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Precise Positioning with Wireless Sensor Nodes

Monitoring Natural Hazards in All Terrains

Joshua D. Kenney, Donald R. Poole,
Gregory C. Willden, and Ben A. Abbott, Ph.D.
Automation and Data Systems Division
Southwest Research Institute®
San Antonio, TX
joshua.kenney@swri.org, donald.poole@swri.org,
gregory.willden@swri.org, and ben.abbott@swri.org

Alan P. Morris Ph.D., Ronald N. McGinnis,
and David A. Ferrill, Ph.D.
Geosciences and Engineering Division
Southwest Research Institute®
San Antonio, TX
alan.morris@swri.org, ronald.mcginnis@swri.org,
and david.ferrill@swri.org

***Abstract*— Prediction, assessment, and mitigation of surface-affecting natural hazard processes such as landslides, avalanches, earthquakes, and floods call upon geoscientists to rapidly deploy instruments and accurately characterize these earth processes, often with little lead time and under dangerous working conditions. Affected areas may have heavy tree canopies, or high atmospheric dust loads (volcanic eruptions), precluding the use of traditional location techniques like Global Positioning System (GPS). The proliferation of inexpensive radio systems provides a technology that has the potential to redefine the approach to rapid characterization of hazardous earth processes. The research effort described in this paper developed and demonstrated an inexpensive, cooperative radar-like technology for precise distance measurement between intelligent radio nodes.**

***Keywords*—wireless sensor networks, localization, radar, distance measurement, hazard monitoring**

I. Introduction

Although monitoring of certain earth processes (e.g., volcanic eruption, flooding) may call upon very specific measurements (e.g., temperature, atmospheric or soil gas composition, water level), precise knowledge of the location of sensor nodes is a universal data requirement and for some applications – such as surface displacement associated with a landslide – the only data requirement. Landslides represent a widespread geologic hazard that results in hundreds of deaths and billions of dollars in property damage throughout the world each year [1].

Recent advances in remote sensing capabilities allow the identification of areas that are susceptible to landslide hazards. Remote sensing data, however, are impractical for near real-time landslide hazards identification due to high costs, survey limitations, and complex data processing requirements. For areas with limited vegetation cover, surface deformation can be measured using precision GPS surveys of benchmark locations. High-cost GPS surveys have proven to be time-consuming and require repeated occupation of predetermined benchmarks, which may be located in hazardous or remote areas [2]. Areas with a significant tree canopy or obscured view (e.g., valley walls) may not receive GPS signals successfully. Other remote sensing techniques, such as photogrammetry, synthetic aperture radar, or light detection and ranging (LIDAR), make infrequent measurements and rely on successful aerial surveys to measure relatively large (i.e., m/yr) deformation rates. These techniques are unsuitable for near real-time monitoring of large, potentially hazardous landslides, and data may be unavailable for critical areas. The state-of-the-science in landslide hazard monitoring was recently summarized in [3]. This study demonstrates the current limitations in delineation of potential landslide hazards: (1) measurements must occur over long periods of time, (2) few survey points are possible with high-precision surveys due to high instrumentation costs, and (3) sparse vegetation and excellent visibility are necessary site requirements. Our research is focused on reducing these limitations.

Large quantities of new, small wireless sensor nodes are very affordable. The field of wireless sensor networks and nodes has been a focus area for funding during the past five years by major agencies such as the Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF). The DARPA programs have been considered a success in that they have transitioned programs from research to the battlefield [e.g., DARPA Networked Embedded Systems Technology (NEST) – shooter location]. The NSF programs have resulted in a variety of technologies including systems fielded to monitor natural hazards. With such an interest in the field, it is not surprising that many of the once hard basic research problems have been reported as solved and often have usable solutions. The fusion of this new wireless sensor technology with tried and true technologies, such as high-precision GPS and other developing technologies such as Interferometric Synthetic Aperture Radar (InSAR), provides opportunities to gather more data, more rapidly, in more hostile environments than ever before. The core innovation of our research focused on applying radar-like precise ranging deployed on wireless sensor nodes to landslide monitoring. We call this method Cooperative Radar Reflector Relative Positioning System (CR3PS).

With this motivation in mind, we chose to combine the evolving techniques in inexpensive radio systems with exploration tools and techniques required for natural hazards characterization. The approach of the research effort was to develop, fabricate, and field-test a proof-of-concept version wireless sensor node system capable of measuring small movements over extended periods of time. Field testing of a prototype of the system included instrumentation of an active

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landslide, Salmon Falls Creek landslide in Idaho. Accuracy achieved has been measured on the order of 0.3 centimeters.

