Achieving a Balance Between Autonomy and Teleoperation in Specifying Plans for a Planetary Rover.

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Abstract

This extended abstract documents our on-going work in the area of determining what autonomy a planetary rover should exhibit, and how the autonomy can be interfaced to the human users of the rover. A key constraint on the autonomy is that human user and machine must be able to cooperatively carry out planetary geological sampling and field-work. We describe an approach that uses an icon-based language to advise an autonomous rover and to present rover feedback to the user. The icon-based language can be translated to plan networks in the $\mathcal{RS}$ model[4, 2]. We present an extensive 'pencil & paper' example of using the interface to carry out cooperative exploration.

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1 Introduction

The purpose of the planetary rovers is to enable the remote scientific exploration of planetary bodies[7, 9]. For relatively close bodies, such as the Moon, teleoperated rovers may well be sufficient for the task. For more distant bodies, like Mars, the telemetry transmission time renders effective teleoperation difficult. In these cases, allowing the rover to have some level of on-board autonomy results in substantially improved performance [7]. The autonomy is necessary to fill out the sparse commands from the user with, for example, the detail necessary to carry them out to ensure that hazardous situations encountered between user commands are handled effectively. One major challenge is to provide a user-interface to the remote machine that strikes a compromise between the benefits of teleoperation (e.g., the ease of identification of the user with the slave robot) and the necessity for autonomy. This paper presents an overview of our on-going work on an icon-based interface to meet this challenge.

The issue of the correct balance of autonomy can only be answered in the context of a task domain. For the rover, this domain is geology. For most geologists, the best answer to planetary geology would be for them to be physically present on the planet[9]! Teleoperation is popular because it facilitates this involvement. But barring this, the next best thing would be to have a semi-intelligent assistant, with whom the geologist has good rapport, doing the planetary field-work. Although the geologist will select the traverse paths and for analyzing and collecting rocks and soils through advising the rover, the rover will also be capable of independent sampling, noticing oddities and acting on unusual information. For the planetary geologist involved in a robotic mission, this relatively intimate interface between human and machine will be a more direct, hands-on and timely activity than on previous missions.

Based on this definition of the level of autonomy of the rover, we put forward the following requirements on the rover control system and its user-interface:

A. A geologist should find the system 'natural' to use.

   (a) It should be possible via the interface to get the look & feel of a situation, so that the user can directly identify with the rover's local environment.
   (b) The rover should possess enough local 'curiosity' to spot geological oddities and do a preliminary inspection of them, in case they should present an opportunity to the user.
   (c) The user should be able to redirect the activities of the rover to take advantage of any opportunities that arise in the on-going exploration.

(d) The user should be able to teach the rover, e.g., updating a reference library of geological characteristics.

B. The rover should exhibit efficient useful autonomy within the overall bounds of the instructions given by the user.

(a) It should avoid hazardous situations.

(b) It should be possible to set some background mission agenda.

(c) There should be a collection of procedures for investigating the environment

(d) The rover should carefully document its environment and activities.

We are designing an interface based on these requirements. The key novelty of our work is that it approaches the issue of autonomy from the perspective of usefulness to the geologist user, rather than simply hazard avoidance [1]. Our approach is to design a graphical interface for rover commands and feedback to maximize the users identification with the rover. The interface will translate advice from the user into plan networks which will then be sent to the rover. Plan networks and translation are represented using the $\mathcal{RS}$ model[3, 2], a special model of distributed computation designed for representing and analyzing plans for autonomous systems. This gives us the ability to make formal guarantees about the behavior of a remote rover, clearly important for reliability.

In the next section we present a description of our interface and the translation to $\mathcal{RS}$ plans. After that, we present an extensive 'pencil & paper' example of using this interface for cooperation exploration of an unknown area. We conclude with a discussion of what work remains to be done.

2 Overview of the Cooperative Interface

There are three levels of abstraction at which on-going exploration can be described:

1. **Regional Level**: This level concerns the overall geology of the region(10's to 100's of km), the location of interesting geological sites in the region, and transit between sites. Much information used at this level is gathered in orbit. Autonomy at this level would include local landmark identification and surveying. User advice at this level would concern criteria for selecting station sites, designation of specific station sites and/or routes, specific oddities to watch for, etc.

