EXECUTIVE SUMMARY REPORT

ROBUST AND (SEMI) AUTONOMOUS PLATFORM FOR INCREASED DISTANCES (RAPID)

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Code:	RAPID_ESR
Version:	1.0
Date:	15/11/2023
Internal code:	GMV 25808/23 V1/23
ESA contract number:	4000136833/21/NL/RA

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	15/11/23	22	Final version of the document.

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1 INTRODUCTION

1.1. PURPOSE

This document provides an overview of the work performed

1.2. SCOPE

This document provides an executive summary for the RAPID activity. The main challenge in RAPID was, first to develop a locomotion system able to perform traverses at high speeds (up to 1.2 m/s) and secondly, 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 *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. Additional tests were conducted in the vicinity

1.3. CONTENTS

This document is structured as follows:

- Section 1Contains the purpose, scope and contents of this document.
- Section 2. Lists the reference and applicable documents
- Section 3. Details the definitions and acronyms used throughout the document.
- Section 4. Explains the RAPID technical solution.
- Section 5. Describes the main challenges for the Rover Platform.
- Section 6. Describes the main challenges for the GNC system
- Section 7. Describes the main chalenges for the HRI
- Section 8. Provides the main results obatained in the different campaign tests.
- Section 9 Summarizes the conclusions and future work

2. REFERENCE AND APPLICABLE DOCUMENTS

2.1. APPLICABLE DOCUMENTS

2.2. REFERENCE DOCUMENTS

The following is the set of documents referenced:

Table 2-1 Reference Documents

Ref	Title
[RD. 1]	L. Gerdes, M. Azkarate, José R. Sánchez-Ibáñez, L. Joudrier, C. Perez-del-Pulgar "Efficient autonomous navigation for planetary rovers with limited resources ". Journal of Field Robotics, August 2020.
[RD. 2]	Sample Fetch Rover A/B1 Study: SPARTAN co-processor unit breadboard analysis and test report. GMV-SFRAB1-BBDR-MEMO-05
[RD. 3]	K. Kapellos, et al, CLEAR Final Report, Trasys, 10/11/2021
[RD. 4]	K. Kapellos, et al, 3D Rover Operations Control System: application to the ExoMars mission," iSAIRAS 2014
[RD. 5]	Lentaris, G., Diamantopoulos, D., Siozios, K., Stamoulias, I., Kostavelis, I., Boukas, E., ... & Aviles, M. A. (2013). SPARTAN: Efficient Implementation of Computer Vision Algorithms for Autonomous Rover Navigation. In 7th HiPEAC Workshop on Reconfigurable Computing.
[RD. 6]	Lentaris, G., Stamoulias, I., Diamantopoulos, D., Maragos, K., Siozios, K., Soudris, D., ... & Gasteratos, A. (2015, March). SPARTAN/SEXTANT/COMPASS: "advancing space rover vision via reconfigurable platforms. In International Symposium on Applied Reconfigurable Computing" (pp. 475-486). Cham: Springer International Publishing.
[RD. 7]	Kostavelis, I., Nalpantidis, L., Boukas, E., Rodrigalvarez, M. A., Stamoulias, I., Lentaris, G., ... & Gasteratos, A. (2014). Spartan: Developing a vision system for future autonomous space exploration robots. Journal of Field Robotics, 31(1), 107-140.
[RD. 8]	R. Trucco et al.: ExoMars Rover Operation Control Center Design Concept and Simulations, ASTRA 2008
[RD. 9]	L. Joudrier, K. Kapellos, K. Wormnes, 3D Based Rover Operations Control System (3DROCS), ASTRA, 2013
[RD. 10]	K. Kapellos.: Crew Lectern for Easy Administration of Robots (CLEAR) – Executive Summary Report, 10 November 2021.
[RD. 11]	T. Krueger e.a.: Roving on Mt. Etna a practical guide – Experiences and lessons learnt from a field campaign for an analog mission, ASTRA, October 18, 2023.

