Acoustical sensors and a range-gated imaging system in a self-routing network for advanced threat analysis

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Abstract: We present a wireless sensor network which is used in an acoustic-optical system for sniper detection. The network consists of mobile nodes, carried by soldiers or mounted on vehicles as well as fixed nodes which are used to forward data to a base station. The mobile nodes are equipped with a microphone array, a GPS receiver and an electronic compass. In case of a sniper attack, each mobile node is capable of estimating the distance and direction of the threat. In addition, preprocessed audio-data from each mobile node will be sent via the wireless network to a base station, where the data will be processed to further enhance the accuracy of the threat localization. Identification and verification of the threat will be attained by a range-gated active imaging system which is automatically orientated towards a calculated GPS coordinate of the threat. In order to properly design the wireless network, we carried out simulations using the freely available network simulator ns-3. This simulator allows including real hardware into a simulation. It is therefore possible to use real mobile nodes to generate real network traffic while the fixed nodes can be simulated. The wireless network can thus be easily investigated by modifying parameters like node location, number of nodes, bandwidth etc. without expensive field experiments and without realizing real hardware in advance. In addition, several experiments have been carried out with real nodes in a rural area.

1 Introduction

In modern conflicts, snipers are a crucial threat. It is therefore important to detect such threats in order to increase the security of soldiers involved in military operations. With funding from the French and German MoDs, ISL is developing a system for joint acoustic and optical detection and localization of a sniper [1]. The system consists of military helmets, each equipped with eight microphones, an imaging system with active laser illumination at 860nm and 1.5um and a wireless sensor network which is used for intruder detection (see Figure 1). By analyzing the mach wave and the muzzle wave, each helmet is capable of detecting and localizing a sniper after the shot. It is even possible to determine the caliber of the projectile.

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Although, the acoustic system is passive, it only works, if there was already a sniper shot. The optical system on the other hand is an active system, but it can detect and identify pointed optics at distances of several kilometers using the cat-eye effect.

In this paper we present the hardware architecture of the sensor nodes used for the wireless network and some preliminary experiments in a real scenario as well as simulations which have been carried out using the freely available network simulator ns-3.
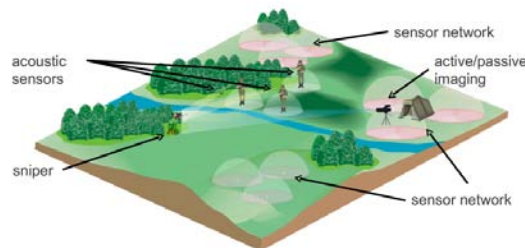

Figure 1: Overview of the system

2 Single components

The two major senses used by human beings for the detection and localization of objects of interest are hearing and view. ISL works on a project in which electro-optical and acoustical systems are networked in order to help localizing snipers. The acoustical sensors are used in order to detect and localize the threat so that the vision system can point to the threat's position and refine its localization.

2.1 Acoustical Sensors

In 2005 the French-German Research Institute of Saint-Louis (ISL) started under the hospice of the German MOD the development of algorithms for the detection and localization of snipers using acoustic arrays. This lead to the development of efficient algorithms for the detection [1], the classification [2], and the localization [3, 4] of sniper shots using an acoustic array mounted on the soldier's helmet (Figure 2).

The principle of the detection algorithm is based on classical signal processing tools inspired from speech processing techniques like blank detection. The Digital Signal Processor (DSP) computes the instantaneous energy of the signal measured by the microphones and compares it to the mean energy on a few seconds. If a transient wave is detected, a classification algorithm is applied. The signals of interest for the here developed acoustic nodes are generated by sniper shots.

