Command Generation for Planetary Rovers Using Virtual Reality

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ABSTRACT

A system architecture is proposed for command generation of planetary rovers through the specification of high-level goals in virtual reality (VR). Through the use of an integrated planning and scheduling system, connected with a high-fidelity simulation model of the rover and its environment, a contingent command sequence could be determined from a set of specified science goals (with given task priorities, constraints, pre-requisites, etc ...). As part of NASA's Advanced Technology Program, this paper describes the work in progress towards enabling such a system and the demonstration of the current status for the Marsokhod '99 Field Experiment in the Mojave Dessert.

1. INTRODUCTION

Commanding a vehicle on the surface of another planet such as Mars cannot be accomplished through standard remote control techniques (via teleoperation) due to the inherent time delay, communication bandwidth and uplink/downlink cycles associated with the task. Obviously, increased on-board autonomy and intelligence for a robotic vehicle is a large part of the solution. One might envision a single, white 'GO' button in mission control, which commands the rover to autonomously explore the surface of Mars, only transmitting back a geological sketch map of the area with selected images and a written interpretation. However, is it really practical, or desirable, for us humans on earth to interact with and direct our mechanized servants in such a limited, out-of-the-loop fashion?

By enabling a virtual presence of the remote site through high-resolution 3D modeling of the terrain, we can gain a greater awareness of the rover's environment and situation, and better determine where we would like the rover to go and what we would like the rover to do. Using VR and web-based technologies, a distributed science team could fluently specify high-level science goals for a team of rover operators to readily implement a conditional sequence of rover commands to accomplish the specified goals. Specification and display of the desired goals and proposed command uplink could be mediated through the same virtual environment, thus providing a digital communication link between the respective science and engineering teams.

Additionally, automated planning and scheduling systems that consider task priority, pre-requisites, time and resource constraints of a semi-autonomous rover could be used in helping to determine a contingent schedule for a selected set of science goals. Furthermore, through high-fidelity simulation, we can gauge what is possible given the rover's capabilities, and partially predict an expected course of action, given a proposed command sequence to be uplinked.

The use of computer models to mediate the human supervisory control of telerobots was recognized some time before the computing power for VR was a reality [Ferrell and Sheridan, 1967]. An early demonstration of the benefits of a model-based approach utilized an on-line computer simulation and graphics display to teach the desired movement and manipulation to a robotic arm [Yoerger, 1982]. To circumvent the inherent difficulties with time delay in teleoperation, a graphical model was superimposed in real-time upon the delayed

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video feedback to predict the actions of the telerobot [Noyes and Sheridan, 1984]. Computer model-to-video calibration was further developed [Kim and Stark, 1985] and the predictor display technique has been successfully demonstrated with the advanced teleoperation system at the Jet Propulsion Laboratory [Bejczy et, al., 1990] [Kim, 1996].

The concept of 'put-that-there', 'point-and-direct' and 'teleprogramming' for remote robots has been realized using computer graphics simulations to generate high-level goals and command sequences for manipulator arms in structured environments [Schneider and Cannon, 1989] [Wang and Cannon, 1993] [Funda et. al. 1992]. More recently, model-based supervisory control has been shown to provide significant benefits for teleoperation, even in the case of minimal time delay [Blackmon & Stark, 1996].

Research at NASA Ames in Virtual Environment Vehicle Control has evolved over the last decade to explore the possibility of using computer models to control planetary rovers in unknown environments [Piguet et. al. 1995] [Stoker et. al. 1995]. However, the use of 3D computer models for telerobotic control necessitates the generation of accurate models of the remote site, which can present a considerable difficulty in remote exploration of unknown environments.

Using panoramic stereo imagery captured by the cameras of a rover (or lander), it is possible to rapidly build photo-realistic 3D models that can be assembled and visualized at mission control in a VR software interface. MarsMap is such a system that was developed and implemented for Mars Pathfinder, providing the mission scientists and operators with a valuable tool for analysis and planning [Stoker et. al., 1999]. Within a half-hour of initial downlink of the stereo panorama images, the data was processed into 3D terrain models, utilizing a process known as the 'Stereo Pipeline'.

