DESIGN AND REALIZATION OF A ROVER AUTONOMY TESTBED

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ABSTRACT

The Rover Autonomy Testbed (RAT) is a mobile robotic platform with the scope to support the investigation of different levels of autonomy, their related perception, communication, presentation and MMI needs and their effectiveness in attaining mission success. The RAT comprises a Physical Flight Segment (PFS), a Virtual Flight Segment (VFS) and a Ground Control Station (GCS). The PFS is a medium-scale, 4-wheel rover platform, fully sensorized for both autonomous and teleoperated mission scenarios. Two onboard computers share the computational duties, with an RTEMS-based computer on LEON3 handling the motion control of the rover, and a Linux computer implementing the functional and executive layers. The VFS, built within the 3DROV environment, offers a virtual "identical" to the PFS for mission preparation and rehearsals plus additional models for running real planetary mission scenarios. Finally, the GCS implements a gateway to the two segments and a sophisticated and modular Eclipse-based environment for mission execution and situational awareness experimentation.

1. MISSION AND SCOPE

The European Cooperation of Space Standardization (ECSS) defines 4 levels of autonomy for spacecraft operability (E1 to E4, see [1]) and proposals have been made for dedicated autonomy classification for exploration robots [2]. In recent years, there has been an increasing need for autonomy in the space domain and the need for the corresponding research and development (R&D) activities. In particular robotic planetary exploration is a domain where autonomy is an enabling factor in order to increase mission effectiveness and scientific return. In this direction the Automation and Robotics Section of ESA/ESTEC recently concluded an R&D activity on the development of a Goal-Oriented Autonomous Controller [3] for planetary rovers with the aim of implementing the autonomy level E4.

The primary goal of the Rover Autonomy Testbed activity has been to develop a planetary exploration rover platform that is enabled –in terms of on-board hardware/software capabilities and ground control completeness– to support research in the field of autonomy. A secondary goal of the RAT development was to arrive to a fully equipped and field-test ready rover platform that is adaptable to the needs of a test campaign, e.g. hosting scientific payloads, supporting development of on-board algorithms [4], training operators, etc.

The RAT activity has been carried out within the ESA General Studies Technology Programme (GSTP) with GMV-Spain as prime contractor and Trasys-Belgium as subcontractor.

2. SYSTEM OVERVIEW

A Physical Flight Segment (PFS), a Virtual Flight Segment (VFS) and a Ground Control Station (GCS) compose the RAT system. The PFS is a fully equipped rover based on ESA's Lunar Rover Model (LRM) platform [5]. The VFS is a virtual realization of the PFS within the 3DROV simulation environment [7].

The GCS comprises the hardware/software ground infrastructure available to the user including the man-machine interfaces (MMIs) and a Communication Tweaker. The latter emulates the communication channel between the two flight segments and ground control and is able to introduce perturbations (e.g. delays and package drops).

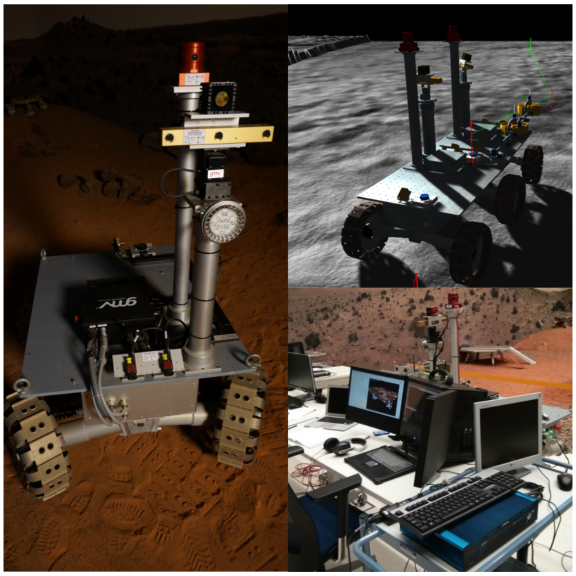


Figure 1. RAT system: PFS LRM Rover (left), VFS virtual rover (right-top) and GCS (right-bottom).

To enhance the mission rehearsal capabilities of the platform both segments, PFS and VFS, have instances of the same Functional Layer. This set of software components is named as the Data Management System (DMS). These DMS components can be fully deployed on-board the PFS with the objective of increasing the rover autonomy or shared between the PFS and the GCS with a seamless transition of component execution (i.e., without need of source code modifications).

3. PHYSICAL FLIGHT SEGMENT (PFS)

The RAT PFS is a fully equipped rover with representative sensors of a planetary exploration rover. The PFS components comprise the LRM rover, navigation sensors (IMU, inclinometer, wheels encoders sun sensor), and perception sensors (stereovision bench, a time-of-flight (TOF) camera, a 360º panoramic imager, two hazard cameras and a rear camera). These avionics elements are controlled by two different On-Board Computers (OBC): a) A representative space OBC named as the Real-Time Control Computer (RTCC), implementing the low-level motion control under RTEMS on a Leon3 synthetized on a Spartan-3 FPGA, and b) a Linux embedded computer implementing the functional and executive layers, known as the Data Management System (DMS).

