THE PROVISCOUT FIELD TRIALS TENERIFE 2012 – INTEGRATED TESTING OF AEROBOT MAPPING, ROVER NAVIGATION AND SCIENCE ASSESSMENT

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ABSTRACT

The FP7-SPACE Project PRoViScout (Planetary Robotics Vision Scout) aimed to demonstrate the feasibility of vision-based autonomous sample identification & selection coupled with vision-based navigation for a long range planetary scouting/exploration mission along with the necessary robotic elements. After 2 years of development and integration, the project held a field trial campaign in the caldera of Tenerife in September 2012. This paper gives an overview of the trials and summarises its major findings in terms of equipment, software integration, trial's logistics & strategy, and the main trial results.

1. INTRODUCTION

Mobile systems are among the most critical of all space missions. In future the number and variety of such platforms will require more autonomy than is feasible today [3], particularly for the **autonomous on-site selection of and access to scientific and mission-strategic targets**. The combination between science-driven and operations-driven decisions taken on-board is a key component of this autonomy. PRoViScout [9] established the building blocks of such future autonomous exploration systems in terms of robotics vision by a decision – based **combination of navigation and scientific target selection,** integrating them into a **framework which was tested in a live field test**.

The **operational objectives** for the PRoViScout field trials were as follows:

- Realise and test all components (sensors, hardware, software) in a representative field environment
- Integrate, test and verify component integration with a demonstrator platform
- Provide a www interface of the system for remote monitoring and visualisation of the activities
- Validate the proposed operational planning approach for autonomous science.

The **science objectives** were to focus on the two most important requirements from a list of geological criteria compiled by the project science team. These were:

- Detect the presence of physical layering (for determination of the sedimentary environment and stratigraphy)
- Detect the presence of anomalously coloured areas in an outcrop (for determination of compositional variation).

The main objective was the combination of science and operations, namely **autonomous science**.

Taken together, these objectives had the clear goal of allowing a suitable validation of the proposed autonomous science concept. Autonomous science is a challenging technical problem which will require significant research and development over the longer-term. The PRoViScout field trials scope was therefore restricted to fundamental proof of concept tests. In particular the field trials sought to establish whether or not, primitive geological characteristics could be detected and evaluated with the proposed sensor suite in a representative Mars analogue environment.

Detection of even primitive targets is a complex problem in a cluttered, noisy, and visually diverse scene where feature/scale information extraction is non-trivial. This observation is further informed by the conclusion from science experts that such analysis and feature detection is difficult to achieve with straightforward vision sensors in isolation. The field trials were configured to be a hard test given the complexity of the selected site, ambient light conditions and target placement, as well as level of integration.

PRoViScout integrated **technical components (SW / HW / Sensors) from 8 European institutions (5 different directly on the rover).** A rehearsal campaign at Aberystwyth University 3 Months before the Tenerife trials verified the interfaces at first time.

2. SITE SELECTION AND TRIALS PLANNING

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 had been collated. The decision for the test site location was made following a field visit in June 2011 and the experience gathered during the PRoVisG field trial on Tenerife in September 2011 [10]. The main justifications for selecting the **Minas de San Jose area in Tenerife** were as follows:

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

One drawback of the chosen 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, budget A2-sized 3D artificial science targets with these specific attributes were created, designed to be inserted into the terrain and merged with the natural geology.

All planning information were summarized in a **Trials planning document**, containing items such as:

a) List of participants / contacts & organization of accomodation: Booking was done in hotel “The Parador” near the test site and a hotel in Vilaflor.

b) *Instructions and information about the test site, environmental issues, authorities treating Do’s and Don’t’s, Health and Safety issues as well as hints which items to bring / to buy*.

c) *Organization / interaction with local support company*: The local company ActiveConnect supported the PRoViScout team in all locally organizational items.

d) *Dealing with local authorities*: To get the official permit for accessing El-Teide National Park, paperwork was finalized several months before the trials.

e) *Supply & transfer of Equipment*: A list of required equipment including information about who was going to bring it to the test site was maintained. Each participating organization was responsible for the transportation of their own hardware components, storage devices & tools.

f) *Test layout & planning*: Requirements and priorities concerning the test layout and planning were collected and discussed in preparing telecons.

g) *Establish / update schedule(s) & responsibilities*: Schedules and responsibilities at different levels of granularity were established and provided (i.e “Overall field trial schedule”, “Responsibilities per day and person”, “Hourly schedules for each day”)

h) Press & dissemination activities: Local and national press were officially invited to attend the press day on site. Participants were giving interviews and the rover was driven around. Flyers in English, Spanish and German language were handed out to members of the press and visiting tourists.

