FP7 FASTER project - Demonstration of Multi-platform Operation for Safer Planetary Traverses

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ABSTRACT

As future planetary missions evolve from local exploration in the vicinity of the lander (up to a few km) to more regional operations (with a reach beyond tens of km), the need for a safe and efficient traverse will be greater than ever. To address these challenges, the EU FP7 FASTER project [1] has tackled for the past 4 years the **F**orward **A**cquisition of **S**oil and **T**errain data for **E**xploration **R**over which culminated in the successful demonstration of the operational scenario in late 2014 in a representative environment.

Building on [2], this paper will briefly recall the selected operational concept for safe traverses for planetary rovers as well as the various sensors created for this project. It will then focus on the latest developments, including the setup and running of the various integration campaigns leading up to the final multi-platform test campaigns at the Airbus DS Mars Yard. Finally, based on the results of the project, it is possible to look ahead to future mission concepts and identify where specific aspects of the FASTER project could contribute to the robustness and safety of future platforms allowing more daring exploration scenarios.

1. INTRODUCTION

As part of the Mars Sample Return programme, the need for long and sustained traverses on the surface will be much greater than for the current generation of science rovers. The Sample Fetching Rover mission will be significantly different due to the inherent challenging requirements called for by the mission [3]. The rover must traverse 15km over the course of a 180-sol nominal mission (~120 sols actual traverse), leading to a challenging minimum average rover speed of 120m/sol across a variety of terrains while locating, navigating to, and retrieving a sample cache.

While current developments are investigating the use of increasing levels of on-board autonomy to improve the traverse speed, operations tend to be carried out in a cautious manner, with -so far- minimal autonomous deliberation. However, one significant challenge of the safe surface traverse will be the reliable identification of hidden obstacles that cannot be inferred from the typical sensor suite currently on-board rover platforms.

During NASA's Mars Exploration Rover mission (MER), on sol 1892 (May 1, 2009), the rover became stuck in soft soil, the machine resting upon a cache of iron-sulphate hidden under a layer of normal-looking soil. During 8 months, specialists at NASA carefully analysed the situation, running Earth-based simulations, to help the rover to make extrication drives in an attempt to free itself.

Figure 1 NASA's Spirit on sol 2052 in loose soil (white sand on the left) after the wheel broke through the darker crusty surface layer (Photo credits: NASA/JPL-Caltech)

To avoid such incidents, the operation of planetary exploration rovers rely on carefully planned traverses that affect the speed the platform can cover per sol. As such, the average travel speed of Curiosity, is about 0.8 cm/s while the theoretical maximum speed of the vehicle is about 2.5 m/s.

To address these design and operation challenges, the Forward Acquisition of Soil and Terrain data for

Exploration Rover (FASTER) system has been conceived bearing in mind the stringent traverse requirements of future missions. In its simplest form, it leverages the operation of a lightweight, highly mobile scout rover as a forward sensor of the primary rover, ascertaining terrain trafficability and identifying potential soil hazards. This increases the safety of the primary rover, allowing additional autonomy functions to be used with the goal of achieving faster overall traverses.

2. SYSTEM CONCEPT

Setup as a multi-platform operation, the FASTER scenario relies on a light mobile rover to scout ahead of the primary rover to estimate terrain trafficability through a range of sensing techniques (Figure 2).

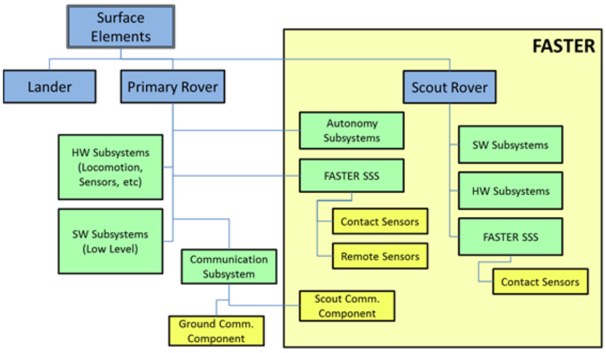

Figure 2- FASTER Concept System Definition

By combining the scout sensor data with the primary rover on-board sensors, a complex multi-layer navigation map is generated that identifies trafficable and hazardous terrain, such as rocks and sand traps, in front of the primary rover. Autonomous path planning, for both the primary and scout rovers as well as autonomous online re-planning, ensure the two rovers can identify and react to the unknown local environment to reach their target without the need for a human in the loop.

