MARS EXPLORATION MOBILITY WITHIN SAFETY CONSTRAINTS

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Abstract

Whether on foot or by vehicle, planning for any safe exploratory activity at a Mars base will need to achieve a complex balance of factors such as: i) the value of the exploratory target site ii) the life support consumables available iii) the capabilities of the vehicle (or the explorer in a spacesuit) iv) the available daylight hours and v) the terrain the expedition must traverse. The balance is complex because the factors themselves are not simple (e.g. the capabilities of a vehicle may include range, speed, climbing ability, maximum payload etc.) and the variables interact in complex ways (e.g. available life support consumables might vary depending on mission and vehicle type, and may be affected by terrain). Reliable methods for planning safe sorties will likely depend on constraint-satisfaction methods - almost certainly delivered as software - moderated by human judgement. A geometrical method for planning under a daylight-only driving policy is offered as an example of a constraint-satisfaction method. It is proposed that this method be tested by implementing it in sortie planning software on the Starchaser Rover as part of the operational testing of Project Marsupial, where it would be combined with human judgement.

Introduction

Contemporary Mars surface operations planning typically distinguishes between two types of exploratory vehicles: unpressurised rovers (a small, unenclosed Apollo LRV-like vehicle able to extend the life support duration of explorers in spacesuits with a range of up to 500km) and pressurised rovers (a larger vehicle capable of supporting explorers in a shirtsleeves environment for days at a time for distances of 500-1000km) [1,2]. It is usually convenient to classify exploratory sorties in terms of range from landing site habitat, duration and/or vehicles required. Short range sorties would be conducted on foot to range over a range of about 10km. Medium range explorations would be conducted over a range of up to about 200km using an unpressurised rover. Longer range sorties would require a pressurised rover.

Whether on foot or by vehicle, planning for any safe Martian exploratory activity will need to achieve a complex balance of factors such as:

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- the capabilities of the vehicle
- the available daylight hours
- the terrain the expedition must traverse

The balance is complex because the factors themselves are not simple (e.g. the capabilities of a vehicle may include range, speed, climbing ability, maximum payload etc.) and the variables interact in complex ways (e.g. available life support consumables vary depending on mission and vehicle type, and may be affected by terrain). It will be argued here that given a specific travel risk policy, and given some capacities expected to be available to rovers by 2020, the maximum radii of medium and long range exploratory circles - and thus the possible sites which might be visited at the Meridiani site - should both be constrained by a single factor: the average maximum safe speed at which an unpressurised rover may be driven over unexplored territory during daylight hours. This will be shown to hold whether the exploration is being conducted by unpressurised rover, or by pressurised rover. A new sortie planning method guaranteeing that a putative mission sequence is both feasible and safe within one such constraint - daylight driving - is proposed. The method is also applicable to short-range exploration near the base without vehicles, when the crucial factor is average walking speed in daylight hours.

Capacity of Rover Vehicles: 2005 and 2020

There are good reasons to design Mars rovers around a fuel cells which power electric motors at each wheel via an electronic transmission [3]. Such vehicles can be simpler, less massive, more controllable and more reliable than other, more familiar vehicular drive trains. Although fuel cell powered vehicles are not likely to compete with hybrid petrol-electric power plants in Earthbound automobiles in the next two decades, the reasons for this have more to do with the economics of mass production and the legacy of a distribution system designed to deliver fossil fuels than with any deficiency of fuel cells as a power plant. These factors do not apply to highly specialised exploration vehicles. According to a 2003 MIT report, with normal development of fuel cell vehicles we may expect improvements in energy consumption of 52%-65% over the next 15 years [4]. (These figures will underestimate the value for a Mars rover, since they include total energy over the lifetime of the vehicle, including manufacture - again, not applicable in the case of a vehicle which is not mass-produced). Furthermore, the power-to-weight ratio, cost and low-temperature performance of fuel cells are all rapidly improving [5].

