Experiments & Analysis of the Role of Solar Power in Limiting Mars Rover Range

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***Abstract*— A common explanation for the limited distance traveled by NASA's past and planned Mars rovers is the limits of solar power. This paper explores this hypothesis and documents a series of experiments with a solar powered rover. A detailed comparison between our rover and Sojourner, with regards to power usage, is presented. Experiments and analysis clearly show that other factors dominate in limiting the range of NASA's solar powered robots when operating on Mars.**

I. MOTIVATION

There are a variety of ways of powering a Mars rover: battery, RTG, and solar power. The advantages of solar power are its renewability (as compared to a primary battery), its low cost and political banality (as compared to an RTG). The only successful Mars rover so far, *Sojourner*, used solar power for these reasons.

Solar power, theoretically, should become more practical as the size of the vehicle is reduced. This is due the square–cube relationship between vehicle surface area and mass as the size of the vehicle changes. But contrary to this intuition, solar race cars, massing hundreds of kg are able to move at speeds in excess of 50km/hr ($\approx 14m/s$) (e.g., see [4]) while *Sojourner*, massing 11.5kg [6], had a top speed of $\approx$0.2cm/sec [9]. This combined with *Sojourner's* small overall traverse (about 100m in 80 days of operations) has given many people, including some mission managers, the wrong impression about solar powered rovers.

In fact, there is strong evidence that programmatic directions in NASA's rover technology research programs are based on the impression that current rover performance is bounded by the limits of solar power on Mars. A recent project review from NASA HQ rejected research in improving rover autonomy in part with the statement: *"The limit on rover speed for Mars missions is primarily due to available power and energy density and not control algorithms"*[11]. This opinion also appears prevalent in much of the technical community.

While power limitations are popularly believed to have a major limiting effect on rover performance, there is no evidence in the technical literature to show whether or not this is really so. The experiments and analysis presented below are designed to answer this question definitively.

II. OVERVIEW OF THE SR1 ROVER

This paper describes SR1 (see video), a solar powered autonomous rover of the approximate size and mass of Sojourner (see Figure 1). This robot was built in a couple weeks using low-cost commercial components. Its purpose is to demonstrate that one does not have to go to extraordinary lengths in order to get speed and endurance performance orders of magnitude larger than those demonstrated by *Sojourner*.

Fig. 1. *The SR1 during a desert test*

While SR1 did not have to operate under all of the constraints endured by an actual Mars Rover, it also was handicapped by ways that no real mission would have to suffer:

- Solar panels had a low efficiency ($\approx 6\%$)
- No mass optimization of vehicle was attempted
- SR1 used soft rubber wheels, reducing rolling efficiency

- Tests took place in early January in Norman, OK (35 degrees North)
- Some of the test days were overcast

We believe this makes up for the advantages our test had over the factors that would effect traverse speed on a Mars mission, e.g.:

- We did not carry mass for thermal control system, science or communications
- The solar flux at Mars is half of what it is at Earth
- Our test course was simpler to navigate than unknown Martial terrain (though the Pathfinder landing site was not unknown for very long into the mission).

Of course the distance covered by a planetary rover is dictated by many more factors than just the top speed of the robot and the energy available for movement – operations plays a very large factor [10]. But the energy required and available along with the speed of the robot does set limits. The experiments described in this paper show that those limits are not nearly as severe as one might suppose from looking at NASA's past and planned planetary rovers.

III. THE SR1 ROBOT MECHANICS

The platform used for SR1 is based upon is a modified 1/10 scale Tamiya Clodbuster four-wheel drive radio controlled vehicle. The plastic tub chassis was refitted with an after market aluminum frame from New Era Models (Figure 2). The two stock 30:1 spur gear transmissions were modified to fit 16 mm Maxon motor assemblies. The motor assembly included a 4.4:1 planetary gearbox and a 2 channel digital magnetic encoder with 16 counts per revolution. The 12v motors provided 740 mNm of torque at each axle. The rubber tires were 152.5mm diameter stock components included in the kit but stuffed with foam to make them more rigid.

