14th International Conference on Information Fusion
Chicago, Illinois, USA, July 5-8, 2011

Fusing Distributed Muzzle Blast and Shockwave Detections

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***Abstract*— The paper presents a novel sensor fusion technique to shooter localization using a wireless network of single-channel acoustic sensors. The unique challenge is that the number of available sensors is very limited. The first contribution of the work is an approach to estimate the miss distance of the shot and the range to the shooter from a single shot using a single sensor. The second contribution is the novel sensor fusion algorithm itself that fuses the miss distance and range estimates of the individual nodes as well as their Time of Arrival observations of the shockwave and the muzzle blast. The performance of both the single sensor method and the network fusion are very promising.**

Keywords: Shooter localization, countersniper system, acoustics, wireless sensor network, muzzle blast, shockwave, consistency function, sensor fusion.

I. INTRODUCTION

Research on acoustic gunshot detection has a long history. Fansler studied the ideal muzzle blast pressure wave in the near field without contamination from echoes or propagation effects [1]. For longer ranges, Stoughton [2] took measurements of ballistic shockwaves using calibrated pressure transducers at known locations, measured bullet speeds, and miss distances of 3 - 55 meters for 5.56 mm and 7.62 mm projectiles. As shockwave duration is directly related to bullet characteristics and the edges of a shockwave are typically well defined,

There are many systems in literature, some even available commercially, that localize the origin of a shot based on detected acoustic signals. This localization is based on the Time of Arrival (ToA) of the shockwave and/or the muzzle blast at multiple microphones. These systems are centralized consisting of one or a few microphone arrays with wired connections to a central processing unit. The microphones within the array have precisely-known separations, enabling accurate Angle of Arrival (AoA) detection. An early such system was Bullet Ears [3]. A few years ago, BBN introduced the vehicle-mounted BOOMERANG that is being used in Iraq and Afghanistan [4]. The most recent system that the US military deployed is made by QinetiQ [5]. It is a wearable device consisting of a pod with four shoulder-worn microphones and a second hand-held component that displays the location of the shots. The typical bearing precisions provided by these systems are 10 degrees or more.

Our team introduced PinPtr, the first wireless sensor network (WSN) based countersniper system in 2003 [6]. PinPtr is based on a large number of inexpensive single-channel sensors that communicate with each other via a low-power radio. The ToA of the shockwave and muzzle blast detected by the sensor nodes are sent to a laptop computer that fuses the observations and displays the estimated shooter location. The widely distributed sensing and unique sensor fusion algorithm [7] enable the system to eliminate erroneous observations due to non Line of Sight (LOS) conditions (i.e. echoes) and to resolve multiple simultaneous shots. The demonstrated accuracy of the system is about 1 meter on average in 3D for shots originating within or near the sensor network. For longer range shots, 1 degree bearing precision for both azimuth and elevation and 10% accuracy in range estimation have been achieved in various US Army MOUT (Military Operations in Urban Terrain) facilities.

The soldier-wearable version of PinPtr we developed in 2006 is based on multi-channel sensor nodes Supporting AoA estimation of both acoustic events [8]. What differentiates it from the commercial systems is that the nodes are connected through a low-power wireless network. This results in higher accuracy and more importantly, it enables accurate caliber estimation and weapon classification. The demonstrated performance of the system is 1 degree trajectory precision and 95% caliber estimation accuracy. The main challenge is to track not only the location of the mobile sensors, but also their self-orientation. The digital compass utilized for this purpose is expensive and susceptible to large error due to metal objects in its vicinity. The system presented here, therefore, utilizes single-channel sensors, but their number is an order of magnitude smaller than that of the original PinPtr system.

Recently, other researchers have started to explore the domain of networked sensing for shooter localization. Damarla et al. presents an approach that does not require the distributed sensors to be time synchronized [9]. The technique relies only on the Time Difference of Arrival (TDoA) of the shockwave and muzzle blast on the same nodes, but assumes a known bullet speed. Early results are based on data collected on high-quality instrumentation microphones and offline processing. Lindgren et al. presents a similar approach [10]. Considering that time synchronization is available on most WSN platforms with little overhead, it is not clear that the tradeoffs these techniques provide are necessary.

The rest of the paper is organized as follows. The next section describes the approach how to estimate the miss distance of a projectile and the range of the shooter using a single microphone. It is followed by a detailed description of the novel sensor fusion approach. Finally, the performance of the approach is evaluated using field data gathered at Aberdeen Proving Grounds.

