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Autonomous UAV-based mapping of large-scale urban firefights

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ABSTRACT

This paper describes experimental results from a live-fire data collect designed to demonstrate the ability of IR and acoustic sensing systems to detect and map high-volume gunfire events from tactical UAVs. The data collect supports an exploratory study of the FightSight concept in which an autonomous UAV-based sensor exploitation and decision support capability is being proposed to provide dynamic situational awareness for large-scale battalion-level firefights in cluttered urban environments. FightSight integrates IR imagery, acoustic data, and 3D scene context data with prior time information in a multi-level, multi-step probabilistic-based fusion process to reliably locate and map the array of urban firing events and firepower movements and trends associated with the evolving urban battlefield situation. Described here are sensor results from live-fire experiments involving simultaneous firing of multiple sub/super-sonic weapons (2-AK47, 2-M16, 1 Beretta, 1 Mortar, 1 rocket) with high optical and acoustic clutter at ranges up to 400m. Sensor-shooter-target configurations and clutter were designed to simulate UAV sensing conditions for a high-intensity firefight in an urban environment. Sensor systems evaluated were an IR bullet tracking system by Lawrence Livermore National Laboratory (LLNL) and an acoustic gunshot detection system by Planning Systems, Inc. (PSI). The results demonstrate convincingly the ability for the LLNL and PSI sensor systems to accurately detect, separate, and localize multiple shooters and the associated shot directions during a high-intensity firefight (77 rounds in 5 sec) in a high acoustic and optical clutter environment with no false alarms. Preliminary fusion processing was also examined that demonstrated an ability to distinguish co-located shooters (shooter density), range to <0.5 m accuracy at 400m, and weapon type.

Keywords: urban, firefight, situational awareness, sniper, UAV, IR, acoustic, sensors, fusion

1. INTRODUCTION

Applied Research Associates, Inc. (ARA) with LLNL and PSI performed an exploratory project to investigate the feasibility of the FightSight concept—an autonomous UAV-based sensor exploitation and decision support capability that provides dynamic situational awareness for large-scale (e.g., battalion level) firefights in urban environments (Figure 1). Battalion level firefights can involve 100's of weapons distributed over several square kilometers and 10's to even 100's of shots per second during intense periods. Thousands of bullets may be fired during a minute of combat and battles can last upwards of several hours. Gunfire detection systems have been developed to detect incoming sniper fire on a single vehicle at an instant of time (e.g., Boomerang [1], WeaponWatch [2], CrossHairs [3]). These systems, however, cannot operate at this immense scale where it is necessary to detect, localize, and distinguish a large number of simultaneous co-located and widely distributed events where LOS limitations, clutter, and spurious light sources will interfere with the solution. Through the use of a single wide-area surveillance UAV, FightSight will accomplish these objectives and provides a real-time 4D symbolic map of the enemy including both the distribution of shooters, shooting directions, and weapon types as well as the firepower movements and trends associated with the dynamically changing battlefield situation. FightSight will make battalion-level urban firefight detection and tracking possible through a 4D fusion methodology that synthesizes IR and acoustic firing event observables (bullet tracks, muzzle flash, muzzle blast) with terrain/scene context, weapon signatures, and prior time-history data. Data fusion is performed at a ground control station within the context of a dynamic probabilistic network to characterize and map the flow of urban firing events.

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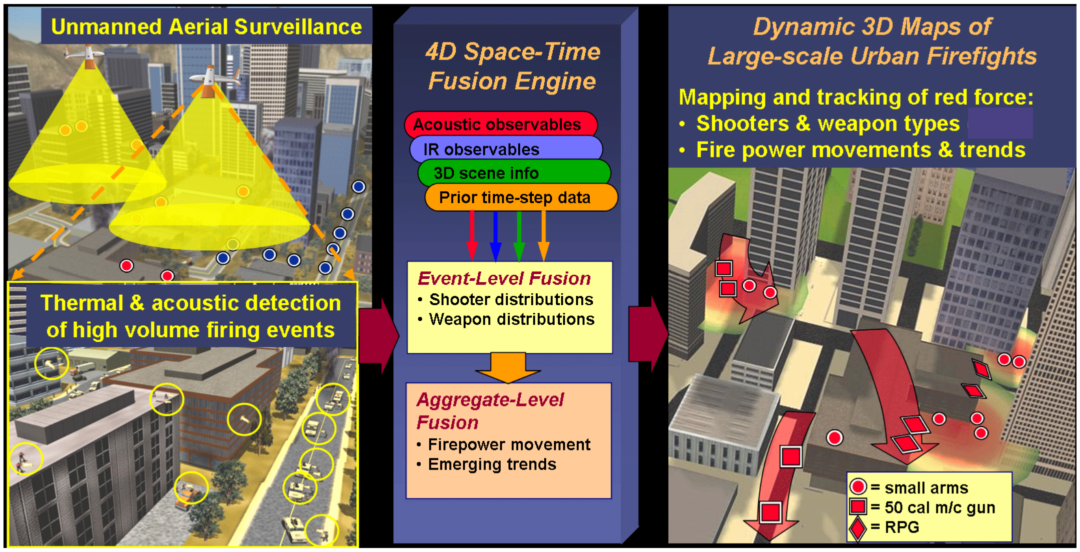


Figure 1: FightSight concept to provide dynamic situational awareness for large-scale firefights in urban environments.

FightSight will provide field commanders and battle command applications (e.g., ASAS-L [4], FBCB2 [5], DCGS-A [6], RAID [7]) with a holistic, up-to-the- minute dynamic picture of the movements, evolution, and emerging firepower tactics of the enemy unit during a large-scale urban battle.

This paper reports results of an exploratory investigation to demonstrate the feasibility and effectiveness of existing IR bullet tracking and acoustic multisource localization COTS sensor technologies for the FightSight methodology. The remainder of this paper is organized as follows: Section 2 describes the live-fire experiments conducted to simulate the perspective of a UAV over an urban environment; Section 3 provides a description of the sensor systems (hardware and algorithms) evaluated, Section 4 presents preliminary results of the live-fire data collect, and Section 5 discusses requirements to extend the capability to operational UAV platforms. A summary is provided in Section 6.

2. EXPERIMENTS

In this section we describe the experiments we designed to evaluate the performance of COTS optical and acoustic sensor technologies (see Section 3) for detecting and localizing multiple simultaneous shooters from airborne platforms over urban environments. An illustrative example of the desired sensor-shooter configuration is shown in Figure 2. Operational parameters of interest included representative sensor view angles (i.e., UAV plan view), shooter/trajectory complexity (multiple sources, crossing/overlapping shots, multiple simultaneous airborne bullets/projectiles, varying weapons, subsonic/supersonic), representative acoustic and optical clutter, and tactically significant range (400m). Motion effects were evaluated through simulation and are discussed in Section 5.

