TOWARDS LONG RANGE ROVER MOBILITY: SURPASSING 1000 M/SOL IN PLANETARY EXPLORATION IN REPRESENTATIVE EARTH ANALOGUES

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ABSTRACT

Background: The Autonomous DEcision Making in Very Long Traverses (ADE) is one of five space robotic research projects in the frame of the PERASPERA Strategic Research Cluster (SRC), funded by the European Commission's Horizon 2020 Research Programme. This SRC aims to develop building blocks for future autonomous space robotics missions to provide the capabilities to meet demanding future mission goals. The challenge of ADE is to demonstrate, in a planetary analogue environment, a highly autonomous rover-based system capable of achieving very long traverses (kilometres per sol) with high reliability while detecting potentially interesting scientific targets.

The Rover Guidance (RG) System: is responsible for autonomous navigation and is developed by Airbus Defence and Space Ltd. by building on expertise acquired from development of the European Space Agency's ExoMars Rover Vehicle GNC system.

The ability to sense, identify, fuse local and orbital information and execute obstacle-free traverse is a critical function of a rover GNC system and is core to RG. While those functions are often shared between ground control and on-board processing in a different ratio dependent on a mission profile, the RG in the ADE project is assumed to be processed completely on-board providing a good basis for a fully autonomous rover system.

RG implements a novel navigation architecture using global maps alongside dynamically reconfigurable multi-mode autonomy. The hazard prevention functionality is also present to ensure rover safety whilst traversing. The multi-mode autonomy architecture allows different navigation algorithms to offer performant solutions in different modes. These are used depending on the level of complexity posed by the perceived environment.

The first version of the RG system was tested and validated during field trials in the scope of the ERGO project in Morocco in late 2018 [1]. The functionality of the system was proven by demonstrating the capability to traverse long distances. The RG system is further extended in the context of ADE with lessons learned from earlier field experiments and expanded upon by including additional autonomy modes and optimised algorithms for improved traverse performances.

The main focus of this paper is to summarize the simulation results and analysis of tests conducted on data collected from planetary analogue sites around the world. A comparison between ADE and ERGO project results are also presented. Finally, the paper concludes with an outlook towards the field testing due to take place on the Spanish island of Fuerteventura in late 2020.

1   INTRODUCTION

The overall goal of the ADE project is to develop a robotic vehicle system that is suitable to increase data collection, improve mission reliability, and perform autonomous long traverse surface exploration, under the most optimal exploitation of locally available resources.

One of the main objectives is to develop autonomous long range navigation with high reliability. Furthermore, interesting environmental features will be detected by an opportunistic science agent.

Space analogue sites are having an increasingly important role regarding testing of existing space robotic systems. Various Earth analogue robotic field trials are also providing the scientific community with useful datasets. For example, the ExoFit trials led by Airbus in Chilean desert in 2019 [2] which tested prospective ExoMars science operations remotely from the UK's Harwell Campus.

Vayugundla et al. presents datasets captured on Mt. Etna, Sicily, Italy [3] with DLR's Lightweight Rover Unit (LRU). ESA also has its own Robotics datasets, which can be publicly accessed [4]. Tests were done on Katwijk beach in the Netherlands by the Heavy Duty Planetary Rover (HDPR) [5].

Chapter 1 provides the goals and objectives of this research project. Chapter 2 presents a brief explanation of ERGO field trials results and analysis regarding improvements. Chapter 3 details requirements and performance metrics used. The core of the paper is presented in Chapter 4 where simulation results are shown in various challenging terrains. Finally, Chapter 5 concludes the paper.

1.1 ADE Consortia

ADE brings together European industrial and research leaders in the space robotics community (refer to Figure 1). The team represents the optimal solution between utilising Operational Grants results from the earlier SRC and including new partners that add additional skills and experiences from the previous PERASPERA projects.
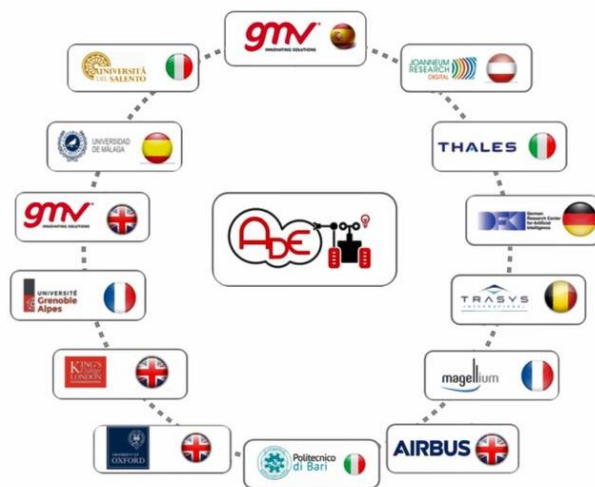

