EURASIAN PHYSICAL TECHNICAL JOURNAL

2024, Volume 21, No. 2 (48)

https://doi.org/10.31489/2024No2/83-91

Received: 28/02/2024 Revised: 11/05/2024 Accepted: 06/06/2024 Published online: 29/06/2024
Original Research Article

UDC 534.6.08

MODELING OF NOISE SOURCES LOCALIZATION ON A CONSTRUCTION SITE BASED ON RADIAL MICROPHONE ARRAY AND HIGHEST SIGNAL DIRECTION INTERSECTIONS

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Abstract. *Noise pollution from construction activities affects both workers and nearby residents. This study proposes a new method for localizing noise sources on construction sites. The method uses a radial microphone array and an algorithm based on the highest signal direction intersections. Simulations show this approach can identify noise source locations with relatively decent accuracy. The method localized noise sources within an area of about 180 m² with an average uncertainty of 6 % for single-spot sources. The uncertainties for multiple-spot sources, particularly two-spot sources, were 83.2 % and 6.1 %, depending on the size and number of sources. These results highlight the method's accuracy and its sensitivity to site conditions. Our approach offers lower computational needs compared to existing solutions. Future work will focus on the refinement of the algorithm and integration of IoT technologies for real-time monitoring.*

Keywords: construction noise, sound source localization, radial microphone array, highest signal direction, sound monitoring, acoustic mapping, signal processing.

1. Introduction

The construction process is one of the causes of noise pollution in settlements that to a certain level affect the quality of life of residents [1]. The construction noise may cause stress, mental state discomfort, exhaustion, sleeping disturbance, or insomnia [2]. It has a greater impact on construction workers than on the general population or nearby residents [3]. Hearing problems have become a common occupational disease among construction workers [4]. [5] states that there are four main factors influencing the occurrence of noise pollution in construction sites: use of heavy machinery (excavator, bulldozer, cranes, loaders, and pile drivers); communication in raised tones; construction activities (piling, welding, banging, hammering); and vehicles. The maximum number of employees in the survey conducted by [5] agreed that construction noise pollution is mainly caused by heavy machinery. Each type of work requires different tools and equipment, which leads to the mixing of different types of noise [2], and potential resonances with levels exceeded. Thus, the permissible sound pressure levels (SPLs) regulated in the CIS should not exceed those given in [6].

Violations related to noise in Kazakhstan are regulated by the Administrative Offences Code, which stipulates that the disturbance of peace from 22:00 to 9:00 on weekdays and from 23:00 to 10:00 on weekends and public holidays, as well as noise unrelated to urgent necessity that disrupts normal rest and peace of individuals, results in fines: 5 monthly calculation indices (MCI) for individuals, 20 for small businesses or non-profit organizations, 30 for medium-sized businesses, and 100 for large businesses (1 MCI = 3692 KZT as of 01.01.2024) [7]. It must be recognized that compliance with noise regulations not only contributes to human health and well-being but also maintains the ecological balance of urban and suburban environments.

Various measures can now be used on construction sites to prevent a breach of silence, including the use of sound-measuring instruments and monitoring systems. Table 1 below provides a comparison of various existing solutions, including commercial and those presented in recent research studies.

Table 1. Comparison of existing sound measuring and monitoring systems.

Features	GM1356 [8]	EM2030P [9]	Cirrus Invictus [10]	AQBot [11]	ASMS [12]	NOMOS [13]	HMAS [14]	CSLF [15]
Type	Instrument	System	System	System	System	System	System	System
Status	Commercial	Commercial	Commercial	Commercial	Prototype	Prototype	Prototype	Prototype
Sensing unit portability	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Autonomous operation	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Weather-resistant	Yes	Yes	Yes	Yes	No	No	Yes	No
Realtime monitoring	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Remote monitoring	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Threshold alarms	No	No	Yes	Yes	Yes	Yes	Yes	No
Data synchronization	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Fixed sensing position	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Noise distraction-free	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Integration of IoT	No	No	No	Yes	Yes	Yes	No	No
Reporting capability	No	Yes	No	Yes	Yes	Yes	No	No
Wireless data transmission	No	Yes	No	Yes	Yes	Yes	Yes	No
Microphone array	No	No	No	No	No	No	Yes	Yes
Direction recognition	No	No	No	No	No	No	Yes	No
Single source localization	No	No	No	No	No	No	Yes	Yes
Multisource localization	No	No	No	No	No	No	No	Yes
Spatial noise mapping	No	No	No	No	No	No	No	Yes

The comparison of considered solutions shows that the commercial solutions disable noise source direction recognition, localization, and spatial mapping, for both single and multiple source cases [8–11].