The operational concept for FightSight involves the use of tactical UAV platforms at low altitudes using near down-looking conditions to maximize line-of-sight (LOS) to the shooters and bullet trajectories, building faces, and streets. For a UAV altitude H and sensor field-of-view FOV, the IR coverage is ~H*FOV while the acoustic coverage is ~2H (assuming 90 degree FOV). Figure 2 was constructed using a UAV altitude of 400m and an IR sensor FOV of 20 degrees, representative of that used in the experiments. Within the yellow FOV cone in Figure 2 are red dots, blue dots, and red lines representing red shooters, blue shooters, and bullet trajectories, respectively. Critical in this image are the angles between the sensor LOS (shown as a blue vertical line) and the shot trajectories. The critical angle we would like to match in our experiments is denoted by θ. For typical urban operations and scenarios, most shots are within ± 15 degrees of horizontal. The experiments were thus designed around the condition $\theta \sim 90 \pm 30$ degrees.

To accomplish these geometric conditions within the constraints of a limited budget, we rotated the scene perspective 90 degrees (vertical to horizontal) by placing the sensors on the ground and separating the various shooters (red dots) in the vertical direction as shown in Figure 3. We used a military MOUT facility for this purpose. This facility provided

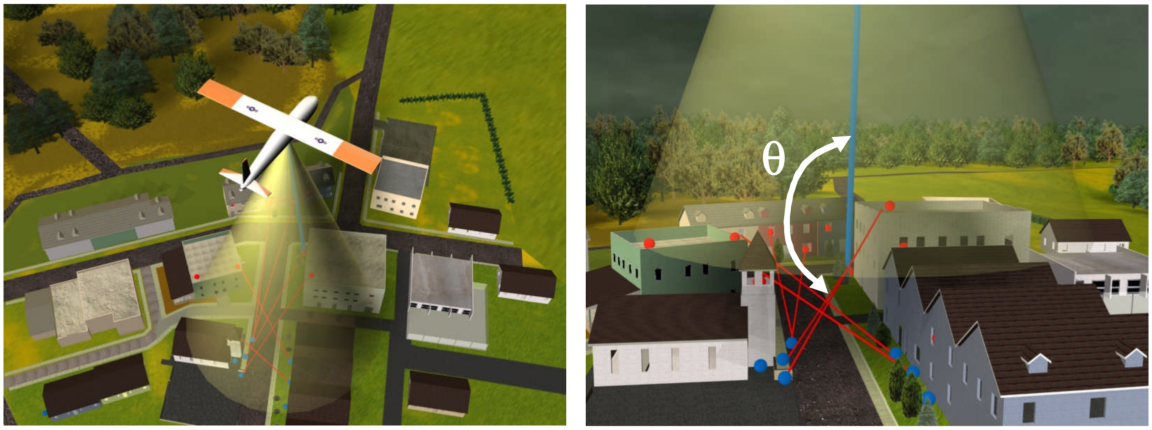
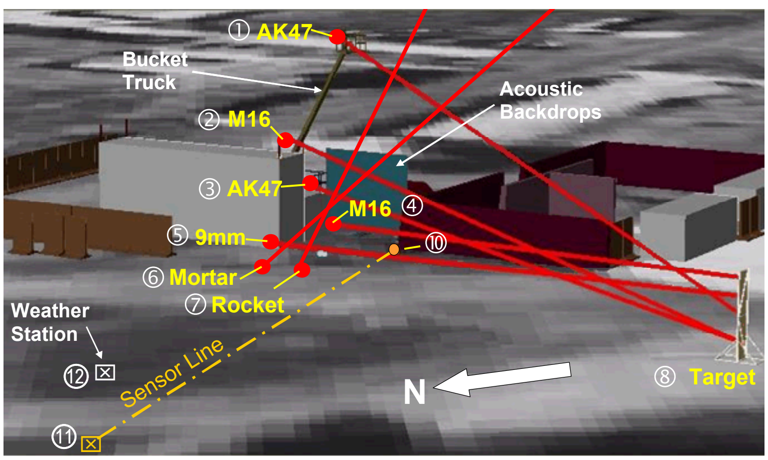
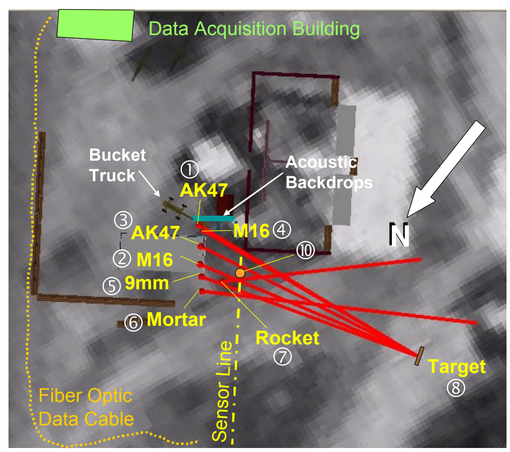
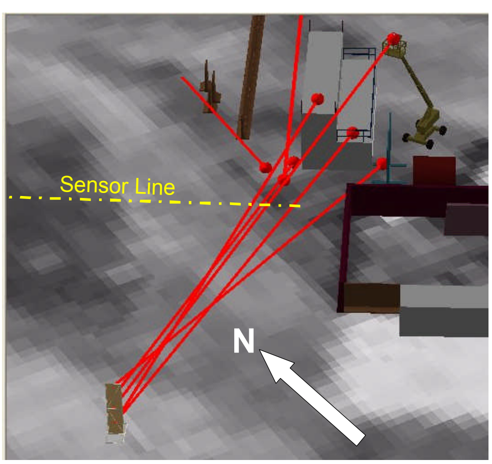


Figure 2. Illustrative FightSight UAV surveillance scenario with relevant sensor-to-shooter/shot-line angle θ.

natural elevation, clutter, and suitable standoff ranges for the sensors. The upper left figure is an approximate 3D terrain model of the test site. It shows the 3D relationships between the nominal shooter positions, shot lines, and sensor positions. The GPS coordinates of the shooter positions as well as the sensor locations and several other key landmarks are indicated in the inset table in Figure 3, relative to the 0 m sensor position (origin). A plan view of the test site and an end view of the gunner deck from behind the target are also shown in Figure 3.







Key	Description	Northing (m)	Easting (m)	Elev (m)
①	AK-47	?	?	11.6
②	M-16	-0.3	6.0	6.5
③	AK-47	0.9	4.3	3.4
④	M-16	2.7	1.6	0.7
⑤	Beretta (9mm)	?	?	1.3
⑥	M224 Mortar	?	?	0.5
⑦	Model Rocket	?	?	0.2
⑧	Target (base)	-21.3	-28.8	-0.5
⑨	Barricade Corner	-4.7	0.6	
⑩	0 m Sensor	0.0	0.0	0.0
	50 m Sensor	29.5	-40.3	-0.9
	100 m Sensor	59.1	-80.6	-1.9
	200 m Sensor	118.2	-161.3	-0.7
⑪	400 m Sensor	282.0	-278.6	-1.4
⑫	Weather Station	27.7	-25.0	2.0

Figure 3. Terrain model of firefight data collect MOUT test site showing relative geometry of shooters and sensors.