Figure 1: ADE Consortia of companies

The authors of this paper are responsible for the on-board autonomous navigation solution. This is provided by Airbus, GMV is the system integrator, DFKI supplies the rover prototype and the University of Oxford is developing an opportunistic science agent along with other partners providing further building blocks of the system.

2　ERGO TEST RESULTS ANALYSIS AND WAY FORWARD

2.1　Analysis of Slow Speed in ERGO

In order to assess areas for improvement from previous developments, the performance of the system during ERGO field trials was analysed. Drive results were presented in [1] and details relevant for this work are included hereafter.

The Figure 2 shows the actual vs. commanded speed over time for a long traverse of 1.3 km from the start to a list of target points.

Several periods were identified where the rover remained stationary when commanded to drive. During approximately 8.5 hours of testing, the rover was stationary for over 3 hours. This time was lost due to issues with parts of the system out of the RG perimeter (i.e. localisation and SLAM). As presented in Figure 2, from approximately 5.5 hours of total traverse time, the rover was stationary for 48% of the time, with a rover speed less than 0.5 cm/s. This includes processing time as well.

In a significant number of cases, this reduction in performance was caused by a high number of re-plan events. Further analysis helped to identify the root cause: the planned paths were incompatible with real rover dynamics constraints.

2.2　Cornerstone Improvements for RG

Several improvements have been made during ADE to reduce the amount of time spent in an idle state [6]. The most important are included below:

- The development of a new Monitors block responsible for validation of the DEM and localisation data input to ensure consistency and quality;

- The addition of a new L0 mode allowing continuous driving without spending time identifying hazards when the rover is traversing an extremely low risk area;

- An increased steering while driving threshold in the rover's locomotion system, allowing for more uninterrupted drives;

- Smoothened and interpolated paths adjusted to the real rover dynamics (e.g. removing sharp corners) to reduce the need for local re-planning and costly manoeuvres such as point-turns;

- A better trajectory control tuning to allow for more accurate path following performance;

- Long term path planning while driving to a close intermediate point to allow for improved traversing efficiency.
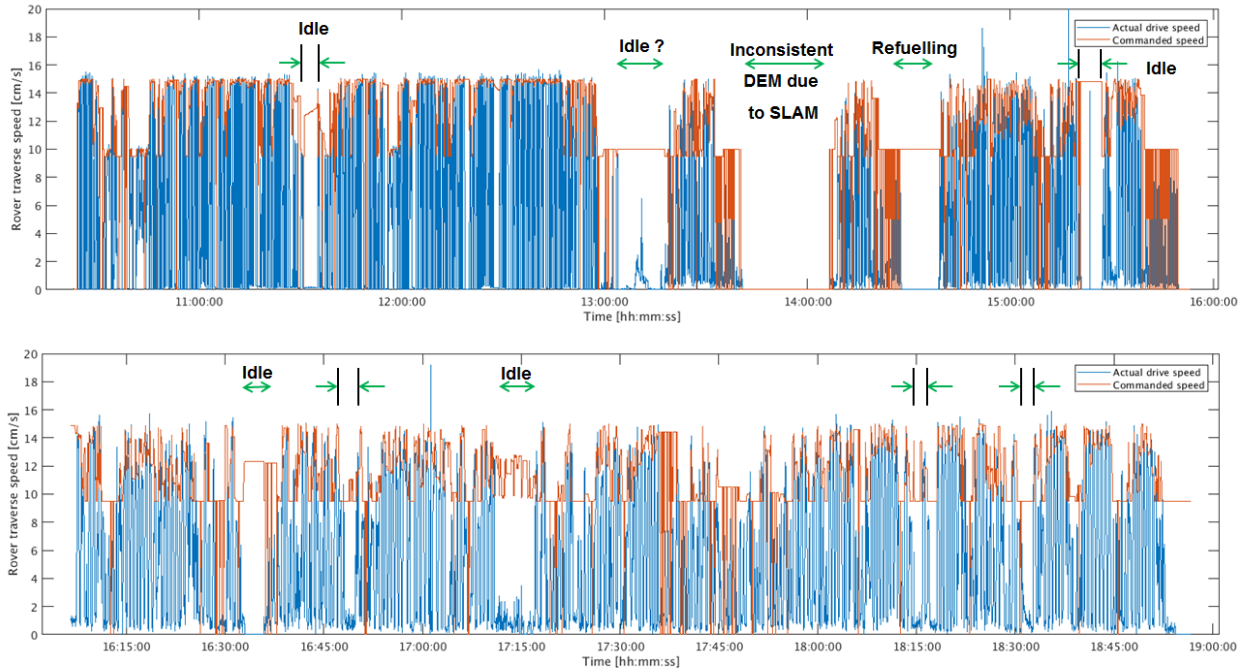
Figure 2 Actual and commanded rover drive speed during Morocco field trials in late 2018, while demonstrating RG long traverse capabilities as part of ERGO project