II. Single Sensor

Whitham showed that the shockwave duration T is a function of the projectile diameter d and length l, the distance b of the microphone from the trajectory of the bullet (miss distance), the Mach number M, and the speed of sound c [11]:

$$T = \frac{1.82Mb^{1/4}}{c(M^2-1)^{3/8}}\frac{d}{l^{1/4}} \approx \frac{1.82d}{c}(\frac{Mb}{l})^{1/4} \tag{1}$$

The shockwave duration depends linearly on the caliber (diameter). Out of the other factors, the miss distance can change from 0 to up to 50 m. The reasonable range for the Mach number and the bullet length are much smaller. Consequently, Sadler [12] demonstrated how a shockwave duration measurement along with equation 1 can be used to estimate the caliber of a projectile. Here we propose the opposite. Assuming a given caliber (e.g., a 7.62 mm projectile), the miss distance can be estimated using the length of a single shockwave detection.

Furthermore, when both the muzzle blast and the shockwave are detected on the same node, it is possible to compute a reasonable estimate of the shooter's range, relying on assumptions about the caliber (e.g. 7.62 mm) and approximate muzzle speed (e.g. 710 m/s for a typical AK-47). That is, a single-channel acoustic sensor can determine the miss distance and the shooter range based on a single shot.

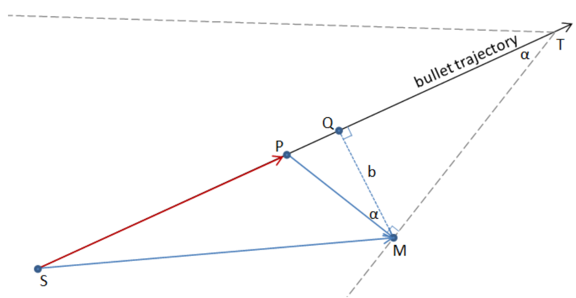

Fig. 1. Geometry of a shot from S and the acoustic events observed at M.

Consider Fig. 1. Points S and M represent the locations of the shooter and the microphone detecting the acoustic events, respectively. Let us denote the range, i.e. the Euclidean distance between points S and M, with $d_{M,S}$. Assuming line-of-sight (LOS) conditions, the detection time of the muzzle blast can be written as

$$t_{mb} = t_{shot} + \frac{d_{M,S}}{c} \tag{2}$$

where t_{shot} is the time of shot, and c is the speed of sound which is assumed to be known. That is, the muzzle blast travels at the speed of sound from S to M, and is, therefore, detected $\frac{d_{M,S}}{c}$ seconds after the weapon is fired.

Since the shockwave does not originate from the muzzle but from the bullet traveling along its trajectory, we need to consider the time traveled by the bullet from the muzzle to a point P on the trajectory, as well as the time traveled by the wavefront of the shockwave from point P to the microphone. (P is defined such that the vector $\vec{MP}$ is a normal vector of the shockwave front.) For simplicity, let us assume for now that the bullet travels at a known constant speed v. The shockwave detection time can be written as

$$t_{sw} = t_{shot} + \frac{d_{S,P}}{v} + \frac{d_{P,M}}{c} \tag{3}$$

The measured shockwave-muzzle blast TDoA can be expressed as

$$t_{mb} - t_{sw} = \frac{d_{M,S}}{c} - \frac{d_{S,P}}{v} - \frac{d_{P,M}}{c} \tag{4}$$

Since we assume a constant bullet speed v, the shockwave front has a conical shape, such that the angle between the trajectory and the conical surface is

$$\alpha = sin^{-1}\frac{c}{v} \tag{5}$$

We notice that $\sphericalangle PMT$ is a right angle; therefore, $\sphericalangle PMQ = \alpha$ because the respective triangles are similar. Knowing α and the calculated miss distance $d_{Q,M}$, we can express distances $d_{S,P}$ and $d_{P,M}$ as follows:

$$d_{P,M} = \frac{d_{Q,M}}{cos(\alpha)} \tag{6}$$

and

$$d_{S,P} = d_{S,Q} - d_{P,Q} \tag{7}$$

where

$$d_{S,Q} = \sqrt(d_{S,M}^2 - d_{Q,M}^2) \tag{8}$$

using the Pythagorean theorem, and

$$d_{P,Q} = d_{Q,M}tan(\alpha) \tag{9}$$

Therefore, Equation 4 can be solved for the range $d_{M,S}$, resulting in a closed-form formula that is extremely fast to evaluate on the target hardware:

$$\begin{aligned} d_{M,S} &= \frac{1}{2(c^4-v^4)}(P - 2\sqrt{Q}) \qquad (10)\\ &\text{where P and Q are defined as}\\ P &= -2v^3 d_{Q,M}\sqrt{v^2+c^2} - 2(t_{mb}-t_{sw})c^3v^2\\ &+2c^2 d_{Q,M} v\sqrt{v^2+c^2} - 2(t_{mb}-t_{sw})cv^4\\ Q &= -2c^4v^4d_{Q,M}^2 + 2(t_{mb}-t_{sw})^2c^6v^4\\ &+(t_{mb}-t_{sw})^2c^4v^6\\ &-2c^7d_{Q,M}(t_{mb}-t_{sw})v\sqrt{v^2+c^2}\\ &+c^8(t_{mb}-t_{sw})^2v^2 + 2c^8d_{Q,M}^2\\ &+2v^5d_{Q,M}\sqrt{v^2+c^2}(t_{mb}-t_{sw})c^3 \end{aligned}$$

While relaxing the assumption of constant bullet speed and incorporating a weapon-specific deceleration constant in the

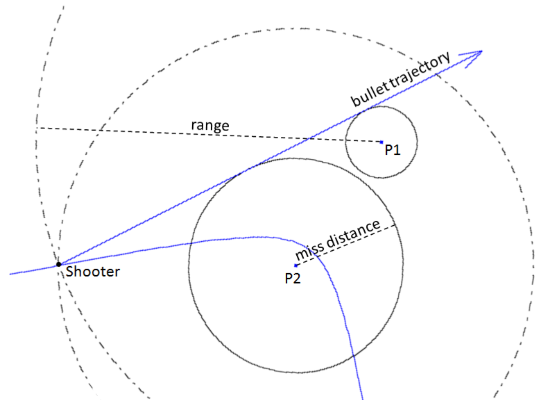

Fig. 2. Shooter position and trajectory reconstruction with a network of single-microphone sensors.

equations would result in more precise results, finding the solution for $d_{M,S}$ would require numerical methods, making the algorithm more computationally expensive.

III. Sensor Fusion

The goal of the sensor fusion is to estimate the shooter position and the trajectory of the supersonic projectile, using shockwave and muzzle blast time-of-arrival measurements as well as miss distance and range estimates from a network of single-microphone sensors.

Consider two sensor nodes (P1 and P2 in Fig. 2) measuring the shockwave duration and the TOA of both the shockwave and the muzzle blast perfectly. The range estimates (computed as described in Section II) define circles that intersect at the shooter location. The same point lies on the hyperbola defined by the muzzle blast TDoA of the two sensors. The projectile trajectory is a tangent of both circles defined by the miss distances. The shockwave TDoA also constrains the trajectory (not illustrated in Fig. 2). If the measurement and other errors are small, the shooter location can be estimated very accurately as shown. (Note that there is another solution symmetrical to the P1 P2 line, so three sensors are needed for an unambiguous solution in 2D.)

We consider a special case of this problem, where detection errors are non-Gaussian and false detections may arise, as well. This is typical of urban environments, where echoes, non-line-of-sight conditions and diffraction cause the signal path and signal shape to be different from what an ideal, free-space model would imply. In fact, is not uncommon that only half of the sensor readings are correct for a particular shot.

Furthermore, we are particularly interested in system performance when the shooter is outside the sensor network, shooting at or close to where the sensors are. This is exactly the case when individual sensors are mounted on soldiers or vehicles, who need to be protected from adversaries shooting at them from a distance.

We assume that sensor nodes are time synchronized, and that the synchronization accuracy is comparable to the sample time (which is in the order of 10 microseconds), and therefore it is negligible. We can also assume that sensor positions are known accurately, as military grade differential GPS can provide better than 10cm accuracy.

Our previous experience with shooter localization in urban terrain show that conventional nonlinear optimization methods are impractical for this particular problems, because of the highly irregular, non-Gaussian noise pattern. Therefore, we resort to search based techniques. First, we estimate the shooter location using the range estimates and muzzle blast TDoAs. Then, we search for the trajectory that originates from around the position estimate and is consistent with the miss distance estimates of the individual sensors.