Immediately thereafter, the 3D models were loaded into the MarsMap VR system for the mission scientists to fly-over the Pathfinder landing site, and even to project a bird's eye view from above. In addition, sensor information returned from the rover, such as 2D images as well as the sequence and location of science experiments was automatically detected and visually archived within MarsMap (Figure 1). By combining the visualization capabilities with a simple measurement tool that was calibrated with the Pathfinder lander, 3D information could easily be extracted from the map data to provide relevant locations, distances, angles, and contours of the terrain topology.

For Mars Pathfinder, this 3D measurement information was typically written on pieces of paper by the mission scientists and then used in operations planning, especially for multi-spectral imaging pointing of the Pathfinder lander camera system. Long-range planning for the Sojourner rover was also frequently visualized by the science team utilizing MarsMap, in particular where terrain navigability was in question.

Since Pathfinder, MarsMap has been further augmented with additional user interface elements to now allow the direct specification of science and imaging goals of a mobile rover platform, with the ability to save this goal information to file for later editing and display. This goal information can then be readily assimilated into the command generation user interface elements of a mission, and the results of the planning can subsequently be visualized in MarsMap. Moreover, MarsMap has been combined with a dynamic simulation engine to allow high-fidelity simulation of a rover's interaction with the environment with the appropriate abstraction layer to accept low-level rover commands from the on-board execution software elements.

2. Command Generation with VR

The following two paragraphs present a conceptual overview of a proposed system for utilizing VR as part of the command generation process for planetary rovers.

A collaborative and distributed science team utilizes a VR interface on a limited number of high-fidelity mission operations centers, along with a larger number of desktop web browsers, to specify a collection of science goals for a rover as part of a long-range plan. The distributed science can simultaneously or asynchronously visualize designated goal 'files', thus utilizing the VR system as a communications medium. The respective science PI's (or designated science team members) then work together to select from this larger goal list and possibly modify goals for the next uplink(s). As part of the tools available to the science PI's, an integrated, ground-based planning and scheduling system connected with a rover simulation model can be used to semi-automatically determine a contingent sequence of rover activities.

The rover operations team oversees and can override this proposed sequence to ensure rover safety, insert appropriate engineering and health commands, and further plan for rover activities where automated planning / task decomposition is insufficient. The resulting proposed uplink is verified by the scheduling system for time and resource constraints, and then sent to the rover simulation to partially predict the resulting outcome of the command sequence. Both the local and distributed science teams can then view the final uplink schedule (as well as rover simulation results).

As part of the research effort to develop and demonstrate the benefits of such a system, a software architecture has been designed and implemented for a modular rover VR planning and display system. Figure 2 illustrates the concepts of this generalized software architecture. The 'RoverVR' interface is made independent of the particular rover base and instrument suite through a set of 'robot', 'instrument' and 'data' objects defined at initialization. Associated with these object classes are specified parameters, including pointers to run-time functions that provide for ...

- Telemetry monitoring and processing of 'data' objects returned form the rover
- Iconic representation of the 'data' in VR
- Display of associated information of the 'data' in VR
- Loading of the 'data' into the VR program
- Methodology of 'data' display in VR
- Interactive manipulation of the 'data' in VR
- Interactive goal planning for defined 'instrument' and 'robot' objects
- Output of a designated goal plan

Upon initialization, defined parameters for the 'robot', 'instrument' and 'data' objects are registered with the 'RoverVR' interface and subsequently used at run-time to enable the data management and planning activities in the VR human interface.

3. Marsokhod '99 Field Experiment

The Marsokhod '99 Field Experiment was designed to develop, demonstrate, and validate technologies and science strategies for high-science, high-technology performance, and cost-effective planetary surface operations. The results of this blind field test are intended to find direct applications in the NASA Mars Exploration Program, and more generally, in the evolving field of planetary surface exploration. Several highlights are worth noting from this month long field experiment in the Mojave dessert.