3   TRAVERSE PERFORMANCE ANALYSIS

Long traverse simulation results of the ERGO project were presented in [7] while results from the Moroccan field trials were published in [1] and [8]. Several new features and improvements were added in ADE as discussed in previous chapter with the aim to further speed up the average traverse velocity while maintaining platform safety.

3.1 Testing Methodology

To test RG component improvements during development for the ADE project, several simulation test cases based on data gathered at real-world planetary analogue locations were prepared. Data sets containing 'orbital data' as well as reference surface photography were collected. Each of these datasets were used to prepare inputs to a proprietary high fidelity simulation environment used to design and validate flight autonomy of planetary rovers (e.g. ExoMars Rover Vehicle or Sample Fetch Rover both primed by Airbus).

3.2 'Orbital' Data Capture

The unmanned aerial vehicle (UAV) based imaging system was flown at various testing sites prior of field tests to capture georeferenced images with a high resolution of approximately 2cm/pix. High resolution raw Digital Elevation Maps (DEMs) along with texture maps were created with automatic post-processing with a very high resolution in the horizontal direction of approximately 3cm/pixel (cell). Post-processed DEMs have a resolution of 25 cm, to mimic super-resolution reconstructions based on images taken by the HiRISE camera on-board the Mars Reconnaissance Orbiter (MRO).

3.3 Performance Metrics

The average velocity rate at which the platform can traverse autonomously greatly depends on the traversability of a given terrain. For example, on easy, relatively flat terrain a rover can improve the average traverse speed, while on rocky, hazardous areas the rover will perform costly hazard avoidance manoeuvres using up precious time budget.

Consequently in order to characterize a traverse, metrics needs to be defined. For simplicity we re-use the NASA/JPL definition from [9]. *Autonomous Traverse Speed Ratio (ATSR)* is the relative measure of average to maximum traverse rate achieved*:*

$$ATSR = \frac{v_{\mathrm{avgAutoNav}}}{v_{\mathrm{maxAutoNav}}}$$

As a generic metric we use a simplified approachability, which we redefine for a single sol:

$$ATS = \frac{\mathrm{TotalTraverseDistance}}{t_{\mathrm{stop}} + t_{\mathrm{drive}}}$$

This metric can be thought of as the average traverse speed (ATS) which includes processing time, stop time and drive time.

In the RG architecture, rover speed decreases as the terrain difficulty increases, and therefore navigation mode increases. The amount of time (cycles) RG spends in each mode is recorded for analysis.

Another important factor considered is the number of trajectory re-plans that occur when the rover deviates from the pre-defined safe path corridor or during a point turn and needs to re-plan or re-adjust accordingly. Such actions can decrease the ATS and hinder the ability to traverse more than 1 km in a single sol.

Lastly, we capture the number of new-hazard stops when the rover needs to pause due to hazards which were not detectable from orbit. These new hazards will decrease average traverse speed to some extent because the rover will need to perform costly avoidance manoeuvres.

3.4 Driving Requirements for Long Term Autonomy

Using the above defined metrics, in the ADE project several improvements over ERGO are defined as RG component requirements [10]:

Table 1 RG long traverse requirements

Metrics	Requirement
Autonomous Traverse Speed Ratio (ATSR)	> 0.32
Average Traverse Speed (ATS)	> 0.048m/s
Traverse Time (TT)	< 6h for 1km
No. of Trajectory control Re-plans	< 213

The system capable of meeting those requirements should be presented in simulation during the integration phase and finally demonstrated in field trials towards the end of the project.

