Mars Navigation System Utilizes GPS

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ABSTRACT

Tasks envisioned for future generation Mars rovers – sample collection, area survey, resource mining, habitat construction, etc. – will require greatly enhanced navigational capabilities over those possessed by the Mars Sojourner rover. Many of these tasks will involve cooperative efforts by multiple rovers and other agents, adding further requirements both for accuracy and commonality between users. This paper presents a new navigation system (a Self-Calibrating Pseudolite Array) that can provide centimeter-level, drift-free localization to multiple rovers within a local area by utilizing GPS-based transceivers deployed in a ground-based array. Such a system of localized beacons can replace or augment a system based on orbiting satellite transmitters, and is capable of fully autonomous operations and calibration. This paper describes the prototype SCPA that has been developed at Stanford to demonstrate these capabilities and then presents results from a set of field trials performed at NASA Ames Research Center. These experiments, which utilize the K9 Mars rover research platform, validate both the navigation and self-calibration capabilities of the system. By carrying an onboard GPS transceiver, K9 was successfully able to calibrate the system using no a priori position information and localized the pseudolite beacons to under 5 cm RMS.

INTRODUCTION

Mars surface exploration presents many challenges for robotic systems. Long communication delays (up to 40 minutes round trip) and limited bandwidth dictate high levels of autonomy. The rovers will be operating in a very uncertain and potentially hostile environment, and in order to perform autonomously they must be able to sense and make sense of the environment around them. This sensing requirement becomes even more critical when multiple rovers or other agents are attempting to cooperate in a common area to do joint tasks such as surveying, resource mining and utilization, or habitat construction.

On Earth, carrier-phase differential GPS (CDGPS) can provide centimeter-level, drift free positioning to multiple users operating within a local area. Although a similar system would be of great benefit for Mars exploration, the high launch costs associated with the large number of satellites required precludes this option for the near future. The smaller orbiting positioning and communications network proposed by JPL would be a great asset, but the roughly 10 meter intermittent positioning it would provide is still inadequate for the more precise continuous-time operations envisioned here [1].

The current research effort has developed a prototype GPS-based local-area positioning system to provide the needed navigation capability. Rather than employing orbiting satellites, small low-power transmitters called pseudolites (short for 'pseudo-satellites') would be distributed on the surface. Multiple users operating in the vicinity of the array could then employ CDGPS-type positioning as if they had access to a full GPS satellite constellation and reference station. This concept is illustrated in Figure 1.

In order to use a pseudolite array for cm-level navigation, the locations of the broadcasting elements must themselves be known to cm-level accuracy. The precise positions of autonomously distributed pseudolites on the Martian surface will not be known beforehand, however, necessitating the development of methods to survey the locations of the array devices. The current research has overcome this difficulty by creating a new type of pseudolite array that is capable of surveying autonomously the locations of the transmitters on the surface after deployment. The resulting system is called a Self-Calibrating Pseudolite Array (SCPA) and utilizes full GPS transceivers instead of separate receivers and pseudolites to accomplish this task.

This paper begins by describing the components of an SCPA, including details of the experimental prototype designed and operated at Stanford. It then proceeds to briefly summarize the navigation and array self-calibration processes. The final section of the paper presents results

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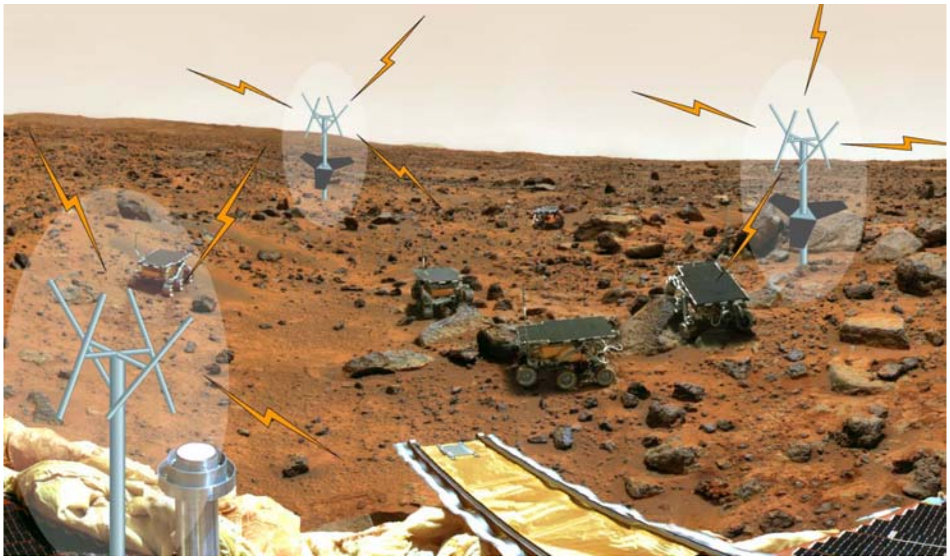

Figure 1: Mars SCPA

from field tests conducted using the K9 rover operated at NASA Ames Research Center. These results include a successful self-calibration of the array from completely unknown initial conditions to a final positioning accuracy of better than 5 cm RMS.

