Autonomous Deployment of a Self-Calibrating Pseudolite Array for Mars Rover Navigation

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Abstract - **A "Self-Calibrating Pseudolite Array (SCPA)" is a self-deployable GPS pseudolite-based local-area navigation system applicable to future-generation Mars rovers. By utilizing bi-directional GPS transceivers (incorporating separate GPS pseudolites and GPS receivers) deployed in a ground-based array, the SCPA can provide all the benefits of satellite-based Carrier-phase Differential GPS (CDGPS), such as drift-free, centimeter-level, and three-dimensional positioning, without requiring a satellite constellation on Mars. Relative geometry change by moving the rover enables the SCPA to self-calibrate both the array locations and the rover trajectory to centimeter-level accuracy. This self-calibration capability of the SCPA overcomes the difficulty of autonomous robotic deployment of the pseudolite-based navigation system on Mars, eliminating the need for accurate *a priori* position information or precise placement of the array. This paper presents new results from the latest field trial of the SCPA conducted in February 2004 using the K9 Mars rover platform operated in the Marscape at NASA Ames Research Center. This field trial demonstrates the entire scenario of the SCPA operation, starting with autonomous array deployment, followed by array self-calibration and centimeter-level navigation for a long traverse. The results show that a 0.2% drift rate is achieved by the SCPA navigation (0.4 meter of the final positioning error after a 174.7 meter traverse).**

INTRODUCTION

Mobility is a key requirement for Mars robotic surface exploration missions. In order to maximize science returns in area surveys, sample collection, or life detection, future-generation Mars rovers will be required to explore an extensive terrain to reach as many sites of interest as possible. Due to long communication delays, a series of robotic tasks, such as moving towards science targets, placing instruments, and picking up samples, must be performed autonomously. Based entirely on their onboard sensor information, the rovers must be able to sense and make sense of the environment around them, figuring out what surroundings looks like, where science targets are located with respect to their current positions, and how to avoid obstacles to reach the targets. This sensing capability for rover navigation, or localization, is a critical requirement for autonomous rover mobility in the uncertain Martian environment.

The Aerospace Robotics Laboratory (ARL) at Stanford University has developed a self-deployable GPS pseudolite-based navigation system, called a Self-Calibrating Pseudolite Array (SCPA) [1]. Navigation using the SCPA follows the same principle as the satellite-based Carrier-phase Differential GPS (CDGPS) [2]. However, rather than employing a satellite constellation, the SCPA consists of several stationary GPS pseudolite transceivers distributed in a ground-based array, and is capable of providing all the CDGPS benefits, such as drift-free, centimeter-level, and three-dimensional relative positioning in a local area.

This GPS-like drift-free nature of the SCPA enables critical scientific tasks that require enhanced rover mobility with very precise localization in a highly repeatable manner for a long duration. For example, the SCPA makes a perfect complement to conventional Mars rover positioning systems based on computer vision, wheel odometers and inertial sensors, providing a drift-free absolute measurement of the rover position over an extensive site. When merged with an obstacle-avoidance system, the SCPA would support path planners for both short and long traverses, enabling the rovers to go precisely to and from any specific science targets, a critical capability for future sample-return missions. Its real-time continuous positioning would also be suitable for feedback-control systems, reducing the number of command cycles required to drive rovers. Furthermore, precise knowledge of the rover motion provided by the SCPA could be augmented with rover computer vision systems, greatly improving the performance of their localization and mapping algorithms. In addition, the RF-based positioning of the SCPA could function reliably in the period of limited visibility (e.g., at night or during severe dust storms).

Figure 1: A Self-Calibrating Pseudolite Array (SCPA) deployed over a dry lakebed area in the "Marscape" at the NASA Ames Research Center

In order to use a pseudolite array for centimeter-level rover navigation, however, the location of the broadcasting pseudolites must be known to centimeter-level accuracy. Unlike conventional pseudolite arrays, which require precise manual pre-surveys of the pseudolite locations, the SCPA is capable of surveying autonomously the pseudolite locations after the deployment, thus eliminating the need for accurate *a priori* position information or precise placement of the pseudolite array. This self-calibration capability makes the SCPA literally "self-deployable," overcoming the difficulty of autonomous robotic deployment of the pseudolite-based navigation system on Mars. The feasibility of the self-calibration capability of the SCPA has been previously demonstrated in a series of field tests, which appear in [3, 4].