In technical and scientific context it was necessary to have a list of objectives with priorities, estimated schedules and backup procedures:

a) Each experiment came with a sequence chart that allowed minute-by-minute monitoring of the experiment in order to find delays early enough.

b) A backup plan was required for potential system failures & unexpected environment conditions.

c) Some decisions had to be made on-site, reacting on circumstances and in better knowledge about expected durations and resources, such as:

- Common file system structure to store data
- Communication via hand-held radios
- Paths for the rover and distribution / timeline of individual experiments’ components (panoramas / visual odometry / science targets, …)
- Daily schedule & responsibilities on/off site.

d) Shakedown days were necessary to verify rover and test infrastructure.

e) Integration of the artificial science targets into the terrain was undertaken once the proposed traverse had been defined. Visibility of the targets along the default traverse provided for a potential "discovery" scenario in the imaging data. To satisfy non-layering science criteria, a natural target was also identified along the proposed traverse, close to where the artificial targets were placed: A blue patch (xenolith), approximately 20 cm across on the side of an outcrop and clearly visible to the cameras from a few metres away.

3. TRIALS EQUIPMENT

The trials used the following **primary** on-site **pieces of hardware**:

- The Aberystwyth University (AU) rover Idris [12] (Figure 1), a robust outdoor rover platform with high payload capacity and off-road capability. Beside carrying the payload instruments, Idris also provided power and communication services. The Idris locomotion subsystem allows driving manually or under software control, while ensuring safety by the use of its laser scanner based obstacle detection system. Batteries carried by the rover support a full day's activities when fully charged.
- The AU PanCam [2] Emulator (AUPE) [8], a Wide Angle Camera system on a Pan-Tilt Unit (PTU), comprising two cameras with R, G & B filters. 12 narrowband geology filters are also available (6 per camera), along with a narrow-angle camera for close-up images of science targets. AUPE supports many different imaging modes. For PRoViScout, AUPE produced panoramic sequences (single images and stereo pairs) in RGB up to a full 360x180 degrees, multispectral image sets, and synchronised monochromatic stereo pairs for Visual Odometry and digital elevation model (DEM) generation.

- A Linux server PC mounted on the rover provided sufficient processing power and data storage for the PRoViSC onboard software modules (Vision Processing, Science Assessment, Navigation, Executive, MMOPS and instrument interfaces).

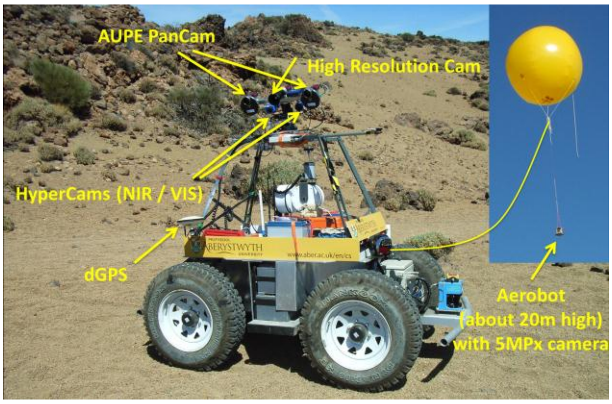


Figure 1. Rover “Idris” with major sensor components.

Two components originally implemented in the PRoViScout system were not used during the trials:

- A zoomable 3D Time of Flight camera with RGB capabilities – this was abandoned due to slight optical degradation of the sensor by time of the trials, and for (eye) safety reasons.
- A Wide Angle Laser Imager (WALI) [4] – this device underwent offline tests prior to the trials.

During the trials, in addition Hypercam – a hyperspectral camera system composed of twin cameras behind visible (400-720 nm) or near-IR (650-1100 nm) liquid crystal tuneable filters (LCTF) – was deployed. Hypercam was controlled (using Microsoft remote desktop) over the trials Wi-Fi network by a separate rover mounted laptop.

