Probabilistic guidance for scheduling Mars rover traverses

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Abstract

The problem of optimizing the use of a rover on Mars for science and mobility is very similar to running a search for a missing person on Earth. In both cases, there are limited resources available, a search area that can be defined, and environmental factors. The Search and Rescue community has over the years developed strategies for making decisions in such an environment. Borrowing techniques from the Search and Rescue field, we provide a framework within which the problem can be broken down into smaller components for which the probability of success or failure can be estimated. This framework provides a basis for discussion which was not here-to-fore available

1. Introduction

The problem of optimizing the use of a rover on Mars for science and mobility is very similar to running a search for a missing person on Earth. In both cases, there are limited resources available, a search area that can be defined, and environmental factors. The Search and Rescue community has over the years developed strategies for making decisions in such an environment. [4, 5]

Recent Mars Exploration Rover (MER) field trials in Arizona have concentrated largely on identifying rocks and features very close to the landing site. In review of these exercises, staying close to the lander was due largely to two reasons. First there is a concern that no science target be overlooked, and second, there is a concern that the rover has a limited lifetime and may fail during the traverse to a more distant location (e.g. local science is better than no science). These concerns in tandem drive the scientist to examine a small local area thoroughly.

Borrowing techniques from the Search and Rescue field, we provide a framework within which the problem can be broken down into smaller components for which the probability of success or failure can be estimated.

This approach has the advantage of providing a framework within which to debate the relative merits of candidate traverses based on specific, defined assumptions, goals, and risks. While many of these quantities will be estimated based on experience and some intuition, the approach brings these items into focus and encourages a healthy debate.

2. Calculating probabilities

By subdividing the search region and assigning probabilities to parameters such as the probability of a feature existing in a certain area, the probability of identifying that feature if the rover visits the area, and the probability of breakdown during the traverse, it is possible to optimize a system of equations to maximize the probability of success. This can in turn be used to guide the scientist when making plans for the rover operations.

We outline the methodology here and illustrate it with an example. The example was taken from a practice exercise in which a rover was taken to a remote location in Arizona by one of the authors (Anderson). Based on 3m resolution aerial photographs, the other author (Hurst) designed an initial search.

2.1. Step 0: Define the total search area.

The MER rovers specifications call for a maximum traverse distance of 600 m over 90 sols. For the recent field trial in Ariona, 300m for 20 sols was used to simulate Mars operations. For this study assuming MER-like conditions, a circle of 600 m radius around the lander defines the maximum search area. If there is terrain that precludes access by the rover, that area is excluded from the total search area and is not considered further. The circle of 600 m radius around the lander is shown in Figure 1.

2.2. Step 1: Subdivide the search area.

The total search area must be subdivided into smaller regions that could be traversed by the rover in one or two sols, but may be larger if an area is deemed to be largely homogeneous. The subregions are chosen by scientists based on all information available. Each subregion should address one feature or one question. The subregions should have boundaries that are clearly defined and easily recognizable in order to facilitate both discussion and implementation.

The subdivision that was generated for the example search is shown in figure 1. The image shown is the only

information that was available at the time the subdivision was done. From the image several overall observations were made. First, a NE trending lineation was observed in the eastern portion of the image. A second, less developed NW lineation was observed in the southern part of the image. There appears to be a plateau area to the east and north, a set of small washes, a larger lowland plain in the central part of the image, and an area of jumbled topography in the NW portion of the image.