2.1. Primary Rover

The primary rover selected for the project was the Airbus DS Bridget Platform. The platform was the first locomotion breadboard for the ExoMars rover project before evolving to support a range of R&D and development activities for indoors and field trials testing (including UK, Tenerife and the Atacama Desert in Chile). Over the course of the FASTER project the platform has seen a number of additional evolutions to fulfil the testing scenarios. A range of upgrades have been implemented to provide a robust platform with well identified and standardised mechanical, electrical and software interfaces. As part of FASTER, its modular frame provides the necessary mechanical and electrical support to all the on-board systems including the On-Board Computer, the GNC and Locomotion computers, mast for the perception stereo bench as well as the Wheel bevameter and its supporting electronics located at the front of the platform. The sensor suite also included the Remote Sensing camera to identify rock hazard and to locate the scout with respect to the Primary rover.

Figure 3- Airbus DS Bridget Rover platform carrying the FASTER Wheel Bevameter sensor on a deployable arm at the front

2.2. Scout Rover

Coyote II is a micro rover with high mobility performance in various terrains developed by DFKI: equipped with its own power source, on-board sensor suite and computer. It is able to perform autonomous exploration tasks. The robust construction of the platform enables to carry several kilograms (>6kg) of payload. Of particular interest is its novel locomotion concept: combining the high mobility performance of hybrid legged-wheels (in the front) with the smooth wheel movement of spherical helical wheels (in the rear) as shown in Figure 4. This enables the scout to move on soft soil as well as on unstructured terrain and can perform side-to-side steering movements.
Within the FASTER project Coyote II acts as scout rover with the aim to improve the mission safety and the effective traverse speed for planetary rover exploration [4]. To avoid uncertain estimations concerning the trafficability of the areas to be explored, the scout rover provides suitable information on the terrain ahead of a primary exploration rover. To handle this task, the Scout is equipped with additional soil sensor payload including the Wheel-Leg-Soil Interaction Observation (WLSIO) system and a Motorized Dynamic Cone Penetrometer (mDCP), both developed by Surrey Space Center (UoS).

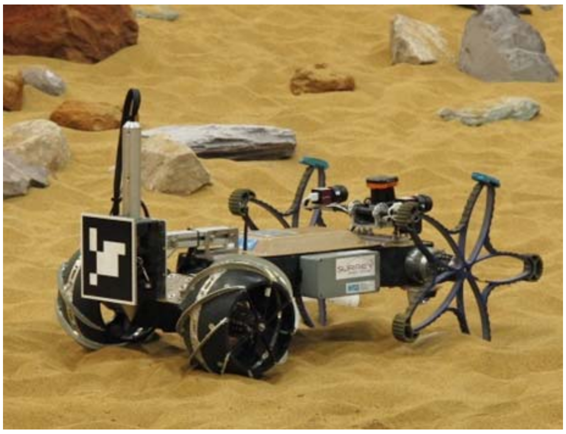

Figure 4 - DFKI Scout Rover platform: carrying the WLSIO and mDCP sensors and its localisation marker

2.3. Soil Sensing System (SSS)

To provide accurate measurements from the rover's surroundings, several novel sensory systems were designed and their sensory readings fused together [5]. These will be briefly introduced below.

Wheel Bevameter

The Wheeled Bevameter (WB) instrument has been developed by LSG for sensing the terrain's physical properties prior the traversal of the robotic vehicle. The WB was the principal terrain testing instrument on the primary rover in the FASTER scenario and was located at the front of the platform as shown Figure 3.

The WB, as conceived in FASTER, uses a dedicated test wheel ("test wheel") placed on the terrain to load the soil for assessment of its response.

The WB includes a deployment and placement mechanism for the test wheel that remains lowered onto the ground during nominal rover motion, including when climbing and descending slopes. In normal mode, the test wheel is free rolling and measures a number of parameters while the rover is in motion: test wheel sinkage (through a laser sensor), vertical load, horizontal reaction force, and rotation rate.

Through processing, the WB data provides an indication of the trafficability through a Trafficability Percentage (Tr [%]) as well an emergency stop function should be generated when a hazardous terrain is identified as a NO-GO.

