RAPID: A Robust and (Semi) Autonomous Platform for Increased Distances

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1 ABSTRACT

Moon is the next step in human exploration. Water, other volatiles, and lunar materials such as regolith, metals, or rare-earth elements are potential resources that can support the sustainable human and robotic exploration of the Moon and the Solar System beyond. Previous Mars and Moon rover missions have highlighted a limitation in mobility, with surface rovers traversing only a few tens of meters per day, except for the manned Apollo rovers. This limitation can be primarily attributed to the rover locomotion system and its power storage capabilities from one side, and the other by the lack/reduced skills in terms of autonomous capability to take decisions on-board.

To address this issue, RAPID, an ESA project led by GMV, aims at developing a semi-autonomous rover capable of safely traversing lunar areas at high speeds (> 1 m/s), using a visual navigation-based Guidance, Navigation and Control (GNC) system and passive suspension targeted for high-speed mobility. This paper discusses the development of this autonomous rover, its different subsystems and the results obtained during the field tests.

2 INTRODUCTION

The main challenge in RAPID is to seamlessly integrate hardware components such as the locomotion system and dedicated avionics with a software system responsible for Sensor fusion, Guidance, and Navigation. This integration enables the rover to autonomously perform long traverses at high speeds in a representative scenario.

In the frame of RAPID a Human-to-Robot Interface (HRI) has also been developed. This interface supports both the remote telemanipulation operation mode, and the interactive autonomy operations mode, that provides to the operator the capability to apply setpoints generated by a haptic device as well as to execute individual robotic activities. The HRI is designed to optimize user awareness through video stream, images snapshots and force feedback.

The validation of the rover demonstrator and the HRI has been performed in a series of preliminary tests and field tests in an analogue scenario located in the vicinity of the natural park of Bárdenas Reales in Spain.

In the following sections we will provide an overview of the environmental characteristics for which the rover has been developed, describe the different subsystems, the main challenges encountered, the decisions made, and the results obtained during the field tests. By sharing these insights, readers will gain an understanding of the advancements made in RAPID to enhance rover exploration capabilities.

3 RAPID CONCEPT

Overview

In RAPID three different subsystems have been developed specifically for the project: a wheeled locomotion system with an effective passive suspension targeted for high-speed mobility, a GNC subsystem that is running in dedicated avionics, and an HRI. These are the key elements of the architecture, which are illustrated in Fig. 1:

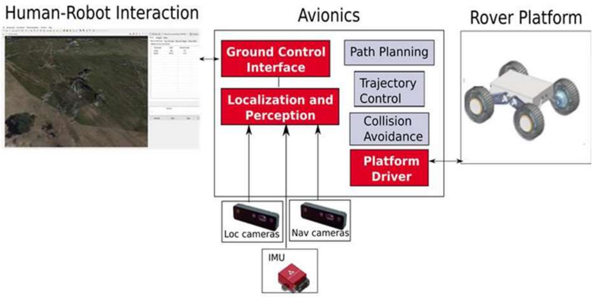

Figure 1: The RAPID Concept

The approach for the technical solution of these subsystems is as follows:

- For the locomotion subsystem, a newly developed rover platform has been designed and integrated by HTR. Robust and reliable, it has excellent locomotion capabilities in which its suspension, the

motors, the robustness of the chassis, and the wheels are key elements.
- For the GNC, RAPID has a novel, semi-autonomous guidance, navigation, and control subsystem that combines the reuse of existing techniques and algorithms using innovative approaches, as well as ad-hoc avionics. This has been a joint work between GMV and UMA, in which the guidance and control part has been inspired on the components available at the ESA-PRL [RD. 1] meanwhile the perception and localization part has been based on GMV's SPARTAN system [RD. 2] , that has been enhanced to cope with the challenges of continuous navigation reaching a maximum speed of 1.2 m/s.
- Finally, for the HRI development, we rely on the outcomes from CLEAR [RD. 3] and we have extended them with the necessary telemanipulation hand controllers and corresponding software as implemented in 3DROCS [RD. 4]. Our design and development have been integrated into the end-to-end robotic operations control system supporting the EL3 mission concept, in which a crew member of the Lunar Gateway operates the robotic asset on the moon surface with the support of a robotic ground control station.