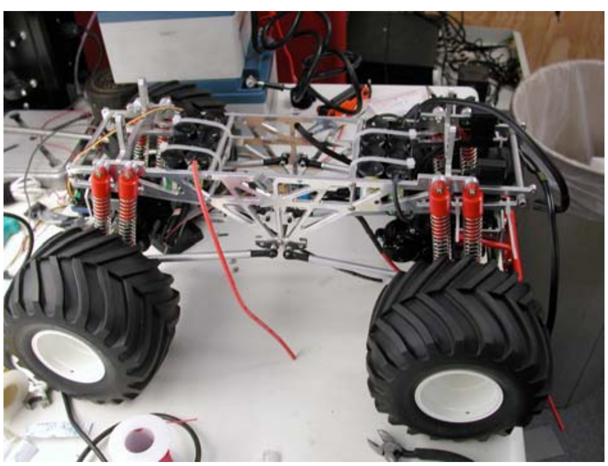

Fig. 2. *The SR1 chassis*

The new chassis provided hard mount places for the batteries, computer, custom power switching board and solar panel. The steering mechanism was reduced from all-wheel steering to only the front pair, but it increased the rigidity for a more positive turning action. Two Uni-Solar USF-11 flexible solar panels were held in place by a double X shaped frame mounted on top of the chassis (see Figure 3). A semi-circular shaped frame was mounted to the front of the rover to hold six Sharp GP2D12 infrared range finding sensors used for navigation.

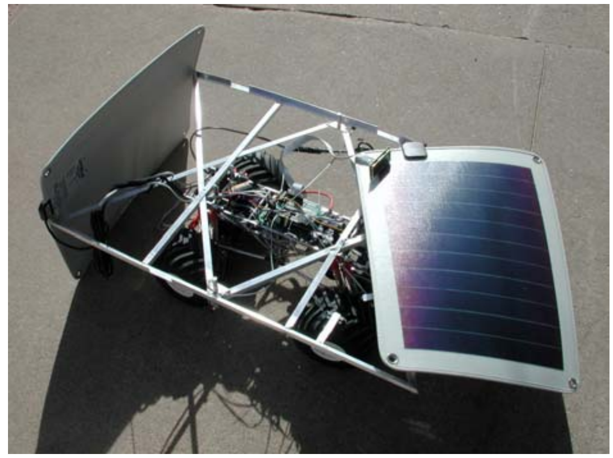

Fig. 3. *SR1 with panels moved so that mount is exposed*

IV. DATA ACQUISITION

The SR1's control and data-acquisition system is a Handy Board [8] that has been modified to handle the GP2D12 sensors. The Handy Board is programmed using IC4 [5] which includes an upload array command, allowing the Handy Board to store data in global arrays and transfer the data to a workstation at a later time.

The DAQ system monitors five keys elements during the execution of the experiments. The data is synced by recording the running mission time as the first element within each new row of data in the logged array. Records indicating solar panel voltage, battery voltage, the current speed of travel, and the odometer reading follow the mission time.

The interface board served as the collection point for the signals that provided these measurements. Power from both the batteries and the solar panel were monitored from their connections to this interface board. Scaled voltages were directly sent to the inputs of the electronic controls. In a similar manner, the encoder signals were collected at the interface board and wired to the Handy Board which transformed the encoder readings into distance and speed.

At the end of each Experiment, a serial connection was established with SR1 using a laptop. Data was transferred and formatted for analysis, which followed the experiments.

V. ANALYSIS

Transferring the data after each experiment yielded four separate data sets (one for each day's test). These sets were combined into a single Excel worksheet for data analysis. Using the time of day as an alignment marker, the data was grouped into its respective data types (panel voltage, battery voltage, and speed). For these groupings, plots were made to show sensor readings at the respective time of occurrence.

A. Panel Voltage

The solar panels of SR1 were tied (through a voltage regulator and diodes to a 30wHr battery system. Prior to the first day of testing the batteries were fully charged. Between tests the batteries were not charged and the robot was kept indoors, so little if any power was provided from the panels to the batteries.

At the start of each day of testing, the rover was outside while the test track was being set up. During this time (approximately 30 minutes) the rover's batteries did charge from the solar panels without the rover's motors running. This pre-charging can be seen in Figure 4 at the beginning of each day's run as the voltage of the panel is high (because of a lack of draw from the battery). This quickly dissipates as the battery voltage starts to drop due to power draw from the motors.