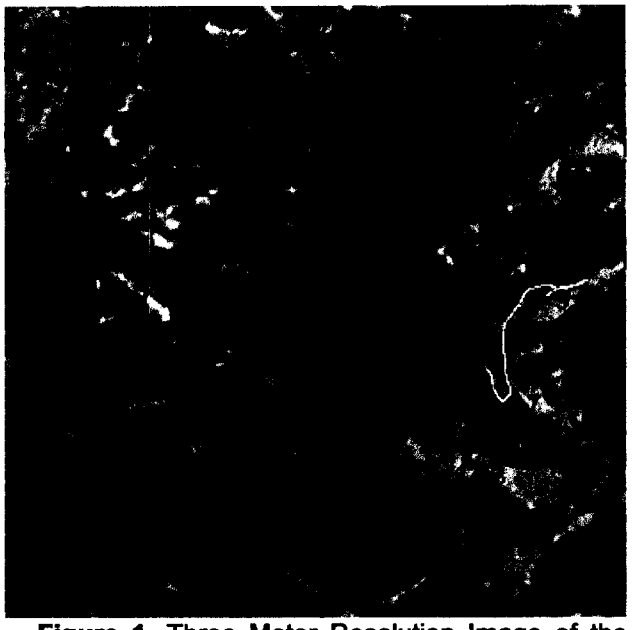

Figure 1. Three Meter Resolution Image of the Search Area. The circle is 600 m radius from the lander. The area has been subdivided into 14 regions. The region labels consist of the region ID and the interest level (1-10) separated by a hypen. Path 1 of the rover is shown in white.

The subregions were chosen as shown in figure 1, with the justification for each region given in Table 1.

2.3 Step 2: Assign interest level to each region

Based on all available information at the time, each region is assigned a numerical interest value I. In our example, we used a scale of 1-10 with 1 being not important, and 10 being highly desirable. Thus area 2 received the highest interest value because it has a small cliff on the northern bank of the wash. The wash will bring materials from the catchment area, and the cliff will expose the stratigraphy. Conversely area 11 received a low importance score because materials found there are likely to be relatively fine grained and difficult to trace back to their source area.

The interest score for each area and brief comments justifying the score are shown in Table 1.

The probability of interest P_i is then just

$$P_i = I/10$$

The interest level can be thought of as a "clue density" or "clue importance" factor. If the area in the subdivision does not have a uniform clue density and clue importance throughout, then consideration should be given to subdividing the region farther.

2.4 Step 3: Assign probability of detection

Assuming the rover visits a region, we need to estimate the probability that interesting things will be found. The Search and Rescue community has devoted considerable effort to this end, developing tables for the probability of detection based on search method, number of searchers, and time spent. Typical experiments consist of salting an area with a known (to the researcher) number of clues, and then getting a group of people to search the area using different numbers of searchers and search techniques. The probability of detection is given by the number of clues found divided by the number of clues salted.

For a rover geologist on Mars, the probability of detection will vary according to the type of target considered. For example, a white rock among a group of black rocks will stand out, while a change of sand grain size may be less obvious.

Novelty detection software [1] can boost the likelihood of detection but is beyond the scope of this paper.

Determining the probability of detection is an area that would benefit from some research and controlled experiments using rovers here on Earth.

For the purposes of the example in this paper, we have assumed that the probability of detection is proportional to the distance traveled in the region.

$$P_d = K\,r$$

Where K is a proportionality constant, and r is the traverse distance in meters. In our example, we assume that K is the area that passes within 10m of the rover divided by one standard "clue area" assumed to be 600 m^2 so $K = 20/600 = 1/30$.

The "clue density" for a given region can be thought of as $600/P_i$.

2.5 Step 4: Estimate the probability of rover breakdown

A major concern when scheduling a rover geologist is that the rover may break down, precluding visiting any more sites. This issue has sometimes been referred to as the "sniper in the hills" syndrome. We have quantified this risk under the assumptions: 1) Our confidence in the robustness of the rover and our ability to drive it safely goes up as we gain experience, 2) the likelihood of breakdown due to wear increases with total distance the

rover has traveled, and 3) the likelihood of breakdown increases in rougher terrain.

We have chosen functions and constants to reflect these assumptions for our example.

We represent the probability of failure as a function of our experience as

$$P_e = 0.9 * 2^{-(d/4)} + 0.1$$

Where d is the total distance traveled by the rover since leaving the lander.

We represent the probability of failure as a function of wear as

$$P_w = 1 - e^{-d/D}$$

Where d is the total distance traveled since leaving the lander, and D is the mean distance between failures for this rover. We have used D= 1800m or 3 times the anticipated mission distance. In deciding the next move however, the incremental probability of failure due to the contemplated distance to be traveled is required and is calculated as

$$P_w(inc) = P_w(n)-P_w(n-1)$$

Where n is the nth traverse, and $P_w(0) = 0$.