A hi-resolution stereoscopic imaging system was utilized with a boresighted spectrometer, with similar imaging properties to the 'PanCam / MiniTES' system which is scheduled to fly on the Mars'01 lander and Mars'03 rover platforms. Prior to the field test, a simulated descent imaging sequence was captured utilizing a helicopter and photographic system that closely matched the profile and optical properties of the Mars '98 and Mars'01 descent imaging systems. A flight copy of the Robotic Arm Camera (RAC) which will fly on the Mars '98 and Mars '01 landers was taken to the field for a three days to image a trench dig while the rover / PanCam simulator remained stationary in a 'lander' mode. Finally, the field test wrapped up with the 'ASRO' event, which explored the interaction between a suited astronaut and a rover assistant in a simulated SEP (Science Experimental Package) deployment.

Figure 3 is an information flow diagram of the extended Marsokhod control system for the field experiment. The right portion of the diagram shows the on-board autonomy architecture. Robust navigation of the six-wheeled rover was performed utilizing a visual servo strategy developed as part of an on-going research effort [Wettergreen et. al., 1996]. Of note is the addition of a model-based executive and mode identification / fault monitoring system as part of a larger research effort into increasing the on-board robustness and intelligence of planetary rovers [Bresina et. al, 1999]. This system makes the use of an uplink command sequence format dubbed CRL (contingent rover language) which enables the on-board executive to take action based upon sensed or deduced information regarding the rover state and knowledge of the environment. The remaining sections of this paper provide a system level overview of the relevant ground-based user interface elements as part of the Marsokhod '99 Field Experiment, particularly related to use of VR for the command generation process.

4. Goal Specification Using 'MarsoVR'

One of the most significant uses of VR for rover command planning is the ability to drive a simulation model of the rover over the high-fidelity terrain models generated from stereo imagery, calculating the rover's kinematics along the traverse. This enables a scientist or rover operator to more confidently specify way-points and suitable navigation strategies for the rover base movement in the near to mid vicinity of the most recently captured stereo image sequence (within reasonable accuracy and depth limitations of the stereo camera system). For the Marsokhod field test, the rover operations team in determining navigation heading and distance estimates to designated science targets (Figure 4, upper left) routinely used this capability. In addition, the interactive driving simulation was used to identify terrain areas unsuitable for rover navigation, and to develop combined navigation strategies using the rover's on-board visual servo and dead reckoning with safeguarding capabilities.

The use of an interactive VR model for instrument and arm placement with a rover has similar advantages as with navigation. In cases where the rover base has not moved, a CAD model of the rover instrument arm can be placed with respect to terrain models captured from the same position to confidently determine rock and ground surfaces within direct reach and to specify end-effector coordinates for a safeguarded move. In case where the target object requires movement of the rover base, the VR model is still quite useful for estimating the ability for the rover to reach a target and for determining a strategy on how best to approach a science target with consideration of instrument placement. Figure 4, upper right shows the use of the 'MarsoVR' interface for specifying the arm end-effector and instrument carousel position on a large, flat rock in the direct reach of the rover.

During the field experiment, panoramic imaging and spectrometer experiments, as well as navigation imaging experiments were also specified by the rover operations team in VR. Using the 'MarsoVR' interface, a user sweeps out the pan & tilt extents along with other camera parameters, including pan/tilt step size, camera resolution and image compression (Figure 4, lower left). Beyond simply estimating the downlink data volume, this utility was extremely useful for visualizing the estimated terrain coverage area, especially when planning for image acquisition sequence to follow a navigation command. For designating spectral targets, the operator points with the 2D mouse and a circle is targeted onto the 3D terrain model showing the desired location and field-of-view for the spectrometer (Figure 4, lower right). The unmodified, original rover image used as the texture on the corresponding 3D model is shown in the planning sub window with a cross-hair on the specified target location.

