DEMONSTRATING AUTONOMOUS MARS ROVER SCIENCE OPERATIONS IN THE ATACAMA DESERT

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ABSTRACT

In order to help prepare for ESA's first mobile robotic mission on Mars, the SAFER activity investigated aspects of the proposed operations strategy in a representative environment. An early ExoMars Rover chassis prototype equipped with several ExoMars payload instrument breadboards was located in the Atacama Desert in Chile with a remote operations and science team situated in the UK to simulate operations over a one week period. The rover system was equipped with full on-board navigation autonomy and partially automated instrument operations. Throughout the course of the week the science and operations team explored a pre-selected region of interest using the rover and payload instruments. This paper presents the results of the field trial from an operations tools perspective and comments on the role of autonomy in such a mission.

1 INTRODUCTION

As the European Space Agency's (ESA) ExoMars Rover[1] mission progress towards eventual launch and requirements for future rover missions such as Mars Sample Return emerge, it is importnat that ESA build operational expertise in the area of remote and autonomous rover operations. Although reference operational procedures for science investigation have been specified for missions such as ExoMars, in-field validation of such approaches has not yet been carried out under realistic operational conditions. The inclusion of autonomy in future missions introduces an additional and novel operational complexity which must also be addressed. Using ExoMars Rover (EMR) as a point of reference, the ESA SAFER project sought to investigate the proposed operations philosophy and procedures by conducting mission simulations in a remote and highly representative environment. For this work the authors provided the core software and the sole autonomous elements of the mission. These comprised autonomous localization and navigation software, the on-board software executive which automated plan execution, and the Overseer Interact mission planning and data co-registration tool used for operations at the UK site and in Chile. This work builds on a previous ESA project called SEEKER which demonstrated long-range fully autonomous navigation in the Atacama[2]. The SAFER work is highly novel for ESA as it represents the first attempt to execute remote operations with an autonomous rover in a representative way in an analogue environment.

In October 2013 the SAFER team deployed to the remote Atacama Desert region of Chile with a representative space rover platform and test versions of some of the ExoMars Pasteur payload instruments – namely the CLUPI close-up imager, the WISDOM[3] ground penetrating radar (GPR), and the PanCam[4] emulator called AUPE II, which includes a Pan and Tilt Unit (PTU) and the High Resolution Camera (HRC). To simulate drilling a manually operated drilling tool was used.

The operations team was based in the UK at a Remote Control Centre (RCC) in order to simulate a series of remote operational commanding cycles simulating 1-2 Sols (Martian Days) of operations per Earth Day. A long-range wireless link connected the rover to in the field to the internet which then allowed the UK based team to submit plans, download representative telemetry and continue their exploration of the selected sites.

This paper focuses on the operations tools, operations for autonomy, data co-registration and the autonomy software used on-board the rover. An operations tool known as Overseer Interact allows users to view the 3D Digital Elevation Map (DEM) for the area, plan waypoints, view data products, prepare mission timelines and automatically co-register data products after downlink. This last aspect was an important contribution for this type of work. For the first time instrument operators and mission scientists were able to see sub-surface GPR data, contextual DEM, PanCam images, local PanCam DEMs and local navigation Digital Terrain Maps (DTM) co-registered and displayed in one interactive 3D scene. This provided a unique modality and allowed a greater understanding of the site and its geological characteristics. Plans prepared in the RCC were dispatched for execution on the rover via the remote link and the Local Control Centre (LCC) in Chile. No changes were made to RCC plans by the LCC team. A typical rover plan consisted of short trajectories with WISDOM soundings carried out en-route. Panoramic and high resolution images of specific targets were scheduled as the team explored various aspects of the site. Trajectories were planned as a series of waypoints which were used as guidance for the on-board autonomous navigation subsystem. This component localized using Visual Odometry, constructed 3D DTMs of the terrain and used this information to path plan towards the final goal or intermediate waypoints avoiding any hazards. PanCam and WISDOM control were fully automated. An on-board executive component managed timeline execution and triggering of planned tasks. To allow for manual activities such as drilling and high-resolution imaging dummy tasks were inserted into the timeline.