3. DEFINITIONS AND ACRONYMS

Concepts and terms used in this document and needing a definition are included in the following table:

Table 3-1: Definitions

Concept / Term	Definition
Rock	*Rock* (https://www.rock-robotics.org/documentation/about/index.html) is a software framework for the development of robotic systems.
Path	A *path* designates a composition or sequence of coordinates from the current point to a final point.
Trajectory	A *trajectory* designates a composition or sequence of motion primitives along the path.
Motion primitives	*Motion primitives* are defined via a defined sequence of control inputs which results in well-characterized motion.
Guidance	*Guidance* consists of the process of guiding the rover through a terrain. This includes creation of a navigation map from Digital Elevation Map (DEM), planning a path on this map, estimating the required resources to achieve this path and reacting to the environment (hazards) while executing the trajectory
Digital Elevation Map (DEM)	The *DEM* is a 2.5D representation of a terrain's surface in Cartesian coordinates, also known as heightmap. DEM is a grid map: a collection of squared cells organized into a grid structure with associated height (i.e. elevation). While man-man objects (e.g. lander platform) are included in this map, the rover itself shall be excluded (e.g. wheels, solar panels, which could be visible in raw sensor data). *Note: this map contains solely height information, other type of information are excluded.*
Uncertainty Map	The *uncertainty map* is a map associated to a DEM, describing the height uncertainty associated to each cell of the DEM. *Note: this map does not contain the height information, as that is contained in the DEM.*
Soil Type Map	The *soil type map* is a map associated to a DEM, describing the type of soil associated to each cell of the DEM. *Note: this map does not contain the height information, as that is contained in the DEM.*
Traversability Map	The *traversability map* is a 2D map identifying which area of the terrain is traversable by a specific locomotion system, including level of difficulty to traverse. This includes information regarding to the locomotion traverse capability: cost function (e.g. ability to climb rocks and drive up slopes). *Note: this excludes any other factors related to navigating through a terrain, e.g. this excludes energy.*
Navigation Map	The *navigation map* is a 2D map onto which the rover path can be planned. This is generally a traversability map and any additional information regarding other aspects that can be taken into account to plan the path, like areas of scientific interest or shadows impacting illumination of the solar panels.
Local, Regional or Global Map	These notions refer to the geographical extent and spatial resolution of the map: *Local map* is high resolution with small geographical extent. *Regional map* is medium resolution with medium geographical extent. *Global map* is low resolution with large geographical extent.
Rover Map	The *rover map* is a map produced with information gathered by sensors on the rover itself at the last sensing capture.
Fused Rover Map	The *fused rover map* is a map produced with information gathered by sensors on the rover itself at the last and previous sensing captures.
Orbital 3D-Model	The *orbital 3D-Model* is the 3D generated model acquired from orbital sensors (e.g. from stereo-images, TOF/Lidar or radar).
Orbital Map	The *orbital map* is a map generated from orbital sensing data. *Note: this terminology can be used in combination with other definitions, e.g. "orbital navigation map".*
Fused Total Map	The *fused total map* is a map produced with information from any sensing sources at any capturing time, e.g. rover, orbital, other mobile or static devices on the surface.
Planned Rover Path	A *planned rover path* designates a desired/planned rover route from the current point to a planned final point (A->B).
Executed Rover Path	An *executed rover path* designates an effective/actual route taken during rover driving execution. This is the result of a rover traverse, from the current point to the effective final point (A-> B').
Planned Rover Trajectory	A *planned rover trajectory* designates a planned list of manoeuvres or motion primitives along the planned path.
Commanded Rover Trajectory	A *commanded rover trajectory* designates the commanded list of rover manoeuvres or motion primitives along the executed rover path. This is the result of the commanding of the rover during a traverse.

Concept / Term	Definition
Executed Rover Trajectory	An *executed rover trajectory* designates the effective/actual rover manoeuvres or motion primitives achieved along the executed rover path. This is the result of a rover traverse.

