MEASURING SYSTEMS

SYSTEM FOR DETERMINING THE SOUND SOURCE COORDINATES

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Abstract. The authors investigated the effect of changes in the acoustic signal propagation speed and the accuracy of sensor positioning on the accuracy of sound source localization. The mean absolute error grows with the displacement of the microphones relative to the nominal coordinates (X, Y). The same trend is observed with an increase in the actual acoustic signal velocity deviation from the velocity under normal environmental conditions.

The authors propose two ways to reduce the error caused by these factors. The first method is to introduce a correction factor for the speed of the acoustic signal. The second method is to reduce the distance between the system's sensors. This makes it possible to place them more accurately relative to each other.

Key words: acoustic signal; error; deep learning; difference-time method; sensor coordinates.

1. Introduction

In today's world, sound is an integral part of many critical technological applications, such as video surveillance [1], security [2], and medical diagnostics [3]. Methods and tools for sound localization [4] can be divided into two broad categories: active and passive.

Active methods are methods in which sound is artificially generated or created to pinpoint its location. These methods are based on active sources that send a signal or sound. Sensors, such as microphones, collect and analyze this signal or echo. The basic idea of active methods is to emit a signal in a controlled manner and to perceive the signal reflected from the object for further analysis. Active methods can determine the distance to objects that can reflect the signal.

Passive methods are methods where there is no particular active signal. Information that can be obtained from natural acoustic signals is collected to determine the coordinates. These include sounds, echoes, noise, and other acoustic phenomena. These methods are based on the analysis of the properties of acoustic signals and their propagation in the environment. Passive methods are usually less accurate than active methods and more sensitive to noise and environmental conditions. However, they offer some benefits, particularly in cases where active signal emission may be undesirable or impossible.

The authors propose a system for determining the coordinates of an acoustic signal based on a passive time-difference method and a neural network [5].

2. Drawbacks

The main disadvantage of passive methods is their sensitivity to environmental conditions. In addition, it is necessary to align the microphones accurately. Therefore, it is crucial to study the influence of these factors on the metrological characteristics of the system for determining the coordinates of a sound source. In particular, the following influencing factors were investigated:

- Determine the coordinates of the sensors (GPS positioning).
- Dependence of sound speed on temperature.
- Temperature measurement error.

3. Goal

This work aims to study the dependence of the error of a sound localization system on the accuracy of determining the coordinates of receivers and changes in the propagation speed of an acoustic signal.

4. Errors in the system for determining the coordinates of the sound source

A coordinate determination system (CDS) [5] based on the difference-time method [4] and a pre- trained neural network (NN) determines the x_m and y_m of the sound source (acoustic signal). For the pre-optimized CDS with nominal parameters, an error of 7.3 × 10^{-5} m in X and 5.9 × 10^{-5} m in Y was obtained. The perimeter of the sound sources was 1500 × 500 m. However, these results were obtained for the ideal case (deviation from the nominal value is 0) and a constant acoustic signal velocity. In natural conditions, several factors affect the accuracy of the CDS. These include the accuracy of the location of the sensors x_i and y_i and the change in velocity Vs with the ambient temperature. The values of x_i, y_i, and V_S are necessary to calculate the time of acoustic signal registration t_{pi} by the formula:

$$t_{pi} = \frac{\sqrt{(x_i - x_m)^2 + (y_i - y_m)^2}}{V_s} \quad (1)$$

It is necessary to study the dependence of the CDS on the factors x_i, y_i, and Vs.

4.1. Dependence of the CDS error on the accuracy of sensor coordinates determination

During the study of the dependence of the CDS on the accuracy of determining the coordinates of the sensors, their positions were generated randomly:

$$x_i = x_{iN} + L_i \cdot \cos(\varphi_i), \quad (2)$$

$$y_i = y_{iN} + L_i \cdot \sin(\varphi_i), \quad (3)$$

where x_i and y_i are the random coordinates of the *i*-th sensor, x_{iN}, and y_{iN} are the nominal coordinates of the *i*-th sensor, L_i is the modulus of the displacement vector of the *i*-th sensor, φ_i is the angle of the displacement vector.