4 SIMULATION TEST RESULTS AND ANALYSIS

Three simulation cases are presented below including Moroccan desert (ERGO field trials), ADE integration test site in Spain and the planned ADE field trials location on Fuerteventura. For each case we present:

- An 'orbital' image showing general characteristics of the terrain,
- An orbital navigation map presenting type of information inferred by the system (based on operator support) – see Table 2 for details,
- A table summarising results of simulation run for particular terrain.

Table 2 Orbital navigation map cost definitions

Tile categories	Cost Value	Colour representation
Tile T0 (completely flat)	0	dark blue
Tile T1 (easy)	1	blue
Tile T2 (medium)	2	green
Tile T3 (hard)	3	orange
Tile T4 (very hard)	4	red
Extended Forbidden	$+\infty$	dark red
Forbidden Terrain	$+\infty$	white / grey

4.1 Morocco

At the end of 2018, ERGO field trials were conducted in the Moroccan desert (see Figure 3), around *Gara Medouar* (coordinates: 31°17'53.8"N 4°23'12.2"W). During these tests presented in [1], the RG's long traverse capability was demonstrated while driving 1.3 km autonomously during one sol. As presented in Chapter 2.2, several improvements were identified and implemented as part of ADE project and are detailed further in [6].

A demonstration and validation of the improved Rover Guidance system was necessary in order to achieve full confidence of the latest software developments. This was done using the Moroccan dataset with the exact same target points used as during the ERGO field trials as seen on Figure 4.

Table 3 shows the results for this comparison. The delta regarding the total traverse between field trials and simulation was mainly due to localisation. The modifications and additions introduced to the RG in ADE are justified by the significant reduction in trajectory re-plans showing the superiority of latest version of the RG sub-system. This improved version of RG allows for far better results, almost doubling the average speed. However, it should be remembered that this was conducted in a representative simulation environment only. Further real world testing is required to establish full confidence in the latest RG version.

Table 3 Comparative results for Morocco test case

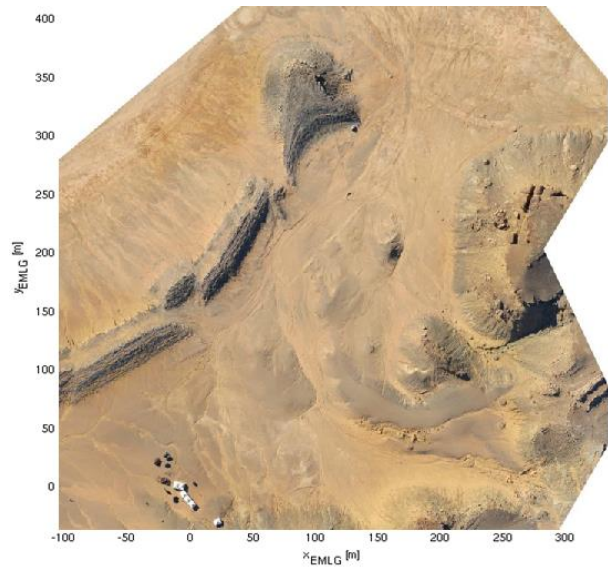|	ERGO field trials	Simulation RG (ADE)
Total distance travelled [m]	856.74	749.69
Total traverse time [h]	5.56	2.49
No. of L1 sessions [#]	372 (81.76%)	296 (87.2%)
No. of L2 sessions [#]	83 (18.24%)	29 (12.8%)
No. trajectory re-plans [#]	101	6
No. of new hazard stops [#]	18	12
Average Traverse Speed [cm/s]	4.27	8.34

