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A Mobile Acoustic Sensor Fusion Network Using Biologically Inspired Sensors and Synchronization

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Abstract - Hostile fire detection is a critical component of situational awareness in the asymmetric battlefields of ongoing and future conflicts. The ability to detect and localize sources of hostile fire in difficult environments can dramatically increase the survivability of dismounted warfighters. Existing individual acoustic hostile fire sensors provide useful information, but are prone to heading errors, variable bearing and range accuracy, as well as reliability issues due to false alarms, limiting the actionability of the information.

The warfighter can have significantly improved hostile fire sensor performance through information fusion. By leveraging existing sensors as a sensor network, the improvements come without additional weight, equipment, or power draw on the already overburdened soldier. Key to this objective is the ability to synchronize sensors over the network accurately, without using large amounts of power or network bandwidth, even when GPS-denied. Bio-inspired synchronization enables the proposed network infrastructure and makes possible sensor fusion algorithms on mobile platforms.

Keywords: Hostile fire detection, sensor fusion, biologically inspired sensors, sensor networks, network synchronization.

1 Introduction

As the digital battlefield evolves, an increasing number of mobile sensors are being deployed in the field. Most new sensors are being designed to share information over squad and higher echelon battlefield networks. Data fusion dramatically enhances detection accuracy, expands mission capability, increases Situational Awareness (SA), and reduces cognitive burden for the soldier currently being inundated with information. Leveraging data from existing sensors to enhance performance and capabilities, rather than adding equipment to the overburdened soldier, makes fusion a very attractive means of improving soldier SA.

In order to implement sensor fusion across a network of mobile sensors (concept shown in Figure 1), very accurate time synchronization is required across all sensors, and adaptive algorithms are needed to effectively fuse sensor information. Synchronization has many challenges, and references like GPS systems can suffer from drift or be denied during operations. The fusion of information from many sensors needs not only good time reference synchronization but intelligent algorithms that can combine information from many sources, and weight information according to the sensor confidence measures with respect to its own data.

To achieve a complete sensor network with mobile sensors, time synchronization, and information fusion for practical use, a team was assembled from academia, Army research groups, and industry. The mobile smart sensors with confidence measures were provided by BioMimetic Systems (BMS) using the bio-inspired PinPoint™ line of acoustic hostile fire sensors. The sensor time synchronization algorithms that do not rely on references like GPS were provided by the University of California team (UCSB). The fusion algorithms and concept of operations were provided by the Army research groups. The effort was extremely collaborative with sensors, synchronization, and fusion algorithms being developed synergistically to ensure interoperability and performance optimization.

The implemented sensor network has gone through

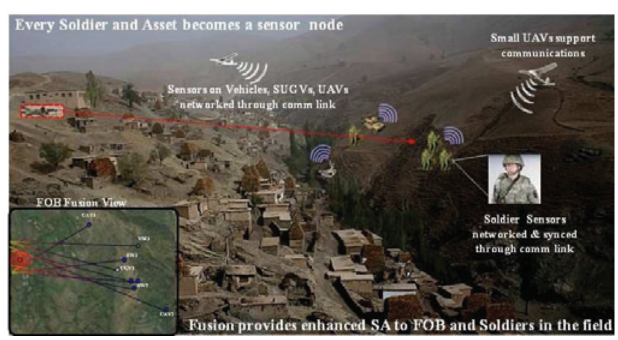

Figure 1. A conceptual diagram of the sensor network

numerous iterations of development and has been used in several field experiments for data collection and evaluation. The hostile fire targets tested against include an array of common small arms used in theaters of combat such as 7.62x39 mm and 5.56x45mm, and against larger threats such as mortars and RPG. Recent performance of the sensor network against these targets with live fire field data from government tests is the focus of the work presented.

2 The Sensor Network

2.1 The Sensors

Figure 2. The PinPoint mobile sensors. The image on the left shows the soldier-worn device; the image on the right shows the compact mobile vehicle sensor.

Two types of sensors were selected for the effort that match equipment that may be used in the field, and that could facilitate various test scenarios (see Figure 2). The first platform is a soldier-worn unit; the sensor is less than 10 cubic inches, weighs under 12 ounces, and is battery-operated using 2 AA cells. The system output is through a serial interface employing a specialized interface to connect to the radio network. The second sensor type is a vehicle mount/unattended ground sensor (UGS); the unit is less than 350 cubic inches, is under three pounds, and can be operated using any number of power sources, consuming only 3.5 watts at peak power. The vehicle unit can be connected directly to the sensor network via an Ethernet interface, using either UDP or TCP. The BioMimetic Systems team provided a mix of soldier and UGS units for the effort. Both the soldier and UGS devices have had significant algorithmic developments for magnetic heading stability and accuracy, to improve fusion and for practical implementation of fusion for field use.