During the course of the five days the mission covered a total of 294 meters fully autonomously. This goes beyond the baseline of current missions which use autonomy sparingly – partly because of resource constraints but also because of a conservative attitude to the use of autonomy. This is an important contribution of this work, it demonstrates the reliability of such autonomous systems in highly representative conditions (operations and environment) and the benefits they can bring allowing more complex plans acquiring more science targets.

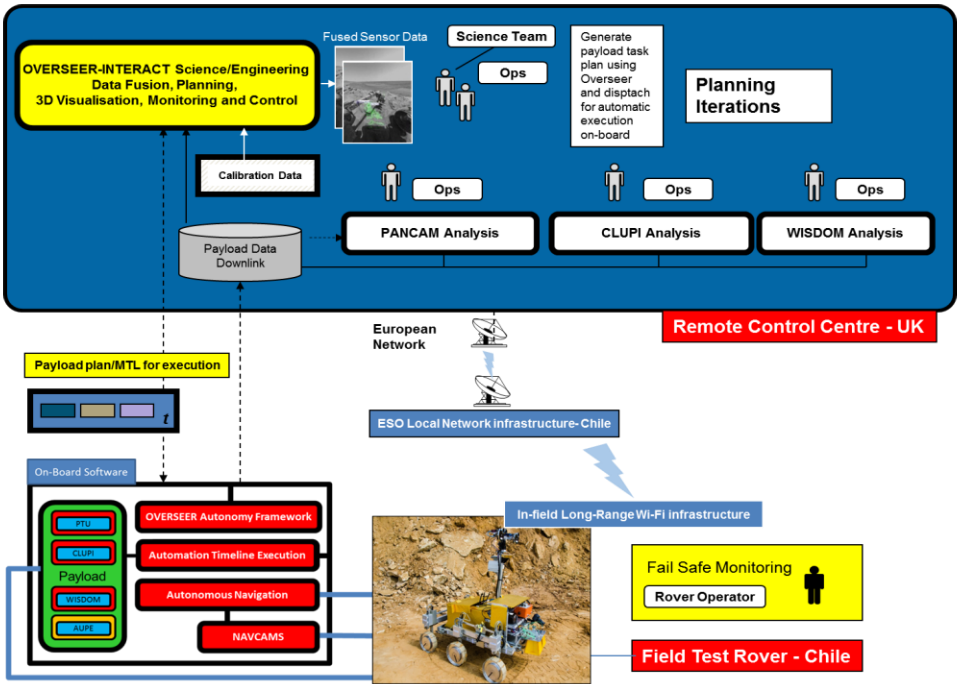

Figure 1: SAFER System including Operations in the UK and the Rover Software/Hardware subsystem in Chile

2 SYSTEM OVERVIEW

The Rover hardware system consisted of a representative, EMR chassis known as Bridget provided by Airbus and several instrument breadboards from EMR namely; WIDSOM, CLUPI and AUPE II. Bridget was provided with a low-level software control interface which allowed control of the rover speed and steering angle. Although EMR will have a drill unit this functionality was not available to SAFER and a hand drilling process was used to simulate aspects of the process.

The complete end-to-end software framework is called Overseer which allows automated execution of payload and rover mobility tasks. In the SAFER case the Overseer architecture was also used in the predecessor SEEKER[2] work although on a different robotic platform. Switching to the new platform proved straightforward given the modular approach used to integrate components. This component orientated, plug-and-play approach facilitated fast integration of the new payload instruments allowing automated timeline execution for two of the primary sensors. The CLUPI instrument was not fully integrated given constraints associated with the instrument breadboard implementation. The primary software components and their functions are as follows:

2.1 Overseer Interact – 3D Operations Planning, Monitoring and Control

Interact provides remote operators with both a visual and task orientated planning environment. Its purpose is to allow the operators to build timelines of activities or plans for dispatch to and execution by the remote rover platform. Operators could review rover data integrated with orbital orthoimages and DEMs in order to plan each Sol (Martian day) activity. Rover drivers could define rover trajectories and move tasks by selecting and shaping linked waypoint sequences using a 3D view of the rover environment. For the SAFER case a series of WISDOM specific move tasks where defined to support various operational modes associated with the instrument such as sounding while moving, stopping to sound at defined intervals or executing raster scan sounding patterns. Operators could also define additional tasks such as payload operations e.g. Panoramic image sequencing and specific spectral filter based imaging. They could also schedule Drill and CLUPI tasks although in practice these were executed with humans in the loop. Once a plan had been prepared it would be reviewed, validated and dispatched to the remote rover for execution. The field test team at the LCC also ran a local copy of Interact to allow monitoring of the rover progress in real-time and facilitate plan uplink to the rover.