The modulus and angle of the displacement vector were calculated as follows:

$$L_i = rand \cdot \Delta_{sensor}, \quad (4)$$

$$\varphi_i = rand \cdot 2\pi, \quad (5)$$

where *rand* is a function that generates a random value in the range from 0 to 1, Δ_{sensor} is the absolute error of the receiver's location relative to the nominal coordinates.

Fig. 1 shows three random locations of sensors S1 and S2 according to (2) and (3).

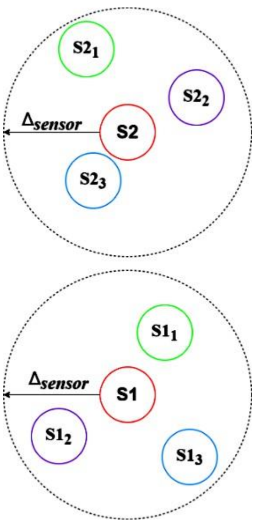


Fig. 1. Random location of S1 and S2

Fig. 1 shows S1 and S2 with random displacement vectors. The modulus of the vector is in the range from 0 to Δ_{sensor}, and the vector angle is from 0 to 2π. For each iteration of the study, the microphones are randomly positioned in terms of the modulus and the angle of the displacement vector.

The study was conducted for nine sensors (Fig. 2) in a straight line. The error was determined for five acoustic signal sources with coordinates: M1 (875, 125), M2 (875, 375), M3 (1250, 250), M4 (1625, 125), and M5 (1625, 375).

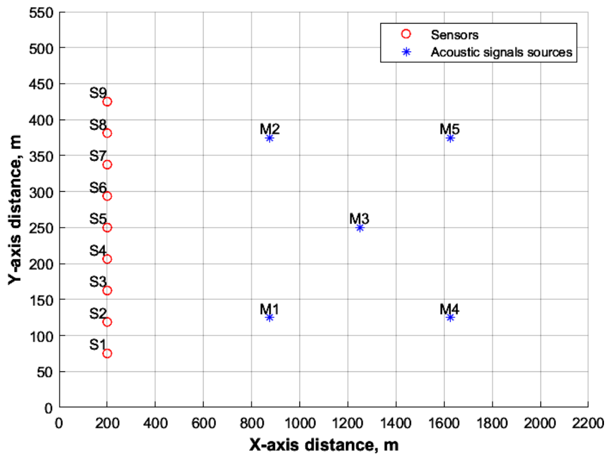


Fig. 2. Location of sensors and sound sources

For each M, time differences were calculated and transmitted to the NN to determine the position of the sound. The study was conducted 1000 times. For each iteration, the mean absolute error (MAE) Δx_{ms} and Δy_{ms} were determined as:

$$\Delta x_{ms} = \frac{\sum_{j=1}^{K} \Delta x_{mj}}{K} = \frac{\sum_{j=1}^{K} x_{mj} - x_{mN}}{K}, \quad (6)$$

$$\Delta y_{ms} = \frac{\sum_{j=1}^{K} \Delta y_{mj}}{K} = \frac{\sum_{j=1}^{K} y_{mj} - y_{mN}}{K}, \quad (7)$$

where Δx_{mj} and Δy_{mj} are the absolute errors of determining x_m and y_m of the acoustic signal source at the *j*-th iteration of the study, K is the number of studies, x_{mN} and y_{mN} are the nominal coordinates of the sound source.

During the study, the values of Δ_{sensor} were: 0.001, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.2 m. The maximum value of the receivers' displacement is 0.2 m. It is twice as large as the best GPS accuracy [6].

Figs. 3, *a* and *b* show the dependence of MAE on the absolute error of sensor placement.

As shown in Fig. 3, increasing the value of Δ_{sensor}, the accuracy of X and Y determination deteriorates. For a value of Δ_{sensor} = 0.1 m, the X detection error is 2.78 m, and the Y detection error is 0.33 m for the sound located in M3. In addition, the accuracy decreases with distance from the sound sources to the microphones. For sources M4 and M5, it does not exceed 5.28 m in X and 0.65 m in Y. For M1 and M2, which are closer to the receivers, it is 1.55 m and 0.31 m for X and Y, respectively.

