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Sojourner on Mars and Lessons Learned for Future Planetary Rovers

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ABSTRACT

On July 4, 1997, the Mars Pathfinder spacecraft successfully landed on Mars in the Ares Vallis landing site and deployed an 11.5-kilogram microrover named Sojourner. This microrover accomplished its primary mission objectives in the first 7 days, and continued to operate for a total of 83 sols (1 sol = Mars day = 1 Earth day + ~24 mins) until the lander lost communication with Earth, probably due to lander battery failure. The microrover navigated to many sites surrounding the lander, and conducted various science and technology experiments using its on-board instruments.

In this paper, the rover navigation performance is analyzed on the basis of received rover telemetry, rover uplink commands and stereo images captured by the lander cameras. Its physical traversal path is redrawn from the stereo images containing tracks and is compared with the rover-recorded path and the driver-planned path. Implications for next-generation planetary rovers are described, including the sub-1-Kg Nanorover being built by NASA to conduct asteroid exploration as part of the Japanese MUSES-C sample return mission and the large rover with the Athena payload which will be used as part of the Mars sample return program.

INTRODUCTION

The Pathfinder spacecraft landed on Mars on July 4, 1997, and the next day the Sojourner rover rolled down a ramp onto the surface and began its exploration of the Mars environment near the lander. The mission called for the rover to move to sites of interest nearly every sol to conduct science and engineering experiments. Equipped with navigation and articulation sensors and vision cameras, the rover carried out its daily traversals autonomously based on sets of driver commands sent from Earth. One of the technology experiments planned for the Sojourner mission was the reconstruction of the actual path of the rover as compared to it's commanded path, so as to give insight for the design and operation of future planetary rovers. This paper presents some of the results of that technology experiment.

The site locations were designated by a human operator using engineering data collected during previous traversals and end-of-sol stereo images captured by the lander IMP (Imager for Mars Pathfinder) cameras. During the traversals the rover autonomously avoided rock, drop-off, and slope hazards. It changed its course to avoid these hazards and turned back toward its goals whenever the hazards were no longer in its way. The rover used "dead reckoning" counting wheel turns and using on-board rate sensors estimate position. Although the rover telemetry recorded its responses to human driver commands in detail, the vehicle's actual positions were not known until examination of the lander stereo images at the end of the sol. A collection of stereo images containing rover tracks allows reconstruction of the rover physical traversal path thoughout the mission. Since the primary purpose for a robotic vehicle on another planet is to move precisely to targets of scientific interest, the ability of the vehicle to sense and navigate to precise locations is important to gauge. The accuracy of navigation of Sojourner and its implications for future planetary rovers is the subject of this paper.

THE ROVER

Sojourner (Figures 1 & 2) is a six-wheeled vehicle 68 cm long, 48 cm wide, and 28 cm high (with 17 cm ground clearance). The body is built on the rocker-bogie chassis which, by use of passive pivot arms, allows the vehicle to maintain an almost constant weight distribution on each wheel on very irregular terrain. As a result, Sojourner was able to traverse obstacles about 1.5 times as big as the wheels, since the rear wheels are able to maintain traction even while pushing the front wheels into vertical steps hard enough to get lifting traction. This consists of linkages, six motorized wheels, and four motorized-steering mechanisms. The vehicle's maximum speed is about 0.7 cm/sec. More details of the design and implementation can be found in [1], [2], [3].

The rover is controlled by an Intel-8085 CPU operating at 2MHz (100KIPS). The on-board memory, addressable in 16 Kbyte pages, includes 16 Kbyte rad-hard PROM, 176 Kbyte EEPROM, 64 Kbyte rad-hard RAM and 512 Kbyte RAM. The navigation sensors consist of a rate gyro, 3 accelerometers for sensing the X, Y, and Z axis motion, and 6 wheel encoders for odometry. Articulation sensors include differential and left and right bogey potentiometers. Wheel steering and APXS (Alpha-Proton X-Ray Spectrometer) positions are monitored by 5 potentiometers. All motor currents and the temperatures of vital components are also monitored.