For the 'MarsoVR' planning interface, all specified science goals and rover commands have a common set of general properties that are specified for purposes planning and scheduling. A constraint on the time window for which the task should be started can be specified if desired. Priorities on task execution as well as downlink of the resulting data are ranked for all tasks. Additionally, pre-requisites for a task, such as other tasks that must precede this task, are also specified. The interface also allows the user to specify general comments that are relevant to the incorporation of this task into the proposed command uplink. These parameters are set through a 2D user interface panel that is integrated with the 'MarsoVR' software program (Figure 5).

'RoverWeb' Interface - As part of the field test web site, a simple image-based, point-and-click interface was implemented to allow the science team members to specify experimental goals remotely. This web-based interface does not require the graphics capability of MarsMap, nor require any special plug-in's such as JAVA, and can thus execute on any standard computer with an Internet browser capability. After selecting a target feature in a rover image along with a goal type (Pan-Cam Image, Navigation Image, Arm Camera Close-Up Image, Spectral Measurement) a scientist completes an Internet form with other information appropriate to the task, and submits this task request. The form information is then translated to an appropriate CRL goal language for command sequence generation and appears for display at mission control at Ames. A copy of the Internet goal form was also posted onto the web so that other scientists could easily monitor the variety of experimental requests made during the mission.

Of course, this electronic method of goal submission was not strictly mandated.

Moreover, as the field experiment evolved, the science team rather made effective use of telecons to typically develop the set of desired goals for the next uplink cycle, and submit the 'science goal requests' as a simple text document detailing the desired set of activities, relevant task parameters, and rationale. This text document with a number of supporting images would be posted into the mission web posting system for other team members to view. After analyzing the proposed set of goals in terms of feasibility, the rover team would respond to this request and often another iteration cycle was required prior to uplink of a sequence that satisfies both science desires and engineering constraints. In terms of effective task planning, it was important for the science team and rover team to have direct verbal interaction, facilitated by a set of central contacts on both the science and rover teams. Verbal communication was essential to ensure that desired goals were understood correctly as well as to provide the science team with better understanding of the rover's capabilities and how to most effectively utilize those capabilities.

5. Command Sequence Generation

Following the submission of rover goals and relevant task parameters, a rover command sequence would be assembled using a 2D forms interface called the 'Command UI'. The 'Command UI' allows the rover operations team to interactively build a contingent sequence of activities to meet the desired goals. The individual activities that comprise the sequence are initially specified at a high-level using the MarsoVR interface, the web-based goal interface, or alternatively specified directly in the 'Command UI'. In fact, in this modular open-architecture design, any custom interface could be used to generate high-level goals for the 'Command UI', given the specification of the 'Contingent Rover Language' (CRL) and the 'Rover Goal Dictionary'.

An operator uses the 'Command UI' to load a set of specified science and engineering tasks for the next uplink into a flat list. Using an iconic representation of the sequence as a hierarchical tree of nodes in time, the operator then selects individual tasks and links these tasks into a sequence. The operator has the ability to place conditional branches into the sequence that are dependent upon run-time information on-board the rover. A typical example of a conditional sequence for the Marsokhod rover consists of ...

- perform visual servo navigation to desired target
- if visual servo navigation is successful ...
  capture hi-res image of the target
  perform 2x2 spectral cube on the target
- else if visual servo navigation fails ...
  capture images to trouble-shoot failure and re-acquire target
- capture end-of-navigation panorama
- capture end-of-navigation images with fixed low-mounted camera

Screen shots of the 'Command UI' elements are shown in Figure 6. These include panels for selecting among the various proposed goals, editing individual goal properties, and display the resultant timeline of the conditional sequence that has constructed with the 'Command UI'.