2.2 Decision Making and Execution Control

The Overseer architecture supports higher-level on-board task planning through the decision making component. In the SAFER case this was not required so downlinked plans were routed directly to the on-board executive component for execution.

The Executive is Interact's primary interface to the components onboard the robot. It manages planning and execution, and is responsible for reporting the current status of the robot and its plan. Upon receiving a pre-prepared plan from ground, the Executive will notify all connected components that a new session has begun and then at the appointed times proceed to execute the tasks that make up the plan. As each task is executed, the appropriate script is located and run in order to command the relevant onboard components. Periodically the Executive will check the plan to detect any task under- or over-runs. Any failures result in the termination of the plan so that operators on the ground can decide the best course of action to take. Although the framework can support for automated planning and re-planning, this was not part of SAFER operations.

2.3 Autonomous Navigation

Overseer also provides a guidance, navigation and control (GNC) function for rover systems based on stereo camera images. This is realized by a set of components which includes 3D mapping, vision based localization known as Visual Odometry (VO), localization fusion and path planning. This component will try to realize a target trajectory and set of waypoints provided by operations team using Interact. During SAFER the rover drivers used representative orbital DEMS with 30cm/pixel resolution during planning. The rover ground clearance is in the order of 20cm so this subsystem provides the autonomy necessary to avoid local obstacles. Rover pose (6 degree of freedom position) is estimated using VO and/or a combination of wheel odometry and inertial measurement unit (IMU) data. This is then used along with local DTMs generated by the mapping component as inputs to path planning which issues the relevant low-level commands to the rover platform in order to reach the target waypoints. The rover may therefore deviate from the nominal trajectory in order to achieve an obstacle free path to each waypoint. In the SAFER case the low-level control interface and Bridget platform supported Ackermann moves and point turns.

2.4 Payload Operations

As part of the Overseer architecture each payload and sensor item is wrapped using a standard Overseer component. This allows the Executive to command the underlying hardware according to an abstract interface. In practice this means that different sensors and low-level software can be swapped out with no changes to the other software components. The Executive commands each payload item using a task definition and parameters provided by the operations team at planning time.

2.5 Building Global Maps

To facilitate communication between the UK based CATAPULT operations center and the LCC a long-range WiFi link was set up to the ESO Paranal observatory approximately 11 km away. An ESO fixed link was then used to connect back to Europe. Remote planning required orbital equivalent imagery for Mars. To facilitate this, an Unmanned Aerial Vehicle (UAV) was flown by RAL Space to capture aerial imagery for photogrammetry to create the global DEMs used during Interact planning.

3 FIELD TRIALS AND RESULTS

The objectives of the SAFER field trials can be summarized as follows:

1. Implement elements of the EMR Reference Experiment cycle – with noted constraints
2. Comment on the efficiency of the mission through experimentation and analysis

For the second point the team were asked to implement a means of integrating disparate, 2D and 3D data (rover, payload and contextual) to provide a full contextual view of the operational area and investigate its impact on operational efficiency. A second sub-goal was to explore ways of optimizing science return vs. resource use. As SAFER was equipped with a fully autonomous GNC sub-system this allowed the team to investigate the impact of autonomy on the operations efficiency. Furthermore, as some team members were part of the trial set-up in Chile and subsequently participated as observers in the operations simulation this allowed a unique opportunity to examine where other types of autonomy could improve the overall science return of the mission.