SCPA DESCRIPTION

System Overview

An SCPA is a distributed system consisting of several GPS transceivers together with a common base-station computer for data processing. The transceivers exchange ranging signals between themselves, and triangulation methods then enable relative positioning of the devices. The current prototype system includes four operational transceivers: three in stationary locations and one mounted on the rover. This is the minimum number of static transceivers needed for both unambiguous dynamic positioning of the rover and for the array self-calibration algorithm. System performance and robustness may be improved by adding redundant transceivers to the array.

The ground-station computer – a 133MHz Pentium laptop running the Windows NT operating system – runs a custom software program that collects the raw data from the transceiver wireless units, combines common-epoch measurements into ranges between transceiver pairs, and computes the corresponding array geometry. This program also allows remote control and diagnostics of the receivers.

A more comprehensive description of the experimental system appears in [2].

GPS Transceivers

Each transceiver consists of a single GPS receiver and a separate pseudolite signal generator. The receiver monitors the pseudolite output signal to form a self-differencing transceiver, as is described in [3]. The receiver is a slightly modified Mitel Orion receiver with custom tracking loops for the non-standard pseudolite data message. The pseudolite is an IntegriNautics IN200C signal generator utilizing a 3% duty cycle RTCM pulsing scheme to help combat the near-far problem associated with near-field operations. The total combined broadcast power of the current experimental system is less than 1μW, the FCC limit for licensed experimental L1 transmission. The low signal power limits the range of operation of the prototype system to about 30-50 meters. Higher power levels will enable operation over baselines of kilometers, provided that line-of-sight is maintained.

Figure 2 shows one of the stationary transceivers from the prototype system. The custom-built dipole broadcast and receive antennas are located on the transparent plastic plate on top of the tripod. Using dipoles instead of commercial GPS patch antennas allows 360° operation around the transceiver because of the omnidirectional pattern and the lack of circular polarization, although this comes at the penalty of losing some multipath rejection. The tote-bucket beneath the tripod holds the transceiver components themselves. In addition to the receiver and pseudolite this bucket contains a 1.6 Mbps Proxim RangeLan2 wireless link for data collection, a 4.4 A-hr NiCd battery pack which gives roughly 4 hours of continuous operation, and RF power amplifiers to improve signal acquisition and tracking.

Figure 2: GPS Transceiver

K9 Rover

The K9 rover used for the experiments at NASA Ames is shown in Figure 3. K9 is a variant of the FIDO rover under development at JPL for future Mars missions. It features a rocker-bogie suspension system, 360° variable steering, and an onboard dead-reckoning system. Typical speed of operation is roughly 10 cm/sec. The large sensor mast holds a stereo camera pair used for terrain mapping. A scanning laser rangefinder is mounted on the front of the rover for obstacle detection. The short vertical mast on the far left side of the photo holds the GPS antennas used for the onboard transceiver.

SCPA OPERATIONS

SCPA Navigation

Navigation using an SCPA follows the same principle as satellite-based differential GPS, and can be accomplished at both the code or carrier levels. Details of conventional GPS navigation can be found in [4]. In order to achieve precise navigation without using atomic clocks, a double-difference ranging solution has been developed between GPS transceivers with both receiving and transmitting elements in a common device. The resulting bidirectional ranging solution involves exchanging ranging signals (corrupted by clock biases) between device pairs. It then

Figure 3: K9 Rover

cancels out the clock biases associated with the transmitter oscillators through the differencing process, as is presented in [5].

Determination of the array geometry and the location of the rover are accomplished by combining the range measurements between transceiver pairs, either using triangulation or standard non-linear optimization techniques. Code-level positioning is available instantaneously, allowing a rough (2-4 meter) navigation capability to all users within the array. Although uncalibrated line and system biases can further degrade the accuracy, code-based ranging is sufficient for many tasks such as general navigation between points and collision avoidance.

If more precise navigation is required – such as for more complex or repetitive tasks like cooperative manipulation or construction – carrier-phase positioning may be performed. Raw carrier-phase ranging accuracy using the SCPA has been demonstrated to better than 0.8 cm RMS [2]. Achieving such accurate positioning is only possible after an additional calibration step is used to resolve the associated integer ambiguities.