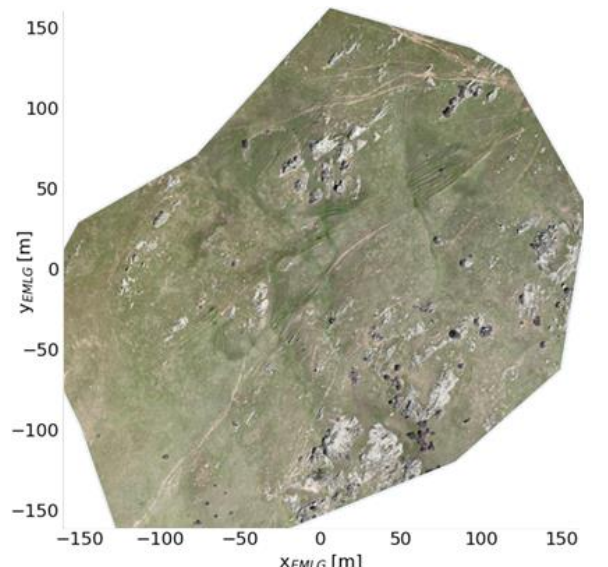Figure 3: Bird's eye view of the test area in Morocco, with the control center in the lower left corner
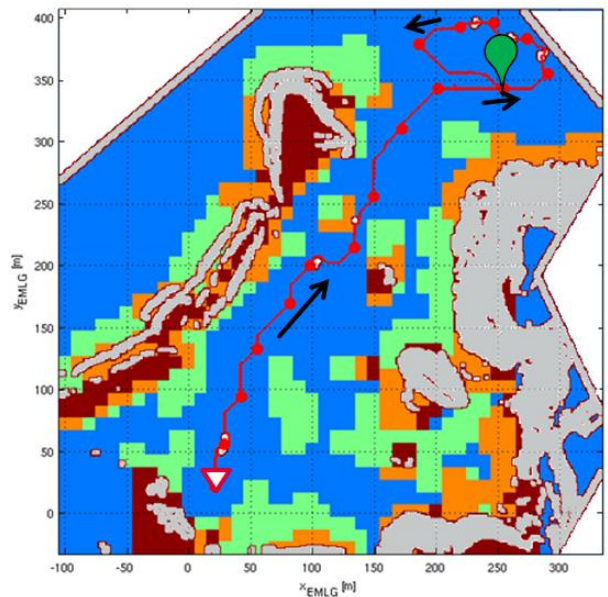

Figure 5 Bird's eye view of Colmenar test area

Figure 4: OrbitalNavMap of test area with target points marked with red dots, start denoted with white triangle, final target point shown with green pin
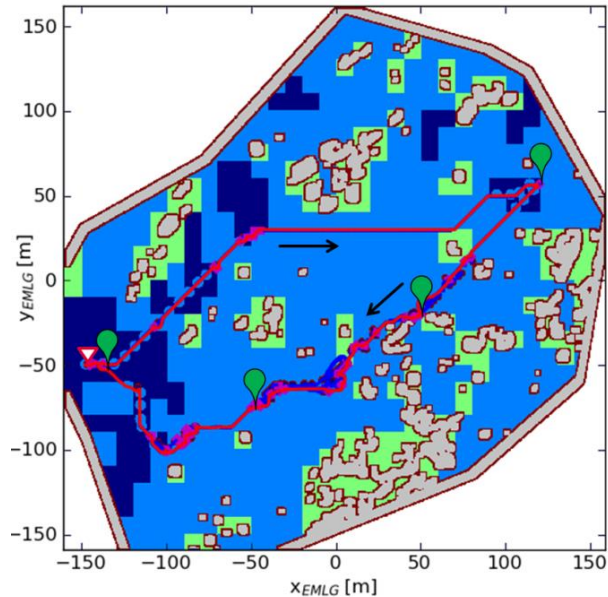

Figure 6 OrbitalNavMap of Colmenar area showing long traverse with intermediate target points

Table 4 Long Traverse Results on Colmenar

	Colmenar
Total distance travelled [m]	753.32
Total traverse time [s]	4.23[h]
No. of L0 sessions [#]	29 (4.83%)
No. of L1 sessions [#]	367 (61.06%)
No. of L2 sessions [#]	205 (34.11%)
No. trajectory re-plans [#]	170
No. of new hazard stops [#]	87
Average Traverse Speed [cm/s]	4.95
Driving/Stop time	1.287

4.2 Colmenar

The ADE integration tests are planned to be conducted in an area near *Dehesa de Navalvillar* in the near vicinity of Madrid, Spain (coordinates: 40°41'59.7"N 3°44'42.4"W). As preparation to these integration trials, multiple simulation campaigns using previously collected data were performed. Initial simulation experiments and orbital data analysis suggests that the Colmenar test area is demanding in terms of traversability. The area is on a strong slope and numerous rocks/hazards are present.

It is visible that traverse time here is driven by the number of trajectory re-plans and new hazards stops which exceed results of other test cases. Analysis showed that these were linked to the demanding traversability of certain areas. However, RG is still capable of spending a substantial amount of cycles in low terrain difficulty navigation modes and maintaining a nominal average traverse speed, thus meeting requirements.