3.1 Operations Simulation - Summary

The EMR Reference experimental cycle outlines how a progressive exploration of a target area should be achieved using the available payload instruments and the rover vehicle itself. Starting with remote stand-off surveys using wide-angle cameras, it then moves toward close-up imaging, sampling, sub-surface sounding, drilling, sample collection and analysis. Over the course of five terrestrial days this subset of instruments was used to simulate the exploration of the target area. The process began with a contextual brief from the on-site geologist – the assumption being that the team would commence operations part-way through an established mission. In addition to the verbal briefing a contextual panoramic image of the site was provided along with two potential commencement points A0 and B0. The operations teams were asked to select one waypoint and commence operations. Having assessed both waypoints using this limited set of data B0 was selected on the basis that it was least risk and offered plausible access to possible targets of interest. To come to this conclusion the operations team made extensive use of the Interact tool to visualize the DEM from different viewpoints, and reference these to what could be seen from the initial panoramic images. This proved to be invaluable, allowing the science team to assess the best approach angles for data acquisition a-priori.

This initial assessment by the science team identified a possible magmatic outcrop at the fringes of the survey area and it became an initial long-term goal. A light-toned area known as Zittau was identified as an intermediate goal for further investigation. During the course of the traverse to Zittau a potential outcrop which exhibited possible sedimentary features was imaged serendipitously. This “discovery image” changed the science goals for the mission. It was then decided to explore Zittau as planned and then subsequently examine this possible outcrop known as Carnot. Following a detailed survey of Zittau using all instruments a full raster scan sounding of an area labeled Honfleur was executed. The final day of the mission included a long autonomous drive of 134 meters toward areas known as Rybnik and Olavarria which indicated signs of possible aqueous activity.

These names came from the operations team, carefully chosen so as to include no prejudice as to the type of feature or its origins.. It should be noted that the reconnaissance team separately named features in their original survey, these names are often more descriptive, but were kept unknown to the operations team until the trial completion. There is a mapping between the names; however for this document we use the RCC names.

