"LINE IN THE SAND"

Prabal Dutta
dutta.4@osu.edu
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ABSTRACT

Intrusion detection along perimeters or borders is a surveillance problem of practical value that is well suited to wireless sensor networks. The goal of the work described here is to rapidly detect and classify intruders along an arbitrary ad hoc border. We examine the requirements of border surveillance in the context of a military scenario called "Line in the Sand" or "LITS." We explore strategies to detect and classify various intruders, develop a prototype to demonstrate our approach, and evaluate the system's performance. Our approach is based on a distributed network of wireless sensors combined into [in]coherent sensor arrays that perform *in situ* signal processing, data aggregation, and array processing. The LITS architecture improves upon existing unattended battlefield ground sensors by eliminating both the need for hand-placement of sensors and radio repeaters, and by replacing the simple radio repeaters with integrated sensors nodes with built-in wireless micro-routers. Hand-placement and repeaters are obviated though the use of ad hoc routing, localization, array processing, and data aggregation.

1. INTRODUCTION

The instrumentation of a militarized or demilitarized ground zone with distributed sensors is a decades-old idea. Unattended ground sensors (UGS) exist today that can detect, classify, and determine the direction of movement of intruding personnel and vehicles. However, existing systems require careful hand placement of sensors, placing a deployment team at risk, or use single mode sensors that limit reliability.

The Remotely Monitored Battlefield Sensor System (REMBASS) is one such system in use today. REMBASS uses remotely monitored sensors hand-placed along likely enemy avenues of approach. These sensors respond to seismic-acoustic energy, infrared energy, and magnetic field changes to detect enemy activities. REMBASS processes the sensor data locally and outputs detection and classification information wirelessly, either directly or through the radio repeaters, to the sensor monitoring set, or SMS. Messages are demodulated, decoded, displayed, and recorded to provide a time-phased record of intruder activity at the SMS.

More recently, dynamic demonstrations have included aerial deployment and data collection. In March 2001, researchers from Berkeley demonstrated the deployment of a sensor network onto a road from an unmanned aerial vehicle (UAV) at Twenty-nine Palms, California, at the Marine Corps Air/Ground Combat Center. The network established a time-synchronized multi-hop communication network among the nodes on the ground whose job was to detect and track vehicles passing through the area. The vehicle tracking information was collected from the sensors using the UAV in a flyover maneuver and then relayed to an observer at the base camp. The drawbacks to this approach include aerial data collection and the use of a magnetometer as the sensor making detection of non-magnetic materials impossible.

This paper develops a border surveillance application for collaborative detection and estimation in wireless sensor networks. This application is representative of other types of surveillance problems. We present requirements, constraints, and guidelines that serve as a basis for the resulting sensor network architecture. We describe the essential components of the sensor network for this domain, including the hardware and sensor platforms, distributed algorithms for routing, tracking, localization, visualization, power management, and intrusion detection and classification.

We envision a border surveillance architecture in which intrusion data are processed locally at each node, shared with neighboring nodes if an anomaly is detected, and finally aggregated upward toward a gateway with wide area networking capability. The motivation for this approach comes from the apparent spatial- and temporal-locality of environment perturbations during intrusions, suggesting a distributed approach that allows individual sensor nodes, or clusters of nodes, to perform localized processing, filtering, and triggering functions. Collaborative signal processing using both coherent and incoherent algorithms will enable more complex data sampling, aggregation, and compression than is possible with an individual node [1, 2].

The remainder of this paper is organized as follows. We discuss the requirements of the LITS application in section 2. Section 3 covers the system architecture. In section 4, we discuss signal detection strategies and implementation techniques.

2. APPLICATION REQUIREMENTS

The general objective of LITS is to enable military personnel to "put tripwires anywhere." The intruder may be a vehicle or person along a guarded perimeter not to exceed 100 meters in length and terminated by a gateway device with significant computation and communication abilities. The most basic requirement of LITS is to detect, track, and classify intruders. Successful detection requires that the LITS system acquire an intruder's initial position with modest accuracy (1-5 meters). Tracking involves maintaining the intruders current position as it moves about in an area covered by the sensor network's field of view. A simplifying assumption for is that only one intruder of each type will be detected and tracked at a time. While the system will be able to detect multiple intruders simultaneously, it will not be able, initially, to track all of them. Violating this assumption may cause tracking to fail. In the future, the system's capability may be enhanced to allow multiple intruders of the same type to be tracked simultaneously. Classification requires that the type of the intruder be identified correctly as either a vehicle or a person.