Motorised Dynamic Cone Penetrometer (mDCP)

The mDCP is a direct-sensing device, which produces impacts that drive the cone tip into the terrain. It is located at the back of the Scout, Figure 5. Measurements of the depth-per-blow are then compared to laboratory measurements of penetrations using volumetric density-calculated soil samples of the Mars Yard 2EW simulant. Through these measurements an average soil density value is derived and compared to the performance of the Primary Rover on similar soil densities in order to formulate the trafficability assessment.

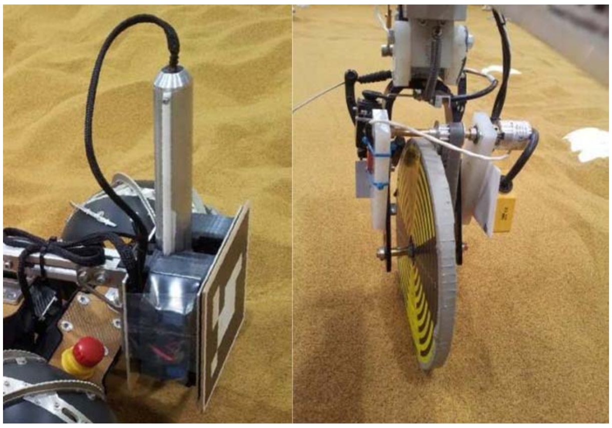

Figure 5- mDCP attached to the scout (left) and WB in front of the primary (right)

Wheel-Leg-Soil Interaction Observation System (WLSIO)

The Scout rover is equipped with two hybrid wheel-legs to enhance its mobility and prevent it from getting stuck in hazardous terrain that would pose a threat to the Primary rover. The WLSIO System performs an on-line analysis of the sinkage to determine the trafficability of the terrain, as inferred from the load bearing capacity of the soil. Two independent and identical WLSIO soil sensing modules are integrated with the Scout Rover, each of them focusing on one of the wheel-legs. Each module consists of an absolute angular position encoder, a current transducer, an IMU, an IR ranger, a camera, and supporting electronics. The sensor system acquired data from all the sensors and combined them to estimate the sinkage of the wheel-leg. Special feet, referred to as Load Testing Feet (LTF), were fitted onto two non-consecutive spokes to replicate the contact pressure of a Primary rover wheel with the reduced mass of the Scout rover. The other three spokes were fitted with flexible rubber feet with a higher contact area that provide lower contact pressure, better load distribution and higher traction.

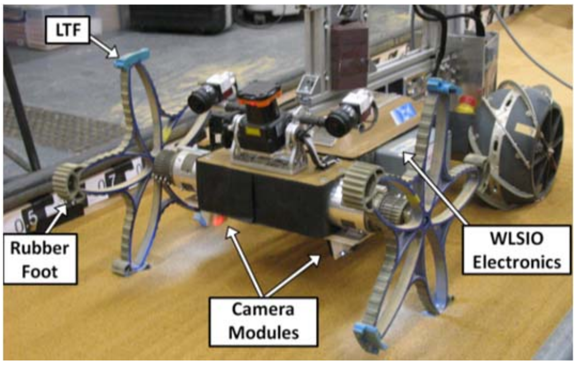

Figure 6 - WLSIO Implementation on the Scout platform

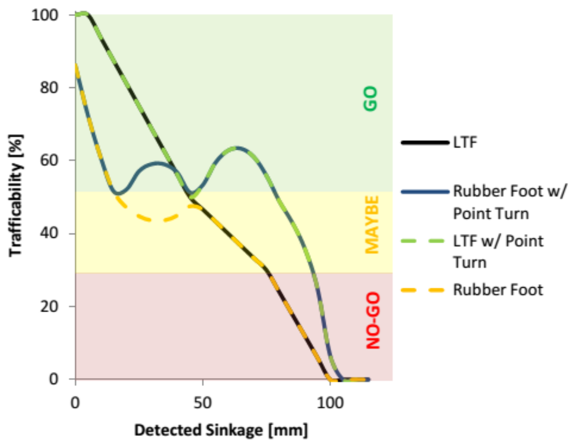

Figure 7- WLSIO Sinkage / Trafficability parameter correlation

Data Fusion System

To maximise the safety of the Primary Rover, the FASTER system must identify hazardous locations while minimising the number of false positives that would slow the traverse. To this end, the data from all the soil sensors needs to be normalised to a set of consistent data that can be compared later. As discussed above, each sensor provided a trafficability percentage Tr-% defined as the ability of the primary rover to traverse safely over a given terrain.