They also do not have a microphone array, which complicates the integration of localization algorithms. The majority of the commercial solutions are not integrated with IoT, which limits simultaneous data synchronization, remote storage, and processing. The latter is partially resolved by [12-13]. However, their prototypes are not weatherable, as well as do not apply any source localization strategies.

The solution namely HMAS by [14] used SEVD-MUSIC and iGSVD-MUSIC localization methods and evaluated their pros and cons. However, its circular visualization tool based on azimuth and elevation angles enables only the recognition of sound source direction by color map, disabling the spatial mapping of both single and multiple sources.

[15] proposed a solution called CSLF that is specialized for construction sites. CSLF does have not as many features as HMAS, but a more comprehensive localization algorithm that enables spatial localization and mapping of multiple noise sources. Its algorithm is a combination of TDOA [16], GCC-PHAT [17], and triangulation. The spatial localization in CSLF was possible due to an array comprising equally distanced microphones connected by cables. However, such an array has limitations in detecting sound sources beyond their canvas. This means that a lot of cables will be needed to cover the entire construction site, and the connection can fail at times if the cables accidentally get crushed by machinery. Moreover, the algorithm makes lots of iterations to get closer to the sources' real locations, which necessitates additional computational power to achieve better approximation accuracy.

It turned out that the solutions discussed above do not cover the needs of effective construction noise monitoring and are not able to spatially localize sources with less computational power. To overcome the shortcomings of existing solutions this study aims to design a radial microphone array (RMA) along with the sound source localization (SSL) algorithm, based on highest signal direction (HSD) intersections. The feasibility of the proposed approaches was studied by simulation and statistically analyzed.

2. Methods

2.1 SSL based on HSD intersections

We assume that the HSD intersections from microphones of the array installed on the corners of a construction site may form polygons delineating potential sources with the centroids representing the next-to-source point, or at least an intersection representing the same. To test this assumption this study proposes a radial array of 7 microphones with the central one in line with the corner bisector of the construction site (Fig. 1).

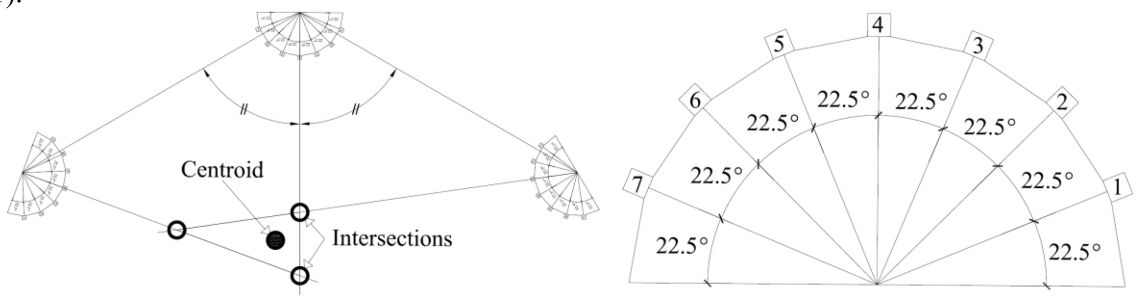

Fig. 1. Array of 7 microphones at the corners of the construction site for SSL

The inter-microphone angles in the proposed array are 22.5°, all comprising a straight angle of 180°. Such a concept helps to cover the construction site's inner corners of any size representing both acute and obtuse angles.

The positions and orientations of microphones in a 2D space help formulate the following linear equation describing the highest signal directions:

$$y_i = k_i \cdot x_i + b_i, \quad (1)$$

where i is an ordinal number of the construction site's corner; y and x are variables equivalent to the SPL and microphone position in the abscissa axis, respectively; k is a slope of the HSD; b is the y-intercept, which is the point where the HSD crosses the y-axis. Determination of k and b are explained in [18].

Each HSD intersection coordinate may be defined by equalizing the expressions obtained by Equation (1) for each corner:

$$y_i = y_{i+1}, \text{or } k_i \cdot x_i + b_i = k_{i+1} \cdot x_{i+1} + b_{i+1}, \quad (2)$$

.

where $x_i = x_{i+1}$ since they are common for the intersected lines.