The above geometry allowed us to systematically vary the number of shooters (1-7), shooter separation (3-6m in depth, 3-12m laterally), and shooter relative orientation (e.g., distributed vs. "stacked" LOS) to evaluate the sensor capabilities under increasing levels of complexity. We also evaluated sensor-to-shooter range (50, 100, 200, 400m), sensor parameters (IR FOV and integration time, see Table 2, and acoustic array orientation), and the clutter environment. We examined the following clutter environment variables: acoustic reflective surfaces (specular reflecting steel and covered blast shield, hard reflective concrete barriers, and proximity to hard reflective ground), source blockage (e.g., shooters hidden from sensor LOS), optical reflective surfaces (freely suspended tin foil strips and tin plates that blew/spun in wind and stationary mirrors), thermal scintillation lines (natural and artificial edges in scene), and sun angles with respect to sensors.

Supersonic and subsonic weapons including small arms, mortars and rockets were used for the data collect. Four supersonic weapons were used including two M16s (semi-auto 3-round bursts, 5.56 x 45 mm NATO, FMJ) and two AK47s (full-auto, 7.62 x 39 mm, FMJ). The subsonic weapons included a single shot 9mm Berretta (pistol), a 60mm mortar M224 with an M720 inert cartridge and 2 charges, and model rockets to simulate self propelled munitions (e.g., RPGs). The rockets used were small hobby rockets including the Estes Gnome (26.0cm x 13.8mm diameter, 12.0 g) and the Estes Firehawk (28.4 cm x 18.7 mm diameter, 18.4 g) powered by Estes 1/2A3-2T and A3-4T rocket engines. Measured and estimated projectile velocity and sound pressure level data for each weapon are provided in Table 2.

Table 1. Weapon projectile velocity and muzzle blast sound pressure level data for field tests.
All quantities measured via calibrated devices except for those in parenthesis.

	Mean (m/s)	**Min (m/s)**	**Max (m/s)**	**Diff (m/s)**	**Std Dev (m/s)**	**SPL (at 100m)**
9mm	300.6	296.9	305.6	8.8	3.1	116 dB
AK47	714.1	702.5	724.8	22.3	6.6	122 dB
M16	958	952.6	963.6	11	3.8	123 dB
Mortar	(200)	--	--	--	--	128 dB
Rocket	(25)	--	--	--	--	*(est)*

We performed live-fire data collects at 50, 100, 200, and 400m sensor standoffs. The 50 and 100m data were used primarily for calibration and system evaluation. The primary data collect was performed at a sensor range of 200m. A reduced set of runs was made at the 400m range under the most demanding set of clutter conditions. For the majority of the 200m and 400m data, all 7 weapons were fired simultaneously from the positions shown in Figure 3. Each small arm was loaded with 15 rounds. The mortar and rocket were loaded with single rounds. The firing sequence consisted of a single shot fired in rapid succession by each of the 5 small arms (typically 2 second duration) to calibrate the scene, followed by rapid discharge of the small arms' magazines and firing of the mortar and rocket. AK-47's were fully automatic and generally discharged within 1.5 seconds. The M-16's only shot 3 round bursts which in rapid succession amounted to about a 3 second duration. The mortar was fired and the rocket was launched generally within the first 3-4 seconds. The single shot 9mm usually took about 3-5 seconds to unload. All totaled, 77 rounds were fired within a period of 5-7 seconds for each data run with a peak firefight intensity of ~30 rounds/sec. This rate is in excess of an average peak firefight intensity of 18 rounds/sec estimated for typical urban CONOPS from examination of urban training data. Data acquisition was initiated approximately 2 seconds before the first shot was fired and continued for 15 seconds.

We conducted experiments from the late morning (~1000) to the late afternoon (~1600) covering a wide range of sun positions relative to the IR sensor FOV. Temperature, wind speed/direction, humidity, and pressure were monitored and digitally recorded throughout the entire test using a Davis Weather Monitor II weather station. The weather station was located midway between the shooters and sensors, as indicated by position 12 in Figure 3, and approximately 2m above the ground. Average temperature for the tests varied from 75 F at 1000 to 85 F at 1600. Average wind speed varied from 5 to 15 mph throughout most of the testing. Wind direction varied.

A stealth micro-UAV with EO/IR cameras (TACMAV [8]) and micro-acoustic array were also evaluated as part of this study. This data has yet to be evaluated and will not be presented here. Although the target UAV platform for initial deployment is small UAV such as the Shadow (see Section 5), micro-UAVs offer considerable tactical advantages in many situations and are being explored accordingly.

3. SENSOR SYSTEMS

The FightSight concept is predicated upon the fusion of IR and acoustic sensory inputs to exploit the most significant gunfire observables and provide the most complete 3D picture of the firefight at any time-slice of the evolving battle. Two state-of-the-art gunfire detection systems were chosen for this purpose and extended to meet the large shot volume/intensity and clutter requirements of the FightSight CONOPS. The two systems used were the Lawrence Livermore National Laboratory (LLNL) IR bullet tracking system (formerly LifeGuard [9]) and Planning Systems, Inc. (PSI) acoustic gunfire detection and localization technologies (SECURES [10]). The IR and acoustic sensor systems were mounted on a moveable test platform (HMWWV) as shown in Figure 4 with the back of the HMWWV aimed at the center of the firefight zone. This enabled easy relocation of the sensors to different standoff distances. Details of each sensor system as well as data acquisition and synchronization are described below.