Taking into account the physical parameters of the Bridget rover, three semantic ranges are distinguished: NO-GO (0-30%), MAYBE (30-65%) and GO (65-100%). These criteria will be used by the path planner to find an optimal safe path to the target waypoint. The detection of GO terrain would result in a straight, fast traverse of both robots. A NO-GO flag would trigger an emergency stop signal and cause a re-planning of the path to avoid the detected hazard. Finally, a MAYBE will require a more detailed investigation to check the terrain parameters by deploying the mDCP. The Data Fusion System therefore provides a consolidated trafficability map, built by combining the trafficability data from all the sensors including the relative position and their specific confidence level.

The map is used by both rover platforms for path planning purposes. The trafficability map is then passed onto the navigation computer as input, to the definition of the next part of the path. The DF system was implemented using ROS middleware [6].

2.4. Software and Autonomy Components

The initial top level mission plan is computed by Ground, prior to the start of the traverse by means of a hierarchical timeline-based mission planner [7]. This plan, organised in sequences of actions for each sub-system, is then uploaded to the primary rover OBC.

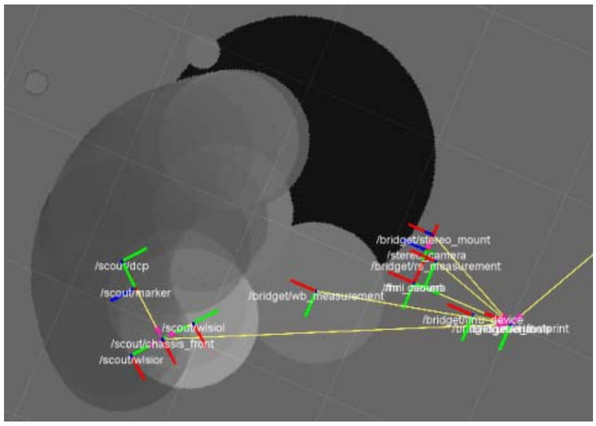

Figure 8 – Data Fusion Trafficability grey map showing the platform coordinate systems and their respective sensors (the lighter the less trafficable)

An automated executive takes care of the execution and monitoring of the plan. The core of the FASTER processing system resided in the On-Board Computer (OBC) system fitted on the Primary Rover. It performed all the necessary high-level processing and commanding of the data acquired by both rover platforms and their sensor suite.

Localisation

The combined odometry is the output of an Extended Kalman Filter (EKF) by combining data from the IMU, the Visual Odometry and the Wheels Odometry. The scout localization (attitude and position) relied on a marker placed at the back of the rover and operating in the FOV of a camera at the front of the primary Rover. A single marker based tracking is less computationally demanding but might be affected of partial occlusions. The scout pose estimation was then estimated to within 5%, on the X and Y axis at ~1m.

Figure 9- Scout Localization in the camera field of view

Mapping

To fulfil the specific FASTER objectives, the mapping activity consisted of four separate functions, namely Perception, Scout Filtering, Local map creation and Map merging. The Perception function uses an approach similar to the ExoMars perception functions and relied on the acquisition of 3 overlapping frontward stereoscopic pairs that are converted into a dense panoramic point cloud.

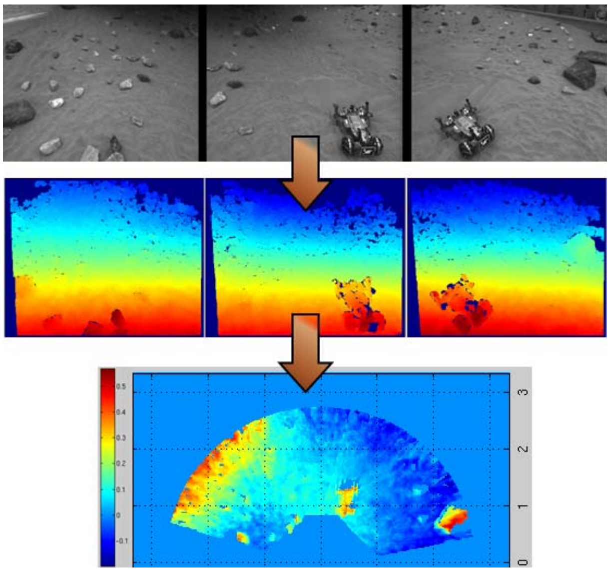

Figure 10 - Perception –Panoramic image data (top) are converted to disparity maps (middle), leading to a dense point cloud (bottom)

During the perception stage, the Scout is captured in the environment and will appear in the Digital Elevation Map (DEM) as a large obstacle. Therefore it must be filtered out, before any path planning is performed on this DEM. The location of the Scout is replaced by a flat traversable terrain (Figure 11, left).

