk.cvut.cz/projects/proviscout/vfeed/.

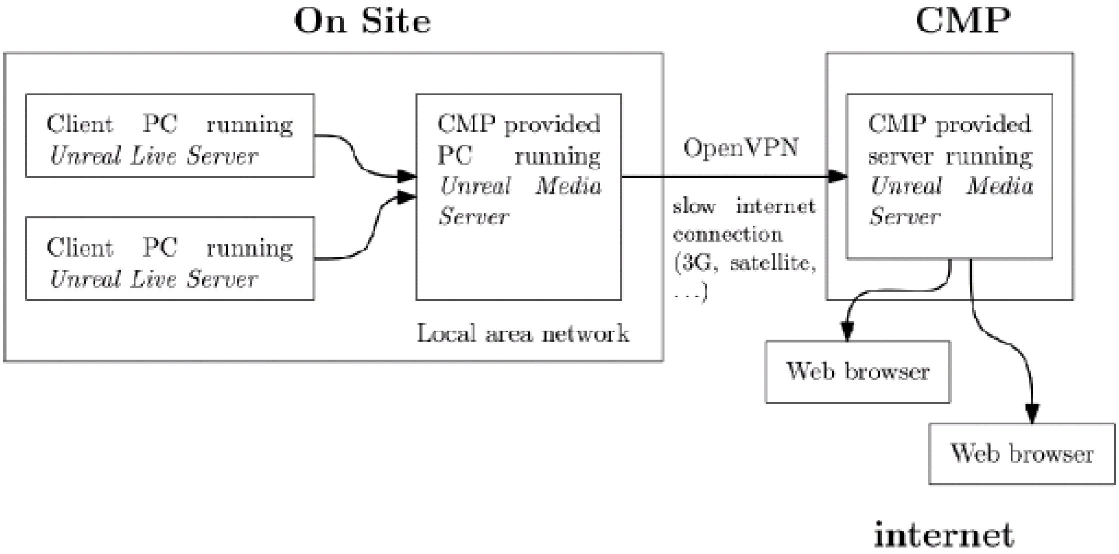
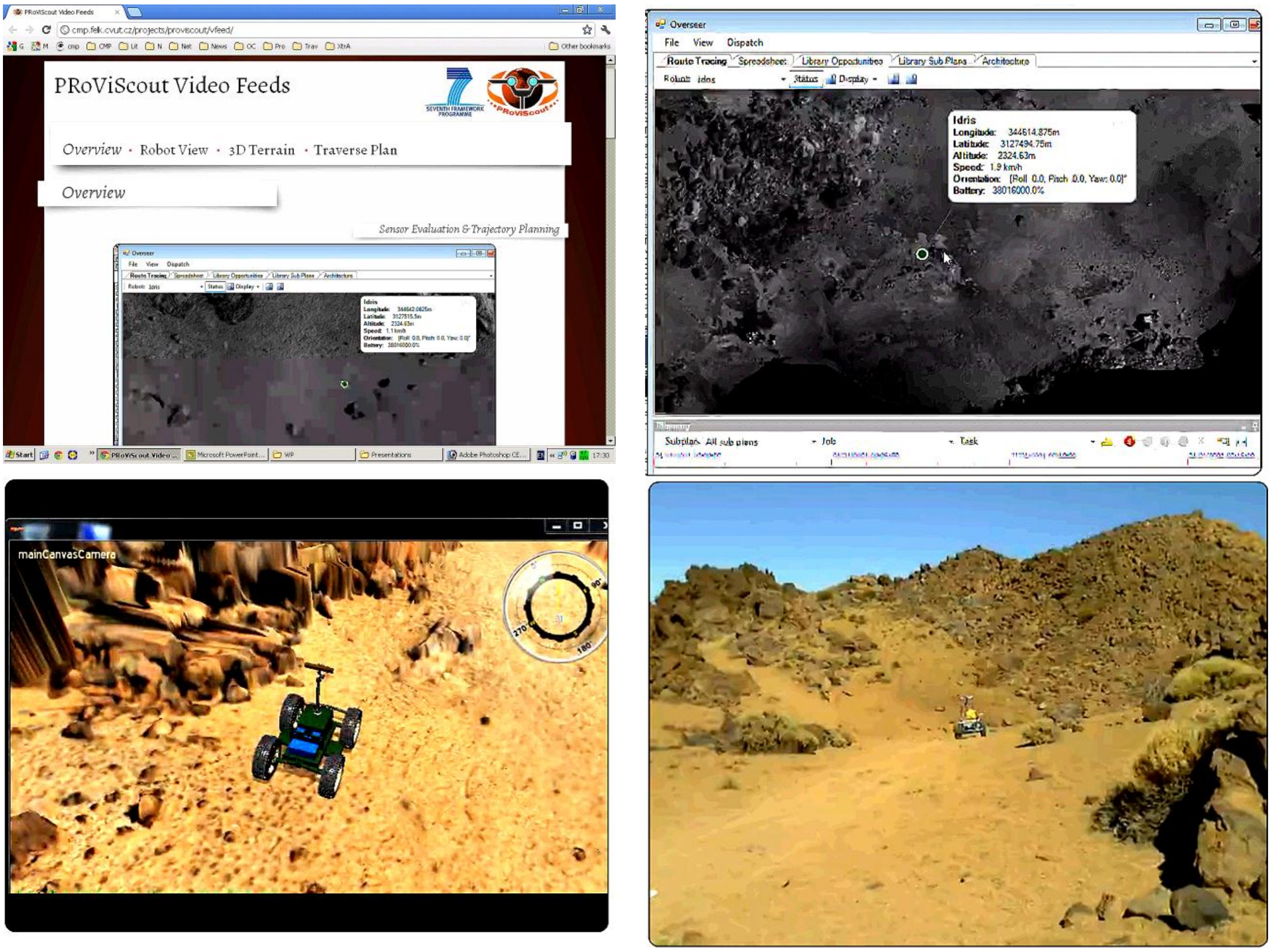


Figure 18: Architecture of the PRoViM web interface.



Idris
Longitude: 344614.875m
Latitude: 3127494.75m
Altitude: 2324.63m
Speed: 1.9 km/h
Orientation: [Roll 0.0, Pitch 0.0, Yaw: 0.0]°
Battery: 38016000.0%

Figure 19: Activity of mission control (planning, simulations, monitoring) were transmitted to a web server via dedicated Unreal Live Servers and OpenVPN technology and then retransmitted as video streams, which could be watched in any web browser on the Internet.

4.1.3.6 System Simulation & Testing

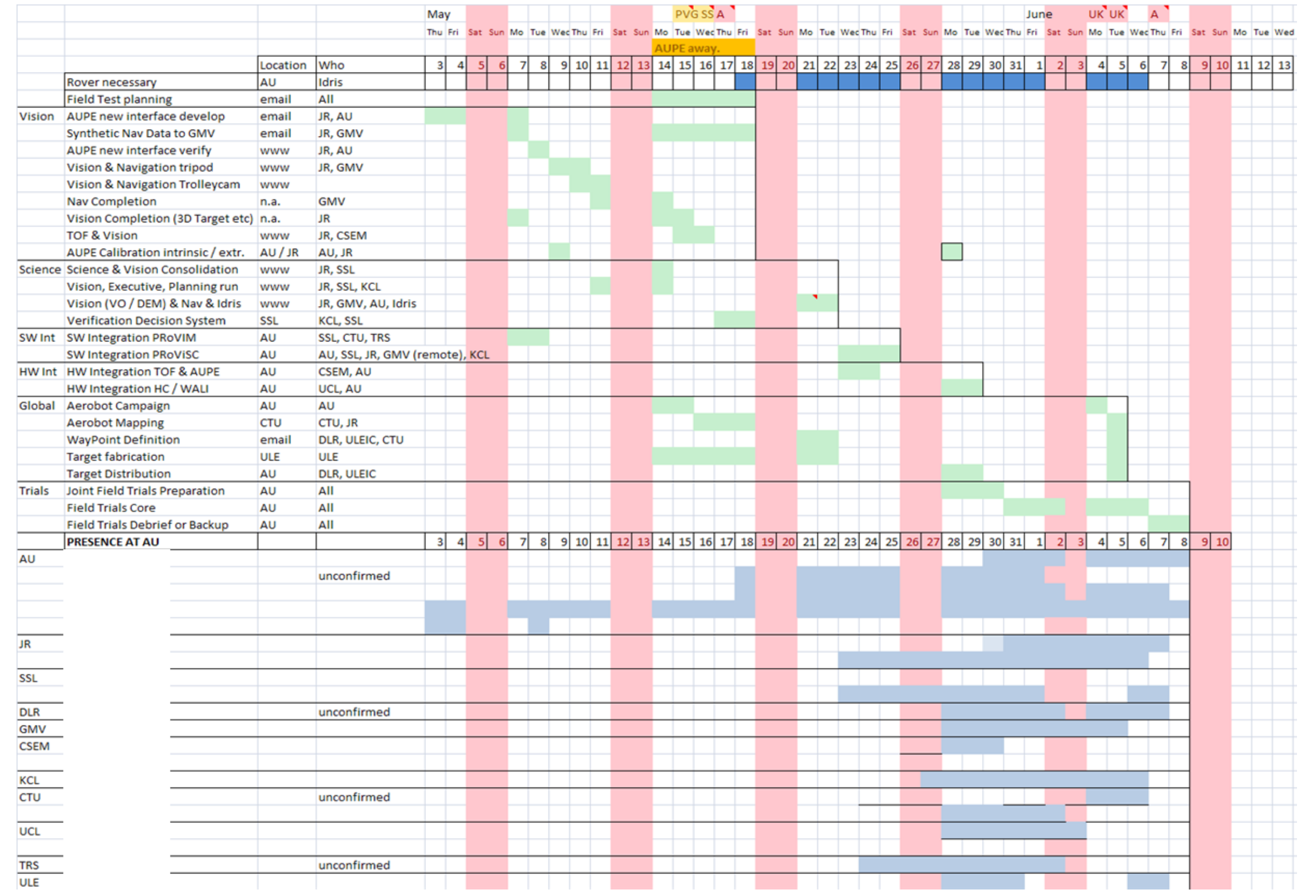
In order to integrate, test and verify developed HW and SW components as well as to implement improvements, a variety of Laboratory Tests, Integration Campaigns and simulations have been performed to ensure the system running during the final field demonstration.