RAPID Challenges

The following is a list of the main challenges that the project had to face to achieve autonomous driving at 1 m/s.

Challenges for the rover platform:

"Fly zones": one of the most challenging tasks for a rover traversing at high speeds is the possibility to "fly", that is, to lose contact with the soil, which means that no steering nor braking is possible.

"Tip over": The effect of lunar gravity conditions on the dynamic stability of the rover during motion is important. Gravity is crucial, since it is the force that keeps the wheels in contact with the ground. A lower gravity vector dramatically decreases this force, while the forces developed from the rover motion dynamics remain unchanged (as the mass of the rover remains the same under lunar gravity conditions). Therefore, the rover can tip over more easily on the lunar surface and wheels can lose contact with the lunar soil very often.

"Slippage": while steering (over turn, lateral skidding), in the worst case may leave the rover stuck in the terrain.

All these problems are particularly important for the rover's safety while driving and had to be avoided.

The approach we decided to follow in RAPID tackles these problems by using the following characteristics:

- Flexible wheels according to HTR patented design. The flexibility of the wheels has been tuned for optimal operational results.
- Four independent suspension arms.
- Skid steering for maximum robustness of the steering system.
- Low centre of gravity.

To this direction, we decided to consider a flexible wheel / flexible suspension baseline design for the high-speed rover and test the system in dynamic simulations for optimal behaviour over typical lunar terrain types, under lunar gravity. As part of the project's tasks, we have adapted the lunar design baseline for the engineering model meant to be built for operation on Earth gravity conditions, locomotion, and suspension.

The rover vehicle is a four wheel rover with flexible wheels that includes the locomotion subsystem, that is, the electromechanical assembly of chassis, suspension system, wheels and actuators (for traction/steering/articulation), the motion control subsystem, consisting of the control computer and servo power system that receives driving commands and drives the locomotion subsystem actuators; and a battery as energy subsystem from which the rover platform draws its energy.

Rover Dimension: An assumed full scale lunar RAPID rover of 1.8 x 1.8 m, with wheels of 650mm diameter was designed. The vehicle would have a 300kg mass on the lunar surface. Scaling this vehicle down for terrestrial gravity (6 x times the lunar gravity), yields a rover of 50 kg of mass and roughly 1 x 1 m footprint, with 340 mm wheels. (Given the planned mass of the full scale RAPID of around 300 kg, we anticipated a target 1/6 mass for the terrestrial scale model equal to 50 kg and linear dimensions scaled to the cubic root of the mass reduction scale, equal to 1.8).

Wheel Selection: The wheels use the patented HTR split hub, all metal leaf spring- caterpillar rim design. The specific wheel solution presents unique advantages in both traction and durability. The use of cryogenic materials for the entire wheel allows for full range use on lunar temperature conditions (-200 C to +150 C). The wheels have also been intensively tested for wear through operation in analogue environments (loaded in regolithic sand chambers) for over +5000 km.

For the needs of RAPID, a special fish-bone grouser has been implemented with success.

Figure 2: HTR wheel for RAPID

Suspension design: After careful evaluation, HTR opted for the crawler suspension concept.

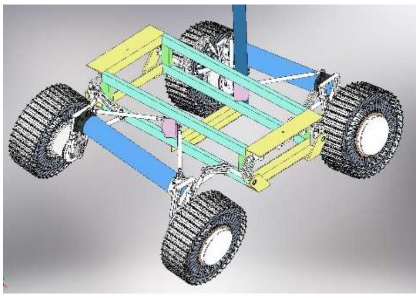

Figure 3: Crawler suspension

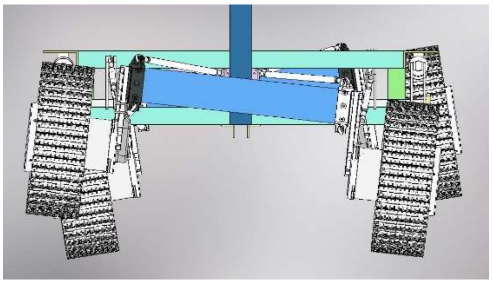

Figure 4: Crawler suspension range indication

The reasons for this selection as opposed to the selection of an independent wheel suspension system are multiple:

- Higher rigidity of the suspended stack, especially for skid steering
- Higher resistance to shocks / collisions (given the high speed of the system inertial forces play a critical role during potential collisions
- Better heat dissipation from in-hub motors (see also following section)

Thermal considerations for in-hub motors: The use of the crawler suspension bridge facilitates also thermal dissipation from in-hub motors. Thermal management is a key issue for the lunar environment and a primary concern for high-speed rovers using powerful motors. The proposed heat management system uses heat pipes and switches for the dissipation of excessive heat from the hub motors towards the bridge.

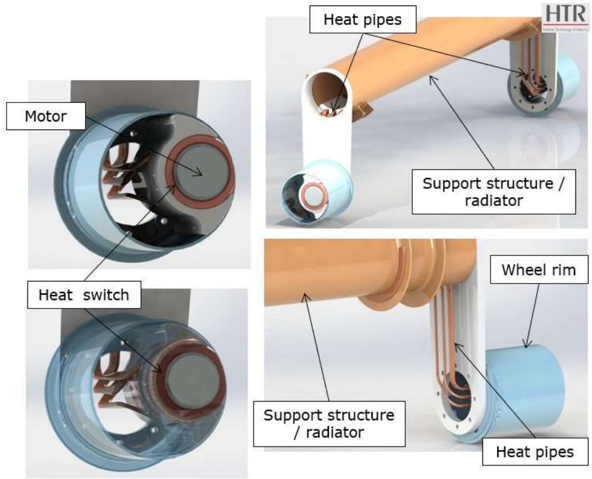

Figure 5: Heat management for in-hub motors

Low level Locomotion Controller: The locomotion controller of HTR for RAPID uses a micro-processor array using CAN, receiving instructions over ROS 2 Humble protocol. Each micro-p card controls one wheel motor on velocity loop, however special attention has been given to suppress peak currents during operation, to avoid motor over-heating and premature damage. These loops are not mere over-current suppressions but use sophisticated algorithms to ensure optimal current levels for motor operation under all circumstances, including when a wheel is blocked. The controller implements also various security layers, forbidding non-synchronous wheel operation, runaway operation etc.

Challenges for the GNC

Overall control loop

Controlling the rover motion is essential to guarantee safe and efficient exploration. A fundamental requirement for planetary rovers is to provide traversing capabilities in rough terrains composed of rocks, pebbles, and loose sand. One typical issue in such scenarios is wheel slippage, which can induce sideslip and degrade the mobility performance due to the soil deformation consuming some amount of tractive power from a driving actuator. Planetary rover control is challenging as the control system needs to be capable of driving the robot while coping with the uncertainties generated by rough terrain and performing onboard space-graded hardware, i.e. using limited computational resources.

The control loop of wheeled robots is generally approached considering two modules: locomotion control and path/trajectory tracking control. While the first translates high-level velocity command into wheel motor torques, the latter ensures the rover can follow a reference path or trajectory in the presence of modelling error and other forms of uncertainty. Locomotion control is usually tackled in an efficient manner using simple control methods such as PID controllers. Two main approaches exist in the literature for path/trajectory tracking control: methods based on a kinematic model, and predictive control approaches. Controllers based on the kinematic models have low computational requirements and provide good performance at moderate speed. However, they do not cope with slippage. In contrast, predictive control approaches are more suitable for slippery terrains and high speeds than kinematic model-based control methods. However, complex and accurate models are required to provide good performance. Moreover, they are computationally expensive, which hampers their online execution on space-graded hardware. Therefore, the RAPID platform was designed to provide intrinsic robustness to slippage at maximum speed to rely on a path/trajectory tracking control method based on a kinematic model.

