Roving Faster Farther Cheaper

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Summary. Current Mars rovers travel a few kilometers per year. Future rovers will need to travel a couple orders of magnitude faster than that in order to move from safe landing zones to areas of scientific interest – which may be many 10s of kilometers away from a suitable landing location. This paper describes a recent field test of the SR-II rover. SR-II is a 22kg solar powered autonomous rover, which during a week long traverse through rough Mars-like terrain was able to cover almost a kilometer per day.

1 Introduction

Rovers are important for conducting in-situ scientific analysis of objectives that are separated by many meters. In the search for answers to the history of Mars these science outcrops could be separated by tens of kilometers. The twin Mars Exploration Rovers have traversed over 15km between them, validating that long distance traverses are possible. However, this was only possible after multiple mission extensions. Under the current procedures for operating a rover on Mars this type of mission will take many years to complete and cost billions of dollars. More rovers could be sent in order to speed this process up, but the cost of the mission would only increase more.

The current state of planetary landing technology has a landing ellipse many kilometers wide. Missions to Mars are therefore limited in landing sites that have a high probability of a safe landing. However, the more interesting scientific outcrops may be located in an area where the odds of a safe landing are too risky. Fast long traverses could be used to get the instrument payload from a safe landing site to where it is needed.

In this paper we will describe the latest field test of the Solar Rover-II (SR-II) robot. SR-II uses a simplified suspension system but exhibits similar mobility capabilities to the rocker bogie suspension used on the 1997 Pathfinder [1] and 2003 MER missions [3]. It uses only two motors, which are located inside of the chassis to maintain a nominal temperature, instead of ten exposed to the atmosphere. SR-II is a combination of simplified mechanics and control algorithms using non-

Fig. 1. SR-II in Anza Borrego.

computationally intensive sensors under the influence of a simple operational strategy. It has been shown under realistic terrain conditions that traverses of 1km per day through rugged terrain are possible under autonomous control.

2 Rover Hardware

SR-II is a four-wheeled rover with a ground clearance greater than a wheel diameter. It has 4-wheel drive and is skid steered using only two motors. The motors and drive train run through a hollow tubular suspension. At the center of the chassis is a geared differential that increases stability for the sensors and assures that all four wheels maintain ground contact with equal force. The rover mechanics are described in detail in [7] and [8].

2.1 Mast Cameras

A stereo camera pair with an integrated fiber optic lens for taking spectrometry readings can be seen on the mast at the top of figure 1. The mast is capable of rotating more than 360^o and tilted approximately 30^o above and below horizontal at a height of 1m from the ground. The pan and tilt drive mechanisms are integrated with the solar panel to save space inside the chassis.

2.2 Electronics

The rover electronics (see Figure 2) include a PowerPC based Mac mini and an XBC processor [2] real-time controller. The XBC provides a low-level interface to many of the sensors that keep track of the health of the rover.

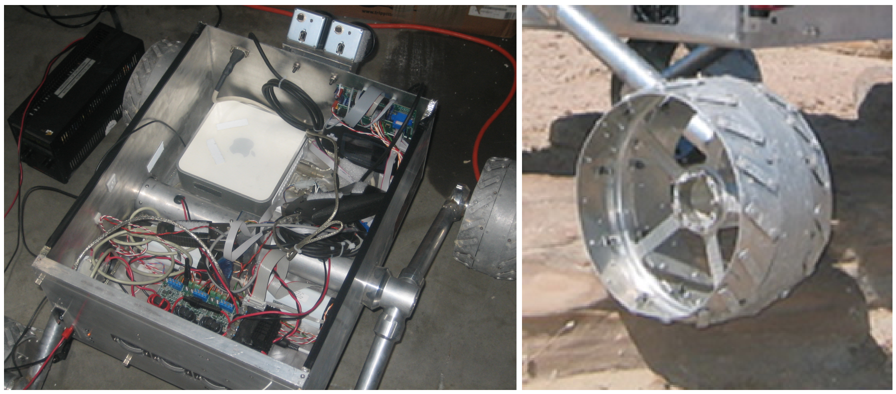

Fig. 2. Left: Inside the SR2 Chassis: Mac-mini, XBC, Power management electronics and stereo navigation cameras (near top) are not currently used. Right: Close-up of the SR2 wheels used in 2006 field test.