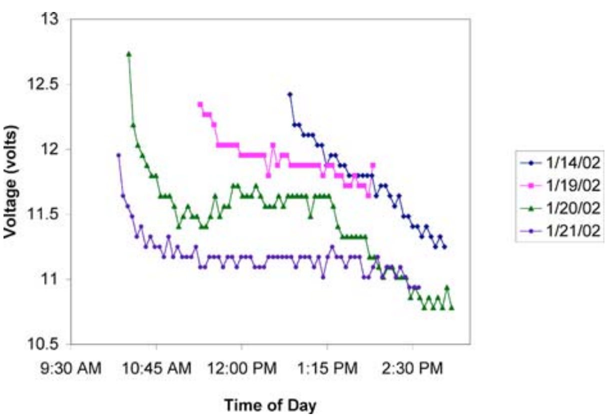

Fig. 4. *The panel voltage as a function of time of day*

During both the second and third days of testing, the rover was operating in adverse conditions. Fair to moderate cloud cover began to appear in the data towards the end of the testing runs. Data from the National Weather Service indicates that approximately only 81% and 89% of the total sunlight was available during January 19 and January 20 respectively. This is visible in the graph as the drop off near the end of the day when the solar panel is no longer able to keep the battery at it nominal charge and the system voltage tails off. The rapid drop off of the first day's panel voltage is believed to be due to a combination of the late start (so the available solar flux was rapidly dropping off) and the initial higher than normal conversion efficiency available from brand new panels – a capability which drops off in a matter of hours of use. The fourth day of testing started with an initial voltage that was much closer to the plateau represented by the rest of the data for the day. This smaller initial voltage drop and minimal variation in voltage output reinforced that panel was settling into a very stable performance zone. The final tests showed that the output of the solar panel was producing ≈ 11.2 volts throughout the length of the final testing day.

Calculations show that during the month of January in Norman, Oklahoma ($35^o15'$N and $97^o29'$W)[1] solar flux peaks at approximately noon CST with an intensity of $0.56kW/m^2$. This is accompanied by the fact that the solar flux quickly drops to approximately $0.2kW/m^2$ by 3:00pm CST (see Figure 7) due to the larger airmass the light must pass through due to the low sun angle[3]. The fact that the panel voltage remained relatively flat is indication that sufficient power was being generated and existed in the batteries to keep the batteries at their nominal voltage vale.

B. Battery Voltage

The battery voltages mimicked the behavior of the solar panel. On the first day of testing, the batteries dropped at a steep rate along with the output from the solar panel. As the data from the following tests were plotted, it could be seen that all of the battery voltages carried very similar behavior to the solar panel data for the respective days. However, two important details were uncovered. First, the battery packs were consistently $\frac{1}{4}$volt lower at any given point in the day during testing. This shows that the power management system was always accepting energy to charge the batteries (see Figure 5). The power management system had been set up to protect the batteries and internal electronics by bleeding off any excess solar energy. This reaction would protect the battery pack in situations where they already contained a full charge. In addition, the power management system also accounted for situations in which the batteries reached dangerously low levels. The power management system would cut power to the motors and send the electronics into hibernation until such a time that the batteries were above a safe operating level and still charging. Second, the variation in the voltages is a little more pronounced when compared to the voltages recorded from the solar panel. These variations are a direct result of dynamically changing weather conditions (namely wind). During the four days of testing, wind speeds averaged 43cm/sec (10–11mph) throughout the day and night. However, during the actual testing time frame the rover was subjected to wind with gusts that were 40 mph. These gusts, when lasting for minutes at a time, can be seen in the data as increases and decreases in power draw depending on whether the rover was headed into the wind or down wind when the data was recorded. Yet even with these dynamic conditions, the battery voltages begin to settle into a predictable plateau much like the Solar Panel. With this being the case it is possible to become more aggressive with the rules governing power management on future solar rovers.

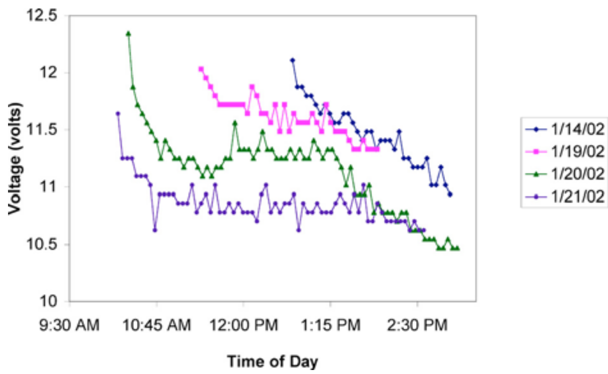

Fig. 5. *The battery voltage as a function of time of day*

C. Speed

Speed was a value that was calculated before it was recorded by the DAQ system. This calculation was based off the current and previous odometer and time readings. This average speed per time segment was graphed vs. the respective time of recording. The data shows that the rover consistently maintained a speed of approximately 41 cm/sec (see Figure 6). As with the battery voltages, significant jumps are present due to the wind velocities. Looking at the entire data set for all four days of testing, instances where the rover was experiencing a tail wind increased the recorded speed to approximately 49 cm/sec. Likewise, when the rover was subjected to headwinds the speed recorded was 35 cm/sec. However, this variation in speed on a daily basis only varies a total of 10 cm/sec maximum between the days highest and lowest recorded speed. Looking at the last set of data when the system began to settle into its designed performance, the variation of speed during the entire run is approximately 7 cm/sec. The variations in wind and light only resulted in small changes in rover performance indicating that the rover was operating well away from the absolute limits of its performance and resource needs.

