3D BASED ROVER OPERATIONS CONTROL SYSTEM

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ABSTRACT

This paper presents the 3DROCS system that is under development at TRASYS in the framework of the 'Ground Control Station For Autonomy' ESA GSTP Activity.
3DROCS aims to support rover planetary exploration operations. The main objectives are to reduce the tactical planning process time, to increase the user awareness on the system behaviour, to improve the Activity Plan understanding and to provide a unified interface for strategic and tactical planning.
To this end, 3DROCS exploits as much as possible the spatiotemporal nature of the rover operations since the location on the planet and the time an operation is executed shall be jointly considered during operations specification and data analysis. 3DROCS proposes: a) the specification of the Activity Plans in a graphical 3D synthetic world as a network of interconnected 3D objects representing the rover Activities b) advanced situational awareness during planning c) possibility for concurrent edition of Activity Plans in a shared 3D environment d) on-line continuous simulation of the Activity Plan during specification and finally a set of 3D based displays for data monitoring and analysis.

1. INTRODUCTION

When controlling from ground rover surface operations for planetary exploration two different operations processes take place simultaneously:

– Strategic Operations Process, with a characteristic time of several sols up to several weeks.
– Tactical Operations Process, with a characteristic time of a few sols.

Next figure shows schematically the tactical and strategic time span on a timeline with several sols, for a sample "soly" tactical cycle.

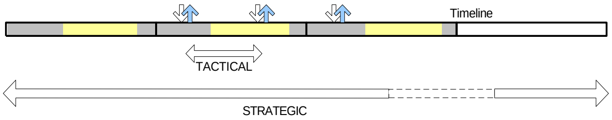


Figure 1. System Tactical and Strategic Operations Processes on a timeline

The *Strategic Operations Process* mainly includes the following activity:

– Mid-term science objectives definition fed to the Tactical Operations Process. These objectives can be formalised in a Strategic Activity Plan.
– Tracking of the Mission scientific goals achievement.

The *Tactical Operations Process* is composed by several steps which the timeline is illustrated in Figure 2.

1. Initially, the downlinked TM is acquired and processed in an automatic way under the responsibility of the 'Downlink Supervisor' team generating engineering and science data.
2. The generated data is assessed, in parallel, from an engineering and scientific point of view. The Rover Engineering team assess the rover housekeeping system data. Housekeeping TM, navigation data, localisation data and images, are analysed with specific tools. The status of the system is derived and added to the database to be available in the next phases.
   In parallel, the Science Support team analyses the science products and images and assess the scientific objectives.
3. Afterwards, rover engineers and scientists work in parallel, with limitied interaction, to specify Preliminary Engineering Activity Plans.
   The Rover engineers define the basic Rover activities for the next planning period (e.g. on/off and communication activities depending on the input Events and Communications data), and any other required maintenance engineering activity. The result is an Events and Communications Skeleton (with fixed activities) and a Preliminary Engineering Activity Plan.
   In parallel, the scientists start specifying their science requests. They do it firstly independently or within the Science Operations Support Team. In a second step all science requests are put in common and re-prioritised to generate a single Preliminary Science Activity Plan.
4. Once all the Preliminary Activity Plans are proposed, the Tactical Activity Planner receives and merges them to generate an Activity Plan consisting in a timeline of Activities that "optimises" the Plan according to a given criterion (e.g. priorities) and fulfils all constraints.

As a result of the planning, a Nominal Activity Plan is generated, along with alternative and contingency sequences.

5. Finally, the Rover Integrated Planning Team generates the Command Products and validates them using the simulator. This step is done iteratively to generate as final output a complete set of validated Command Products that are uplinked to the flight segment.