II. Technical Approach

A. General Approach: Ranging, Radar, and Beacons

Southwest Research Institute (SwRI®) has created a patented [4] technique to measure relative motion over a surface. Radio nodes were scattered over the area, and the distance between nodes was measured. Using distance estimates between all the nodes, a three-dimensional characterization of the surface was generated. Ranges are measured by electromagnetic wave time-of-travel. The speed of electromagnetic waves through the air is well-known. Therefore, using the time-of-travel and speed, the distance between nodes is easily calculated. In practice, high-precision time-of-travel can be measured by way of phase difference. That is, when possible, a continuous wave compared against itself for phase deviation is an accurate and easy-to-implement method for measuring time-of-flight. This is a basic principle of simple radar systems.

Radar is a very mature technology, first demonstrated in the early 1900's. Radar systems can be used to find range and instantaneous range-rate. Often, the range resolution on a radar system is a function of its bandwidth, as these systems use envelope detection. One of the reasons for this is that the phase change upon wave scattering is generally not known. However, for this application, the targeted node is cooperative. The target node receives the transmitted electromagnetic wave, amplifies it, but retains the original phase information. This gives the cooperative target an effectively huge radar cross section (RCS) equal to the antenna size times the low noise amplifier gain and the power amplifier gain. The time (or phase) delay of the gain and delay stages on the target node can also be precisely measured on the target node or removed by way of calibration. Our original design utilized a delay in order to allow for this process of actively reflecting. The delay was necessary to (1) allow all the typical radar clutter to return first and be ignored, before the return of real interest arrives, and (2) prevent a feedback loop oscillation in the target node.

During field work, we modified the design to include a method of doubling the frequency at the cooperative node while retaining the original phase information. The frequency doubling method does not require a delay yet retains the properties necessary for high accuracy. The delays of the doubling method are small and are determined as part of initial calibration. Circuits and components for doubling are well-known and operate consistently over environmental conditions. One of the particular devices we used was the Mini-Circuits ZX90-2-11-S+, but many such parts are available. With known phase and time delays at the cooperative target, the actual phase of the return can be measured. This increases the range resolution from the reciprocal of the envelope bandwidth to the reciprocal of the carrier frequency.

The overall approach of either method is different than traditional beacon systems. Typical beacon systems transmit at a different frequency and must be phase locked in order to measure the phase of the signal return. Phase locking is a very difficult problem for spatially distributed systems, and the lock errors would surely be larger than any phase calibration errors in the proposed system. The frequency doubling method does not require a phase lock since it simply multiplies the transmitted (or received from the perspective of the reflector) signal by itself.

B. Continuous Wave Phase Measurement

As noted previously, the new method utilized in SwRI's prototype was partially inspired by modern radars, such as existing radar surveying instruments known as Tellurometers, which measure phase differences between separate frequency radar returns to achieve measurement accuracies of less than 1.5 cm. However, performing continuous wave (CW) phase measurement in a wireless environment is much different than any analogous radar implementation. That is, although wireless sensor circuitry with CW phase measurement components allows ranging with sub-centimeter resolution, the practical limits of power and oscillator synchronization do not allow direct implementation of precision CW-based systems. This new SwRI approach to CW phase measurement is not limited by these power and oscillator difficulties [4].

The SwRI design is easier to understand in light of a classic radar design. Figure 1 shows a typical radar approach. In this case, when a measurement is desired, transmission of radio frequency (RF) energy is initiated by the control element of the system. The base-band transmit (BB Tx) portion creates a waveform that is transmitted by the radio frequency transmit portion (RF Tx) and ultimately detected by the base-band receive portion (BB Rx). The RF receive (RF Rx) portion of the system recovers the energy that is reflected by the passive device whose distance is to be measured and passes it on to the BB Rx for time-of-flight comparison. The control portion determines the distance by measuring the roundtrip time of flight of the RF energy. Many techniques can be used to evaluate the time-of-flight measurement, but a core issue for practical realization of radars is the need for oscillator synchronization. For this reason, practical implementations of radars utilize some method (e.g., single oscillator or phase lock) to synchronize their oscillators. Although expensive with respect to the amount of RF energy required to acquire a reflection, the very nature of the reflector being passive aids in the oscillator synchronization. That is, if the reflector were to be an active, cooperative portion of the system, all of its utilized oscillators would require synchronization. High accuracy synchronization of distributed oscillators is a very difficult problem.