This paper begins with brief descriptions of the SCPA system, the GPS pseudolite transceivers, and the K9 rover. It then proceeds to describe the operation of the SCPA, focusing on the autonomous array deployment and the array self-calibration algorithm. The final section presents new results from the latest set of field trials conducted using the K9 Mars rover platform operated in the Marscape at NASA Ames Research Center. This field trial demonstrates the entire scenario of the SCPA operation, starting with autonomous array deployment, followed by array self-calibration and centimeter-level navigation for a long traverse. These results show that a 0.2% drift rate is achieved by the SCPA navigation (0.4 meter of the final positioning error after a 174.7 meter traverse).

SCPA DESCRIPTION

System Overview

An SCPA is a distributed system consisting of several GPS transceivers. The GPS transceivers exchange ranging signals among themselves, and then triangulation methods enable relative positioning of the devices. The current prototype system includes four operational GPS transceivers: three deployed in stationary locations and one mounted on the K9 rover (Figure 1). This is the minimum number of stationary GPS transceivers required both for determining unambiguous dynamic 2-D positioning of the rover and for resolving unknown array locations via the array self-calibration algorithm. Extra GPS transceivers can be added to the array, improving system robustness with redundant ranging signals, or enabling 3-D positioning capabilities of the SCPA [4]. A more comprehensive description of the experimental system appears in [5].

GPS Transceivers

Each GPS transceiver consists of a collocated GPS receiver and pseudolite; it is thus able both to transmit and receive ranging signals bi-directionally. A pseudolite, short for "pseudo satellite," is a compact low-power GPS transmitter that can broadcast ranging signals similar to those transmitted by the GPS satellites. A GPS receiver tracks and measures ranging signals transmitted both from its own collocated pseudolite and from other pseudolites deployed in an array.

The measurement of the ranging signals are corrupted by clock biases associated with both transmitter and receiver oscillators. In order to eliminate the clock biases from the measurements, a double-difference ranging solution has been developed. The detailed formulations for this bi-directional ranging are presented in [1, 6].

The resulting bidirectional ranging solution, thus free from both receiver and pseudolite clock biases, provides two different types of ranges: an absolute range (R) based on C/A code-phase measurements and a delta range (ΔR) based on integrated carrier-phase (ICP) measurements. The absolute range is a time-of-flight measure available at each sampling instant with meter-level accuracy, while the delta range is a precise Doppler measurement integrated over time with centimeter-level accuracy.

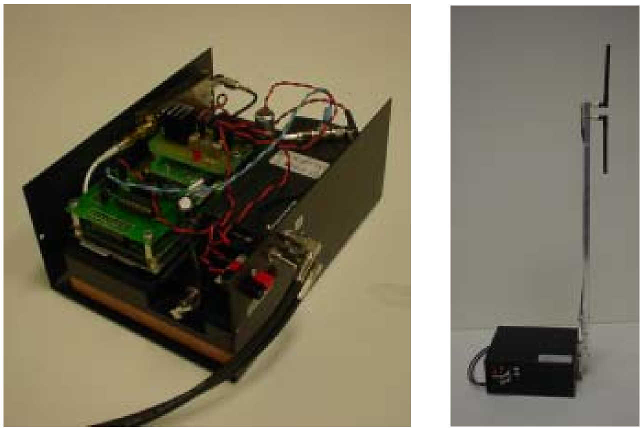

Figure 2: GPS transceiver box

The prototype GPS transceiver box, shown in Figure 2, includes a single GPS receiver (Novatel Allstar OEM, L1-Only, 10Hz CP), a modified pseudolite signal generator (IntegriNautics IN200C, L1-only, 2% RTCM pulsing), an 802.11 WLAN adapter (OTC WiSER 2400IP) for wireless data collection, and a pair of custom GPS dipole antennas for transmitting and receiving (Galtronics 1.5GHz whip). With less than 1 μW of pseudolite transmitting power, the maximum operational range has been tested up to 200 meters. Higher power levels will expand the operational range over kilometers, provided that line-of-sight is maintained.