Obstacles are commonly detected by the perception subsystem, which is commonly made up of two sets of stereo cameras, called Navigation Cameras (NavCams) and Localization Cameras (LocCams). Usually, the NavCam is located on top of a mast. In RAPID we decided to attach them to a gimbal which hangs from an arc.

The RAPID GNC architecture consists of three iterative stages that run in parallel at different rates: Localization and Mapping, Guidance and control, and obstacle detection from afar. In a nutshell, localization is continuously computed for online pose state estimation while, in parallel, a Digital Elevation Map (DEM) of the area in front of the rover is generated and used for refining the global map. By the time the rover reaches the mapped area, the path planning execution is completed within a security range that allows emergency braking. Additional information regarding potential hazards is detected from monocular images and used in the path computation to guide the rover towards obstacle-free areas. To summarize, the navigation cycle performs as follows at each iteration:

1. During traverses, Visual Odometry (VO) operates in parallel, delivering precise localization estimates at a rate of 5 Hz.
2. At 1Hz the NavCams capture the area in front of the rover while moving. Recognizing the limitations of stereo vision at greater distances, the mapping range was set up to 6 m. to ensure an accuracy within 20 mm. To maintain continuous motion, the NavCam's field of view was limited to a distance that allows for path computation while considering the time required for emergency braking in the presence of unavoidable hazards.
3. Using the newly generated DEM, the GNC system computes the path and control commands, which are subsequently executed by the locomotion control. Consequently, the DEM generation operates at a rate of 1 Hz.
4. Additionally, an object detector is periodically used in parallel to identify rocks and subsidence on the lunar surface at distances beyond 6 m, which provides the GNC system with relevant information to anticipate potential hazards.

Table 1. Computational time required per subsystem.

System	Time (ms)
DEM Mapping	~1000 ms
GNC (Path planning + high-level control)	~150 ms
Locomotion control	~333 ms
Time to stop at max speed 1.2 m/s	~500 ms
Total	**~1983 ms**

Overall, the distance at which the rover can react to obstacles detected in the DEM is key to guaranteeing a safe traverse, since it has a direct influence on the time required for the guidance algorithm to stop the rover or to deviate depending on the obstacles detected in the traverse (Figure 6). The control loop commits to that global deadline to stop the rover (see Tab. 1), resulting in a minimum safety distance of 3 m.

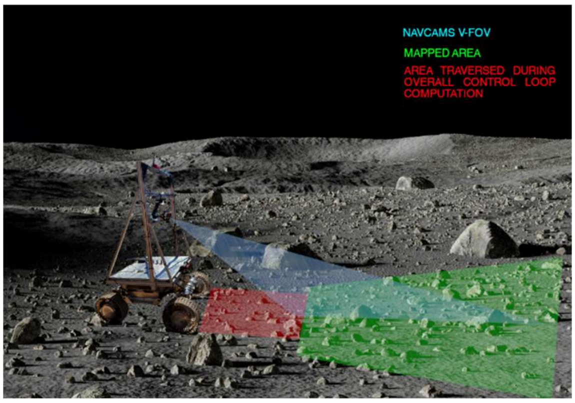

Figure 6: Mapping constraints for continuous navigation

A GNC for continuous driving

Previous rovers have been developed following the "Stop and Go" paradigm. In previous projects such as [RD. 2] , the SPARTAN navigation system was designed to capture the area in front of the rover, build the map and plan the path during the Stop stage. Once the desired path was computed, the rover executed the planned trajectory while running Visual Odometry for localization. Thus, more computationally expensive tasks could be performed without time constraints. Moreover, potential localization errors (i.e. drift) could be refined periodically while being stopped. However, Stop & Go strategies are very limited in terms of the time required for exploring wide areas.