3.1. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 3-2: Acronyms

Acronym	Definition
3DROCS	3D Rover Operations Control System
3DROV	3D Rover Operations Simulator
APU	Application processing Unit
CAN	Controller Area Network
CLEAR	Crew Lectern for Easy Administration of robots
DEM	Digital Elevation Map
EL3	European Large Logistic Lander
ESA	European Space Agency
FOV	Field of View
FPGA	Field-Programmable Gate Array
GNC	Guidance Navigation and Control
HW	Hardware
HRI	Human Robot Interaction
IMU	Inertial Measurement Unit
LIDAR	Light Detection And Ranging
LOCCAM	Localisation Camera
MMI	Man Machine Interface
NAVCAM	Navigation Camera
OBC	On-Board Computer
ROS	Robotic Operating System
SW	Software
UX	User Experience
VIO	Visual inertial Odometry

4. TECHNICAL SOLUTION

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 the Figure 4-1:

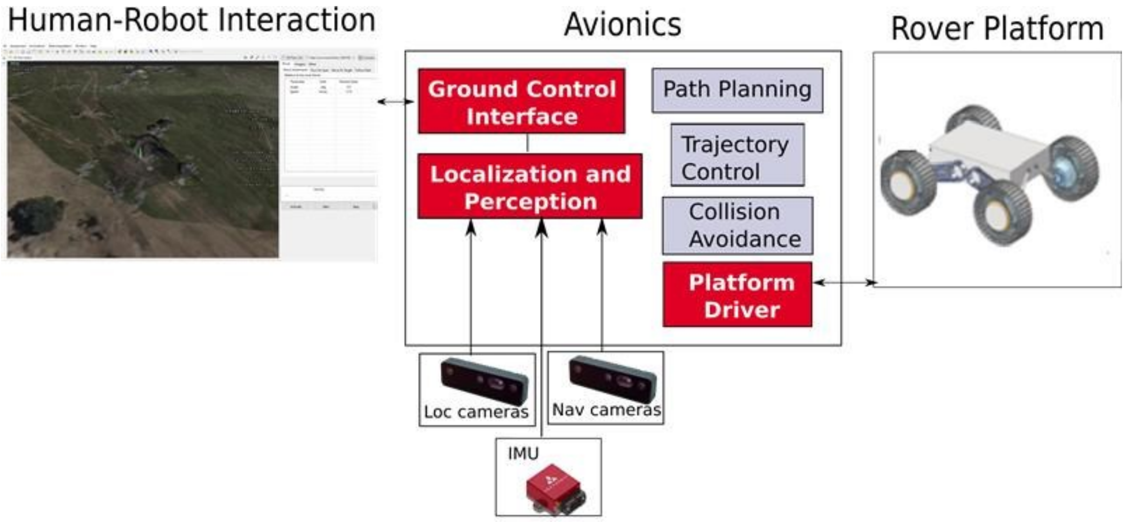

Figure 4-1: The RAPID Concept

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.

5. CHALLENGES FOR THE ROVER PLATFORM

The main challenges that the rover platform had to face to achieve autonomous driving at average speeds of 1 m/s were the following:

- **"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 (overturn, 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. A HTR wheel is showed in the Figure 5-1.

Figure 5-1: HTR wheel for RAPID

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

Suspension design: After careful evaluation, HTR opted for the crawler suspension concept as shown in the Figure 5-2 and Figure 5-3:

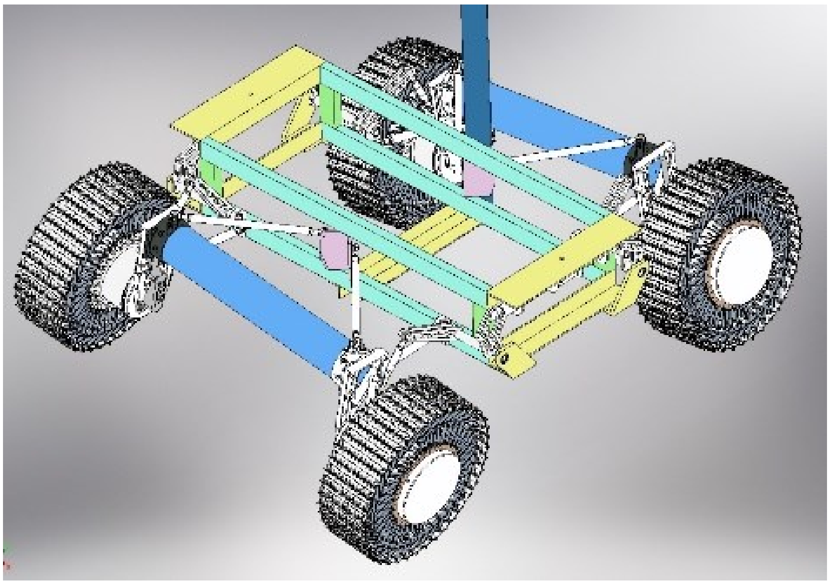

Figure 5-2: Crawler suspension

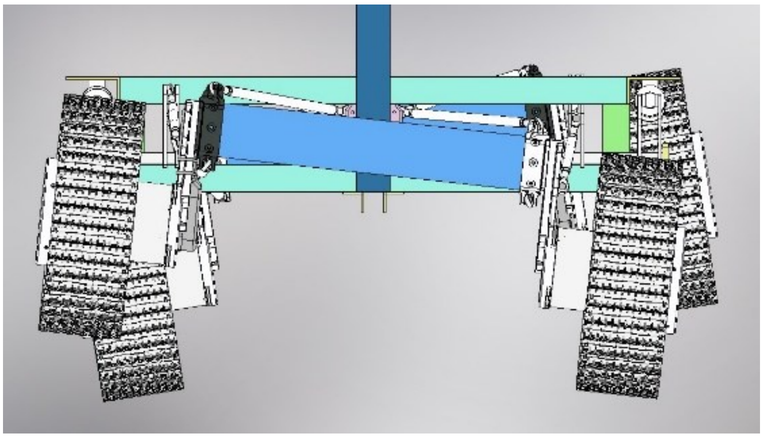

Figure 5-3: Crawler suspension range indication

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 as shown in Figure 5-4:

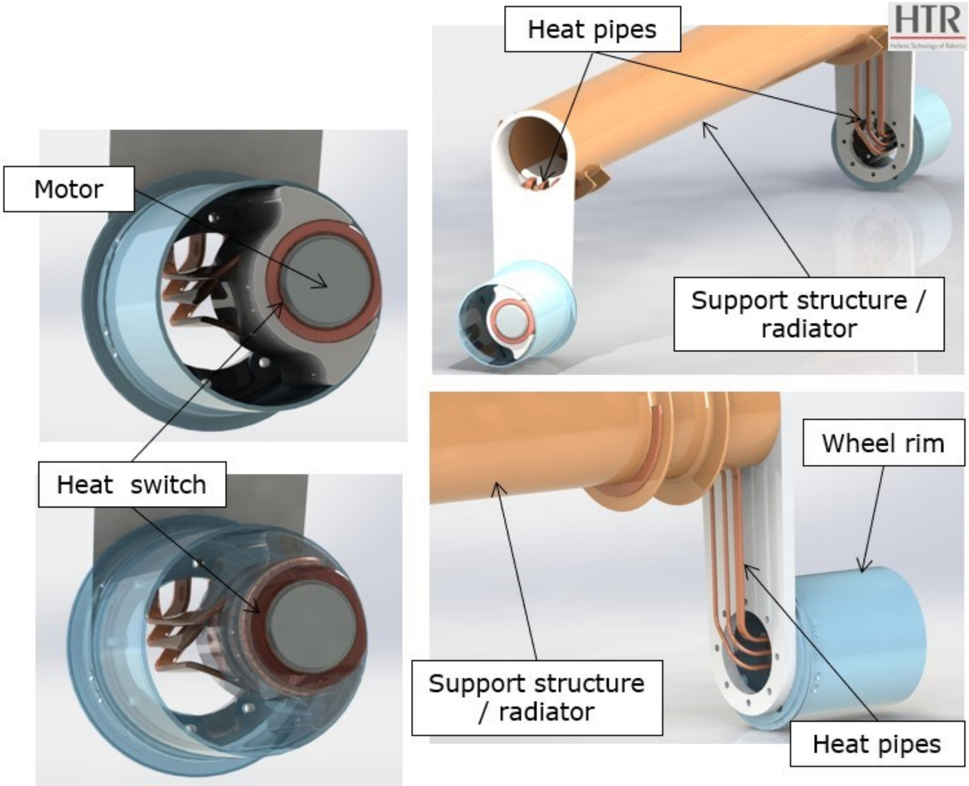

Figure 5-4: Heat management for in-hub motors

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.