(a) Lab Tests

Hardware and software testing has occurred on many occasions during the project. Much of this work has involved **the testing of individual hardware and software components in isolation** (referred to as 'unit' testing), in readiness for the Internal Integration Test which **brought the components together for integration tests**. The driving force has been to ensure that the goals of the PRoViScout project would be delivered, and a successful final Tenerife Field Trial in September 2012 would be achieved.

Continuously during the project, the internal test plan was updated. Given the necessity to bring key PRoViScout partners together for the number of integration campaigns that have been undertaken, it has often proved to be a complex timetabling and logistics activity to ensure that the right partners were available at the right times, with the right equipment being available. With so many software modules and the rover and sensor hardware being constantly improved, ensuring that versions of all hardware and software could be 'frozen' at key dates for integrated test purposes took a good deal of effort to organise.

Table 2 shows an example plan that was constructed to highlight person and hardware availability, and the required integration tests that were to be performed prior to and during the Integration Campaign 4.



May — PVG SS A — June — UK UK — A

Thu Fri Sat Sun Mo Tue Wed Thu Fri Sat Sun Mo Tue Wed Thu Fri Sat Sun Mo Tue Wed Thu Fri Sat Sun Mo Tue Wed Thu Fri Sat Sun Mo Tue Wed Thu Fri Sat Sun Mo Tue Wed

AUPE away.

3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13

		Location	Who
	Rover necessary	AU	Idris
	Field Test planning	email	All
Vision	AUPE new interface develop	email	JR, AU
	Synthetic Nav Data to GMV	email	JR, GMV
	AUPE new interface verify	www	JR, AU
	Vision & Navigation tripod	www	JR, GMV
	Vision & Navigation Trolleycam	www	
	Nav Completion	n.a.	GMV
	Vision Completion (3D Target etc)	n.a.	JR
	TOF & Vision	www	JR, CSEM
	AUPE Calibration intrinsic / extr.	AU / JR	AU, JR
Science	Science & Vision Consolidation	www	JR, SSL
	Vision, Executive, Planning run	www	JR, SSL, KCL
	Vision (VO / DEM) & Nav & Idris	www	JR, GMV, AU, Idris
	Verification Decision System	SSL	KCL, SSL
SW Int	SW Integration PRoVIM	AU	SSL, CTU, TRS
	SW Integration PRoViSC	AU	AU, SSL, JR, GMV (remote), KCL
HW Int	HW Integration TOF & AUPE	AU	CSEM, AU
	HW Integration HC / WALI	AU	UCL, AU
Global	Aerobot Campaign	AU	AU
	Aerobot Mapping	CTU	CTU, JR
	WayPoint Definition	email	DLR, ULEIC, CTU
	Target fabrication	ULE	ULE
	Target Distribution	AU	DLR, ULEIC
Trials	Joint Field Trials Preparation	AU	All
	Field Trials Core	AU	All
	Field Trials Debrief or Backup	AU	All
	PRESENCE AT AU		
AU			
			unconfirmed
JR			
SSL			
DLR			unconfirmed
GMV			
CSEM			
KCL			
CTU			unconfirmed
UCL			
TRS			unconfirmed
ULE			

Table 2: Test plan between May and June 2012.

As well as unit tests, some elements of integration tests were conducted at SciSys, and the AU Planetary Analogue Terrain Laboratory (PATLab), and the AU Robotics Workshop.

Figure 20: (Left) Sorting out the complex wiring problem when integrating all of the cameras onto the Idris rover platform. (Right) Starting up Idris to begin preliminary integration tests at the AU Robotic Workshop.

Figure 21: (Left) "Shake-up" of the Idris rover with mounted cameras to test the mechanical integration. (Right) Members from the CSEM and AU partners during the Integration Campaign 3 at Aberystwyth.

(b) MER Processing

In order to **verify the implemented 3D vision, science assessment and 3D reconstruction algorithms** developed and improved in the context of PRoViScout and related projects (i.e. PRoVisG) as well as to **show the benefits of the autonomous science selection approach and its applicability in planetary environment**, these algorithms were applied to PDS-archived MER imaging data serving as real comprehensive data from a planetary surface.

The 3D Vision Product Generation, Science Assessment Algorithms and the 3D Reconstruction Cycle developed by CTU were successfully tested.

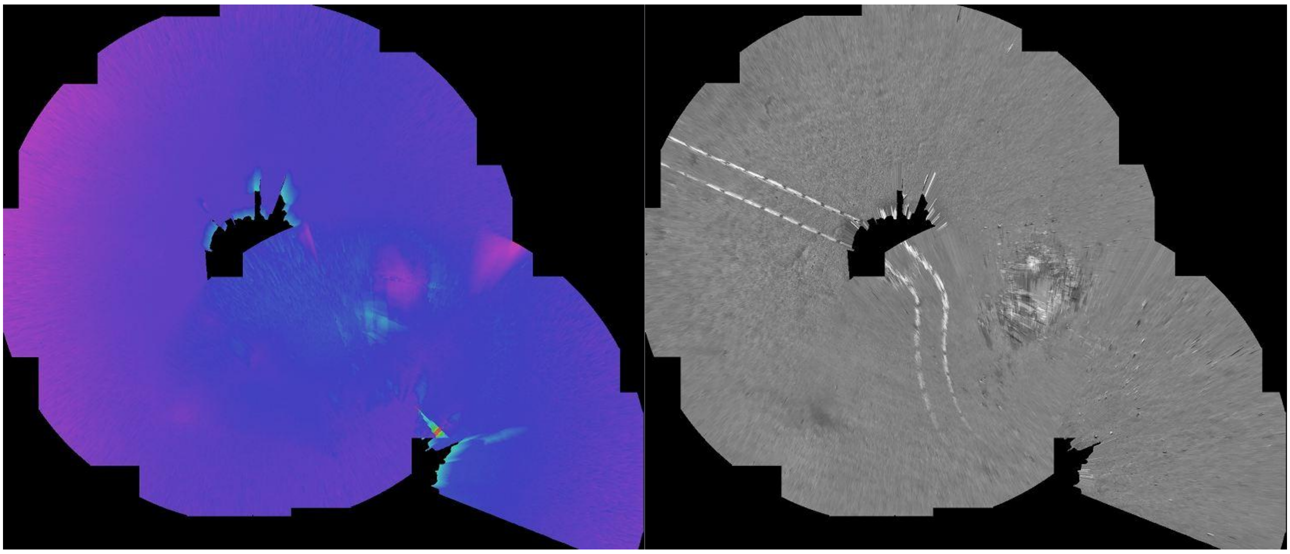


Figure 22: Processed Opportunity NavCam data taken on site 81/82, sol 1157/1160: left: spherical multisite DEM, right corresponding ortho image. Artifacts at individual stereo images borders are visible.

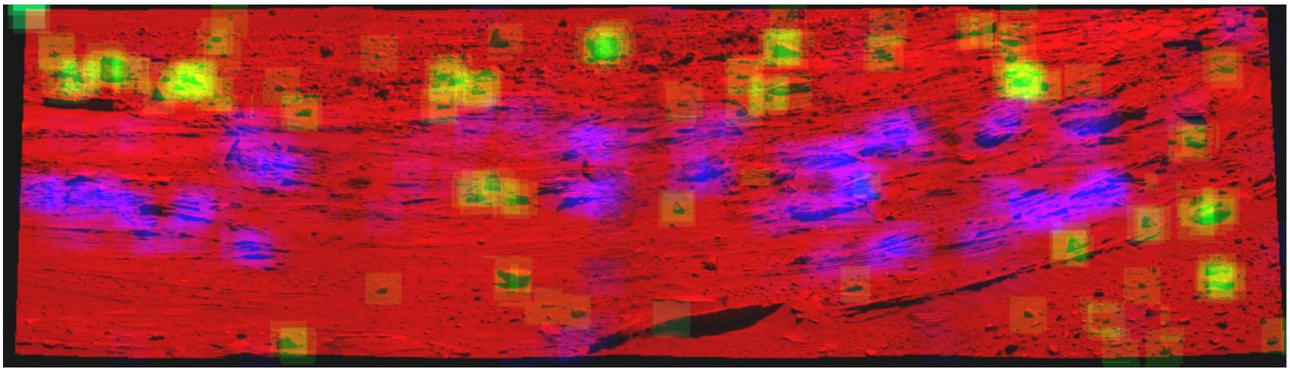


Figure 23: Classification result for Spirit PanCam panorama taken on site 125 / sol 774, Green: rocks, blue: sediment layers.