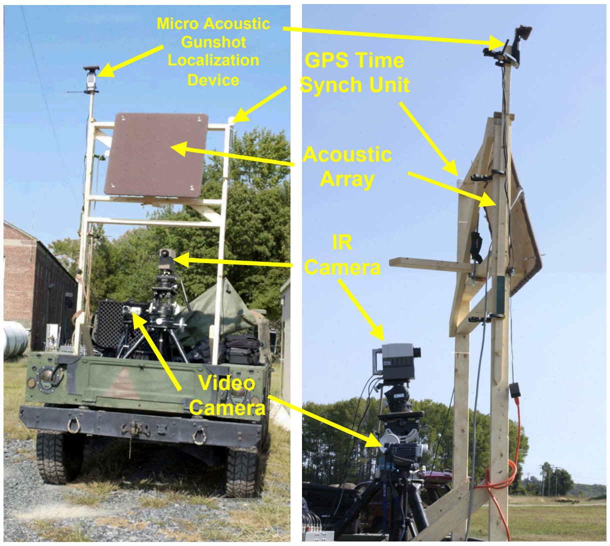


Figure 4. Firefight data collect sensors. [Photo by authors]

3.1. IR bullet tracking

The LLNL IR bullet tracking system LifeGuard [9] was adapted for these experiments. This system uses a midwave-IR (MWIR) camera to detect and track the thermal signature of bullets, mortars, RPG, and artillery shells in flight. Unlike pure muzzle flash based systems, the LLNL system locates the source of gunfire when the muzzle flash is not within the LOS of the sensor by extrapolating observed bullet tracks back to the shooter position. If the muzzle flash is observable, the system uses it in the source localization procedure. Furthermore, the bullet tracking system provides valuable data on the shot direction. The tracking data also provides critical weapon classification data (e.g., bullet speed, projectile thermal profile/dynamics) for the 4D FightSight fusion engine (see Section 4.3).

The IR sensor system evaluated is composed of the FLIR Systems Phoenix midwave IR camera and the FLIR Systems Digital Transfer System (DTS) electronics package shown in Figure 5. Detailed sensor specifications can be found at http://www.indigosystems.com/products/core_phoenix.html. The IR camera resolution was 320 x 256 pixels. The camera lenses evaluated included 13, 25, 50, and 100 mm focal lengths all with a 2.3 f/#. The lens FOV, coverage, and image plane resolution (pixel size) at the four ranges tested are shown in Table 2. A frame rate of 350Hz was used for these measurements. Frame rates as low as 100Hz can be employed with improved sensors and processing algorithms (see Section 5).

Table 2. IR sensor parameters for firefight data collect.

Range (m)	Lens (mm)	FOV_x (deg)	FOV_y (deg)	X (m)	Y (m)	Pixel Size (m)
50	**13**	**40.5**	**32.9**	**36.9**	**29.5**	**0.12**
	25	21.7	17.5	19.2	15.4	0.06
	50	11.0	8.8	9.6	7.7	0.03
100	13	40.5	32.9	73.8	59.1	0.23
	25	**21.7**	**17.5**	**38.3**	**30.8**	**0.12**
	50	11.0	8.8	19.3	15.4	0.06
200	13	40.5	32.9	147.6	118.1	0.46
	25	21.7	17.5	76.7	61.6	0.24
	50	**11.0**	**8.8**	**38.5**	**30.8**	0.12
400	13	40.5	32.9	295.1	236.2	0.92
	25	21.7	17.5	153.3	123.1	0.48
	50	11.0	8.8	77.0	61.6	0.24
	100	**5.5**	**4.4**	**38.4**	**30.7**	**0.12**

Figure 5. FLIR Phoenix IR sensor system. . [Photo by authors]

The MWIR image processing algorithms used (1) frame-differencing (change-detection) techniques coupled with spatio-temporal filtering to generate image streaks from projectiles, (2) threshold and feature extraction to identify streak-like objects, (3) feature filtering to remove streaks not meeting bullet trajectory criteria, and (4) a 4-state Kalman filter to compute the optimal trajectory for each correlated set of image streaks. Integration times of 1.0 and 2.8 ms were evaluated. More algorithm details are provided in Section 4.1.

3.2. Acoustic multi-source localization

Planning Systems, Inc. (PSI) developed an acoustic sensing system for the experiment that leveraged their prior work in this area [10]. The basic components of the acoustic sensor system is shown in Figure 6. A spiral array was designed and fabricated for these measurements consisting of 32 Knowles WP-3502 waterproof microphones distributed over a 32 in x 32 in area. The spiral design provides good beamforming resolution over the frequency range (100-3500 Hz) and standoff distances of the expected acoustic sources. The microphones (Figure 6a) were built into a single printed circuit board (PCB) base and wrapped with an open-celled 40 ppi foam to act as a wind screen, as shown in Figure 6(b). The PCB provides for positive and static registration of the microphone locations as well as integrated wiring for the array connections. The array design incorporates a non-standard biasing circuit that allows the small lightweight electret microphones to handle much higher sound pressure levels (SPLs) than they would normally be capable of independently. The acoustic array was attached to a breakout box that provided power to the bias circuitry and access to the microphone signals. A Dewetron 32-channel data acquisition (DAQ) system (Figure 6c) was connected to the breakout box. The DAQ system provided simultaneously sampling of all 32 channels at a sampling rate of 10 kHz.

The detection algorithm used in Phase 1 was an impulse detector with background tracker. This detector is based on the patented SECURES [10] gunshot detection algorithm. For this algorithm, candidate events must exceed absolute level and relative level thresholds as well as meet rise-time and pulse-width criteria. Measured shot parameters resulting from the detection process are: time of event, received sound pressure level, pulse width, total power. Time series data from the front-end beamformer was saved in a buffer for later classification analysis in the fusion processing chain. The localization algorithm uses array data saved in the acquired data files to map acoustic intensity as a function of position. The algorithm performs high-resolution adaptive beamforming over a search grid to localize sources. A typical search grid is 41x41 or 1681 localized positions. The coverage areas used in Phase 1 varied from 200x200 meters down to 20x20 meters with resolutions down to 0.5 meters. The algorithms do not rely upon bullet shock wave data to perform localization since UAV sensors will be out of the range of this disturbance. No front-end beamforming was performed to reduce platform or flow noise since Phase1 testing was performed under static conditions (see Section 5).

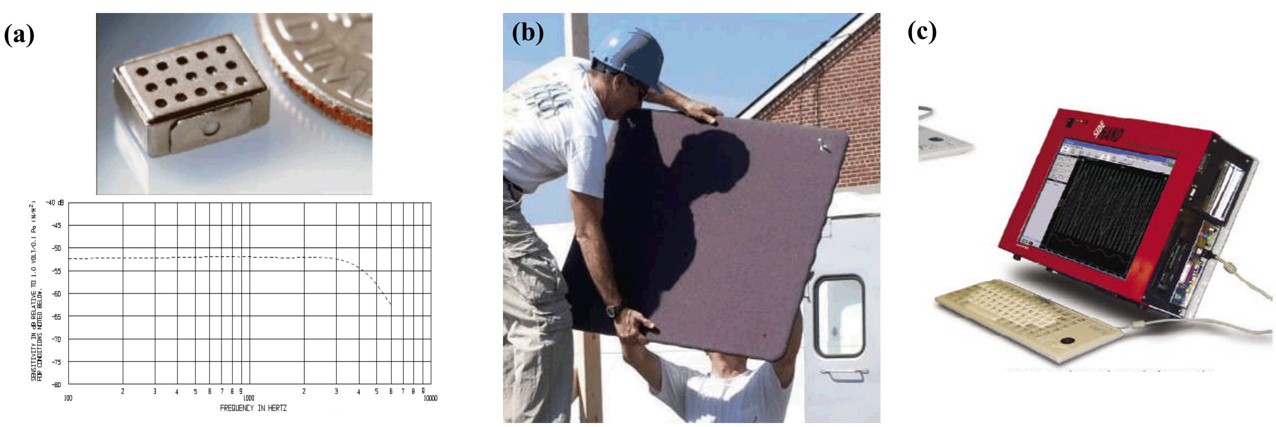


Figure 6. PSI acoustic sensing system. (a) Knowles WP-3502 electret microphones and nominal frequency response [courtesy Knowles Electronics], (b) array being installed on the sensor frame mounted in back of HMWWV [photo taken by authors], (c) Dewetron 32-channel data acquisition system [courtesy Dewetron].