The centroid coordinates may be defined as the arithmetic mean of HSD intersection coordinates:

$$x_m = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad (3)$$

$$y_m = \frac{1}{n}\sum_{i=1}^{n} y_i, \quad (4)$$

where *n* is a number of HSD intersection clusters; *m* is a number of potential sources.

2.2 Decay-based SPL

In [19] was assumed that in an unobstructed homogeneous medium, the sound decay (*D*) occurs uniformly, i.e., *D* is constant. It is also known that point sound propagates spherically around its source if there is no reverberation [20]. Therefore, when the source is located within the construction site, the measured sound values at its corners (L_P) represent the decayed SPLs at different distances (Fig. 2).

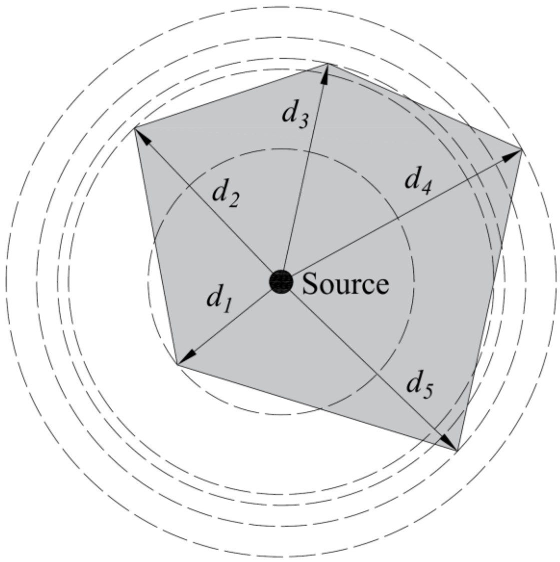

Fig. 2. Scheme of spherical sound propagation on the construction site:
d_1, d_2, d_3, d_4, d_5 – distances from the source to five corners of the construction site

Figure 2 above presents the spherical propagation of the point sound source and the distances from it to the corners of the construction site. The following equation may be used to define the SPL decay, based on the spherical propagation of the sound discussed above:

$$D_m = \frac{L_{P_{i+1}} - L_{P_i}}{d_{i+1} - d_i}, \quad (5)$$

where i is the ordinal number of the measured point (e.g., corner of construction site); d is a distance between source and the microphone array. In other words, SPL measured at different corners of the construction site will be parameters of the sound source at different distances from it. Therefore, the SPL at the sound source L_{P_m} (dB) can be calculated as follows:

$$L_{P_m} = L_{P_i} + D_m \cdot d_i \quad (6)$$

The combination of Equations (5) and (6) gives the following:

$$L_{P_m} = L_{P_i} + \frac{L_{P_{i+1}} - L_{P_i}}{d_{i+1} - d_i} \cdot d_i \quad (7)$$

It is important to note that the proposed equation does not consider environmental constraints.

2.3 Proximity-based SPL

The nature of sound propagation [21] provides an equation for finding the sound value at one point along its path given the sound value at another point:

$$L_{p_{d_2}} = L_{P_{d_1}} - 20\log_{10}\frac{d_2}{d_1}, \quad (8)$$

where $L_{P_{d_1}}$ is the known SPL at the first point along the sound propagation path (usually measured data or equipment supplier data); $L_{p_{d_2}}$ is the unknown sound pressure value at the second point, farther from the source; d_1 is the distance from the source to the first point; d_2 is the distance from the source to the second point.

We now consider the reverse equation to find SPL at a distance d_1 from the sound source given the SPL at a distance d_2 (farther from the source than d_1). This helps deriving the $L_{P_{d1}}$:

$$L_{p_{d_1}} = L_{P_{d_2}} + 20\log_{10}\frac{d_2}{d_1} \qquad (9)$$

The calculations using Equations (8) and (9) help assuming that if the sound pressure value is 50 dB at a distance of 10 m from the sound source, then the sound pressure value will be 30 dB at a distance of 100 m. Suppose d_1 is very close to the sound source, for example, at a distance of 0.1 m.

The maximum approximate value at the sound source can be found by substituting 0.1 m into Equation (18). However, the calculation yields a negative value, -10 dB, which is inappropriate. Moreover, if d_1 is assumed to be 0.001 m, then the sound pressure value (the assumed value at the source) will be equal to -50 dB, which is also inappropriate on one hand and significantly different from the value of $L_{P_{d_1}}$ at d_1 =0.1 m on the other hand. This approach is not suitable for finding the sound pressure at the sound source. However, while logical, it may contribute to finding an optimal solution. For example, by considering the limits of functions as the distance approaches zero ($d_1 \rightarrow 0$).