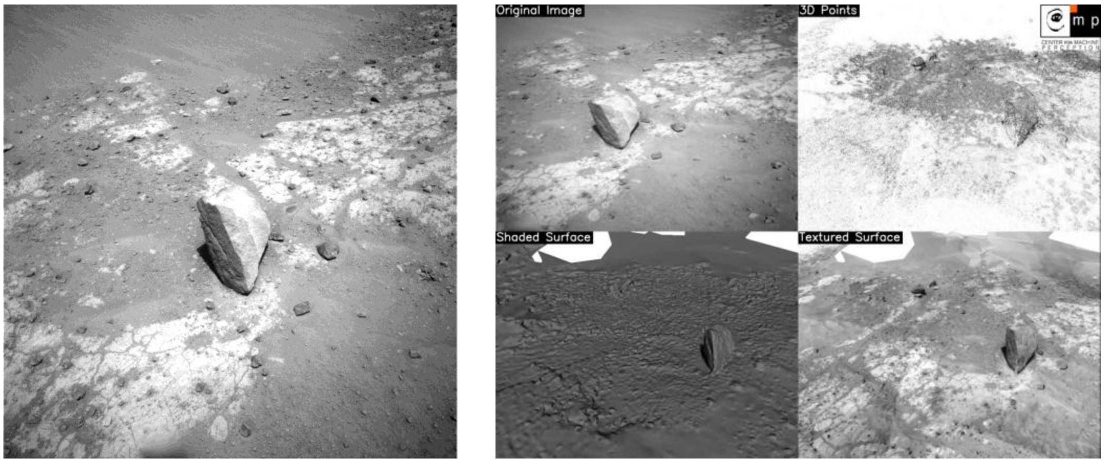


Figure 24: MER 360° image sequence showing a rock & 3D reconstruction result by CTU processing pipeline.

(c) AMASE Contribution

As preparation for the PRoViScout deployment on AMASE 2011, DLR organized a preparatory workshop, hosted by Aberystwyth University (AU) in July 2011. During this workshop, the PRoViScout sensor suite was tested and prepared for field deployment in Svalbard. The workshop included detailed shake-downs of the instruments and software in the lab and at Clarach Bay, as well as calibration of PanCam.

From 8–21 August 2011, a part of the PRoViScout team participated in the Arctic Mars Analogue Svalbard Expedition (AMASE) 2011 in the Svalbard archipelago, Norway, together with ~30 ESA and NASA scientists and engineers involved in Mars exploration. During AMASE, a part of the PRoViScout sensor suite, including PanCam (Aberystwyth AUPE-1 emulator) and a WALI emulator were deployed in several Mars-analogue field sites in Svalbard as part of an integrated, Mars rover-representative instrument suite (including field models of ExoMars and MSL instruments) to test science goals and performance and utility for astrobiology sample targeting. Figure 2522 shows the workflow during AMASE.

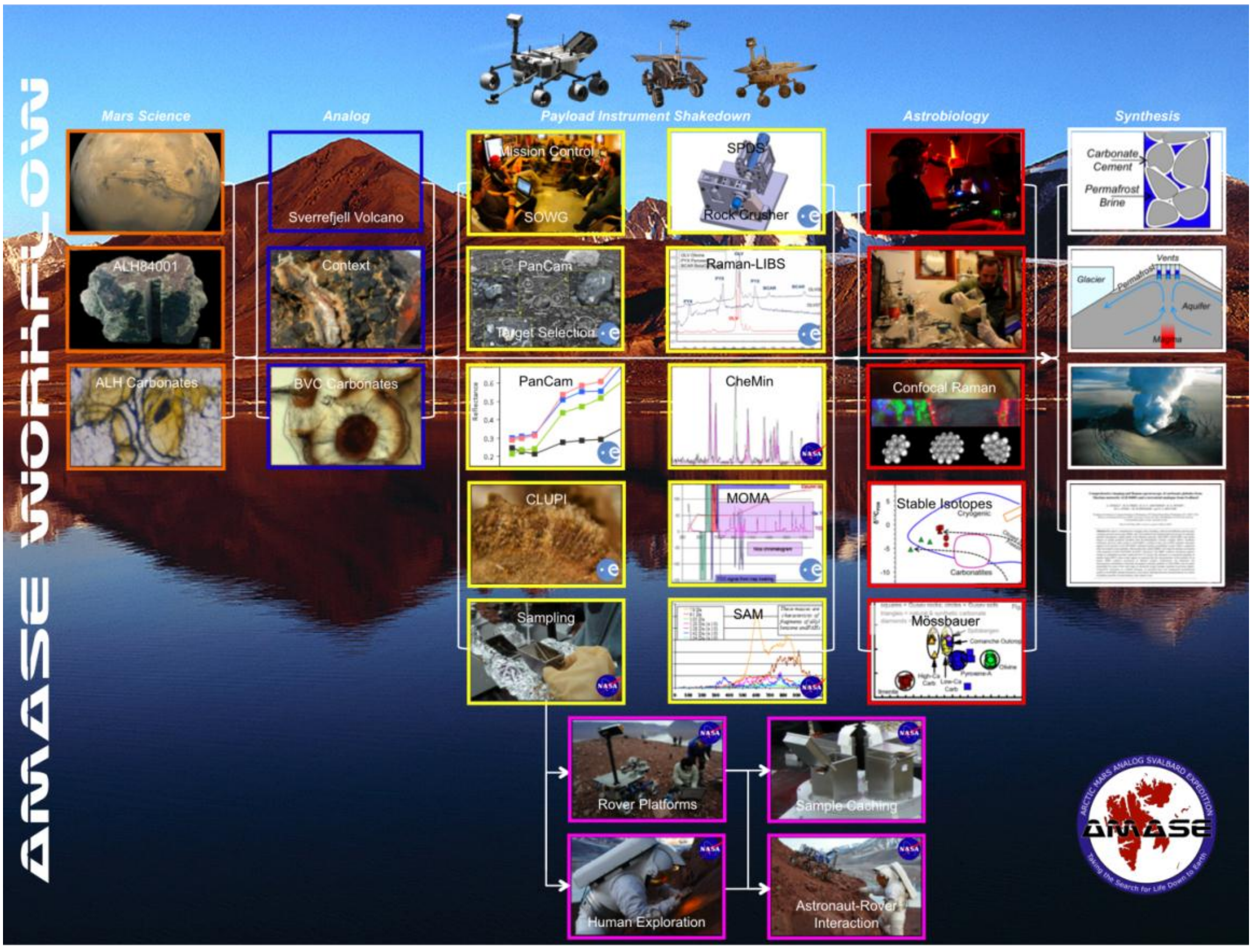


Figure 25: Workflow during the Arctic Mars Analogue Svalbard Expedition (AMASE): 1) selection of a Mars-analogue field site, 2) in-situ investigation of the field site using ExoMars, Proviscout and MSL instruments, 3) selection and caching of samples, 4) laboratory investigation of the samples using a combination of payload and laboratory instruments, 5) data synthesis.

(d) Integration Tests Internal

The Integrated Test Internal has built upon the unit and laboratory integration tests. It brought the components together for integration tests. The driving force was to ensure that that the goals of the PRoViScout project would be delivered, and a successful final Tenerife Field Trial in September 2012 would be achieved.

Two integration campaigns were performed, one at a site in Wales, UK (Ysbyty Ystwyth), and one as a remote partner connection campaign with the rover at Aberystwyth. Finally an aerobot and communication infrastructure test was undertaken just prior to packing and transportation of all of the field trial equipment to Tenerife.

Summary of Integration Campaign 4 at Ysbyty Ystwyth, Wales

The major software/hardware integration campaign took place during the period **2012-05-23 to 2012-06-06**. The number of days at the chosen site approximated to the field trial duration that would be experienced in Tenerife. The site was a quarry at Ysbyty Ystwyth near Aberystwyth, Wales (approx. 40 minutes drive). A good deal of effort went into the selection of the Ysbyty Ystwyth quarry site. We needed a location that was not too far away, but one that forced us to collect all of the equipment together and transport it away from Aberystwyth, thus ensuring that we could not be reliant upon local infrastructure. Most importantly, the site had to be sufficiently remote to allow the 3D-TOF to be powered and tested in an environment that would be safe to all humans in the area. Finally, the site had to sufficiently large and varied (slopes etc.) to exercise the Vision Processing Visual Odometry (VO) and Navigation software modules.

The campaign required the use of the AU Robotics Group transportation van, which doubled as a 'mission' control room. Preliminary check-out work was first conducted at the AU Robotics Workshop before packing and travelling to Ysbyty Ystwyth. Despite some periods of mixed weather, Integration Campaign 4 provided the most realistic tests so far undertaken within the PRoViScout period, in preparation for the final field trial in Tenerife.

Based upon the lessons learnt from Integration Campaign 3, it was realised that further rationalisation of the camera mounting head was required. Too many control and power cables were being routed via a very restricted opening and there was significant weight being place upon the heavy-duty PTU. Prior to travelling to the Ysbyty Ystwyth site for the first tests, several hours were spent redesigning the camera mounting configuration to improve the reliability of all of the connections, and to speed up the mounting and un-mounting of the camera head which was required to allow the Idris rover to be able to be moved in and out of the transportation van.