Table 1. RAT-PFS platform technical specifications

Dimensions	1200 x 900 mm
Mass (overall/payload)	120 kg / 60kg
Locomotion Formula	4x4x4 (wheels x driving x steering)
Suspension	two-bogie w. passive longitudinal differential
Wheels	elastic - titanium alloy
Nominal Speed	440-480 m/h on flat sandy terrain
Power	2x 24V/31Ah LiPo batteries

The perception and navigation sensors (see Figure 2) are in charge of perceiving the external world and acquiring measurements to estimate the rover position and pose.

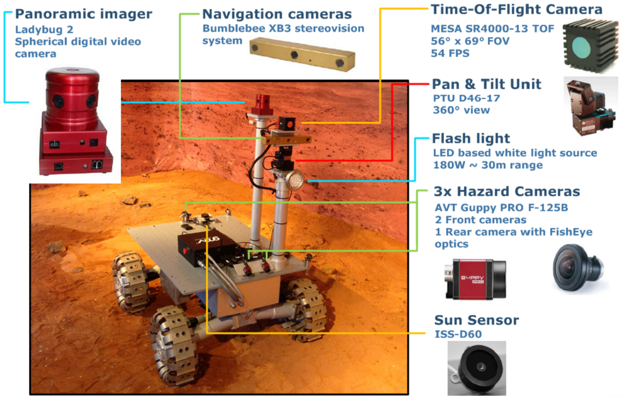


Figure 2. RAT-PFS perception sensors.

The navigation stereo-bench and the TOF camera are both mounted on a Pan&Tilt unit (PTU) unit on top of a telescopic mast. The panoramic imager is mounted on a separate fixed mast, while the set of hazard cameras are placed on the PFS deck (two cameras at the front and one camera at the rear part with a fish-eye lens).

A dedicated analysis for the placement of the perception sensors was performed, with the aim of maximizing the situational awareness for both the autonomous navigation and the teleoperation scenarios. As a result the height and inclination of the hazard cameras was determined to cover the short range (see Figure 3), the stereovision bench and TOF were set to be covering a medium, and partly adjustable, range (by means of a variable height using the telescopic mast). The panoramic imager was placed on an independent mast to cover the long range by offering contextual situational awareness upon request.

As navigation sensors the PFS includes an IMU, a 2-axis inclinometer and a sun sensor.

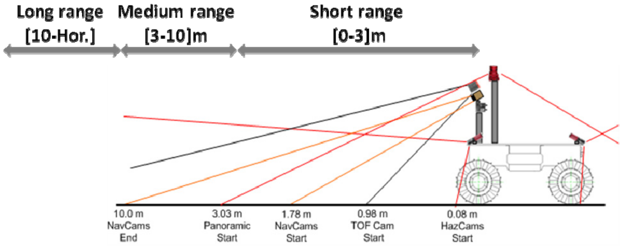


Figure 3. Coverage of RAT perception sensors.

3.1. Data Management System (DMS)

The RAT DMS follows a modular architecture and comprises several modules (Figure 5) built using the GenoM framework [6]. A fundamental component is the Functional Layer Manager acting as a gateway between the GCS and the DMS GenoM modules. It provides the following capabilities: a) decoding of Telecommands (TC), b) acquisition and periodical delivery at 1Hz of housekeeping telemetry and c) interconnection/coordination between the DMS modules.

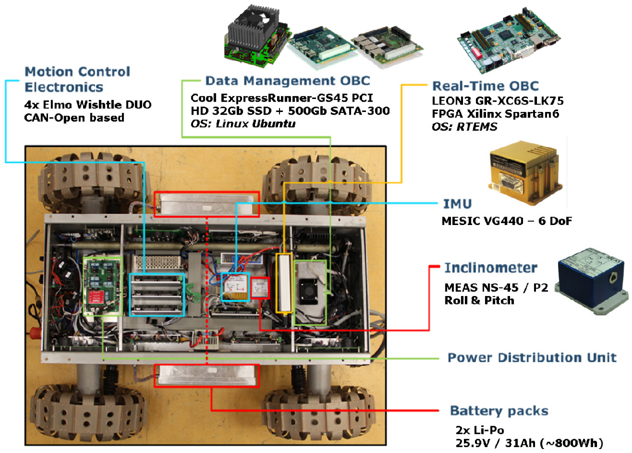


Figure 4. RAT-LRM avionics and navigation sensors.

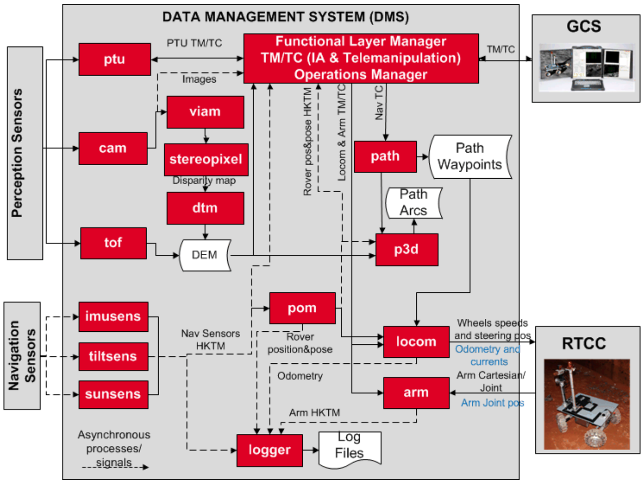


Figure 5. RAT-DMS Software Architecture.