K9 Rover

The K9 rover used for the field test at NASA Ames is shown in Figure 3. The K9 is a six-wheel rocker-bogey chassis outfitted with electronics and instruments to support research for remote science exploration and autonomous operation on future Mars missions. The large sensor mast holds a stereo camera used for terrain mapping. A scanning laser rangefinder is mounted on the front of the rover for obstacle detection. Currently, the K9 rover determines its position using a dead-reckoning odometry. Onboard sensors, including wheel encoders, a compass, inclinometers, and an IMU, are fused to estimate the rover position and attitude using a Kalman filter.

Figure 3: K9 rover

The mobile component of the SCPA has been integrated into the K9 rover; the onboard GPS transceiver box is bolted inside the K9's main electronics bay and the GPS transceiver antenna is mounted vertically on the right-rear corner (Figure 3). Real-time positioning updates by the SCPA are sent to the K9's main CPU through a serial port.

SCPA OPERATION

Array Deployment

The operation of the SCPA starts with deploying stationary GPS transceiver units autonomously in a fixed array. One possible deployment method is that the K9 rover carries the stationary transceivers to be deployed and places them on the field one by one. After placing one of the stationary units (Figure 4), the distance between the K9 rover and the first unit can be calculated from the delta range between the two based on the ICP Doppler measurements. Although the ICP-based delta range is given in centimeter-level accuracy by the bi-directional transceiver ranging, the measurement of the absolute distance between the two is corrupted by a meter-level initial bias caused by the uncertainty of robotic deployment. The initial bias of the placement uncertainty can be assumed to be roughly less than a half meter, provided that the stationary transceiver is placed somewhere within a half meter from the K9. This placement uncertainty is calibrated later to centimeter-level accuracy in the self-calibration process; therefore no precise deployment capability on the K9 rover is necessary.

