Source Localization using Wireless Sensor Networks

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Outline

Introduction

- Low-cost, low-power, multi-functional wireless sensor networks are becoming readily available.
- The sensor nodes are small in size and are able to sense, process data, and communicate with each other wirelessly.
- Wireless sensor networks have several potential applications, especially in the area of military operations.

Sniper detection

- A gun shot produces several detectable phenomena, such as muzzle blast and shockwaves.
- Muzzle blast is the acoustic signature associated with the ejection of the bullet from the sniper's rifle.
- The muzzle blast is a loud, characteristic noise originating from the end of the muzzle and propagating spherically.
- Shockwaves can be detected acoustically at ranges from hundreds of meters and can be used to accurately determine projectile trajectories.
- The shock waveform is distinctive and cannot be produced by any other natural phenomenon.

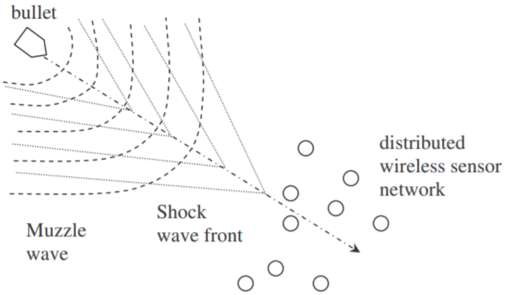

Figure 1: Shock wave front and muzzle wave detection by a group of distributed wireless sensors

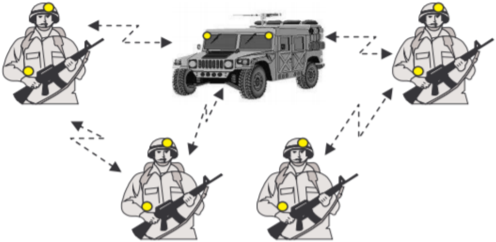

Figure 2: Wireless network-based counter-sniper system consisting of vehicular and wearable sensors.

Two step source localization process

A two-step source localization process is proposed in this work for counter-sniper applications:

- The Time Difference Of Arrival (TDOA) values are first determined using the Generalized Cross Correlation (GCC) method.
- The TDOA values are used by a hybrid spherical interpolation/maximum likelihood (SI/ML) estimation method to determine the shooter location.

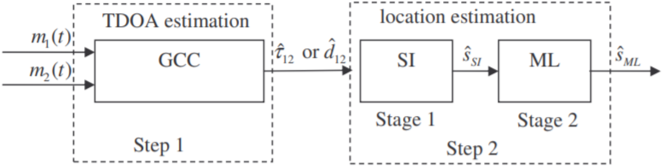

Figure 3: Two-step source localization model using GCC and hybrid SI/ML methods. Step 1 performs the TDOA estimation using GCC; Step 2 performs the location estimation in two stages: estimate determined by SI method in stage 1 is used as initial values for ML method in stage 2.

1.Time difference of arrival estimation

The generalized cross correlation (GCC) technique is used to estimate the time difference of arrival $\hat{T}_{12}$ for a pair of received signals m_1(t) and m_2(t). The $\hat{T}_{12}$ values are then converted into range difference of arrival $\hat{d}_{12}$ values using the relationship.

$$\hat{d}_{12} = \hat{T}_{12} V$$

where V=345m/s is the speed of sound.

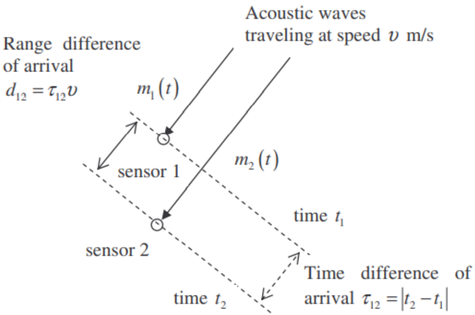

Figure 4: Range difference of arrival at two acoustic sensors

The true RDOA values d_{ij} are determined using the known sensor and source positions. The additive white Gaussian noise model used to generate the measured RDOA values $\hat{d}_{ij}$

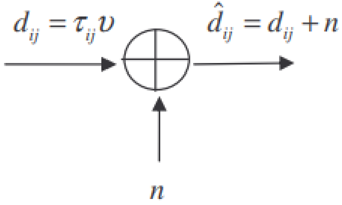

Figure 5: Modeling of range difference of arrival (RDOA).