The perception and navigation sensors modules allow acquisition and conditioning of the sensor data as well as estimation of the rover position and attitude:

- *Imusens*: Memsic IMU VG440 data acquisition (Euler angles, angular rates and linear accelerations).
- *Tiltsens*: It measures rover's pitch and roll angles through a dual-axis electrolytic fluid inclinometer.
- *Sunsens*: Azimuth and elevation of the sun.
- TOF: Acquisition of DEM maps generated by the MESA SR-4000 time-of-flight camera.
- *Cam*: Image acquisition of all the PFS cameras: navcams (Bumblebee XB3 stereovision bench), front & rear hazcams (Guppy PRO F-125) and the panoramic imager (Ladybug2).
- *PTU*: Control of the pan and tilt unit (D46-17) hosting the stereovision bench and the TOF camera.
- *Localisation module (POM)*: This module allows to estimate the position and pose of all RAT body frame by acquiring measurements from several motion estimators (see Figure 6) and applying a fast Kalman-like filter.

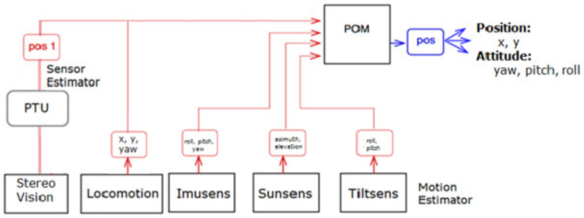


Figure 6. DMS localization modules.

The stereovision tool-chain is composed by three components offering generation of digital elevation maps (DEM) from stereo images: a) Viam as the imaging acquisition module able to acquire left and right images from the stereovision bench, b) Stereopixel for the disparity map computation, and c) DTM as the digital-elevation model (DEM) generation module.

The navigation tool-chain allows finding a path between a starting position and a desired target over the DEM, while avoiding obstacles. Subsequently it decomposes the path into intermediate waypoints and navigates through them. It comprises the following modules:

- *P3d*: Contains the path-planning algorithm.
- *Path*: Is in charge of navigation using the computed waypoints.
- *Locom*: Interacts with the low-level locomotion controller (onboard the RTCC). It commands the different locomotion modes (e.g., single and double-Ackerman, crab and turn-on-spot) and computes the control setpoints.
- *Arm*: This module allows controlling the Rover Robotic Payload (RRP: 5-DOF robotic arm available only in the VFS) either in Joint-mode or Cartesian-based mode.
- *Logger*: Is responsible for time-stamped data logging onboard the DMS.

3.2. Real-Time Controller (RTCC) System

The RAT PFS implements a distributed motion control architecture for low-level axis control over CANOpen, using Elmo's SimplIQ Whistle controllers. The RTCC is responsible for the multi-axis coordination for the PFS over the CAN-bus.

The RTCC is based on a GR-XC3S (45 MHz) board with a Spartan-3 XC3S1500 FPGA using a Leon 3 SoC processor and a CAN IP core & interface. The RTCC software is a monolithic application developed under RTEMS and is decomposed into the following independent tasks:

- *Init Locomotion Task*: Non-periodic task in charge of initializing all internal data structures and also initializing the communication with the Elmo Whistle controllers. It is only being executed during initialization (homing of steering wheels) and every time that the locomotion mode changes from Standby to Interactive Autonomy or Teleoperation modes (see Section 6.4).
- *LRM OBDH Ethernet Task*: Is responsible for interfacing with the DMS computer. It receives high-level motion commands (at maximum 20Hz) and transforms them into messages to be transmitted over the CAN bus to the Elmo controllers.
- *LRM HK Task*: Is a housekeeping task generating telemetry (TM) messages to the DMS with rover locomotion data (e.g., velocity, position of axes) using a UDP/IP socket.
- *OBDH CANBUS Task*: Is in charge of forwarding CAN Bus messages to Elmo Whistle controllers. It also useful also as a monitoring tool, checking fault messages on the CAN bus.

3.3. Reference Frames Definition and Calibration

The main RAT Cartesian reference frames are depicted in Figure 7. These frames are defined from the point of view of an observer placed on the rover's guiding point, which is the geometric centre point of the rover chassis.