A. Finding the shooter position

There are two classes of data available, muzzle blast TDoAs and ranges, each of which alone are sufficient to find the shooter position, respectively. In this section, we look into both multilateration and trilateration, and then we reason that a combination of the two methods may give better results.

Finding the shooter position given a set of muzzle blast TDoAs can be cast as a classic multilateration problem. A pair of sensors constrain the shooter location on a hyperbolic curve, the foci of which are the two sensors, and the distance difference, which is constant for all points on the hyperbola, is $c\Delta t$ (c is the speed of sound, and Δt is the TDoA between the pair of sensors). For three sensors, two such independent hyperbolas can be constructed, the intersection of which yields the shooter position.

Since we expect echoes in an urban setting, the resulting erroneous detections will manifest as large outliers, which cause direct methods and conventional nonlinear optimization techniques to fail. Search-based methods, however, tend to be more robust to such outliers.

We divide a predefined search space (an area of interest, or an area around the sensor network that is still within the sensing range of the individual microphones) into small regions, and for each such region, we evaluate a metric that indicates how well the sensor readings support that the shot originates from that particular region.

We observe that, if the particular region *is* the true shooter position, when we compute the shot times from the muzzle blast ToAs and region-microphone distances, most of the shot times will roughly be identical (forming a consistent cluster), except for the outliers (if present). However, for any other region, the shot times will not align.

Therefore, the search algorithm looks for the region with the most consistent cluster of a given minimum cardinality $threshold_{cardinality}$, which is a predefined parameter. Formally, for every region, where C is the centroid of the region, we compute the shot times $t_{shot,i}$ from the muzzle blast ToAs $t_{mb,i}$ each sensor report, supposing that the shot came from C as:

$$t_{shot,i} = t_{mb,i} - d(C, P_i)/c \tag{11}$$

where c is the speed of sound and P_i are the sensor positions.

Then, we find the subset of cardinality $threshold_{cardinality}$ for which the variance of the computed shot times

$variance(t_{shot,i})$ is the minimal. It is the variance of this subset that is used as the metric for the region. The region with the lowest reported variance within the search space will be reported as the shooter location.

Trilateration can be carried out with a search-based technique in a similar manner. The metric function in this case is the number of range estimates that are consistent with the particular region. We say that a range estimate is consistent with the region if the range estimate is greater than the distance between the microphone and the point of the region closest to the microphone, and if the range estimate is less than the distance between the microphone and the point of the region farthest from the microphone. The region with the highest metric function value will be reported as the shooter location, as long as the value is above a threshold $threshold_{score}$.

We observed that the above two techniques have very different error patters, if the shooter position is far outside the sensor field. In the case of multilateration, the rough direction of the shooter position from the sensor field is good, however, the distance component often has larger errors. This is because the hyperbolas, defined by pairs of sensors for which a TDoA is reported, intersect in very small angles far from the foci. Since the point is far from the foci, it will be close to the asymptotes. However, even small errors in the TDoAs will cause a large variation in the location of the point of intersection: it will still be close to the asymptotes (hence the reliable *direction* component), but the *distance* component will have a fair amount of error.

In the case of trilateration, the situation is quite the opposite. The *distance* of the resulting shooter position estimate is resilient to errors in the range estimates that are inputs to the trilateration algorithm. However, the *direction* component can exhibit large errors. This is because trilateration looks for an intersection point of circles: a crescent shaped region of uncertainty will be observed when errors are present in the ranges (which are the radii of the circles), distorting the position estimate.

We, therefore, propose to combine the two techniques. The metric function of the combined trilateration-multilateration search is a combination of the respective metrics. Since the multilateration search looks for a minimum, while the trilateration search finds a maximum, we convert the latter to a minimum finding problem by using the reciprocal of the score. Therefore, the metric function of the combined technique will be the product of the multilateration metric and the reciprocal of the trilateration score.