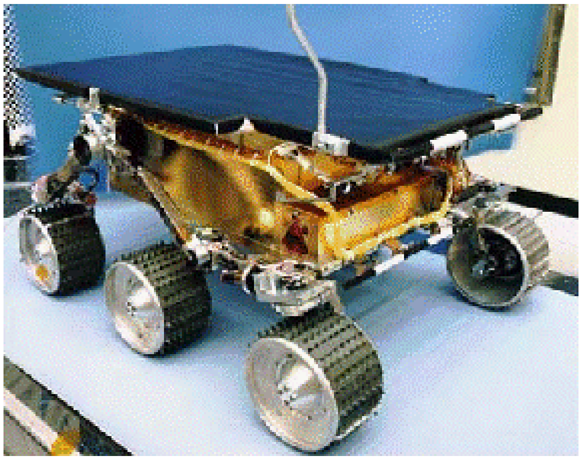

Figure 1: The Sojourner Rover

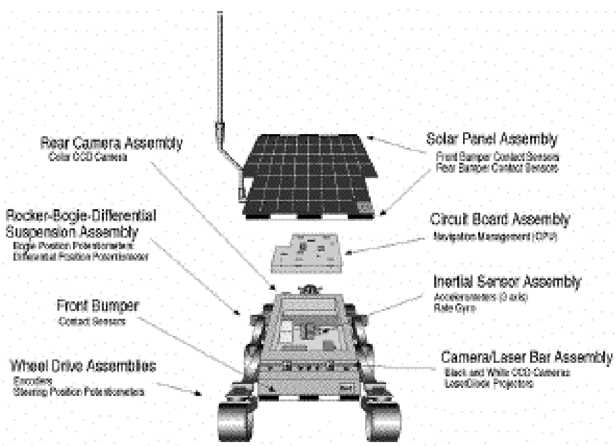

Figure 2: The rover assembly

The two front black and white CCD cameras (768 x 484 pixels) provide hazard detection and science/operation imaging. The rear color CCD camera is used for science imaging and APXS target verification. A suite of five infrared laser stripe projectors, coupled with the front CCD cameras, provide the proximity sensing and hazard detection capability for the vehicle. This system operates by locating the image of the laser stripes on a few selected scan lines of the camera images. Deviations of the detected locations from the nominal flat-terrain values indicate that the terrain is uneven. An array of elevation values is created from the stripe-camera intercepts. Proximity hazards are detected when elevation differences between adjacent points in the array exceed a threshold, or when the difference between the highest and lowest point in the array exceeds a threshold. Other hazards include excessive roll or pitch, or excessive articulation of the chassis, or contact with bump sensors on the front or rear of the vehicle.

A bidirectional UHF radio modem (9600 bits/second) allows the vehicle to transmit telemetry and to receive commands from earth via the lander. On-board science instruments include an Alpha Proton X-Ray Spectrometer (APXS) , the WAE (Wheel Abrasion Experiment), and the MAE (Material Adherence Experiment). The vehicle is powered by a 15-watt GaAs solar panel backed up in case of failure by a non-rechargeable Lithium battery, which was also used for nighttime APXS operations.

The rover is operated on the basis of a fixed local coordinate frame with origin at the center of the lander base and the X and Y axes pointed to Martian North and East (right-hand rule), respectively (Martian North is defined by the Lander sun finder). The vehicle's X,Y positions are calculated (at ~2 Hz rate) by integrating its odometer (average of the six wheel encoder counts) with the heading changes produced by the rate gyro. Due to the low processor speed and lack of floating point arithmetic, millimeter (mm) and Binary Angle Measurement (BAM) are used as distance and turn angle units respectively (1 Deg = 182 BAM or 360 Degs = 65,536 BAM). While moving, the vehicle monitored its inclination, articulation, contact sensing, motor and power currents, and temperatures to be sure they did not exceed limit conditions based on risk level settings. Being too close and heading toward lander conditions are also monitored. The rover periodically sends a heartbeat signal to the lander at one vehicle-length intervals. In the absence of this communication signal, the vehicle is autonomously backed up half of its length and a communication retry takes place. The rover motion is commanded by one of the following commands: Turn, Move, Go to Waypoint, Find Rock , and Position APXS.