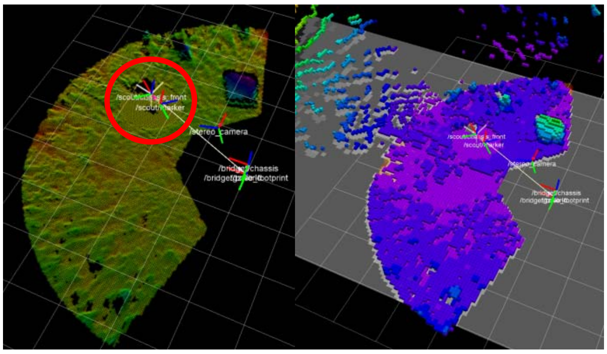

Figure 11 - Scout Filtering (left- scout location highlighted red) and Local map Generation (Right)

Once the Scout has been filtered from the Primary rover DEM, the point cloud generated by the Scout laser scanner is added to create a single map consisting of the perception data from the two platforms from different locations (Figure 11, right). As the two rovers progress along their path, the local maps are then merged into a global map that consolidates the DEM data from the traverses, as well as from the Data Fusion System (Figure 12).

Paths Planning

Once a consolidated map is available, the path planning function can derive a safe path for the main platform: based on the local DEM and trafficability assessment. This path is then sent to the Scout that will generate its own path to follow as much of the planned Prime rover path as possible.

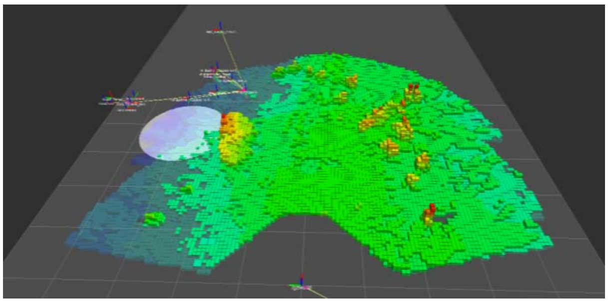

Figure 12 - Consolidated Global Map - DEM+ Sensor data fusion

3. INTEGRATION AND SUB-SYSTEM TESTING

As a complex heterogeneous system, a staged approach was implemented to address the verification and validation of the system at each stage of the development. As the components and subsystems are being integrated, the emphasis evolves from the initial hardware testing to the software integration. Four initial development and testing streams were addressed in parallel: Sensors, Scout, Primary Rover and Ground Control (i.e. Test TM/TC infrastructure); the 3 foremost streams representing the functional layer of a typical 3-layer autonomous architecture.

Once each stream acquired the necessary maturity, the interaction between the various elements became the focus of the development including Primary Rover–Scout communications, or the Sensor/platform integration and testing. The integration of the FASTER sub-systems occurred over the course of 5 Integration campaigns lasting on average 4 to 5 days each between April 2014 and August 2014. They took place at various location including Airbus DS, Surrey University in the UK and DFKI in Germany.

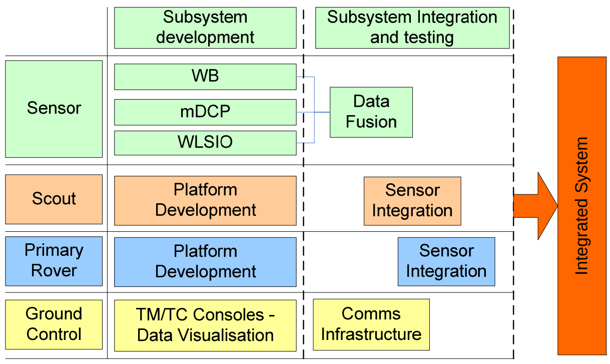

Figure 13- Sub-system and system level Integration and Test Logic

Beyond the development of the specific subsystems and platforms, these campaigns have been critical to setup the necessary infrastructure to perform the high-level control and scenario planning activities in preparation to the testing of the Integrated FASTER System. The operation of the system is carried out from the Local Control Centre (LCC) comprising several PCs and located in the Airbus DS Mars Yard Control Room. These included:

- ROS GNC supervision station: (1) monitoring and visualising the progress of the operations, (2) the map related information (point clouds, DEM, paths, etc.) and (3) the high level progress in the rover traverse (e.g. global navigation).
- Mission Planning and Executive supervision PC: orchestration of the operations execution (aka. Executive).
- Scout Rover GNC & Soil Sensing monitoring PC: supervision of the scout specific software.

This distributed setup facilitated the follow-up during the course of operations by their respective subsystem specialists, and was well adapted to the development, testing, integration and validation phases of FASTER.

4. INTEGRATED TESTING PROCESS

After various sub-systems of the Functional layer are being integrated, only then can the Executive functions be implemented to test the higher level functions in charge of the various platforms autonomous functions and collaborative behaviours. The pan-European nature and large team of the FASTER project imposed a range of technical and operational constraints, such as the minimisation of travel which was desirable for both the personnel and the hardware. This led therefore to the preparation and execution of 4 test campaigns between July and October 2014 dedicated to specific integration and development activities comprising:

- a shakedown of the various systems,
- a functional verification of the key functions,
- a full system testing against a representative mission scenario,
- and a final demonstration.

4.1. Test Setup

The FASTER test campaigns were initially anticipated to make use of outdoor field trials to perform some of the integrated tests. However, the Airbus DS Mars Yard facility opened in March 2014 to support the key GNC testing activities for the ExoMars rover mission. Through careful planning, the FASTER team was able to make use of the facility by interleaving its testing campaigns with the ExoMars testing activities.

The ~30m x 13m facility (Figure 15) provided the project with a new and flexible representative environment that provided consistency and valuable repeatability across tests. Moreover, it provided the team constant round-the-clock stable lighting conditions, power and security that avoided the need to pack the platform and the network infrastructure at the end of every testing day.

As shown Figure 14, the test setup consisted of 3 systems that needed to be integrated to demonstrate the full scope of the test scenario: the Local Control Centre (LCC) providing the high-level TM/TC, the Prime rover with sensors, and the Scout with sensors. The LCC is located in the facility Control Room, with the Prime and Scout Rover Systems being located onto the testing area. At the LCC, the Rover operations are planned and telecommand loads prepared and despatched to the Prime rover.

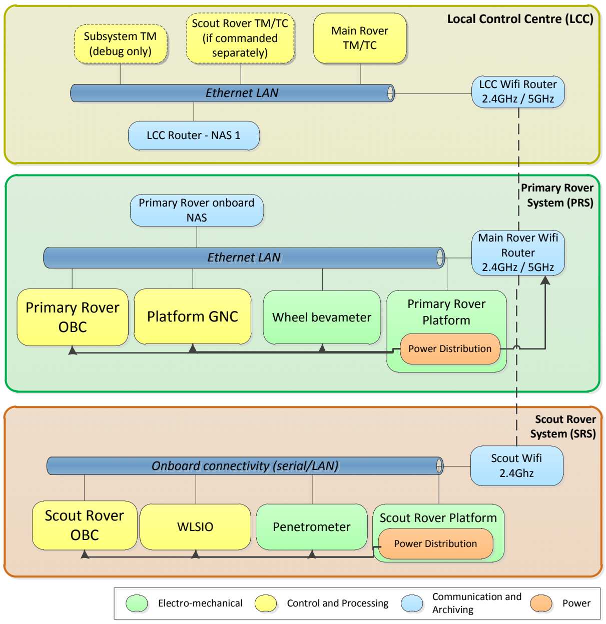

Figure 14- FASTER Test Architecture.

Figure 15- Panoramic view of the Airbus DS Mars Yard with the Control room visible at the opposite end

The Prime Rover system then receives the telecommand loads, executes them and returns telemetry and other report data to the LCC in response. In the process, it can also despatch some of these commands to the Scout for execution. Finally the Scout executes the telecommand and returns the telemetry and other reports to the Prime rover and relays them to the LCC.