3.3. Data acquisition and hardware synchronization

A block diagram of the IR and acoustic sensors, GPS timing, and data acquisition systems is shown in Figure 7. The system consists of essentially two components: remotely located sensor systems with data acquisition sub systems (back of HMWWV, see Figure 4) and sensor control and data storage/processing computers located in an adjacent building behind the line of fire. The sensor systems in the HMWWV were powered by 120VAC extension chords from adjacent buildings. Data was transmitted from the sensor systems to the data processing building using a 2 channel optical fiber link (500m cable). Windows laptops running XP Remote Desktop served as a remote control and viewing station for the IR and acoustic DAQ systems, as well as data storage and a processing host for the data in Matlab. Time synchronization was provided by a GPS-605 unit (see http://www.symmttm.com/pdf/Gps/ds_gps_605.pdf for details). This unit receives UTC time from the GPS system and encodes the time into IRIG B serial time format. That input is applied to both the DAS module attached to the IR camera (resulting in a timestamp on every image) and the COM port on the acoustic DAQ system (whose software automatically time-tags the acquired data).

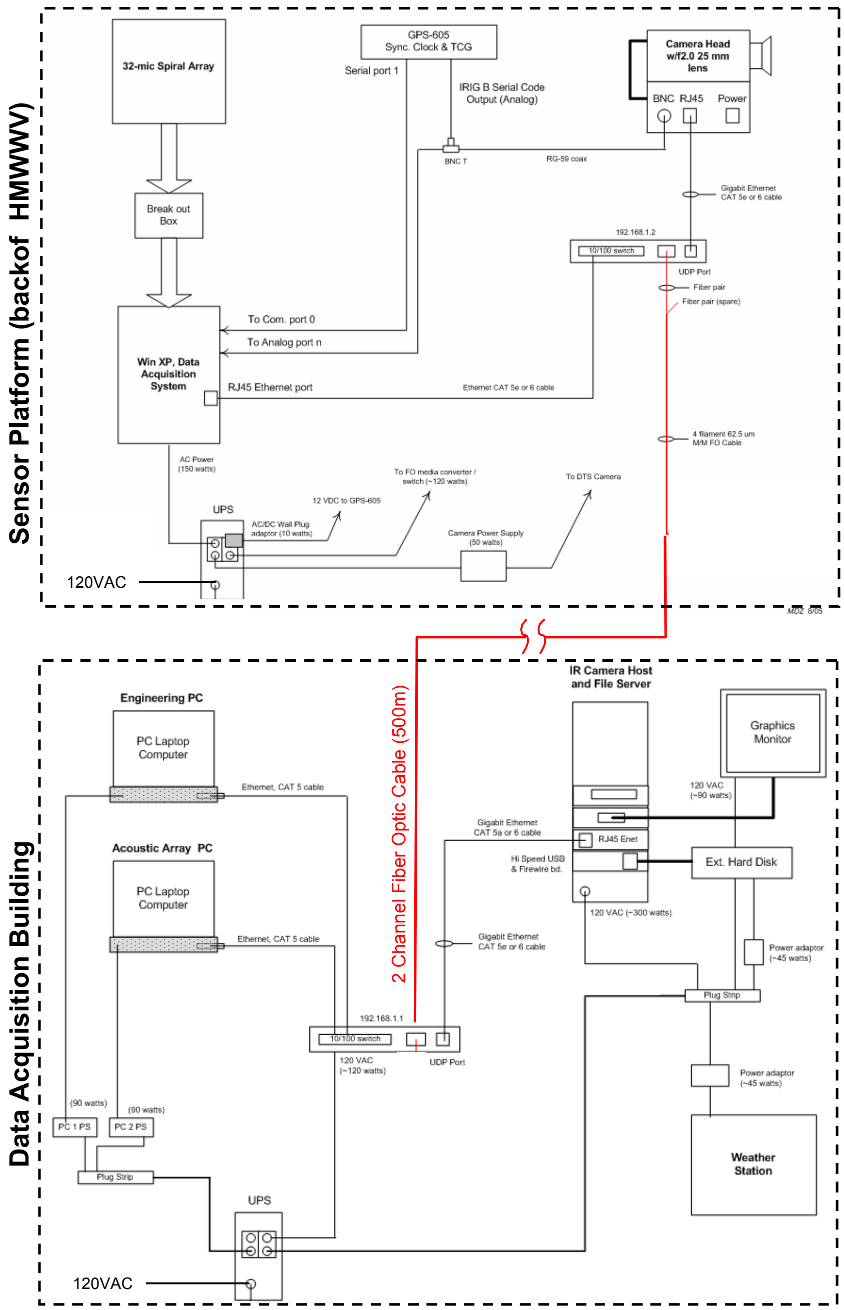


Figure 7. Block diagram of the IR and acoustic sensor, GPS timing, and data acquisition systems.

4. PRELIMINARY RESULTS

In this section, we present results from the 200m and 400m ranges that demonstrate convincingly the power of these sensor systems for detecting and localizing multiple simultaneous shooters (supersonic and subsonic weapons) from airborne platforms over cluttered urban environments. This section is divided into three sections: IR bullet tracking, Acoustic multisource localization, and Fusion processing.

4.1. IR bullet tracking

A set of results typical of what we were able to achieve at all ranges tested is shown in Figure 8. This particular data set was taken with the sensors positioned at the 200m range point with a 50mm lens and 2.8ms integration time. The sun was behind the sensor and full clutter conditions were present.

