Real-Time Gunshot Localization Using Acoustics

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Introduction

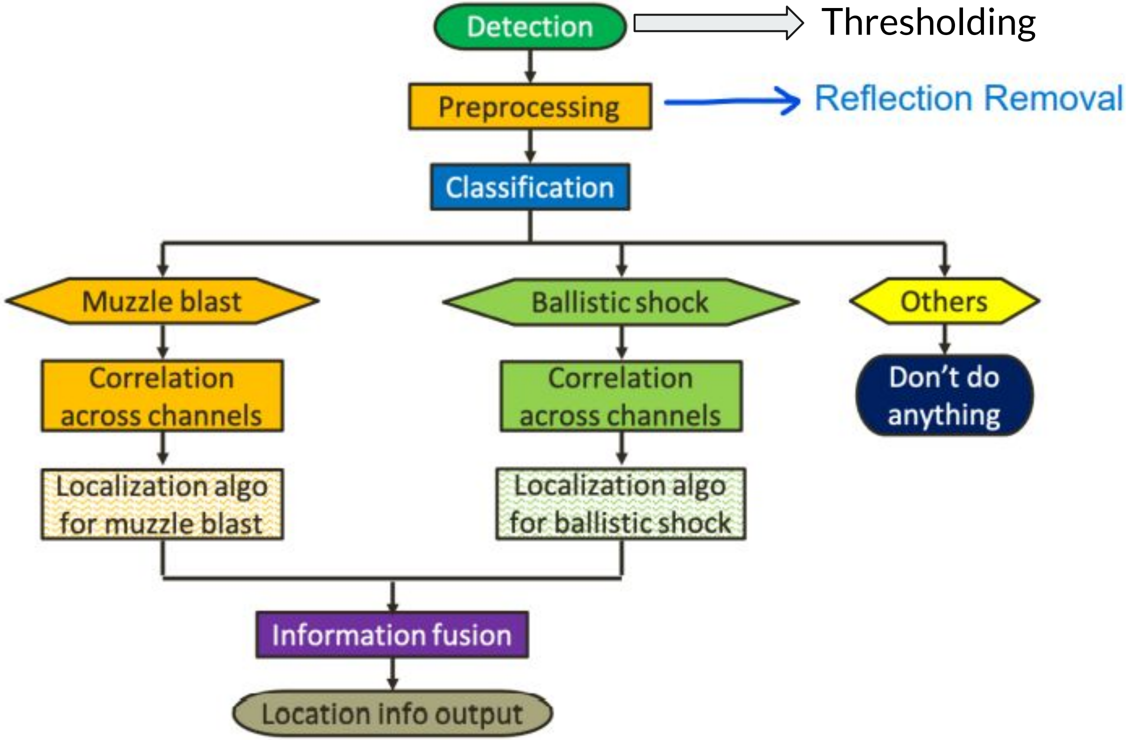
Signatures left by a Gunfire

- ✓ Sound of charge explosion in gun muzzle,
- Light of the charge explosion,
- ✓ Sound of the bullet travelling, which is only perceptible if the bullet's speed is supersonic,
- 'Sight' of the bullet travelling,
- Sound of the bullet hitting the target
- Smell of the gunfire

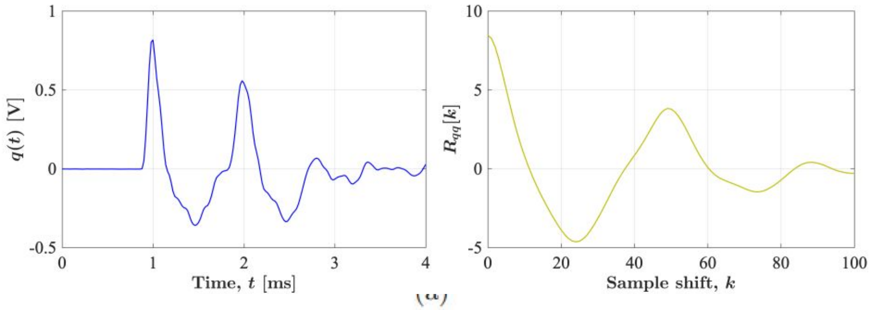
Classification of acoustic targeting devices based on mobility:

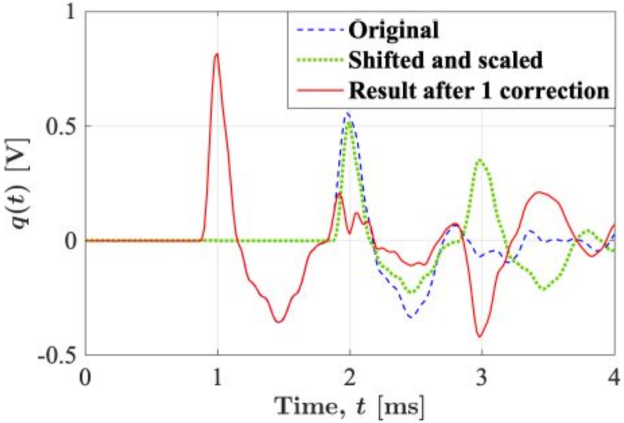
- ✓ Static Devices (city, forward camps in forests)
- Vehicle-mounted
- Helmet mounted or shoulder worn

Gunshot Localization Algorithm Flow



Reflection Minimization





Find autocorrelation

$$R_{qr}[k] := \sum_{i=\max(0,-k)}^{N-1-\min(0,-k)} q[i+k]r[i].$$

Find

γ = Ratio of the second peak of Rqq to the peak at zero shift

α = attenuation ratio

$$\alpha = 0.5(1 - \sqrt{1 - 4\gamma^2})/\gamma.$$

Delay, scale and subtract from the original signal = 1 correction

M corrections:

$$\hat{q}[i] = \sum_{j=0}^{M} (-\alpha)^j q[i - jk^*].$$

Gunshot Event Categorization

Muzzle Blast signature:

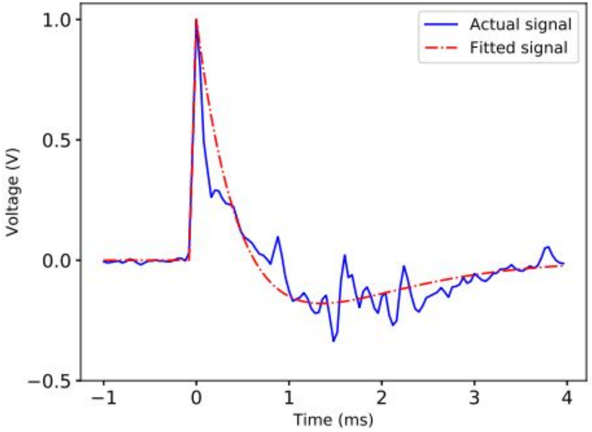
$$f_{\text{Friedlander}}(t) = \begin{cases} 0, & t \le t_0, \\ A\,(t - t_0)/t_r\,, & t_0 < t \le t_0 + t_r, \\ A\,[1 - (t - t_0 - t_r)/t_d]\,\mathrm{e}^{-(t-t_0-t_r)/t_d}, & t > t_0 + t_r. \end{cases}$$

A = peak amplitude

t_0 = TOA

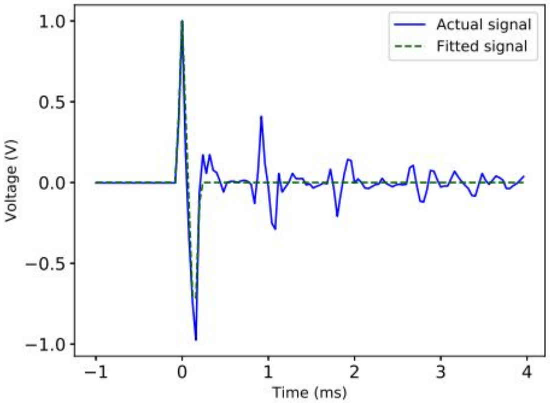
t_r = Rise Time (Can be neglected)

t_d = Decay time



'N' wave signature for ballistic shocks:

$$f_{\text{N-wave}}(t) = \begin{cases} 0, & t \le T_0, \\ B\,(t - T_0)/T_r\,, & T_0 < t \le T_0 + T_r, \\ B\,[1 - 2(t - T_0 - T_r)/T_d]\,, & T_0 + T_r < t < T_0 + T_r + T_d, \\ B\,[(t - T_0 - T_r - T_d)/T_r - 1]\,, & T_0 + T_r + T_d < t < T_0 + 2T_r + T_d, \\ 0, & t > T_0 + 2T_r + T_d. \end{cases}$$



Fit both signatures.