The Turn command in general causes the vehicle to change its heading in place. The four steered wheels are adjusted into their appropriate positions, then the vehicle wheels are turned until the desired heading, indicated by integrating the rate gyro, is met. In case the gyro is disabled, the odometry is used to calculate the heading changes; if both the gyro and odometer are disabled, timing is used in the calculation. The Turn To command causes the vehicle to turn to a specific heading, while the Turn By command causes the vehicle to turn to a relative heading. The Turn At command causes the vehicle to turn so as to point to a specific X,Y position.

The Move command enables the vehicle to move for a specified distance, using only odometry and no hazard avoidance. This "blind move" is useful when the terrain is clearly seen by the operator (in images from the lander) and the move is a short one. The Set Steering Position parameter of the Move command determines the arc radius of the move.

The Go to Waypoint command causes the vehicle to traverse to a specified X,Y location. The vehicle drives forward a distance of one wheel radius and stops for laser proximity scanning. A terrain height map is constructed internally from the information provided by the lasers and CCD imagers. If an obstacle is detected on the left, the vehicle will turn right, and visa versa. A flag is set which indicates the direction of the turn, and the vehicle will continue turning by increments until a hazard-free zone at least as wide as the vehicle is detected by the laser scanning system. If the clear zone is wider than the vehicle turning circle, then the rover drives straight ahead far enough to bring the obstacle alongside. Then the rover begins an arc toward the goal point, clears all memory of the hazard avoidance maneuver, and continues. If the clear zone is narrower than the vehicle turning circle (but wider than the vehicle) then a "thread-the-needle" maneuver is attempted. This maneuver centers the rover on the perpendicular bisector between the two hazards, and moves straight ahead along that line until a zone big enough to turn around is detected. Once such a zone is detected, all memory of the maneuver is deleted and the rover begins an arc toward the goal. If an obstacle is encountered prior to detection of a free turning circle, then the rover backs straight out to the point where the thread-the-needle maneuver began, and the rover continues to turn until another hazard-free zone is detected. Arcs toward the goal are calculated to three values: if the rover is already pointed toward the goal (within a small deadband) then the rover goes straight, if the rover heading is outside that deadband but less than about 1 radian, then a large-radius turn (about 2 meters) is begun which turns toward the goal, and if the heading is more than 1 radian from the goal direction, then a short radius turn (about 1 meter) is begun which turns toward the goal. Note than a turn in place maneuver is not used here, since that would cause the rover to become trapped in "box canyons" whereas the present algorithm does not.

The Find Rock command is very similar to the Go to Waypoint command, except that after a hazard is detected at approximately the X,Y position of the waypoint, then the rover centers it's heading between the edges of the rock using proximity sensing. If the destination coordinates are reached without any rocks found along the way, a spiral search is performed until the rock is found. Go to Waypoint and Find Rock commands also contain a maximum time duration for execution. If that time is exceeded then the command terminates.

The Position APXS command enables the vehicle to move backward until the APXS sensor head contacts the rock that has been found or until the maximum allowable distance has been reached without contact or time-out.

For every uplink command, the vehicle sends either an acknowledge message or the telemetry collected during execution of the commands, including any error messages. Navigation telemetry in general contains the time tag, the command sequence number, the current X,Y and heading values, steering positions, inclination and articulation values, motor currents, temperatures, and contact and encoder information. In addition, the Go to Waypoint and Rock Finding telemetry data also include the obstacle height map provided by the proximity and hazard avoidance mechanism for every 6.5 cm of traverse.

The health check telemetry provides a snapshot of the current status of the vehicle. In addition to almost all of the navigation information, the power supply current and voltage status, individual wheel odometer readings, communication error counts, device fail counts, min/max accelerometer values, motor current values, and average motor currents of the last traversal are reported here. Other rover telemetry data is designed to report data from science, engineering experiments and rover housekeeping utilities.

In a Turn command, the rover completes a turn when the gyro heading is in within +/- 1.5 degrees of the desired heading. In a Move command, the rover completes a move once the average six wheel encoder count exceeds the desired encoder count. Part of the distance errors are due to the wheel slippage, and they depend on the terrain the vehicle traverses.