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Two transient waves are measured when a sniper shot is triggered: the Mach wave generated by the supersonic bullet is the first wave that is measured; the muzzle wave generated by the explosion of the powder in the barrel is the second wave of interest [5]. The Mach wave has a specific N-shape. The classification algorithm evaluates if the detected transient wave has characteristics that are similar to an N-shaped signal [4], and if this is the case, the localization algorithm is applied in order to determine the position of the shooter, the shot trajectory and the caliber of the weapon that has been used. This is possible if the direction of arrival (DOA) computed using beamforming, and the time of arrival (toA) of both Mach and muzzle waves are estimated correctly [2]. Those algorithms have been tested on synthetic and measured data, in free field and in urban environment and showed good performance.

Figure 2: helmet-mounted acoustic array

Real time demonstrators have been developed that use eight microphones, one GPS receiver for the array's position estimation, and a magnetic compass for the array's orientation estimation. An Analog Devices SHARC DSP is used in order to apply the detection/classification/localization algorithms. Every single acoustic array computes the estimated trajectory of the detected shot and sends the relevant information (estimated DOA and toA of the Mach and muzzle waves, estimated shooter position and trajectory angle, estimated caliber, and Mach wave duration and amplitude) to the fusion center either through the wireless network using ZigBee, either using wired communication for static acoustic arrays. The data gathered in the fusion center is then reprocessed in order to refine the estimated position of the shooter and then send the information to the range-gated imaging system.

2.2 Range-gated imaging sensor

(a)   (b)

Figure 3: ISL range-gated imaging systems operating at (a) NIR and (b) SWIR wavelengths.

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A range-gated imaging sensor is used for identification and verification of the threat by an operator. This active sensor consists of an intensified image sensor which is dedicated to a laser illuminator. Here, either a laser diode or a solid state laser is used to emit light in the near infrared (NIR) or the eye-safe short-wave infrared (SWIR) spectral range, respectively. The imaging sensor has a resolution of 1394 x 1040 sensor elements and a field of view (FOV) between 1 and 2.5 degree i.e 17.4 mrad to 43.6 mrad. Thus the instantaneous field of view (IFOV) i.e. the FOV of a single sensor element is 12 µrad and 31 µrad.

Due to the application of pulse laser sources and gated imaging sensor a range-gated viewing can be realized. Here, only light which arrives at the sensor within a certain timing window contributes to the imaging process [7, 8, 9]. Thus a precise time of flight or a selection of the imaging range (i.e. the range-gate) can be realized. Range-gated imaging sensors are capable to localize distant objects with very high precision.

The orientation and all relevant parameters of the imaging system can be controlled by the operator with a man-machine-interface (MMI) through the network. In the case of an attack by a sniper, the range-gated imaging system can be automatically orientated to the region-of-interest. Further, an automatic adjustment of all relevant system parameters is realized to enable an immediate view on the scene for the operator.

2.3 Sensor network

In 2010, we realized 12 communication modules (figure 4) based on an Intel Xscale PXA270 processor running on Linux. Each module is equipped with a Lassen iQ GPS and the wireless communication was implemented with USB WIFI sticks. Unfortunately, the embedded Linux system only supported USB 1.1 which of course limits the bandwidth on the WIFI channel to approximately 1Mbit/s, even though the WIFI stick is compatible with the IEEE 802.11g (54Mbit/s) standard [6].
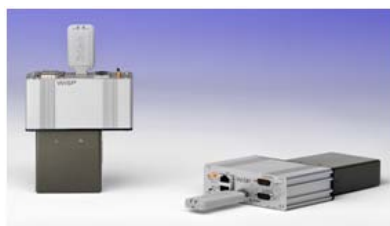

Figure 4: WiSP2 modules with USB WIFI sticks

On the ISL proving ground in Baldersheim first tests have been carried out with the WiSP2 modules. Eleven modules have been distributed over an area of about 100m x 300m (Figure 5). We used B.A.T.M.A.N. as routing protocol on all nodes. The base station was located near node 0 in a bunker. Node 9 was located behind the mound to the right side of Figure 5 and was only visible for node 8. As can be seen, the network architecture was nearly linear with some redundant nodes (nodes 2, 3 and 7).