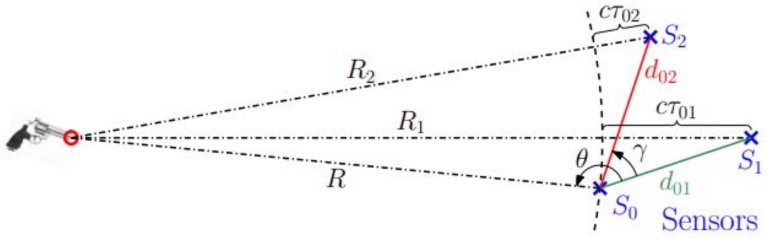
Determine goodness of fitting (chi square measure)

Characterise the event into muzzle blast, ballistic shock or none

Algorithms for localizing gun-shooter from muzzle blast

Wavefront Curvature Method

- Planar localization technique assuming circular wavefront expansion
- Min sensors required = 3



$$R = \frac{d_{01}}{2}\frac{1-\eta_{01}^2}{\cos\theta+\eta_{01}}, \quad R = \frac{d_{02}}{2}\frac{1-\eta_{02}^2}{\cos(\theta-\gamma)+\eta_{02}}.$$

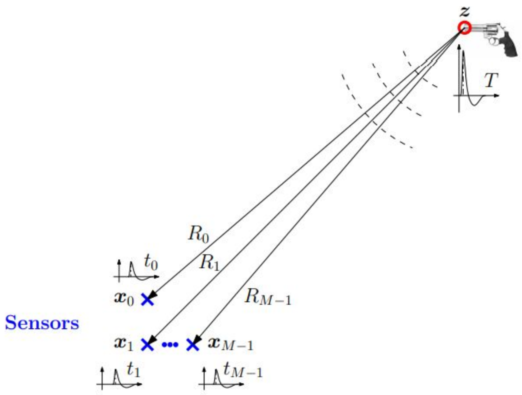
- 2 mathematically possible solutions
  Near one to be ignored
- Error:

$$\epsilon_{wc} = |R_2 - R_1 - c\tau_{12}|.$$

$$\theta = \tan^{-1}\left(\frac{\sin\gamma}{\cos\gamma-\delta}\right) \pm \cos^{-1}\left(\frac{\delta\eta_{01}-\eta_{02}}{\sqrt{1+\delta^2-2\delta\cos\gamma}}\right), \qquad \delta := \frac{d_{02}(1-\eta_{02}^2)}{d_{01}(1-\eta_{01}^2)}.$$

Algorithms for localizing gun-shooter from muzzle blast

Non-linear least squares method



$$ct_i = \mathscr{D}(\boldsymbol{x}_i, \boldsymbol{z}) + cT, \qquad i \in \{0, 1, \ldots, M-1\}.$$

C: ambient speed of sound

T: Instant of gunfire at the position z

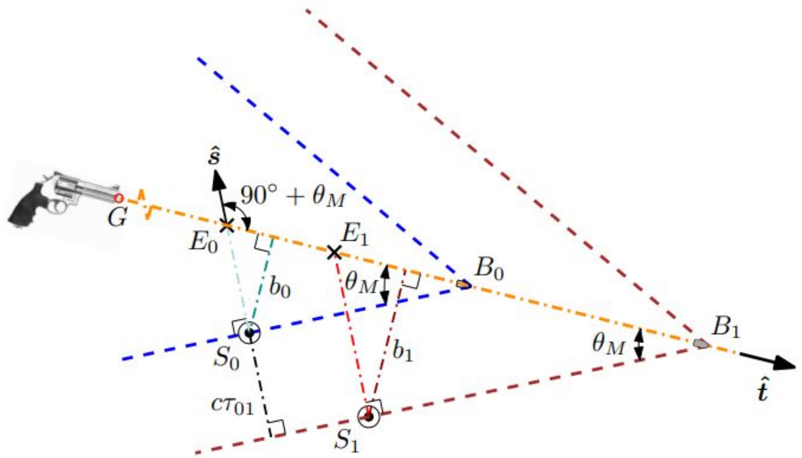
$$\boldsymbol{z}^{(k+1)} = \boldsymbol{z}^{(k)} - \left(J\left(\boldsymbol{z}^{(k)}\right)^{\mathrm{T}} J\left(\boldsymbol{z}^{(k)}\right)\right)^{-1} J\left(\boldsymbol{z}^{(k)}\right)^{\mathrm{T}} \boldsymbol{r}\left(\boldsymbol{z}^{(k)}\right)$$