6. CHALLENGES FOR THE GNC

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.

6.1. CONTINUOUS GUIDANCE AND DRIVING – 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 6-1: 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 6-1). The control loop commits to that global deadline to stop the rover (see Table 6-1), resulting in a minimum safety distance of 3 m.

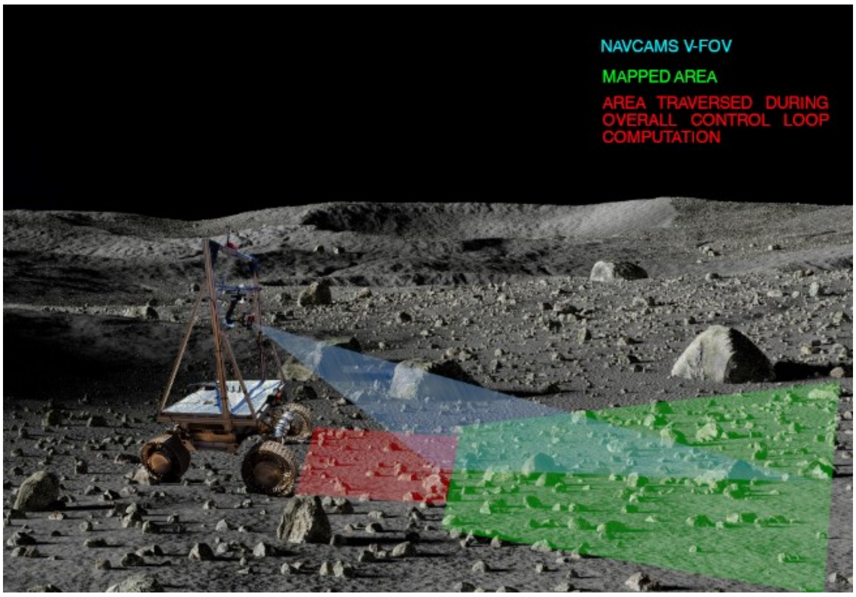

Figure 6-1: Mapping constraints for continuous navigation

6.2. 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.

7. 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. 8][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:

- *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.

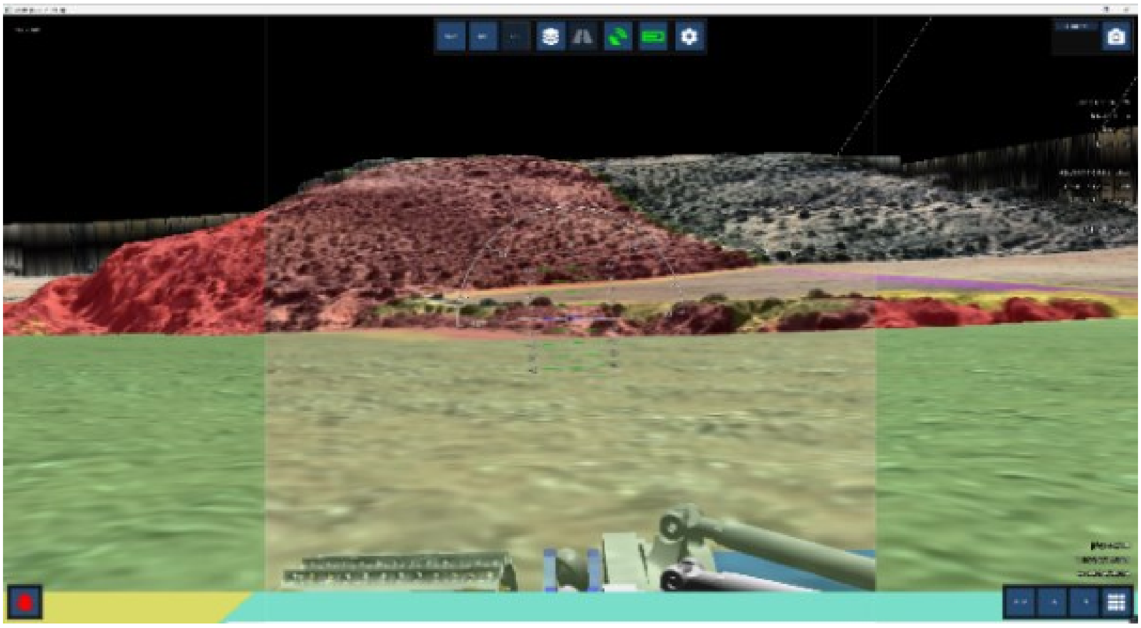

Figure 7-1: The RAPID GCS is organised around a main full touch screen application where the synthetic 3D scene is augmented with the live video feedback.