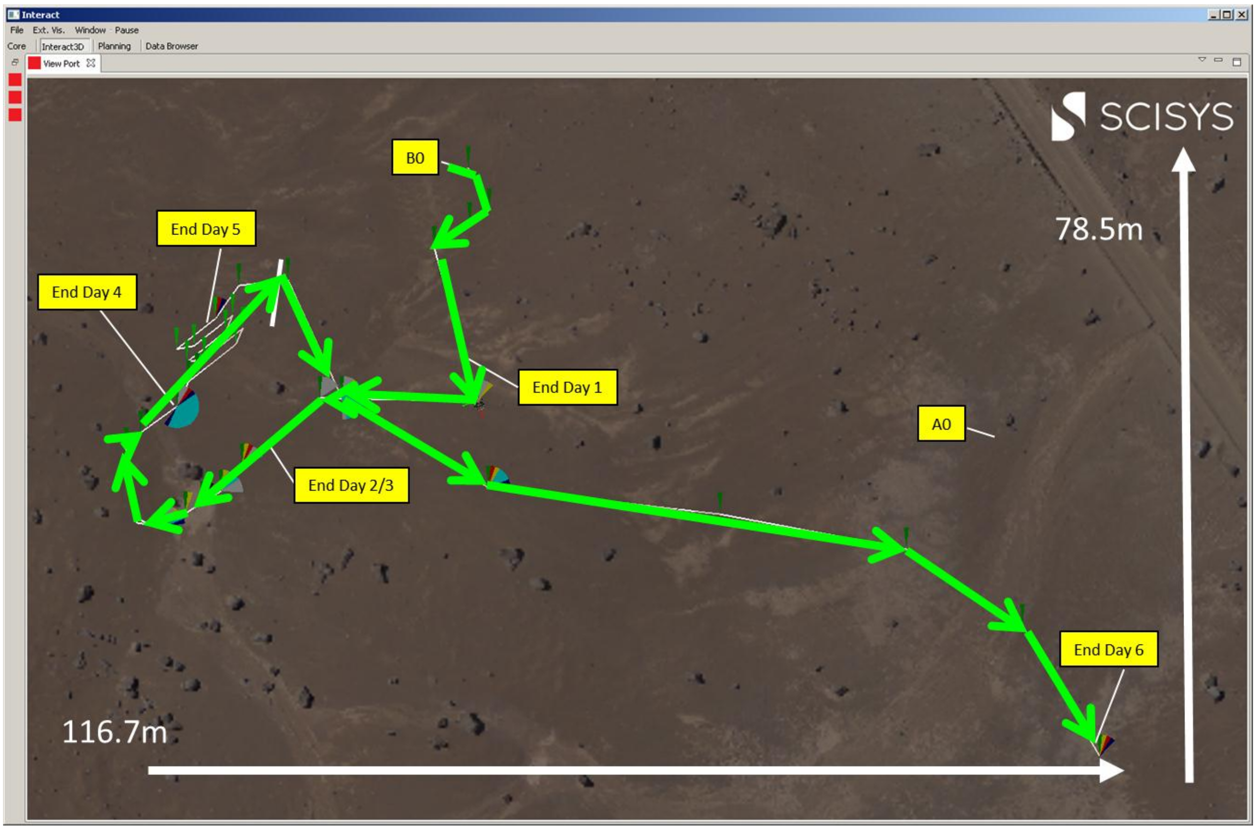

Figure 2: SAFER Field Trials. The image shows the progress over the five days of operations

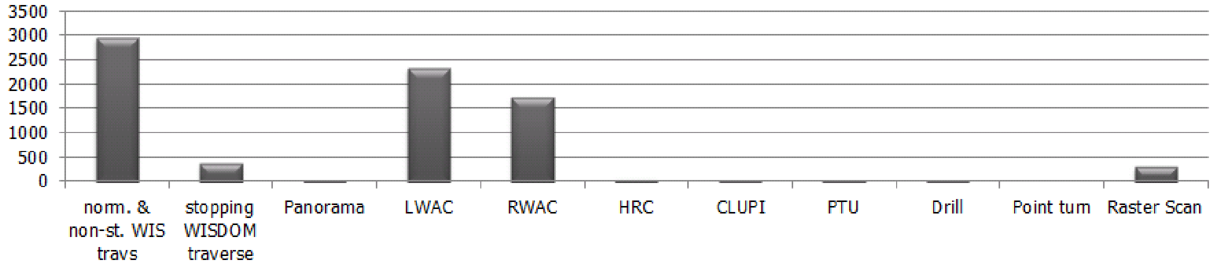

Figure 3: Data volume – number of products generated per instrument over five days of operations

3.2 Activity Summary

In total 6 plans containing a total of 89 tasks were executed over a total cumulative distance of approximately 294 meters.

A simple analysis suggests the HRC was used most often. However the task encoding meant that each HRC acquisition requires a discrete timeline task whereas multiple PanCam images using several filters and full panoramic imaging, could be achieved with one task. Figure 3 shows the actual data volumes per instrument highlighting the intense use of both the PanCam stereo pair cameras and the WISDOM instrument.

Over the course of 5 days and 6 plans the average distance per day was approximately 50 m. Average real operations time, i.e. where the rover was active, was in the order of 1 hrs 45 mins. Average operational days were around 14 hours. Given the short duration of the trials with limited preparation this pattern was inevitable - significant hours of effort were spent on infrastructure and system shakedown in the first days of the trial. Operational efficiency improved noticeably toward the end of the trials with an increase and reliance on the on-board autonomy as discussed further below.

Operational highlights and achievements can be summarized as follows:

1. Reference mission implementation – with noted limitations
2. Long duration Autonomous traverse - 134 m max in complex terrain
3. Long-range image acquisition –precision targeting of WISDOM and HRC
4. Co-Registration of Data for 3D analysis
5. All traverses carried out autonomously for all six plans – total distance 294.08 m

Over the entire trial period the team explored an area which was approximately the size of a football field spending most of the time (4 days) in a 40 m x 50 m area. During that period elements of the (tailored) ExoMars surface reference cycle (SAFER objective 1) were executed and achieved with some caveats which were as follows:

- The reference cycle begins with a remote survey of an area in order to discover appropriate outcrops and subsequent surveying of the outcrop itself. The team correctly identified remote outcrop and a light-toned secondary science target using remote survey instruments.
- Outcrop surveying was fragmented i.e. some regions of interest were not imaged because of rover positioning errors caused by manual replacement of the rover in the field after overnight extraction.
- Full polarization WISDOM sounding of the immediate Zittau area was executed as planned along with extensive imaging. A raster scan of a potential drill site was partially executed – the traverse stopped several meters short of the nominal 50 m target following a premature battery discharge
- Drilling was executed but at the end of the mission. The nature of terrain was such that full trenching was required to reach 2m in depth which would have corrupted the fidelity of the operations simulation had it been done inline.