Lastly, we represent the probability of failure as a function of topography as

$$P_t = MAX [s/Sm, h/Hm]$$

Where s is the RMS slope in radians at 0.3m scale, and h is the RMS height in meters at 0.3m scale for the contemplated traverse. Sm and Hm are the maximum traversable slope and height derived from engineering data or field tests. We have assumed Sm = 0.5 radians, and Hm = 0.2m in our example. In our image, we have assigned s=0.1 to smooth regions, s=0.2 to intermediate regions, and s=0.4 to rough regions. We did not use h.

The RMS slope and RMS height at 30 cm scales can be generated from imagery with 3 m resolution or better. Shepard et al [2] [3] discuss a method of extrapolating the RMS slope and height at small scales from a measurement of the fractal dimension given by the Hurst exponent and the RMS slope and RMS height at a larger scale. The extrapolation appears to be reliable for 1-2 orders of magnitude. We have not done this for our example but have instead assigned values to s and h based on a visual inspection of the 3m imagery.

These three components are combined to yield the total incremental probability of failure during the contemplated move as:

$$P_b = 1 - (Pe) * (1-Pw(inc)) * (1-Pt)$$

2.6. Step 5: Obtain the overall probability of success

The probability of interest, the probability of detection, and the probability of breakdown are combined to obtain the overall probability of success for a given traverse:

$$P = P_i * P_d * (1-P_b)$$

2.7. Step 6: Choose the optimal traverse

Having generated a suite of possible traverses and the probability of success for each one, choose the set of traverses which are logistically consistent and which maximize the overall probability of success, or argue why one or more sub-P is not correct.

It is important to note that this process is not one that is done once and then frozen. As information comes in our knowledge base increases and therefore all variables in the probability calculations change. We may get some information early in the traverse that increases the interest level for a certain region. Engineering data from the rover may hint of an imminent breakdown, We may find that the topography is different than predicted from the initial imagery. Areas behind the rover naturally become outside the possible future search area as the traverse progresses. All of these factors would provoke a reevaluation of the probabilities of success, and a consequent replan for the remaining traverse.

3. Discussion

The single largest difficulty encountered in working through the example, is estimating the probability of detection (Pd) for a given traverse.

A way to rectify this situation is to experiment with earth-bound rover mockup data to determine the probability of detection of known target types. Presumably, the scientist will have some idea of what type of targets might be expected in a given region from the orbital imagery if nothing else.

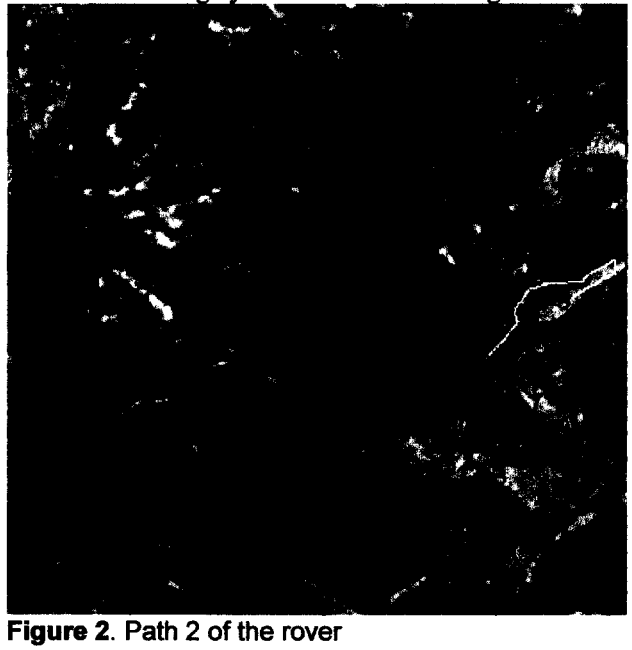

Figure 2. Path 2 of the rover

We present two possible paths. The first path is shown as the white line in Figure 1 and in Table 2. The second path is shown in Figure 2 and Table 3. Both paths have similar overall probability scores. Path 1 has 6.5, and Path 2 has 6.8. This difference is similar to the probability gain from one sol of activities. It is significant that Path 2 gains a higher probability score earlier in the traverse. Since it also has a higher overall probability score it would be the preferable path. It should be noted however that the higher score of Path 2 relies on being able to find a route out of wash 2 that does not retrace the path on the way in. If such a route can not be traversed, then the probability of detection of something new would decrease on the portions of the path that are being retraced.