Current path planning methods for planetary exploration are based on a two-level approach. On a high level, a global map is provided. In planetary exploration, this map is commonly obtained from orbital imagery. It contains surface elevations and could provide some relevant information about terrain features. This map is translated into a cost map that is used to obtain a global path to be followed by the rover. The path is split into a set of waypoints the rover must reach, avoiding going far from them. For this purpose, trajectory control methods are used. Conservative pure pursuit has been proposed for planetary exploration. This is the approach followed in RAPID. It guarantees the rover will be within a safe corridor around the obtained waypoints. However, this global map sometimes needs to be corrected when obstacles that are not on the global map are found. For this purpose, the chosen path planning method needs to meet this requirement. To accomplish it, some recent works [RD. 1] proposed the use of multi-layered maps that include global information, but also local information such as detected obstacles during the traverse. In RAPID, these obstacles are included in the cost map, at a given rate new DEMs are being computed, from these DEMs is it possible to identify obstacles. Additionally, an AI algorithm can detect obstacles from the images taken by the NavCams. Based on this information the path is modified to avoid the obstacles detected if needed. The way the path is modified has a direct impact on computation time. If the path is globally corrected, then the path should be entirely recalculated with its corresponding processing time. To speed up this process, literature proposes to repair only the involved section of the path that would avoid the obstacle, following the predefined global map as much as possible.

For the RAPID rover, whose objective speed is slightly greater than 1m/s, the way in which the obstacles are detected when moving is a challenge, where the configuration of the cameras plays a crucial role. The frequency for NavCams allows the generation of a DEM at 1 Hz.

On the other hand, once the obstacle is detected, the rover needs to react as fast as possible. This response depends directly on the rover speed. Therefore, the used path planning algorithm needs to be fast enough to accomplish the required response time. In this sense, one of the faster methods is the Fast-Marching Method, which has been demonstrated to generate an optimal and smooth path with a suitable performance in planetary exploration use cases [RD. 1] . It is the method used in RAPID.

Continuous localization and perception

In the context of planetary rover operations on the lunar surface, ensuring the safety and efficiency of continuous navigation is paramount. The proposed approach relies on an ad hoc solution using SPARTAN (Space Performance and Robust Terrain Awareness Network), a low-cost and high-performance vision architecture for space exploratory rovers. SPARTAN leverages advanced implementations of Visual Odometry (VO) and Stereo Mapping algorithms, offering robust navigation capabilities in challenging environments [RD. 5] [RD. 6] [RD. 7]. Notably, SPARTAN is versatile and can be adapted to platforms with varying computational constraints, as an FPGA version of SPARTAN is available [RD. 2] .

Effective localization is particularly challenging during high-speed rover operations. SPARTAN VO operates at sufficient frequency to ensure the computation does not limit the traversal speed, with a requirement of over 70% image overlap between consecutive frames to ensure precise VO estimates. The positioning of the cameras in the RAPID rover is critical to achieving this overlap. To minimize mechanical vibrations, the LocCams are strategically located on the rover's chassis, and their tilt orientation was fine-tuned to ensure optimal image overlap, even at maximum speed.

The NavCams system is equipped with a Cardan joint (gimbal) to maintain a fixed orientation w.r.t. its axis of rotation, effectively countering mechanical vibrations. The NavCams system is also attached to the rover using and a gimbal and an arc. The arc holds the gimbal and the cameras at 1.35 m. and contributes to reduce the vibrations of the cameras w.r.t. using a mast. The NavCams are tilted 25 deg and provided a FOV of 89.5 deg., to provide DEMs up to 6 m in front of the rover. Unlike traditional "Stop & Go" approaches, mapping at very close distances were strategically avoided, as it does not yield substantial information. The closest distance to be mapped was set to ~2 m. corresponding to the distance traversed at full speed during the computation of the overall control loop plus a safety margin for computational time variations and bottlenecks. The farthest area is not considered for the mapping, resulting in a DEM for the range between 2 and 6 m. in front of the rover, which fulfils the control loop requirements for obstacle avoidance. The NavCam system also serves a vital role in obstacle detection from afar, identifying rocks and subsidence on the lunar surface through monocular images. This capability enables the Guidance module to proactively anticipate potential obstacles in the rover's path.

Consideration of the camera baseline is also essential. A large baseline between stereo pairs enhances depth accuracy and mapping/VO capabilities. However, it reduces left/right image overlap, limiting the effectiveness of VO. Furthermore, a large baseline places additional demands on the gimbal system for camera stabilization due to increased inertial moments. To strike a balance, a compact solution with a ~75 mm. baseline was adopted for both NavCams and LocCams.