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In Go to Waypoint and Rock Finding commands, the rover reaches its destination when dX * dY < 100 mm^2; dX and dY are distances from the vehicle to its target position in X and Y respectively. In case the rover can not get to its destination due to an obstacle at the destination, the rover declares a successful command completion when it comes within 500 mm^2 of the target destination. The vehicle monitors the progress of the GoTo Waypoint and Find Rock commands and enforces a time limit (which is a parameter of the command).

THE ROVER CONTROL WORKSTATION

The rover is indirectly controlled by human operators using the Rover Control Workstation (RCW). The RCW's customized graphical user interface software provides tools for the operator to generate commands with parameter checking capabilities, and to designate waypoints in a 3-D image display. A command sequence which comprises multiple commands is built based on requests from the scientists, vehicle engineering telemetry, and the end-of-sol stereo images captured by the lander cameras. The rover 3-D icon shown on the RCW display allows the operator to assess traverse ability by placing the icon over a 3-D Martian terrain image set at any position and orientation. The rover's current position and heading are also acquired by matching the icon with the rover's physical position in the stereo images. This capability allows the operator to re-initialize the vehicle's true position and orientation at the beginning of a sol. In Go to Waypoint designation, the operator specifies the rover destinations by placing the rover 3-D cursor at each waypoint, then clicking the mouse to identify these destinations. The RCW records these waypoints and generates the Go to Waypoint commands automatically. Other commands are generated from operator-specified parameter values, and the command sequence file is created. The accuracy of the designation depends on the distance between the stereo cameras, image resolution, and human designation ability. The overall accuracy of the designation was estimated at about 2 to 3 percent for cross and down ranges, and for heading.

THE ROVER NAVIGATION PERFORMANCE ANALYSIS

The rover traversed 49 sols out of 83 active sols on Mars. It visited 16 distinct sites (9 rock and 7 soil locations), analyzed them using its on-board instruments, and captured over 500 images [4]. The rover had almost circumnavigated the lander in its 100-meter traversal. Since the terrain near the lander where the rover had been deployed is nearly obstacle-free [Figure 3], most of the traversal commands used during the first 12 sols were low-level commands (i.e. Move, Turn, and Position APXS commands). The commands were used thereafter whenever the driver determined that the rover might have to negotiate a rocky/drop-off terrain. The rover demonstrated its ability to negotiate rocky/drop-off terrain on sol 24 and sol 33 during the execution of Go to Waypoint commands. To increase the traversal accuracy, the Turn At commands were used to adjust the rover heading toward its destinations before the Go to Waypoint or Move commands were issued.

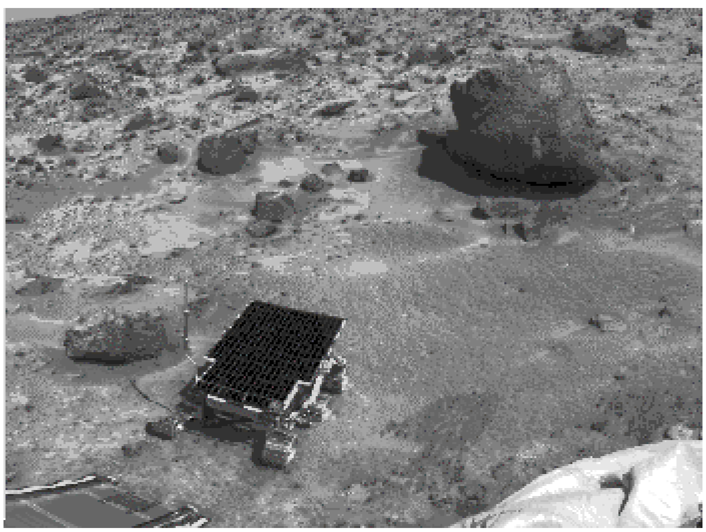

Figure 3: Obstacle-free area near the ramp

Due to relatively erratic observed performance of the vehicle in maintaining it's heading knowledge during the mission, the gyro was deliberately disabled after sol 49. Subsequently, all the turn-in-place turns were then determined by a virtual heading sensor based on the wheel odometers. The arcing movement toward destination mechanism in the Go to Waypoint command was automatically replaced by straight movement and turn-in-place mechanisms.