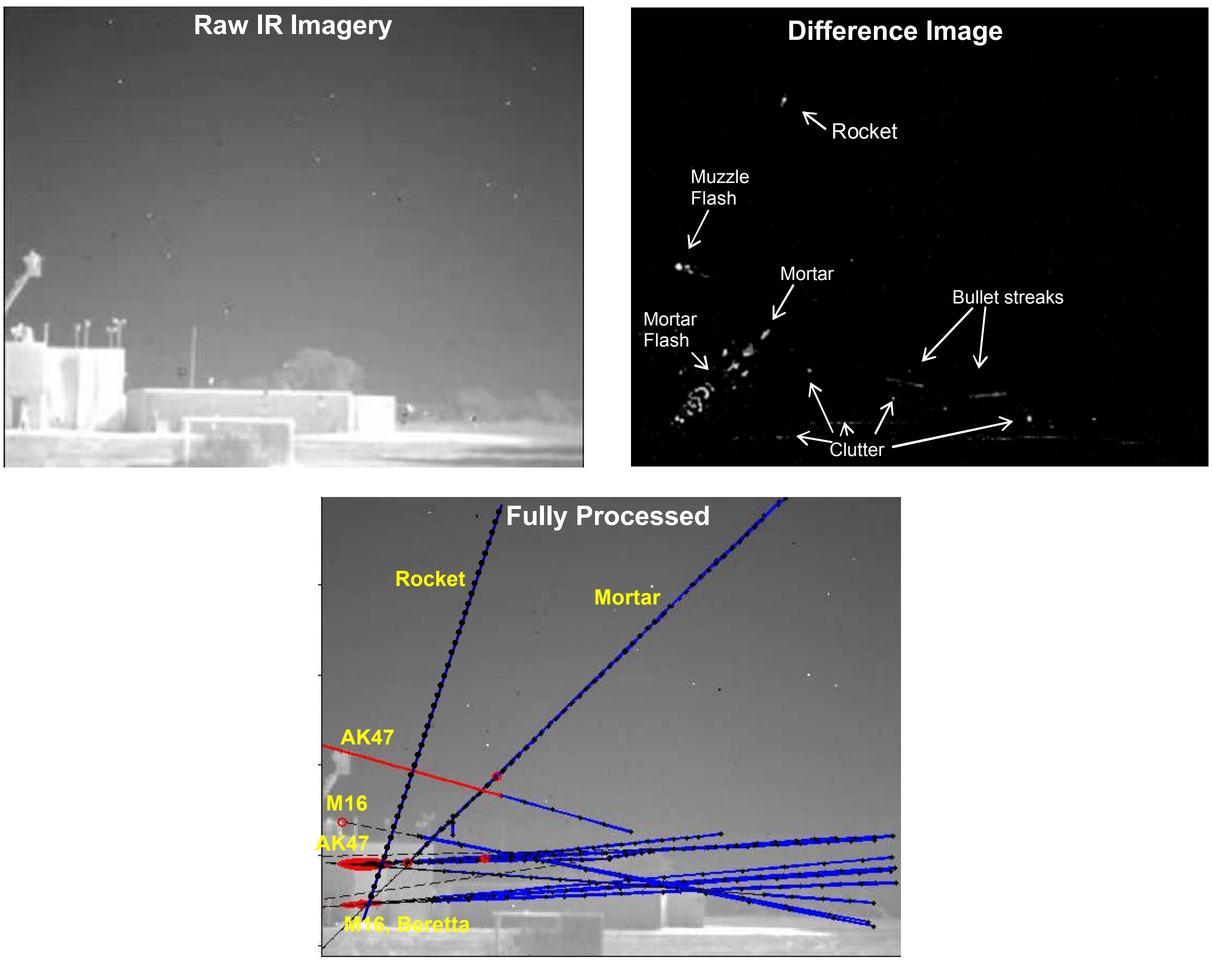


Figure 8. IR bullet tracking results for live-fire test at 200m range with full optical clutter: 77 rounds in 5 seconds, Pd=0.91, FAR=0.

The upper left image in Figure 8 is taken from the raw IR data feed from the camera. The upper right image is a result of the frame differencing procedure used in the initial stages of processing. Temporal and spatial filters are employed to reduce the image noise. The image shows streak signatures produced from the bullets, a muzzle flash produced from one of the AK-47s within the camera LOS, a glare from the rocket plume, and a mortar flash and corresponding mortar in flight. Also visible are several examples of clutter in the image. These are associated with the moving reflective surfaces introduced into the scene (tin plates suspended from fishing line that were spinning in the relatively brisk breeze) as well as line clutter produced by scintillation off of edges in the scene. The bottom image is the result produced by projectile detection and tracking algorithms. Here, various feature extraction methods are employed to remove objects not meeting specific projectile criteria. The remaining feature set is then fed into a 4-state Kalman filter to compute the optimal trajectory for each correlated set of objects. The filter is updated with subsequent image frames to compute the full trajectory.

The fully processed image in Figure 8 shows the resulting filtered tracks (in blue) and shooter position error ellipses (in red). As shown, the IR bullet tracking system was able to detect and track large volumes of 'simultaneous' sub/super-sonic bullets, mortars, and rockets (75 rounds + mortar + rocket over 5 sec interval). Furthermore, the system was not affected by optical clutter (natural, artificial, sun angles) and produced no false alarms for all the data sets interrogated. The bullet tracks are determined with subpixel accuracy due to the Kalman-Filtering operation across the entire bullet trajectory. The shooter location error ellipses are generally very narrow in lateral direction (high certainty of shooter position in this direction) and extended along the shot axis. Uncertainty along the shot axis decreases with the number of shots fired (multiple trajectories from one gun point converge on more precise location in plane). Uncertainty in this direction also decreases by using ballistics information as an input to the Kalman filter (i.e., bullet caliber and muzzle velocity). Muzzle flash data, not used in this result, can reduce the error ellipses considerably. In Figure 8, the error ellipse for the AK-47 is typically much larger than the M-16 since it was more difficult to detect these shots due to smaller projectile velocity and caliber.

Data taken at 400m using a 100mm lens (which maintained the same coverage area as shown in Figure 8, see Table 2) produced identical results to those shown above, indicating that atmospheric absorption was largely negligible over this range. We estimate that in the band of the mid-wave sensor we are using, atmospheric absorption increases from about 2% to 4% going from 200 m to 400 m (percentage of photons emanating from object that are absorbed by atmosphere). Increasing the coverage and hence ground pixel size (by decreasing lens size to say 50mm) caused a decrease in the signal level (and hence detection probability) due to the algorithms chosen for the analysis. Enhanced algorithms (e.g., frame integration, spatial matched filtering, enhanced feature recognition, dynamic programming) will allow us to increase the allowable ground pixel size for a given noise level and thus increase coverage (or range) proportionally. Combined with noise reduction techniques and enhanced sensors, a performance (coverage and/or range) increase by a n order of magnitude or better is anticipated.

4.2. Acoustic multi-source localization

A representative set of weapon fire localization results we obtained with the acoustic array is shown in Figure 9. The data is from the same 200m run used in Figure 8. The data is presented with the array localization results superimposed over an IR image taken from the back of the HMWVV with 3D terrain model data completing the image. The array data was aligned to the IR image manually through a least squares procedure using the single "calibration" shots fired by each weapon before the actual firefight ensued. Automated procedures using known orientation of array relative to IR camera and 3D terrain data image registration procedures would be used in an operational setting (see Section 5).