HRI Challenges: telemanipulation

Ground Control Stations for robotic assets have been extensively studied and developed supporting a significant number of ESA analogue field tests as well as ESA robotic missions such as ExoMars and Prospect ([RD. 10] [RD. 9] [RD. 10] [RD. 11]). In this activity, we build on this solid basis and adapt/extend it focusing on the additional challenges introduced by the targeted operations concept involving an orbiter crew member and the high speed of the robotic asset under control.

Indeed, in RAPID, we followed the user experience-driven development approach initiated in the CLEAR activity [RD.3]: the MMIs are organized not around the technical constraints and technology, but around the user and the application needs based on state-of-the-art MMIs on touch screens and well-established ergonomic criteria. This approach is adapted for operations performed by an orbiter crew member that is a highly qualified trained person but is neither a robotics expert nor a programmer or software developer.

On the other hand, high speed operations on the moon surface imply increased risk of a) *tipping over,* especially when turning on a slopped terrain, and b) *collision* as the time required to avoid an obstacle increases with the speed.

Enhanced situational awareness of the operator is therefore introduced by:

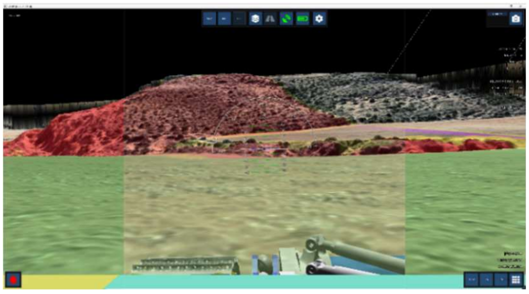

Figure 7: The RAPID GCS is organised around a main full touch screen application where the synthetic 3D scene is augmented with the live video feedback.

- *Providing haptic feedback* that prevents the operator to provoke tipping over situations; the forces reflected on the Force Feedback haptic device (Novint Falcon) are function of the travelling speed, the curvature and the local terrain topology imposing the operator to decrease either the speed or the curvature in the safe limits.
- *Providing visual feedback* of the operations environment indicating the free, the dangerous and the forbidden areas function of the rover speed. On-line, the size of the visual representation of the dangerous and forbidden areas is adapted guiding the operator to drive the rover always at a safe distance from the obstacles.

4 PRELIMINARY AND FIELD TEST RESULTS

Testing for the RAPID project was conducted at three different levels:

- A first unitary testing level for isolated components were performed by each partner.
- Integration tests were conducted to individually integrate different components as soon as they were ready.
- A third level of testing consisted of preliminary tests, first with the rover platform on different terrain, and secondly, once the GNC and the HRI were integrated, with the rover platform, in an open field located near GMV facilities.
- Final field tests were conducted in Cabanillas, in the vicinity of the Parque Natural de las Bárdenas Reales,

The project used an iterative approach, and both unitary tests and integration tests were used to identify areas for improvement. Simulation tests were conducted separately at rover level (interaction with the soil, vibration analysis), GNC level (path planning, trajectory control and collision avoidance) and Ground Control Station level.

Preliminary tests

Preliminary tests were conducted in Dehesa de Navalvillar, a test area located in the vicinity of Madrid. This test site, not being geologically/soil representative of Mars/Moon, offers adequate morphological characteristics for medium-representative test fields, including some very interesting features; it is a very large area that includes areas with no trees and very short grass or directly sand-covered soil.

The preliminary tests executed were a subset of the field tests. We performed tests related to basic functionalities of the rover, that allowed us to test its correct behaviour in certain areas, like:

- The correct behaviour of the rover while traversing at different speeds was verified (0.3, 0.5, 0.8 m/s) and that the suspension and the gimbal reduced the vibrations allowing the correct generation of images by the NavCams and LocCams
- It was also verified that the DEM generation can be executed at a rate of 1 Hz, which is the optimal frequency for guidance replanning.
- Ground control station commanding in teleoperated mode and semi-autonomous mode was also tested and verified.