3.3 Data Co-registration and Display

A second SAFER objective was to provide co-registered integration of the various SAFER instrument and contextual datasets. This was achieved successfully toward the end of the operational trials as illustrated by Figure 4. Being able to see GPR data in context with the underlying 3D terrain was extremely beneficial. It aided group understanding and has the potential to significantly improve overall operations efficiency.

As well as being able to review the data, integration of the timeline planning tool into the 3D view was a great benefit. This allowed the team to create new plans *in the context of previously captured data*, as well providing a graphical interface to select traverse targets and tools to measure distances and pointing angles. For example, the middle image in Figure 4 shows PanCam imagery overlaid onto the global DEM, projected from the rover position it was acquired. Planning can then occur directly

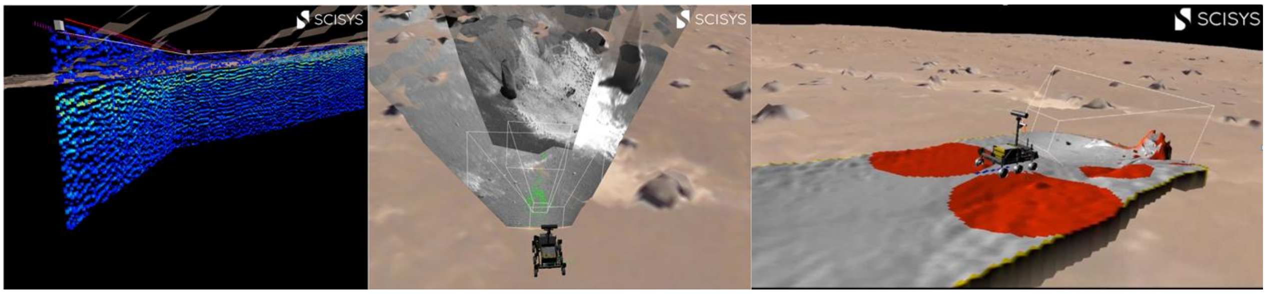

Figure 4: Overseer Interact 3D Data Co-registration.
Left to right are GPR subsurface soundings integrated into the 3D Orbital DEM, NAVCAM and PANCAM images overlaid on the surface, and local DTMs and traversability maps generated by the rover overlaid on global DEM.

in the same 3D space, to acquire images of science targets from the most advantageous angles. As well as integrating raw data products, the Interact tool also allowed the co-registration and integration of derived data products generated by other members of the science team, for example the global orbital DEM overlaid with local high resolution DEMs produced by Joanneum Research.

To perform co-registration we use the timestamps associated with each data product combined with the position recorded by the Overseer GNC software. With a platform model of sensor mounting positions we can translate from Sensor Reference Frame (SRF) into a Vehicle Reference Frame (VRF), and then combined with an initial Lander Reference Frame (LRF, the start point of the mission) we can display all data in a unified Global Reference Frame (GRF). For cameras the pointing angles and lens parameters are also stored – this allows us to re-project the images captures into the 3D environment.

3.4 Data Labeling

The need to label and name regions of interest in the returned data products became a crucial part of operations and yet was not anticipated in advance. Serendipitously we were able to deploy a web-based labeling solution we had available that is being used in the ongoing ESA MASTER project, being carried out by SCISYS, which investigates increased levels of science autonomy. This tool allowed any team member to upload and share data products of interest, and select and annotate regions within them. Further developed labeling and annotation tools will be vital for future operations to enable easier sharing and search of data products. This would suggest new ways to co-register and browse data – rather than the time-based browsing and registration used in SAFER it would also be possible to relate data by object captured, or type of object. Our projection of all products into a common 3D environment could also allow the co-registration of labels, so science targets identified in one image could be automatically labeled in other data products capturing the same target for example.