Figure 4: Deployment of the first transceiver unit

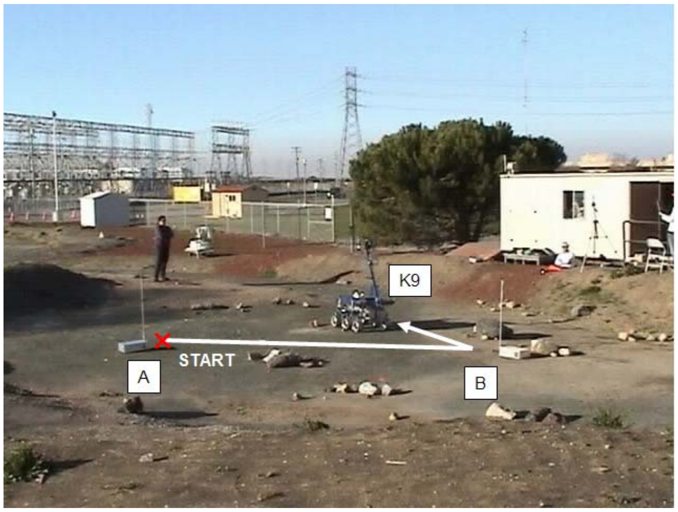

Figure 5: Deployment of the second transceiver unit

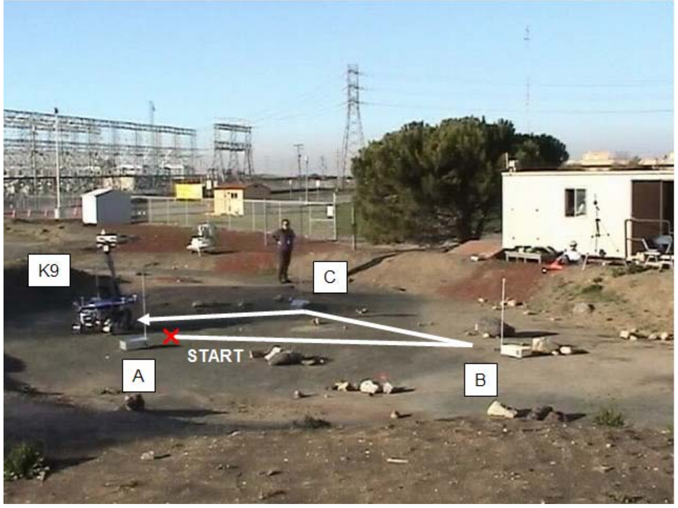

Figure 6: Deployment of the third transceiver unit

Once the second stationary unit is deployed (Figure 5), the K9 rover can instantly start meter-level 2-D positioning via a triangulation of the two delta ranges. Again, this inaccuracy is caused by the placement uncertainty of the two stationary units, although it is sufficient for many rover tasks such as general navigation between waypoints and collision avoidance. Placing the third stationary unit (Figure 6) completes the SCPA deployment with the minimum configuration required for full operation. This third transceiver provides better geometry for the triangulation and also provides the capability of array calibration to centimeter-level accuracy, where three delta ranges, or three measurement constraints, are required to resolve all the uncertainties to be calibrated.

Array Self-Calibration

The array self-calibration process takes multiple steps to complete. First, after the deployment of the transceiver arrays, the meter-level estimate of the array geometry and the rover location is obtained by the triangulation of absolute ranges, which are calculated either by the instantaneous code-phase measurements, by coarse knowledge of the array locations measured during the array deployment, or by external rover position information obtained from the onboard dead-reckoning system.

Next, a rover equipped with a GPS transceiver drives around the deployed arrays doing science tasks, while collecting ICP Doppler measurements. This relative geometry change by rover motion is necessary to resolve initial biases in the absolute ranges. For instance, a circumnavigation around the array by the rover provides sufficient observability for all the unknown initial biases (Figure 7). The initial biases in the absolute ranges include the uncertainty of pseudolite array placements, integer ambiguity in the ICP measurements, and RF line biases.

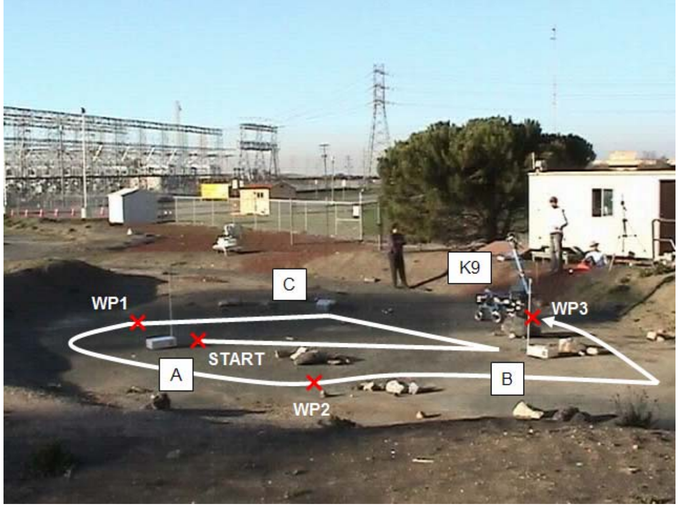

Figure 7: Circumnavigating maneuver for self-calibration

Then, by batch-processing the delta ranges via a non-linear iterative least square (ILS) method, the SCPA is able to determine simultaneously both the array locations and the trajectories of mobile units to centimeter-level accuracy. Note that the only data used in this self-calibration process are the delta ranges based on the ICP Doppler measurements; hence no external information about the rover motion is required. The complete description of the array self-calibration algorithm is in [1].

One remarkable feature of this array self-calibration is that, once the array is calibrated, all the past trajectories followed by the K9 rover after the second unit placement are corrected from meter-level accuracy to centimeter-level accuracy. Furthermore, the locations of the science targets identified before the self-calibration step are also calibrated to centimeter-level accuracy.

Navigation after the Self-Calibration

Once all the initial biases in the range measurements are calibrated, the K9 rover is ready to operate with centimeter-level navigation anywhere within the array. The K9 rover can also move far outside the array as long as the lines of sight (LOS) are maintained (Figure 9). However, the accuracy of the position estimate by triangulation may be degraded depending on the geometry of the array and the rover location, the well known Dilution of Precision (DOP) [2]. Figure 8 shows the confidence ellipse of the positioning estimate based on a triangle array with a 10 meter baseline and 0.1 meter errors in range measurements. Note that the confidence ellipse is drawn 10 times larger than the actual scale. Although the stretched shape of the ellipse indicates that bearing errors become significant as the rover moves away from the array, the bearing error is still bounded approximately by 1 meter over an extensive area of 100 x 100 square meters outside the array.