In addition to the fundamental requirements of detection, tracking, and classification, the LITS system must implement algorithms for routing, localization, time synchronization, visualization, and power management. A small number of co-located sensors could correlate their data to improve redundancy and reduce false positives. Conversely, once an intrusion event is detected in an interior node, messages may need to be propagated through additional nodes along the 100-meter perimeter and the peripheral gateway before being delivered to the base camp. Therefore, an ad hoc routing protocol is necessary to move messages between interior nodes and from interior nodes to the peripheral gateways for further processing and relaying to a base camp. Localization and time synchronization are necessary for at least two reasons. First, collaborative signal processing algorithms based on space and time diversity requires awareness of location and relative time. Second, intrusions must be reported to the base camp with sufficient location and time information to be useful. Visualization of the sensor nodes, breach locations, and intruder types and numbers will aid the base camp responding at the correct place and with an appropriate amount of force. Power management is essential for maximizing the useful life of these sensors.

In the longer term, we expect that sensor nodes will need to be electro-mechanically self-contained and hermetically sealed for extended outdoor operating. For demonstration purposes, our nodes will not be tolerant to inclement weather.

3. System Architecture

Our system is composed of the following types of hardware: sensor nodes (“nodes”), SOCOM radio repeaters (“repeaters”), special GPS-equipped nodes (“landmarks”), and moderately powerful computation and communication devices (gateways).

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Figure 1: System architecture of the Line in the Sand.

We assume, without loss of generality, that a mechanism exists to facilitate secure wide area communications, perhaps through SOCOM transceivers. That is, when the ultimate destination of the surveillance information is located far away, their exists some gateway to deliver the messages to the destination. We focus our efforts here, instead, on the problems of matched filtering, tracking, intra-network routing, power management, localization, time synchronization, and visualization within the context of fulfilling the requirements set forth earlier.

4. Signal Detection

Sensors can be used to detect various analogues of people or vehicles including acoustic signature, ferrous content, velocity, position, thermal signature, etc. A number of assumptions are being made regarding the detectability of intruders. Some weighted combination of the detectable factors described below must be present in order for the Line in the Sand to function. The estimation and matching techniques that will be employed are discussed elsewhere. It is worth noting that the synchronization and communications bandwidth necessary to implement coherent detection algorithms may be unavailable from our computationally- and communications-limited senor nodes.

4.1. Acoustic

The system may be able to detect an intruder’s presence through an acoustic signature. Acoustic sensors do not require line of sight for their operation, and so they may be more robust due to a reduced sensitivity to orientation than many other sensors. Acoustics will work best for low frequency signatures that lend themselves to detection and analysis on bandwidth-limited systems like our sensor nodes.

Frequency-domain analysis of the acoustical signals may be necessary, and potentially a more complex time-frequency analysis of the signal may be required. A common technique for converting discretely sampled time-domain signals to frequency-domain signals is through a Discrete Fourier Transform (DFT), a variation of the Fast Fourier Transform (FFT) [3, 4]. The effectiveness of the DFT in detecting the intruder’s signature is dependent on the sampling rate, signal bandwidth, and window size. A low sampling rate could result in the detection of aliasing. A wide window provides excellent frequency localization at the expense of temporal localization. Conversely, a narrow window provides excellent temporal localization at the expense of spectral localization.

This tradeoff is important because there is a desire to use time of flight for triangulating the intruder’s position based on arrival times of the acoustic signals at multiple nodes. Finding a window size that optimizes frequency localization and provides sufficient temporal resolution for triangulation may not be possible. Furthermore, this approach could require distributed multilateration techniques [5] or beamforming techniques that must sample and communicate relatively high bit rate data streams consisting of sampled waveforms [REF] over bandwidth-limited links.

