

Operations Concepts for Mars Missions with Multiple Mobile Spacecraft

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ABSTRACT

Missions are being proposed which involve landing a varying number (anywhere from one to 24) of small mobile spacecraft on Mars. Mission proposals include sample returns, in situ geochemistry and geology, and instrument deployment functions. This paper discusses changes needed in traditional space operations methods for support of rover operations. Relevant differences include more frequent commanding, higher risk acceptance, streamlined procedures, and reliance on additional spacecraft autonomy, advanced fault protection, and prenegotiated decisions. New methods are especially important for missions with several Mars rovers operating concurrently against time limits. This paper also discusses likely mission design limits imposed by operations constraints.

Key Words: Rover missions, planetary missions, Mars missions, autonomous spacecraft operations, sample return missions, surface operations, round trip light time

1. INTRODUCTION - THE PROBLEM

The most familiar planetary operations techniques are oriented towards planetary encounters / flybys, long-duration orbital missions, or stationary surface landers (Ref. 1). While similar in some respects to stationary surface landers, a rover's mobility introduces important new operations requirements.

The essential differences between rover operations and immobile surface operations boil down to two: (a) round trip light time delay combined with a non-deterministic

spacecraft environment, and (b) ground decision making speed. These are introduced briefly below. It is important that BOTH problems must be addressed. Solving only one of the two does not bring about a satisfactory rover mission.

1.1 Light Time Delay

Although JPL operations long ago learned to compensate for lengthy time delays introduced by round trip light time, the techniques which have evolved to support these kinds of missions are not sufficient for command and control of rovers, especially rovers being operated against time limits. This is because whereas stationary landers can be commanded as if their spacecraft states were deterministic, rover state changes more frequently and less predictably. The rover encounters and must react to obstacles whose exact effect cannot be predicted with much certainty beyond a few feet ahead, if then. A rover commanded in the traditional way would have to stop, downlink, and wait for recommanding every few feet. Since the light time delay to Mars is up to 22 minutes (and since many low energy trajectories from Earth to Mars typically arrive near the time of maximum light time delay! (Ref. 2)), rover progress would be unacceptably slow for many desirable mission scenarios.

As will be discussed below, the light time delay problem will be solved by onboard autonomy and changes to conventional spacecraft fault protection strategies. However, applying these solutions without speeding up ground decision making, as discussed in the next paragraph, could tend to result in rovers with too much autonomy.

1.2 Ground Decision Making Speed

Many spacecraft operations decisions are made by committee. Reasons include the fact that some decisions are too much responsibility for one person, the need to satisfy a diverse customer community, and the distributed nature of the engineering knowledge base.

Without speeding up ground decision making, autonomy would tend to result in rovers which either spend a disproportionate amount of time waiting for earth redirection, or they would have to be programmed to fulfill too many objectives without checking with ground for new priorities.

Sometimes it is proposed to get rid of committees for the sake of quicker decision making turnaround for rover missions. It is argued they could be replaced by a single well-trained operator assisted by automation. We take the view that there are too many diverse customer communities for this to come about, and until many rovers have been to the planets, so much responsibility cannot be vested in a single individual. We must streamline the decision making, true, but all legitimate customer communities must feel they are represented in the decision making process. First, we propose to have small negotiating committees, empowered to make decisions for the whole community. Second, we propose that the decision making process be guided by a "decision tree", prenegotiated between the customers and the project before the surface operations phase.

2. COMPOUNDING THE PROBLEM

2.1 Multiple Rovers

Missions with more than two rovers provide different operations problems from those with only one or two. The desire to reduce mission risk results in plans to provide for multiple rovers per mission: if a few fail, the mission can still be considered a success. But there's a downside. The operations system has to be able to operate a larger number of elements concurrently.

This tends to increase the number of personnel and interfaces, and magnify expectations of mission return.

2.2 Time Limits

Spacecraft operations are usually up against time limits. Regardless of the type of mission, funding is set to stop at a given time. Spacecraft consumables and mechanism lifetimes may be running out. Rover missions can have additional time limits.

If multiple rovers are used serially, in an operations environment with a minimum number of personnel, there will be a lot of pressure in conflicting directions to: (a) finish one rover mission quickly, or park it, and start the next one, (b) go slowly on the first mission to get the maximum out of it, wearing out the first rover before the second is deployed, and (c) switch to parallel and coordinated operations to speed up mission return.