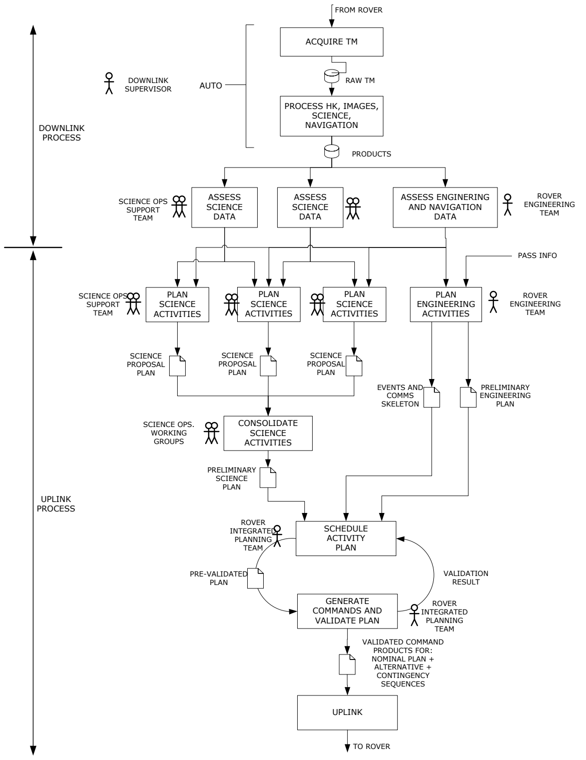


Figure 2. System Tactical Operations Processes on a timeline

As a result of the described operations process a Rover Operations Control System (ROCS) is designed as a set of interoperating modules as represented in Figure 3. We briefly present each of them.

TM Acquisition and Processing. This module receives the TM packets and processes them to the appropriate level to generate products to be further analysed by the engineering and science teams.

Rover HK Data Assessment and Planning. This module allows the Rover engineering team a) to analyse the Rover system status, b) to specify a Communications and Activities Skeleton Plan, and c) to provide a Preliminary Engineering Plan with engineering activities.

Science Data Assessment and Planning. This module allows the scientists a) to analyse imagery and instruments products to identify potential scientific targets and b) to define the activities they would like the Rover instruments to execute, how to execute them and under which conditions.

The **Rover Planning** contains the modules for the uplink part of the Tactical Operations Process:

– Activity Planning. It is the module used to integrate all science and engineering activities and schedule them in a semi-automatic way so that constraints and resources are respected
– Activity Plan Validation and Command Generation. This module provides the tools for the translation from activities to command products to be uplinked.
– Robotic Visualisation and Planning. A high fidelity 3D representation of the actual Rover environment and its simulated state.

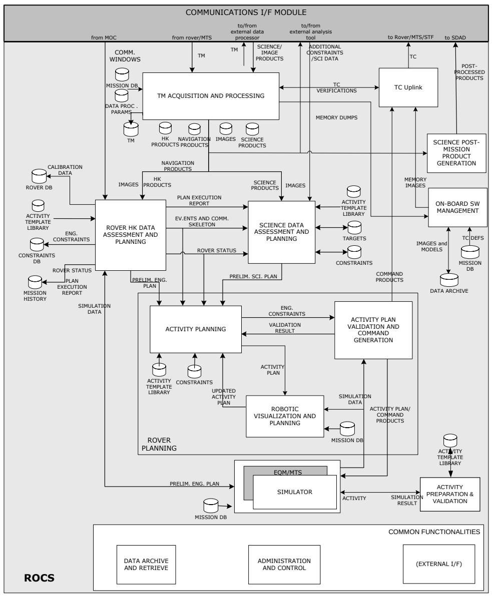


Figure 3. ROCS High level architecture

TC Uplink. This module covers the uplink process of telecommands and activities.

Operational Simulator. It is used to validate the generated command products before uplink. It is able to simulate the Rover kinematics, dynamics (including environment interaction), movable subsystems dynamics and on-board sub-systems models (thermal, power). It can simulate the on-board software on a dedicated emulator.

2. 3DROCS SYSTEM OBJECTIVES

3DROCS is designed in the context presented here above. The main objectives are to reduce the tactical planning process time, to increase the user awareness on the system behaviour, to improve the Activity Plan understanding, to support Activities specification and validation, and to provide a unified interface for strategic and tactical planning. These aspects are further discussed in the following two sections.

