Multi-Modal Sensor System Integrating COTS Technology for Surveillance and Tracking

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Abstract—The feasibility of low-cost, Commercial Off-The-Shelf (COTS) sensor nodes is studied in a distributed network, aiming at dynamic surveillance and tracking of ground targets. Data acquisition by the low-cost (< $50 US) miniature radar is described. We demonstrate the detection, ranging and velocity estimation capabilities of the mini-radar, and compare results to simulations. Furthermore, we integrate the radar output with supplemental sensor modalities, such as acoustic and vibration transducers, and infrared sensors. The method provides innovative solutions for detecting, identifying, and tracking vehicles and dismounts over a wide area in noisy conditions. This study presents a step towards distributed intelligent decision support and demonstrates effectiveness of small cheap sensors in identifying unique but similar events. Our work supports a pervasive sensor implementation relevant to the affordable open system architecture attribute of the U.S. Air Force Layered Sensing paradigm.

I. INTRODUCTION

An autonomous sensor network is a collection of sensor nodes with limited processing, power, and communication capabilities that monitor a real world environment through differing modalities. The nodes gather information about the local environment, preprocess the data, and transmit the output via wireless channels to a base station. The base station may broadcast commands to all or some of the sensor nodes in the network. Using intelligent framework design, the network can support decision making and provide the capability to detect, track, and identify targets over a wide area. Sensor networks are often composed of sensor nodes mounted on autonomous vehicles, sensor nodes on the ground, and remote base stations. In actual deployment environments, a node may not be able to reach all the other nodes within its physical wireless transmission range, i.e. not all the nodes are within one hop of the others. Challenging research issues include dynamic network partition due to node mobility, node failures, wireless channel interference/fading, and network congestion [1]. We need to assure reliable communication among the nodes and with a remote base station, despite these various adverse factors. Given the harsh operating environment of the proposed system, our foremost design goal should be robustness. A relevant area of research is delay tolerant networks [2]. Another requirement is to minimize the target detection delay and maximize classification accuracy, while minimizing the consumption of network resources (bandwidth, memory, and power).

In this work we introduce a sensory network consisting of several COTS sensors including radar, infrared, acoustic, and magnetic nodes, that can be used as an integrated surveillance and sensing system. Short-range radar detectors has been used in commercial applications, including traffic management, and proximity sensing [3,4]. We describe the acquisition properties and implementation of a low-cost (< $50 US) miniature radar. We then demonstrate the detection, ranging and velocity estimation capabilities of the mini-radar. We discuss the integration of the radar and other sensor data and the possibilities of developing a robust pervasive sensor system using multi-modal technology, relevant to the affordable open system architecture attribute of the U.S. Air Force Layered Sensing paradigm [5].

II. MINIATURE MULTI-FUNCTION RADAR

This section describes the small, low-cost, COTS K-band radars that are used on the sensor nodes to help detect and characterize targets. We also describe the COTS hardware that combines the various sensor modalities into a single, autonomous node. The RF transceivers are manufactured by M/A-COM (Tyco Electronics) model MACS-007802-0M1RSV, and are used primarily for automotive applications, e.g., front and rear-end collision detection, in ground speed measurements, and as motion detectors, e.g., automatic door openers [6]. The radar utilizes a Gunn diode oscillator and transmits a continuous wave at 24.125 GHz. It also has 0.3 GHz of bandwidth that can be controlled by applying an external voltage, making it capable of estimating target
range and velocity. The low-power consumption (typically < 0.5 Watt) and small size make these devices excellent candidates for autonomous, compact sensors in a distributed network.

An external voltage pulse ramp using a waveform generator is applied to the radar which then emits a continuous frequency modulated K-band signal with 300 MHz bandwidth. The received energy is internally mixed with the transmitted signal and low-pass filtered to supply in-phase and quadrature output components on separate pins. Fast Fourier Transform (FFT) is performed over samples within the chirp (fast-time) to extract range information about a target. A second FFT is performed over a series of chirps (slow-time) to estimate the velocity of the target.

Figure 2 shows the results of a simple moving dismount experiment performed with the radar. A small K-band antenna was secured to the waveguide flange seen in Figure 1. The radar was supplied with a ramp waveform (between 0.5 and 10 volts) at a PRF of 1 kHz, and a human dismount walked toward the radar at approximately 0.5 m/s. When the target was about 3 meters away, the complex output waveforms were captured on an oscilloscope over 10 ramp cycles (chirps). The data was processed and is displayed on the range/Doppler intensity plot (normalized), as seen in Figure 2a. Note the energy concentrated at the proper location representing scattering from the moving dismount. The range-rate is pointed in the negative region of the graph in y-axis as the Target is moving toward the radar and distance is decreasing, which will be the reverse when the Target moves away from the radar. Cross-validation of the radar sensor output with other type of sensors is described in the next section.