DATA ANALYSIS

Since the true physical position of the vehicle at any moment was not known until end-of-sol images became available, the vehicle's response to every single navigation command could not be measured. Therefore, in this analysis, the heading and distance errors for every sol are determined from the end-of-sol position estimate made by the rover as identified in the downlink telemetry as compared to the position of the rover as initialized by the driver using the end-of-sol stereo images from the IMP. The traversal distance per sol is defined as the total distances the rover moved during its traversals, both forward (+) and backward (-). The traversal heading per sol is defined as the total change in heading which the rover integrated during its traversal, both left and right turns, in that particular sol.

Extraction of the downlink navigation telemetry of every sol results in the final vehicle position and heading, and the total traversal distance and total turn angle per sol. The Set Vehicle Position command in an uplink command of the subsequent sol defines the true position and heading of the vehicle at the end of the previous sol. This position is determined by the driver through the end-of-sol stereo images. The distance between the end-of-sol telemetry position and physical position is the rover distance error per sol. The difference between the end-of-sol telemetry heading and its physical heading is the heading error per sol. Figure 4 shows the error distance as a function of total distance traveled for each sol.

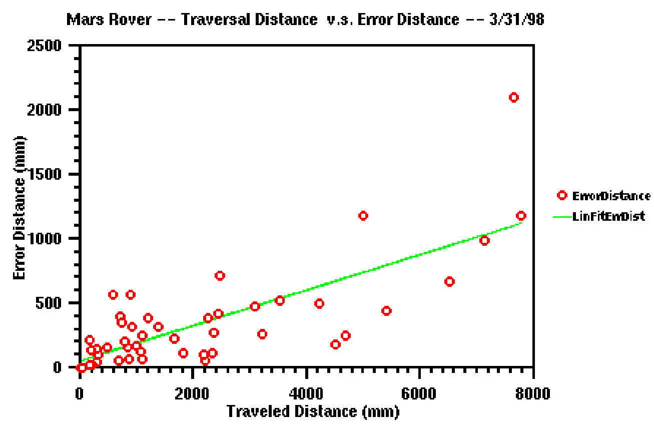

Figure 4: Error Distance vs. Distance Traveled together with Linear-fitted Curve.

Based on the gyro data from turn-in-place turns and the odometry data from health checks before and after each turn was performed, the turns accounted for by both the gyro and the odometer can be compared. There are only 55 turns which contain both gyro-based and odometer-based turn information. The gyro turn error percentage is defined as the difference between the absolutes of the odometry-based turn and the gyro-based turn divided by the absolute of the gyro-based turn. Figure 5 shows the gyro turn errors v.s. gyro turn angles with the linear-fitting curve overlaid. The turn errors are greater when the vehicle makes right turns; these indicate that the gyro was drifting to the left while turning.

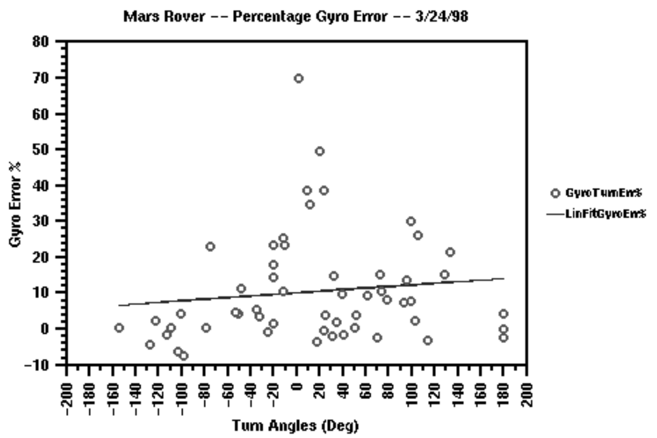

Figure 5: Gyro Turn errors vs. Gyro Turn angles with the linear-fitting curve overlaid.

PATH RECONSTRUCTION

The stereo images of the rover captured by the lander IMP cameras were used to determine the end-of-sol physical vehicle position and orientation. By extending the use of these images the true vehicle traversal paths can be reconstructed. Out of more than 1000 stereo images, there are 272 stereo images containing the rover tracks which can be used for path reconstruction. A custom program was modified and used to trace all the rover tracks, thereby determining the XYZ position of any defined point in the image using triangulation together with the image's camera model.