B. Trajectory estimation

The problem formulation of trajectory estimation is the following. Given a set of known microphone positions P_i and miss distance estimates r_i, find the trajectory L and binary measurement weights $w_i \in 0, 1$ that minimizes

$$\sum_{i=1}^{n} w_i(d(L, P_i) - r_i)^2 \tag{12}$$

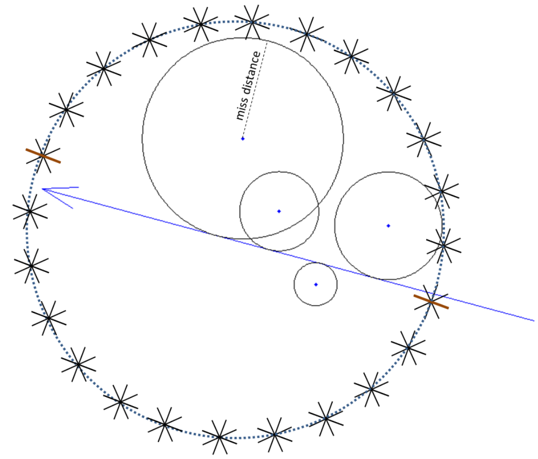

Fig. 3. Search for bullet trajectory. A large circle is constructed first that encompasses the entire sensor field, as well as the circles with radii equal to the miss distance estimate centered at the sensors. Several discrete pivot points are evaluated along the perimeter of the large circle. At each pivot point, several possible trajectories are tested for fitness. In this particular case, the highlighted line segment which is close to parallel with the true trajectory will provide the best fitness.

with the constraint

$$\sum w_i > threshold_{weight} \tag{13}$$

where $d(L, P_i)$ is the function returning the distance of a point to a line. The constraint states that at least $threshold_{weight}$ miss distance measurements must contribute to the result.

The search algorithm evaluates, with a given granularity, all geometrically feasible trajectories, i.e. those that either cross the sensor field, or pass close to the edge of the sensor field.

The miss distance estimates r_i define circles of radius r_i with the microphone positions P_i as centers. When no errors are present, the trajectory is a line that is tangent to all circles. It is easy to notice, that the line must intersect a large circle that encompasses all circles defined by microphone positions and the corresponding miss distance estimates. We therefore select pivot points on the circumference of the large circle with some granularity (e.g. 360 points). Then, for every point, we test all lines that go through this point with some granularity, e.g. if θ is the angle of the line and the x axis, with let θ run from $-\pi$ to π with one degree increments.

Note that if a shooter location estimate is present, enumeration of the possible trajectories is simpler. There is only one pivot point: the shooter location estimate. There is no need to evaluate a series of points along the circumference of a large circle.

To evaluate a line, we compute the value of a metric that expresses how consistent it is with the miss distance estimates. For each microphone position P_i we compute the difference of the miss distance estimate and the microphone's distance from the line $\Delta d_i = d(L, P_i) - r_i$. The metric we return is the variance of the $threshold_{weight}$ smallest Δd_i values for line L. This way, potential outliers with high Δd_i values for

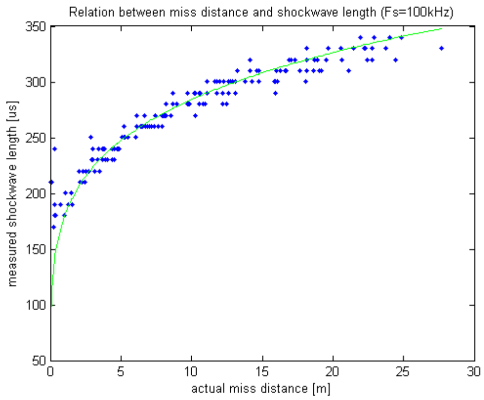

Fig. 4. Miss distances vs. shockwave duration.

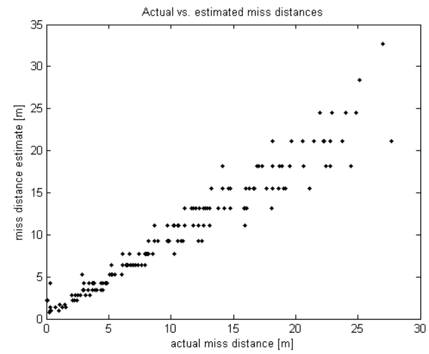

Fig. 5. Actual vs. estimated miss distances.

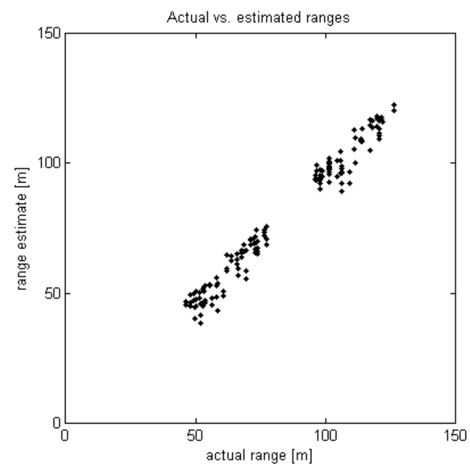

Fig. 6. Actual vs. estimated ranges.

the true trajectory will be filtered out, and will not contribute to the metric.