4. TRIALS LOGISTICS AND INFRASTRUCTURE

The field trials conduct demanded infrastructure and support systems to ensure that all goals were met within the window of opportunity provided by the Site Authorities. The site chosen required the rover to operate at some considerable distance from the nearest accessible road. Easy communication and data exchange between operators and with the rover was essential. Further, it was neither desirable nor possible to accommodate all team staff at the rover operations site.

The infrastructure adopted for the field trials is summarised here and described more detailed in [12]. Heavy use was made of the rover transportation and operations control vehicle - a large, modified box Luton van - which was used to transport the rover and its support systems to Tenerife from the UK. After unloading the rover, the van was converted into a fully-functioning mission control centre, with tables, chairs, power, communications, shade and cooling.

As well as operating as a mission control centre, the van was equipped with tools and equipment to operate, service, maintain and modify the rover, and to support the fitting of instruments and equipment both in the field and back at the hotel. Solar panels on the van allowed charging of batteries in the field, with a petrol driven electric generator as backup.

The rover operations site was supplied with a gazebo, table and chairs (Figure *2*). A tape fence was erected at the rover operations site to protect the site from visitors – and the visitors from potential injury by the rover.

At each of the two sites, local wifi networks were provided for team members to connect to. The two sites were joined by a high-bandwidth long-distance wireless link (range of up to 22km). An additional dedicated wireless link was set up to communicate with the rover itself. Monitoring webcams mounted in the field (or on the rover) enabled control centre staff to drive the rover remotely and allowed them to see, hear and be aware of what was happening in, on and around the rover during field trial operations. To aid communication between team members themselves, and between the two sites, personal mobile radios were provided. Staff were instructed to use a dedicated communication protocol.

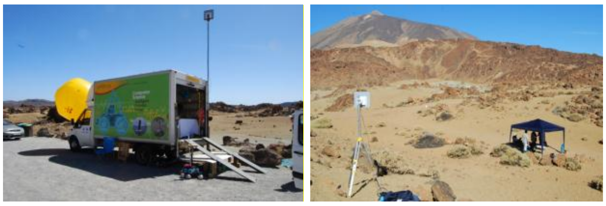


Figure 2: Mission control van and rover operations site.

Additional data communication facilities were provided by a local company on the main trial days. A V-SAT satellite broadband link connected the PRoViScout local network to the wider Internet, allowing upload of gathered data to the project FTP site, upload of images and text to the public web site, and enabling personal communications for team members.

The personal and co-operative aspects were considered to be of great importance to this project and the success of the field trial in particular. In the harsh environment of the field test site, ensuring the well-being and comfort of participants was essential for efficient co-operation and achievement of goals within a limited time frame. As well as shade, tables and seating, team members were supplied with food and drink in the field to save time and maintain energy and hydration levels. This activity was supported by a local logistics firm.

5. MAPPING BY AEROBOT IMAGERY

The PRoViScout field trial included flying a tethered aerobot over the field test site (Figure 3). The AU aerobot [6] provided area context for the rover, at a scale intermediate between ground observations and orbital imagery. Images captured by the aerobot were used to generate an area DEM for mission planning and waypoint selection.

Figure 3. Rover “Idris” with coupled aerobot on test site

The AU aerobot's primary sensor is a 5 Mega-pixel monochrome camera (Prosilica GC2450 with Sony ICX625 monochrome CCD sensor with a resolution of 2448x2050). Images captured by the camera with up to 15 frames per second at full sensor resolution with 8 or 12 bit pixel data are stored on-board the aerobot for later retrieval. Aerobot operation is coordinated by an embedded Linux computer, managing the capture of images according to a pre-defined schedule. Auto-exposure is used to maximise the number of images useful for DEM reconstruction. The captured images are stored on an internal SSD for download after the flight.

The AU aerobot hangs from a tethered helium envelope, using a suspension system (“Picavet”) designed to reduce any swinging motion of the payload. The envelope used for PRoViScout was 7 feet (2.13m) in diameter, uprated from an original 6 feet (1.83m) to allow for the reduced air density at the field test site altitude. Power for the aerobot allows up to 120 minutes of operation, however flights were limited to 90 minutes to avoid possible problems with over-discharging the batteries.