Following manual construction of a contingent schedule using the 'Command UI', the sequence of tasks would be further decomposed into a set of low-level rover task primitives using a planning and scheduling system based upon the Just-In-Case approach [Drummond et. al., 1994]. This system accepts a seed schedule and can also automatically add contingent branches to the schedule where appropriate based upon such things as time and resource constraints. More information regarding the automated scheduling and task decomposition is provided in a companion paper written for the Marsokhod '99 field experiment [Bresina et. al., 1999]. This low-level sequence of commands can then be uplinked to the rover and understood by on-board model-based executive.

6. Rover Simulation

Once the rover team has constructed a contingent sequence of rover activities, the various branches of the sequence can be tested using a high-fidelity software simulation of the Marsokhod rover to verify and predict the outcome of the proposed command sequences [Sweet et. al., 1999]. This simulation model is constructed using a hybrid discrete continuous scripting language [Carlson and Gupta, 1998] and is integrated directly with the same terrain model database utilized for the interactive goal specification and task planning in VR. The simulation makes use of a modified rover / terrain 'settling' algorithm presented in [Lincoln, 1996]. A friction model of the rover / wheel soil interaction was adapted from [Andrade et. al., 1998] and also incorporated into the simulation code.

The simulation was developed to accept the same suite of rover commands output by the on-board model-based executive and produce the same telemetry stream available to the executive and mode identification / fault monitoring system. By using the same communications system used on-board, no modification is required to interface the on-board autonomy software programs to the simulation. The resulting simulated rover telemetry (and full state data) can then be visualized and analyzed in 'MarsoVR' with the same tools to view the actual downlink information from the rover. Unfortunately for the field test, the simulation was not heavily utilized due to timing and human resource constraints in the accelerated development schedule. However, it is being utilized more heavily following the field test, especially for continual development of the rover on-board autonomy, prior top validation of the algorithms on the actual rover hardware system.

7. Analysis and Future Directions

Goal generation and task planning in VR was extremely useful for the rover operations team during the Marsokhod '99 Field Experiment. This was particularly true for navigation, manipulation and imaging operations, but less useful for spectral targeting and other strictly image based operations. Without assistance from the rover ops team, the science team made limited use of the VR tools, due to the short duration of their stay at Ames (only 3 days on-site) and the lack of previous familiarization with these tools. Although some use was made early on with the web goal generation tools, the science team largely relied upon the use of telecons and written text files that were handed off to the rover ops team to specify goals for the next uplink.

Currently, the automated planning and scheduling system largely performs a straightforward task decomposition form the goal parameters, with 'canned' engineering contingencies strategically placed to handle expected failure modalities. . Additional contingencies were structured within an uplink through human design of the sequence in the 'Command UI'. There was limited to no automatic planning based upon environmental knowledge and no link with the simulation model. Furthermore, the simulation model was not exploited for command sequence verification and testing prior to uplink.

These and other limitations of the current system were largely due to human resource limitations and the accelerated development schedule for the field test. In addition, somewhat competing goals between science investigation and technology development restricted the testing of technology during the mission. Nevertheless, the excitement of this work and the larger effort by the combined rover operations and autonomy teams continues. To Mars and beyond ...

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Figure 1: MarsMap virtual reality (VR) provided Mars Pathfinder mission scientists and operators with a valuable tool for analysis and planning.