IV. RESULTS

A. Single sensor

A team from NIST carried out an evaluation of the wearable PinPtr shooter location system [8] at the US Army Aberdeen Test Center in April 2006 [13]. The setup emulated an urban environment with mock-up wooden buildings to create reverberations and echoes. There were 10 sensor nodes deployed at surveyed locations in an approximately 30×30 m area. Five fixed targets behind the sensor network were used for aiming. Firing positions were located at 50, 100, 200 and 300 meters away from the targets. The projectile always passed over or close to the sensor field, thus typically the majority of the sensors were able to detect the acoustic shockwave. Six different weapons types were tested: AK-47 and M240 firing 7.62 mm projectiles, M16, M4 and M249 with 5.56mm ammunition, and the .50 caliber M107. All sensor detections were saved to enable experimenting with different localization techniques.

From this experimental live fire detection data set, we selected all 168 shockwave detections of AK-47 shots fired from a distance of 50-130 m from the sensors and downsampled the shockwave duration to 100 kHz from the original 1 MHz. The high sampling rate of the data was necessary because the wearable PinPtr system relied on multichannel sensor for AoA estimation. For a single channel system the higher cost and power requirements does not justify that high of a sampling rate. Fig. 4 shows the relation between shockwave duration and miss distance. Notice how the quantization of the very short shockwaves due to the sampling rate is apparent.

Using Equation 10, the miss distances were estimate for all 168 data points. The results, actual vs. estimated miss distances, are shown in Fig. 5. The actual miss distances ranged from 0 to 28 m.

As expected, the accuracy of miss distance estimation degrades as the miss distance grows. The reason for this is inherent in how the shockwave duration is measured. Close to the bullet's path, the shockwave has a very pronounced 'N' shape, with sharp rising and falling edges. The beginning of the sharp edges can be identified relatively unambiguously using a threshold on the slope. However, when the sensor is far from the trajectory, the rising and falling edges are smoother and less pronounced, which makes it harder for our detection algorithm to unambiguously identify when the 'N' wave starts and ends. This uncertainty propagates into the miss distance estimates. Still, the standard deviation of miss distance estimates was 1.76 m with a mean of -0.28 m.

As described in Section II, it is possible to compute the range when there is at least one shockwave and muzzle blast detection available on a single node. For all 168 data points, we computed the range, assuming a projectile speed of 650 m/s and sound propagation speed of 340 m/s. The resulting range estimates versus the ground truth ranges are shown in Fig. 6.

The mean range estimation error was -4.3 m, with a standard deviation of 7.3 m. The negative bias of the range estimates can be attributed to the fact that the proposed range estimation technique assumes a fixed projectile velocity. This could, however, be greatly improved. Since the weapon-specific bullet deceleration function can be approximated with a simple linear function [8], we could use a simple iterative approach.