A battery charging protection system was implemented using thermal sensors on each of the batteries to prevent over charging. Current meters signal how much power is flowing from the batteries and solar panel to the motors and electronics, the XBC uses these to detect a stalled motor. A PID control loop on the XBC uses back-EMF to position the mast and control the speed of the drive motors. However, a separate motor driver H-bridge circuit was created to handle the more powerful drive motors. During normal driving operations the XBC would simply relay the sensory information and drive motor positions to the Mac mini over a serial connection.

The primary sensors used for navigation and hazard avoidance are connected to the Mac mini through a serial port hub. Three Hokuyo URG-04LX scanning lasers are mounted to the chassis and underside of the solar panel on the forward end of the rover. The lasers prove to be effective in detecting obstacles 2 to 3 meters away even in the extreme desert sunlight.

A Honeywell HMR300 magnetic compass is used to simulate an IMU system. The compass provides pitch and roll angles up to $\pm 45^o$ as well as heading information to the Mac Mini. A hand held GPS was also attached to the rover but only to supply ground truth location data for logging. The rover did not use onboard GPS data for navigation.

2.3 Solar Power

Two 12 volt 4.5Ah Ni-MH batteries are used to store energy from the solar panel. The $0.72m^2$ solar panel has 6 strings with 31 silicon cells per string potentially giving a maximum of 120 watts. The avionics used between 17 and 60 watts depending on the computational loads. On level ground the mobility system requires only about 10 to 11 watts to cruise at 15cm/second. On much more difficult terrain the drive motors can pull up to 50 watts to climb over rocks greater than a wheel diameter. The power system has not yet been optimized but in the transition to a flight system for Mars there would be a decrease of about 50% in solar flux but also a decrease in rover weight by about two-thirds. Thus the present ratio of power generation to use is approximately correct.

2.4 The Wheels

The wheel design uses a three piece tire made of sheet aluminum less than 1mm thick. The center band is 200mm in diameter by 30mm wide and is completely smooth. It is backed by the main supporting structure of the wheel, figure 2, a 5 spoked ring that connects to the wheel hub and axle. The middle portion of the center band is effectively rigid, the inner and outer edge bands are fastened to the rim of the center band. The edge bands are conically shaped inward at a 20^o angle from the centerline making the wheel 110mm wide. These edge bands have 18 raised grousers fastened at a 45^o angle to the centerline of the axle. The concept is to have as little drag as possible when driving straight on hard surfaces while maintaining the ability to climb over various obstacles. The combination of the thin sheet metal and the 5 spoked support ring allow the outer edges of the tire to deform, making more surface contact with the terrain which allows the rover to climb more effectively.

3 Remote User Interface

CommandCenter is a GUI program that allows the remote user to communicate with SR-II [9]. All mission plans are posted on CommandCenter and uploaded to the rover. Its primary purpose is to view the health of the rover and show updated position information. The map on the GUI displays where the rover believes it is and where other way-points are in relation to it. CommandCenter can also be used to tele-operate the rover if it needs help or needs to be put to sleep. New way-points can also be added to the plan that include the option of taking panoramic images once the rover reaches them.

4 Onboard Autonomy

The rover receives a list of way-points from the CommandCenter application described above. The way-points are in rectilinear coordinates where the origin was the rover's starting position at the beginning of the traverse and the Y-axis is aligned with North.

The onboard system checks to see if there are any outstanding way-points. If so, it takes the next point, calculates the vector between the current position and the way-point and starts toward the new point. If there are no points, it waits for a point or another command. Each way-point may contain an optional science operation (e.g., record a stereo panorama, take a spectrometer reading, etc). The rover will pause at the way-point and do the attached operation, if one exists, before proceeding to the next way-point.

If the rover is moving toward a way-point, it may encounter an obstacle or hazard. If an obstacle is detected by the forward laser in the rover's path (a 70cm wide swath up to 2m in front of the rover or the way-point, whichever is closer), then the full sweep of laser data is searched to check if the rover should go around the obstacle to the left or right. The forward laser sweeps the semi-circle forward of the rover along the plane defined by the skid plate of the chassis (approximately 1 wheel diameter above the surface). This is the maximum height of an obstacle or step that the rover can reliably surmount. If the entire forward path is blocked, the rover will continue forward at reduced speed.

A laser mounted at a 45^o downward angle detects the distance to the ground along a line approximately 60cm in front of the wheels as the rover moves. Both positive and negative obstacles can be detected by this sensor. If a positive or negative obstacle is detected in front of the wheels or a positive obstacle is detected in front of the body, the rover will turn to avoid the obstacle; stopping and performing a point turn if needed. The definition of an obstacle is determined in part by the roll and pitch of the rover at that time. E.g., if the rover is going down hill then a positive obstacle is less of an obstacle, and may simply be the bottom of the slope.