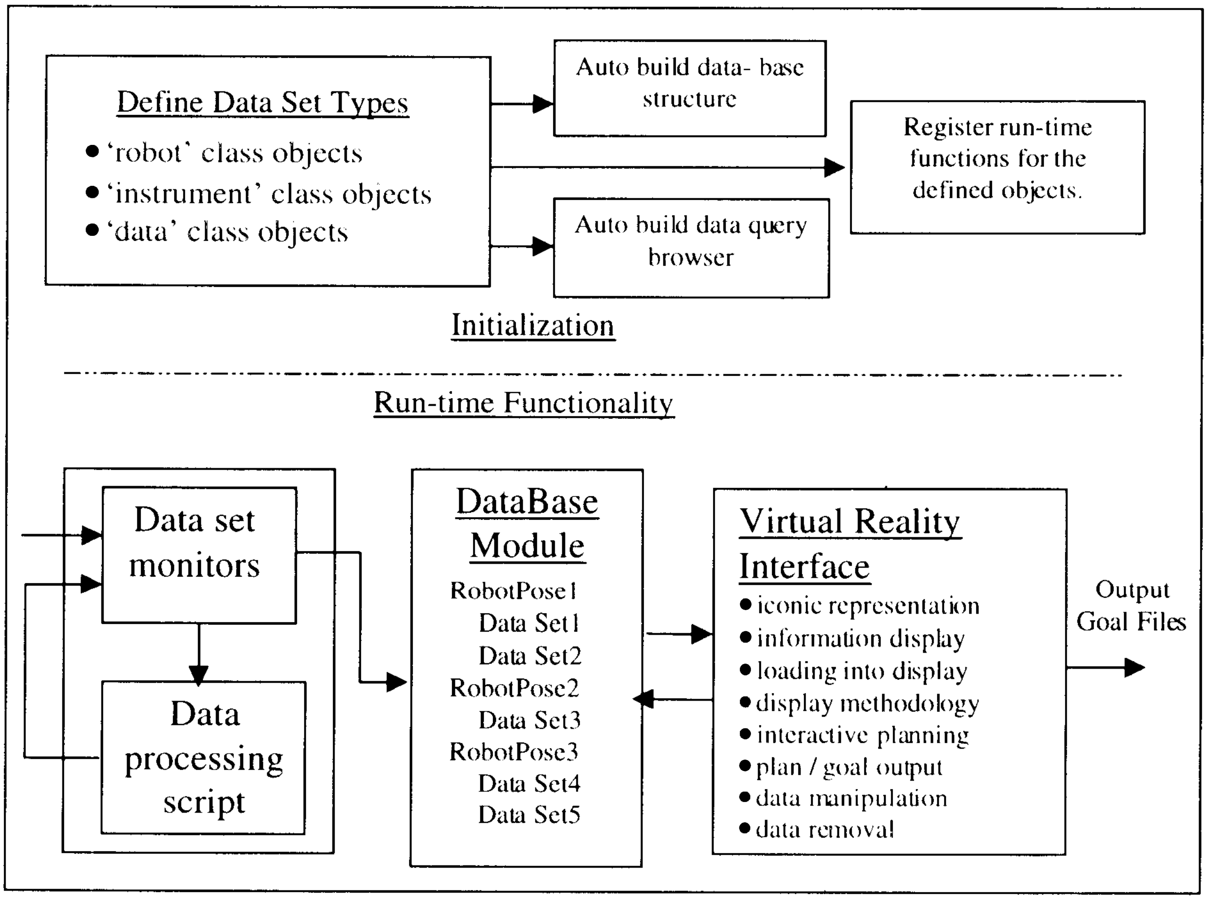

Figure 2: Generalized software architecture that has been developed for a modularized rover VR planning and display system.