A contemporary vehicle of about the size and mass of the putative unpressurised rover is the 1,760kg 80kWe Honda FCX, capable of carrying 4 persons for about 257km between refills [6]. The fuel for this vehicle is hydrogen gas, which would probably not be available in quantity from in-situ resource production, at least for the first missions. Nevertheless, taking into account the mostly flat landscape likely around safe landing sites, the lower gravity and the lower payload requirements, it seems reasonable to expect that by 2020 this target could reached or exceeded in a less massive, lower powered rover using a fuel available from in-situ resources, such as carbon monoxide. We should also expect equivalent improvements in the performance of the larger, pressurised rover. Today, 190KWe fuel cell passenger buses under test in cities in Europe, Australia, China and the United States can carry up to 70 persons about 200km between refills [7]. Again, given the rate of improvement of fuel cells and associated vehicle technology, it seems reasonable to expect a better performance from a pressurised vehicle, the payload for which would be far less than in a commercial bus.

Daylight driving risk policy

Assuming an unpressurised rover could sustain an average safe travel speed V_{ur} of 30 km/h, and that the EVA suits of 2020 can support life for 10 hours, the maximum theoretical safe radius of exploration appears to be 300 km. However, this oversimplifies the reality, since i) reserves of consumables could be drawn from the unpressurised rover and ii) travel at night would probably be considered too risky in an unpressurised rover, due to the cold and reduced visibility, in all but the gravest emergencies. So given a fully provisioned unpressurised rover which could extend life-support of the crew (say, to 16 hours), the maximum radius is actually more likely to be limited by the available daylight hours. In equatorial regions this is roughly 12.25 hours in all seasons [8], during which time the unpressurised rover could theoretically be driven back a maximum of 367.5 km.

Geometrical sortie planning method

To describe the constraints and lay the groundwork for the geometrical sortie planning method, we begin by considering the case of medium range sorties. Later, the idea will be extended for long and short range sorties. Given the policy of driveback in daylight only, there will be a medium-range exploration circle of safety around any landing site on Mars with its radius set by the amount of daylight remaining and the speed of the unpressurised rover. Explorers must stay within this circle at all times to be able to reach the habitat before nightfall. Moreover, this circle shrinks steadily as the daylight hours are consumed. This relationship can be expressed as:

$$(T_d - T_e) - \frac{R_s}{\overline{V}_{ur}} = 0$$

where T_d is total daylight hours
T_e is elapsed hours (hours since dawn)
$\overline{V}_{ur}$ is the permitted average driveback speed limit of unpressurised rover
R_s is the maximum safe range

Now given an average driveback speed limit (again set by practical safety considerations rather than rover capabilities), it is possible to calculate a maximum safe range for any time of the day, or conversely for a given range calculate the latest departure time for safe return:

$$T_e = T_d - \frac{R_s}{\overline{V}_{ur}}$$

Remaining with a T_d of 12.25 hours and a $\overline{V}_{ur}$ of 30kph, we are then able to express the safety constraint at Meridiani as a graph (see Figure 1).

The line of safety represents the maximum allowable safe distance from base at any time during daylight hours. At dawn an unpressurised rover could be at a maximum of 367.5km from the base; by dusk it must have reduced this to zero. But for medium range sorties, not all positions on the line are feasible, because the rover must depart the base no earlier than dawn. Therefore a line of feasibility is added which forms a triangle centred on the local noon, which represents the furthest

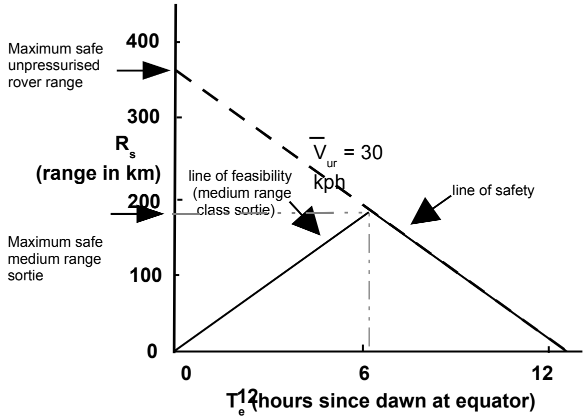

Figure 1. Constraints on a medium range sortie (equatorial region)

the rover can traverse and still return safely (183.75km). All medium range sorties must be conducted at points under the area formed by this safety triangle.