3. Results and discussion

Figure 3 below shows the results of the simulation for single-spot sound sources to check the feasibility of the proposed SSL algorithm based on HSD intersections. The simulation was performed in Excel.

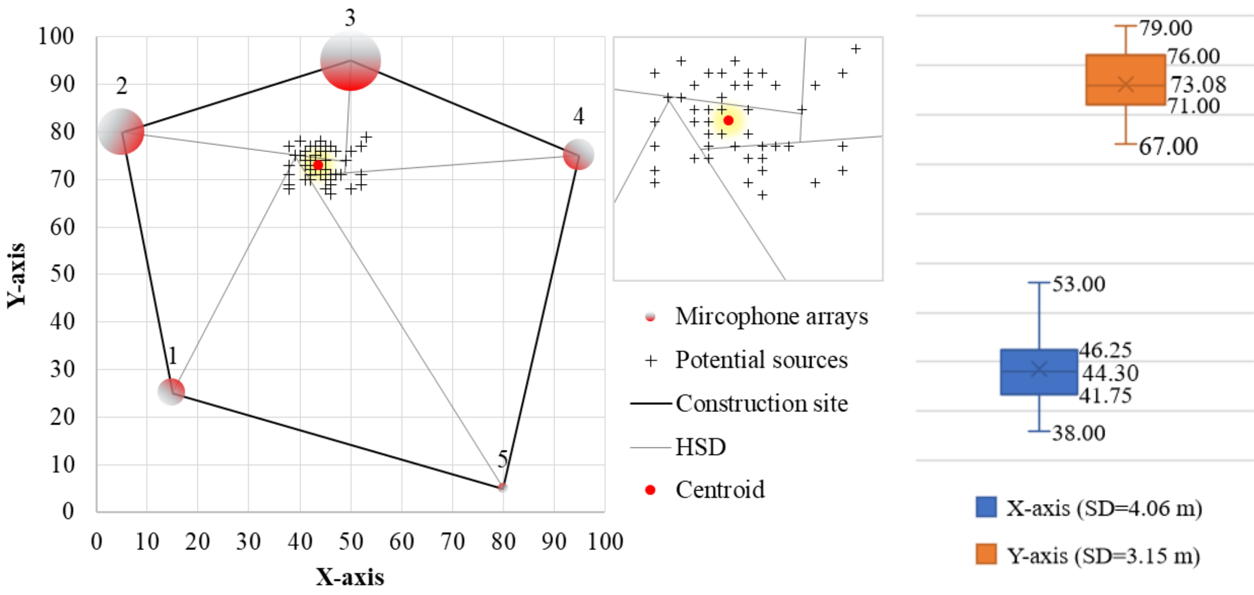

Fig. 3. The single-spot sound source simulation results

From Figure 3 is seen that the construction site (marked with bold line) is arranged on a simulated space referenced to the Cartesian system [18], with dimensions of 100 by 100 m. The microphone arrays (marked with gradient-color circles) were set on their corners. After numerous iterations, a total of 50 potential sources (marked with a plus-sign) were irregularly distributed on a random spot covering about 180 m^2. Such a scenario was chosen to associate with the real situation on the construction site. Examples include masonry work on a similar spot, where distinctive noises may occur over a short period. These sounds can include the operation of a crane delivering brick blocks, the use of an angle grinder for cutting and sanding bricks, or masonry workers communicating in raised voices.

The simulation showed that for the chosen spot the highest signal directions (marked with a grey line) were stable forming an irregular pentagonal polygon. Its centroid (marked with red point) coordinates [43.504; 73.146] were expectedly located in the vicinity of potential sources. The Boxplot diagram in Figure 3 shows that the potential sources were spread in the ranges of 38-53 m and 67-79 m along the X and Y axes, respectively, forming a kind of cluster. The variability of the spread was characterized by the estimation of Standard Deviation (SD) for both X and Y coordinates, which yielded 4.06 and 3.15 m, respectively. The mean coordinates [44.30; 73.08] of the cluster were also depicted in the Boxplot.

Evaluation of the algorithm incorporated such measures of descriptive statistics, as SD, Variance (i.e., Dispersion), and Range. The scatter of values for each of these measures on the X and Y axes was calculated to obtain their coverage areas (Fig. 4).