2.2 The Radio Network

Figure 3. The radio network. Several radio networks were used, including a version of the Nett Warrior prototype system shown to the left, using a smartphone and IP radios. Wi-fi networks were also used with the vehicle systems, as well as mesh radios, to test various network options.

The multiple radio networks have been used to explore a range of configurations for possible field use. The Nett Warrior interface was created by the Natick Soldier Center (NSRDEC), and employs smartphones to interface soldier-worn devices to MPU radios, with the potential option of using 4G communication directly. The vehicle sensors were put on mobile Wi-fi networks created using a high powered router and wireless dongles connected to each sensor, providing a solid connection at up to 100 meters from the router. A mobile network using military mesh radios was also used during some tests to explore other connectivity options. The driving factor for the choice of radio network was the ability to write synchronization code that could access the proper communications layer, to have seamless algorithm operation from the sensors in the field.

3 The Synchronization Algorithm

Based on previous studies of network synchronization[2-11], UCSB has developed a new high-performance, pulse-coupled synchronization protocol, inspired by flashing fireflies, circadian neurons, and spawning coral. The algorithm can rapidly synchronize rhythms through exchanging pulsatile signals. In the pulse-coupled synchronization strategy, each sensor marks its individual time slot starting point by sending a pulse, and, by adjusting its state upon receiving a pulse from adjacent nodes, the whole network can be synchronized. Compared with conventional packet-based synchronization strategies, the pulse-coupled synchronization strategy has many advantages. For example, the pulse-coupled synchronization strategy can operate exclusively at the physical layer[1], by transmitting simple identical pulses instead of packet messages; this eliminates the imprecision in traditional packet-based synchronization strategies due to Media Access Control (MAC) layer delays, protocol processing, or software implementation. Furthermore, the pulse-coupled synchronization strategy treats each received pulse

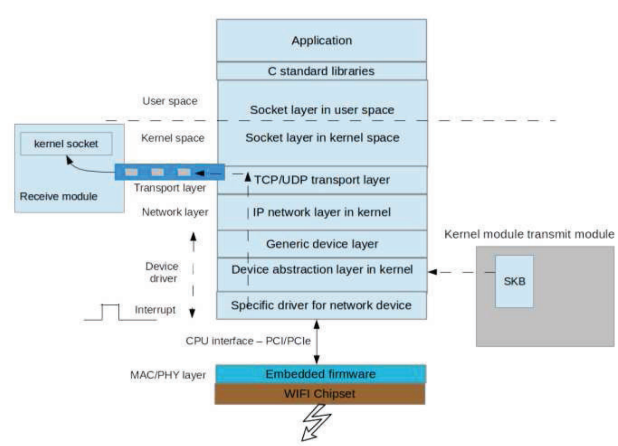

Figure 4: Implementation strategy of the synchronization algorithm at the kernel level

identically, since exchanged pulses are independent of their origin[1], thus avoiding requirements for memory storage of node information. This also makes the procedure at each node independent of the node identity; hence, the synchronization strategy is inherently scalable.

3.1 Implementation as a kernel module

The implementation as a kernel module was done using two independent threads: transmit and receive. The transmit thread operates in the device abstraction layer of the kernel structure. Low latency is achieved by writing the outgoing message directly into the output queue, thus bypassing the upper layers of the networking stack. The receive thread operates at the network layer by using a kernel socket to receive the pulses emitted by neighboring nodes. Although this approach might be subject to processing delays, it allows rescuing important information such as timestamps from the incoming message. Figure 4 shows the implementation strategy of the algorithm at the kernel level.