2. **Local Level**: This levels concerns a particular geological sampling area (10's to 100's of meters / field of view), its relationship to the regional geology and the determination of experimental sites. Autonomy at this level would consist of inspection and limited sampling of the local environment, following geological features and regions, etc. User advice at this level would include spotting of oddities during transit, directions to sample specific areas, or to watch or follow specific features.

3. **Experimental Level**: This level concerns the siting and scheduling of sampling machinery. Autonomy at this level would simply be scheduling of experiments to minimize some criterion such as time or energy, and default selection of sampling sites relative to the rover. User advice at this level would constrain the set of experiments performed and their ordering, as well as directing sampling to specific regions around the rover.

Our levels form a hierarchy: so local actions are done in the context of regional activity, and experimental actions are done in the context of local actions. Data from local actions can influence regional interpretation, and experimental action may influence local interpretation. This approach is very important, because human field geologists go though many iterations of this context and interpretation process. We refer to this relationship as 'zoom-in' and 'zoom-out' in our example of geological exploration. Note that our regional level is similar to the *Sprint* phase of [6], and our local and experimental levels correspond roughly to their *Graze* phase.

Now we address the problem of getting the look & feel of a remote machine's environment and on-going work across to a remote user.

Scenarios

At each level, the actual interface to the rover control is via a set of *scenarios*. A scenario is a graphical representation of the environment and on-going rover control at that level; it is implemented as a 2-D icon map, where an icon is a movable, stereotyped graphic symbol denoting some aspect of the rover sensory data or action control. The icons may be cross-referenced to other sensory data, for example, a (segment of a) visual image or spectral map, a template for visual identification of a sample, etc.

User input in any scenario is via 'advice': A user inspecting a scenario will see what the rover has encountered to date, but will not be able to see *current* sensory data because of the time delay. Thus, the most a user can provide to the rover is instructions on how to act *should* a situation arise or advice or instructions to redirect its activity towards another area. Even redirection cannot have the force of an immediate command, because the current environment of the rover may prohibit the command being directly executed. However, the rover controller can guarantee to follow remote advice at the soonest possible time.

Advice is represented in a scenario as a stringing together of relevant icons. For example, at the regional level, to direct the rover to some landmark, that icon is strung together with some motion command icon. This is accomplished by moving a copy of the icon onto some "plan line" on the scenario display screen, and then moving the motion command icon down onto the plan line. It should also be possible to modify the motion command to describe what route to take. The key notion here is that advice construction should be very visual (to preserve the geologist's impression that he is dealing directly with the environment) and be directly connected to a view of the locality of the rover.

Communication

We assume that the rover will communicate with Earth somewhere between 15 minute intervals to 6 or 8 hour intervals. In all cases, we assume the delay is sufficient to prohibit any direct interactive control of the machine, but frequent enough to allow the machine to be redirected to interesting features.

2.1 Translation to $\mathcal{RS}$

The icon-based programming environment developed for $\mathcal{RS}$ [4] can be extended to present a geologist with an 'iconic' vocabulary for describing sample acquisition and geological field experiments. The vocabulary might also be linked to visual data (e.g., icons denoting parts of the Lunar or Martian landscape). The icons might also denote actions to be taken based on future sensory data. The geologist, with minimum knowledge of $\mathcal{RS}$ or robotics, describes his plan by stringing icons together. For example, Figure 1 shows an icon plan instructing the robot that whenever it sees a rock that matches `rock-template-1` it should acquire the nearest sample and analyze it with instrument `XRD`, and that this instruction should have priority `priority-1`.

The icon plan can be automatically translated into an autonomous task plan in $\mathcal{RS}$; a plan capable of autonomously directing the rover to carry out the experiment on Mars. The plan would contain various default information to handle conditions not mentioned by the geologist, including reflexes to avoid possible problems or to take advantage of new opportunities.