3.5 Role of Autonomy & Automation

The SCISYS autonomous navigation system was used extensively during the trial period. Given energy constraints that apply to surface missions such autonomy is used sparingly on MER [5] and Curiosity in order to maximize range. Typically operators will use a mix of blind drives and functions such as VO and path planning in order to reach target waypoints given that image processing based applications are computationally intensive and ultimately reduce the energy available for rover traverses. However when the terrain is complex there is a clear limit to what can be achieved using blind drives given that typically operators can only use 3D information out to 30 m for safe navigation. The SAFER valley site was a complex area from a navigation perspective containing dense boulder fields with soft sand and sloped terrain. The operations team therefore relied fully on the autonomous navigation system to reach the waypoints and targets requested by the lead scientist. In particular the WISDOM team required precise positioning of the instrument orthogonal to the edges of eroded and slopped channels during traverses. This required complex and reliable localization and control from the autonomous GNC system.

In the early phases the team proceeded cautiously with a significant degree of effort being spent in analyzing the performance of the GNC system. Trajectories were carefully chosen to limit navigation complexity. As the trials progressed and the technology was shown to deliver the expected performance the operations team relied more heavily on the autonomy and also task automation to deliver the high volume of data products demanded by the science team. The operations profile shifted from executing large numbers of atomic tasks to using high-level abstract tasks – see Figure 5. This simplified planning operations as the team outsourced some of the complexity to the on-board autonomy. Although the number of tasks scheduled dropped or remained at a steady level, the use of high-level tasks resulted in an increase in the complexity of the operations achieved. For example, the long drive of 134 meters and precise imaging of the HRC on a target 40 m from the start point was achieved on the final day. It was observed that the team leveraged the autonomy in

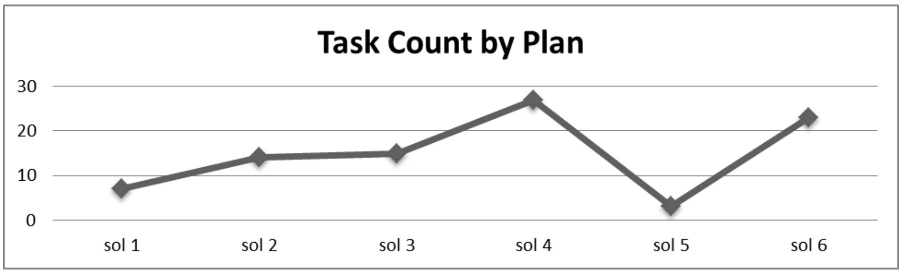

Figure 5: Total Scheduled Tasks Over Six Plans. *This shows the tasks scheduled per sol. The complexity of operations increased significantly during the final days even though the task count dropped or stayed constant.*

order to achieve more complex operations in a fixed time period.

After the trial it was possible to analyze the executed plans to measure the effect this confidence in autonomy had on operations. To summarize, we considered each plan and split them according a conservative navigation policy where the limit on a drive was the area possible to survey with the rover instruments from the start point. In effect, we consider the case where the rover is not permitted to drive "over the horizon" into unseen, unknown ground (where autonomy must be used for safe, reliable navigation). In total without the autonomous GNC system it would have taken approximately 17 sols to capture the science targets we were able to acquire in 6. Of particular note are the Sol 4 operations round the large rocks at Zittau – this involved a drive into unseen terrain occluded by the rocks and precise instrument alignment for WISDOM to ensure perpendicular crossing of a feature of interest identified from the global DEM. The Sol 6 long-range drive also represented a long drive into unseen terrain, and the autonomous acquisition of high-accuracy HRC images (4-degree field of view) after around 40m traverse.

3.6 Increasing Science Return through Autonomy

We also derived a complexity measure in order to measure the overall complexity of operations achieved in terms of science activities and operations loading. This qualitative measure is a function of several normalized parameters including: distance travelled; number of over the horizon events; number of precise orthogonal crossings; drive slip measure. A complexity measure was generated for each sol indicating the relative complexity of a given sol versus the maximum possible for these trials. This allows us to plot the complexity of operations which correlates strongly with science return achieved versus the operational loading (which is approximated here as the number of tasks scheduled by the ops team). Figure 6 highlights how the operational effort drops or stays constant while the complexity of operations increases. In effect this measure shows how the team used and leveraged the on-board autonomy in order to achieve greater science return. This is an important result in terms of autonomy acceptance as it also shows how the team learnt to trust the autonomy components based on the experiences of the previous sols.