In this example, we have assumed that the interest level, Pi, remains constant during the time the rover is in the area. A better assumption might be that the interest level will decrease as the rover examines more and more of an area. That is, presumably the most important clues would be found early in the visit and the probability that another important clue would be found decreases with time.

4. Conclusion

We have described a methodology for breaking down the problem of designing a search path for a rover geologist on Mars into smaller, easily understood and debatable pieces. The performance of various candidate paths can be compared numerically to each other with explicit and specified underlying assumptions.

10. References

[1] R. Castaño, R. C. Anderson, T. Estlin, D. DeCoste, F. Fisher, D. Gaines, D. Mazzoni, M. Judd, "Rover Traverse Science for Increased Mission Science Return," *Proceedings of the 2003 IEEE Aerospace Conference*, Big Sky, Montana, March 2003.

[2] Shepard, M.K., "Estimating Surface Roughness at Scales Below Sensor Resolution, http://web99.arc.nasa.gov/~vgulick/MSLS99_Wkshp/Shepard_abs.pdf

[3] Shepard, MK, Brackett RA, Arvidson RE, "Self-Affine (Fractal) Topography – Surface Parameterization and Radar Scattering", JGR, 100, 11709-11718, 1995.

[4] LaValla and Stoffel Eds, Search is an Emergency: A text for Managing Search Operation, ERI, 1987.

[5] Colwell, M, New concepts for Grid-Searching, Technical Publications Series, International Search and Rescue Trade Association V1, N1, 1992.

Table 1. Search Subregions

Label	Pi	comment	Area (m^2)	roughness
1	7	wash, different orientation from other washes	7200	0.2
2	9	wash and cliff	10854	0.2
3	7	wash	11628	0.2
4	7	mouth of wash	10656	0.1
5	6	plains	12600	0.1
6	4	plateau	32193	0.4
7	4	plateau	29160	0.4
8	8	edge below different terrain	22500	0.2
9	4	plateau	13608	0.4

Table 2. Probabilities for Path 1. The distance of the planned traverse and the azimuth are given for each day. The probabilities given are: P = probability gain for that day; Pi = probability that something of high interest (a clue) exists in the subregion; Pd = probability that the rover will discover a clue if it visits the subregion (the clue is assumed to exist); Pb = probability that the rover will break down during the traverse; Pe = probability of failure as a function of experience used in calculating Pb; Pw = probability of failure as a function of wear used in calculating Pb; Pt = probability of failure as a function of topography used in calculating Pb.

Sol	Dist(m)	Az(deg)	Description and Justification	P	Pi	Pd	Pb	Pe	Pw	Pt
1	1	165	Sample soil and rocks very near lander. Probability of breakdown is unknown and hence assumed high. Guarantee some science. Area 5	0.0014	0.6	0.03	0.928	0.91	6E-04	0.2
2	10	165	Sample materials at mouth of wash, Area 5	0.0395	0.6	0.33	0.802	0.7516	0.006	0.2
3	24	165	Sample materials in wash, Area 5	0.3284	0.6	0.8	0.316	0.1329	0.014	0.2
4	24	165	Sample materials in wash, Area 1	0.3291	0.7	0.8	0.412	0.0021	0.019	0.4
5	24	40	Traverse wash and sample materials, Area 1	0.3271	0.7	0.8	0.416	3E-05	0.027	0.4
6	24	0	Sample N wall of wash, Area 1	0.3255	0.7	0.8	0.419	5E-07	0.031	0.4
7	24	0	Traverse plain, Area 5	0.369	0.6	0.8	0.231	8E-09	0.039	0.2
8	24	0	Traverse plain, Area 5	0.3673	0.6	0.8	0.235	1E-10	0.043	0.2
9	24	0	Traverse plain, Area 5	0.3644	0.6	0.8	0.241	2E-12	0.051	0.2
10	24	0	Traverse plain, Area 4	0.4231	0.7	0.8	0.244	3E-14	0.055	0.2
11	24	40	Turn into wash along base of cliff, Area 2	0.4048	0.9	0.8	0.438	0	0.063	0.4
12	24	40	Traverse wash, Area 2	0.403	0.9	0.8	0.44	0	0.067	0.4
13	24	54	Arrive at base of cliff, Area 2	0.3998	0.9	0.8	0.445	0	0.075	0.4
14	24	90	Along base of cliff, Area 2	0.3981	0.9	0.8	0.447	0	0.079	0.4
15	24	90	Along base of cliff, Area 2	0.395	0.9	0.8	0.451	0	0.086	0.4
16	24	90	Along base of cliff, Area 2	0.3933	0.9	0.8	0.454	0	0.09	0.4
17	24	65	Enter upper part of wash	0.3902	0.9	0.8	0.458	0	0.097	0.4
18	24	245	retrace path, nothing new Area 2	0.0486	0.9	0.1	0.46	0	0.1	0.4
19	24	245	South side of wash, Area 2	0.3856	0.9	0.8	0.464	0	0.107	0.4
20	24	245	South side of wash, Area 2	0.3841	0.9	0.8	0.467	0	0.111	0.4
			SUM	6.4774						