III. DESCRIPTION OF SBT80 AND WiEYE DATA

Within the distributed network, radar data are supplemented with data obtained using WiEye [7] and SBT80 sensor nodes which are developed by EasySen, and have a range of modalities.

Each sensor board sits atop a TelosB mote capable of storing, processing, and transmitting sensor data. Multiple modalities provide improved reliability and classification by cross-correlating and integrating the sensor outputs. The WiEye sensor platform continuously monitors the environment and provides an initial detection capability. It uses a long range passive infrared sensor that detects moving vehicles up to a 50 m range, and moving dismounts (humans) up to a 10 m range. The wide-angle detection region is bounded by a 100 degree cone. In our integrates system paradigm, these are considered “sentry” nodes which activate the radar and SBT80 nodes when a target is in range.

The SBT80 sensor platform contains several sensor modalities that can be used for classification purposes. A
dual axis magnetometer measures variations in the local magnetic field as ferrous metals transverse in proximity. The data can be used to create signatures for different vehicle models, or to determine if individuals are carrying large metal objects. An acoustic sensor provides a raw audio waveform of the surrounding area. A dual axis accelerometer provides seismic information which can be used to detect a detonation or infer characteristics of a target. The SBT80 also includes optical and temperature sensors, which were not used in the present experiments. An overview of the sensor modalities is given in Table I.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor Type</th>
<th>Description</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyco MACOM</td>
<td>Radar</td>
<td>K-band 24.125 GHz</td>
<td>Yes</td>
</tr>
<tr>
<td>WiEye EasySen</td>
<td>Passive</td>
<td>Long-range (20-150 ft)</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Infrared</td>
<td>Photodiode</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Visual Light</td>
<td>Microphone</td>
<td>No</td>
</tr>
<tr>
<td>SBT80 EasySen</td>
<td>Acoustic</td>
<td>Microphone omni-direct</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Magnetic</td>
<td>Dual-axis, &lt; 0.1 mGauss</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Acceleration</td>
<td>Dual-axis 800 mV/g</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Infrared</td>
<td>Silicon photodiode</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Visual Light</td>
<td>Photodiode</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>Analog</td>
<td>No</td>
</tr>
</tbody>
</table>

We have conducted experiments with various target configurations using model trains as moving Targets. As the Target enters the WiEye sentry field-of-view, the WiEye broadcasts a wake up message to the radar and to the SBT80 motes, which capture multiple sensor data sets. In order to capture velocity, a series of timestamps are sent to the base station. Clocks has been synchronized in each experiment using timestamp beacons. For simplicity only a single hop separates sensor motes from the base station. Using the location information of the sentries and their timestamps, the velocity can be estimated in order to validate radar results. For every run, 2000 data points have been captured by SBT80 and WiEye, at sampling frequency of 2000 Hz, giving a sampling window of 1 seconds.

Experiments have been conducted with target velocities up to 1.25 m/s. We applied various reflective wrapping (aluminum foil) over the front portion of the moving target, in order to test the classification performance of the multi-sensory system. In addition, WiEye sentries have been used for velocity estimation along the straight section of the track to support Doppler radar results.

Multiple Signal Classification (MUSIC) algorithm has been used for spectral density estimation for all sensory modalities, to allow for a unified data processing and consequent data integration. MUSIC estimates the eigenvectors of the sample correlation matrix and it makes use of the pseudo-spectrum estimate of the mean corrected input signal for each sensor at normalized frequencies at which the pseudospectrum is evaluated [8-10]. In the experimentale valuations we used model order 10, which has been a reasonable compromise value across various modalities.

IV. INTEGRATION OF RADAR INTO WIRELESS MOTE

The wireless mote platform supports a wide variety of sensor modalities. Most of these packages come prebuilt for the specified target mote. For example both the WiEye and SBT80 sensor board have on board circuitry and sockets to plug directly into the TelosB mote. The TelosB mote itself contains 8 input ports that connect directly to the Analog to Digital Controller located on the mote’s microcontroller. The mote also contains output ports connected to the Digital to Analog Controller (DAC) as well as the ability to supply 3.3 volts of power from its own battery supply.

The WiEye and SBT80 sensor boards require no modification to work with the TelosB mote as they were manufactured to be essentially plug and play with the TelosB platform. However, the miniature Doppler radar was not built to such specifications. In order to retrieve signals from the radar required some additional circuitry to integrate the radar and the wireless mote platform. This presented some challenges but we successfully integrated the two independently manufactured devices.