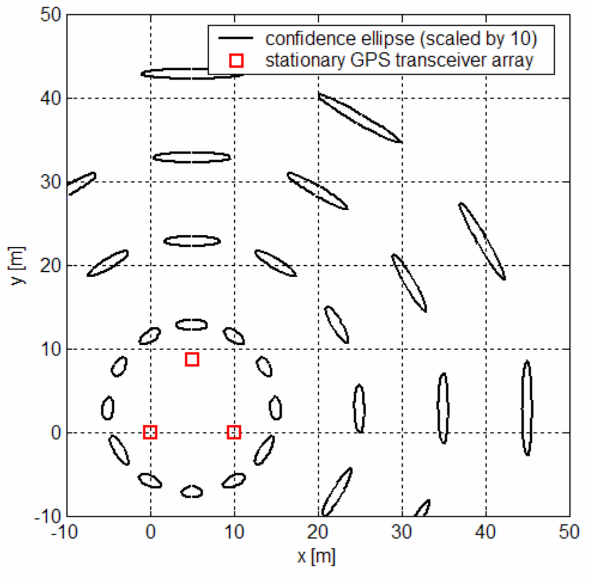

Figure 8: Confidence ellipse of positioning estimate

FIELD DEMONSTRATION

A series of field tests has been performed using the prototype system in order to verify both the navigation and self-calibration capabilities of the SCPA [4]. The results from the latest set of field trials are presented in this section in order to demonstrate the entire scenario of the SCPA operation, starting with autonomous array deployment. The field tests were conducted in February 2004 using the K9 Mars rover platform operated in the Marscape at NASA Ames Research Center. The Marscape is a 3/4 acre lot of the Ames outdoor test site with Mars-analog terrains that has been designed to incorporate typical aspects of the Martian environment and geology of greatest science interest. The SCPA was deployed on a dry lakebed area of the Marscape (Figures 1, 9).