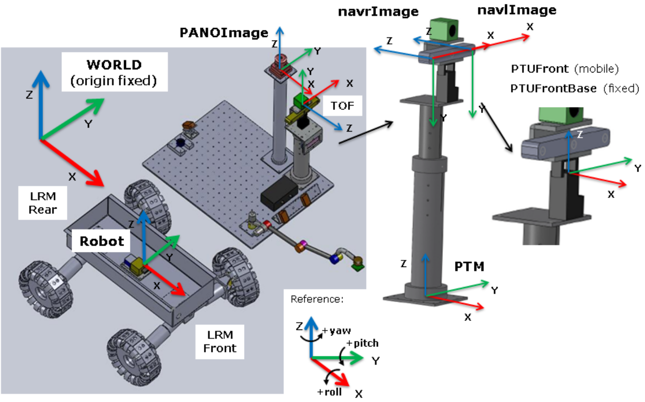


Figure 7. RAT-PFS main reference frames.

In order to precisely determine the location and orientation of the different reference frames separate calibration procedures were defined and executed for the internal elements, the external sensors and steering wheels zero-position. The Nikon K600 optical system was used for the calibration.

The Robot frame was defined using the front plate screws together with the PFS roll longitudinal axis. All the support plates of the perception and navigation sensors were precisely engraved with calibration points to allow the placement of the K600 space probe tip. The wheel steering calibration was performed using metallic frames mounted over the rover's wheels. Finally, an automated process was developed to read all the measurements of the reference points and compute the geometry defining the reference frame positions and orientations.

4. VIRTUAL FLIGHT SEGMENT (VFS)

The driving philosophy behind the VFS is to obtain a tool that provides the means to effectively support the development and the operations of the mission at hand. High level design requirements of the VFS include the following:

- *Generic end-to-end simulation capabilities*. For assessing the design on a system or mission level, the VFS environment must be flexible and generic. It must be able to simulate a mission scenario from the early stage of its definition until its completion. Thus it is essential to have the capability to incorporate models of robotic systems and scientific instruments interacting with the virtual environment to simulate the daily operations and scientific outputs of a given scenario. Finally, the RAT VFS shall represent and support the Moon planetary environment.
- *Same behaviour and interfaces with the PFS*. The rehearsal of the operations using the real hardware is a time consuming task. The VFS shall be able to substitute the PFS and allow a realistic training of the operators. In addition, during operations, the VFS shall support the validation and the predictive simulation of the commands to be executed by the PFS. This provides the operator with the necessary confidence and allows him to anticipate on safety critical situations.

To this end we use the 3DROV tool [7] dedicated for simulation of planetary rover operations. It provides the needed infrastructure and a set of models and tools that allow a) to represent a virtual robotic system in its environment and b) to simulate operations of the robotic system in interaction with the considered environment.

The 3DROV is instantiated for the RAT-PFS robotic system operating in a Lunar environment. The following models have been implemented:

VFS MODELS	
ROVER VEHICLE	LRM kinematics and mechanical dynamics; motors dynamics.
IMU	Model of the processing chain including temperature impact, errors and noise.
SUN SENSOR	Transformation of the global sun angles to azimuth and elevation wrt the sensor frame.
INCLINOMETER	Model of the processing chain including models of errors and noise.
ROBOTIC ARM	RRP kinematics and mechanical dynamics; motors dynamics.
MAST	Mast kinematics.
PANORAMIC IMAGER	Resources consumption and images generation.
3D TOF CAMERA	Resources consumption and DEM generation.
POWER	Solar panels, battery and electrical network models.
COMMUNICATIONS	Rover, lander, orbiter and ground communications data fluxes.
DATA HANDLING	Memory mass management and processing units power consumption.
CONTROLLER	Use of the PFS on-board controller with interfaces to the motors and sensors models.
ORBITAL & TIMEKEEPING	Solar, planetary and orbiter ephemerides
ATMOSPHERE	Moon atmospheric conditions.

Figure 8. The VFS models.

The *Environment models* introduce the environmental conditions in which the RAT operations are performed. In particular:

- The *Orbital and Timekeeping model* keeps track of solar, planetary and orbiter ephemerides, line of sight conditions, and solar time. It is typically used by the 3D Visualisation tool to compute on-line the shadows, by the solar panel model to retrieve solar angles, by the onboard radio communication software to retrieve rover-orbiter or orbiter-Earth viewing geometry and communication lags. The component is based on the NASA/NAIF Spice Toolkit.
- The *Atmosphere model* provides data on the planetary atmospheric conditions: solar flux, surface temperatures and ground emissivity are computed by the sun position and derived by data sources such as the DIVINER Lunar Radiometer Experiment. These magnitudes are essential for other sim-

ulation modules such as the cameras, the thermal s/s models, and the solar panel models.

The *Rover Models* include models of the physical system, e.g. rover mechanical platform, motors, sensors, etc. They are mainly modelled in the 20Sim engineering tool and they comprise C/C++ code. In view of the simulation objectives, the considered models include the kinematics/dynamics models of the rover platform and the robotic arm, the power, communications and data handling s/s's models, etc.