2.1. Reduce the Tactical Planning Process Time

In the typical tactical planning process, Activity Plans are constructed by individual users without the possibility to validate them locally and without any information about the plans proposed by the other users. In addition, the final integration into a single, base line plan for the next sol starts only after all the individual plans have been submitted. This implies:

- Many changes in the plan occur at the late stages of the process while the users are unable to understand whether or not their activities are included and if not why they have been rejected.
- Accentuates the possibility of initial bad rover plans since they are proposed without any information about the plans proposed by the other teams. This increases the time needed to synthesise and validate the final plan.
- The sequential approach of synthesizing the final plan after all individual plans have been submitted, increases the global planning time.

As the full process shall be performed in only a few hours, an efficient planning needs to be performed so that the final plan would only require major rework in exceptional cases. This can be achieved by introducing in the planning process the following:

- **Collaborative work**: All users may work in a shared area where the published Activity Plans can be seen by all, and each user can complete the plan specification if needed.
- **Efficient any time simulations**: each user should be able to simulate in depth the Activity Plan under specification in order to validate it and most importantly to better understand it.
- **Mixed initiative planning approach**: following the approach the role of a human actor in the planning loop is absolutely desirable. So, the collaboration between the automatic planning processing and the user manual and interactive planning shall be considered.

3DROCS supports these aspects providing:

- A distributed collaborative system.
- Integrated in the tool efficient simulators.
- Simple to use mechanisms for exchanging Activity Plans with the Activity Planner with possibility to edit and rehearse them.

2.2. Improve the Activity Plan Understanding

During the planning process, the most important point to be achieved is good situational awareness by the operators (scientists and engineers) enabling proper decision-making and efficient planning. The situational awareness that is necessary at several stages of the process includes:

- The possibility to easily access and afterwards assess the downloaded data in an efficient way. This includes a combined visualisation of the data that cover all the important variables of the behaviour to be analysed and understood. **Visualisation into a 3D environment** is an important aspect since the rover operations and the behaviour of the different sub-systems are greatly influenced by the environmental conditions. For example, the level of the solar power generation can be better understood if the position/attitude of the rover on the terrain is visualised in addition with the solar panels configuration and the sun position.
- Understanding of the Activity Plan(s) being created whether manually or by means of an automatic planner. Activity Plans is the result of a complex automatic or human reasoning finding a valid schedule for the activities that are related by constraints from various sources: energy limitations, communication opportunities, flight rules, etc. The incorporation of the Activity Plans into the 3D visualization environment and the rehearsal of the plan is the most appropriate way for the operator to understand for an Activity Plan the scheduling choices that have been performed and the available margins for improvement. In this way the Activities of the plan are represented as active 'glyphs' that when activated can rehearse the corresponding rover operation. The same mechanisms allow to asses already executed or simulated Activity Plans and analyze the choices taken on-board. By incorporating different Activity Plans side-by-side there is the possibility to compare them.