Track positions were determined and recorded, and the rover physical path over the entire mission is plotted in Figure 6. The physical path, which has many incomplete sections due to lack of stereo images containing track information, is drawn on the navigation telemetry plot (rover's internal-knowledge plot) for comparison. Even with missing of track data, the combined drawing demonstrates the accuracy of the rover navigation, and how the vehicle's internal knowledge had perceived its navigation. Note that for some sols, the redrawing of vehicle tracks cannot be done correctly, since some of the stereo images contain multiple tracks with one overlaid the others.

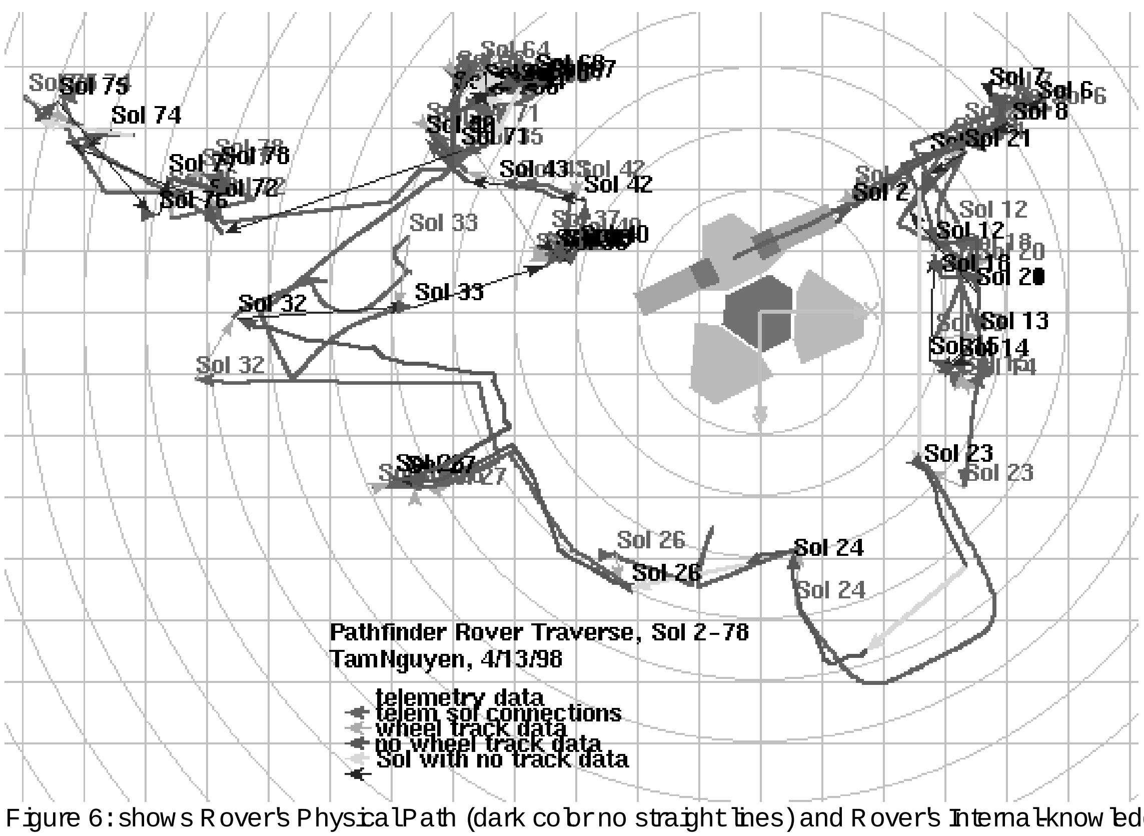

Figure 6: shows Rover's Physical Path (dark color no straight lines) and Rover's Internal-knowledge Path (light color) of the entire mission (Grid size = 1 m2)