In Figure 9, the two red circles represent the coverage associated with 1° to 3° accuracy at the 200m range. All data falls within the 3 degree accuracy zone. However, if we examine the data more closely, the individual detections can be classified by weapon type based on their various signature attributes and by weapon location based on unique terrain interaction features (see Section 4.3). When this is done, the individual detections can be grouped according to the unique source, as shown by the various color-coded dots in Figure 9. In this case, the array clearly provides a tactically significant precision of ~1° in a very challenging acoustic MOUT environment including a specular reflecting steel blast shield, hard reflective concrete barriers, and proximity to hard reflective ground. At 400m the results were very similar in character, except the precision fell to ~3° due to the decreased signal level resulting from propagation losses and interference with the ground (see SPL plot in Figure 10). Reflections from the ground also appear to bias the shooter location downwards contributing to the lower precision. This issue is an artifact of the experimental test geometry when the array and shooters were close to the ground. This issue will diminish in the more desirable UAV-to-ground surveillance geometry.

Comparing Figures 8 and 9, it is clear that a finite size acoustic array mounted on a UAV is no match for the IR system in terms of shooter localization accuracy. However, one of the greatest strengths of the acoustic system lies with the fact that it provides very wide area coverage (Figure 11) and thus an ability to separate widely dispersed sources of gunfire. This is a key element of the FightSight solution framework and one that provides much needed cueing information for

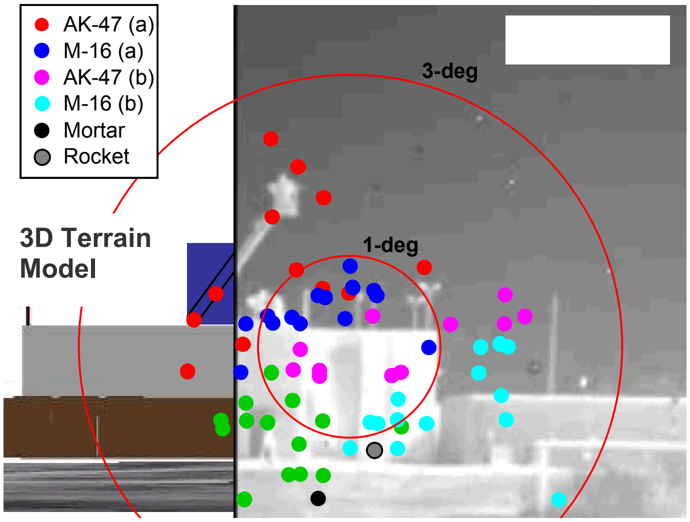


Figure 9. Acoustic firefight multisource localization at 200m range, full acoustic clutter: 77 rounds in 5 seconds, Pd=0.98, FAR=0.02

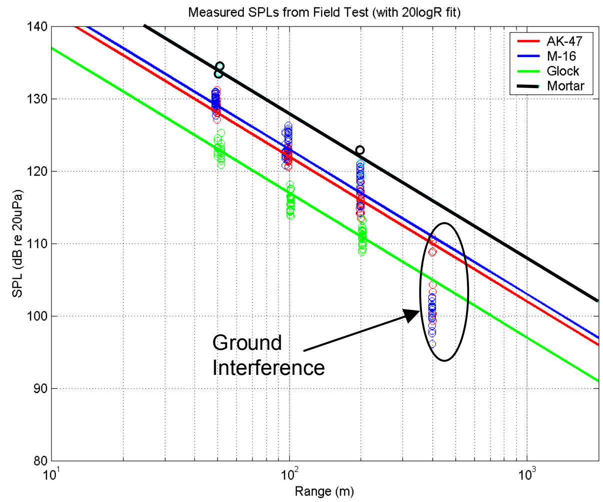


Figure 10. Measured sound pressure levels at ranges tested; lines represent 20logR fit (spherical spreading).

either the IR sensors or the UAV. Simulated results for the array coverage from a UAV at 500m are shown in Figure 11(a). The plot shows the array coverage for a tactically significant 4m resolution (ability to resolve two sources separated by 4m). Complete coverage in the coverage zone can be obtained if one tolerates larger resolutions. An example is shown in Figure 11(b) comparing the IR FOV/coverage relative to the acoustic array for the 200m range data assuming a 10m resolution. While the IR sensor is providing detailed results in a specific region, the acoustic array is localizing sources well outside that area for subsequent IR interrogation. In addition, the acoustic sensor data can resolve ambiguities in the IR data (e.g., co-located weapons, range, completely hidden shots, inclement weather effects) and enhances the shooter localization accuracy by decreasing the IR error ellipses. More is said on the collaborative use of IR and acoustic sensors in Section 4.3.

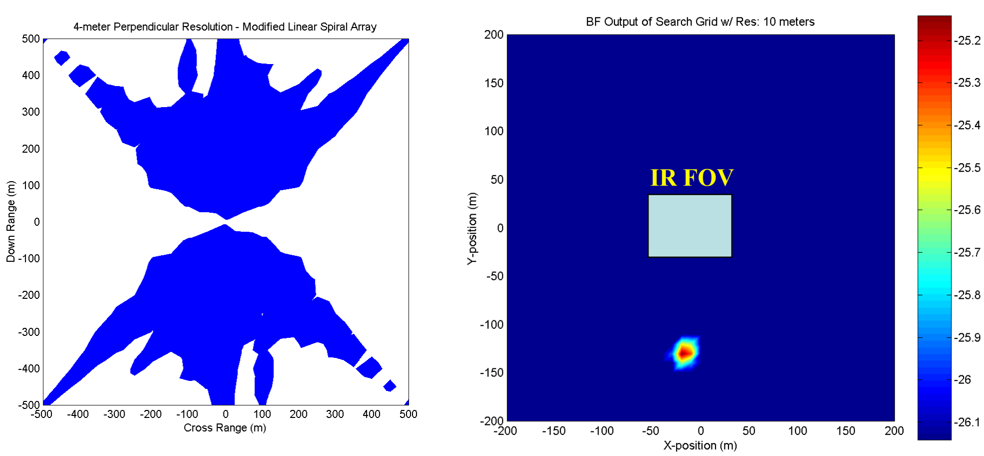


Figure 11. Acoustic array coverage: (a) simulated results for a UAV at 500m with 4m resolution at ground plane (90º FOV, 100 - 3500 Hz); (b) measured results from field test comparing IR and acoustic coverage areas for 200m range.