4.2. Dependence of the CDS error on changes in the sound propagation speed

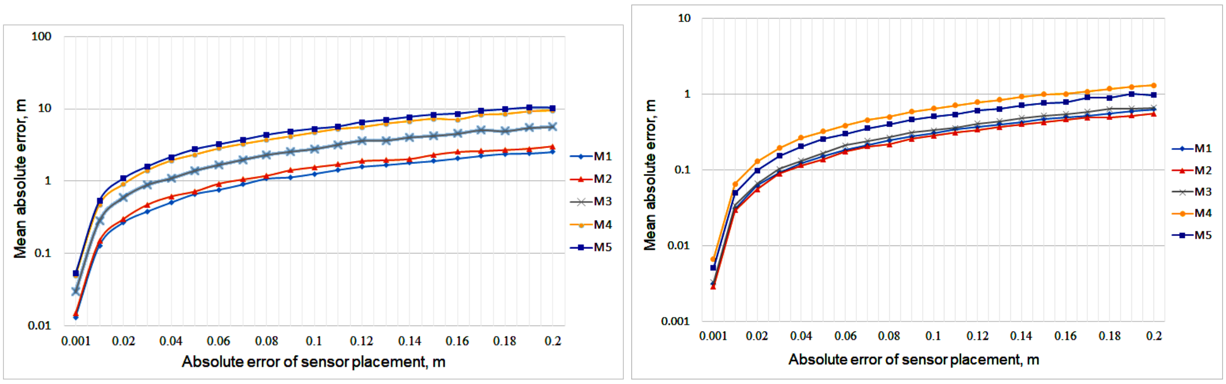
During this study, the propagation speed of the acoustic signal was randomly generated by the formula:

$$V_S = V_{SN} + rand - 0.5 \times 2 \times \Delta_{sound}, \quad (8)$$

where *Vs* is the random sound velocity, V_{SN} is the nominal sound velocity at a temperature of 20 °C, Δ_{sound} is the absolute error of the sound velocity.

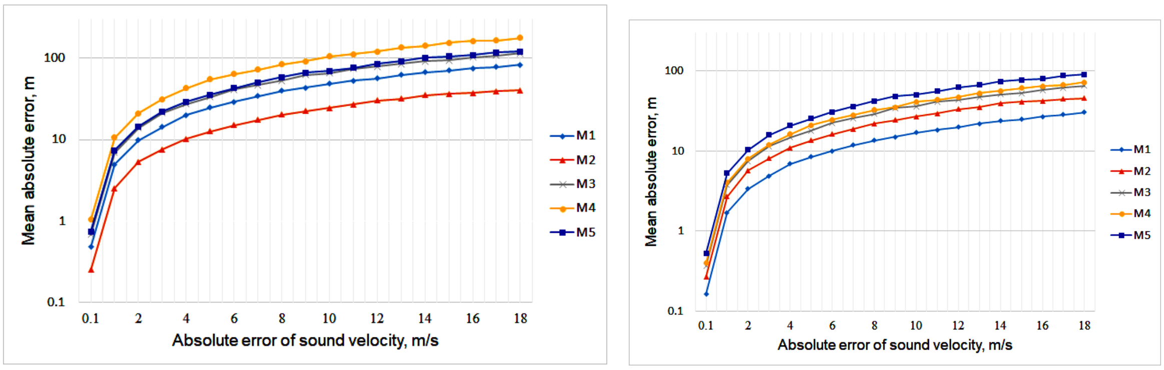
The value of Δ_{sound} varied in the range from 0.1 to 18 m/s (specific values: 0.1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 m/s). The study was conducted for the temperature range from –10 °C to 50 °C. The maximum change in the acoustic signal velocity is ± 18 m/s, which corresponds to a temperature deviation of ± 30 °C from 20 °C (normal conditions).