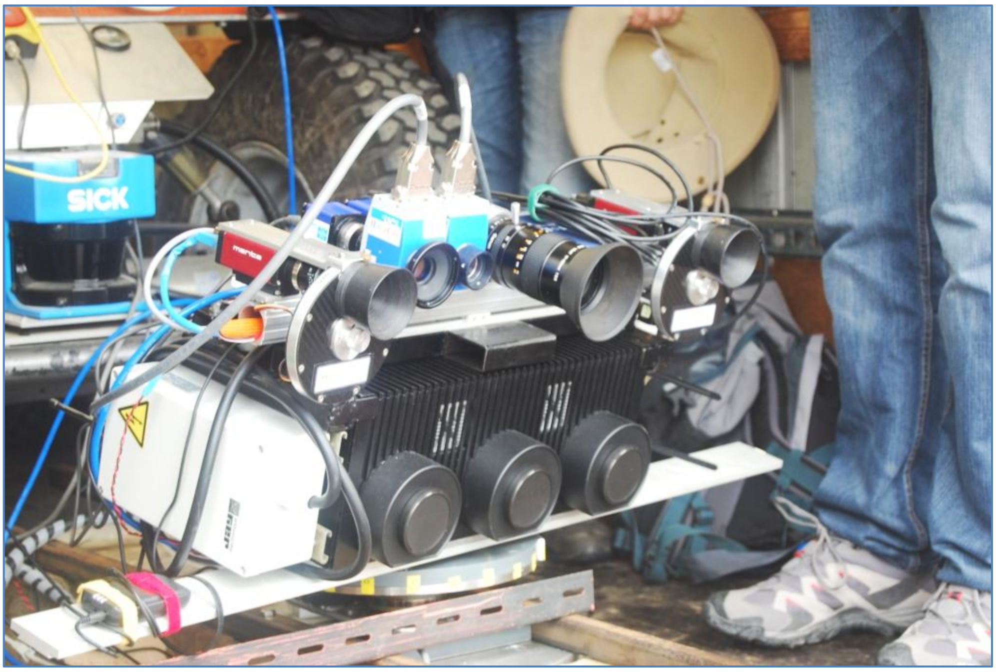


Figure 26: Close up of the PRoViScout camera head and heavy-load PTU with the 3D-TOF, HyperCams (VIS and NIR), and AUPE-2. Note that the camera head shown here has a different configuration to that shown during the Integration Campaign 3.

Figure 27: Left & Middle: The Idris rover undergoing locomotion tests during Integration Campaign 4. Right: Testing the GMV navigation software during Integration Campaign 4.

Summary of Integration Campaign 5 at AU Workshop - Remote Tests

Based upon the results from the Ysbyty Ystwyth integration campaign, it was decided that some of the software modules required additional tests in preparation for the final Tenerife field trial. The 5th Integration campaign, which occurred during the period **2012-07-13 to 2012-07-25**, involved an internet connection being established with the Idris rover PC based at the AU Robotics Workshop. Text communication between remote team members at their home institutions was established using a web chat room (www.chatzy.com), and AU team members started, monitored, and stopped (when requested) the various PRoViScout software models whilst ensuring that Idris moved in a safe manner.

Figure 28: The Idris rover undergoing remote software integration tests outside at the AU Robotics Workshop. Note the heavy-duty PTU has been replaced with the standard AU PTU and only the AUPE-2 cameras were used during Integration Campaign 5.

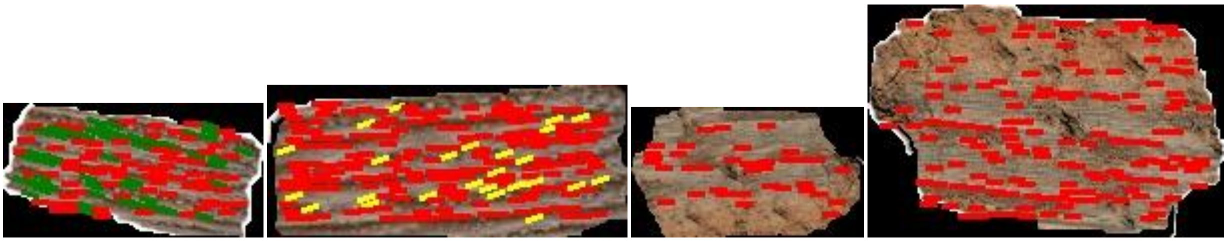


Figure 29: Extracted rocks from the AUPE-2 captured scene and their analysis by the Science Assessment software during Integration Campaign 5. The left two images are of "Butts bench" and the right two of "Tome".

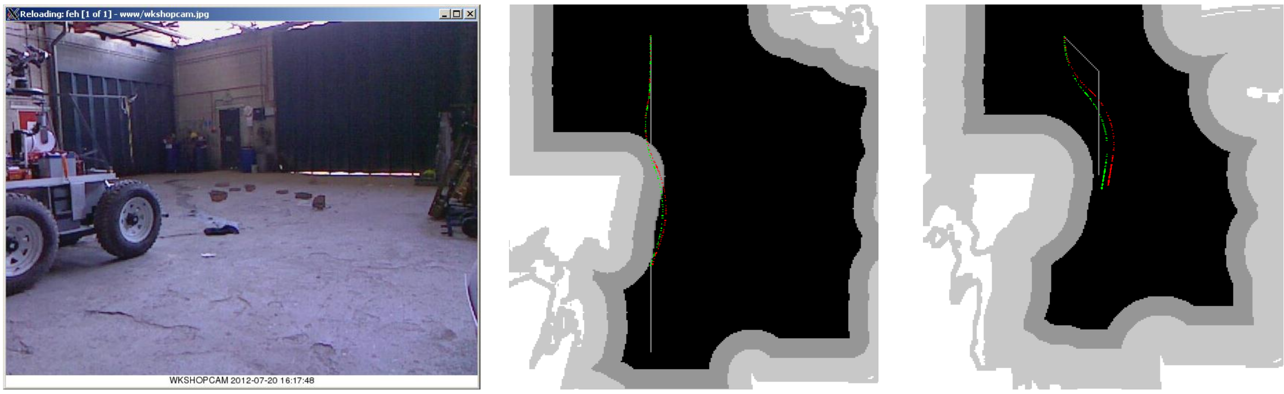


Figure 30: Navigation tests during Integration Campaign 5. Odometry (red) and Kalman filter (green) trajectories (Left:x=4m, y=1m; Right: x=8m, y=0m) at AU Workshop.

Summary of Final Test Campaign - Pre Van and Equipment Travel to Tenerife

Prior to departure for Tenerife, we wanted to test the new (larger - 7' diameter) tethered aerobot envelope that had recently been delivered. Having calculated the nett lift that our original (6' - diameter) envelope would generate at the altitude we would be operating at in Tenerife, we realised that a larger envelope would be required (see Figure 31). We also wanted to undertake a final test of the communications infrastructure that would be used in Tenerife and to assign IP addresses etc. The aerobot envelop and communication infrastructure both performed as required, and all of the field trials equipment was loaded into the AU Robotics Research Group Luton van, and the journey to Tenerife commenced.

Figure 31: (Left) Testing the new 7' diameter tethered aerobot envelope. (Right) Final tests of the communications infrastructure to assign IP addresses etc. prior to departure to Tenerife. (Right Top) the van with communications antenna was parked some distance away from Idris. (Right Middle/Bottom), the local antenna placed in closer proximity to Idris.

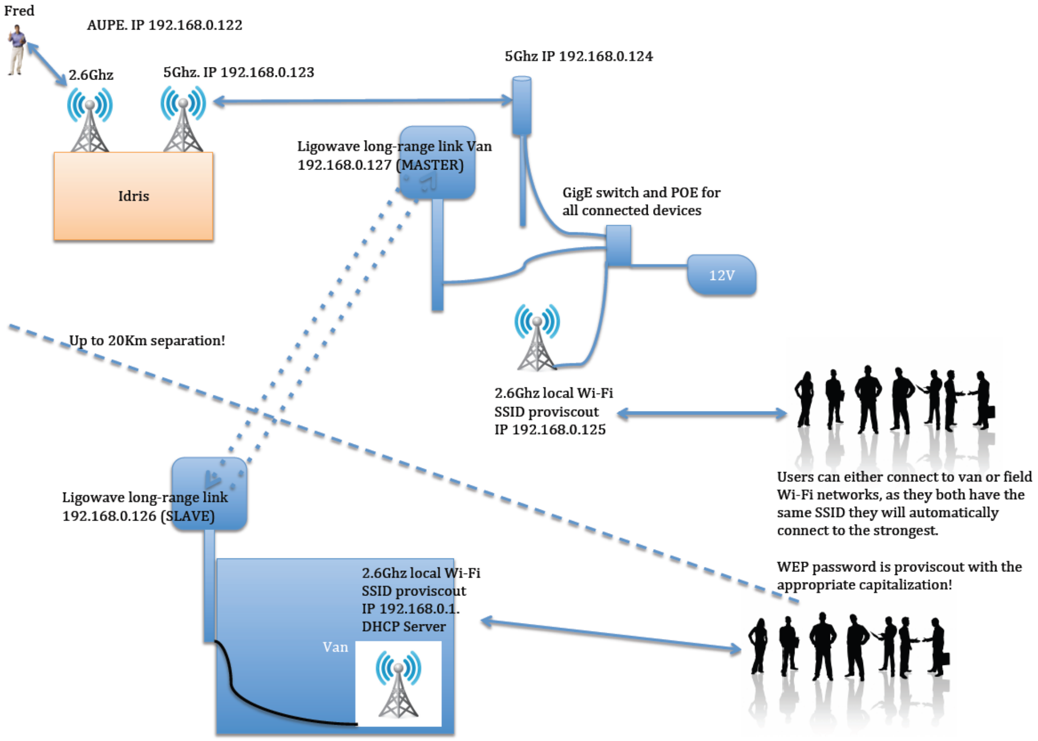


Figure 32: The communications network used during the Tenerife Field Trial.

4.1.3.7 Integrated Test External

Site selection considerations for the Tenerife Field Trials had been taken already early in the Project. Among others, two main candidates were considered, namely Montana Rajada (being challenging in terms of permission as well as traversability & access by car, see Figure 33) and the Minas de San Jose Area (with minor scientific challgenge). After a trade-off it was decided to go to Minas de San Jose.