4.3 Fuerteventura

Final field trials of the ADE project are planned to be conducted on Fuerteventura near *La Oliva* town in the test area nicknamed 4.4. (coordinates: 28°39'21.3"N 13°58'39.8"W). This terrain is characterised by several flat sandy areas with dry riverbeds as well as moderate slopes up to 20% (see Figure 7). It contains assets that can be considered interesting from scientific perspective (e.g. outcrops, rocky riverbeds).

Terrain is not overly complex, although with enough local hazards and rocks which are not visible from 'satellite' data, being enough to force RG to stop and re-plan a non-negligible number of times. However, as RG spends the majority of the time in low difficulty navigation modes, with high average speeds, the ATS requirement is easily met.

In comparison with test results in Colmenar shown in Table 4, the average traverse speed is 35% higher in the Fuerteventura 4.4 area during the same traverse time. The difference is explained by larger benign flat areas without too many rocks, also shown by increased L0 mode usage.

In comparison with the Morocco test case, where an extremely low amount of new hazards appear during the traverse, allowing for increased traverse performance, with almost 8.5 cm/s traverse speed, on Fuerteventura a healthy amount of hazards appear still demonstrating RG meets its requirements in a more difficult environment.

Table 5 Long Traverse Results in Fuerteventura

	Fuerteventura
Total distance travelled [m]	1014.34
Total traverse time [s]	4.20 [h]
No. of L0 sessions [#]	91 (16.43%)
No. of L1 sessions [#]	320 (57.76%)
No. of L2 sessions [#]	143 (25.81%)
No. trajectory re-plans [#]	57
No. of new hazard stops [#]	37
Average Traverse Speed [cm/s]	6.72
Driving/Stop time	2.102

Figure 7 Birds eye view of Fuerteventura 4.4 test area in the Spanish Canary Islands
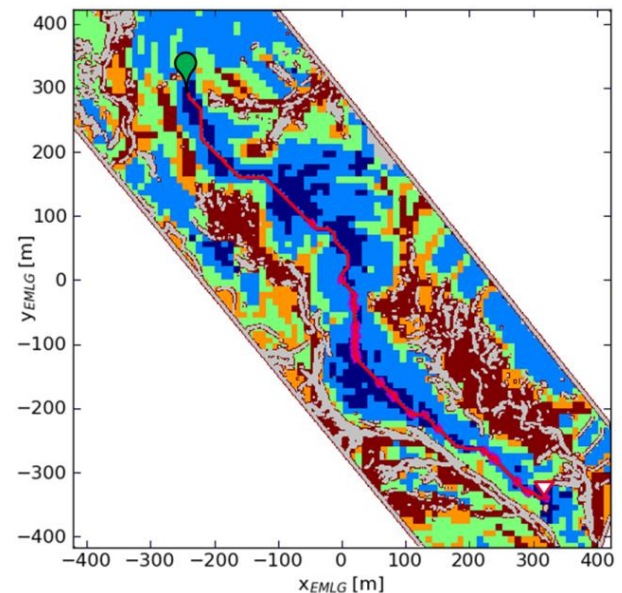

Figure 8 OrbitalNavMap of Fuerteventura 4.4 area with traversed 1km path (shown in red), the target is shown with a green pin at the top left corner

5 CONCLUSION

The results, presented above, show that the desired improvements between ERGO and ADE have been achieved and the ADE performance specific requirements are met. During testing the average rover speed was noticeably increased and allowed for drives of 1km in less than 6h independent of terrain complexity while re-plan stops were below the threshold value.

The robustness concept of the proposed solution was tested using datasets from three different planetary analogous sites in a high fidelity simulator paving the way for field trials testing.

The implemented improvements in the RG system delivered a solution that outperforms any known long range GNC system with the architecture that respects current flight missions' implementation constraints. This performance is demonstrated in high fidelity simulations using three different planetary analogue datasets and it is planned to be finally validated in field trials at the end of ADE project.

From the evolution of the presented system and the results of past missions, while platform capabilities limit the difficulty of the terrain that can be negotiated, overall traverse performance is typically limited by the lack of solutions that can relax the processing load and increase speed while traversing benign terrains, while at the same time keeping the platform safe to prevent mission loss.

Acknowledgement

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