2. Least-squares Spherical Interpolation (SI) Method

- The Spherical Interpolation method is chosen for the closed-form least squares (LS) source location estimation based on the measured range difference of arrival(RDOA) values.The distance between source and sensor i is denoted by euclidean norm

$$D_i = ||\underline{x_i} - \underline{\hat{s}}|| = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2}$$

The distance from origin to the point x_i is denoted by

$$R_i = ||\underline{x_i}|| \tag{1}$$

Similarly, the estimated distance from the origin to the source is denoted by

$$\hat{R}_s = ||\underline{\hat{s}}|| \tag{2}$$

RDOA between sensor i and sensor1 is denoted by

$$\hat{d}_{i1} = D_i - D_1 = D_i - \hat{R}_s$$

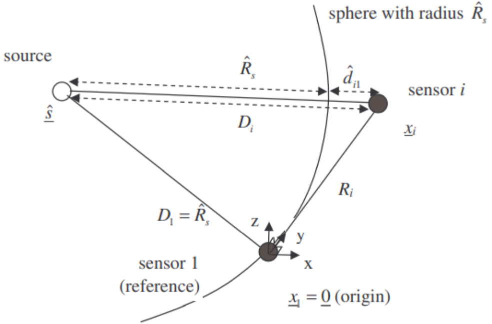

Figure 6: Notations used in Spherical Interpolation (SI) method for a single source, sensor i and the reference sensor 1

Source location estimation is given as:

$$\underline{\hat{s}} = \frac{1}{2}\left(s^T P_d^{\perp} W P_d^{\perp} s\right)^{-1} s^T P_d^{\perp T} W P_d^{\perp} \underline{\delta}\right)$$

where projection matrix:

$$P_d^{\perp} = I - \frac{\underline{d d^T}}{\underline{d^T d}}$$

$$\underline{\delta} = \begin{bmatrix} R_2^2 - d_{21}^2 \\ R_3^2 - d_{31}^2 \\ . \\ . \\ . \\ R_N^2 - d_{N1}^2 \end{bmatrix}$$

$$\underline{d} = \begin{bmatrix} d_{21} \\ d_{31} \\ . \\ . \\ . \\ d_{N1} \end{bmatrix}$$

$$S = \begin{bmatrix} x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \\ . & . & . \\ . & . & . \\ . & . & . \\ x_N & y_N & z_N \end{bmatrix}$$

$$W = \begin{bmatrix} w_{11} & w_{12} & . & . & w_{1N} \\ w_{21} & w_{22} & . & . & w_{2N} \\ . & . & . & . & . \\ . & . & . & . & . \\ w_{N1} & w_{N2} & . & . & w_{NN} \end{bmatrix}$$

3.Maximum Likelihood Estimator

- The errors η in the measurement of the range difference of arrival (RDOA) d_{ij} are assumed to be zero mean Gaussian and independent for each sensor.

$$\Gamma = \Delta + \eta$$

Likelihood function of Γ given source location $\underline{s}$ is

$$f(\Gamma, \underline{s}) = \frac{1}{2\pi^{\frac{N-1}{2}} \left| \sum \right|^{\frac{1}{2}}} e^{\frac{1}{2} h^T(\underline{s}) \sum^{-1} h(\underline{s})}$$

ML cost function is

$$J_{ML}(\underline{s}) = h^T(\underline{s}) \sum^{-1} h(\underline{s})$$

The cost function can be minimized by using Levenberg-Marquardt method provided by MATLAB.