VI. COMPARISON OF THE SR1 TO SOJOURNER

The SR1 rover had a solar panel size of approximately $0.25m^2$, which is about the same size as that of Sojourner. During our test runs of SR1, the sun never climbed more than about 35^o into the sky, while during the start of the Pathfinder mission the sun was near zenith at local noon. However the solar flux, which is about $1.3kw/m^2$ at the

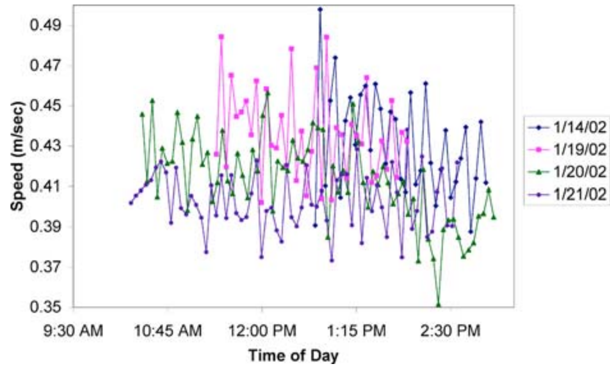

Fig. 6. *Rover speed verses time of day*

Earth's atmosphere is only about $0.62kw/m^2$ at the top of Mars' atmosphere. And while the Martian atmosphere is much thinner than that of Earth's, there is much more dust scattered in the Martian atmosphere leading to an optical density of the Martian atmosphere of 0.4 [12] compared to typical values of 0.15 for Earth.

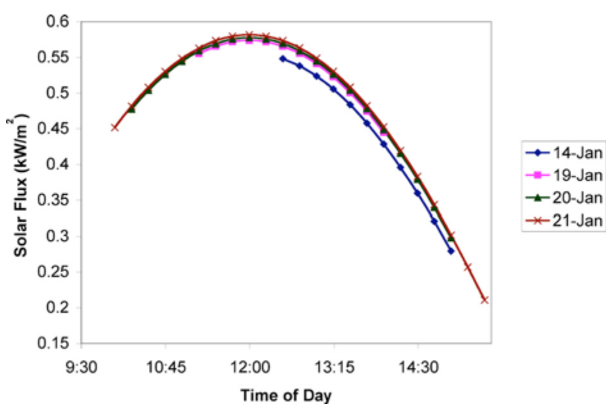

Fig. 7. *The solar flux reaching SR1 as a function of time of day*

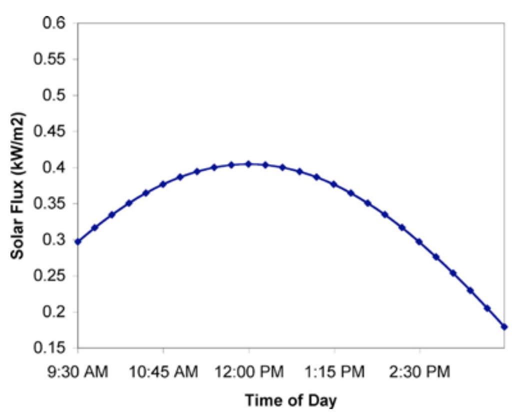

Fig. 8. *The solar flux reaching Sojourner on Mars as a function of time of day*

The value of F_p, the energy entering a flat solar panel that is oriented parallel to the ground can be calculated by:

$$F_p = F_o \cos(\alpha) e^{\frac{-\tau}{\cos(\alpha)}}$$

Where F_o is the solar flux at the top of the atmosphere, α is the zenith angle of the Sun and τ is the optical depth. Figures 7 and 8 display the solar flux *received* by the solar panel on SR1 and Sojourner respectively, as a function of day time, calculated for their location and dates of mission. The energy under those curves is approximately $2.9kw - hr/m^2$ for SR1 and $2.1kw - hr/m^2$ for Sojourner.

Sojourner had solar panels that averaged 15% efficiency, while SR1's averaged 6%. Sojourner's panel was $0.22m^2$ in size while SR1's was $0.25m^2$. Thus Sojourner's panel delivered approximately 69w-hr for the interval in question while SR1's yielded 44w-hr.