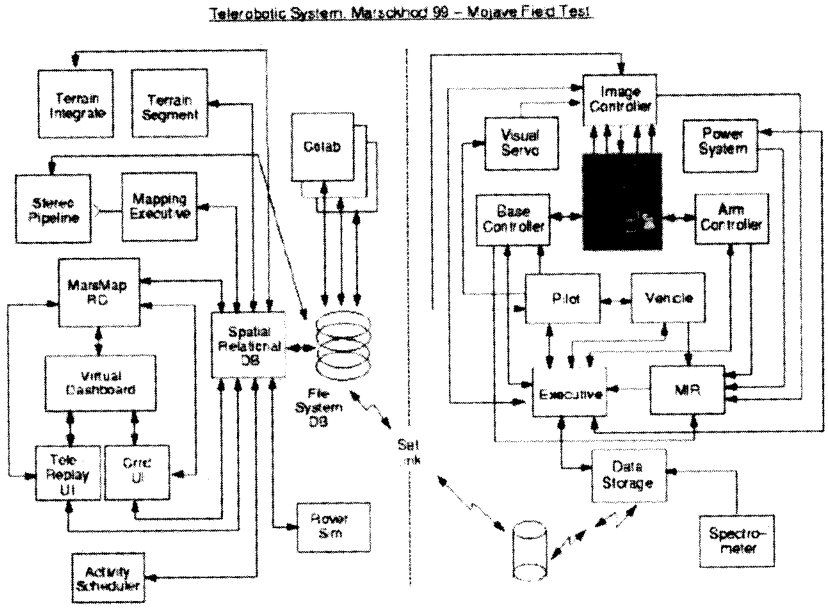

Figure 3: Information flow diagram of the extended Marsokhod control system for the field experiment.

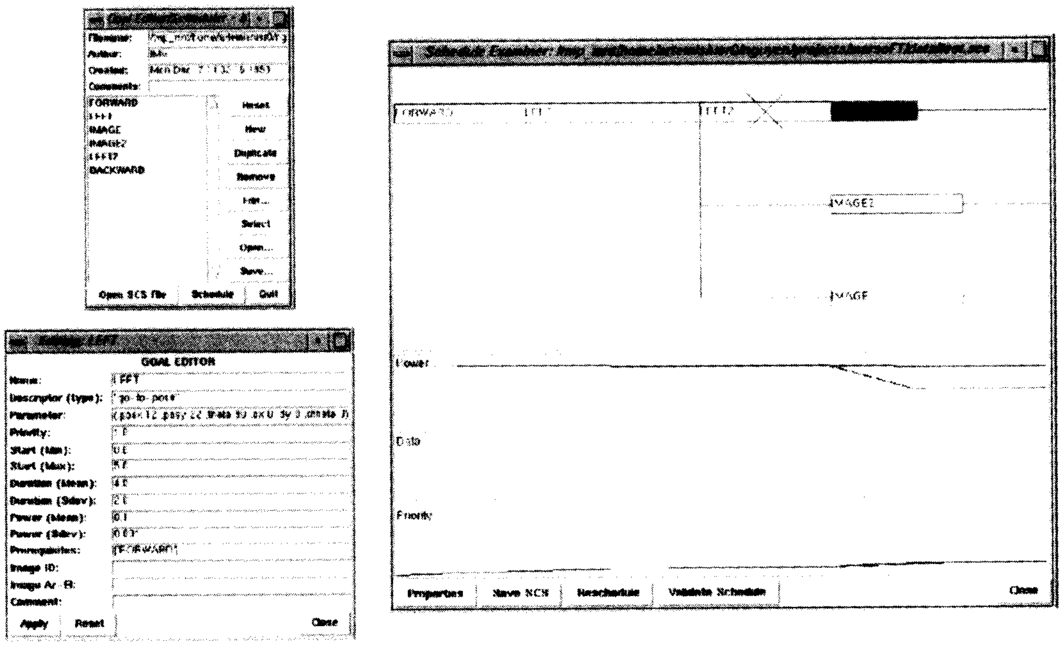

Figure 7: 'Command UI' elements for selecting among the various proposed goals, editing individual goal properties, and display of the resultant timeline of the conditional sequence that has been constructed.