For example, the geologist may want to carry out a specific experiment on a particular rock. However, when the rover carries out the plan on Mars, it may find that due to the geologist's incomplete information, there is more than one candidate rock. The rover might respond autonomously by carrying out the experiment on all candidates, if there are only a few, or by choosing an 'appropriate' candidate if there are many, etc. Alternatively, the rover may find that the candidate rock is not available, perhaps because it crumbled during the process of acquisition. In that case, the rover may select an alternative rock. All deviations from the advice, especially substitutions of samples, will be thoroughly documented, so that the geologist knows exactly where the sample came from.

Ideally, the translation from icon plan to $\mathcal{RS}$ plan network would be via a 'reactive' planner such as that we suggest in [5]. In our current test implementation, simple script-based translation is used: Associated with each icon scenario is a plan script in which the 'slots' can be filled in by inspecting which icons the user has selected. An $\mathcal{RS}$ architecture and icon environment similar to that discussed above are described in some of our previous work [4].

Figure 1: Icon Plan for Opportunistic Sample Analysis.

3 An example of cooperative exploration

We tested the ability of the proposed interface to support cooperative exploration conducting a brief field excursion of the Florissant Fossil Beds via advice to the rover. One of the authors (Allton) made a short geological exploration trip to this area and detailed her observations and conclusions (Figure 2). The objective was to find the areas of fossil-bearing rock.

In this section, we present an edited transcript of the trip report, with the salient parts annotated FB1...FB8. As a 'pencil & paper' exercise, we constructed a version of our interface to handle this trip, and we detail here how this trip might have been carried out as a cooperative activity between a geologist and a remote rover.

3.1 Interface architecture

We need the following levels and scenarios for the examples

1. **Regional:**
   (a) **Classify Scenario:** This scenario contains advice on how to identify particular landmarks and regional areas.
   (b) **Transit Scenario:** This scenario contains advice on where the rover should travel.
2. **Local:**
   (a) **Checking Scenario:** This scenario contains advice on what sensing or sampling the rover should do while in transit.

A visit to Florissant Fossil Beds National Monument,
as an example of Local Site Investigation on Mars

(FB1) As I approached within 5-10 km of the site, the numerous high hills of rounded pink granite boulders and the sharp descent of the road and the stream suddenly changed to relatively flat-floored grassy valley with a few rolling hills covered in pine, fir and spruce. This was the terrain in which the site was located.
(FB2) At the ranger station, in preparation for an investigation on foot, detailed information about the site geology was gained from study of a 3-d terrain model and examination of hand-sized rock specimens of known composition.
(FB3) The park management does not provide maps showing the location of the fossil beds, to prevent theft. Also, I was restricted to official trails, and only one trail appeared to intersect an exposure of the fossil-bearing bearing shale and the overlying caprock.
(FB4) I proceeded to the exposure, and recognized the shale from the layered appearance and relationship to the caprock breccia. Next, I formed a better description of the shale bed for future reference: I examined several hand samples of each kind of rock present. For each, I noted the overall "feel", color, size and shape. I stepped back to a field of view of several feet and noted the color and thickness of the layers in the fresh shale, the absence of strata tilt, and the color and morphology of the weathered face.
(FB5) I then went to a nearby bench with a fine view across and up the valley. I noted the elevation of this shale exposure over the valley floor, and its relationship to other topographic features – the pines rooted mainly in the caprock on the rolling hills, and the exposures of petrified giant redwood stumps in the lower mudflow rock. I searched the scene again looking for the shale's weathered morphology and color at the elevation between the redwood stumps and the pine-covered hills. No match was visible.
(FB6) I proceeded down the trail, becoming more confident in identifying the nearby rock strata. I was able, from a few white fragments, to recognize that a petrified redwood stump was nearby, and to locate it. Soon I could locate redwood stumps at distances of 0.5km based on the scatter of white fragments.
(FB7) Presently I saw what appeared to be tailings from a quarry about 0.5km west of the trail. The tailings were positioned just below the caprock and were likely from the shale. Further on, where the trail intersected a pine-covered hill, some out of place shale fragments were seen. This prompted a more careful look around the area, which revealed the remains of an old vehicle track crossing the trail at that point. The track led back to the tailings. Another possible source of the fragments was a nearby excavated redwood stump. The shale/caprock contact was observed about 5 meters up the hill.
(FB8) I suspected from this that the disguised vehicle tracks led to the quarry from which the best of Florissant's fossils, and the nearby fragments, came. I examined the trail-side fragments of shale. They were found to have amazing paper-thin laminations, a feature not observed in the previous shale samples. I surmised that paper-thin laminations is characteristic of good fossil-bearing rocks.