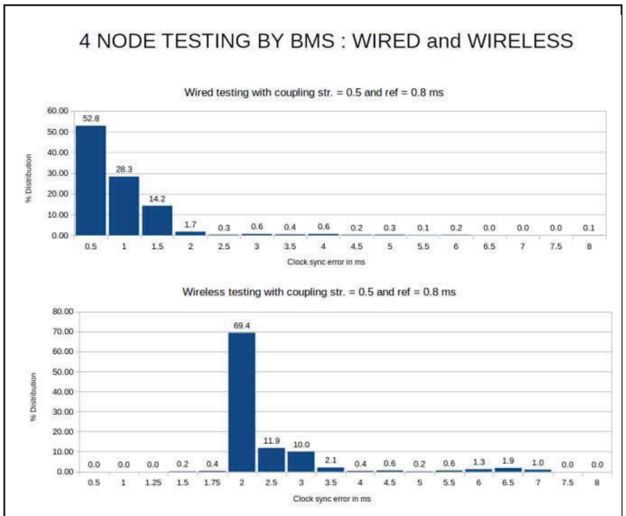

Figure 5. Tuned synchronization algorithm performance

An important process to ensure proper time synchronization is the tuning of the coupling strength and the refractory period. Varying the parameters affects both the synchronization accuracy and the synchronization rate. As a result of the tuning process, a coupling strength of 0.5 and a refractory period of 0.8 ms were found to be optimal. Figure 5 shows a performance summary after the tuning process for both wired and wireless networks.

4 The Sensor Fusion Algorithm

The individual acoustic sensors are composed of a passive array of microphones, able to localize a gunfire event by measuring the time of arrival (TOA) and the direction of arrival (DOA), for both the shockwave (SW) generated by the supersonic bullet, and the acoustic wave generated by the muzzle blast (MB). Figure 6 illustrates the geometry of the shockwave and the muzzle blast for the i^{th} sensor node, when the orientation of the bullet trajectory is ω with respect to the horizontal axis. After detecting gunfire, each sensor system processes these raw measurements to produce a relative

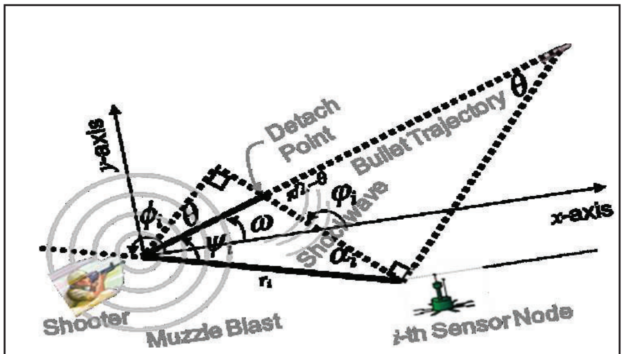

Figure 6. Individual sensor information extraction

shooter location estimate. Each sensor system provides the bearing and range of the shooter, relative to its own location. These relative estimates are communicated to a master node on the network, along with the estimated location and orientation of each sensor. The fusion algorithm combines this information through a set of confidence-weighted bearing intersection equations, to produce a geo-rectified estimate of the shooter location.

The information fusion scheme of the distributed sensor data can be posed as a weighted nonlinear least squares problem[12,13]. The sensors have been designed to provide essential confidence metrics used in the fusion scheme for the relative shooter position estimates at each sensor. These confidence measures indicate the estimated level of accuracy in the calculated range and bearing of stand-alone sensors. Performance of the weighted nonlinear least squares is highly dependent on the consistency of the confidence measures used as weights. The fusion algorithm uses initial filtering algorithms to group data and exclude potential outliers or false alarms, using consistency checks across the received time-sensitive data. The initial algorithms focused on single source targets, with strict positional and temporal segregation of data.

Algorithms were expanded to include multi-target and multi-shot scenarios. Traditionally, multi-target localization involves a maximum likelihood-based approach, where the estimated number of shooters is calculated by observing all possible sensor-to-hostile fire source associations. As the number of sensors and shooters increases, the possible combination of sensor-to-data associations dramatically increases, and the problem often becomes intractable.

To alleviate the computational issues, a finite point process approach was implemented for multi-shooter localization of hostile fire events. After modeling the measurements as a Poisson point process (PPP), a twofold scheme was used that includes an expectation maximization (EM) algorithm to estimate the source of fire locations for a given number of shooters, and an information theoretic algorithm to select the number of potential shooters. The localization scheme does not require solving the data association problem, and can account for clutter noise as well as missed detections.

The localization problem is formulated in two dimensions and the measurements considered are the range and the bearing to the targets. Each sensor acquires range and bearing estimates for multiple events, either from a single shooter location or multiple shooter locations. The algorithm uses this data to estimate the number of targets and their corresponding locations based on all the measurements, including the erroneous ones. It is likely that the number of targets is different from the number of measurements due to possible false alarms and/or missed detections. The main advantage of this scheme is that it scales linearly with the size of the problem, and avoids the complications of dimensionality associated with the traditional multiple hypothesis testing-based multi-target localization scheme.