The DEM has been generated using 3D reconstruction and mapping pipeline based on Structure from Motion http://ptak.felk.cvut.cz/sfmservice/ and multi-view reconstruction pipeline [11]. Additional functionality has been added to allow to geo-register the resulting 3D reconstruction and to generate a DEM in the vertical direction, which was derived from the geo-referenced 3D model and stored in a convenient format for further use in the PRoViM chain. DEM generation by the reconstruction and mapping pipeline consists of the following processing steps:

1. A set of photographs is captured by an Aerobot camera and downloaded to the server.
2. When available, GPS coordinates of the cameras are logged when taking the photographs.
3. A 3D reconstruction of the terrain is computed by a multiview reconstruction pipeline, which is capable of processing completely general image data and produces a textured general 3D mesh.

As geometric reference, a set of 80 white circular targets were distributed in the scene and measured by dGPS. The targets were well visible in Aerobot imagery and could be detected and semiautomatically localized and used to rectify the resulting reconstruction by fitting the computed camera centres to the measured GPS coordinates. Alternatively, when GPS measurements are not available or are not sufficiently accurate, reference points can be manually detected in images and their reference position used to achieve an equivalent result. The second option has been used in PRoViScout field trials.

Figure 4. Left: DEM of whole test site (length approximately 400m) generated during the trials from aerobot images. Right: Corresponding ortho image.

6. TRIALS ROVER SOFTWARE ENVIRONMENT

The on-board components (Figure 5) consist of the rover together with the sensors and pointing devices as well as Mission Management components: the *Executive*, the *MMOPS* (Mars Mission On-Board Planner and Scheduler [7]), a science assessment module, and navigation & vision processing modules.

The **Executive** has two main purposes:

- Act as an interface between the PRoViM (Section 9) monitoring operations element and the rover, including providing status/monitoring information such as rover position and timeline, and receiving plans and science templates from Overseer and forwarding these to MMOPS for possible insertion into the plan. Therefore providing a tool to support fully autonomous operations whilst allowing real-time monitoring and control.
- Maintain a model of the onboard plan as prescribed by MMOPS and execute this at appropriate times.

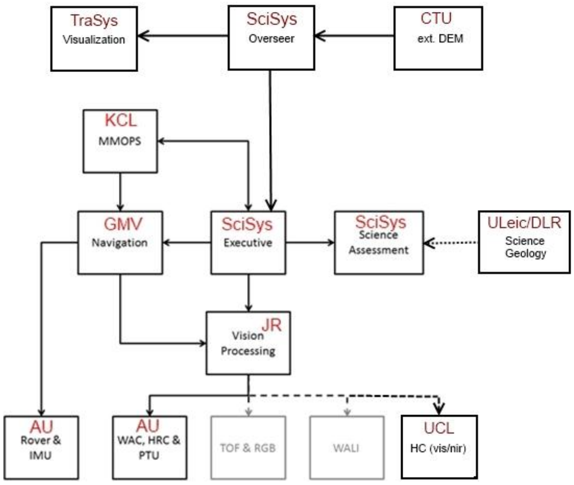


Figure 5. System components having been integrated and tested during Tenerife field trial. WALI & 3D-TOF were not available on site (grey & dashed line). The HyperCams (HC) were not integrated to the vision processing software (dashed line).

MMOPS was relied upon to update and ensure the consistency of the mission timeline and provides deliberative, high-level mission management capability. In addition to receiving an initial plan, it received requests to add navigation tasks and science opportunities to the timeline. Before doing so it ensured that there are enough resources (time, power, memory) for continued operation using static and dynamic information.

Timeline validation and repairing (as required) was planned to occur periodically to ensure correct operation of the rover. Depending on the type of sub plan currently executing, task failures/overruns were treated differently. For example, if a science opportunity sub plan failed, this would have simply been removed and execution to be continued as normal.

As part of the science assessment tasks, the science assessment component (Section 8) used the stereo-derived 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. Science assessment and MMOPS are in more detail addressed in [5].