Figure 2: The Fossil-Beds Exploration

(b) **Station Scenario:** This scenario contains advice on what the rover should do once it has located a sampling station.

3. **Experimental:**

   (a) **Look&Feel Scenario:** This scenario describes a short set of experiments to quickly get the 'look and feel' of a sample site.

   (b) **Full Test Scenario:** This scenario describes a full analysis of a sample site.

3.2 Cooperative example

Table 1 summarizes the use of the interface to carry out the fossil-beds exploration example with a remote rover.

The rover is directed via the **transit** scenario (Figure 3), which contains a 2-d icon map showing landmarks. A landmark is just any designated quantity that can be used for navigation: e.g., an absolute position, a geological feature, etc. Typically, landmarks might be spotted by satellite (and hence be labeled with some approximate position and some 'test' to apply to sensory input to see if the rover is at the landmark, e.g., a particular spectral image). Alternatively, landmarks could be placed by humans, after some analysis of the sensory data in those regions. It is useful to have multiple display and input capabilities available for landmarks, e.g., visual images of the area that the rover has classified under a specific landmark, etc. Advice on where to move is again specified using an icon menu. The actions are divided into three classes: actions (e.g., 'move to'), destinations (i.e., landmarks) and path definitions, and transit conditions (e.g., safest route, fastest route, etc). In the case where the rover is looking for something (e.g., fossil-bearing rock) it is necessary for it do some sensory checks as it is traversing ground.

At the local **checking** scenario, we have advice on what the rover should do in transit. The local **checking** scenario may flag the 'white fragments' from the petrified stump (FB6) as being 'different', and this information will appear on the local icon map. This data marks the mudflow rock strata and can be fed back into the regional view of the distribution of the mudflow rock (upon which the shale can normally be found) – and example of the 'zoom-out' process. Note that it may be relevant to have different **checking** scenarios prepared for different parts of the traversal. The list of available **checking** scenarios might be displayed, for example, at the transit level, and could be part of the transit plan. The local checking advice might be to check the sensory input every, say, 20 minutes to determine if any particular spectra were in view. If such spectral signatures were detected, then the rover would veer from its current trajectory, onto a new path towards the area.

The local **station** scenario tells the rover what to do once it thinks it is at a station. Again it may be relevant to have 'different' **station** scenarios prepared and invoked in different situations, as dictated, say, by the advice in the transit scenario. In this case, for FB4 the local **station** scenario would say that once the rover thinks it has found some shale, it should do a quick look & feel experimental test, to survey the area. The local **station** scenario would also dictate how the new data gained from the experimental test should affect the regional level. For example, the advice could simply be that the experimental data obtained be used to refine the 'shale' template which is being used at regional and local levels to identify the regions of interest to the rover. The local **station** scenario might also contain the default advice that the rover is to continue moving slowly over the region of interest using a more detailed **checking** scenario (i.e. 'grazing') and 'zooming' this data out to the regional level to refine its world view (FB5).

On the experimental level, a full test scenario might be appropriate at FB8. We have taken a detailed schedule of sample analysis using deployable instruments at a single rover stop by Somoano[8] and programmed the steps required to accomplish this activity. The analysis activity described by Somoano is based on the interaction between use of the instruments, the necessity to prepare samples differently for different instruments, the duration of each analysis, and communication opportunities. Many of the instrument constraints could be reasoned about in an automatic fashion. Indeed, allowing the rover this freedom enables it to tailor the schedule to suit events in its environment.