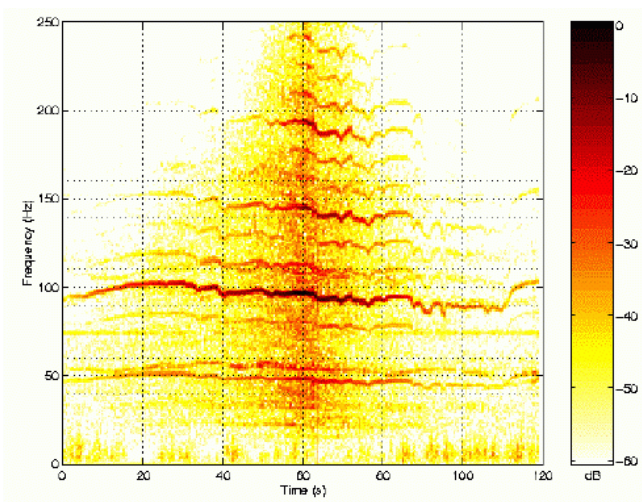

Figure 2: Spectrogram of a tank traveling at a constant speed of 20 mph at Aberdeen Proving Ground (APG), MD [6].

Acoustic signals can be detected using microphones or piezo film sensors. The output of these sensors is a time-varying voltage, current, or resistance that is proportional to the amplitude of the ambient noise.

4.2. MAGNETIC

The Twenty-nine Palms demonstration used commercial HMC1002 dual-axis magnetometers from Honeywell to detect changes in the earth's magnetic field caused by the movement of magnetic materials near the sensor. These sensors have a resolution of approximately 1 mGauss and were able to detect passenger vehicle at a distance of more than 5 meters and busses and trucks at a range of more than 10 meters. A trace of a typical magnetometer is shown in Figure 3.

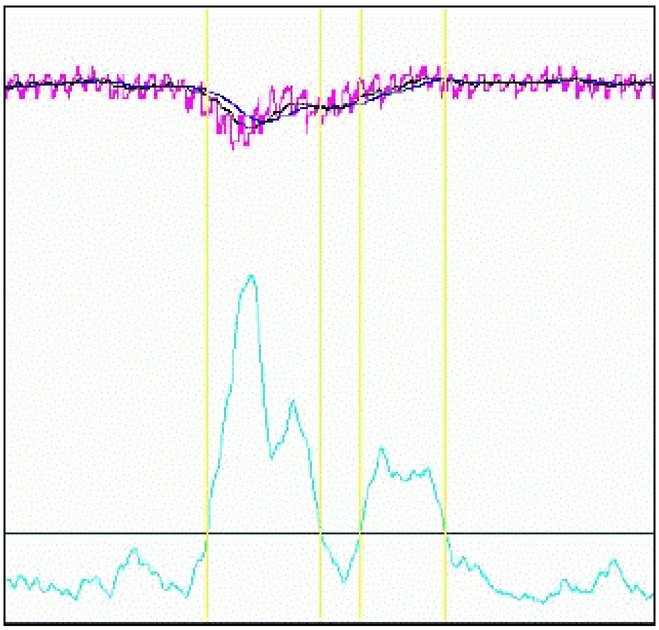

Figure 3: Magnetometer signal detection and processing. The purple signal is the raw signal, the dark blue is the raw signal after low pass filtering, and the light blue signal is dark blue signal after high pass filtering [7].

The output from the magnetometer was amplified and employed a software-controlled output nulling feature to trim out the DC component of the earth's magnetic field to avoid saturating the amplifier and analog-to-digital converter.

4.3. ULTRASONIC RANGING

Ultrasonic rangefinders can measure the distance to one or more objects within the sensor's field of view. The sensor works by initiating an ultrasonic sound or "ping" and waiting for its echo. The elapsed time between these two events is called the time of flight. The distance can be computed as one-half the product of the time of flight and speed of sound: Distance = Time of Flight × Speed of Sound / 2.

An ultrasonic rangefinder is composed of one or two ultrasonic transducers and a signal processing circuit. The transducer(s) convert electrical signals to ultrasonic signals and vice versa. The signal processing circuit generates a drive voltage to initiate the ping pulse, amplifies and filters any reflected signals, and performs the time of flight computation. Simple circuits will toggle output pins to signal the time of flight. More sophisticated signal processing circuitry can be used to convert the time of flight into actual distance measurements in metric or standard units, and may allow configuring multiple sensors in a bus configuration, relieving the controlling processor from unnecessary input/output overhead.

Many ultrasonic rangefinders will report distance based on the first echo that is received and will ignore any other echoes. Some rangefinders can report multiple echoes, allowing the sensor to detect multiple objects at varying depths within the field of view. The Devantech SRF04 ultrasonic rangefinder can detect one echo in its field of view up to a distance of 3 meters [8]. The Devantech SRF08 can detect up to sixteen distinct echoes at up to 6 meters distance and allows up to sixteen units to be attached to an I^2C bus [9]. The SRF08 rangefinder is shown in Figure 4. Note the existence of an integrated cadmium sulfide photocell.