The earliest time a rover could reach a target at a given range may be read off the line of feasibility; the latest time it may remain there is read off the line of safety. A safety margin of say 5% may be added to the diagram by shifting the apex of the safety triangle 0.6125 hours to the left but maintaining the dawn and dusk crossing points at zero range. This has the effect of making all departure and arrival times away from the base slightly earlier, which protects against small unexpected delays (Figure 2).

Usually sorties would include one or more stops of various durations at the target for exploratory work. A single stop must fit within the triangle of safety truncated horizontally by the range. In a sortie with multiple stops, the alternating sequence of bands representing drive and stop operations must arranged left to right so that they all fit within the available time/range limits. Since the most distant targets are generally the most constrained, sortie planning should begin with those.

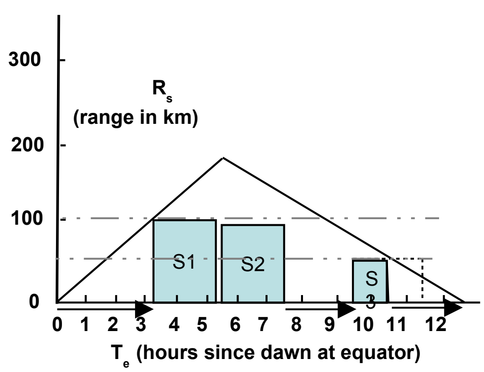

Fig 2. A feasible and safe sortie with a 5% safety margin.

Figure 2 shows a feasible and safe medium range sortie, which originates at a habitat placed for the sake of example near the geometric centre of the NASA Mars Exploration Rover Opportunity's landing ellipse at 5.0° W and 2.0° S (see Fig. 3).

Suppose that the sites to be visited are

1) the rim of a large filled double crater on the western boarder of the P2 middle plains of Terra Meridiani 100 km northwest

2) the small hematite "island" outside of main local deposition boundary 98km to the northwest

3) the north rim of an large undivided crater at the southern limit of the P2 middle plains 50km south-southwest.

A stop of two hours is initially proposed for each site. Moving from left to right and beginning with the furthest site (double crater), and assuming the rover can leave at first light, the horizontal 100km line intersects with the line of feasibility at 3.3hrs. This is the arrival time at Site 1. The rectangle representing the proposed 2-hour duration at this range falls entirely within the safety triangle, and so is permitted. Next a short traverse of 2km (3.9 minutes) is measured off, marking the arrival time at Site 2. The two hour rectangle at the 98km range still fits beneath the safety rectangle. Next comes a third traverse of 100km to Site 3, at which the 50km horizontal line intersects the line of safety at approximately the 9.5 hour mark.

Now however, we encounter a problem: the 2-hour rectangle representing the stop cannot fit beneath the line of safety. However, this is easily overcome: if the S3 duration was reduced to 1.5 hours, it would be safe, so that solution is plotted. Alternatively, if 2 hours at Site 3 was required, the duration of S1 and/or S2 could be reduced to allow more time at S3.

Long range sorties are also constrained by the unpressurised rover driveback, but can reach target sites at greater ranges if we assume that the pressurised rover will carry the smaller unpressurised rover with it, perhaps folded up on the roof, just as the Apollo LRV was folded into a package small and light enough to be carries on a Grumman LEM [9]. Here we also stipulate that in the event of an accident it will still be possible to stay at the accident site overnight, either using the (immobilised) pressurised rover or else camping in an emergency inflatable shelter. The overnight stay allows for a departure at or near dawn. Under these conditions, the area of safety becomes the larger triangle in Figure 1, thus providing the maximum safe driveback of about 348 km, allowing for a 5% margin, which stays constant regardless of when the pressurised rover accident occurs.