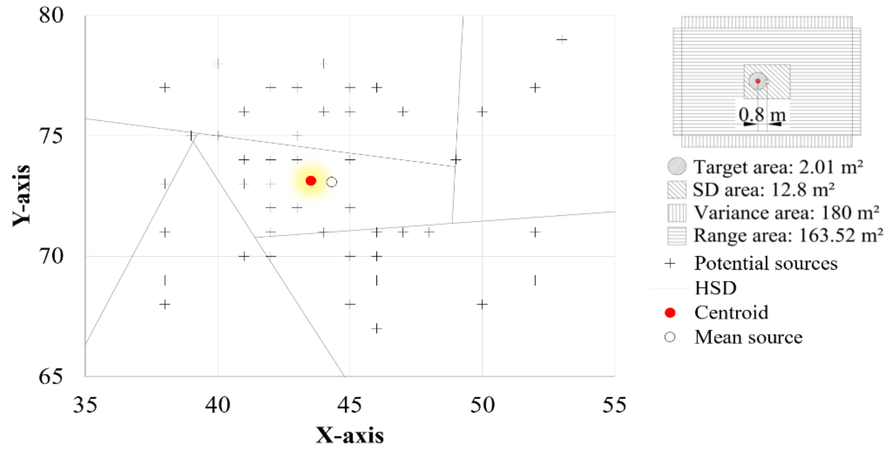

Fig. 4. The scatter analysis

Figure 4 shows the zoomed-in view of the studied spot, where it can be seen that the centroid is close to the mean source, the coordinates of which were estimated as the arithmetic mean of the coordinates of all potential sources. The distance between the centroid and the mean source is 0.8 m. The area of the circle described by this distance (radius) was taken as a target area, which is roughly 2.01 m^2. To assess the uncertainty (%) of the proposed algorithm, the ratios of this target area to the coverage areas derived from the scatter of statistical measures were calculated. The uncertainties amounted to 15.7, 1.1, and 1.2 %, respectively With coverage areas of SD, Variance, and Range being 12.8, 180, and 163.52 m^2. The average uncertainty amounted to 6 %.

Figure 5 shows the results of the simulation for the case of multiple-spot sound sources, in particular, two spots were considered in the same space. Both spots were iteratively filled with 50 potential sources.

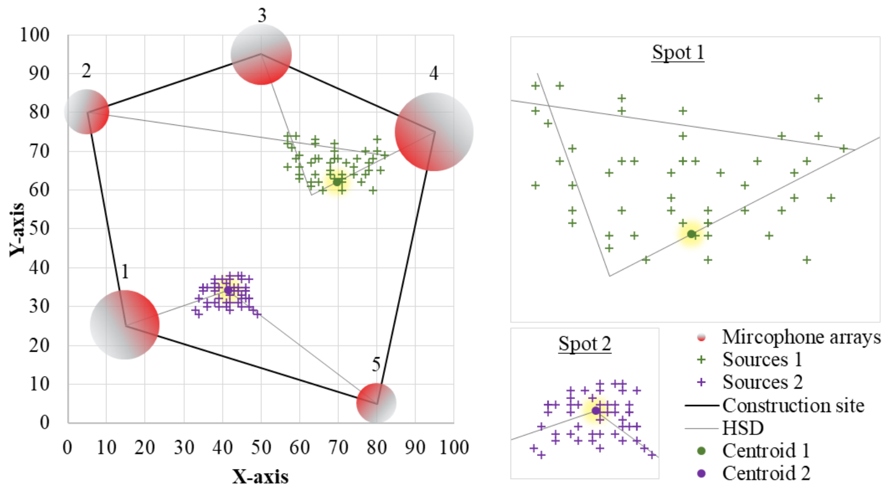

Fig. 5. The two-spot sound sources simulation results

Figure 5 shows that the size of spot 1 is almost twice as wide as spot 2. Such a scenario may often occur in reality when construction works are carried out simultaneously on several spots, and the size of the spots may vary considerably. For the considered case our algorithm consistently produced intersections of HSDs with the 2-4 microphone arrays resulting in a triangle, and a single intersection resulted by 1 and 5 arrays. The coordinates of centroids were [69.657; 62.083] and [41.41; 34.19] for the triangle and intersection, respectively.

Figure 6 presents Boxplots for both considered spots.