4.3. Fusion Processing

The results of Sections 4.1 and 4.2 demonstrate convincingly the capability of the LLNL IR bullet tracking and PSI multisource acoustic localization sensor systems to detect and localize high-volume simultaneous gun-fire from airborne platforms over cluttered urban environments. The ultimate power of this information, however, is derived from the FightSight 4D fusion methodology which synthesizes dynamic IR imagery, acoustic data, scene context, weapon signatures, blue force tracking data, and prior time-history data to characterize and map the flow of urban firing events. The end-to-end fusion process is composed of 5 primary components:

1. Registration: UAV firing event localization data is aligned with real world coordinates.
2. 4D Localization: Combines IR and acoustic event observables, 3D scene context information, ballistics data, and prior time step data to characterize individual firing events (3D position and shot direction) with high accuracy and low false alarms.
3. Weapon Classification: Determines the weapon type associated with each firing event using joint acoustic-IR feature matching, blue force tracking data, and inferencing based on prior weapon distributions.
4. Probabilistic Reasoning: The 4D fused localization and classification elements and the subsequent force tracking procedures are subjected to uncertainties due to sensor resolution and bias, signal noise, terrain data/models, environmental conditions, and enemy CONOPS. The event and dynamic flow mapping process will thus be implemented within a dynamic probabilistic network.
5. Force Tracking: Situation Assessment module where firefight distributions and movements are tracked over time and used to assess (and update) probabilities for subsequent enemy motions/actions. This step correlates firing event state-history data with battlefield state-space to track space-time evolution of events ("connect the red dots") and subsequently infers/predicts important trends, tactics, and possible aggregate level behaviors.

Preliminary fusion processing demonstrated several important capabilities. By exploiting unique features of the collective acoustic-IR-terrain data base, we were able to distinguish co-located or "stacked" shooters separated by 5m in the radial direction and localize their positions to <0.5m at a 400m range. For the urban UAV application, this result would correspond to differentiating the presence of multiple shooters firing from different floors within a single building. Fusion of the acoustic and IR localization results was also shown to reduce the error ellipses in the bullet tracks in Figure 8 due to the greater precision of the acoustic system along the projectile direction. Scene reasoning with the 3D terrain data reduces these error ellipses further since the terrain data defines firing location boundaries (shots can't be fired from space). Finally, a preliminary study of the available classification features from the IR bullet tracking, IR muzzle flash, acoustic muzzle blast, and terrain interaction data were cataloged and used to perform robust classification of all shots fired.

5. UAV INTEGRATION AND CONOPS

As part of this exploratory investigation, a detailed system study was completed to establish requirements for deploying a FightSight system in theater. Although the bulk of this study is outside the scope of this paper, key results that relate to the sensor performance are summarized here. Due to the high stability of the proposed UAV gimbal systems combined with the low platform motion (roll/pitch/yaw/speed) relative to the IR camera frame rate, image misalignment is very small and easily corrected. Innovative geospatial alignment procedures were developed using terrain imagery and 3D terrain models that suggest registration accuracies in all 3 coordinate directions equal to that of the available terrain data (e.g., 1m) are achievable. By employing state-of-the-art COTS sensor technologies (e.g., 640x512 versus 320x256 camera used for these tests) and enhanced processing algorithms, coverage area and/or range can be increased by an order of magnitude or better over what was demonstrated here. Even better performance can be expected with next generation sensor technologies. UAV platform noise issues will limit the acoustic surveillance altitude. By employing specialized front end beamforming methods, conformal array technologies, and leveraging specialized flow control technologies, tactically significant flight altitudes that will provide very wide area continuous coverage should be achievable without any active noise control measures (e.g., engine muffler). Processing requirements both on the UAV (i.e., bullet tracking and shooter localization) and at the ground control station (i.e., classification, 4D fusion, force tracking) were evaluated within the context of average and maximum firing rates during a typical battalion-level firefight. Because of the high intermittency of the battle (intense outbursts followed by long quiet periods), data buffering relieves a significant portion of the computational load. UAV processing requirements (IR and acoustic) are ~24 GFLOPS on average which can be achieved with COTS FPGAs in a compact (UAV compatible) package. Required bandwidth to transmit the firefight observables to the GCS is ~500 kbps which is achievable with today's wireless technologies. We estimate that FightSight can provide accurate and complete computer interpretable reports of enemy activities within less than 1 minute. Such a capability will revolutionize the urban battle command and control structure. A hardware packaging study was also completed considering all payload/weight/power requirements for the Shadow UAV and a preliminary system design was developed. The combined results of the high-intensity firefight data collect and systems study illustrate that the FightSight concept is ready for full system development and integration.

6. SUMMARY

FightSight is an exploratory project to develop an autonomous UAV-based sensor exploitation and decision support capability for mapping large-scale (e.g., battalion level) urban firefights. The FightSight system concept is unique in that it is designed to accommodate 100's of weapons distributed over several square kilometers, 10's to even 100's of shots per second during intense periods, 1000's of bullets fired during a minute of combat, and battles lasting upwards of several hours. Existing gunfire detection and localization systems designed for single shots at an instant in time cannot operate at this immense scale. FightSight makes battalion-level urban firefight detection and tracking possible through a 4D fusion methodology that synthesizes IR and acoustic firing event observables (bullet tracks, muzzle flash, muzzle blast) with terrain/scene context, weapon signatures, and prior time-history data within the context of a dynamic probabilistic network to characterize and map the flow of urban firing events.

This paper describes experimental results from a live-fire data collect designed to demonstrate the feasibility and effectiveness of existing IR and acoustic COTS sensor systems for the FightSight methodology. Experiments were conducted at a military MOUT facility with ground based IR and acoustic sensor systems and a geometric configuration that simulated the perspective of an airborne platform over a cluttered urban environment. The results demonstrate convincingly the power of these sensor systems to detect and localize multiple simultaneous supersonic and subsonic weapons. One key result is that the evaluated IR bullet tracking system is not affected by optical clutter and easily determines accurate firing locations and firing directions of large volumes of 'simultaneous' sub/supersonic bullet, mortar, and rocket fire (77 rounds in 5 sec) with no false alarms at 400m range using COTS MWIR sensors. Likewise, the evaluated acoustic sensor system can reliably detect, separate, and localize multiple co-located and widely dispersed weapons during a high-intensity firefight (77 rounds in 5 sec) with a tactically significant precision of 1-3 degrees using a single UAV-compatible compact array at 400m range. This was done with a high probability of detection (>95%) and low false alarm rates (<5%), while rejecting reflections and reverberation produced from a high acoustic clutter environment. The results also established the merit of several key elements of the FightSight acoustic-IR-terrain fusion framework including the ability to distinguish "stacked" shooters (shooter densities), range to <0.5 m accuracy at 400m, sensor event association and scene reasoning to reduce in-plane shooter localization uncertainties, and robust weapon classification. A detailed system study was also completed to establish requirements for deploying a FightSight system in theater on a Shadow UAV. This study demonstrates the readiness of the developed concept for full system development and integration.

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