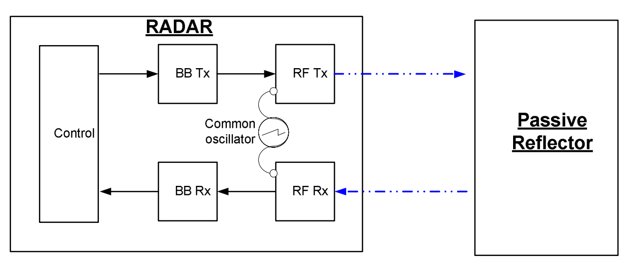

Figure 1. Classic Basic Radar Positioning Technique

The SwRI design incorporates an active reflector but does not require distributed oscillators. This is accomplished by sending a pulse from the transmitter (interrogator) and using a "delay line" at the reflector (responder) to avoid sending it back too early (i.e., during the transmit pulse, before the receiver is activated). Figure 2 shows a block diagram of the SwRI approach.

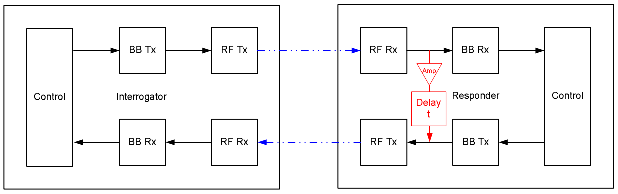

Figure 2. New SwRI Continuous Wave Phase Measurement Technique

The block diagram shows two sensor modules. The major components are the wireless control, base-band transmit (BB Tx), RF transmit (RF Tx), base-band receive (BB Rx), and RF receive (RF Rx). The red lines show the RF path utilized when a unit is a responder. The dashed lines show the RF air gap paths. The return signal path has been amplified and delayed (using a nominal delay of 0.1 microsecond or 100 feet) in order to separate the response signal from any natural radar reflections which occur as the transmitted energy reflects off of the sensor enclosure or other objects near the responder.

Once the sensor network is in place, distance measurement between individual sensors can begin. For distance measurement, the sensors rely on measuring and comparing the phase of successive returns from a neighboring sensor. These measurements provide a timeline of relative distance changes between sensors. However, in order for these relative measurements to translate into absolute distances, the system must be initialized with known inter-sensor distances.

Two design requirements are necessary to achieve and utilize the initialization baseline collected at system startup: (1) the ability to properly calibrate the system for the turnaround time from the responder and (2) the repeatability of the turnaround time. To address the first requirement, each sensor is outfitted with enough computing and storage capability to perform the phase measurement, burst averaging, and range comparison. To meet the second requirement, the delay mechanism is designed to be stable and reliable over time. Avoiding base-band processing and tapping the system at intermediate frequency (IF) provides turnaround repeatability within the picoseconds level.

Distance monitoring and collection software runs periodically on each node. It collects data and reverifies position. The collected data is moved to a host computer where it is collated and displayed.

C. Additional Considerations

1) Antenna Considerations

In order to process, analyze, and display returns from separate targets, radars must be able to isolate and distinguish each potential target. This isolation is typically accomplished by scanning highly directive antenna beams over fixed areas of space. Targets can be temporally separated because, for any given time, the radar's antenna is known to be oriented in a specific direction. This technique provides a high degree of separation, even in a target (or emission) dense environment.

Omni-directional antennas, such as those typically used in wireless applications, provide no such natural separation. Signals are received by omni-directional antennas simultaneously from all directions, and it is impossible to know from which direction any given signal has been received. Similarly, when an omni-directional antenna transmits, its energy is spread evenly in all directions. There is no method of knowing where to focus the transmitted energy for a given target because, again, there is no knowledge of the angle of arrival (AOA) of any specific target reflection. It is for these reasons that omni-directional antennas are seldom (if ever) used for radar applications. There are no adequate means of target separation when omni-directional antennas are used.

The application case for our method is not typical for radar. The wireless range monitoring network consists of a spatial grid of cooperating sensor nodes. Each sensor in the wireless network can serve, at any given time, as a radar transmitter or as a cooperative "target." The transmit/receive schedules for each sensor node will be propagated throughout the network via a specific wireless communication schema. Via this schema, each network node will coordinate transmit/receive intervals with its neighboring nodes. In this way, for any given transmitting node, only a single active "target" will be expected to respond during a specific time interval. To summarize, identification, separation, and isolation of targets is made possible by controlling the sensor's viewing environment through wireless communications.