RDOA error $h(\underline{s})$ is repressented by

$$h(\underline{s}) = \begin{bmatrix} ||\underline{s} - \underline{x_2}|| - ||\underline{s} - \underline{x_1}|| - \hat{d}_{12} \\ ||\underline{s} - \underline{x_3}|| - ||\underline{s} - \underline{x_1}|| - \hat{d}_{13} \\ . \\ . \\ . \\ ||\underline{s} - \underline{x_N}|| - ||\underline{s} - \underline{x_1}|| - \hat{d}_{1N} \end{bmatrix}$$

noise covariance matrix:

$$\sum = \sigma_N^2 \begin{bmatrix} 1 & \frac{1}{2} & . & . & \frac{1}{2} \\ \frac{1}{2} & . & . & . & \frac{1}{2} \\ . & . & . & . & . \\ . & . & . & . & . \\ \frac{1}{2} & \frac{1}{2} & . & . & 1 \end{bmatrix}$$

4.Cramer Rao Lower Bound

- The minimum mean-squared error for any estimate of a non-random parameter is given by the Cramer Rao Bound.
- The Cramer Rao Bound (CRB) gives a lower bound on the error variance of any unbiased estimate. The variance of any unbiased estimator of s is bounded by

$$E\left[\left(\underline{\hat{s}}-\underline{s}\right)\left(\underline{\hat{s}}-\underline{s}\right)^{\gamma}\right] \geq F^{-1}\left(\underline{s}\right)$$

where F($\underline{s}$) is the Fisher information matrix, expressed as

$$F(\underline{s}) = E\left\{\left[\frac{\partial logf\left(\Gamma,\underline{s}\right)}{\partial \underline{s}}\right]\left[\frac{\partial logf\left(\Gamma,\underline{s}\right)}{\partial \underline{s}}\right]^{\gamma}\right\}$$

Performance metrics

Error mean

$$\mu = \frac{1}{M}\sum_{i=1}^{M}(\hat{s}_i - s)$$

Error variance

$$\sigma^2 = \frac{1}{M}\sum_{i=1}^{M}(\hat{s}_i - s - \mu)^2$$

Root Mean Square (RMS) error

$$\gamma = \sqrt{\mu^2 + \sigma^2}$$

Simulation Results

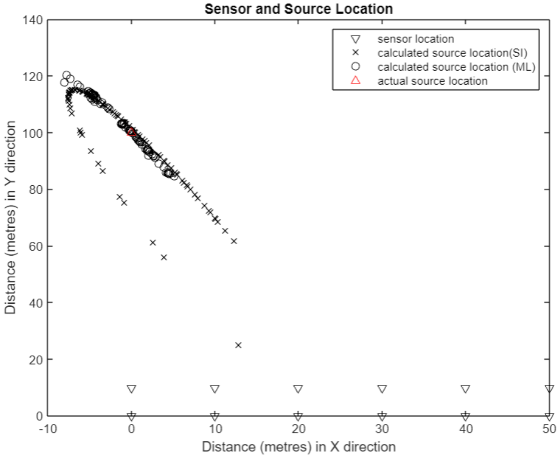

Figure 7: Location estimation using the SI and ML methods with d=100m and inter-sensor spacing=10m with 24 sensors nodes with SI output as initial guess

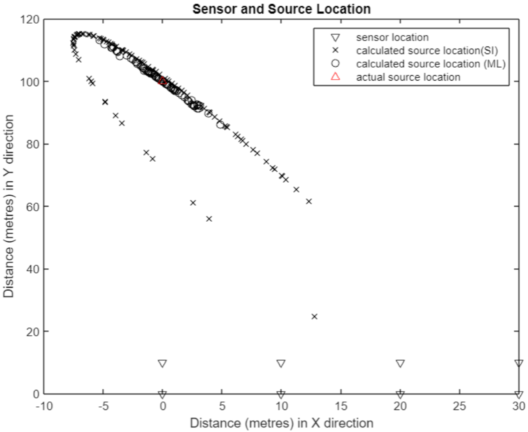

Figure 8: Location estimation using the SI and ML methods with d=100m and inter sensor nodes with exact initial guess