4.2. Trials Execution

To maximise the efficiency of the time-constrained campaigns, a number of trial procedures were produced. Addressing the validation requirements for each of the specific campaigns as well as test schedule to plan and guide the daily activities for the whole team. Opportunities for parallel testing were identified and implemented where possible to allow the testing of several elements at the same time (e.g. duplicating the OBC functions between Primary Rover and Scout) which proved to be extremely valuable, especially for the shakedown activities.
Daily reviews of the day's activities were important in assessing progress and improving overall performance of the trials. Morning Briefings prior to testing, reviewed the trial schedule in light of the latest test data available, while Evening Debrief took place at the end of the day to review and record the objectives set for the day against their success criteria.
However, due to the nature of the testing, the maturity of the systems, and the inherent complexity of some of the functions under test, flexibility in the schedule was necessary to allow for unexpected issues arising during testing. Test schedule and traceability matrices were updated regularly to follow the progress of the testing and refocus some of the verification activities. To mitigate delays naturally occurring as systems are being prepared for testing, alternative activities were performed instead.

Nevertheless, as the system became increasingly complex and integrated, fewer alternative scheduling options were possible, putting more pressure on the timely preparation of the overall system. However, unlike outdoor testing, the Mars Yard provided the team with a consistent environment irrespective of the length of the testing day which helped mitigate schedule slippage over the course of the testing week.

4.3. Mission Scenario Verification and Validation

To exercise and demonstrate all the hazard identification states and re-planning activities, a Mission scenario was setup to constrain the behaviour of both platforms in the Mars Yard by going through specific locations designed to triggered hazard events.
With the facility being used as part of an ongoing project, it was not possible to simulate sand traps by bringing fine sand or other contaminants into the facility. The development of a sand trap analogue was therefore necessary to replicate the physical behaviour of a duricrust breaking under the load of the instruments or the wheels. To this end, the analogue consisted of a frame on which metallic cables were stretched with right angle hooks. A paper cover was then used to support the sand and render the trap invisible to the platforms. As the WB or the WLSIO pierced the paper, a localised representative sinkage was produced, leading to the identification of a hazard.

Table 1- Mission Scenario operations

ID	Operations
1	First path targeting shortest path to Target through right sand bank
2	"Maybe" area identified by the Scout WLSIO, triggers mDCP deployment – Path identified as No-Go
3	New path generated to avoid the right bank and rocks
4	"Maybe" area identified by the Scout WLSIO, triggers mDCP deployment – Path identified as Go
5	Shortest path planned to reach target through Sand Trap
6	Scout identify Sand Trap – Path is flagged as No-Go
7	New path generated to avoid the sand trap
8	New path generated to avoid the rock in the path
9	Target is reached

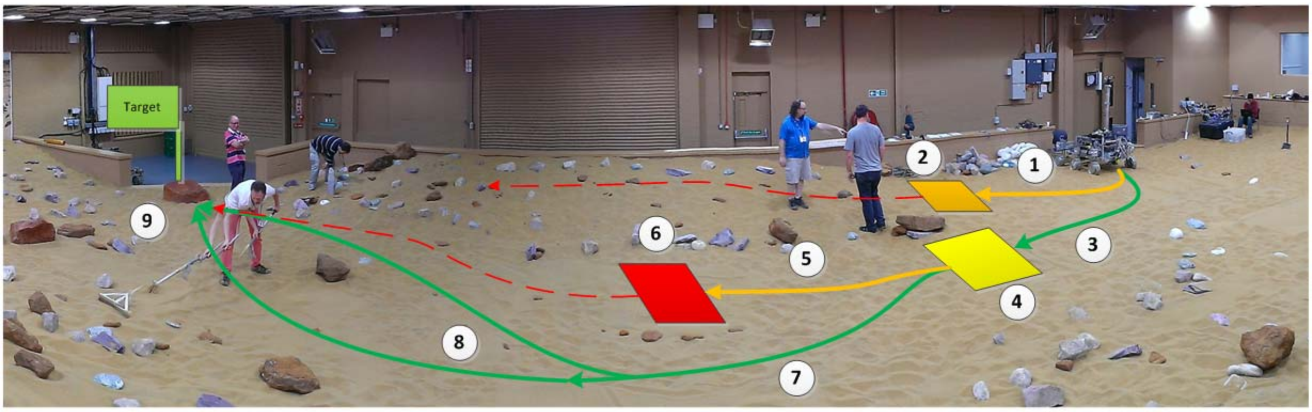

Figure 16 - Representative Mission Scenario to exercise all the FASTER functions

4.4. Project Outcome

Test results

The project concluded at the end of October 2014. Despite the inherent complexity in testing such a setup, it has successfully demonstrated all the key functionalities and underlying technologies of the system:

- The sensors were successfully validated
- The operation of the platforms and their payload was successful
- The online sensor data fusion and global mapping were successfully demonstrated
- The automated mission planner and executive layers were successfully implemented and validated.