Figs. 4, *a* and *b* demonstrate the dependence of MAE on changes in the sound propagation speed.



a *b*

Fig. 3. Dependence of MAE on the absolute sensor detection error: a – X coordinate; b – Y coordinate



a *b*

Fig. 4. Dependence of MAE on the change of sound propagation speed: a – X coordinate; b – Y coordinate

As shown in Fig. 4, the MAE value increases with the change in Δ_{sound}. For the increment of Δ_{sound} = 18 m/s, the error in locating the source M3 is 114.68 m for X and 65.55 m for Y. As in the previous study, the accuracy deteriorates with the distance between M and the sensors. For M4 and M5, the error does not exceed 178 m in X and 91 m in Y. For closer sources (M1 and M2), the MAE is 83 m in X and 46 m in Y. According to the study results (Fig. 4), the most significant impact on the MAE is the change in sound propagation speed.

5. Methods to reduce the error of the sound source location system

The distance between each sensor was reduced from 44 m to 1 m (Fig. 5). The goal of this decision is to minimize the impact of the accuracy of sensor placement. Only one receiver was placed by GPS with laser rangefinders [7]. The GPS reference error only affects one sensor, not all. The displacement vectors, in this case, are the same.

A correction factor is introduced to reduce the error caused by changes in the sound velocity. Changing the speed of the acoustic signal according to (1) affects the time of its registration and changes the time difference fed to the NN for determining X and Y. Therefore, before determining the coordinates, it is necessary to correct the time difference for the changed velocity.

To determine the correction factor, consider a system consisting of two sensors, S1 and S2. The arrival times of the acoustic signal t_{p1N} and t_{p2N} at the nominal speed V_{SN} = 343.1 m/s for each of S1 and S2 are calculated as follows:

$$t_{p1N} = \frac{R_1}{V_{SN}}, \quad (9)$$

$$t_{p2N} = \frac{R_2}{V_{SN}}, \quad (10)$$

where R_1 and R_2 are the distances from the sound source to S1 and S2, respectively.

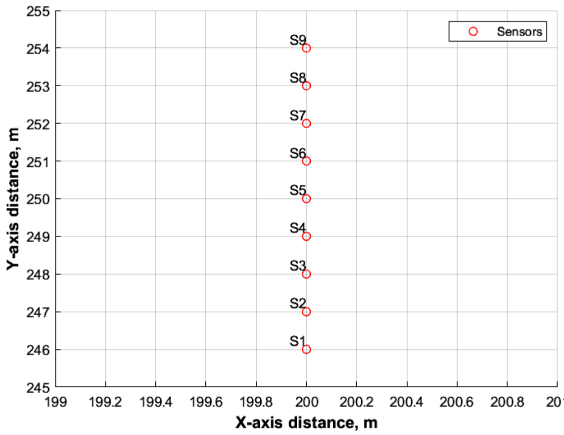


Fig. 5. Sensor placement with a distance of 1 m between them

Then, the difference in the time of acoustic signal registration Δt_{pN} between S1 and S2 is the next:

$$\Delta t_{pN} = t_{p1N} - t_{p2N} = \frac{R_1 - R_2}{V_{SN}}. \quad (11)$$

In the case of deviation of the velocity V_S from V_{SN}, the times of acoustic signal registration t_{p1} and t_{p2} are equal to:

$$t_{p1} = \frac{R_1}{V_S} \quad (12)$$

$$t_{p2} = \frac{R_2}{V_S} \quad (13)$$

In this case, the time difference Δt_p is calculated as:

$$\Delta t_p = t_{p1} - t_{p2} = \frac{R_1 - R_2}{V_S}. \quad (14)$$

Then, the ratio of the time differences Δt_p to Δt_{pN} is inversely proportional to the ratio of velocities:

$$\frac{\Delta t_{pN}}{\Delta t_p} = \frac{R_1 - R_2}{V_{SN}} \times \frac{V_S}{R_1 - R_2} = \frac{V_S}{V_{SN}} \quad (15)$$

Knowing the actual velocity of the acoustic signal V_S makes it possible to obtain and correct the time difference Δt_p to the nominal one Δt_{pN} as:

$$\Delta t_{pN} = \Delta t_p \times \frac{V_S}{V_{SN}}. \quad (16)$$

Thus, the time differences Δt_{pi} reduced to Δt_{pNi} corresponding to the propagation speed of the acoustic signal under normal environmental conditions.