The **Navigation component** was in charge of instructing the Platform to move the rover from one location to another. This invoked the vision processing module (see below) to take stereo images and construct 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 provided a set of utilities to perform various functions involving imagery, including:

- Image acquisition in RGB and stereo
- Mapping (DEM generation, hazard and slope maps) from stereo
- Construction of a panoramic image for SARA
- Visual odometry.

7. TRIALS LOCOMOTION AND NAVIGATION

Long-range navigation starts by requesting from the local DEM an intermediate local waypoint as close as possible to the desired final target. Later on the path-planning algorithm is triggered in order to find the optimum path between the current rover position and such intermediate waypoint avoiding obstacles higher than wheel radius and generating a list of internal navigation waypoints. Finally the navigation component starts the rover motion performing a classical sense-decide-act control loop [1] (see Figure 6) at 10Hz:

a) Estimation of the rover position using Kalman filtering (wheels odometry as main source but also with the capability of including visual gyro, IMU and visual odometry measurements)
b) Guiding trajectory computation taking into account rover non-holonomic constraints
c) Locomotion commanding by sending double-Ackerman steering commands to the four wheels.

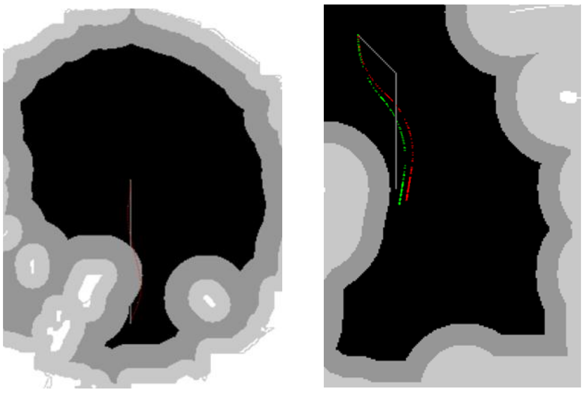


Figure 6. Navigation map with enhanced obstacles (left) and rover navigation trajectories (right) (real in green, guidance in red and path-planning in gray).

8. TRIALS SCIENCE & PLANNING

The Science Assessment and Response Agent (SARA) assesses images based on a set of fundamental operations and compares these against given scientific priorities. Each image is analysed to extract the various objects within the scene (this including background soil, sky, rocks), using several methods of segmentation from graph-based colour, hue, watershed etc. The identified objects are then analysed for the parameters specified within a “Mode” value defined in the contextual model, defining the object albedo, colour, size and roughness. The contextual model also contains information describing how to combine the outputs of the various analysis stages and rank the objects with importance.

Classification categories fall into three areas: structure, texture and composition. Scale is also important as a bolder field could appear as a material with impurities if scale is unknown. The SARA capabilities allow to identify and rank objects in terms of albedo (using average grayscale of the object, colour, roughness (surface topography), shape (elliptical / roundness / circumference / area), and layering (direction / orientation / multiple / cross bedding). A fused analysis of the various parameters provides a cumulative overall classification with respect to science importance.

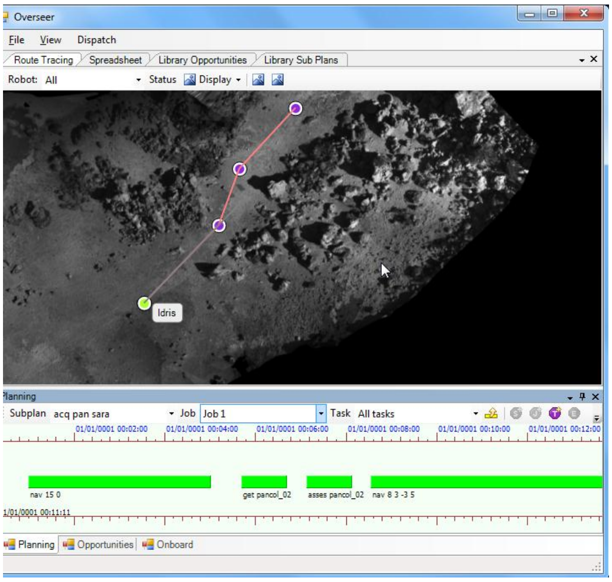
Using information regarding the camera and the target within the scene further image/instrument acquisitions can be scheduled as the system transforms the target position in the original camera reference frame to the reference frame of the new camera (generating appropriate pan and tilt angles to centre the image on the target). Figure 7 shows the SARA output obtained during the field trial, here the system was configured to identify regions with a particular composition.