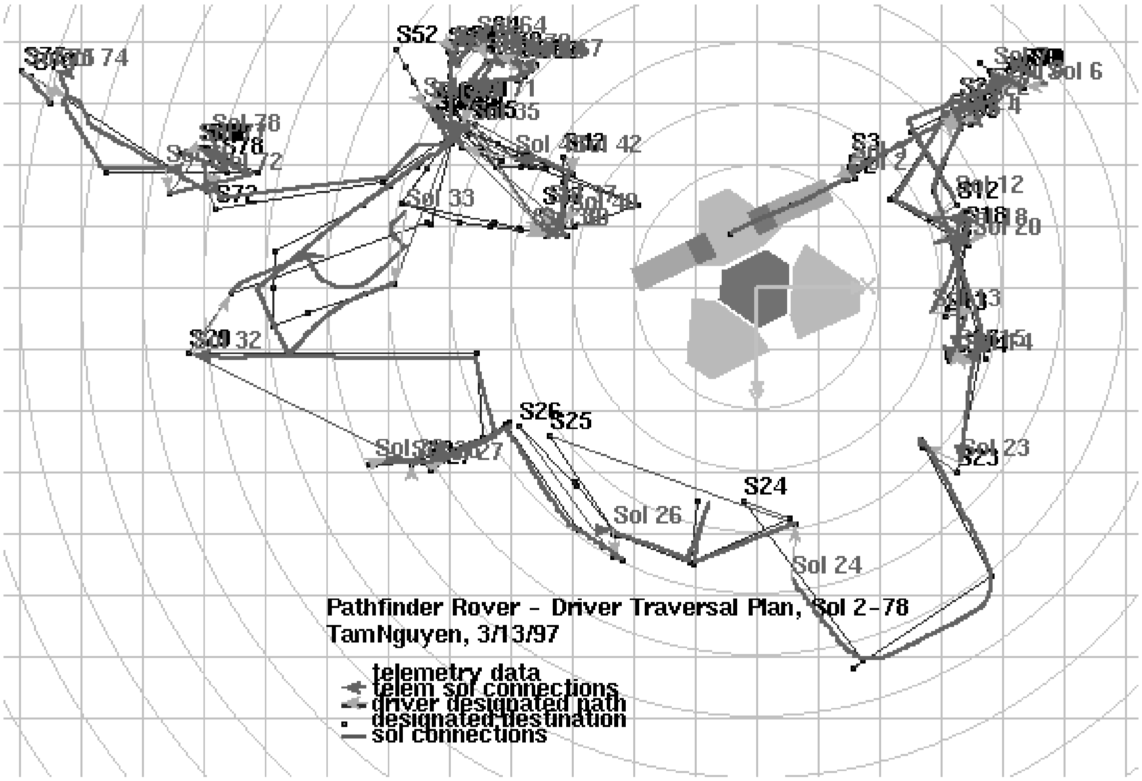

Figure 7: shows Rover's Driver-planned Path (dark & narrow width lines, connected designated destinations) and Rover's Internal-knowledge Path (wider width lines) of the entire mission (Grid size = 1 m2)

Most of vehicle end-of-sol positions were found to be to the right of its internal knowledge paths as seen in Figure 6; this observation agrees with the gyro left-drifted behavior discussed above. All the navigation commands were extracted from the uplink command sequences, and the navigation planned by the driver for the entire mission is plotted together with the rover's internal-knowledge plot in Figure 7. This shows the driver-expectation destination positions of rover for every single navigational command. These destinations closely match the rover's internal-knowledge, since it is servoing to it's internal representation of the commanded path.

DISCUSSION

Autonomous navigation of the Sojourner rover, combined with human assistance through the Rover Control Workstation, has proven the rover's capability to traverse to designated sites for science and engineering experiments. The average heading error was about 6.8 percent, chiefly due to gyro inaccuracy. Testing with the same type of gyro subsequent to the mission indicates that switching noise from the DC-DC converters probably contributed greatly to the magnitude of the gyro drift, and that with clean power the manufacturers specifications for drift are achieved (0.01 deg/sec-root(Hz)). The heading error also influenced the distance error, defined as the ratio of the vehicle error distance to the traversed distance. The distance error includes the cross and down range error components, which were often difficult to disambiguate due to the complex nature of the rover path and the many turns involved. For almost all sols in Figure 4, it was the cross range error component that contributed most significantly to the distance error. Evaluating the cross and down range errors mathematically would be inappropriate since there were no lander stereo images at the end of every single navigation command to be used in determining the physical position and orientation of the vehicle. The cross and down range errors caused by gyro drift were noticed on Earth during the testing phase, but there was no other micro gyro available on the market at that time suitable for the design and space constraints. Wheel slippage might have contributed insignificantly to the rover navigation performance error since in some early mission sols (sol 4) with straight moves, the gyro heading error was low, resulting in the a distance error.