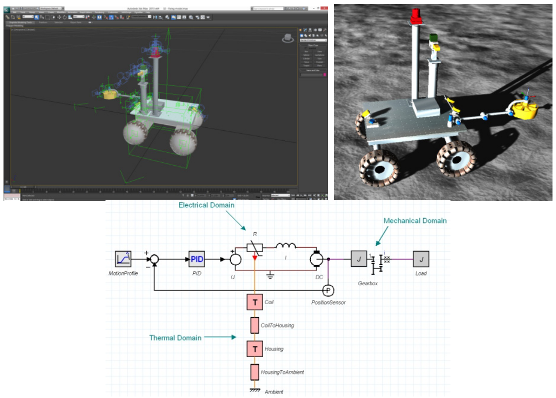


Figure 9. a) The rover mechanical dynamic model is based on Bullet b) 20Sim is used for the motors and sensor electrical and the thermal dynamics.

The rover model includes also the models of the IMU, the Inclinometer the Sun sensor and the Camera sensors. In particular, the output of the IMU and the Inclinometer models is computed based on the position, speed and acceleration of the corresponding bodies as provided by the rover mechanical dynamic model and the characteristics of the particular devices (bias stability, angle random walk, bandwidth, etc). The sun sensor model receives from the environment model the sun angles (azimuth and elevation) expressed wrt to the global frame of the terrain patch that the rover is traversing and transforms them to the rover body frame (Robot frame in *Figure 7*). Finally, all cameras are modelled to provide power consumption, data rate and thermal information function to their operational mode. Images and TOF DEMs are generated by the 3D Visualisation component.

The rover model is completed with:

- The *Power system model* that predicts the instantaneous energy flow in the power conditioning and distribution network in terms of current, voltages and losses at each relevant node.
- The *Communications s/s model* which simulates the data flux between the Rover, the Orbiter, the Ground and a data-relay Moon station according to a selected communication scenario. The available commuication windows, the relative position between Rover-Orbiter-data relay Moon station-Ground, and the communication hardware are also parameters of the model.
- The *Data Handling model* simulates the data flux and storage within and between the Rover subsystems (e.g., equipment, payloads, data generators, processors and communication s/s) as well as the power demand of the corresponding units.

The *3D Visualisation component* is used a) for visualizing in 3D the evolution of the VFS models b) as an integrated component of the rover model and the controller model providing information related to the rover dynamics and the physical contacts (terrain interaction), and finally c) as a synthetic images generator to feed vision based algorithms. The Moon South Pole terrain has been used a reference mission scenario from the ESA Lunar Lander mission study. It has been reconstructed and integrated into the VFS using the Lunar Orbiter Laser Altimeter (LOLA) data; to visualise so large terrains GPU-based geometry clipmaps strategies are used.

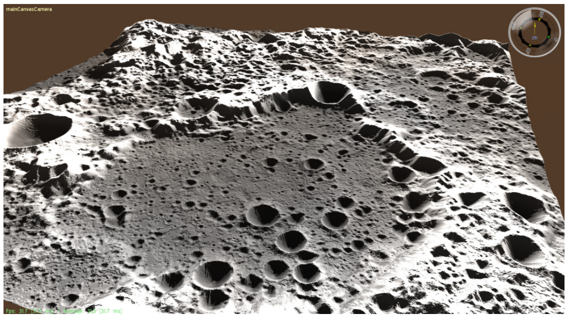


Figure 10. The South Pole terrain as extracted by the LRO data (85deg South - 5m/pixel, 180Km).

The *Rover Controller model* consists of a copy of the RAT DMS thus providing the same functionality and TM/TC interface to the Ground Segment as the PFS. The DMS temporal characteristics are based on the simulated time while dedicated stubs named as the Virtual Devices Access library (VDAL) interface with the simulated models. The VDAL is based on Remote Procedure Calls (RPC) using a XDR file for the definition of the robotics perception and actuation interfaces.

5. GROUND CONTROL STATION (GCS)

The RAT Ground Control Station provides an end-to-end system for specification, validation by simulation, monitoring and control of rover operations. It supports both Interactive Autonomy (IA) and Telemanipulation operational modes:

- In the IA operational mode the robotic activities are executed on-board under the supervision of the on-ground operator.
- In the Telemanipulation operational mode the operator extends his manipulation and sensing capability to the remote location using a master device that remotely controls the rover located at the operations site.

The RAT GCS is based on the ESA DREAMS system [10] mainly used for space payload servicing applications [8], [9]. In the context of the RAT developments we focused on:

- The customisation for rover operations.
- The re-engineering of the DREAMS system to use modern frameworks such as Eclipse RCP.
- The identification, the development and the assessment of dedicated functionalities to improve the operators' situational awareness.

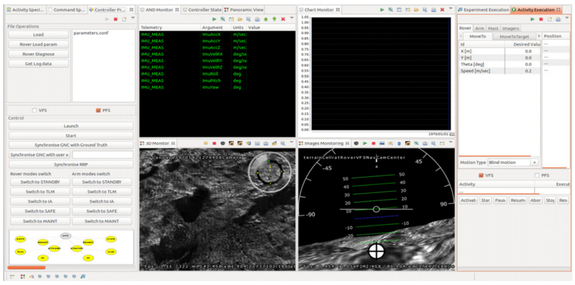


Figure 11. The GCS views during the Utilization phase.