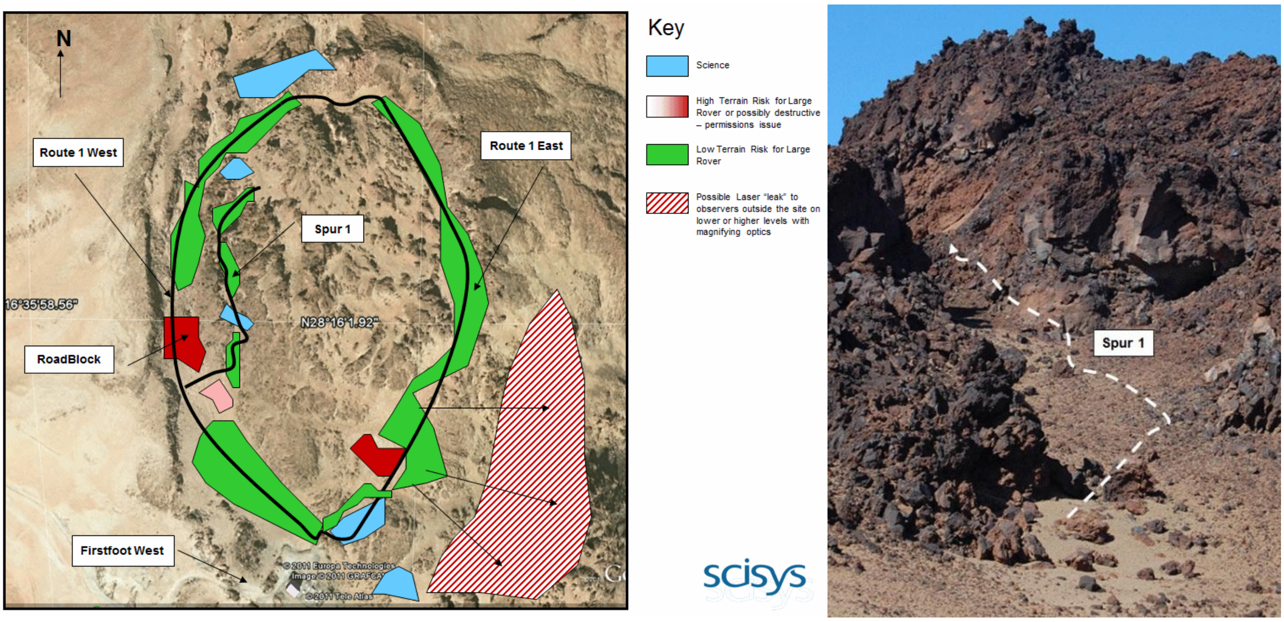


Figure 33: Evaluation of Montana Rajada potential Field Trials site in Tenerife. Left: Classification of site portions related to traversability and science targets. Right: Excerpt from traverse planning.

After thorough preparation the external integrated field test took place from 10th to 19th of September 2012 in the El-Teide National Park / Minas de San José on Tenerife. All hard- and software components developed during PRoViScout and related projects should finally be integrated to the rover platform to test their performance under realistic Mars-like conditions.

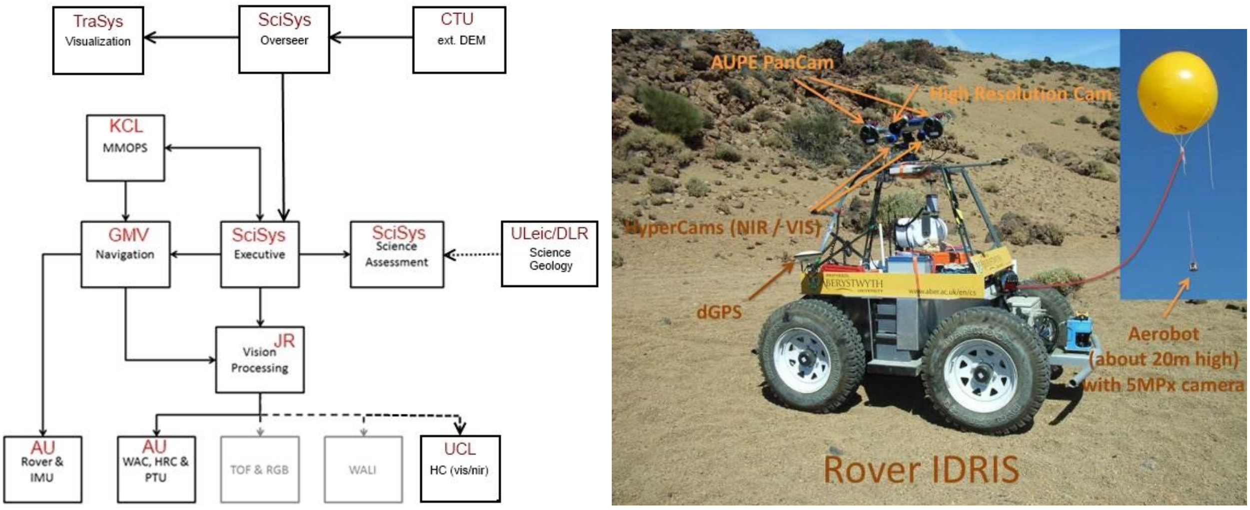


Figure 34: System components having been integrated and tested during Tenerife field trial. WALI & 3D-TOF were not available on site (grey & dashed line). The HyperCams (HC) were not integrated to the vision processing software (dashed line).

During a variety of internal tests and campaigns afore, the single system components have been tested and improved. A full integration of all components wasn't reached by the beginning of the external test. Furthermore, not all sensors could come into operation during the trials (see Figure 34).

External Field Trial Planning & Logistics

The decision for the test site location was made on the base of a field visit in June 2011 and the experience gathered during the PRoVisG field trial on Tenerife in September 2011. The field test planning and organization was managed by task leader JR. All planning information were summarized in the internal deliverable D7.2.1. This document was continually updated until the beginning of the trials and provided to all field test participants via the CMS.

Test Setup & Realisation

During the field test, all available hardware and software components were integrated to the rover and to the software modules PRoViM and PRoVisc. The performance of the system was continually evaluated. To verify the navigated path and the generated 3D data of the work area, an overview digital terrain model with geo-referenced coordinates was generated. To make this possible, JR placed more than 80 GPS measured white landmarks in the terrain, creating a photogrammetric network along the rover's planned route. Overlapping aerial images of the terrain and markers were then used to create a 3D reconstruction by CTU. The aerial images were captured by the AU Aerobot. In a final demonstration at the end of the trials, the rover was required to navigate autonomously between three given waypoints: a start point, an intermediate stop and an end point. Each section of the route was at least 30m in length. At a maximum speed of 20 cm per second, Idris followed its planned route, scanning the terrain metre by metre and constantly updating its 3D map and navigation path. Due to a lack of geologically interesting Mars-like rocks along the traverse, ULEIC prepared some artificial targets and placed them near the second waypoint, to be detected by the science assessment component of PRoVisc. These targets were detected as potential regions of interest, which led to Idris' on-board system reacting and trying to get closer to the targets to capture high resolution image data. The whole mission was controlled remotely from the control centre situated in the van. The real time 3D visualization system 3D-ROV by TRS enabled operators to monitor Idris and its behaviour at the test site. During the field trial, a live web stream on the PRoViScout website was used to broadcast the 3D visualization, a display of information from the Overseer component, and a video feed of the rover itself as viewed from an on-site webcam.

Figure 35: (Left) An early start to get set up. (Right) End of the day and everyone helped to bring all of the equipment back to the van.

Figure 36: Left: The AU tethered aerobot with aerial camera being towed by the Idris rover during the PRoViScout Tenerife Field Trial. Right: A late afternoon flight proved to be problematic given the increased wind speeds and lower atmospheric densities experienced later in the Tenerife day.

Field Trial Supervision, Documentation & Data Storage

For everyday data storage and exchange, AU provided a hard drive with a pre-defined directory structure in the wireless PRoViScout network at the Parador. Next day schedules containing time and responsibility information were provided by JR after having discussed results and problems in everyday's team meetings. Overall documentation of the trials (who did what when incl. pictorials) was done by JR and published as LogBook on the PRoviScout website. Detailed documentation was individually done by the participating parties. For future missions it might be useful to define a protocol template to be used by all team members. These information would allow to quantifiably analyse single on-site actions and be valuable input for the planning of future field trials.

All data produced & processed on-board Idris as well as on board of the Aerobot and taken by participants' SLR cameras was made available to PRoViScout members on the PRoViScout internal ftp page. This will be maintained at least for 2 years after PRoViScout termination.

Scientific Performance of the Field Trial

A full assessment of the scientific performance of the robotics field trial was conducted both on site and post facto once all the test results have been collated.
The main justifications for selecting the Minas de San Jose site were as follows:

- general suitability of the terrain for rover-based traversing (i.e. geomorphology, surface type and lack of visible intrusions from the rover's perspective)
- authorized access (compared to other more scientifically interesting sites)
- logistical access.

However, one drawback of the site was the absence of suitable natural geological features displaying layering. This attribute was chosen because it is one of the most fundamental features and diagnostic indicators in field geology. To compensate for the lack of natural layering, ULEIC prepared artificial targets that were designed to be inserted into the terrain and merge with the natural geology. No budget was assigned to the effort of creating the targets so they could not be made much greater than A2 size.

Other Integrated Tests External of HRC and WALI

Aside from the Tenerife field test, at MSSL/UCL, an integrated stereo and hyperspectral imaging system (Figure 37) was developed and tested in two pre-selected sites located in Brecon Beacon, Wales, where NERC airborne datasets and WALI images had been acquired in previous relevant scientific studies. These showed that these nearby sites contained a number of extremophile environments including endolithic cyanobacteria in spring deposit terraces, bright pink alkaliphillic biomass growing on rock surfaces (Figure 38), and possible ferric oxide staining on the surface of carbonate deposits. The integrated imaging instruments built at MSSL provided visible and near infrared hyperspectral images of the astrobiological interesting content and stereo images provided the 3D information on the surrounding context. The stereo capability allowed 3D reconstruction of detected geological and biological features and further research possibilities of structurally different bio-signature types or any extensive classification as well as recognition of fossilized biomat structures.