Obstacles detected by the angled laser that are in front of a wheel are avoided by the rover initiating a turn during its forward progress. Obstacles in front of the body are avoided by a turn in place until a clear path is found.

When avoiding an obstacle, the rover must pass the obstacle by two vehicle lengths before the rover will try and resume its path toward the way-point. If another obstacle is detected prior to reaching this safe path distance, the rover will avoid and proceed 2 vehicle lengths past the most recently detected obstacle before resuming its course. If the rover turns left at the first obstacle it detects, it will turn left at all future obstacles until it has been able to resume its path to the way-point. A similar strategy is pursued if the rover had turned right.

When the obstacle reaches within a specified distance of the goal way-point (currently three rover lengths), it will move toward the next way-point. If the rover fails to make progress toward a way-point for a specified amount of time (currently set at 15 minutes) meaning that the rover is no closer to the way-point now then it was fifteen minutes ago, it will stop and call for help. This will usually be due to a way-point being placed in an area that cannot be reached by the rover. This scenario has not occurred in a real field test, though it has been demonstrated in a test situation.

At any time, if the rover detects that it only has a few minutes of battery life left (determined by battery voltage and load), then it will initiate a timed sleep. If this is before 3pm local time, then the rover will power down all of the sensors and put the Mac to sleep, allowing the batteries to charge for twenty minutes. If it is after 3pm, it is assumed that insufficient sunlight is available for a quick charge, and the rover will sleep until the following morning.

The operator can interrupt the rover at any time (except during a sleep, whose interruption currently requires physical contact) to put the rover in a manual mode. When the rover gets into a situation where it is calling for help, going into manual mode is the only way to get the rover to move. In manual mode the rover can be teleoperated, and/or the way-point list may be edited.

The on board autonomy is written in Common Lisp running on LispWorks on the Mac-Mini. LispWorks provides support for multi-threading (which is used to decouple sensing from mobility operations) and external function calls (to C and objective C functions which control the sensors and communications to command center respectively).

5 Field Test Results

The Anza Borrego field test site was selected because it reflects similar geological features that are analogous to the most easily accessible layered or sedimentary materials on Mars [4] (e.g., Figure 3). The topography is relatively low, with elements of non-traversable terrain such as steep slopes, escarpments, deep channels and large rocks relative to the scale of the rover. This configuration of terrain elements is seen on Mars where layered rock is created by wind and lake-water sediments. The test site is located near the western edge of the Salton Sea Lake where similar processes are taking place [6].

Fig. 3. Left: SR-II successfully navigated through 100s of meters of sedimentary materials. Right: a wheel rim caught on an edge of one of the rocks requiring a short tele-operation to extricate it.

The field test was completed in 8 days where SR-II was able to traverse over 5km along a predetermined path of way-points. On several days the rover almost traversed a kilometer. On average fewer than three hours (and never more than four and one half) of driving time were spent each day. This limitation was due to the elevated air temperatures (in excess of 46^oC) during prime solar power time (noon). The high heat reduced the solar panel's efficiency limiting the recharging of the rover's batteries, but more severely it limited the endurance of the field test personal.

Google Earth images were used to select the way-points the rover would follow. Prior to the start of the test a total of 148 way-points were imported by Command-Center. The software converted the Lat/Long coordinates from the KML file given by Google Earth into relative positions in meters from the start. The operator selected various target way-points to conduct science, then sent the final compiled way point list to the rover as a plan. During the test, the rover continuously recorded sensor values and GPS positions into a log file.

Each day of driving was completed by letting SR-II autonomously navigate from way point to way point. During the traverse the rover operator intervention occurred only 6 times. This situation was resolved by tele-operating the rover a few meters away from the incident spot. Three of these events were caused by rocks catching the inner edge of the rovers wheel as it made a skid turn (Figure 3). Similar situations may be solved in the future by adding hub caps to decrease the chances that a protruding rock will snag a wheel. In the current cases rover would initially detect a stalled drive motor and begin a series of maneuvers to free itself. When this failed to free the rover a message was sent to CommandCenter indicating what caused the rover to stop and ask how to proceed. On one occasion the rover slid on a slope and was angled at what it considered a severe roll angle. It called for help and was tele-operated about a meter whereupon it could continue on its own. The other two occasions of operator intervention were due to operator impatience – the rover looked as if the rover might have difficulty making its way around a feature and a short manual tele-operation was done instead. In most cases, cooler heads prevailed and the rover was allowed to find its own way.