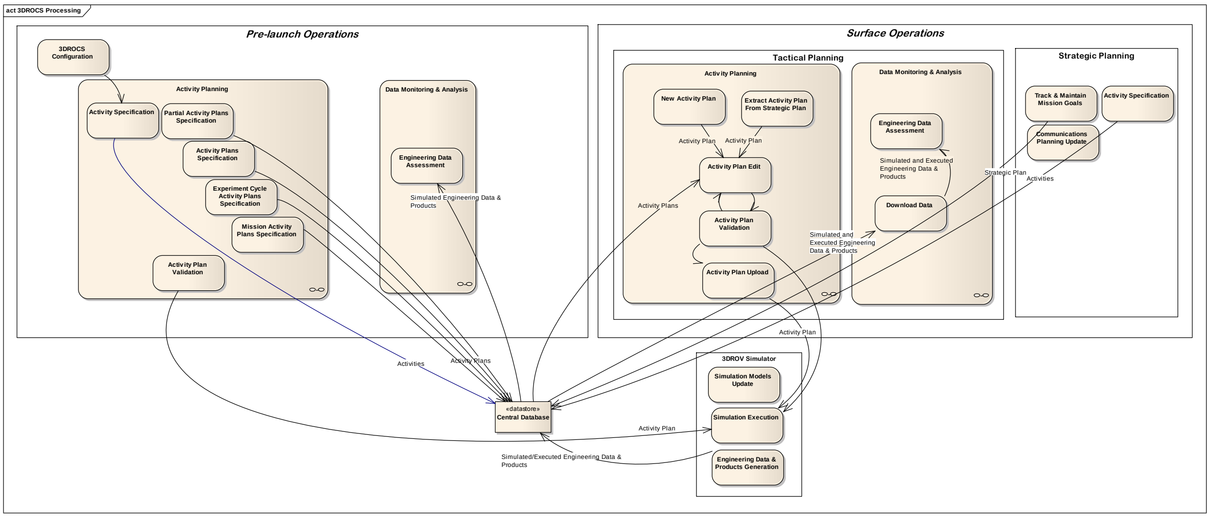
3. 3DROCS ORERATIONS CONCEPT AND GLOBAL ARCHITECTURE

3DROCS focuses in two phases of a planetary exploration mission: *the Pre-launch phase* and the *Surface Operations phase*.

During the Pre-launch phase the main activities in the scope of 3DROCS are:

- The **specification of the rover Activities:** Activities are the building blocks for commanding the Rover. 3DROCS provides the necessary MMIs to specify Activities that are later used to construct Activity Plans (see section 4.1).
- The **specification and the validation of Activity Plans** that implement part of an experiment. Activity Plans are specified as a network of Activities. To this end, 3DROCS provides a 3D-based Activity Plan Editor (see section 4.2). The specified Activity Plans are used a) as building blocks to specify the Experiment Cycles in the form of sequences of Activity Plans or as template Activity Plans that are adapted and reused during operations to facilitate the Tactical Planning.

- The **preparation of Tactical and Strategic Plans.** The specified Activity Plans and the Experiment Cycles are composed in long term **Strategic Plans** that implement the mission objectives. These Strategic Plans are used during operations as guidelines for the operations and support the tracking of the mission goals.
- The **support for closed loop operations rehearsal**. The Activity Plan is translated into command products that are simulated. In 3DROCS, the 3DROV simulator is used for this purpose.



During the **Operations phase** the main activities in the scope of 3DROCS are:

- **Engineering Data Assessment**. Activity execution status, housekeeping TM, navigation data, localisation data and images, health status vector, etc. are analysed on dedicated MMIs. 3DROCS provides 3D based chart, alphanumeric, synoptic and images displays that allow to visualise the downloaded data, to analyse them in relation to the location and the time they have been produced, to replay them and to compare them with the simulated data (see section 5). Finally, the engineering data produced by the validation (simulation/testing) of Activity Plans may be used during operations for the analysis of the real data and for the tuning of the simulation models.
- **Tracking and updating the mission goals**. The Strategic Plans specified during the pre-launch phase are updated wrt the executed parts of the mission and possibly adapted to the new situations discovered during operations. In this way the operator tracks and updates the mission goals. In 3DROCS, this is performed using the Activity Plan Editor that provides the necessary mechanisms (e.g. grouping, ungrouping, coherency checking) to facilitate the editing of complex Activity Plans.
- **Activity Planning**. The operator specifies the Activity Plan to be uploaded and executed for the next sol(s). 3DROCS supports manual planning and provides the operator with the following possibilities: a) Extract from the maintained strategic plan the part to be executed during the next sol(s) of interest. b) Use one or more Activity Plans, already specified during the pre-launch phase, as basis for the planning. c) Create and edit a completely new Activity Plan by adding and interconnecting Activities.
- **Updating the models**: As a result of the Rover data assessment it shall be possible to update Rover models, like for example resource usage models, physical parameters, newly derived constraints, etc, all of them having an impact in the Tactical Operations Process.' 3DROCS supports this activity by providing 3D graphical displays for the analysis and the comparison of simulated vs executed data

The ROCS system is organised in a set of Planning and Data Monitoring and Analysis components presented in the following two sections (section 4 and section 5).