The overall rover control and navigation design which allows the driver to reset the vehicle position every single sol had eliminated rover cumulative navigation errors. The rover 3D-cursor in the RCW enables the driver to measure the rover position and orientation accurately, and directs the rover to its destination. However, with the inaccuracy of the gyro, designation of rover destinations sometimes became cumbersome and lengthy, especially when the APXS was to be placed on a rock.

FUTURE MISSIONS

Two current rover missions are under development: the Athena rover for Mars and the MUSES-CN mission to an asteroid, which is a joint mission with the Japanese space agency ISAS. The Athena rover is the result of an Announcement of Opportunity issued by NASA in the summer of 1997. Prof. Stephen Squyres of Cornell

University is the Principal Investigator for the science payload for that rover. The Athena rover will be large (~1 m long and ~50Kg) and go much farther from the lander than did Sojourner (perhaps Km instead of <10 m). The MUSES-CN rover has been dubbed a nanorover [5], since it is much smaller than the microrover Sojourner (~15 cm long, <1Kg), and it will not have a lander at all, but just fall ballistically onto the asteroid from an orbiter. Thus neither Athena nor the nanorover will have the benefit of the close proximity of a lander which can be used to provide a fixed observation platform and coordinate frame. Thus, the Sojourner mission strategy of using the lander stereo cameras to reestablish the precise position and orientation of the rover once per day is not applicable.

Instead, the rovers must determine their own position and orientation. As we have seen, the Sojourner vehicle lost track of it's orientation relatively quickly due to drift in its rate gyro. In the case of both Athena and the nanorover, some sort of celestial navigation is required to maintain heading knowledge. (Neither Mars nor the asteroid is thought to have a global magnetic field which would be useful for heading measurement.)

Athena will have a sun sensor, which will allow the direction vector to the sun to be measured with respect to the vehicle coordinate frame. Accelerometers will allow measurement of the local gravity vector in the same coordinates. Knowledge of the precise time of day will allow the prediction of where the sun should be in the sky (assuming the latitude and longitude are known), and thus allow computation of the rover's heading in global coordinates.

It is planned for the nanorover to image the star field whenever the absolute orientation in space is needed. The camera will be able to image stars as dim as about the limit of human vision on a dark night, which gives about 4000 stars in the celestial field. Any random field-of-view of the camera will have approximately visible 7 stars expected. Because the angles between stars can be accurately measured in such an image, the angles and relative brightness between any two allow rapid and precise identification of the stars in a star catalog. Such a catalog can be sorted by star brightness, and contain the precise angles and ID numbers of the nearby stars.

By these techniques, the rover heading knowledge will be maintained over the long term. However, it is impractical to continuously make stellar observations. Thus Athena will also have rate gyros (with better power filtering than Sojourner), and the nanorover will use odometry. Odometry on an asteroid with only 10 microgees of surface gravity may be suspect, but if the speed is less than about 2 mm per second, then rolling contact will be maintained. At speeds higher than this, the motion will be intermittent ballistic hopping. For the MUSES-CN mission, rolling at low speed will be done for precise navigation to nearby science targets, and ballistic hopping will be attempted to reach distant targets. During ballistic hops, star finding will be employed to maintain the knowledge of the vehicle attitude. Also, the approximate attitude can be inferred from the distribution of power from the solar panels which cover the exposed faces of the body of the rover.

For these future missions, the rover will require an improved navigation system, including reliable accelerometers, an accurate gyro, and a sun sensor, together with terrain mapping capability. This must be a navigation system with much greater accuracy, to allow the rover to navigate autonomously for hundreds of meters per sol with much less intervention from human operators. The rover will have to reach its destination precisely in order to perform science experiments as commanded.

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