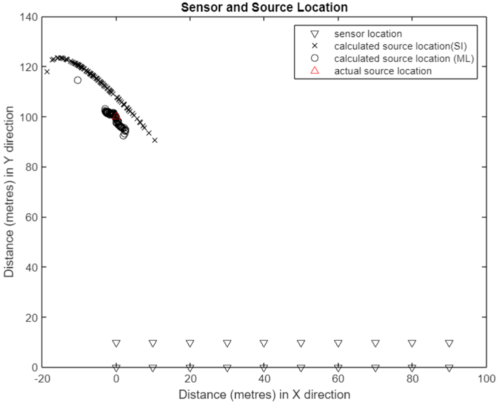

Figure 9: Location estimation using the SI and ML sensor spacing d=100m with 40 sensor nodes with SI output as initial guess

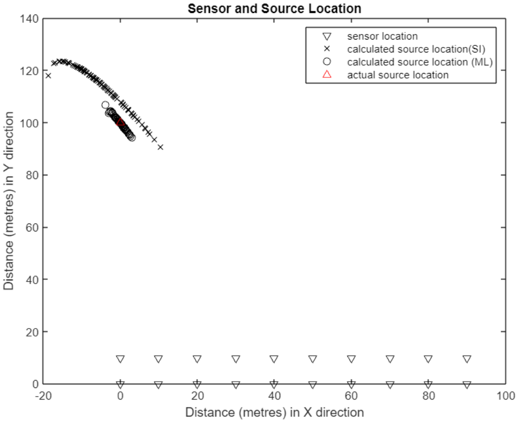

Figure 10: Location estimation using the SI and ML sensor spacing d=100m with 40 sensor nodes with exact initial guess

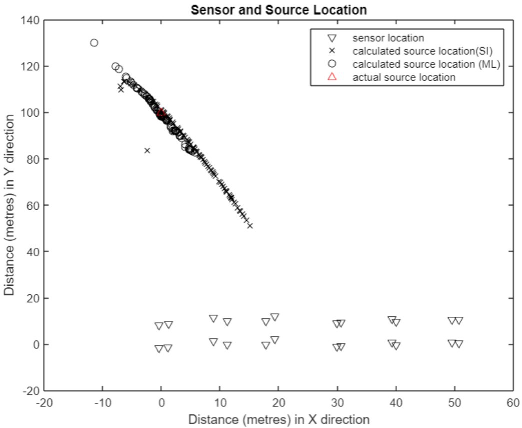

Figure 11: Location estimation using the SI and ML methods with d=100m and inter sensor spacing=10m with 24 sensors nodes with SI output as initial guess with location petrubations.

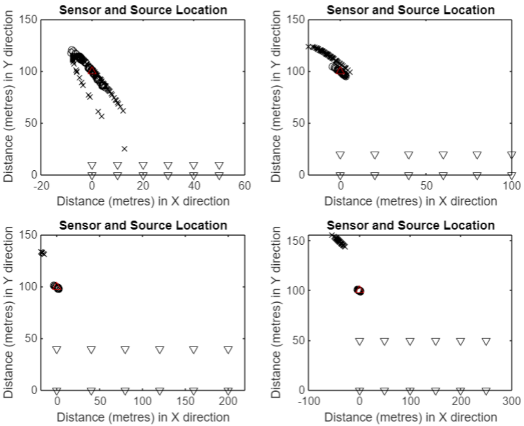

Figure 12: Location estimation using the SI and ML methods with d=100m and inter sensor spacing=10m, 20m, 40m and 50m with 24 sensors nodes with SI output as initial guess

References

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THANK YOU