Sojourner used ≈3w for steering and driving and another 3w for the computation system[9]. The robot also used about 4w to power the heater during the day – in order to build up a thermal reserve to keep things warm during the Martian night [7]. The heaters were the only regularly used power drain for which SR1 did not have a direct analog. Other subsystems such as telecom or the APX were used only when the rover was standing still, or very infrequently. Over the six daylight hours in the interval for the calculations above, Sojourner would have used 24w-hr on the heater. When the 69w-hr total is reduced by 24, the power Sojourner had available for movement and computation was virtually identical to that of SR1.

Sojourner had rigid wheels and ran (for the first two-thirds of its mission) across level ground that was covered with soft soil. SR1 ran across a level hard surface, but had soft plastic wheels. The energy expended by SR1 in the rolling deformation of the wheels can be calculated by:

$$Power = \frac{F_w D V}{2R_t \sqrt{2\frac{D}{R_t} - \frac{D^2}{R_t^2}}}$$

Where F_w is the force of the vehicle weight on a wheel, D is the deflection of the wheel, V is the vehicle velocity, and R_t is the radius of the tire. Plugging in the appropriate values for SR1 yields 1.4w of energy are absorbed by each of the soft tires when the wheels are rolling at 41cm/sec, SR1's nominal speed. The rebound resilience of these tires is the percentage of absorbed energy returned to the system by the elastic restoring force of the tire material. The measured rebound resilience of SR1's tires is 23.8% which means the total energy lost by SR1 through rolling resistance is 4.27w. Since Sojourner expended a total of 3w for mobility, we can be sure that the rolling resistance of sojourner on Mars, at its nominal speed, is less than the energy lost by SR1.

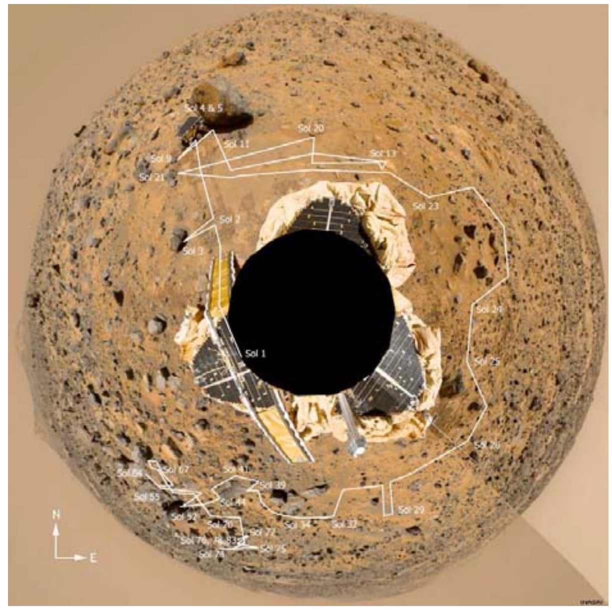

Fig. 9. *Traverse path of Sojourner* (NASA)*[2]*

VII. CONCLUSIONS

Figure 9 shows the path taken by the Sojourner rover and when it was where. Until day 32, the path was clear and level. We have established that the Mars environment did not require any more energy to traverse than did our test track. The energy available for mobility to the Sojourner rover and SR1 were virtually the same. Yet SR1 traversed thousands of times the daily distance of Sojourner and at 200 times the speed (see video). Therefore, one must conclude that energy was not the limiting factor and that Sojourner's travel must have been limited primarily by its mechanical design and/or operational constraints. We believe that mechanical inefficiencies can account for at most a small factor of the difference. The Sojourner rover traveled slowly because it was designed to travel slowly. Our research shows that this design decision was not a requirement of the available energy, but must have been made for other reasons. We believe that limited knowledge of the environment, distrust of autonomous navigation, and operational conservatism all combined, along with the time required to do scientific measurements, to limit the range of the rover. A more automated system would allow science to be done more quickly and over a larger and more representative piece of Mars. Automated rovers such as that described in [10] show that small (10-50kg) rovers operating under Mars conditions can make substantial traverses in a timely manner to promote future science and exploration. Future research in rover autonomy and higher speed mobility will prove very beneficial to future planetary rovers, and should be supported.

Acknowledgments

The authors wish to thank William Herbst of Wesleyan University, Donna Shirley and Alois Winterholler of OU, Jake Matijevic of JPL and Mike Ravine of MSSS for their assistance with this research. This work was supported in part by a contract from Malin Space Sciences Inc.

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