Initial guess solution z(0) from WCM.

$$J_{ij}(\boldsymbol{z}) := \frac{\partial r_i}{\partial z_j} = \frac{x_{ij} - z_j}{\mathscr{D}(\boldsymbol{x}_i, \boldsymbol{z})} - \frac{x_{0j} - z_j}{\mathscr{D}(\boldsymbol{x}_0, \boldsymbol{z})}.$$

*Other algorithms like Bancroft's method and Localization using multiple direction-of-arrival vectors briefly discussed in the paper

Algorithms for localizing gun-shooter from shock wave



Mach Number:

$M = V_b / c > 1$

Mach Angle:

$\theta_M = \sin^{-1}(1/M)$

Whitham's formula:

$$T_d = \frac{1.82 M b^{1/4} d}{c(M^2 - 1)^{3/8} \ell^{1/4}}.$$

d = caliber (diameter) of bullet

l = length (diameter) of bullet

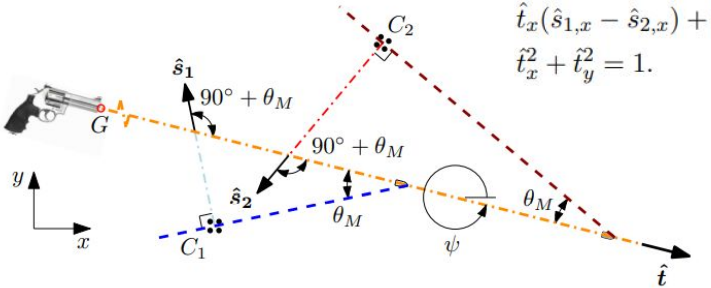
b = miss distance

Estimation of bullet trajectory direction

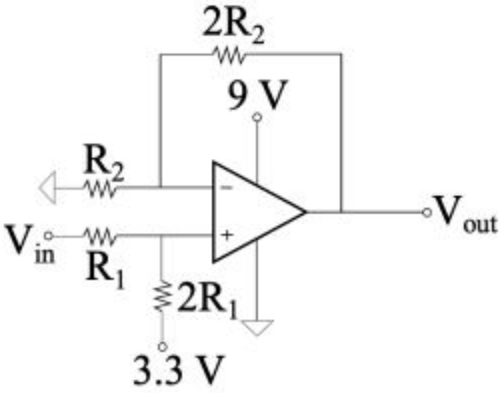
1. Direction of bullet trajectory (needs to be solved for approx bearing angle)
2. Finding a point on the trajectory
3. Locating the shooter

- Need **at least two** spatially-separated clusters of sensors for solving any and all of the above localization problems
- Linearity of the wavefront is a fact instead of an assumption for the ballistic shock
  => No requirement of the sensor array to be far from the bullet trajectory
- Sensors on either side of the trajectory

$$\hat{t} \cdot \hat{s}_i = \cos(90° + \theta_M) = -\sin\theta_M,$$
$$\hat{t}_x(\hat{s}_{1,x} - \hat{s}_{2,x}) + \hat{t}_y(\hat{s}_{1,y} - \hat{s}_{2,y}) = 0,$$
$$\hat{t}_x^2 + \hat{t}_y^2 = 1.$$