4. PLANNING

4.1. Activities Specification

Activities are the main entities handled by 3DROCS: experiment cycles are described as a sequence of Activities to be executed, Activities are used by the Activity Planner to produce the plan to be uploaded, when uploaded they are understood and executed by the on-board mission management system.

3DROCS provides the operator dedicated HMIs to define the set of Activities to be considered. They are characterised by:

- A uniquely defined identifier
- A set of parameters defined by their id, their type, their size, their validity range and a short description. Application dedicated types are considered.

- A set of events; pre-conditions, post-conditions, and exceptions are considered.
- Information indicating the products to be produced during the Activity execution, their type and size as well as their downlink priority.
- Information related to the 3D representation of the Activity
- A short description.

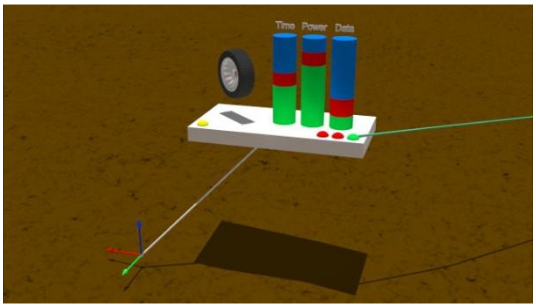


Figure 4. 3D View of an Activity

The 3D representation of an Activity is a user defined 3D object with a standardized shape that allows to:

- Easily identify the subsystem related to the Activity and the objectives of the Activity.
- Facilitate the connectivity between Activities. Input/output ports represent the Activity start and its possible ends.
- Visually represent the required resources. Duration, power and memory mass consumption are considered.
- Visualise the start and end time of the Activity
- Visually represent the location on the planetary surface the Activity is expected to take place.

4.2. Activity Plan Specification

3DROCS provides the operator the means to sequence Activities and already defined Activity Plans in order to specify a new Activity Plan. The operator, in the 3D canvas, manipulates graphically Activities, Activities inter-connections and group of Activities. In particular the operator has the possibility to:

- Select an Activity from the Activity Specification component and to insert it into the Activity Plan Editor. Drag and drop operation on the Activity Icon is supported.
- Indicate the location the Activity takes place by connecting the 'location port' of the Activity to a point of the terrain using a line segment. A circular area around the location is created allowing latter the operator to easily select it and to graphically relocate the Activity by dragging on the terrain the location area.

  The Activity related to the Travel operation is located in a specific way by indicating the starting location, the final location and optionally the intermediary way-points to be visited. In this case the location area is a polygonal oriented shape the intermediate nodes of which represent the waypoints and the extreme points represent the start/end travel positions. This polygonal representation may be reshaped by the operator using the usual controls (add, move, delete node). Alternatively, the operator may request the automatic computation of the path of the Situational Awareness component.
- Connect an output port of an Activity with the input port of one or more other Activities using oriented line segments indicating the precedence order of the Activities execution. A connection may be edited or removed.
- Group graphically a set of Activities under a single name. The created Activity Group is represented graphically by an automatically created 3D representation including the external input/output ports and the resources corresponding to the most 'expensive' execution path. The initial conditions of the Group are identified automatically by the state of the subsystems at the last Activity(s) that precede the Group.