2) Frequency Considerations

In order to translate into reliable distance measurements, phase angle differences must be measured relative to known distances. For radar applications, target distances are generally unknown, so single phase measurements are ambiguous. To combat this range ambiguity, Tellurometers operate at two or more carrier frequencies and compare the phase measurements from each frequency. The unambiguous accuracy of Tellurometers is limited from the carrier frequency difference as:

$$R_{unamb} = c / (2\,|f_1 - f_2|)$$

The wireless carrier frequency band is fairly narrow. The 802.15.4 standard provides a range of 2400-2483.5 MHz. Even if the two extremes of the band were used, the minimum unambiguous range accuracy would only be around 1.8 m using the Tellurometer approach.

To solve this problem, this sensor design requires apriori knowledge of the radar-to-target distance. As long as the apriori measurement is accurate to within one-half of the carrier wavelength (approximately 12 cm at 2.4 GHz), phase differences can be measured relative to this known distance. In applications where inter-sensor distances are expected to change rapidly, the time interval between successive sensor measurements can be adjusted to ensure that there is practically no likelihood of more than one-half wavelength change between measurements.

Radars are traditionally high-power systems. Even Tellurometers, which are relatively low-power radars, have transmitter output powers of hundreds of milliwatts (e.g., the MRB 201 Tellurometer has a transmit power of 200 mW). Radars also have highly directive antennas which boost their Effective Radiated Power (ERP) by additional tens of dB. In contrast, wireless transmitters are restricted to less than 1 mW of output power and use omni-directional antennas with usually less than 5 dB of gain. Thus, a key design element is the distribution and spacing of the sensors in the grid network such that neighboring nodes are well within the detection radius of the radiating sensor.

D. Data Collection Via Wireless Sensor Network

The SwRI sensor node design utilized the Texas Instruments ChipCon CC2510 development kit. This kit included a reference design that aided in the rapid development and deployment of a capable wireless sensor node basis. A collection of these nodes was purchased and then augmented to support our CR3PS technique.

The 2.4 GHz transceiver modules employ the new 802.15.4 format. The usable bandwidth is about 750 kHz. This means our time of arrival accuracy (if properly calibrated) was approximately 1 ms each way. This yields a range accuracy of about 300 meters for any given processed burst. Additional averaging of bursts reduces this uncertainty by the square root of the number. For example, 10 cm accuracy may be achieved using 9 million bursts, which is not a problem for stationary objects. However, there is a lower bound on the uncertainty due to (1) the ability to properly calibrate the system for the turnaround time from the responder and (2) the repeatability of the turnaround time. By avoiding base-band processing (perhaps tapping the system at IF), the turnaround repeatability is very good (i.e., picoseconds). For this reason we use separate RF circuitry for the radar portion of the system.

For deployment, basic collection software was generated that establishes the positioning through the CR3PS approach and then collects data and reverifies position in a periodic fashion. The collected data was collected and transferred to a host computer where it was collated and displayed in an engineering fashion.

III. Prototype System

This research effort was set up so that once the system was designed, packaged, tested, and calibrated, it could then be put into a field test. The field tests provided data for analysis that could be compared with classic instrumentation methods and thereby tell how well the new system worked. Once field data were acquired, they were used for further analysis.

The effort began by prototyping the radar system. As stated before, in order to better support available component technologies, the delay-based approach in the original design was replaced (although both methods were proven) with a frequency-doubling approach. The overall signal flow of the doubling concept is shown in Figure 3. This frequency-doubling technique relies on the existence of phase-coherent parts in the frequency range of the radar. The *interrogator* issues a CW signal that is actively received by the *responder*, where the CW signal is doubled in frequency and then sent back to the *interrogator*. The signals do not collide nor do they cause feedback since they differ drastically in frequency. Filtering is crucial in this aspect since the real-world non-linear distortion portions of the signals result in multiples of the CW frequency. Upon receiving the signal back from the *responder*, the *interrogator* compares the phase of the received signal with a doubled version of the original CW signal. In this way, only one oscillator is ever used; and the properties necessary to retain the large RCS while utilizing a narrow band signal are preserved. An example of the packaged nodes is shown in Figure 4.