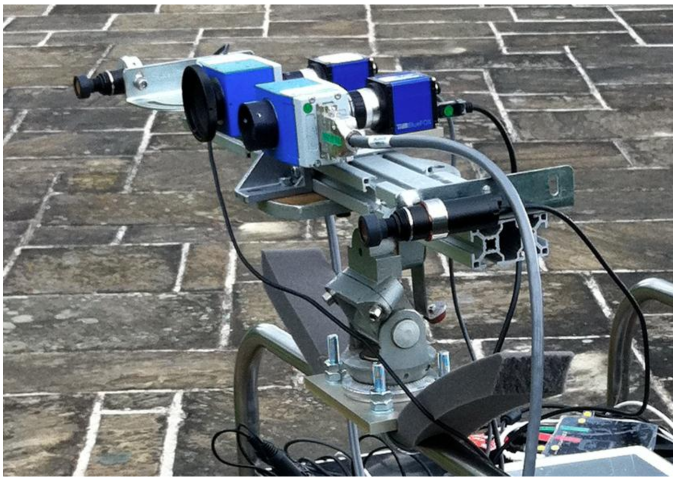


Figure 37: HyperCam-1 (dual visible and NIR filter configuration) trolley mounted for testing at MSSL, with stereo 'DogCams' at the ends of the optical bench.

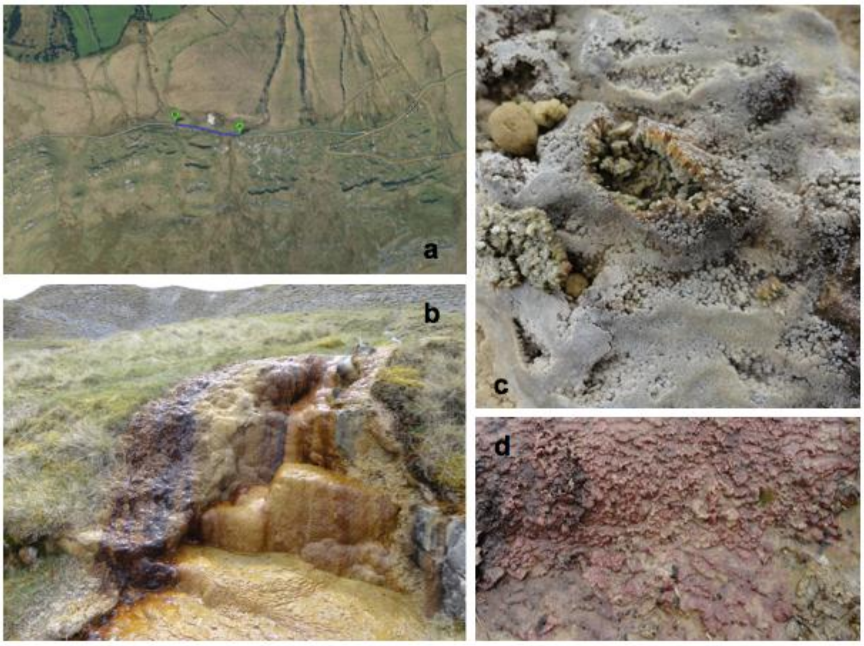


Figure 38: a) Location of Sites A and B in Brecon Beacon for Field deployment of the MSSL stereo hyperspectral imaging systems. b) Site B showing a massive mineralogical deposit and potential bio-signatures. c) Green and orange endoliths. d) Pink alkaliphillic biomats

The alkaline nature of these sites contrasts well with acidic, volcanic sites (e.g. Tenerife/Spain) and mineralogical deposits provide a challenge for hyperspectral imaging which are priority targets for any astrobiological focused mission to Mars. In addition, the sites also have a combination of endolithic cyanobacteria in the spring terraces, which is of particular interest to astrobiology since endolithic environments on Mars have been theorized to constitute potential refuges for extraterrestrial microbial communities and bright pink alkaliphillic biomats growing on the surface.

Summary of Field Trials Findings

Following the field trials from PRoVisG and PRoViScout, a lot of experience in planning and organization was acquired. The major findings consisting of known issues, having been confirmed in Tenerife, as well as completely new experiences are summarized in the following (compiled in cooperation with the PRoVisG Team):

Team / Responsibilities

- For the field test it was inevitable to have different people with different roles, such as in a real mission.
- For each of the entities, one official was assigned who was mentioned in the participants list handed out to all participants and to the local authorities.
- To guarantee a good organization on-site, a local support team was introduced (Active Connect Team). Their tasks included:
  - Providing interpretation services
  - Organizing authorization to access to the El Teide National Park
  - Liaising with local institutions and organizations (Local Government, Police, Local officials)
  - Organizing the press day event in conjunction with Astrium Ltd's PR department
  - Organizing local logistics and equipment hire
  - Providing the trials team with food and water during the day
  - Restoring the park to its natural condition after completion of the field trials and having the test sites checked and approved by the Park Authorities.

Objectives / Priorities / Schedules / Backup Procedures

- It was necessary to have a list of objectives with priorities, estimated schedules and backup procedures.
- Each experiment came with a sequence chart that allows minute-by-minute monitoring of the experiment in order to find delays early enough.
- In general it was necessary to stick to the schedule to avoid a loss of time.
- A backup plan was required for potential system failures & unexpected environment conditions.
- For some experiments the realization deviated from planning due to immediate availability of resources.
- Some decisions had to be made on-site, reacting on circumstances and in better knowledge about expected durations, such as:
    - Common file system structure to store the captured data
    - Communication procedures via hand-held radios
    - Paths for the rover and distribution / timeline of individual experiments' components (panoramas / VO / science targets, …)
    - Daily schedule.
- Shakedown days were necessary to ensure that rover and test infrastructure have been set up and were functioning correctly.

Site Selection

- The test site(s) should be chosen carefully, concerning:
    - environmental restrictions
    - altitude and temperature / climate
    - diseases / health risks etc.
- It was useful to brief all field trial participants in advance to guarantee smooth functioning on-site and efficient conduct of the trials

Site infrastructure

The conduct of field trials demanded infrastructure and support systems to ensure that all goals were met within the window of opportunity provided by the Site Authorities. Essential operational capabilities were necessary to ensure the efficient execution of tests and operations and to maintain high levels of communications between parties and equipment. The following items were regarded as essential as infrastructure:

- Box van to transport the rover and support equipment and to act as an in-the-field Local Control Centre.
- Communications
    - For broadcast: V-SAT satellite broadband links to allow upload of image data to the internet FTP site, to the field trials website, to provide email, Skype, VPN and data access for the whole team
    - Personal mobile radios for members of the team working in the field, at the local control centre and at the Parador
    - Wifi link up between the Rover and the local control centre to allow remote control operations – repeater stations extended the range to around 1km line of sight
    - Mobile phones where they were able to obtain sufficient signal
- Tools and equipment to operate, service, maintain and modify the Rover, and to support the fitting of instruments and equipment in the field and back at the Parador

- Monitoring webcams mounted in the field (or on the rover) to enable local control centre staff to drive the rover remotely and to enable them to see, hear and be aware of what was happening in, on and around the rover during trials operations
- Batteries capable of providing sufficient power for one full day of operations
- Solar panels and a petrol driven electric generator as backup to power the local control centre equipment and to allow charging of batteries in the field where required.
- Shade for personnel and equipment – gazebo with side panels – to avoid the effects of direct sunlight.
- Furniture for the local control centre (tables, chairs)
- Computing and communications equipment for the local control centre to support control of and communications with the rover
- Food and drink facilities for the team both in the field and at the local control centre to maintain energy levels and maintain hydration.
- Fence to protect the site from visitors and the visitors from injury by the rover

Other Issues

- There are a whole range of issues that arise during field trials and this is what makes them such rich learning experiences and valuable events. Avoiding test personnel from appearing in test imaging such as Pancam panoramas is one such issue that had not been considered but had effects during tests on-site. Such matters required diligence and attention to detail. Of particular value is to encourage the test team to be constantly vigilant and supportive in the pursuit of the test goals. This requires concentration and positive attitudes from all team members, but also the ability to recognize when the team needs rest, food and water or other essential sustenance.
- As with all field trials, unexpected events and situations happen that need to be accommodated. Good preparation is essential and repays the team over and over, allowing better overall results. Establishing a daily routine for the tests help with the organization of the team and makes it easier for team members to make the maximum contribution. They are better able to anticipate events and to spot when things need attention. They are also able to pace themselves which leads to a more harmonious team environment that is so important to productivity and good results.

4.1.3.8 Reports

In the following, the **executive summaries of all formal deliverables** are given.

The **D2.1.1 Science Requirements Document** reviews previous landed missions with a remotely-controlled mobile component with respect to their overall characteristics and their main scientific goals. We critically assess their scientific achievements, considering the geological context in which they operated. Future mission characteristics and objectives (astrobiology) are considered, and incorporated into knowledge gained from previous experience. Based on these considerations, we define the scientific objectives that will be addressed by the project. We classify science requirements with respect to different instrument classes, which might be probing different objects or geologic environments. We also define the products that will be the results of the project, based on their benefit to scientific analysis. Finally, we discuss the respective merits of different candidate field sites for the PRoViScout field test.

The **D2.3.1 System Design Document** presents the PRoViScout system architecture based on specified requirements and the existing software/hardware & expertise provided by the partners. It outlines the basic system decomposition, operating modes, software interface requirements, hardware and electrical architecture. The architecture reflects the design philosophy for the project which seeks to minimise integration efforts in favour of improving algorithmic capabilities in order to advance the autonomous science concept.

The **D2.4.1 Mission Requirements Document** a spectrum of mission and target scenarios which could make use of the PRoViScout system and looks in particular at the commanding, vision processing chain, data handling and archiving of mission data aspects. Past, present and future missions have been analysed to understand their science and operational goals, processing methods in order to establish the mission requirements for the PRoViScout frame work. In deriving the mission requirements from the investigated missions and the PRoViScout objectives three base scenarios have been proposed; a single exploration rover, a single rover with an aerial vehicle and a multiple heterogeneous rover systems. Each has been analysed for their system configuration, environmental constraints, scenario test criteria and requirements.