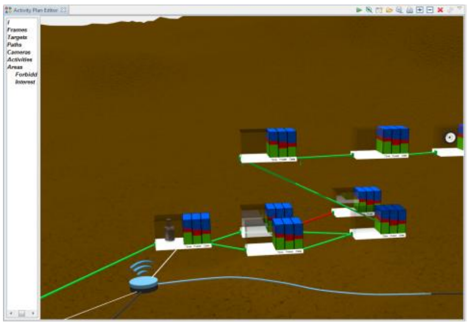


Figure 5. Activity Plan Editor

4.3. On-line Activity Plan Simulation

The Activity Plan under specification is continuously simulated. Every change in the Activity Plan specification that affects the simulated results initiates a new simulation to update the estimation of the required resources.
The state of the simulation is reflected in the Activity Plan Editor. In particular, the system:

- Updates the displayed level of resources of the Activity Plan following the simulation results.
- Highlights the paths that have been simulated.
- Visualises the communication windows together with the downloaded products.
- Visualises the significant ephemerides events.
- In case of failure indicates the executed path, the last Activity that has been executed and the reason it failed.

4.4. Situational Awareness during Planning

3DROCS supports the operator during the Activity Plan

specification providing him with *predictions and aids* related to the power, the communications and the mechanical subsystems.
Predictions are visualised in the 3D scene in an intuitive way in the form of overlaid maps. The operator has access to the exact value of the predicted measurements either on 2D/3D monitoring displays (see section 5) or by pointing the cursor on the overlaid maps.

Power situational awareness is supported by computing and visualising in the 3D synthetic scene the following maps:

- Global solar energy maps that provide awareness on the solar energy provided at each point of the environment in which the rover operates.
- Time dependant solar energy maps that are precise solar energy maps computed and overlaid on the terrain at a user selected time point.
- Rover power generation maps that are energy maps overlaid on the rover panels indicating the rover power generation at the given position and solar panels configuration.
- Communications situational awareness is supported by computing and visualising communications related information. Given an Activity Plan under specification, the system computes and visualises in the scene the instants and the locations where the rover/orbiter communications will take place. On operators' request or by pointing over the communications glyph in the scene, specific communication information is displayed (the duration, the bit-rate, etc).

Mechanical Dynamics situational awareness is supported by computing and visualising in the 3D canvas mechanisms subsystems information including:

- The path to be followed by the rover to reach a target point; in this case the A* automatic path planning algorithm is considered.
- The terrain slope maps to provide a visual indication of the slopes (steep, moderate, ...). The operator, by selecting a particular point of the map, is informed about the values of the computed slopes.
- Reachability maps indicating the targets that are reachable by the rover's manipulator and the drill.

Imaging situational awareness is obtained by the visualisation in the synthetic scene of the footprint of a selected camera. In addition, for a camera hold by a mechanism, the operator may request the joint configuration of the mechanism in order to ensure that a given area is seen by the given camera.

4.5. Activity Plan Collaborative Specification

3DROCS provides the users with a shared activity space, the Collaborative Area, to support collaborative planning. Collaborative planning may be performed over a dedicated 'session' that guarantees that all participants work on the same data, operational constraints and versions (environment model, rover model, simulator, etc).
The Collaborative Area includes:

- A 'Meeting Area' allowing the registration of a new participant, the display of the registered participants, and the establishment of collaborations relationships between participants.
- The 'Activities Area' that indicates the Activities that may potentially be used at the current planning session.
- The 'Activity Plans Area' gathering the Activity Plans under specification.
- The 'Data Area' that allows exchanging of documents and other supporting material.

The sharing of the Activity Plans is based on a check-in/check-out mechanism that allows the operator to commit and to retrieve the latest version of a shared Activity Plan. The operator reports his motivation in a textual structured form.
Collaborative specification of an Activity Plan can be based also on a concurrent edition of the same Activity Plan. Two modes are considered:

- In the 'Synchronised View' mode several operators can view the Activity Plan in the scene in a synchronised way. The 3D scene of the Activity Plan Editors of the remote operators is rendered from the same view point as the 3D scene of the 'synchronising' operator. The synchronisation of the views is performed either after the user request or periodically at a user defined period.
- In the ‘Concurrent edition’ mode two or more operators concurrently edit the same version of an Activity Plan. In this case, every change performed by an operator is immediately applied to all the operators.