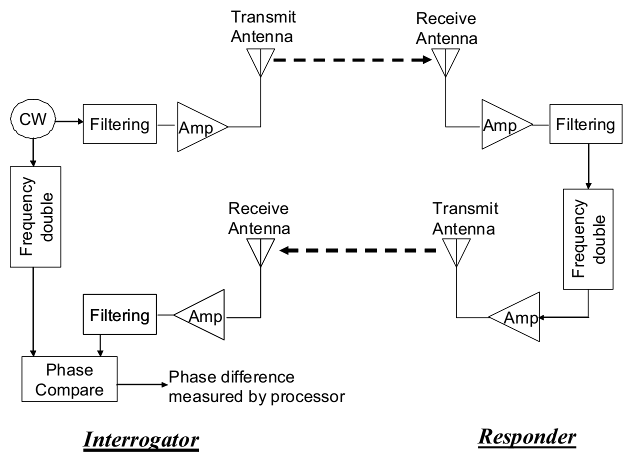

Figure 3. Signal Flow of the Frequency-Doubling Method Used

Figure 4. Revised Unit Using Commercial Wireless Sensor Node Board and Minicircuits RF Parts

The original sensor-node design consisted of an antenna mount and sensor node assembly. Each sensor node had an array of three short antennas installed inside a section of one-inch inside-diameter plastic pipe attached to a metal (T-section) fence post. The plastic pipe extends from the ground level vertically upward to a height of 18 inches above the top of the metal post. The plastic pipe that contains the antennas is attached to the metal post using several metal hose clamps, and all of the three antennas were in the 18 inches of plastic pipe above the metal fence post to avoid interference from the post. One antenna was for transmitting, another for receiving, and a third for data communication among the controlling processor nodes. Through a sequence of experiments, it was determined that considerably less self-interference was obtained from an antenna positioning structure with the elements separated by about ten inches. Figure 5 shows the separated elements placed in two polyvinyl chloride (PVC) tubes. Antenna mounts were then retrofitted to match this new antenna mount design.

Figure 5. Dual Pole Antenna Element (Farthest Back Pair of Tubes)

Successful use of the sensor node processor required programming at a very low level. Because the primary objective of this effort was to show the network can be built that measures position with about one centimeter accuracy, a simplified programming approach was used. A basic flooding-based program was developed for all of the nodes such that all nodes allow control from any other node and flood messages to all of the nodes. This is a classic ad hoc networking approach that results in an extremely reliable and flexible delivery mechanism at the cost of excessive power use. With respect to our experiments, however, the power used by the networking protocol is far less than that of the power required to make a radar measurement. Thus, focus on optimizing this algorithm was not deemed worthwhile with respect to the research goals. Under field tests, the sleep times used were separated to include two readings per responder per day.

For deployment and collection efforts, the processor nodes were dug out of the ground, the non-volatile memory was downloaded to a host computer for offline processing, the processor node memory was cleared, and the nodes were replaced into the units and reburied. The plan is for future efforts to focus on more aggressive network programming and processing techniques.

IV. Results and Conclusions

The resulting graphs of the radar returns showed most of the nodes performed as designed and generated radar returns in the sub-centimeter range. Laboratory-based tests measured the units to generate measurements close to 3 millimeters in accuracy.

Limited geologic data collection and interpretation for the Salmon Falls Creek landside were conducted during this project. Previous workers had performed a detailed analysis of the landslide, and the results had been published, which provided a strong foundation for this study. Our geological analyses provided important refinements of this previous work, including (1) an improved interpretation of the cross-sectional geometry of the landslide slip plane at depth, (2) recognition of pit craters associated with dilational faults and fissures within the landslide, and (3) analysis of clay mineralogy of the sedimentary deposits underneath the capping basalts that provide the glide horizon for the Salmon Falls Creek landslide.

In order to help calibrate the wireless sensor data, as well as provide an independent study to quantify the rate of movement of the landslide, we conducted a real-time kinematic differential global positioning system campaign. A total of seven surveys were conducted at ten node locations (Figure 6) on the landslide during this time period. These node locations were chosen using a combination of metrics including maximum inter-node communication range, potential signal reflection by surrounding rock, and relative interest to the geological survey effort. At each node location, two measurements were collected. One measurement was performed at the base of each wireless sensor node (i.e., near the interface between the ground and the base of the antennae), and one measurement was performed at the top of each wireless sensor node (i.e., the top of the antennae). The results from this campaign have proven that the landslide rate of movement is consistently declining. In addition, the results show that the measurable movement of this landslide is approaching the limits of commercially available GPS technologies. While the precision of measurement for the radar-based system exceeds that of the GPS survey, our results in elevation accuracy did not exceed GPS due to the geometry setup. A graph of the radar readings for one pair of our nodes is shown in Figure 7.