Field tests

Two weeks of field testing were conducted in Cabanillas (Navarra, Spain), in the vicinity of the Bárdenas Reales Natural Park. The scenario consisted of a very large area, (200x300m) semi-ploughed land, with reduces slopes and scattered obstacles. These tests covered:

- **Rover basic checks**, calibration and localization and mapping aimed to verify that the rover is in good health. The teleoperated mode of GCS was used for this purpose.
- **Localization and mapping** test aimed to verify the performances of the localization and perception system. Different configurations were used:
  - Perception provided fully by Spartan, for both localization (based on visual odometry obtained from images from the LocCams) and perception (DEM generation from NavCams images)
  - localization provided using Spartan's Visual Odometry & DEMs generated from the point-clouds provided by the NavCams firmware.
  - Localization directly provided by GPS and Perception provided by the NavCams.
- **Obstacle avoidance and path planning**: tests aimed to verify that the rover can detect and avoid obstacles, build a correct path, and follow the trajectory.
- **Traversability and speed**: verify the correct execution of rover's traverses at different distances and speeds while still maintaining the capability to safely avoid obstacles ahead.

The tests demonstrated the capability of the rover platform to run at 1.2 m/s while teleoperated. It also demonstrated the capability of the rover to run at 1 m/s in the absence of obstacles. During the final days of testing, and after some fixes and system fine-tuning. we were also able to demonstrate the capability of the system to detect obstacles on its way and replan the trajectory while driving at high speeds. All these features were achieved in harsh terrain with different slopes. The following table of main tests conducted during the last days of the tests shows the distance traversed, the maximum and average speed, the commanded speed and the number of path replanning tasks that were executed.

Tab. 2 shows different tests conducted at different max speeds. Note that mean speed is strongly affected by the number of spot turns (in which the speed is reduced to 0), particularly when the angle for the spot turn is high.

Table 2. Traversed lengths and speed

#	Spartan In The Loop	Max Comm, speed	Max Real Speed	Mean speed	Dist. Traver. [m]	Spot Turn
1	No	0.3 m/s	0,31	0,19	41,74	1
2	Yes	0.3 m/s	0,32	0,20	14,66	3
3	Yes	0.3 m/s	0,33	0,20	30,37	3
4	No	0.3 m/s	0,69	0,22	21,02	1
5	No	0.5 m/s	0,66	0,31	32,99	4
6	Yes	0.6 m/s	0,60	0,38	20,79	3
7	Yes	1 m/s	0,82	0,49	30,96	0

Although most of the project objectives have been covered, we are currently working in the final fine tuning of the system, focusing on both localization and perception and guidance improvements. We have also identified improvements that will be performed in future activities.

5 CONCLUSIONS AND FUTURE WORK

RAPID is a very ambitious project with the goal of developing a semi-autonomous rover system capable of traversing at very high speeds. The design of the system has been based on the lessons learnt of previous missions. In a nutshell, the achievements accomplished can be summarized as follows:

- The rover platform was developed following a flexible wheel / flexible crawler suspension design. The terrestrial prototype demonstrated its validity in very rough terrain with many different slopes. It also demonstrated its robustness under harsh conditions (dust, difficult terrain, and high temperatures)
- The combination of a gimbal, an arc and suspension reduced vibrations at high speed which allowed the NavCams to obtain valid images for DEM generation.
- The use of separate CPU(s) for the GNC subsystem also proved that the system has enough computing power to meet the deadlines of the control loop in continuous driving mode, reacting in time to newly detected obstacles.

- The GCS is developed following an agile approach supporting RAPID during all the project phases including the field tests. The HMIs follow UX best practices and feature characteristics dedicated to high-speed moon operations.

Some of the flaws found during the field tests are problems in which we are working now, while others are out of the scope of RAPID and will be tackled in future projects.

Figure 8: The RAPID Rover during the field tests in Cabanillas.

Overall RAPID provides a rover based on an innovative design which paves the road for future Lunar and Martian exploration rovers capable of traversing long distances at high speed.

6 ACKNOWLEDGEMENTS

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