Hardware and Software for Acoustic Gunshot Localization

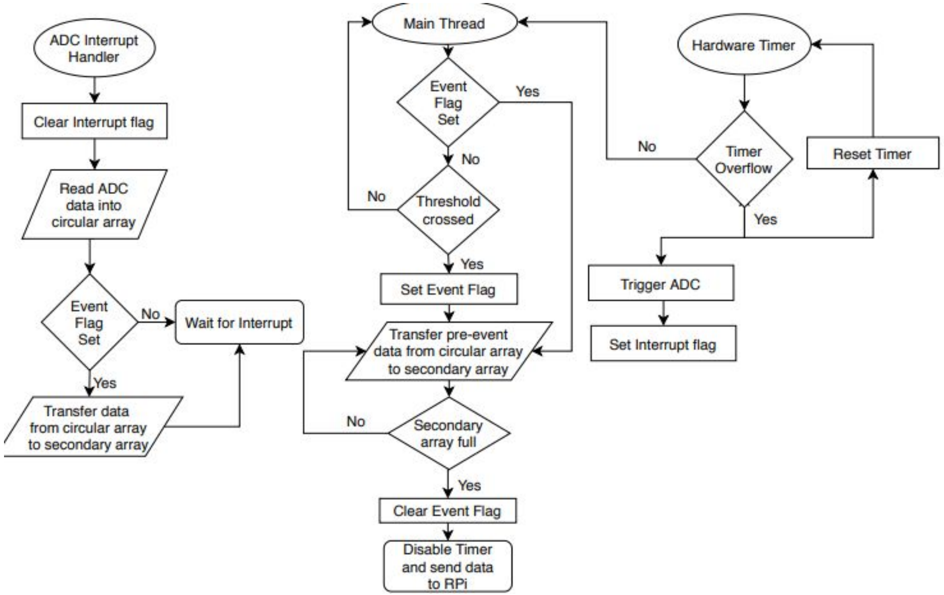


Sennheiser MD-42 microphones
sensitivity of 2 mV/Pa

Tetrahedron (3D)/Square (2D)
1m distance b/w mics

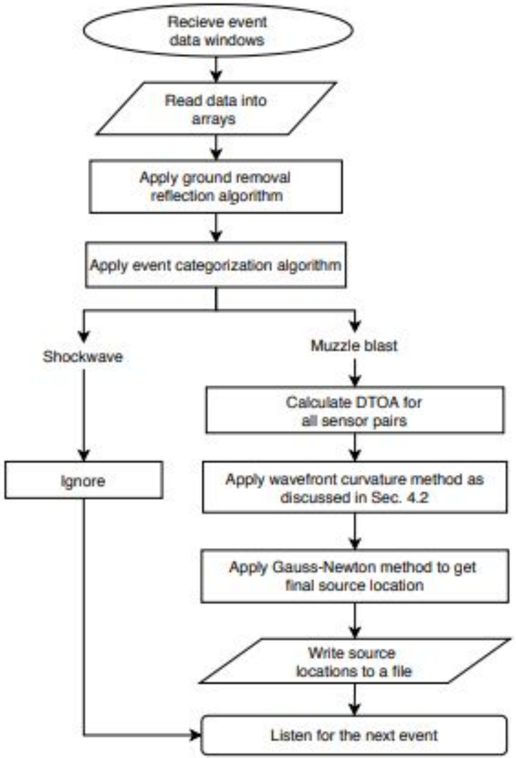
Biasing Circuit
Shifting Voltage range from 0 to 3.3 V to −1.65 to +1.65 V

Data Acquisition and Processing on Tiva Board Online



- Tiva C Series TM4C1294 Connected LaunchPad Evaluation Board
- 2 12-bit ADC modules
- Functions:
  - Continuously ‘listen’ on all microphone channels (4)
  - Detect the acoustic event on any microphone channel
  - Acquire data in a brief time window
  - Pass on the collected data over Ethernet to a downstream microprocessor (Rpi)
- DC offset correction for each microphone:
  - event checking algorithm starts only after 6.25 ms post boot (500 samples @80Khz)
  - Average of the acquired voltage values for this initial 6.25 ms is calculated for each channel to get their respective DC voltages
- Pre-event data recording:
  - 0.3ms experimental = 24 samples @80kHz
  - 100 samples buffer implemented
- Event Detection on any microphone:
  - Transfer sampled data to 25th entry of secondary buffer
  - 1-24 entries of secondary buffer <= recent 24 entries of circular buffer
  - done for all four channels, even though the event is detected on only one channel
- Secondary buffer size:
  - 4ms gunshot event
  - 0.3ms pre-event
  - $\sqrt{2}/c$ = 4.2ms travel time
  - Total 8.5ms; 8.75ms = 700 samples
  - Buffer size = 4x700
- Ethernet Transfer:
  - Secondary array filled; 2 packets transmitted for each channel:
    i. Channel Number
    ii. Channel Data