The Robotic Vision Systems developed within the PRoViScout project require a set of training images that show surfaces analogous to those likely encountered on Mars. Moreover, the images need to provide contextual information that enables the system and operators to infer general properties of the geologic environment of the relevant targets. Such images may be ground-based, taken during geologic field campaigns, or may be airborne, acquired with aerial vehicles such as kites or airplanes. In the **D3.1.1 WWW Catalogue of Targets** we describe the Web-based Catalogue of Targets that was developed following the specifications documented in the PRoViScout Science Requirement Document. The catalogue enables user-friendly uploading of images together with attributes (metadata) that contain important information related to the image source and to its geologic content. It also offers easy-to-use access to the image catalogue, which enables users to search for and download specified subsets of images for further processing. The catalogue is hosted in the IDIS Interior and Surfaces Node of the EU FP7-funded Europlanet Consortium and hence benefits from and increases synergies between different FP7 space projects.

The **D3.2.1 Organics / Biological Substudy Report** details work on a) characterisation of the fluorescence response of different astrobiological targets by experimentally generating high-spectral-resolution excitation-emission matrices (EEMs) which will assist with the selection of optimal wavelengths for driving and detecting fluorescent signal. b) determination of the window of opportunity before such fluorescent signals are degraded by the martian surface conditions. Two studies were conducted: the destruction of biosignatures of photosynthetic cyanobacteria by cosmic rays on Mars, and the degradation of the fluorescence of polycyclic aromatic hydrocarbons (PAHs) by unfiltered solar UV radiation. c) the design, development and field testing of a hand-held fluorescence imaging device, WALI (the Wide Angle Laser Imager). This is comprised of both white-light and 365nm UV LED light sources, a sample light-exclusion tube, and sensitive DSLR camera for acquiring imagery. Much of this work has also now been published in the peer-reviewed literature, as indicated.

The research project PRoViScout (Planetary Robotics Vision Scout) establishes an architecture for future autonomous planetary missions of earth like terrains: Envisioned platforms are rovers and aerial vehicles. On these platforms, sensors are attached. The visual data captured by a variety of vision sensors are turned into data products that allow autonomous decisions about navigation and scientific target selection in a core processing module. Thus, the required extent of data transferred and the inevitable time delay via a continuous remote control, are reduced dramatically. Document **D4.1.1 PRoViScout Sensors** summarizes the current status of the sensor development with an emphasis on the TOF and the AUPE instruments. The final document for the HyperCam and WALI has been delivered in May 2012.

D4.3.1 Navigation & Mapping Component: The base for on-board navigation is a local DEM which is used by path planning in terms of traversability, possible hazards, locomotion costs, reliability and information content. Terrain modelling can be performed by a laser scanner, laser illuminated cameras, radio-frequency (RF) imagers or stereovision cameras which appear the best compromise for reliability and accuracy on one side and mass, power consumption and space qualification readiness on the other. Within PRoViScout a 3D-TOF camera is used for this purpose. DEM resolution should be much better than a wheel rover size to allow terrain crossing analysis.

The **D4.4.1 TVCR Software Module** describes the PRoViScout decision module. The purpose of the Decision Module is to manage plans. Plans are initially constructed manually and downloaded to the executive. During execution, the Decision Module monitors the progress of the execution of the plan and responds to discrepancies in the execution process by modifying the plan. If, during execution, science opportunities are detected (during planned science assessments), the Decision Module is called upon to modify the plan, if possible, to exploit each opportunity as it is discovered. The most likely change to the plan will be to insert the new actions that exploit the opportunity, modifying the context in order to accommodate this change. In principle, plan modification is constrained by several factors: primarily, the availability of resources (power and time are foremost of these), but also the relative priority of activities within the plan and the opportunity itself. The Decision Module modifies the plan by applying standard plan modification operations. These operations include insertion, deletion, linking and clearing. In order to avoid searching large numbers of alternatives, which is impractical on-board a platform with limited computational resources, the Module is designed to consider plan modifications in a standard sequence and greedily arrive at an executable and effective plan.

The D4.5.1 PRoViSC Prototype document outlines the core interfaces and relationships between the main on-board components for ProViScout – known collectively as PROVISC. This consists of several applications that work together to provide the required functionality onboard. A key operating principle for PRoViScout was to minimise effort spent on integration in order to maximise algorithm development.

The D4.6.1 3D Vision Processing Framework summarizes the structure of the 3D Vision processing component of the PRoViSC (Planetary Robotics Vision Scouting Chain). The CORBA interfaces of vision sensors access, DEM generation, visual odometry, and a pattern recognition component are described, and the overall structure of these on-board components are outlined. The Aerobot mapping strategy is documented, some use cases are given and further development hints are expressed.

D5.1.2 PRoViM SW Overlay & Basic Components describes the three primary components that have been developed for the PRoViScout concept namely: (1) Overseer – Off-board planning, monitoring and control, (2) Vision and Rendering and (3) Web Backend. Taken together the three components provide a rich and novel way of supporting an autonomous exploration platform. This document focuses primarily on the Overseer planning, monitoring and control element which allows operators to generate and construct a plan which will provide a high-level reference point for the on-board PROVISC components. A key feature of this system is the ability for scientists and operators to dictate how the system should respond to serendipitous science events at a high-level. This is achieved by allowing users to specify what actions to take should a particular science event occur. The detailed specifics of the actions are however determined autonomously by the on-board system at planning time. An interesting outcome of this work is its generic applicability to a range of autonomous or automated mobile platforms. The toolset specified here could be used to support various ground based or even underwater vehicles.

The 3D Robotic Visualisation and Rendering function mainly includes: (a) The 3D Scene Rendering module that renders in a photo-realistic virtual scene the real or the simulated rover and its surrounding environment. (b) The Rover S/S's Movement Control that supports the specification of 'targets' to be reached be the rover mechanisms. (c) The Data Monitoring that allows animating the robotic system in the synthetic scene, displaying on-line in 3D and analysing downloaded or simulated data. The **D5.2.1 PRoViM Visualization Interface** Report presents all the development process of the 3D Visualization and Rendering software from the requirements to the design, and presents test results.

The **D5.2.2 3D Robotic Visualization & Rendering Package SW User Manual** report presents the software user manual and test results of the 3D Visualization and Rendering software.

The goal of the PRoViM web Interface is to provide ability to monotor and present the PRoViM provessing and mission control over web to distant participants of the mission or trial. Document **D5.3.1 PRoViM Web Interface** reviews requirements following from the PRoViScout needs, overviews the suitable technologies for implementing such a system and finally desribes the solution that has been implemented. The final system is based on a lightweight web technology allowing to transfer graphical output of comuters running PRoViM and related software over the web via a date efficient channel to a web server which them serves the users over the broad-band Internet.

Simulation is an important step towards a smooth integration of the system. The Morphology and Texture simulator is a component of the simulation chain that allows to exercise, as much as possible the vision algorithms, but most importantly to close the loop of the control chain without the need of the targeted hardware. The Morphology and Texture simulator models in 3D the elements of a robotized system and the morphology and the texture of the environment is which it evolves. It includes the rover, the surrounding terrain and the models of the vision sensors (cameras and stereo head). Images quality parameters associated to a camera are adjustable, e.g. noise, distortion, glare for testing in various conditions. Lighting sources associated to cameras but also celestial objects are modeled as well. Ambient conditions are therefore adjusted to the simulation needs by adapting direct sunlight intensity and direction, ambient light and surface reflexivity characteristics. On request of the rover controller simulator synthetic images are generated to support the simulation of vision processing tasks. The report **D6.1.1 Morphology and Texture Simulation Package & SW User Manual** presents all the development process of the Morphology and Texture simulator from the requirements to the design, the software user manual and test results.

The first part of the **D6.2.1 Aerobot Context Document** describes the AU aerobot component of the PRoViScout project and is the main documentation output of Task 6.2. It describes the concept of a tethered aerobot in general, and the specific design and testing of the AU aerobot and its use in the PRoViScout reference mission to provide data for the construction of a high-resolution DEM of the wider area surrounding a ground-based rover. This document also discusses the possibilities for further scientific exploitation of the AU aerobot beyond its primary function of providing image data for DEM generation, by adding a multispectral imaging capability. The document’s final part discusses the work performed at UCL/MSSL on a tethered balloon aerobot, which was used to test fly a version of the wide-angle laser imager (WALI) over the MSSL grounds in March 2011. This section discusses the technical design of the aerobot and WALI instrument and summarises the results obtained. The possibilities for future exploitation of the UCL aerobot are also briefly discussed.

The **D64.1 AMASE Contribution Report** summarizes the main objectives and results of the PRoViScout deployment were in the AMASE expedition: (1) Test and demonstrate the utility of the ExoMars PanCam to correctly identify broad mineralogy, compositional units, geological structures, and morphological biosignatures, and lead a rover-like instrument suite to science targets of astrobiological interest by narrowing down the target space to lithologies of interest. Test and demonstrate the utility of the PanCam High Resolution Channel (HRC) to enhance the remote identification and characterization of scientific targets. (2) Assess the utility of UV-induced fluorescence measurements using a WALI emulator for the detection of organics and extremophiles in Mars-analogue soils and rocks. (3) Test the AMASE subset of the PRoViScout instrumentation (PanCam+WALI) in combination with other rover instrumentation, in order to learn how to effectively collect and use multi-instrument data to achieve a common astrobiology goal, and to learn how to detect, identify, select and sample compounds, minerals and rock types of interest at suitable spatial and detection sensitivity scales to ensure that the best and most diverse sample set is analyzed.