Conversely, when multiple rovers are run in parallel, again with small operations teams, one can expect many more deadlines per day. Attempts to operate without increasing the number of personnel will result in increased risk for individual rovers.

Sample return missions have an additional source of time pressure. Samples must be returned to the lander in time for final sample packaging and return rocket ascent to meet low energy return flight schedules.

3. SOLUTIONS

This paragraph discusses the range of solutions proposed to mitigate the above problems for small-rover missions being most actively proposed in NASA at the present time.

3.1 Onboard Autonomy

Onboard autonomy is needed so that the rover can continue to work without being recommanded more than once per day. It must be able to react to many unexpected

changes in its environment as it moves along a planned course. Our studies indicate that a Mars rover mission without autonomy might be expected to have a disappointingly low mission return (Ref. 3).

Autonomy must come with a specialized, higher-order spacecraft command language. This should serve to effectively eliminate "sequencing" in the usual sense from the routine operations tasks (though some sort of software simulation could still be utilized). In effect, the lower-level sequencing and command development functions, conventionally done on the ground, are moved onboard. The use of this limited autonomy means that the rover schedule is non-deterministic. (Note that low-level commanding and deterministic control is still available to ground for exception conditions: see paragraph 3.7.)

JPL has developed and proposed a "behavior-based" method of rover command and control (Refs. 4, 5). It attempts to achieve high level objectives provided by earth commanding, while reacting to obstacles within the range of its programming. Although not yet fully developed, the basic capability has been demonstrated (Refs. 5, 6). This is opposed to forms of autonomy proposed in earlier years for large-rover missions, in which autonomous rovers perform onboard replanning (Ref. 3). For that reason, the onboard decision-making architecture is quite different from that proposed for those larger rovers (Ref. 7).

It is important that this form of autonomy is used strictly to simplify the mission operations and enhance return. Complex, subsystem-oriented autonomy is sometimes proposed for other spacecraft which has the ironic effect of increasing the number of engineering activities and the need for earth checking of spacecraft states. Autonomy with these effects would increase our costs while reducing mission return and should not be considered.

3.2 Maintain Fluid Expectations

Granting autonomy to the spacecraft results in a non-deterministic situation. Exact simulations of mission results cannot be expected. For example, if 10 activities are programmed for a certain day, the rover might execute only six if it finds the environment out of the expected range at some point. Alternately, it could execute more than 10 activities if programmed to attempt autonomous recoveries. All this means that even data quantities cannot be projected exactly with respect to time.

Simulations of rover activity may not be accurate, but it is important that people do not conclude that a lack of accuracy here is any kind of a mission failure. This could present a problem to those who feel a need for these exact projections.

3.3 Reduced Team Sizes, Simplified Procedures

A core operations team for each rover would be reduced in size, to be able to turn around uplink commands at the rate of one a day. This small team would need to organize its activities around the Mars day length for certain periods, depending on mission duration and objectives. Time would still be needed for daily meetings with other rover teams and management. This keeps the core team in touch with the rest of the project and the outside world. It is needed because of continually changing priorities, the need to keep each other abreast of newly discovered facts, and (we must assume) spacecraft problems. The use of prenegotiated decisions (see 3.5), will facilitate streamlined procedures.

3.4 Daily Command Turnaround

We have proposed daily ground recommanding of Mars rovers. After trial and error with various scenarios, it turns out that daily turnaround seems to provide for a reasonable amount of rover activity, a reasonable amount of earth control with frequent opportunities for redirection, and enough time to receive data describing each daily activity period and spacecraft health.

An exception allowing for two command turnarounds per day is being considered for specific, highly constrained situations in missions where daylight periods are long and projected surface lifetime is short. These fast command turnaround scenarios will be facilitated by prenegotiating decisions where possible, paragraph 3.5.

It is possible to conceive of highly autonomous missions where rovers simply wander around and send back results. Recommending might be sporadic, and would be devoted to resetting the priorities of the autonomous control system as the mission progressed. None of the Mars rover missions currently being proposed seem to fit this type of scheme.

3.5 Prenegotiated Decision Tree

In order to speed up ground decision making, we foresee the need to negotiate decisions before landing. The results of this negotiation will be a decision tree in which we try to anticipate as many situations as reasonable. An attempt will be made to "cover the waterfront" so that when situations don't meet the prenegotiated ones exactly, there are at least enough similarities to speed things up. We are guessing this decision tree might have on the order of 100 nodes, depending of course on the type and scope of the mission.