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All nodes have been accessible and the communication to all nodes was stable. Network throughput was measured from node 0 to node 10 using iperf with about 460kbits/s. Even after removal of the redundant nodes, the network was still functional. Due to the limitations on the wireless communication link of the WiSP2 modules, a new generation of communication platform has been developed (WiSP3). This platform is based on an ARM 8 CPU running at 600MHz and also provides a real 802.11b/g wireless communications interface. The platform was extended to also include a second wireless communication interface based on ZigBee which will be used to connect wireless sensors to the communication platform. First tests with this new communication platform showed a network throughput on the Wifi channel of up to 22 Mbit/s between two stations, which is near to the theoretical limit for IEEE 802.11g at 54Mbit/s. For the same scenario as before (shown in Figure 5) it was possible to achieve a bandwidth of up to 10 Mbit/s between node 0 and node 10.

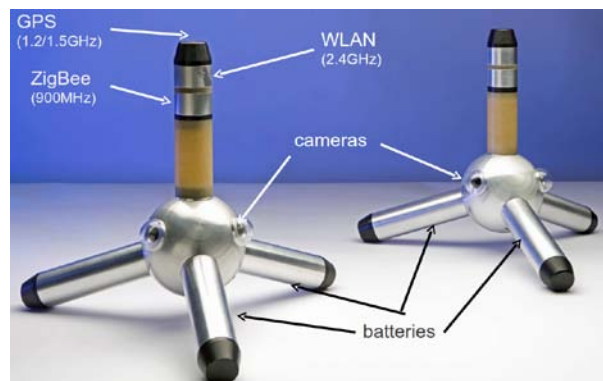Figure 5: Field tests on ISL proving ground, sensors distributed on a 100x300m area.

Figure 6: WiSP3 platform

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3 Data-fusion and sensor network

For each sensor connected to a sensor platform, the raw data has to be read and possibly pre-processed. Since multiple different sensors can be connected to one platform, the platform provides the possibility of intelligent data fusion in order to only send relevant data over the wireless network. This leads to reduced energy consumption and also reduces the risk of network congestion. To illustrate this, we assume that a platform will be used to detect intrusion into a restricted area (Figure 7).
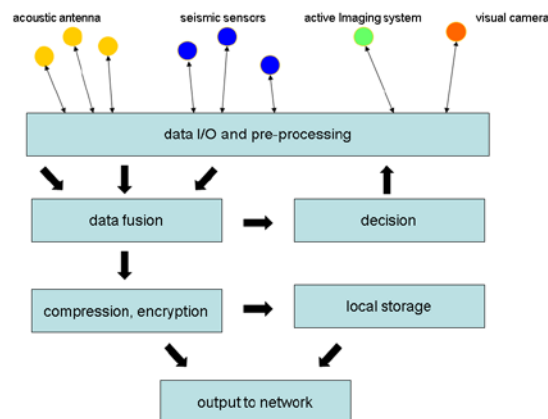