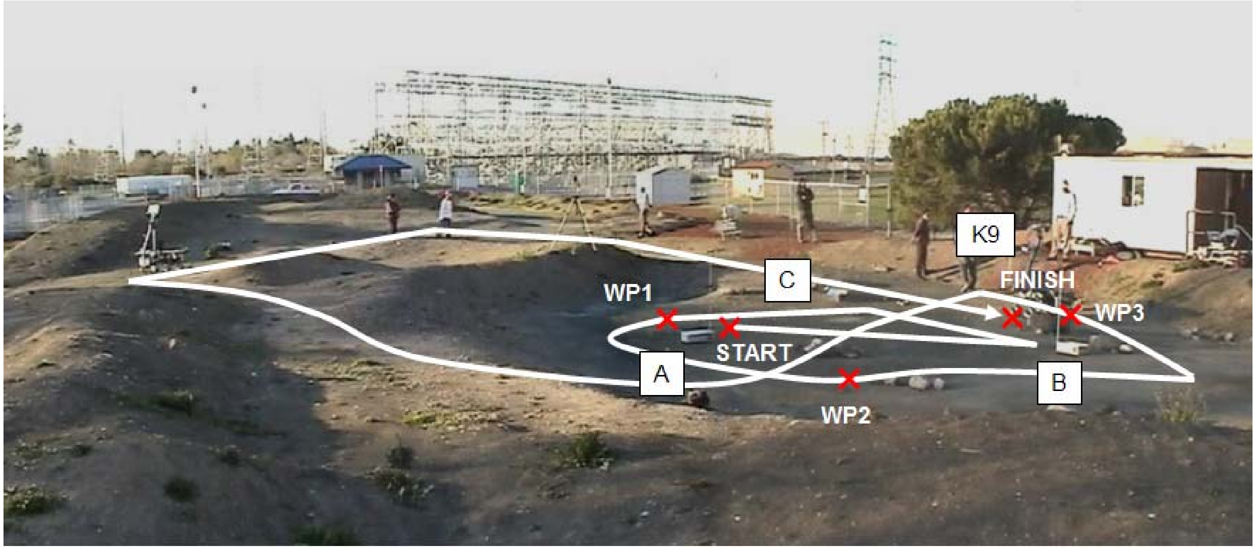

Figure 9: Long traverse navigation outside the array

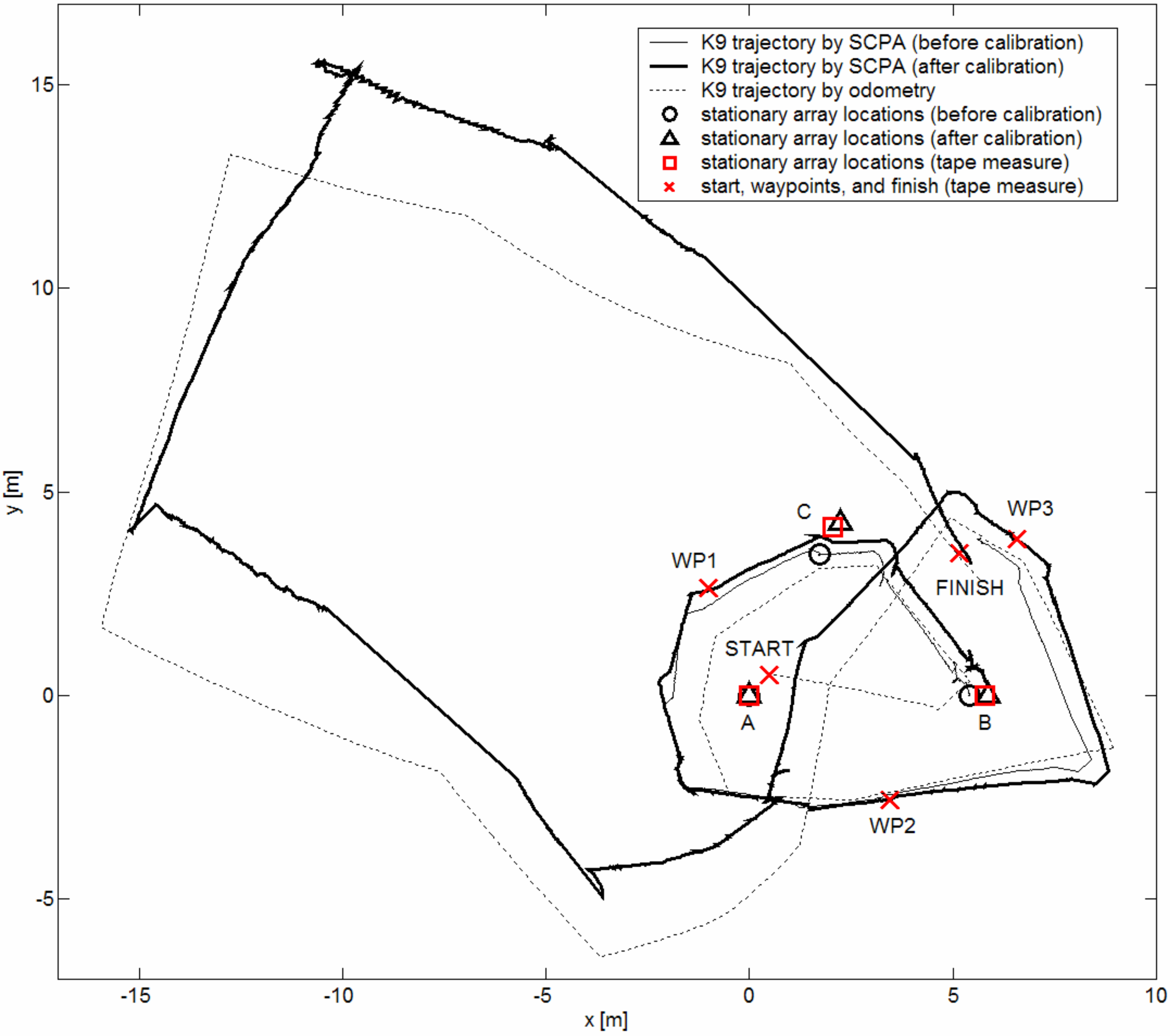

Figure 10: Self-calibration results for the K9 trajectory and the stationary array locations