The system keeps track of all the check-in/check-out operations have been performed over an Activity Plan together with the consecutive versions and the provided explanations (motivation and constraints).

4.6. Activity Plan Replay

The Activity Plan under specification can be replayed applying a VCR like control. During the replay:

- The Activities of the Activity Plan are highlighted in the order of their execution and for a period related to their duration.
- The 3D visualisation of the Activity resources is updated in the 3D canvas of the Activity Plan Editor.
- The 3D model of the rover is animated following the state of the current Activity.
- The Environmental Conditions are reflected in the 3D scene setting the current position of the sun and

of other stars if present.

During the replay, the animated Activity Plan can be saved as a video that later can be distributed and replayed.

5. DATA MONITORING AND ANALYSIS

A planetary exploration rover is a complex system with hundreds of parameters describing their evolution. Most of them can be better understood when considered in their context, i.e. the location on the planet and the time have been produced. The usual approaches of monitoring in 2D through alphanumerical, graphical (charts) or synoptic displays cannot capture and correlate the required information. 3D views is the best way to visualize an important amount of heterogeneous information capturing its spatiotemporal characteristics.

3DROCS supports:

- the *configuration* of the engineering data to be monitored and analysed
- the *monitoring of engineering* data during the Activity Planning process
- the *on-line monitoring* of engineering data during operations
- the *post-processing* of engineering data in view of their analysis and operations replay.

The following types of data are considered:

- Simulated data (controlled and executed)
- Downloaded data (controlled and executed)
- On-line monitored data

The following types of 3D displays are considered:

- 3D chart and alphanumerical displays,
- 3D Activity Plans displays,
- 3D synoptic displays, and
- 3D Images displays.

5.1. 3D Chart and Alphanumerical Displays

The 3D chart displays provide the operator an immediate and intuitive view of the *location* a telemetry has been produced, the *time* it has been produced, a qualitative information on the telemetry, and the telemetry value itself.

Location: One or more 3D paths are generated in the 3D scene taking into account the TM position and the associated values. The colour of each chart is visually encoding each associated value, the warning and the alarm regions.

Time: One or more 2D charts are generated on top of the 3D canvas. The associated values are plotted with respect to time. Indicator for the warning and alarm regions are visible on the chart.

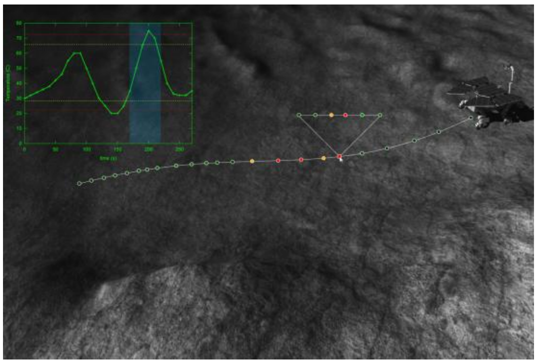


Figure 6. 3D Chart and Alphanumerical displays

The operator has the possibility to click on the generated 3D chart and acquire the TM information for that point. The respective 2D chart provides also feedback about the selected TM using an indicator that displays the time and the associated value.

In an equivalent way, the operator has the possibility to click on the generated 2D chart and acquire the TM information for that point. The respective 3D chart provides feedback about the selected TM using an indicator that displays the position and the associated value. If the selected position is out of sight, the software smoothly adjusts the camera position close to that point.

In addition, the operator has the possibility to request to move the scene at the following points: minimum/maximum value of the telemetry, next alarm/warning, at a given point in time, at a given distance on the path.

The view of the display can be modified on-line. In particular the operator has the possibility to:

- Toggle the visualisation of the rover.
- Toggle the visualisation of the path followed by the rover.
- Toggle the visualisation of a particular TM. In this case the corresponding curve is hidden/shown.
- Modify the colour and the width of the TM curve.
- Toggle the visualisation of the time/distance labels.