In years beyond the first explorations, when a second or third pressurised rover could be delivered, the full range of these long duration vehicles would become safely available. There would be a way to extend this limited range for a first mission if necessary, however. As described in [3], the pressurised rover would tow a detachable trailer containing consumables for life support, an inflatable shelter and power. This would be left at a points along the outbound route corresponding to the safe driveback circle set by available daylight hours, where it could serve as overnight camping stop for a crew driveback in an unpressurised rover. The trailer could also serve the same function for a rescue crew coming from the habitat to aid

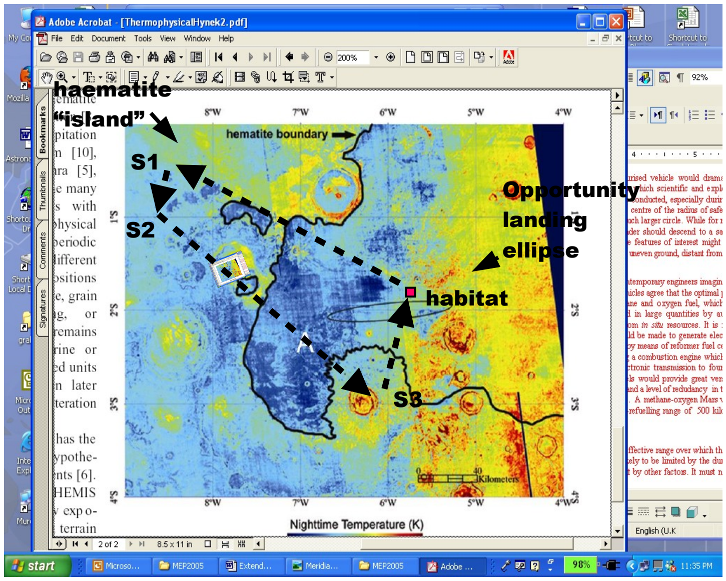

Fig 3. The plotted path of the medium range sortie.
(map from Hynek, et.al., 2004 [10])

the stranded sortie team. The trailer would be picked up during the return leg of the journey for reuse. Such a portable life-support trailer could also have other uses in emergencies, a so are consistent with the design philosophy of multi-use technologies.

The geometric method of feasible, safe sortie planning applies for short range explorations on foot. Here, the crucial factor is average safe walking velocity in an EVA suit, which might be conservatively estimated to be 2km/hr, which sets the maximum feasible, safe radius to 12.25km. Note that short-range safety circles of this radius may also be centred on the pressurised rover during long duration missions, where the pressurised rover becomes the safe haven after dark.

Safety Constraint Software for Mission Planning

To support mission planning before sorties and to facilitate replanning in the event of unexpected eventualities, these methods would be embodied in software running in the rovers and inside the habitat. For the practical purposes of analog research, it is proposed that these ideas and software be developed by adding an algorithm implementing the geometrical method describe above to the existing navigation software package of the Starchaser Rover [11]. With the software suitably parameterised for the daylight hours of Central Australia, experimental sorties could be planned, modified and executed with the software in order to subject it to human factors testing in the field.

Other factors must also be included to constrain mission plans within safety limits, but they will use different methods. N.J. Wilkinson, for instance, has suggested a methodology for determining safe, low environmental impact traversal paths using local topographic and slope data, and which takes into account the relative locations of the base camp and sites of interest.

His traverse generation assistant aims to quickly build up a network of roads to which the rover would confine itself, conferring the benefits of proven safety and mechanical damage limitation to the terrain [12]. Available life support consumables are already measured in simulation by the Starchaser's software, but these measurements would need to form the input to experimentally determined equations representing the relationships between stored consumables (air, water, fuel, etc.) and actual time/distance, and best displayed graphically on the route map.

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