The testing process followed the same steps as described earlier in the SCPA operation section. First, the K9 rover placed one of the stationary transceiver units (A) next to the starting location (START), then proceeded to deploy the other two stationary units (B, C), as shown in Figures 4, 5, and 6. Since there was no mechanical SCPA deployment system designed on the K9 rover yet, each stationary unit was placed manually next to the rover in this field test. Next, the K9 rover drove around the array, while stopping at three waypoints (WP1, WP2, and WP3), as shown in Figure 7. The self-calibration was executed when the rover reached WP3. Then, the K9 continued to roll for a long traverse after the array calibration, returning back close to WP3, where the final destination (FINISH) was set. The entire trajectory followed by the K9 rover during this trial is illustrated in Figure 9. The overall traverse was approximately 174 meters in length and it took about 75 minutes to complete.

Figure 10 shows the successful results of the array deployment, the array self-calibration, and the long traverse navigation. The locations of the stationary units (A, B, and C), the starting location (START), the waypoints (WP1, WP2, WP3), and the final destination (FINISH) were pre-surveyed by tape measure to provide a truth metric. In Figure 10, their locations are shown by square-markers and x-markers in the figure as true reference. The thin solid line shows the K9 trajectory calculated by the uncalibrated SCPA after the placement of the second stationary unit (B). The circlemarkers show the initial estimate for the stationary array locations. Because of the placement uncertainty, they are biased by meters from their true references in the figure. Before the array calibration, the errors for the locations of the stationary transceiver units and the waypoints from the true reference were 0.49 meter RMS and 0.45 meter RMS, respectively.

When the array self-calibration was executed at WP3, both the K9 trajectory and the stationary array locations were calibrated from meter-level accuracy to centimeter-level accuracy. In Figure 10, the thick solid line shows the K9 trajectory calculated by the calibrated SCPA and the triangle-markers show the calibrated stationary array locations; now both match their true references within centimeters. As a result of the array self-calibration, the errors for the locations of the stationary transceiver units and the waypoints from the true reference were successfully reduced to 0.13 meter RMS and 0.09 meter RMS, respectively.

The dashed line shows the K9 trajectory calculated by the dead-reckoning system based on the K9 onboard odometry (wheel encoders, compass, and IMU). In Figure 10, the odometry solution was plotted on top of the SCPA solution by aligning their first straight trajectories from the stationary unit B to the stationary unit C with a half-meter offset. This offset is based on the fact that the SCPA measures the location of the GPS transceiver antenna mounted on the right-rear corner of the K9, while the odometry measures the motion of the center of the K9 body. As expected, the odometry solution tended to drift away gradually as the rover moved around, although it was able to capture the rover motions precisely at each short instance and reliably provided continuous positioning solutions without an outage.

After the long traverse from WP3 to FINISH, the final rover position error at FINISH by the SCPA solution was 0.39 meter from the true reference. This validates that the drift-free nature of the SCPA is applicable for a long traverse. The resulting drift rate was 0.2% after a 174 meter traverse.

CONCLUSIONS

The Self-Calibrating Pseudolite Array (SCPA) provides an effective means of acquiring CDGPS-type centimeter-level positioning in locations without access to the GPS satellite constellation, such as on the surface of Mars. The entire operational scenario of the Mars rover navigation using the SCPA has been experimentally demonstrated using the K9 rover operated in the Marscape at NASA Ames. The field test results have validated the feasibility of the "carry and plant" method for autonomous array deployment without the need for accurate *a priori* position information or precise placement of the pseudolite array; therefore, the SCPA is a self-deployable navigation system, suitable for use in future robotics mission on Mars. In addition, the long traverse capability of the SCPA was demonstrated over an extensive area, even far outside the array, with a total traverse of 174 meters. Furthermore, the drift-free nature of the SCPA has revealed that the centimeter-level accuracy is maintained during the long traverse with the drift rate of 0.2%. This low drift rate would be an attractive feature for many robotic science tasks like retrieving samples, which will require precise navigation towards specific locations. The SCPA could be a critical enabling technology for enhanced rover mobility in future Mars missions.

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