Figure 4: Devantech SRF08 ultrasonic rangefinder.

The beam pattern of the SRF08 is shown in Figure 5. There is an error on the distance axis of the graph – the range of the unit is 6 meters even though only about 3 meters is shown of the graph.

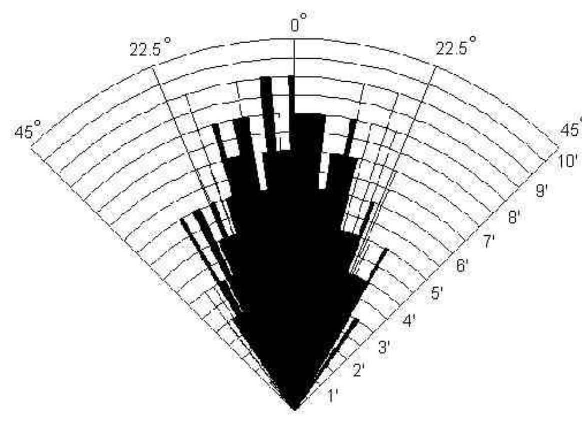

Figure 5: Devantech SRF08 ultrasonic rangefinder's beam pattern.

Both the SRF04 and SRF08 sensors use the same ultrasonic transducer, so the differences are implemented entirely in the signal processing circuitry. The critical parameters for an ultrasonic rangefinder are the beam pattern, minimum range, maximum range, and object size.

4.4. MICROPOWER IMPULSE RADAR

Micro-power impulse radar (MIR) detectors rely on pulse Doppler radar motion sensing, such as the one shown in Figure 6. Such units are built with low-power electronics and draw less than 3mA at 5 volts. Such minimal power requirements make MIR ideal for our application.

Figure 6: Micropower impulse radar [10].

The radiation beam pattern of the MIR sensor is shown in Figure 7.

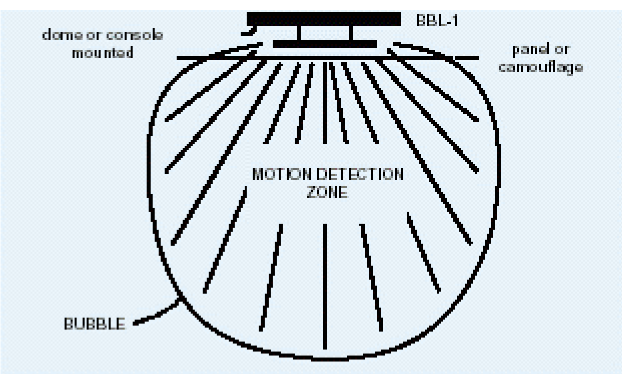

Figure 7: Micropower impulse radar beam pattern.

The detection zone or bubble radius is adjustable from one to six feet.

4.5. PYROELECTRIC

A passive infrared (PIR) or pyroelectric sensor is used by the security industry is a special purpose radiometer used to detect the body heat of an intruder. It is an almost ideal sensor because it is passive. The detector's presence itself cannot be detected as is the case for active sensors such as ultrasonic or microwave.

For detection, an intrusion sensor is sensitive to changes in infrared energy rather than absolute levels. The sensor accommodates itself to the background conditions in the room and perceives the intruder as a change in this state of equilibrium. This change principle is fundamental to the detection process and PIR sensors are designed to maximize this by a process known as chopping, either mechanically or electronically. Many intrusion sensors use the real background as a reference completely avoiding the use of a chopper. By optically dividing the area to be protected into a number of separate and separated fields-of-view, when an intruder moves through the area it appears and disappears from view and by doing so modulates the reference condition. The signal produced is proportional to the difference in temperature between the intruder and the background.

Commercial pyroelectric detectors are available from a wide variety of sources. The Model 442-3 sensor from Eltec, shown in FIG, is an integrated Lithium Tantalate pyroelectric parallel opposed dual element high gain detector with complete integral analog signal processing. This unit offers greatly improved detection capability over an extended temperature range of -40 to +70° degrees C with no significant change in noise or sensitivity and significantly reduced temperature spiking.

Figure 8: Eltec 442-3 pyroelectric sensor with built-in signal conditioning.

4.6. SEISMIC

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4.7. PROPRIOCEPTIVE

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