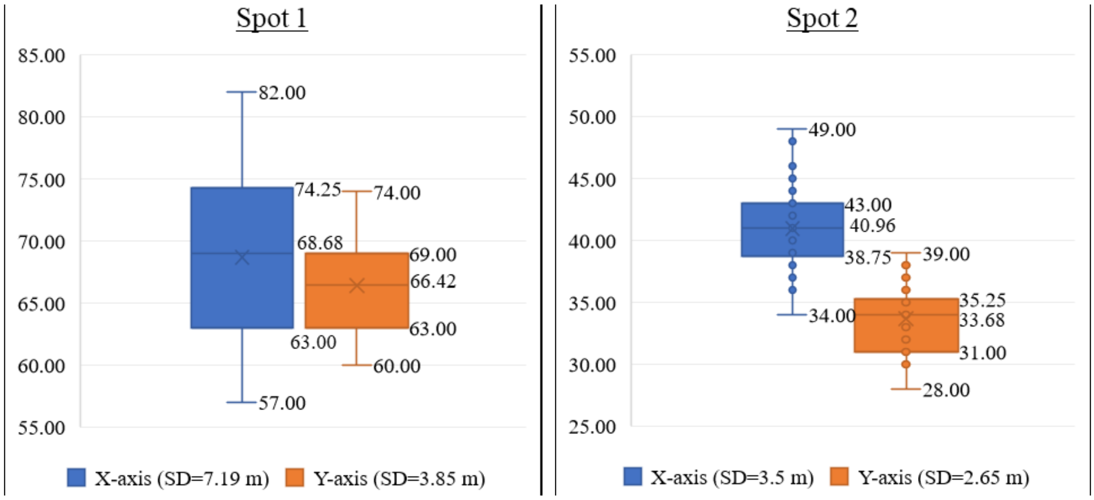

Fig. 6. The boxplots for two spots of sound sources

Boxplots above show the distribution ranges for X and Y coordinates of 57-82 and 60-74 for spot 1, as well as 34-49 and 28-39 for spot 2, respectively. The mean coordinates of the spots are [68.68; 66.42] and [40.96; 33.68], correspondingly. The distance between centroids to the means amounted to 4.45 and 0.68 m, which in turn define the target areas of 62.08 and 1.45 m^2, accordingly. The coverage areas of SD, Variance, and Range amounted to 768.78, 350.00, and 27.73 m^2 for spot 1, and 85.67, 165.00, and 9.26 m^2 for spot 2. The corresponding uncertainties amounted to 8.1, 17.7, and 223.9 % for spot 1, and 1.7, 0.9, and 15.7 % for spot 2. The average uncertainties for the spots amounted to 83.2 and 6.1 %, showing a large difference. Such a difference is rather related to the influence of the area covered by the construction processes. The influence of too many (fifty) simultaneously appearing sound sources should not go unnoticed either. This suggests the importance of considering each case and duration of noise separately.

The proposed SSL method based on RMA and HSD intersections offers significant advancements. Unlike GM1356 [8] and EM2030P [9], our method enables identifying noise source directions. It also supports spatial noise mapping, unlike Cirrus Invictus [10] and AQBot [11]. The use of a radial array reduces cabling needs and enhances detection accuracy compared to CSLF [15]. Additionally, our algorithm requires less computational power than HMAS [14] while maintaining decent accuracy. These improvements make our method more effective for managing noise pollution on construction sites.

4. Conclusion

This study developed an effective method for localizing noise sources on construction sites using a radial microphone array (RMA) and a sound source localization (SSL) algorithm based on the highest signal direction (HSD) intersections. Our simulations demonstrated the feasibility of this approach, forming stable polygons for accurate noise source localization. The potential noise sources were clustered within 180 m^2, with centroid coordinates [43.504; 73.146] and an average uncertainty of 6% for single-spot sources. The algorithm produced centroids at [69.657; 62.083] and [41.41; 34.19], with uncertainties of 83.2% and 6.1%, respectively For multiple-spot sources. These results highlight the algorithm's effectiveness and the influence of field size and noise source number. The proposed RMA and SSL algorithm significantly improves over existing commercial solutions, offering accurate noise source localization with lower computational power. This can enhance noise management on construction sites, improving health and safety for workers and reducing noise pollution in nearby communities. Future work will aim to refine the algorithm, reduce uncertainties, and integrate IoT technologies for real-time, remote monitoring, and data synchronization, increasing the system's practical utility and effectiveness.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Utepov Ye.B. Supervision, Methodology; Imanov A.Zh.: Writing - Original Draft, Conceptualization; Mukanova B.G.: Formal analysis; Nazarova A.G.: Software; Aniskin A.: Resources; Akhazhanov S.B.: Validation

The final manuscript was read and approved by all authors.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19674718).

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