5 Experimental Results

5.1 Small Arms testing

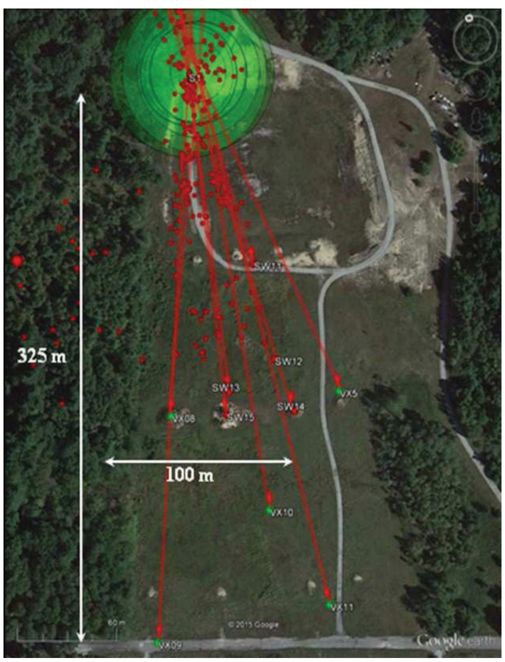

Figure 7. Individual sensor detections for a single shooter scenario using 5 sensor nodes of each type

Numerous live fire evaluation and data collection events were conducted with the sensor network at various government facilities. The prototype sensor network employed from 6 to 12 sensors in various configurations and scenarios. Numerous ranges with significantly different terrain were used at the Fort Devens facility in Massachusetts for small arms testing, to provide a range of test environments. Over the two primary evaluation tests, roughly 500 rounds were fired at sensors from 150 to 400 meters out, with miss distances from 5 to 55 meters, using three common small arms weapon types.

Figures 7 and 8 show GPS overlays for a single scenario from the test set. The scenario represents the movements of a small squad along a road, while taking fire, with vehicle support to the rear and one or two placed UGS sensors. The time stamped sensor data collected over the radio networks was run through the fusion algorithms again offline in real time, to create overlays and perform more extensive data analysis. The data in Figure 7 represents the individual sensor detects (red dots) in response to 30 rounds of live fire (300 possible detects over 10 sensors) from various small arms. Note the individual detects often have range estimates that are very short, and a ridge to the left of the range biased some sensor detects away from the true shooter position. In contrast, the data shown in Figure 8 from the sensor network (magenta dots) produced shooter estimates that were unbiased by the terrain, and were very accurate, with more than 80 percent of the detects within 25 meters, and 100 percent were within 50 meters.

In one of these tests, responses from the fusion network

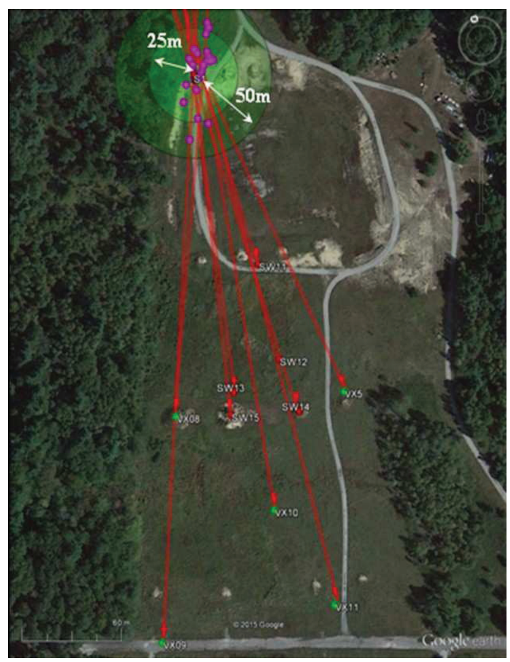

Figure 8. Sensor network performance using fusion algorithms and data from all sensors in the network

were calculated and then pushed back to individual sensors in roughly a second after the last sensor detect arrived at the fusion node.

Even in the simple single shooter case, individual sensors in an operational scenario and relevant environment showed distinct limitations, based on the terrain and shot line that were unavoidable in a relevant operational scenario. As scenarios became more complicated with multiple shooters and multiple shots from individual shooters, fusion helped to mitigate many of the issues seen with the individual sensors caused by terrain, and drastically reduce poor shooter localization or false alarms caused by environmental echoes.