Array Self-Calibration

Array self-calibration to determine these carrier-phase integers follows a multiple-step process (Figure 4).

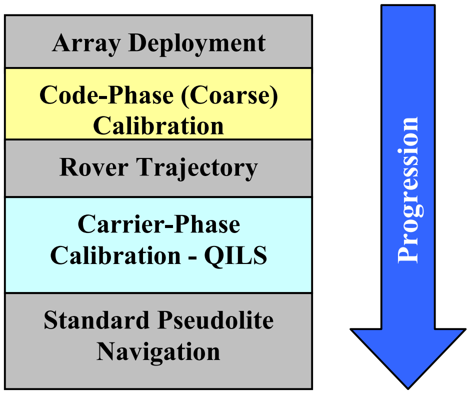

Figure 4: Self-Calibration Process

Following array deployment, initial coarse calibration is obtained by using code-level bidirectional ranging between the transceivers to triangulate their relative positions. The self-calibration process itself then utilizes the relative motion of a transceiver-bearing rover to alter the array geometry over time. During this motion the unknown carrier-phase integers remain constant.

A batch process collects carrier-range data during the course of this maneuver, and is subsequently able to determine both the integers and the actual positions of the static transceivers to centimeter-level accuracy via a non-linear iterative optimization process. The current solution algorithm, Quadratic Iterative Least Squares (QILS), is described fully in [6]. Comparing multiple solutions stemming from stochastic variations in the initial estimate ensures that the iteration process does not converge to false local minima.

At least three range measurements from the rover to the static transceivers must be available for self-calibration, and rover motion must be considerable – but not unreasonably so – for successful convergence. For example, a circumnavigation of the array by the rover is sufficient. Note that the rover does not have to drive a tightly defined trajectory in order to calibrate the array, since the algorithm backs out the actual rover trajectory as part of its solution. This calibration process can also be used to remove unknown line biases from the code-range solution.

FIELD TESTS

A series of field tests have been performed using the prototype system in order to verify both the navigation and self-calibration capabilities of the SCPA. Several of these tests were performed at NASA Ames Research Center at Moffett Field, California, using the K9 rover. Results from these experiments are presented below. Other testing without the K9 rover has been performed on a large open field at Stanford University [2].

Test Location

Testing at Ames is done in a large empty lot near the inlet of the large 80’ by 120’ subsonic wind tunnel, yielding a moderately high multipath environment. Figure 5 shows the experimental system in operation, including all three static transceivers (placed in a triangle approximately 20 meters apart) and the K9 rover.

Code-Phase Calibration

The testing process for the SCPA follows the same steps as the self-calibration process described earlier. The stationary transceivers are arrayed in the test area in an triangular configuration 20 meters to a side. The rover starts outside of the array near to one edge of the triangle. The locations of these transceivers are pre-surveyed to provide a truth metric; knowledge of these positions, however, is not used at any time during the self-calibration

Figure 5: NASA Ames Test Site

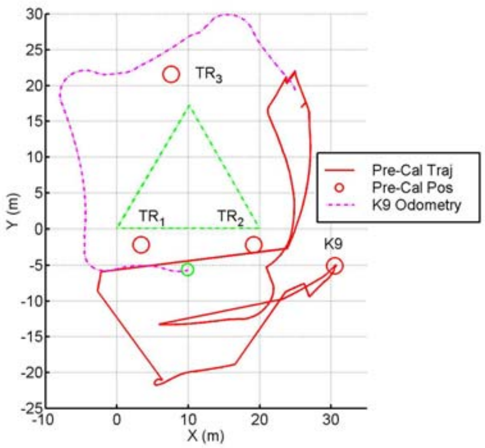

Figure 6: Pre-Calibration Positions and Trajectory

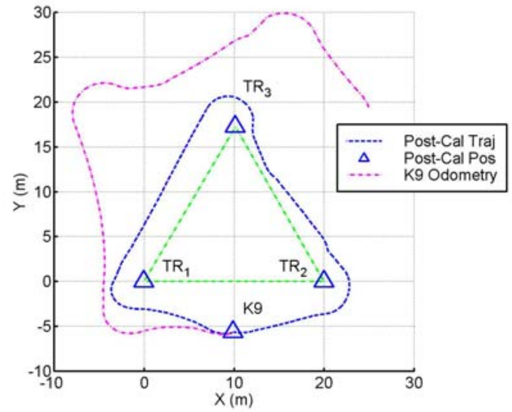

Figure 7: Post-Calibration Positions and Trajectory

process. Once the array is in place, averaged code-range measurements between the transceivers are used to generate an initial estimate of the transceiver locations. Figure 6 shows the transceiver locations as determined by this coarse calibration step. The actual locations are at the corners of the large dotted triangle, while the true rover position is at the small circle underneath the triangle.