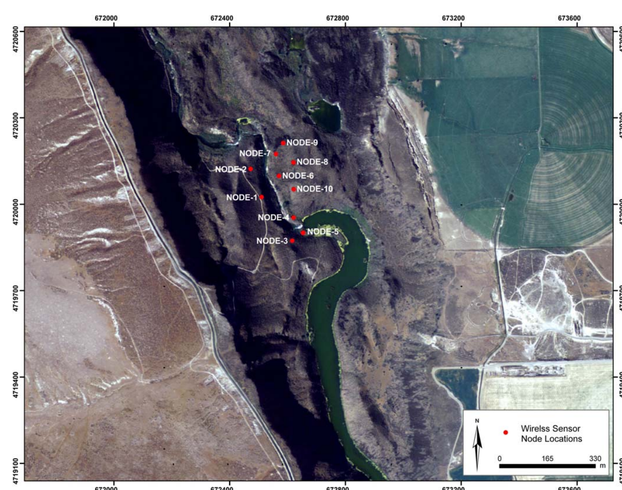

Figure 6. Locations of the Ten SwRI Sensor Node Sites

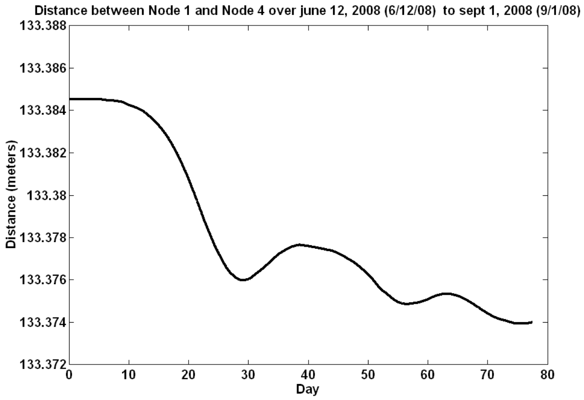

Figure 7. Example Radar Return Data

The deployment of the wireless sensor system showed some potential limitations of the approach. First of all, the sampling frequency (i.e., once every hour) resulted in a battery life of about six months. While this was sufficient for the application, future applications need to examine required battery life in the context of sampling cycles and power requirements of the RF hardware. This power trade will also affect the maximum inter-node distance for position measurements. Although data communication was possible at over 300 m, this particular configuration only allowed distance measurement up to 100 m. Finally, it was determined that care must be taken in choosing node locations in this specific environment as multipath caused by rock walls tended to corrupt phase measurements.

The goal of this effort was field verification of a unique method for precise positioning with wireless sensor nodes. Now that the approach has been deemed feasible by comparison against GPS surveys as a ground truth, the stage is set for additional experiments in laboratory and field environments. Initial laboratory experiments confirmed the analytical assessment with respect to measuring the phase difference. That is, at reasonable signal-to-noise ratios (much easier to accomplish at low power in our scenario since we use basic tones), tens of degrees of angle difference are very easy to differentiate. As such, the desired sub-centimeter accuracy matches the design requirement. Analysis in the presence of strong reflection and multipath is still needed. New configurations and experimental runs will allow performance comparison to further verify and enhance the capabilities of our wireless sensor system.

While there have been many scientific articles in the field of distance and relative position sensing in sensor networks (see [6], [7], [8], and [9]), our research aimed to demonstrate the application of a low-cost, low-power, attritable positioning sensor system to a specific geological characterization campaign. The actual deployment of the described system and its successful operation in a rugged environment prove the practicality of using such systems for data collection in locations once deemed inaccessible by geologists. This effort also illustrated the advantages of using wireless sensor nodes to reduce time of measurement, decrease instrumentation costs, and overcome requirements of excellent visibility and sparse vegetation.

A partnering research organization was also able to verify the operation of low-power tilt sensors in conjunction with our sensor network. These types of sensors and technologies could be combined with our distance measurement technology to provide additional environment characterization in the same sensor node platform. It is likely that future opportunities would thus combine more sensor technologies with the positioning capability.

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