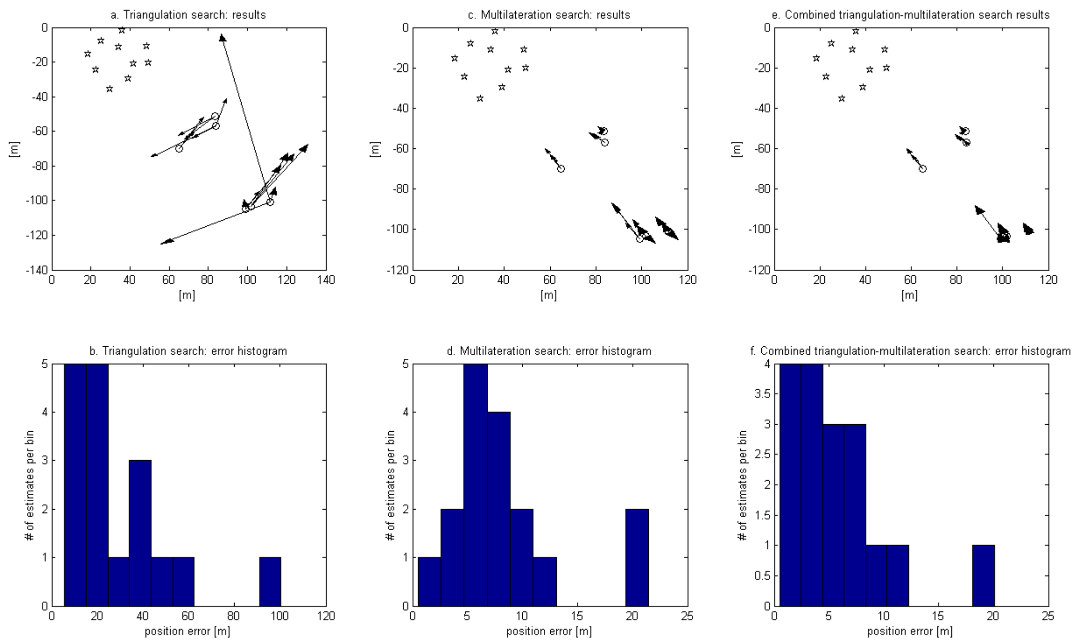

Fig. 7. Shooter location estimation results. Subfigures a., c. and e. display the map of sensors, marked with pentagrams, along with arrows pointing from the estimated to the actual shooter locations represent positioning errors for each positioning method, respectively. Subfigures b., d. and f. present the histograms of the corresponding positioning errors.

Initially, the range could be estimated using a projectile speed of 650 m/s assuming an AK-47 from approximately 50 m range. Once the actual range estimate is computed, the speed corresponding to that range could used to refine thew range estimate. We leave this for future work.

It is important to note that uncertainty of range estimates grows with the shooter-sensor distance. Expressing the range estimation errors as a percentage of the range gives an average absolute range estimation error of 6.7%.

B. Networked operation

We compared the performance of the three shooter position estimation approaches, described in Section III, using the same experimental data set of 17 AK-47 shots. In each case, the weapon was fired outside the sensor field, approximately 50 to 130 meters away from the individual sensors.

In all three cases, we ran the search algorithms on a 1 m by 1 m resolution grid, covering a 150 m by 150 m search space. We required that at least five of the sensors contribute to the reported result, i.e. $threshold_{cardinality}$, $threshold_{score}$ and $threshold_{weight}$ were set to 5 (see Section III).

As expected, trilateration search (Figure 7 a. and b.) was the weakest performer, with two huge outliers. Discarding those two outliers, the mean positioning error was 22 m, with a standard deviation of 12 m. Interestingly, the error vectors almost never point towards or away the sensor network, they are typically perpendicular to the lines connecting the sensors and the shooter position. This can be attributed to the fact that errors in the input range estimates cause significant uncertainty in the intersection point of circles (defined by the range estimates as radii around the microphone locations as centers of the circles), particularly when the shooter position is far from the sensor network.

Multilateration search, on the other hand, performed significantly better, with a quite different error pattern (Figure 7 c. and d.). The mean position error was 8.5 m, with a standard deviation of 5.3 m. Positioning errors where somewhat higher for longer range shots. The error pattern, as expected, showed a pronounced error component pointing in the direction or away from the sensor field. Intuitively, in a typical case, the bearing of the shooter position estimate from the sensor network's point of view is typically correct, while the distance to the shooter has a fair amount of error. Overall, the errors are, on average, less than 10% of the shooter's distance from the sensors field.

As seen in Figure 7 e. and f., the combined trilateration-multilateration techniqe brings together the best traits of the above two methods. It improves over the accuracy of multilateration search, by reducing the radial components of the errors for almost every shot. The mean position error decreased to 5.5 m, with a standard deviation of 4.7 m.

Trajectory estimation results are presented in Figure 8. First, we evaluated how the trajectory estimation algorithm performs when it is not supplied any information on the shooter position (Subfigure a.). The algorithm generated 360 pivot points on a circle large enough to encompass the entire sensor field and all