5.1. Method to reduce the error of the CDS caused by the accuracy of determining the coordinates of sensors

The random coordinates x_i and y_i in the case of applying the proposed method of error reduction are calculated as follows:

$$x_i = x_{iN} + L \cdot \cos(\varphi), \quad (17)$$

$$y_i = y_{iN} + L \cdot \sin(\varphi), \quad 18)$$

where L and φ are the modulus and angle of the displacement vector.

The modulus and angle of the displacement vector are defined as follows:

$$L = rand \cdot \Delta_{sensor}, \quad (19)$$

$$\varphi = rand \cdot 2\pi. \quad 20)$$

Equations (17) and (18) differ from (2) and (3) in that the modulus of the displacement vector L and the displacement angle φ are the same for all receivers. Fig. 6 shows three random locations of sensors S1 and S2 according to (17) and (18).

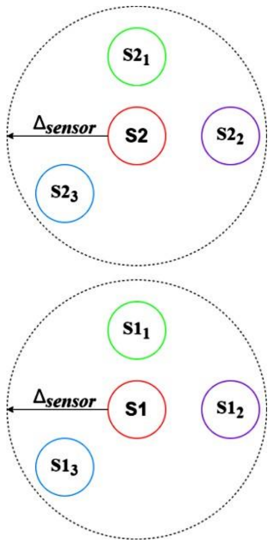


Fig. 6. Random location of S1 and S2 with the same displacement vector

Fig. 7 depicts the dependence of MAE on the absolute error Δ_{sensor}. The results are presented for the adjusted sensor arrangement with a smaller base (Fig. 5) and the same displacement vector (Fig. 6).

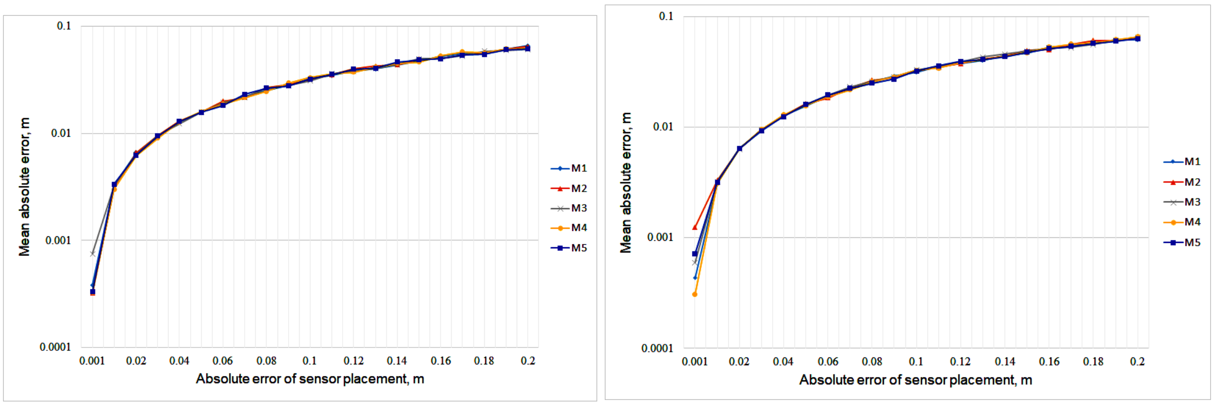
As shown in Fig. 7, the change in Δ_{sensor} leads to an increase in the MAE. However, in this case, for all sources (M1, M2, M3, M4, M5), the MAE decreased to 3.3×10^{-2} m for X and Y compared to the previous experiment. This behavior results from reducing the distance between the microphones from 44 m to 1 m. Only one of the microphones was geo-referenced with GPS (Δ_{sensor}= 0.1 m).