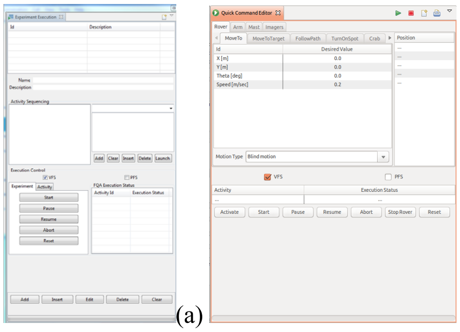
5.1. Architecture

The RAT GCS consists of a set of communicating components presented hereafter. The *Configuration component* allows to configure through dedicated MMIs elements of the different components of the RAT system including:

- the GCS components (characteristics of the cameras to be monitored, information for connecting with the GCS database, TM XML description, ...),
- the PFS/VFS Controller including parameters of the controller modules ranging from general ones such as the log level and the log directory to more specific ones, such as the IMU Sensor integration mode,
- the distribution of the DMS modules execution between on-ground and on-board (see section 6.3)
- the Communication Tweaker.

We use the *Activity Preparation component* for the specification and validation through simulation of new Activities and Activity Plans. The Activities are instances of user defined Template Activities while Activity Plans are specified as sequences of Activities.

The *Activity Execution component* allows the execution and supervision of the prepared Activities and Activity Plans. In addition, via the 'Quick Command Editor' the operator has access to the most frequently used Activities with the possibility to set their parameters and request their execution. To facilitate the parameters specification, dedicated areas visualise relevant TM issued by the targeted controller. User defined annotations of the 3D scene (3D Monitoring component) such as paths and target points may be referenced as parameters and automatically translated into their numerical values.



Id	Desired Value
X [m]	0.0
Y [m]	0.0
Theta [deg]	0.0
Speed [m/sec]	0.2

Motion Type: Blind motion

Figure 12. a) The Activity Plan Execution View b) The 'Quick Command Editor'.

The *3D Monitoring component* visualises in a synthetic scene the rover and the environment in which it operates. The synthetic representation of the terrain is enhanced on-line using the newly downloaded DEMs. At any moment the operator may annotate the scene by adding forbidden areas or areas of interest, paths and targets. The paths and the targets may be used as parameters for the execution of Activities or as aids for telemanipulation. In addition, if predictive simulation is active, a 'phantom' rover is also displayed in the scene.

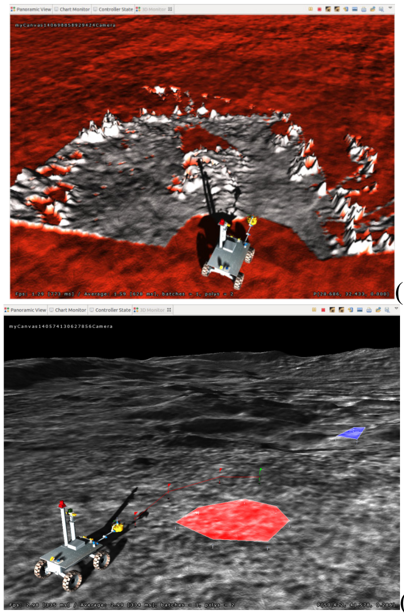


Figure 13. The 3D Monitoring component View a) terrain enhanced with downloaded DEMs b) 3D scene annotated with areas and paths.

The *Images Monitor component* displays, on dedicated MMIs, images grabbed by the RAT PFS/VFS imaging sources. The operator may configure the images monitoring process (selection of the camera source), set the image characteristics (e.g., quality between high, medium and low), request to start/stop the video source image acquisition.

To improve the operators' situational awareness the system provides the possibility to overlay visual cues on the real images. They indicate the heading and the inclination of the rover as well as the distance and the direction to the next target.

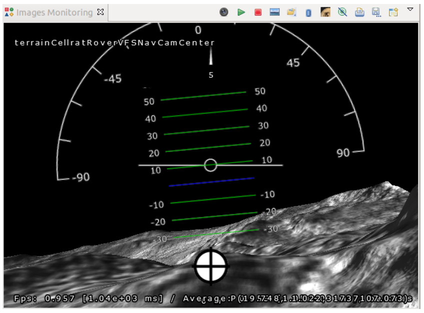


Figure 14. The Images Monitoring component View with overlayed visual cues.

The *Telemanipulation component* allows to configure and teleoperate the rover and the arm using hand controllers. To decrease the operators' workload during telemanipulation, the system provides the possibility of 'gesture aids' that allow to specify constraints on the requested motion: the outputs of the hand controllers are filtered to allow only a straight motion or a turn on spot or to follow a predefined path in the scene.

The *2D Monitoring component* visualizes TM parameters received by a targeted controller and alerts the operator in case of predefined range violation using alphanumerical, chart and state machines displays.

The *Data Base Server component* manages the database where the Activities are stored and organised in experiments.

Finally, the *Data Handling component* provides the internal ground station components with a unique access to the TM/TC of the PFS and the VFS. The communications status is continuously monitored and visualised.