Table 3. Probabilities for Path 2. See Table 2 caption for a definition of the probabilities on the right side of the table.

Sol	Dist(m)	Az(m)	Description and Justification	P	Pi	Pd	Pb	Pe	Pw	Pt
			Sample soil and rocks very near lander. Probability of breakdown is unknown and hence assumed high.							
1	1	45	Guarantee some science. Area 5	0.0014	0.6	0.03	0.928	0.91	6E-04	0.2
2	10	45	Travese plains, Area 5	0.0395	0.6	0.33	0.802	0.7516	0.006	0.2
3	14	45	Sample semicircular cliff Area 5	0.1926	0.6	0.47	0.312	0.1329	0.008	0.2
4	24	0	Sample materials in wash, Area 4	0.4345	0.7	0.8	0.224	0.0117	0.019	0.2
5	24	32	Traverse wash and sample, Area 2	0.4228	0.9	0.8	0.413	0.0002	0.021	0.4
6	24	32	Traverse wash and sample, Area 2	0.4185	0.9	0.8	0.419	3E-06	0.031	0.4
7	24	60	Traverse wash to base of cliff, Area 2	0.4174	0.9	0.8	0.42	4E-08	0.034	0.4
8	24	90	Base of cliff, Area 2	0.4131	0.9	0.8	0.426	7E-10	0.044	0.4
9	24	90	Base of cliff, Area 2	0.4122	0.9	0.8	0.428	1E-11	0.046	0.4
10	24	90	Base of cliff, to center of wash, Area 2	0.4079	0.9	0.8	0.433	2E-13	0.056	0.4
11	24	90	Base of cliff, cross wash, Area 2	0.407	0.9	0.8	0.435	3E-15	0.058	0.4
12	24	54	Up center of wash adjacent to cliff, Area 2	0.4028	0.9	0.8	0.44	0	0.067	0.4
13	24	54	Up center of wash adjacent to cliff, Area 2	0.402	0.9	0.8	0.442	0	0.069	0.4
14	24	54	Up center of wash adjacent to cliff, Area 2	0.3979	0.9	0.8	0.447	0	0.079	0.4
15	24	180	Up south wall of wash, Area 2	0.3971	0.9	0.8	0.448	0	0.081	0.4
16	24	240	Along south wall of wash, Area 2	0.3931	0.9	0.8	0.454	0	0.09	0.4
17	24	240	Along south wall of wash, Area 2	0.3924	0.9	0.8	0.455	0	0.092	0.4
18	24	240	Along south wall of wash, Area 2	0.0486	0.9	0.1	0.461	0	0.101	0.4
19	24	240	Along south wall of wash, Area 2	0.3878	0.9	0.8	0.461	0	0.102	0.4
20	24	240	Into center of semicircular hill, Area 2	0.3839	0.9	0.8	0.467	0	0.111	0.4
			SUM	6.7726						