The project closed with a final workshop gathering some 40 participants from across academia and industry. It provided an opportunity to present and discuss some of the project outcomes, as well as presenting a live demonstration of the FASTER system, including the execution of pre-planned complex behaviour such as "Traverse in Team".

Applicability to future Planetary Missions

The FASTER concept introduced a number of novel hardware and software concepts that could find applications in future planetary missions by addressing the specific challenges encountered by mobile planetary robotic systems. Design evolutions would be required, however to transform the fundamental principles demonstrated here into a flight system would limit the impact on the rover system and its operation (e.g. wheel-integrated sensing).
The use of the Scout platform highlighted the benefits of a highly mobile platform to explore ahead of a primary rover and could be considered further to explore environments too hazardous to the Science rover. However, the energy management of such a small and nimble platform will need to be assessed as it would constrain the applicability of this concept at this stage.
The Executive and collaborative functions developed over the course of the project provided a unique insight in the range of applications where such behaviours could be of benefit including: the Explorer Scout scenario described above, Lander/Rover coordination to facilitate the return of samples or other multi-platform setups where various source of data are consolidated (e.g. rover and mapping aerobots).

5. CONCLUSION

Unlike any previous planetary exploration mission, the FASTER concept proposes the combination of a primary exploration rover with a micro scout rover, acting as remote sensor unit. Within this concept, the scout rover plays an important role by assessing the trafficability of the primary rover's planned path and thereby allows a faster and saver traversal over long distances. The key objectives of the projects have been achieved by successfully validating of all the crucial functionalities of the integrated system, demonstrating the collaborative behaviour of the two platforms as it tackled the reference scenario in a representative test environment.
This project provided valuable insights in term of the quantification of engineering soil parameters, such as trafficability, from a heterogeneous and distributed suite of sensors. Such a method is likely to find application in the design and operation of future planetary rovers. In addition, the implementation of the executive layer hinted at the challenges and benefits of implementing additional autonomy functions to provide re-scheduling and re-planning functionalities based on the assessment of the local environment and platform condition.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] FASTER Project Website, Accessed 28/04/2015 https://www.faster-fp7-space.eu

[2] Y. Nevatia, F. Bulens, J. Gancet, Y. Gao, S. Al-Mili, R. U. Sonsalla, T. P. Kaupisch, M. Fritsche, T. Vögele, E. Allouis, K. Skocki, S. Ransom, C. Saaj, M. Matthews, B. Yeomans, L. Richter, *Safe Long-Range Travel for Planetary Rovers through Forward Sensing*, 12th ASTRA Symposium, ESA, 2013.

[3] E.Allouis, T.Jorden, N.patel, A.Ratcliffe, *Sample fetching Rover – Lightweight Rover Concepts for Mars Sample Return*, 11th ASTRA Symposium, ESA, 2011

[4] R. U. Sonsalla, M. Fritsche, T. Voegele, F. Kirchner *"Concept Study for the FASTER Micro Scout Rover"*, 12th ASTRA Symposium ESA, 2013.

[5] W. A. Lewinger, F. Comin, S. Ransom, L. Richter, S. Al-Milli, C. Spiteri, Y. Gao, M. Matthews, C. Saaj, *"Multi-Level Soil Sensing Systems to Identify Safe Trafficability Areas for Extra-Planetary Rovers"*, 12th ASTRA Symposium, ESA, 2013.

[6] Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, A. Y. Ng", *ROS: an open-source Robot Operation System*", In ICRA workshop on Open Source Software, 2009.

[7] Juan M. Delfa Victoria, Fratini Simone, Policella Nicola, O. von Stryk, Y. Gao, and A. Donati. *Planning mars rovers with hierarchical timeline networks*. Acta Futura, 9(9):21–29, 2014.