5.2. GCS Hardware and MMIs

The GCS hardware comprises two workstations and several MMI devices. One of the workstations is specifically equipped for high performance 3D visualization. The second workstation runs functional layer components and parts of the simulation system. The layout of the GCS is a result of a trade-off between functionality and portability. The former incorporates situational awareness and operator comfort while the latter enables the system to be easily transported and installed at a field-testing site.

The following GCS hardware elements are depicted in *Figure 15*:

- Workstation 1 (ACME Seahawk 100) for the main GCS software and visualization components.
- Workstation 2 (Kontron CB753) for the VFS.
- MMI devices: Joystick, gamepad, space mouse and mouse.
- WiFi access point router and Ethernet switch.

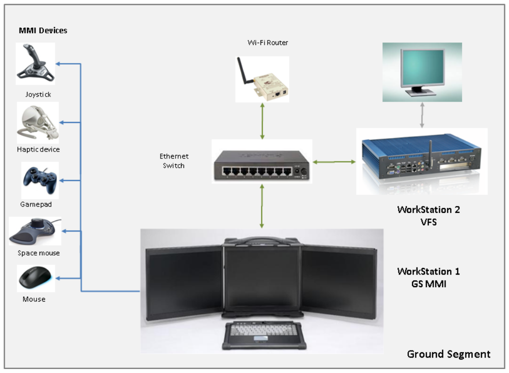


Figure 15. The RAT-GCS equipment.

6. COMPONENTS INTEROPERATIBILITY, OPERATIONAL MODES AND AUTONOMY

6.1. Components interoperability

The RAT is intended for robotics design engineers as a high-fidelity investigation, testing and validation environment, It enables space robotics mission elements to be integrated, exercised and assessed following a two-step philosophy: a) Simulation (via the VFS) where all electro/mechanical and HW devices are modelled in SW and b) HW-based setup (via the PFS) where a real tesbed is used in a planetary exploration scenario.

The RAT allows investigation of the different robotics design options from an autonomy viewpoint but also from system and mission viewpoints (e.g., perception devices, navigation approach, etc.) in order to perform trade-offs and quantify the impact of each element in the system performances and and budgets.

6.2. Communication Tweaker

The Communication Tweaker is an intermediate software module that runs on the GCS and acts as a transparent filter and simulator of customized communication conditions between the GCS and the PFS/VFS (depending on the mode).

The tweaker provides the following capabilities: a) Configurable delay of forwarded telecommands and telemetry packets, b) Individual shaping of the network bandwidth (uplink/downlink) through wired Ethernet interface eth0, and c) Configurable randomized dropping of telecommands and telemetry packets.

This module allows configuring different scenario conditions, for example:

- ISS vs. Moon-based communications (delays from 0.1s up to 4s and drop rates from 1% up to 5%).
- Direct link Rover-Earth (100 Mbit/s).
- UHF link rover-Lander (0.1 Mbit/s for housekeeping data, 0.9 Mbit/s for scientific data).
- X-band link Lander-Earth (1 Mbit/s for telemetry and 10 Kbit/s for telecommands).

6.3. Seamless transition of components

All the RAT segments (PFS, VFS and GCS) include a functional layer based on DMS components. Within the the RAT we are able to seamlessly transfer functional layer software components from on-ground to on-board and vice-versa without source code modifications. This enables us to modify our operations strategy on the fly based on available resources.

Figure 16 provides a schematic example of mapping and navigation components moved on-ground while leaving on-board the rover only basic motion control abilities.

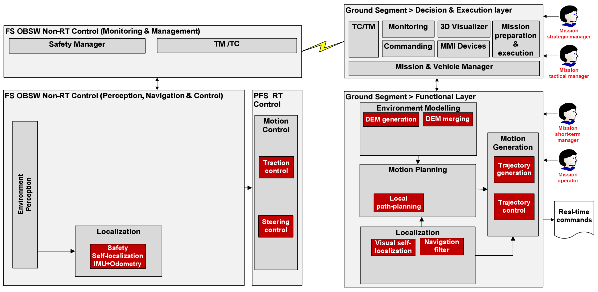


Figure 16. Seamless transition of components.

6.4. Operational Modes

Four main have been defined for the RAT enabling safe and robust operability of the system. Figure 17 depicts the modes and the allowable transitions.

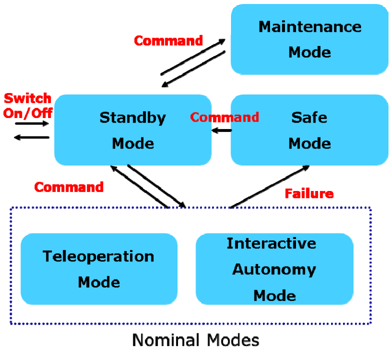


Figure 17. RAT operational modes.

The following modes have been defined:

- *Standby Mode*: The rover remains in a secure state with minimal operational capabilities enforcing minimum energy consumption.
- *Maintenance Mode*: The user will be able to select the maintenance mode only from standby state. In this mode, the rover is running only the minimal infrastructure to communicate with the outside world and will permit on-board software reconfiguration and modification
- *Safe Mode*: When an abnormal condition is detected by the on-board safety manager the rover is safely stopped and goes into this mode. All motion and processing modules are turned-off, however the operator can perform diagnostics.
- *Nominal Mode*: The main mode for operations. It is split into two sub-modes: a) Interactive Autonomy using GCS TC's and b) Teleoperation using MMI devices.