3.6 Rover Fault Protection Strategy

JPL spacecraft are normally equipped with "fault protection" capabilities which are automatically invoked whenever onboard diagnostics detect error states. These routines initiate a canned recovery procedure. Generally the spacecraft is forced into a safe state, but one that is nonproductive with respect to mission return, until returned by the ground to a productive state. Mobile spacecraft autonomy calls for a change in the usual concept of spacecraft fault protection. This is because the rover frequently gets into unpredictable states during autonomous operations. If the usual fault protection were allowed to interrupt the rover's progress at those times, we would get no

benefit from the autonomy. Luckily this change need not take the form of a wholesale redesign, and need not engender undue acceptance of new risks.

Assuming NASA Class A (ie, low-risk) rover missions, we still need fault protection against pathological conditions. What needs to be added is a layer of protection between behavior control and fault protection. This layer handles conditions which are in some sense unexpected but not pathological. This layer corresponds neatly to what roboticists refer to as "reflex" technology. The rover uses reflexes as part of its autonomy to get through a large number of unexpected but generically foreseen obstacle conditions, while staying roughly on course, but is programmed to invoke the lower levels of fault protection when these reflexes fail to keep it out of trouble. Whereas the behavior control layer and reflexes are non-deterministic, the fault protection modes below the reflex level are deterministic, to facilitate troubleshooting and recovery.

Missions below NASA Class A can take more risks as part of lowering mission costs. The rover missions being most actively considered at this time fall into these classes. Fault protection may be less rigorous, perhaps offset by element-level redundancy, ie, more rovers per mission. In these cases, robotic reflexes will still be used as part of a natural implementation of the autonomy scheme.

3.7 Lower Level Commanding

Unless it is decided that higher risk is acceptable for some rover mission, all the traditional spacecraft and operations functions need to be available for troubleshooting in the event of spacecraft problems. Fallback capabilities must include the ability to override the autonomy and use a set of low-autonomy spacecraft operations commands and modes. These low-autonomy modes correspond to conventional spacecraft operational modes. Unlike the non-deterministic operations modes discussed above in connection with autonomous operations, these modes are

deterministic. They may be used to get out of fault protection states, or to operate in environmental or hardware failure situations for which the autonomy is not programmed. In general, operating extensively through low-level commands must be expected to greatly reduce mission return.

3.8 Serial Operations Preferred

Relying on parallel operation of multiple rovers should be avoided until we have a better hands-on understanding of rover mission pitfalls -- most obviously uncertainties about the terrain. It should be recognized, though, that it may be desirable to include more than one rover even on near-term missions, to reduce the risk arising from depending on just one unit. In the event that several rovers are landed close in time, it is proposed that rovers nevertheless be deployed and operated serially through the point of mission success for each rover, then reactivated and selectively operated in parallel to increase mission return.

4. RELATIONSHIP TO PROPOSED MISSION SET

This paragraph relates the above principles to three proposed rover missions: MESUR Pathfinder, MESUR Network, and a small-rover Mars sample return mission.

MESUR Pathfinder may be authorized as a precursor to MESUR Network. It is presently conceived as having one or two landers. One rover per lander may or may not be included in the flight system. If two rovers and landers are flown, and if the two aircraft are provided delta-V for separated arrival dates, serial operation of the two rovers is envisioned. If a short surface mission duration is decided on, and the lander(s) is targeted for an area with a long daylight period, two command turnarounds per day may be attempted.

MESUR Network is presently conceived as having 16 landers, some or all of which may have a rover. We expect the landings in waves of four or eight, possibly separated

by a few weeks, possibly separated by the two years between launch opportunities. An orbiter assists in communication, but not rover navigation. We picture deploying and operating each rover serially for about ten days. Once each rover from a given landing "wave" has been deployed and operated for ten days, we foresee switching to parallel operation of selected rovers for enhanced mission return.

A small Mars sample return mission has been described which has two landers and one or two rovers per lander (Ref. 8). In this case an orbiter is needed for communications and assistance in navigation. Rovers would be asked to cover up to several kilometers in the course of a mission, to get a diversity of samples. A single command might be sufficient for a kilometer traverse. The current thinking is to run all the rovers in parallel, once one sample has been stored in each lander using serial operations. A separate operations team is needed for each rover, and their activities must be timed with respect to local daylight to optimize return.

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