The two MERs Spirit and Opportunity have travelled several tens of kilometres on the Martian surface, and produced hundreds of thousands of images in various geological and morphologic environments. In such way they provide a huge data base to be utilized in the PRoViScout project, which deals with the enhancement of scientific output of future planetary surface mobility missions.

The **D6.5.2 MER Exploitation Report** summarizes the experimenting activities using MER vision data during the 30 Months ProViScout lifetime under various objectives such as the automatic selection of scientifically interesting targets, mapping & navigation, as well as the combination of different cues to increase the scientific output.

The document **D6.6.2 Internal Tests summary** brings together and summarises in one place all of the internal testing that has been undertaken throughout the PRoViScout project. Hardware and software testing has occurred on many occasions during the project. Some of this work has involved the testing of individual hardware and software components in isolation (referred to as 'unit' testing), whilst other work has brought the components together for integration tests. The driving force throughout has been to ensure that that the goals of the PRoViScout project would be delivered, and a successful final Tenerife Field Trial in September 2012 would be achieved.

The PRoViScout reference data provide a baseline for developing and testing vision algorithms for scientific target recognition, visual navigation, trajectory planning, rover visualization, 3D terrain modelling and evaluation, and sensor assessment. The document **D7.1.1 PRoViScout Reference Data Set** reviews several test and reference sets that have been collected during the PRoViScout development and field trials. Data sets are available upon the request from the central PRoViScout repository or from individual partners.

The **D7.1.2 Satellite Workshop Organization & Publications** document summarizes satellite workshops organized by PRoViScout, activities of PRoViScout in the scope of SpaceMaster, and reviews PRoViScout publications. In 2012, the PRoViScout consortium co-organized five satellite workshops at meetings targeting planetary research and computer vision and photogrammetry. PRoViScout participation in SpaceMaster allowed for the dissemination of the results of the project amongst students interested in space technology. Topics for master theses were formulated and offered to students. Four master students defended their theses. The PRoViScout consortium published and presented a number of scientific results in journals, including two papers in IEEE PAMI (impact factor 4.9. in 2011) and in Astrobiology (impact factor 2.15 in 2012), conferences, workshops and at various public events.

The **D7.3.1 Spin-Off Document** gives an overview of further use of PRoViScout results by identifying opportunities and evaluating use cases in space and terrestrial sciences plus commercial or public applications, on top of the “regularly planned” results PRoViScout is providing (software & dissemination). One typical example is to use a rover with vision capabilities for these applications. Such applications are e.g. rover actions in contaminated areas, arctic expeditions or underwater explorations. For each opportunity and use case several aspects (unless confidential) are given both on entire system level and concerning its individual components.

The document **D7.4.1 PRoViScout.eu** gives a pointer to the Deliverable D7.4.1 the “Web site incl. Maintenance“ of the PRoVisG Project. The actual deliverable is the web page www.provisg.eu.

The **D7.5.1 Dissemination Plan Draft** summarizes the dissemination strategy for the FP7-SPACE Project PRoViScout. It addresses the following aspects as seen from a period close to project start:

- Dissemination goals are formulated as given from the considerations during proposal writing and project negotiations, as well as the related FP7-SPACE Call
- Relevant project content being straightforward and strategically important is identified
- The target groups that can profit from PRoViScout dissemination are identified
- The media for dissemination best fitting for the PRoViScout objectives are outlined
- Specific dissemination such as conferences, field trials, or the PRoViScout reference data set are addressed in more detail, as far as known during Project start.
- Specific strategies (internal and external) to facilitate dissemination and make it most efficient and in accordance with quality requirements are suggested.

This draft was replaced by the final dissemination plan close to the end of the project.

The **D7.5.2 Dissemination Plan** summarizes the dissemination strategy for the FP7-SPACE Project PRoViScout. This document had a precursor – draft – version where the dissemination plans were pointed out close to the start of the Project. Now it is the a-posteriori status description at the end of PRoViScout.

The **3D-TOF Defects Report** is an additionally delivered report summarizing the 3D-TOF defects that have appeared during the PRoViScout project runtime.

4.1.4. Potential Impact, Main Dissemination Activities & Exploitation Results

4.1.4.1 Potential Impact

To **make robotic rovers more independent and efficient**, instead of waiting for instructions from Earth, **PRoViScout has implemented an on-board vision-based identification and planning system**. It is able to **identify objects of interest and interpret their relevance to various mission goals**. Rovers can “see” important scientific or navigation features in the terrain and task themselves to gather more detailed data about previously unseen targets, whilst carefully prioritising and allocating their limited resources and keeping track of possible hazards.

PRoViScout has helped to **develop a unified and generic approach for robotic vision on-board processing**, namely the **combination of navigation and scientific target selection** by **addressing all relevant existing approaches** to this topic and **integrating them into a framework ready for and exposed to field demonstration**.

Although PRoViScout was not intended to directly interface to the ongoing definition of mission objectives, its processing facilities allow for explicit feasibility statements and the access to essential environment parameters. It integrated a novel sensor suite just evolving from European Industry and Science, which offers the chance to combine science and engineering objectives in an efficient yet straightforward manner: **Robust 3D and 2D in real-time, with little weight, minimum power consumption** and fully integrated into an operational end-to-end demonstrator. This was the pre-step for promising application both in mid-term space missions and the civil security domain.

In terms of **general public awareness**, the field test campaign focused attention of European press, education and, as a consequence, also public bodies that are responsible for the funding of space research in general.

Biannual presence on **dedicated conferences** and dedicated workshops within major relating conferences complete the set of impacts. **Publication took** place both on a technical basis as result of conference contributions, and scientifically as result of specific research areas addressed in ProViScout, such as tasking, integrating scientific selection & navigation, and scientific target classification.

PRoViScout has dealt with **real research challenges** (rather than mainly integration and trials), and inherently it has **addressed potential Earth based applications** that do not and will not emerge over the next few years without such efforts. **Mutual benefits** were guaranteed by the **proposers’ involvement in major relating European initiatives** such as ExoMars PanCam, Eurobot, EC-FP7 PRoVisG and the UK national CREST Project Autonomous Robot Scientist.

4.1.4.2 Dissemination & Spin-Off

PRoViScout dissemination activities included a large number of scientific publications, invited talks, presentations, participation to workshops, summer schools, working with students within SpaceMaster program as well as reaching out to general public by TV and general media:

PRoViScout results have been presented on **general as well as dedicated conferences**, e.g. at the ICCV 2011, CVPR 2012, and at **dedicated workshops** co-organized by PRoViScout, E2M:CVVT 2011 and 2012: Workshop on Computer Vision in Vehicle Technology: From Earth to Mars where CTU presented results of the project in invited talks.

A **set of reference data** for DEM generation and visual odometry has been generated during the Tenerife 2012 field trial and is available at the CTU.

SpaceMaster activities continued and as a result four MSc theses, which were finalized (Jan Smisek – 3D Camera Calibration (CTU, JR), Cenek Albl – Pancam Bundle Adjustment (CTU, JR), Josef Strunc – Fusing Shape form Shading with Stereo (CTU, AU), Rober Marc – Sensitivity Analysis of Virtual Terrain Accuracy for Vision based Algorithms (CTU, ESTEC, TraSys) brought also three publications and presentations.

The **PRoViScout results** are gradually being published and made **available via standard scientific publications, research reports and data**.

A summary of all PRoViScout dissemination activities can be found in the dissemination list.

Website

The **PRoViScout website** www.proviscout.eu was set up with project start and has **been maintained and further filled** with contents during the whole project runtime.

All information about structure and content of the project website are summarized in the deliverable D7.4.1. It was agreed by JR to further maintain the PRoViScout web site for a couple of years after PRoViScout termination.

One major driver for PRoViScout dissemination on www.proviscout.eu was the PRoViScout Field Trials Event in September 2012. Whilst access statistics on the web site was about 200 – 300 unique users per Month, this was boosted up to almost 1000 during September 2012, with more than 80,000 access actions, with largest access onto the proviscout-events page that contained the web log of the field trials.

Spin-Off

In terms of **Spin-off**, a specific Deliverable (**D7.3.1 the Spin-Off Document**) documents a comprehensive collection of possible methods to further exploit the PRoViScout results by identifying opportunities and evaluating use cases in space and terrestrial sciences plus commercial or public applications, on top of the "regularly planned" results PRoViScout is providing (HW & SW framework (demonstrator) & dissemination).

During the final phases of the project a spin-out assessment was carried out for the technology as a whole. This took into account the latest status of the 3DTOF and updated the original brief to extend the spin-out potential to the whole system. To begin with we looked at recent developments from the EUROP/EURON roadmaps (SRA) and aligned the various PRoViScout sub-component technology with the application areas identified in the SRA. Overall we noted a number of areas of applications for the core technology.

Because the developed **3D-TOF/RGB** camera couldn’t be completely integrated and tested during the project duration of PRoViScout, its final spin-off on industrial and space applications is currently not foreseeable. However, a remarkable list of innovations can be expected.

The **3D vision & navigation** aspects as elaborated in PRoViScout will be further followed by JR in their tunnel survey, construction and monitoring activities. Localization, visual odometry and hazard avoidance by DEM generation & analysis could be used for robot agents in construction environment.

The **navigation & vision system** is considered as being of interest for other fields of GMV activities (i.e. satellite rendezvous and docking). Further, the knowledge and experience gathered during the system’s development is quite valuable for acquiring and participating in related future activities as the Exomars-ROCC (Rover Operations Control Centre).

In the **planetary exploration domain**, PRoViScout participants are involved in some submissions for FP7-SPACE Call 2013 (closed November 21, 2012) that intend to exploit PRoViScout components.

4.1.5. Address of project public website and relevant contact details

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