Transitions between modes occur either by ground command or by internal conditions that trigger a state change.

7. SYSTEM INTEGRATION AND FUNCTIONAL VALIDATION

The RAT system has followed an incremental and iterative integration, verification and validation process due to the complexity of the system. Initially the software elements were integrated applying a two-fold approach: RTCC with DMS and VFS with GCS). Subsequently the DMS VDAL was used as bridge between PFS and VFS and by means of several collocations between GMV and Trasys the system evolved through different stages: a) laboratory, b) operations and c) Test Readiness Review (including an extensive set of verification test cases at unitary and system level).

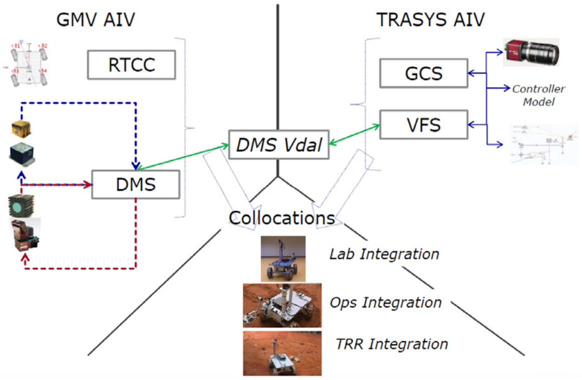


Figure 18. RAT AIV Process.

Finally, during the Factory Acceptance Test the RAT was validated functionally with the purpose of demonstrating its teleoperation capabilities and the following experiments were carried out:

1. Teleoperation of the RAT in a Moon South Pole using solely the VFS.
2. Mapping of GMV Mars yard: a) Incremental mapping of the environment using DEM import, b) Correction of rover position and pose (FARO laser system)
3. Teleoperation of RAT under low lighting conditions using different illumination sources (2KW external spotlight; RAT 85W LED lamp; and complete darkness).
4. Scientific goal discovery of hidden items within the GMV Mars yard keeping the operator isolated at the Control Centre and without direct view of the rover operating only through GCS data.

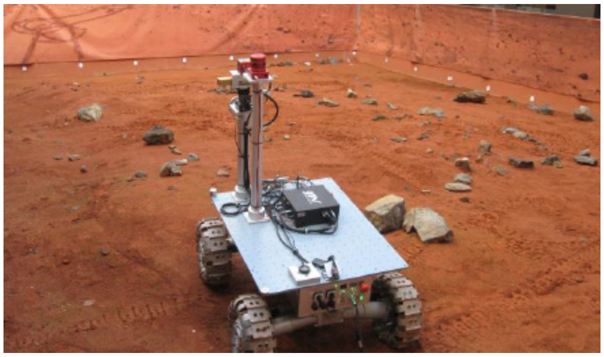


Figure 19. Scientific goal discovery experiment at GMV Mars yard.

8. CONCLUSIONS AND FUTURE WORK

The Rover Autonomy Testbed implements a novel and multifunctional testbed for planetary robotics research and development activities. A major success of the RAT lies on the fact that numerous tools and systems –ESA and non-ESA developed– were integrated into a rover testbed: the GenoM framework, the 3DROV environment, RTEMS, CANOpen IP cores, the Lunar Rover Model platform, just to name a few. This showcases and proves the incremental research and development approach needed in the field or (space) robotics in order to obtain fully operational systems. A novelty of this activity is that alongside a very complex physical rover platform an identical virtual was developed, which can assist experiment execution, mission rehearsal and can act as a predictive simulation tool without long preparation and setup overheads.

Besides arriving at a multi-purpose and robust testbed, the RAT development has provided invaluable experience to both the industrial partners and the Agency on the system engineering challenges involved.

Some key lessons learned from the RAT activity are captured hereafter. Due to the complexity and the broad scope of the project, a "Waterfall" development approach proved to be inefficient. It is recommended to consider a hybrid "Agile-Waterfall" approach in order to have an iterative development basis and ensure that the customer needs are captured as the project evolves. While developing the RAT, newer more modern and powerful robotic frameworks emerged (e.g., ROS, RoCK). Though the GenoM framework proved to be very suitable for the application, it has not been widely adopted by the user community and this creates a concern on the maintainability/extendibility of our system. Having spacious and well-instrumented lab facilities proved to be of paramount importance for the RAT development, showing that one should consider well in advance the tools and facilities needed for such development. Furthermore, it is strongly advised that numerous co-locations of the developing parties are planned and budgeted early on in the project. Finally the ultimate verification of such systems should happen through a multi-day field test campaign preferably in an unknown outdoors environment.

As the basic development stage of the RAT just concluded, the future work includes heavy utilization, experimentation and design modifications where needed. Some immediate plans include investigation of interfacing the DMS with the RoCK framework, integration of the GOAC controller to the system and a field test campaign in the CNES SEROM Mars yard.

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