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

During the trials an initial plan was presented, consisting of several navigation, image capture and science assessment actions, interleaved so that after each navigation leg the rover would capture an image and perform a science assessment looking for possible science targets. The initial plan also included default science operations to be performed at the goal location. In order to test the complete behaviour, the plan was allocated much larger resource limits than would be relevant to operations in the trials, but simulation trials have also been performed using lower limits that force decisions about the relative priorities of alternative science operations. During the field trials, in some runs (though not in all) the science assessment agent identified useful science opportunities and these were presented to the planner as proposed response actions, with priorities. The planner confirmed the validity of the plan when these operations were inserted and dispatched a new plan to the executive.

9. TRIALS CONTROL & MONITORING

Operational planning for the PRoViScout field trials was realised by the OVERSEER UI front end (Figure 8) to create mission plans, define science opportunity sub-fragments, dispatch plans and observe progress during execution. The Executive (Section 6) was responsible for core graphing the execution of the proposed plans on the rover platform. As science requests were generated and serviced, plan updates were implemented and relayed back to the OVERSEER planning interface.



Robot: All

Subplan: acq pan sara

Job: Job 1

Task: All tasks

Figure 8. OVERSEER UI showing rover tracking in 2D display at Minas de San Jose and plan execution status

The Monitoring and the Control of the operations was supported by the 3D Robotic Visualisation and Rendering (3D-RV) tool. It includes the models of all elements of the robotic system (platform, locomotion, cameras, …) and the model of the 3D environment, stemming from the aerobot images. The targets and the rover global waypoints were placed in 3D-RV and the motions were rehearsed in order to check their feasibility. 3D-RV was interfaced to the Executive on the control PC. During the operations the rover motion was monitored in the reconstructed 3D scene allowing the operators to better supervise, understand and analyze the system behavior.

A **web based system** for monitoring and visualisation of experimental missions providing a unified www presentation of the mission status was developed. The system was designed to support remote missions connected over only a slow, e.g. satellite, network. On 16th and 17th September, 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 server and transformed into a live video (Figure 9) over http://cmp.felk.cvut.cz/projects/proviscout/vfeed/.

10. MAJOR EVENTS, RESULTS AND FINDINGS

During preparation phase and trials as well as thereafter a couple of results and findings were recorded on various levels of procedures, system and project:

1) During the Trials, regular meetings were made before or after dinner, covering topics such as the timeline for the next day and responsibilities / presence for staff on the different locations.

2) Most of the trials time was needed for system setup and interfacing between components (Section 4).

3) The Trials' log book [13] was generated by JR dedicated staff on an everyday basis. Originally

generated for the Public, it gives a valuable insight into the trials' procedures also for experts.

4) The artificial science targets proved to be very realistic in terms of geological features and natural colour and response to illumination i.e. shadowing to accentuate texture. Visibility of the targets along the default traverse provided for a potential "discovery" scenario in the PanCam data.

5) One major obstacle was a broken PTU component during the second full trial day. Despite intense effort, the tilt axis could not be repaired on-site so it was fixed at a representative angle. The restricted tilt capability during tests lead to invisible regions close to the rover which caused some hazardous events that could only be overcome by human intervention.