5.2. 3D Synoptic Displays

The 3D synoptic displays provide the operator a 3D view of the rover reflecting the current status of the telemetry using visual effects including:

- Level of transparency
- Colour change
- Colour blinking
- Colour gradient
- Shape change/scaling
- Cue visualisation (e.g. dashed line)
- Mechanical joint animation

Additional effects are derived by combination of the previous effects.

The following image demonstrates a typical 3d synoptic display. The telemetries visualized are the power generated by the solar panels, the energy consumption on the motors and the cameras and the communication antenna transmission power.

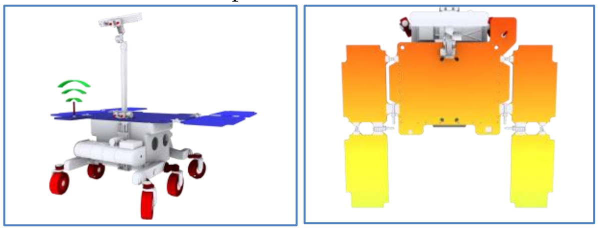


Figure 7. 3D Synoptic displays

Synoptic displays can also be more specialized, displaying only parts of the rover. For example one synoptic display can visualize the TM of the Drill component and another the TM of the solar panels (temperature distribution).
The view of the display can be modified on-line. In particular the operator has the possibility to:

– Toggle the visualisation of parts of the 3D model.
– Toggle the activation status of a visual cue.
– Toggle the visualisation of the rover.
– Toggle the visualisation of the path followed by the rover.

5.3. 3D Activity Plans Display

The *3D Activity Plans displays* allow the operator to visualise and compare two Activity Plans. The Activity Plans to be compared shall be related in the sense that they may represent the simulated, the controlled or the executed version of the same Activity Plan.
The system allows:

– The identification of the branch of the planned Activity Plan that has been executed/simulated. The operator has the possibility to highlight on the planned Activity Plan only the branch that has been executed/simulated. The possibility to show/hide the other branches is provided.
– The comparison between Activity Plans at global level (comparison between expected/controlled and achieved final resources availability, availability at a given time/location point, etc).
– The comparison between Activity Plans at Activity level (comparison between expected and effective start time/location, duration and resources consumption).

The operator has the possibility to modify the view of the display while monitoring:

– Toggle the visualisation of the rover.
– Toggle the visualisation of the rover path.
– Toggle the visualisation of the time curve over the path.
– Toggle the products produced by the Activity Plan.

5.4. 3D Images Display

The *3D Images displays* provide the operator an immediate and intuitive view of all the images acquired by a given set cameras during the time period represented by the data under analysis.
Images may be visualised either overlaid on the 3D terrain or as glyphs at the acquisition location. Activating the glyph, information on the acquired image is provided.

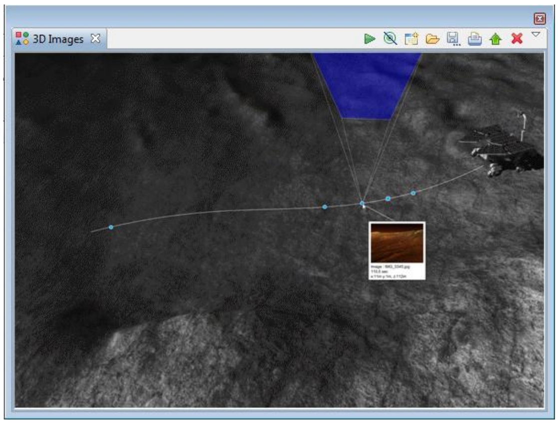


Figure 8. 3D Images display

The view of the display may be configured and modified on-line to:

– Associate additional cameras to the display
– Associate the products stream to be visualised. Possible options are the data generated during the Activity planning process, the on-line monitored data and finally simulated/executed data loaded for analysis.
– Configure the display by specifying if the path (including the corresponding time curve) and the rover will be visible as well as if the images will be displayed as glyphs or projections.
– Request a replay mode. In this case to operator has access to a VCR type of control to view progressively the images.

6. REFERENCES

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