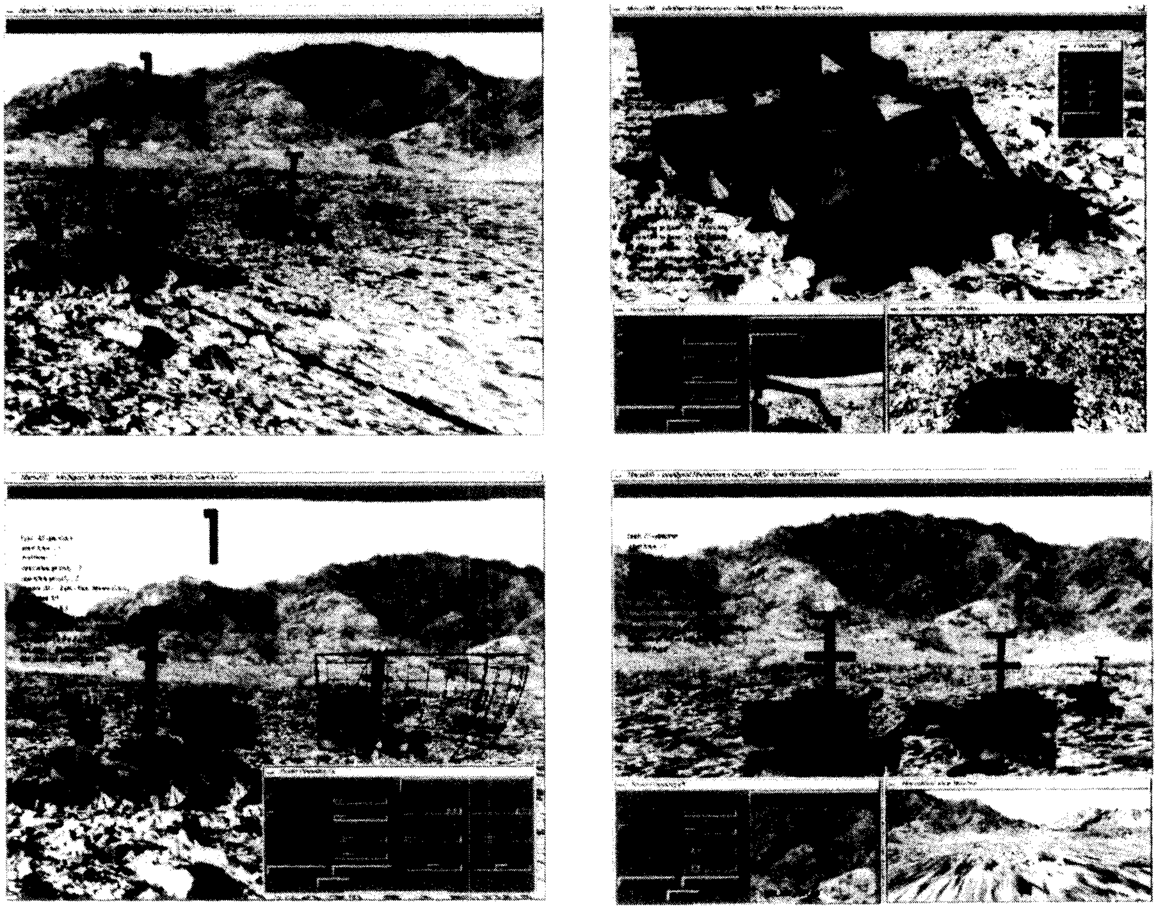

Figure 4: 'MarsoVR' is used to interactively plan rover goals and commands, ranging from navigation heading and distance coordinates, arm placement, panoramic imaging and spectral target selection.

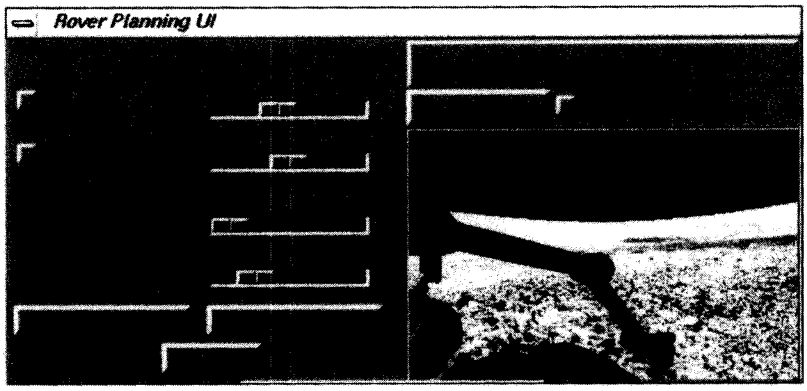

Figure 5: Generic parameters set for every goal include an optional window for task starting time, execution and downlink priorities, task pre-requisites and general comments.