3.7 Science Autonomy

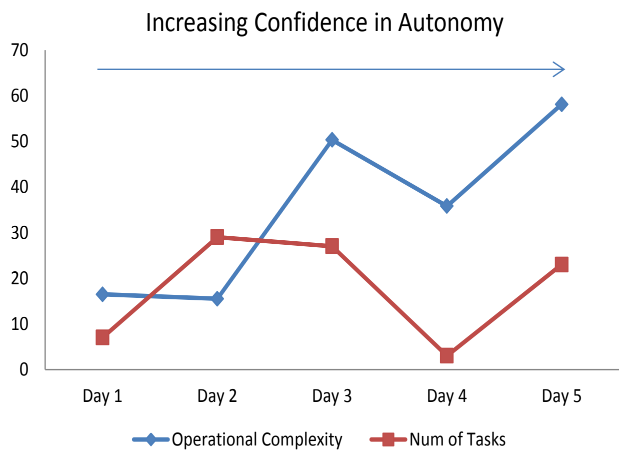

Figure 6: Increasing Science Return.

Having a presence both in the field site and the RCC provided us with a unique perspective on the mission and the efficiency of operations. It highlighted the potential benefits of science autonomy whereby the rover is able to detect possible targets of interest to alert the operations team on the next downlink. A drawback of remote Mars missions is the limited bandwidth - the rover is unable to fully return all data. Operators will use low-resolution thumbnails to check for targets of interest. This introduces a risk that targets may be missed. By providing the rover with a means of detecting targets locally using full resolution imagery it may be possible to reduce the likelihood that such targets are missed. During the first two days the operations team came close to an interesting science target – a dried out river bed with sedimentary layering – but only discovered this through serendipitous imaging brought on by a manual positioning error. The target is clearly visible in the rover

NavCam images as the rover traversed toward the primary target of Zittau. The authors are currently working on an evolution of previous work in the area of science autonomy[6] for ESA with the goal of being able to learn from domain experts and detect novel features in an image. Initial tests have shown that with the current prototype system known as MASTER, the target could have been detected by the rover earlier and thus have alerted the team to its potential importance.

4 CONCLUSIONS

We have described the SAFER field trial simulation which explored the operational aspects of future robotic missions such as ESA's ExoMars Rover. To this end a trial was executed with a rover system deployed in a representative environment, in this case the Atacama Desert in Chile, and a remote operations center located in the UK. The trial succeeded in implementing key aspects of the EMR reference experiment cycle over a five day period. SAFER has identified a number of lessons learned which would both improve the efficiency of future field trial simulations and also how mission operations could generate more science return. In particular the trial was able to uniquely identify specific cases where autonomous systems proved to be both reliable and essential to the achievement of daily, tactical science goals and strategic "discovery" goals through the use of science autonomy. These autonomous systems clearly contributed to an increased science return that would have been otherwise impossible in the time available. These cases and the use of more adaptable autonomy will be investigated in future work by the authors that will include a return to the Atacama region to conduct further trials.

Datasets captured in this trial, and the previous SEEKER trial has proven to be invaluable for the testing of autonomous systems and show the added-value of such operations.

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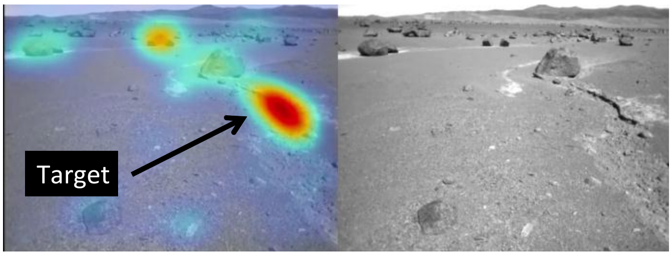

Figure 7: MASTER Science Autonomy. *Right is the NAVCAM image. Left shows a saliency detection step identifying the real science target as potentially novel.*

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