Figure 3 shows the hardware setup of our radar mote system. Initially we used separate power supplies but the mote platform expects to power the sensor that it is reading from. The addition of a self powered sensor to the mote’s ADC introduced unwanted noise and DC offsets in our experiments. We rectified this by supplying both devices with 4 volts from a common power source. The Doppler radar can operate at this minimum voltage and the mote has an on board power regulator that steps the 4 volt power supply down to the motes 3.3 volt operating range. With the addition of the common power source the unwanted noise disappeared.
Figure 3. Diagram of integration of radar transceiver with the wireless mote environment.

The integrated system must provide reliable and accurate reading of the actual signal from the radar using the mote. The mote ADC has a 12 bit resolution. A series of reference experiments using a standard lab oscilloscope has confirmed that the accuracy was indeed sufficient for our goals. We managed to achieve the sampling speed of 200kHz by tuning the programmable parameters of the mote ADC using standardized TinyOS data structures and interfaces. When we physically connected our components together we found that the signal from the radar was dropping to zero regardless of the object profile in front of it, due to impedance differences in the two devices. To solve this we introduced a voltage follower circuit between the output of the Doppler radar’s I channel and the mote’s input port. The voltage follower circuit acted as a buffer between the two devices and was built using off the shelf components. In the applied circuitry, the Doppler radar receives its tuning voltage input from a lab signal generator. However, signal generator chips can serve to this purpose and we intend to use such electronic design in future experiments.

V. EXPERIMENTS WITH THE MULTI-MODAL SENSOR SYSTEM

Figure 4 shows examples of MUSIC power spectrum estimations for the vibration signals in the case of full forward movement (1.25 m/s), backward movement, and slow movement, respectively. The nominal distance between target and SBT80 was 0.5 m in these experiments. The pseudo-spectrum is estimated for 25 sample runs for each experimental and target configurations. The power spectra have characteristic peaks; the average peak value over 25 experiments are shown in Table II. The standard error of the peak frequency is ±20 Hz, indicating that the observed shift in the frequencies can be used to classify movement types.

Figure 4. Power spectra of vibration signals over 25 runs; conditions: Forward fast, Backwards, Forward slow.

<table>
<thead>
<tr>
<th>Movement Class</th>
<th>Peak 1 (Hz)</th>
<th>Peak 2 (Hz)</th>
<th>Peak 3 (Hz)</th>
<th>Peak 4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Fast</td>
<td>134</td>
<td>204</td>
<td>284</td>
<td>386</td>
</tr>
<tr>
<td>Backward</td>
<td>94</td>
<td>194</td>
<td>*</td>
<td>382</td>
</tr>
</tbody>
</table>
Power spectral estimation has been conducted for the other sensory modalities as well. Figure 5 shows PSD of acoustic signals estimated by PMUSIC technique using the same parameters as for the vibration data. For the acoustic data we conducted background subtraction to eliminate the sensitivity to variable background. We observe characteristic peaks, which are used for movement classification similarly as for vibration data displayed in Table II.

Finally, spectral estimation for the radar 'T' channel data are shown in Fig. 6, for various reflectivity. We observe that the power spectra change depending on the reflectivity, which effect can be used to estimate radar cross section. Figure 7 shows examples of Doppler estimation of range and velocity. Clearly, even with low reflectivity, the Doppler method works reasonably well for target tracking. We have conducted successful experiments with a variety of conditions and determined the target range and velocity within the radar FOV.

VI. DISCUSSION AND CONCLUSIONS

In the project introduced in this paper we develop an experimental methodology for a distributed multi-modal system using radar and supplementary sensor data for surveillance and tracking. Our research goal is to develop a sensor network using commercial off-the-shelf (COTS) components and to provide innovative solutions for detecting, tracking and classifying different targets and events in conditions with high noise and clutter. Our distributed system consists of a suite of radar transceivers, supplemented by acoustic, vibration, magnetic, and infrared sensors. The experiments with our low cost transceivers indicate the feasibility of detecting, tracking and classifying different types of targets. The major results of our studies are summarized as follows:

1. The Doppler radar can detect the range and velocity of a target with good precision which is validated by measurement using WiEye sensors.
2. The radar, in conjunction with other sensors can be used effectively to classify different types of objects and events.
3. Integrating the radar sensors with wireless sensor motes using WiEye and SBT80 platform provides a robust system, which can aim a decision support system for surveillance and tracking in difficult scenarios with high noise levels.
cost radar can be used effectively to classify different types of objects and events separately and in conjunction with other sensors. Experiments have shown that even for small event changes, there is a notable difference in the SBT80 acoustic and vibration signals. The acoustic and vibration sensors provide information complementary to the radars. For example, for given range and velocity parameters determined by the radar sensors, the actual scenario of the movement of the target can vary depending on the actual track characteristics. Using multiple sensors we can account for the variable features of the object, such as humans, dismounts, and vehicles. Detailed elaboration of the proposed method of sensor fusion and target feature identification is the objective of future research.

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REFERENCES