8. 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, with a final campaign of extended test in Colmenar.

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.

8.1. 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.

8.2. 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.

Table 8-1 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 8-1: Traversed lengths and speed

#	Spartan on the Loop	Max Comm speed [m/s]	Max Real Speed [m/s]	Mean Speed [m/s]	Dist Traver. [m]	Spot Turns
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

In the light of the conclusions obtained in the extended tests, it was obvious the need to perform additional tests to fix the problems found in the perception and localization system as well as guidance, and therefore an additional set of tests were conducted from September till November'2023 in Dehesa de Navalvillar (Colmenar).

8.3. EXTENDED FIELD TESTS

During the extended tests, we worked on many different areas, and this provided excellent results, namely:

- Improvements in Guidance that were required (and related components)
- Analysis of performances of Spartan for Visual mapping
- Analysis of performances of Spartan for visual Odometry
- Additional ground station tests for high latency
- Finally, a set of performance parameters was obtained.

As a global result, we obtained an average speed while driving at 1.0 m/s of 0.5 m/s, due to the need of the system to perform point turns. These point turns were due to the difficulty of the rover to perform sharp turns at high speed when the local path is repaired due to obstacles which takes it out of the planned trajectory, forcing it to realign to the planned trajectory by doing point turns.

Nevertheless, the concept of "continuous driving", that was one of the main objectives for the project was proved and demonstrated at lower speeds (i.e 30 cm/s), in which the number of point turns decreased radically.

The conclusion was that, in order to obtain average speeds higher than 0.5 m/s, it would be necessary to adapt the speed dynamically depending on the turns to be performed to follow the trajectory. That is, *to mimic the way a human driver would drive, because it is a totally different thing to drive at 1m/s than 10cm/s, driving 1m/s in the moments in which it is doing a sharp turn is not affordable.*

Unfortunately, reaching this level of refinement in Guidance was out of the scope of RAPID, since it implies profound changes on the guidance algorithms that are not affordable with the budget and schedule planned.

But this is solely a limitation of Guidance, and not of the rover platform. **In fact, in teleoperated mode the rover reaches this average speed. Fine-tuning of guidance would be required to achieve this mark**. This is left as extra work to be performed in future projects, with a new project (FASTNAV) in which these and other improvements can be properly addressed.

In the following Table 8-2, we will describe the results for performance parameters obtained during the extended tests while navigating at different speeds. Note that only tests performed with successful results are included in this table.

Table 8-2: Performance Parameters in Extended Field Test

Metric Name	Metric Description	Reference speed = 0.5 m/s	Reference speed = 0.7 m/s	Reference speed = 1 m/s
Commanded Autonomous traverse speed ratio	Average navigation speed divided by designed maximum rover speed	57,15 %	60,95 %	35,94 %
Autonomous traverse speed average	Estimated traverse speed in average actually by the rover in autonomous mode.	0,26 m/s	0,37 m/s	0,28 m/s
Spot turn time ratio	Time the rover stays performing a spot turn	34,50 %	37,98 %	63,47%
Completed Distance	Estimated distance covered actually by the rover in autonomous mode. Basis of comparison for Completed Distance	123,12	175,50	121,48
Number of traverses		5	8	4

9. 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.
- The paradigm of "continuous driving" was tested and demonstrated during the project.
- Although very high average speeds were achieved, the initial objective of an average speed of 1 m/s was not reached due to the need to add improvements in Guidance that are out of the scope or RAPID. These improvements would consist of adapting dynamically rover's speed and other guidance parameters in real time to those restrictions imposed by the trajectory. This is left as pending work for future projects.

Figure 9-1: 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.

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