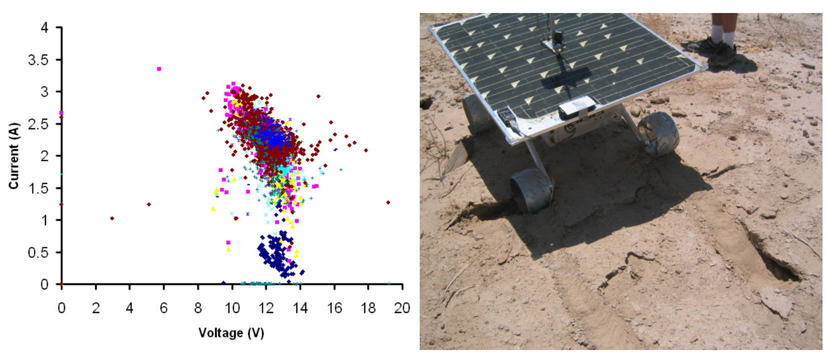

Fig. 4. Left: Solar panel power characteristics. Right: SR-II autonomously driving out of a sink hole

The power system on the rover was also being tested while out in the field. The current system allowed the the rover to operate for about three hours. Late in the day the rover would become starved for power because the batteries had been drained making it difficult for the rover to climb over rocks. It is apparent that the batteries were being used as the primary power source. While in the field, the surface of the solar panel was approximately 30^oC higher than originally planned for. The average power output of the panel was less than 35 watts (figure 4). The lack of power from the solar panel is due to the decrease in voltage as the solar cells heat up. In the event that the voltage dropped too low the rover put itself into sleep mode without any complications.

Analysis of the motor current data from the total 5km traverse showed that on average only about 17 watts of power is needed for the mobility system. During the experiment the rover drove across various surface textures, from loose sand to hard packed soil that occasionally collapsed into a sinkhole, figure 4.

The log files from all 8 days of traverse were converted into Google Maps KML files and uploaded to Google Earth. Figure 5 shows location data of the path the rover took overlayed on the desired path. This allows us to view the accuracy of the rover's computed position which is based on odometry and compass heading. On day 6 the rovers path deviated significantly when a previous version of the control software was loaded which did not take into account magnetic declination for the compass. Aside from this instance, dead-reckoning errors caused by wheel slippage was less than 2%, and usually less than 1% of the distance traveled. After a kilometer long traverse the rover would actually be within ten meters or so of where it thought it was.

The dead reckoning errors seem low, but have been consistent over a number of trials with various types of terrain (though not sand). Our current theory for these results is that slippage errors, over long enough traverses, tend to cancel each other out. This phenomenon has also been observed in Pacific canoe voyages[1].

6 Conclusion

The simplified mobility system of SR-II is quite capable of traversing Mars-like terrain while being very power efficient in most cases. More power is required when the rover changes direction compared to Rocky style rovers. However, only a small portion of the traverse is spent turning, even on complex terrain. As a result of the simpler mobility and despite the comparatively large amount of power used on SR-II for the computation and communication (when compared to similar class vehicles such as Sojourner) it has a much larger range per sol [5].

The hazard avoidance system was acceptable in finding a safe path between waypoints. This is significant because the hazard avoidance system is much simpler than that used by MER, and SR-II has, theoretically, lower overall mobility than MER [3]. These two factors might lead one to expect that the rover would be more prone

[1] Personal communication from Ben Finney, University of Hawaii, April 2007.

Fig. 5. Each section of the path is a single days drive.

to get lost or get stuck or have other problems related to ground hazards. Yet this was not the case.

Traverses of a kilometer or more per day are possible with a single communication cycle, rather than the few meters currently being done on Mars. We believe that future robotic missions to Mars should accomplish more scientific goals by relying on the autonomous capabilities of the rover. We believe that the operational philosophy of providing numerous, widely spaced way-points per communication cycle was largely responsible for the significant distances traveled per day. This difference in operations is more significant for improved performance than the hardware and software differences between SR-II and MER. The rover covered as much ground as it could – there was always more for it to do.

Additional field tests are planned for 2007. We will use an improved solar panel/battery system and wheel design. We expect increased endurance from the new power system. The new wheels will hopefully further reduce the already rare occurrences where operator intervention is required. Experiments comparing stereo navigation with the current laser scanner system are also planned.

Acknowledgments

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