Localization on RPi Board Online



- Raspberry Pi Compute Module 3+
- Solution:
- Getting the 2-D coordinates of the source from the wavefront curvature method
- providing the solution as initial guess for the classical non linear least square estimation method
- 100ms pause for Rpi to process
- minimum time between two gunshot events = 100ms
- Time required to report the location estimate = 100ms

Results and Discussions

Offline | Blast Wave | Tetrahedral Array

- 25kHz Sampling
- Calibrating Microphone distances based on the reverse nonlinear least-squares method
- Choosing Reference microphone:
  - For any reference sensor, the remaining sensors yield corresponding normalized DTOA values (η's)
  - Identify η_max for each sensor
  - Choose sensor with lowest η_max as reference
- Max error in:
  - Bearing Angle = 3°
  - Range = 200%

Online | Blast Wave | Square Array

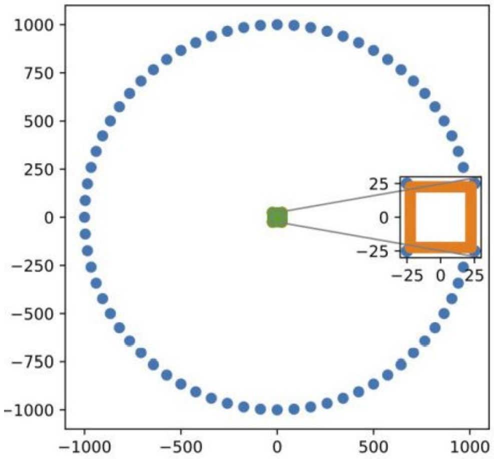
- WCM for initial guess
- nonlinear least squares for refinement
- Procedure:
  (4 triplets)
  - Choose best reference for each triplet
  - WCM for preliminary estimate
  - Calculate error for each triplet
  - Choose the triplet which gives minimum error
  - Identify best reference among all hydrophones
  - Non-linear least square method for refined estimate
- Max error in:
  - Bearing Angle = 2°
  - Range = 40%

Parameter	Normalized Range Error	
	Improved Online Implementation	First Offline Implementation
Maximum	0.40	2.22
Median	0.21	0.36
Mean	0.21	0.60

Results and Discussions

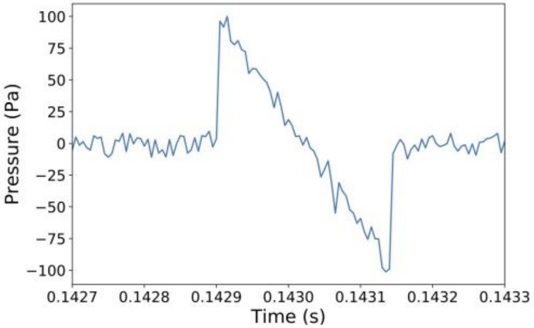
Shock Wave | Security System | Simulation

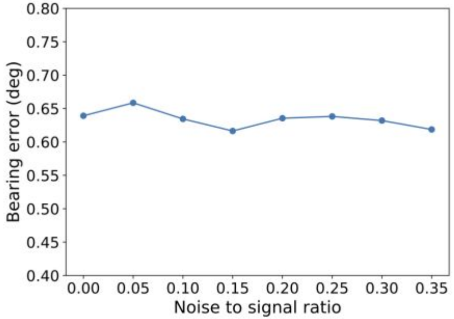
- 500 gunshot events simulated
- Max error in:
  - Bearing Angle = 1.75 degrees



Effect of Noise

- Addition of zero-mean Gaussian noise to the ideal 'N'-wave signal





No effect (cross-correlation is independent of Noise)

Thank You