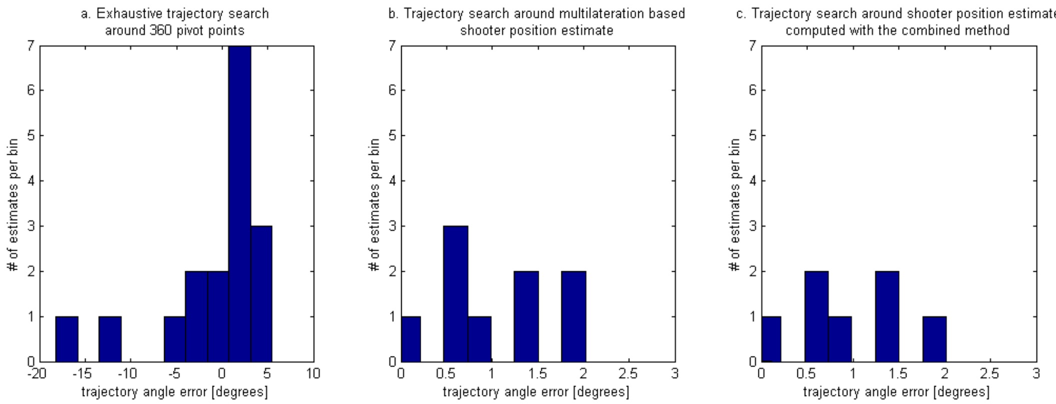

Fig. 8. Trajectory estimation results. Subfigure a. shows the angular errors of trajectories computed with an exhaustive search among all geometrically feasible trajectories. Subfigure b. presents the histogram of trajectory angle errors assuming a known the shooter location estimate, computed with multilateration search. Similarly, Subfigure c. presents the angular error histogram when the shooter location, computed with the combined method is used to restrict the trajectory search space.

the circles with miss distance length radii around the sensors. At all pivot points, possible trajectories with angles ranging from $-\pi$ to π were evaluated in 1 degree increments. With this setup, the angular error of trajectory estimation (i.e. the angle of the actual and the estimated trajectory) was typically under 5 degrees, with two large outliers of 18 and 11 degrees, respectively. The mean angular error was 0.8 degrees, with a standard deviation of 6 degrees.

When the algorithm was supplied a point on the trajectory, the overall performance improved significantly. We evaluated the possible trajectories originating from the position estimate, having angles ranging from $-\pi$ to π, with one degree increments. Subfigure b. shows the angular error histogram of trajectory estimation when the output of multilateration search is used as the known point on the trajectory. The mean angular error was 0.4 degree in this case, with a standard deviation of 0.8 degree. When we used the more precise shooter position estimate, computed with the combined trilateration-multilateration method (Subfigure c.), the mean angular error decreased to 0.2 degree, and the standard deviation of the error decreased slightly, but still remained around 0.8 degree.

The reason for this marginal improvement between the two searches constrained by muzzle blast position is simple. While the combined method gives better position estimates than the multilateration search, the improvement is mostly in the radial component of the position errors. Hence, both shooter position estimates will be very close to the true trajectory and both will serve as excellent pivot points for the trajectory search.

V. Conclusions and Future Work

The contribution of this work is threefold. First, we described how miss distance estimates, computed from the shockwave duration with assumptions on the caliber, can be used, along with the time difference of shockwave and muzzle blast signals, to estimate the shooter range using a single microphone. To the best of our knowledge, this is the first report of shooter range estimation using a single microphone in the literature. Second, we showed, using and experimental data set of 17 shots, fired with AK-47 rifles, that the reported ranges estimates, when incorporated into the networked sensor fusion, will improve the shooter localization accuracy. Third, we described a technique to carry out trajectory estimation using exclusively the miss distance estimates. Our preliminary results show that the proposed trajectory estimation technique, when augmented with the shooter position estimate, can typically compute the trajectory of the supersonic projectile with better than 2 degree accuracy.

We see several interesting directions of future work to enhance the proposed techniques. First, shooter position estimation and trajectory estimation could be carried out simultaneously within a combined search algorithm, with a combined fitness metric for shooter location and trajectory angle. While such an approach would increase the dimensionality of the search, geometric constraints could be used to limit the search space, by excluding trajectories that are not geometrically feasible.

Also, note that none of the proposed search algorithms make use of the shockwave TDoA information available in the network. While shockwave TDoA is often not sufficient to compute the trajectory in the geometric configurations we consider (e.g. when the bullet passes on one side of the sensor field), shockwave detection times could be used to validate the trajectory computed with the search technique proposed in this paper. It would be particularly interesting to see whether shockwave TDoAs would help finding out if the original assumption on the caliber is valid, and whether it would be possible to correct the caliber assumption based on the shockwave TDoAs.

Obviously, more extensive experimental evaluation is required to investigate how the proposed techniques perform when synchronization errors or sensor positioning errors are present. Also, experimenting with different weapon types and calibers is left for future work.

ACKNOWLEDGEMENT

This research was supported in part by the DARPA Transformative Apps program and ARO MURI grant W911NF- 06-1-0076.

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