Figure 7: Example of a typical data flow on a sensor platform

Therefore a set of acoustic antennas and seismic sensors as well as a visible and an IR camera as well as a magnetic compass and a GPS will be connected to the platform. As long as there is no significant signal detected by the acoustic and seismic sensors, the cameras could be switched to a power-save mode. In the event of an intrusion, the direction, distance and the type (vehicle, human activity…) of the possible threat will be calculated based on the raw sensor data of the acoustic and seismic sensors. Depending on the time of day either the visible or the infrared camera will be pointed in the detected direction to record a series of images. These images could be further processed (hot spot detection, compression, encryption) and stored locally. Due to the fact that different types of sensors are used, a confidence level can be calculated. Based on this confidence level, either a short text message (containing only the GPS position of the platform, the direction and distance of the threat) or additionally a series of significant images will be forwarded to the network. Figure 8 shows the complete process flow for this example.
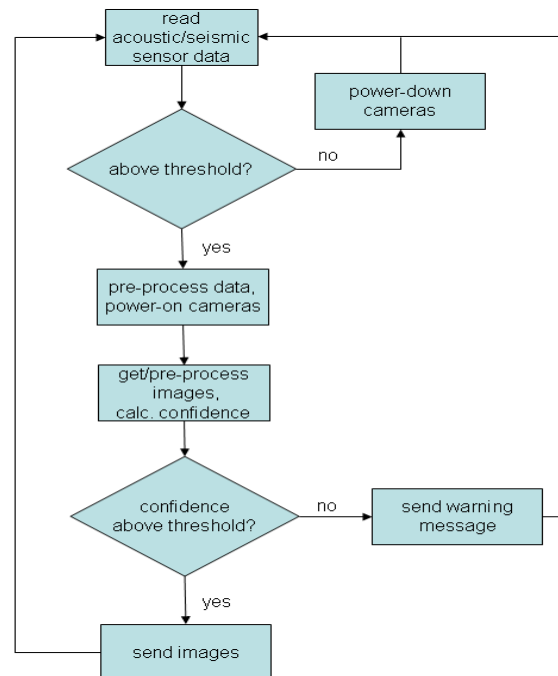
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Figure 8**:** Process flow for the example application

4 Discussion and Conclusion

In the presented sensor network distinct and contrary types of sensor are applied to detect, localize and identify a threat in means of an attacking sniper. As depicted in figure 9, each sensor has its specific advantages and drawbacks. While the acoustic sensor's strength can be found in the coverage of a hemispherical detection and observation area, the single sensor is leaking in the precision in the localization of the threat. Especially, accuracies in the distance estimation around 15% are not suitable for precise localization issues or for the preparation of countermeasures. This drawback can be reduced (but not completely avoided) by fusion of the information of different acoustical sensor nodes.

The active imaging offers high spatial resolution with horizontal and vertical IFOV of some tens of μrad i.e. some meters on a kilometric scale. In addition, the photon time-of-flight measurement enables 3D imaging and precise range estimation. A critical drawback of this technique is the limitation of active imaging to a narrow field of view (horizontal and vertical axis) i.e. some hundred meters on the kilometric scale. Therefore, this technique cannot be applied for 24/7 observation of a large field of view.

In the fusion of acoustic sensors and active imaging one can use the advantages of both sensor systems. As long as the angle between acoustic sensor, threat and active imaging system is small, the poor range estimation of the acoustic sensor has no impact on the orientation of the imaging system. If the angle exceeds a certain limit, the risk to get the threat out of the FOV of the imaging system increases rapidly. Therefore, the distribution and position of the sensor nodes has impact on the performance of an acousto-electro-optical sensor network.
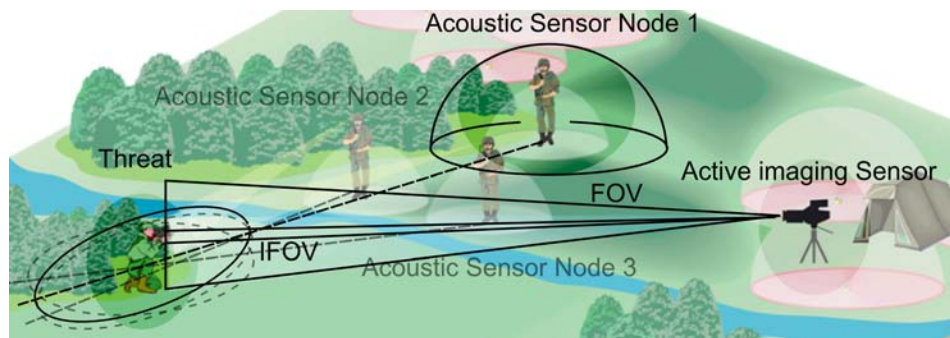

Figure 9**:** Sensor network of acoustic and active imaging sensors can lead to an improvement in the localization of threats (sniper) by data fusion.

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