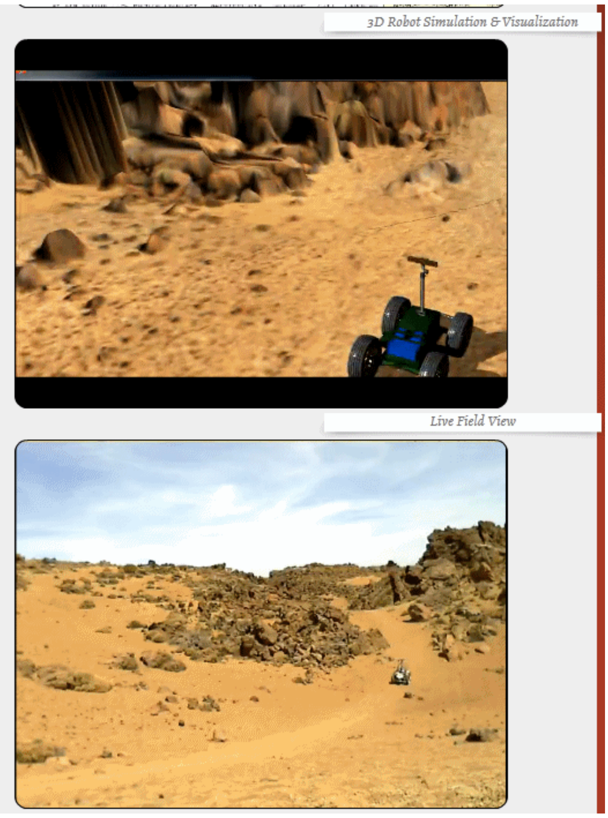


Figure 9.: Screenshots showing integrated behaviour enabled by the SW framework (as available to public www on 16th and 17th September 2012). Top: PRoViM, Bottom: Field Web cam

6) Many issues arise during field trials. This is what makes them such rich learning experiences and valuable events (for example, avoiding test personnel from appearing in test imaging such as PanCam panoramas). 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.

7) 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 helps 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.

8) On-site SARA feedback was as follows:

- The 2.5D artificial targets prepared in advance of the field trial proved to be very realistic in terms of geological features and natural colour and response to illumination i.e. (e.g. shadowing for texture).
- Initial PanCam images showed that structural and textural features in the targets were difficult to resolve under sometimes harsh natural illumination (most days were bright with little or no cloud).
- However, analysis of the images by SARA identified that layering was present.
- Following the PTU breakage (see 5) targets were no longer visible in the field of view of a proximal rover because they were too low to the ground. It was not possible to relocate the targets higher up on the outcrop because they would not merge well into the natural surface (i.e. obvious un-natural joins and false positive detections would result).
- Science criteria were switched to colour and a natural feature on an outcrop was selected near to where the artificial targets were emplaced.
- Colour calibrated images were therefore acquired for SARA to work in real colour-space.
- SARA functioned reasonably robustly albeit in isolation to the end-to-end operations work flow.

9) SARA post facto feedback after collation of results:

- PanCam Spatial resolution limits detection of geological features at discovery distances (i.e. realistic distances to warrant rover deviation based on centimetric features) unless they are obvious and large-scale.
- Science assessment of a single attribute at a time works but is not really realistic as it stands. There are too many potential variables in geology to just rely on one attribute and no weighting criteria.
- Each attribute can be selected as prime at any part of the traverse (i.e. in scenarios were one attribute may be more significant in certain locations and less in others).
- Science assessment using multiple attributes and weighting criteria is not yet possible and this should be implemented as soon as possible.
- Thematic imaging will become more important in scouting where spectral parameters may introduce more significant indicators than structure, texture and RGB only.

11. CONCLUSIONS

The PRoViScout field trials at Tenerife in September 2012 lasted 9 days. In this period, the integration of aerobot mapping, on-board locomotion, mapping, navigation, science assessment, and decision, as well as full remote control of rover Idris and its subsystems, could be accomplished. The rover and its subsystems successfully underwent a couple of autonomous drives with all components operationally working together.
Complete end-to-end tests with autonomous decisions of the rover system in the loop could only be accomplished the very last day for a couple of times and short trajectories up to 20 meters.

PRoViScout yielded much valuable experience of how to organise and run a major field trial involving many participants and organisations. Infrastructure worked well technically, and it also provided a comfortable and productive environment for co-operation.

Given the strong PRoViScout participation and investment from several non-prime industrial space companies, there is also a focus on identifying practical routes to technology infusion in forthcoming missions. The proposed architecture has been developed with concepts such as adjustable autonomy in mind to smooth this transition. Some components have already been used to craft the autonomy concepts for ExoMars such as the Phase A and B MMOPS initiative. During the trials, various elements of the work were evaluated for relevance to mission like a Sample Fetching Rover.

12. ACKNOWLEDGEMENTS

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