Table **1** shows the corresponding position errors. The errors for the stationary transceivers are 2.76 meters RMS, an acceptable result for code-phase positioning. The positioning error for K9 is greater than 20 meters, however, most likely due to strong multipath from the surrounding fence. With such a small array, errors of this magnitude greatly cripple its navigational effectiveness.

Calibration Trajectory

The K9 rover now circumnavigates the array to provide the geometry change needed for self-calibration. The overall trajectory is approximately 100 meters in length, and takes 20 minutes to complete. During the trajectory carrier-range data is collected between the transceiver on K9 and each of the stationary transceivers, the carrier phase integers having been estimated from the results of the code-phase calibration. Figure 6 also presents the rover trajectory as determined from these carrier-phase range measurements. Rather than a smooth loop around the array, the large errors in the integer estimates have produced an almost unrecognizable hash of segments and jumps. For comparison the path computed by the wheel encoders onboard K9 is also presented as a dashed line. Although the odometry trajectory does not return to the starting point like the true trajectory, the character of the loop is readily apparent.

Carrier-Phase Calibration

The self-calibration algorithm mentioned earlier is now applied to the range data collected during the preceding trajectory. Even with such large initial errors in the array estimate, the algorithm successfully converges to the correct array geometry and rover path. Figure 7 shows these results, and the corresponding errors in the locations of the stationary transceivers are displayed in
Table **2**. The calculated trajectory now matches the true trajectory to within centimeters, and RMS position errors for the stationary transceivers have been reduced to 4.2 cm RMS. The error associated with K9 is slightly higher because a hardware failure in one of the receivers during testing caused a loss of clock synchronization, creating a slight drift in the measured ranges.

During this field experiment the self-calibration process reduced the positioning errors in the array by three orders of magnitude. Extensive Monte-Carlo simulations utilizing over 100,000 different configurations show that the self-calibration techniques employed are successfully able to localize the array elements over a wide range of

Table 1: Initial (Code-Phase) Position Errors

Transceiver	X (m)	Y (m)
1	3.38	-2.13
2	-0.87	-2.13
3	-2.52	4.27
K9	20.42	0.60

Table 2: Final (Carrier-Phase) Position Errors

Transceiver	X (m)	Y (m)
1	-0.01	0.03
2	-0.05	0.03
3	0.06	-0.05
K9	-0.16	0.09

array shapes and with initial errors in the position estimates as large as the size of the array itself. Self-calibration success is 100% for up to a 75% variation in the nominal array geometry and for initial estimation biases of less than 20% of the array size. This corresponds to 20 meters of code-phase multipath error in a 100 meter array, towards the upper end of what is experienced in the actual experimental system. When biases are allowed to increase to 100% of the array size, self-calibration effectiveness is still 99.80% [7].

CONCLUSIONS

The Self-Calibrating Pseudolite Array described herein provides an effective means of acquiring CDGPS-type precise positioning in locations without access to the terrestrial GPS constellation, such as on the surface of Mars. Knowledge of the locations of the (autonomously deployed) pseudolites is necessary for successful navigation within the array. Using the QILS algorithm together with limited motion of one of the GPS transceivers, the positions of the array elements may be determined to centimeter-level accuracy.

The field tests conducted at NASA Ames Research Center using the K9 Mars rover prototype demonstrate the viability and accuracy of the SCPA. Code-level positioning errors in low-multipath situations are less than 3 meters, sufficient for coarse-level navigation over wide areas. Once carrier-phase self-calibration has been conducted, positioning accuracy increases to better than 5 cm RMS, a level which would enable precise control and cooperative operations between multiple robots.

While the experiments described in this paper are confined to a 2-dimensional geometry, the navigation and self-calibration capabilities of the SCPA are applicable to 3-dimensional configurations. A theoretical description and the experimental validation of such a 3-dimensional SCPA appears in [8].

The Self-Calibrating Pseudolite Array described in this paper is capable of providing extremely accurate and repeatable navigation without any additional augmentation. In practice, however, an SCPA on the Martian surface would ideally be used in conjunction with a complementary set of sensors in order to provide additional information beyond the scope of the raw GPS-based position data. Computer vision or scanning lasers, for example, would be required for obstacle detection and avoidance, and would also be useful for fine servoing control. Additionally, blending the SCPA navigation data with an inertial navigation or dead reckoning system would provide an additional level of robustness in case of GPS cycle slips or signal loss due to intervening terrain or other obstacles. Because of its capability for centimeter-level, drift-free positioning for multiple agents, an SCPA would be a critical enabling technology for such an integrated sensing and navigation system.

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