Analysis of the full range of scenarios tested also showed significant improvement in shooter localization performance by the sensor network. Scenarios included single shooter, multi-shooter, and rapid fire conditions. Fusion solution performance was averaged over all conditions, and was evaluated in terms of angular error, range error, and GPS position error calculated as RMS. Solutions were also evaluated compared to solutions for individual sensors under each given condition. Detections for individual sensors and the fusion module were over 95% for the test set. Table 1 shows a tabulated comparison of the sensor network performance to the performance of the individual sensors.

Table 1. Sensor fusion improvement in performance over individual sensor performance

Detection Metric (RMS)	Fusion Performance	Improvement over Individual Sensor
Angular Error	2.4 degs	61 %
Range Error	20.4 m	69 %
% Range Error	8.7 %	68.4 %
Shooter GPS Error	24.4 m	67.4 %

The data in Table 1 represents comparisons of the accuracy of the fused solution estimate pushed back to the sensor, as compared to the accuracy of the estimate produced by the sensor itself for that sensor location. If a sensor did not generate a solution for a given shot, it was not included in the analysis.

5.2 Mortar, RPG and Recoilless Rifle Testing

The Adaptive Red Team/Technical Support and Operational Analysis (ART/TSOA) group provided an opportunity to test the sensor network against a different class of hostile fire threat at a live fire event held in 2014. Several hundred rounds were fired over four days, in situationally relevant scenarios and environments. Round types included mortar, RPG, ATGM, and recoilless rifle. The data was processed live through the Nett Warrior infrastructure, as well as post-processed through the first generation mortar fusion algorithms, with hand synchronization of the sensors offline.

The mortar algorithms used at the test were a first generation variant of the small arms fusion algorithm, with modifications made to accept solutions that did not have range estimates and used a generalized classifier for high explosive (HE) events. Prior to testing the fusion algorithms and classifier against live fire at the event, the algorithms had never been trained with relevant data, and only acoustic model data had been used to test and train the system.

Figure 9 shows a GPS overlay of the test range, sensor distribution, launch and impact areas, and the sensor network detections for mortar scenarios (magenta dots). The sensor network included five soldier-worn and five vehicle sensors, grouped in two rough clusters near relevant terrain features and small roads. Sensors were roughly 600 to 1000 meters from the launch and impact sites. Soldier-worn systems were connected through the Nett Warrior network using smartphones and MPU radios; the vehicle sensors were connected through a simple IP radio network. The networks were bridged so sensor fusion could receive information from both networks. Note the bridging of the radio networks did not allow synchronization to run live; all sensors were synchronized prior to deployment each day.

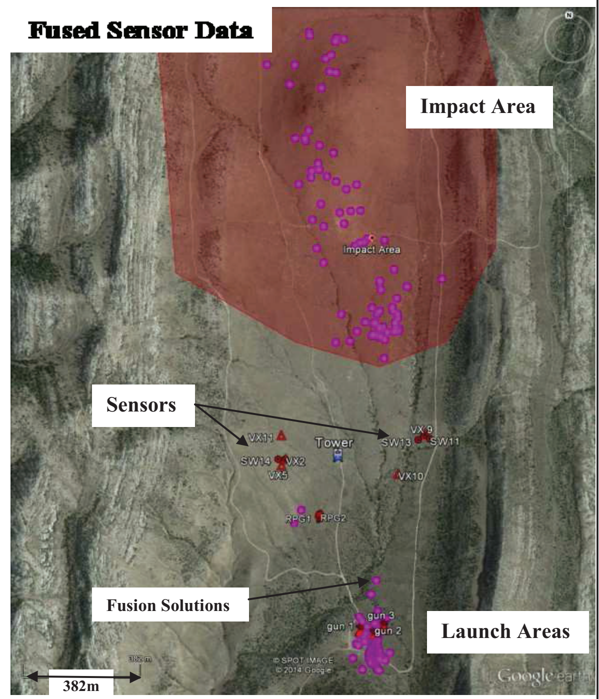

Figure 9. A GPS overview of the mortar and RPG test area showing sensor placement launch and impact areas, as well as network launch and impact detections

Approximately 122 mortar rounds were launched during the test day (shown in Figure 9), using a mix of two different sizes of mortar round and a mix of high explosive and dummy shells. While all launches and HE impacts were detected by the network, only 65 to 85 percent of the events were classified properly to create localized solutions. No ground truth was provided for shell impact, so analysis focused on localization of the launch area. Localization error analysis was based on government-provided launch positions for the three weapon sites used in the event. Analysis for the three sites was grouped together. Of the launch events detected, the localization error distribution of the detects (see Figure 10) was:

- Detects within 25 meters: 39.1 %
- Detects within 50 meters: 78.3 %
- Detects within 100 meters: 95.7 %

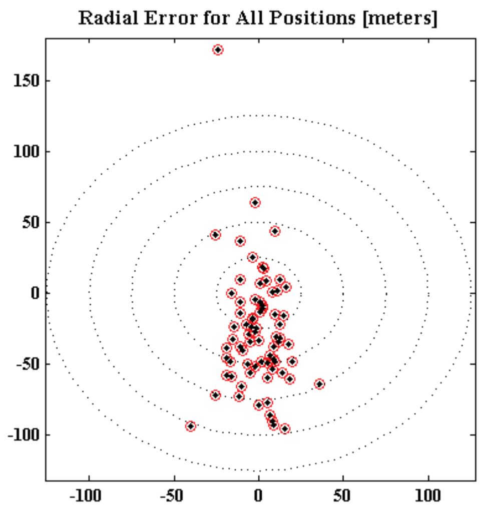

Figure 10. Mortar launch localization error for three different launch areas overlayed

A second test day focused on more direct fire weapons, using RPGs and recoilless rifle. An estimated total of 66

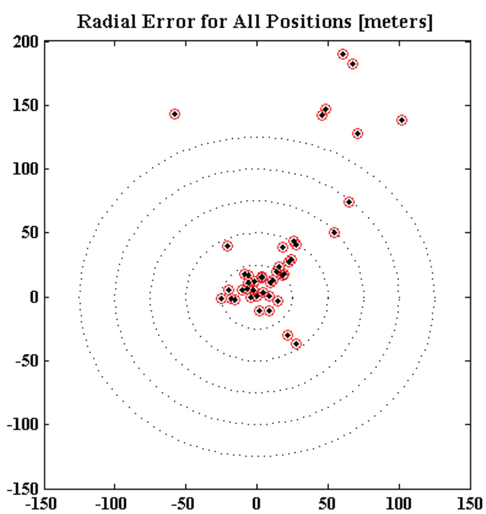

Figure 11. RPG and Recoilless Rifle Localization for two different locations overlayed

rounds were fired, approximately 10% or less did not detonate to create impact events. Detection and classification performance was similar to mortar testing, although launch sites were considerably closer to the sensors, with an average distance of 200 to 300 meters. The distribution of classified and localized launch events is shown in Figure 11.

Of the launch events detected, the localization error distribution of the detects was:

- Detects within 25 meters: 58.1 %
- Detects within 50 meters: 79.1 %
- Detects within 100 meters: 83.7 %

6 Conclusion

There are many challenges to creating a mobile sensor network, but the task is not insurmountable. Through a collaborative effort between academia, industry and government labs, a first generation mobile hostile detection sensor network was created and tested against live fire threats in relevant operational environments. Time synchronization of the mobile network is a critical component for fusing data across multiple sensors, and will become even more crucial as more complicated scenarios with multiple shooters and multiple shots per shooter are explored. The bio-inspired synchronization algorithm provided by UCSB is a very promising technology for achieving a robust and effective synchronization scheme for a mobile network that may experience significant periods in GPS-denied territory. The combination of the bio-inspired smart sensors with accurate confidence metrics, in conjunction with the time synchronization protocols provided, created an excellent platform for sensor fusion algorithms that could be quickly tested in relevant scenarios, under the guidance of Army subject matter experts.

Performance against live fire from small arms was very good and showed marked improvement over performance of the individual sensors in stand-alone mode. The improvement was not only in localization of the shooter position, but also in reduction of poor estimates and false alarms, creating potentially much more reliable and actionable information for a warfighter. The first generation of mortar and high explosive event fusion algorithms were extremely effective, even without prior training with live fire data. The ability to detect and localize threats such as mortar, RPG, and recoilless rifle was demonstrated with live fire out to the effective ranges of the weapons, and localization was sufficient to produce actionable information.

The prototype mobile hostile fire detection sensor network still requires significant development before it can be transferred to the hands of soldiers, but the initial results show the technology is not only possible, but realizable for relevant operational environments. Future generations of algorithms and sensors will only improve robustness and performance, as integration increases between the components of the sensor network. The collaboration between the UCSB, BioMimetic Systems, ARL, and ARDEC has proven to be very fruitful, and has quickly provided encouraging results for sensor fusion technology.

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