So, rather than presenting the machine with a detailed schedule, the input might be more like that shown in figure 4, which partially describes a version of Somoano's final analysis plan in iconic format and assumes that the rover can handle the scheduling issues. The example in figure 4 is laid out as follows. The central part of the scenario

Figure 3: The Transit Scenario.

Example	Level	Scenario	Activity	Comments
FB1	regional	classify	regional image	from orbit
FB2	regional	classify	regional topographic data	from orbit
FB4	regional	transit	proceed to suspected shale exposure	
	experimental	look & feel	examine hand specimens	ZOOM-IN
	local	station	learn appearance of weathered face of confirmed shale	ZOOM-OUT
FB5	regional	classify	apply appearance of confirmed shale exposure to distant scene	ZOOM-OUT
FB6	regional	transit	proceed on path	
	local	checking	observe rock types on path, identify new rock type (white tree stump fragments)	
	regional	classify	apply confirmed appearance of new rock type to distant scene, this information allows us to map the location of the mudflow rock, over which we know to look for shale	ZOOM-OUT
FB7	regional	classify	identify shale at a distance	
	local	checking	detect 'out of place' (wrong statigraphic level) shale segments	
	local	checking	detect tracks, stump excavation	
	local	checking	identify shale exposure nearby	
FB8	experimental	look & feel	examine fragments and identify new shale type	ZOOM-IN

Table 1: Fossil-beds example done in terms of interface scenarios

is a local area map or composite video image of the sampling area. The user points to parts of the image, which are resolved into 3-d positions relative to the rover, and then denoted by icons that can be embedded in the sampling schedule. The types of sample are soil, fragment, pebble, boulder and regolith. The instruments are also denoted by icons: Alpha-Proton X-Ray Spectrometer (AXPS), X-Ray Diffractometer (XRD), X-Ray Fluorescence Spectrometer (XRF), etc[8]. The schedule is constructed as a table of sample and instrument icon pairs. Additionally, a row in the table can be augmented with a priority level icon. This allows the human user to indicate the relative importance of sample analyses.

4 Discussion

This paper has described the status of our on-going work on the issue of balancing autonomy in a planetary rover. Our approach is novel in that it defines the level of autonomy by considering the issue of cooperation between a geological user and a remote rover. We use a graphical interface to maximize the rapport between the user and the remote machine, and also suggest that this be connected to tools such as 'telepresence' and 'virtual reality' to further help the user identify with the rover. Plans are constructed using icons. These icon strings can then be translated into $\mathcal{RS}$ task plans. The $\mathcal{RS}$ model supports the representation and analysis of plans that can 'adapt' themselves to suit an uncertain and dynamic environment. Our implementation so far is restricted to that described in[4]; figures 1,3,4 have been constructed using our icon environment, but do not yet translate to $\mathcal{RS}$ plans (the video image in figure 4 is a mock-up using a *Viking* 1 shot of Mars).

The form of cooperative activity we describe is more akin to the '(single)master-slave' teleoperation concept than to the way remote missions have traditionally been managed. For example, during *Viking*, a group of 10–12 scientists would take days to debate where to sample next, and only then could the engineers decide on how to accomplish that. The management on autonomous rover mission needs to be more like the management of a manned mission.

Figure 4: Sample Selection Scenario.

For example, during *Apollo* EVA's decisions were made by small group of highly involved and intergrated personnel in a matter of seconds to minutes.

Much work remains to be done. A useful and comfortable interface, of which the one described in the previous section is but a sketch, needs to be developed and tested on cooperative examples. Much of the implementation detail in this paper, such as the nature of the schedule reasoning to implement the scenario in figure 4, have not be filled in. Although many details of the low-level rover architecture are partially independent of this interface, e.g., path following and hazard avoidance, the higher-level functionality should economically implement the autonomy that this form of interface deems useful. Indeed, even if this interface were never implemented, the exercise of designing it will yield data on interaction between autonomy and cooperative exploration that will be useful in rover design.

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