5.2. Method to reduce the error of the CDS caused by the change in sound velocity

The time difference was corrected for the actual velocity V_S according to (16). The velocity V_S was defined as [8]:

$$V_S = 331.3 + (0.606 \cdot \theta)\ , \quad (21)$$

where θ is the ambient temperature.



a *b*

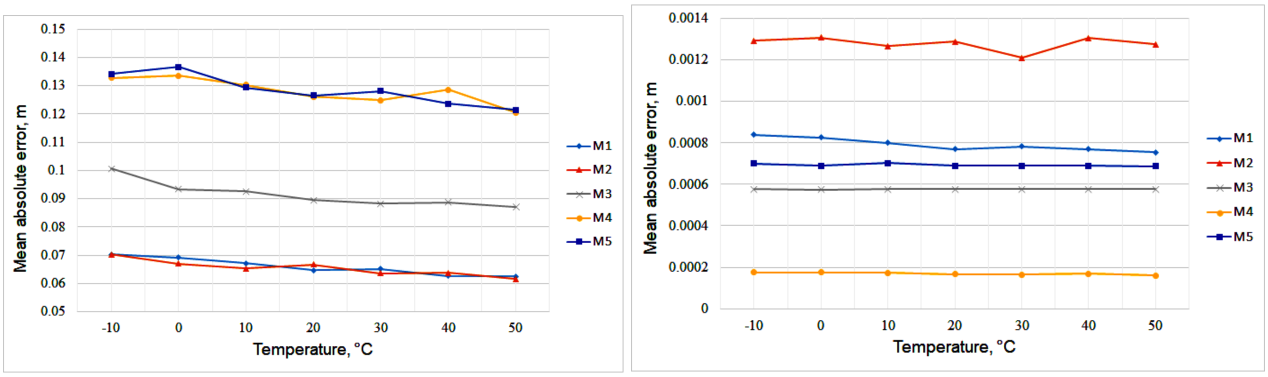
Fig. 7. Dependence of MAE on the absolute sensor detection error: a – X coordinate; b – Y coordinate

The tests were conducted for a temperature range from –10 °C to 50 °C with a step of 10 °C. Absolute temperature measurement error $\Delta_\theta = \pm 0.1$ °C. This value can be achieved with a platinum resistance thermometer [9]. The actual propagation velocity of the acoustic signal $V_{S\theta}$ was calculated as:

$$V_{S\theta} = 331.3 + 0.606 \cdot \theta + rand - 0.5 \cdot 2 \cdot \Delta_\theta \quad (22)$$

Fig. 8 depicts the results of studying MAE's dependence on acoustic signal velocity changes.

For the preliminary results (Fig. 4) for source M3, the accuracy of the X coordinate was 114.68 m and 65.55 m for Y. The correction method of Δt_p significantly reduced the MAE. In this case, it does not exceed 0.1 m in X and 5.8×10^{-4} m in Y. The change in the speed of the acoustic signal still exerts the most significant influence on the error of the systems.



a *b*

Fig. 8. MAE values with correction factor: a – X coordinate; b – Y coordinate

6. Conclusion

While researching passive methods of sound source localization was shown that the study of errors is vital in ensuring measurement accuracy, reliability, and quality. One of the disadvantages is the sensitivity to environmental conditions and the accuracy of the receivers' reference to the coordinate grid. There were studied two methods of reducing the mean absolute error of the system for determining the coordinates of an acoustic signal source. Applying the acoustic signal velocity correction method diminishes the error from 114.7 m to 0.1 m for X-coordinate and 65.6 m to 5.8×10^{-4} m for Y-coordinate. Positioning the sensors and linking them to a GPS coordinate grid reduces the error from 2.8 m to 3.1×10^{-2} m for X-one and from 0.3 m to 3.3×10^{-2} m for Y-one. The most significant impact on the exactness of the system for determining the source's coordinates causes the change in the velocity of the acoustic signal. So, the maximal error in the localization of the acoustic signal source is equal to 0.1 m for an area of 1500 × 500 m^2.

7. Conflict of interests

The authors claim no possible financial or other conflicts over the work.

8. Gratitude

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