CHAPTER 9

Method for determining three acoustic sensors for registering the ballistic wave of an artillery shot

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Abstract

The chapter addresses the problem of improving the accuracy of determining the coordinates of the point where an artillery projectile impacts the surface under conditions of random disturbances by means of a rational selection of acoustic sensors for registering the ballistic wave. The factors influencing the effectiveness of acoustic measurements are analyzed, including registration errors, the probability of the sensors being in an operational state, and their spatial arrangement relative to the firing direction line. An approach is proposed for determining three most suitable acoustic measuring devices from the available set, taking into account the combined effect of the specified factors. The obtained results create prerequisites for the practical implementation of the artillery shot verification method and for estimating the coordinates of the projectile impact point in a mode close to real time.

Keywords

Artillery shot, acoustic sensors, ballistic wave, shot verification, random disturbances, trajectory approximation.

9.1 Introduction

In modern conditions of employment of artillery units, operational verification of firing results and estimation of the coordinates of the projectile impact point under uncertainty and random disturbances become particularly important. In practice, the effectiveness of such estimations depends not only on the selected method of processing measurement information, but also on the configuration of the measuring

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system, in particular on the composition and spatial arrangement of the acoustic sensors used during firing.

One of the promising directions for solving the problem of artillery shot verification is the application of acoustic methods based on the registration of sound signals generated during the shot and the subsequent flight of the projectile. Analysis of the temporal characteristics of the ballistic wave makes it possible to obtain information suitable for estimating the coordinates of the projectile impact point and for analyzing firing accuracy, which is consistent with the results of known studies in this field [1].

At the same time, processing of acoustic information is associated with the need to take into account the complex nature of sound wave generation and propagation, the influence of the external environment, as well as the characteristics of specific munitions and firing conditions. This necessitates the use of mathematical modeling for signal processing, estimation of wave arrival times between sensors, and construction of projectile motion models. The use of simplified but informative models in this case allows computational costs to be reduced and ensures the possibility of practical implementation of verification methods in a mode close to real time.

In a more general context, the problem of firing result verification is considered as a component of combat process modeling aimed at increasing the effectiveness of fire actions through rational use of available resources and reduction of decision-making time. Formalized models in this case make it possible to describe the firing process as a sequence of interconnected states and transitions between them, providing a quantitative assessment of firing results, analysis of probabilistic characteristics of target engagement, as well as consideration of random disturbances and uncertainties of external conditions [2].

The solution of such problems is complicated by the fact that the corresponding systems are characterized by a large number of interrelated parameters and cannot be fully investigated within the framework of full-scale experiments. Under these conditions, mathematical modeling plays a key role, making it possible to analyze a wide range of possible operating modes of the system and to evaluate their characteristics under various application conditions [3, 4]. To describe the complex dynamics of such systems, it is expedient to use universal approximation methods and analytical approaches, in particular models based on the solution of systems of differential equations, which make it possible to reconstruct behavioral characteristics even in cases where certain parameters cannot be measured directly [5, 6].

With an increase in the dimensionality of the parameter space, the computational complexity of the corresponding models increases significantly, which leads to the need to combine numerical methods, approximation algorithms, and optimization procedures. The application of such approaches makes it possible to work with high-dimensional parameter spaces, solve inverse problems, and analyze the sensitivity of results to variations in initial conditions, which is fundamentally important for estimation and prediction problems under uncertainty [7, 8]. At the same time, consideration of local effects and interactions of parameters in time and space creates the basis for constructing generalized models suitable for further analysis and control of system evolution [9].

Under practical conditions, approaches based on large-scale computational experiments followed by the formation of generalized models or data libraries suitable for rapid analysis and interpretation of results prove to be effective. The use of such generalized representations makes it possible to significantly reduce computational costs at the stage of practical application of models and to ensure decision-making in a mode close to real time, which is especially important for tasks of operational verification of firing results [10].

In view of the above, this chapter addresses the problem of increasing the reliability of determining the coordinates of the point of impact of an artillery projectile with the surface by means of a rational selection of acoustic measuring devices for registering the ballistic wave. It is assumed that a sensor configuration will be formed from the available set of measuring devices, taking into account their geometric arrangement, the probability of an operational state, and random measurement errors. Implementation of such an approach creates prerequisites for building an effective sensor system for verification of artillery shots under conditions of a changing environment and random disturbances.

9.2 Features of constructing a sensor system for shot verification in the artillery firing area

For verification of artillery gun shots in the firing area, a sensor system is deployed, the structure of which is shown in **Fig. 9.1**.

In **Fig. 9.1**, the following notations are adopted:

– AU1, AU2, AU3, …, AU_n are artillery units located in the firing area;

– GS1, GS2, GS3, …, GS_n are sensor groups installed on or near the artillery units;

– AS1, AS2, AS3, …, AS_n are acoustic sensors distributed within the artillery firing area;

– u_{GS1}, u_{GS2}, u_{GS3}, …, u_{GSn} are output signals of sensor groups GS1, GS2, GS3, …, GS_n;

– u_{S1}, u_{S2}, u_{S3}, …, u_{Sn} are output signals of acoustic sensors AS1, AS2, AS3, …, AS_n;

– $\mathbf{U}_S$ is vector of signals transmitted from the intermediate equipment to the computing unit;

– $\mathbf{U}_{CB}$ is vector of signals transmitted from the computing unit to the fire control unit;

– $\mathbf{U}_{SC}$ is vector of signals transmitted from the fire control unit to the computing unit.

The sensor groups GS1, GS2, GS3, ..., GS_n include measuring devices intended for determining projectile motion parameters along the flight trajectory as well as parameters of the external environment that affect the firing process. Each group includes instruments for measuring the initial velocity, elevation and firing direction angles, as well as sensors of meteorological characteristics.

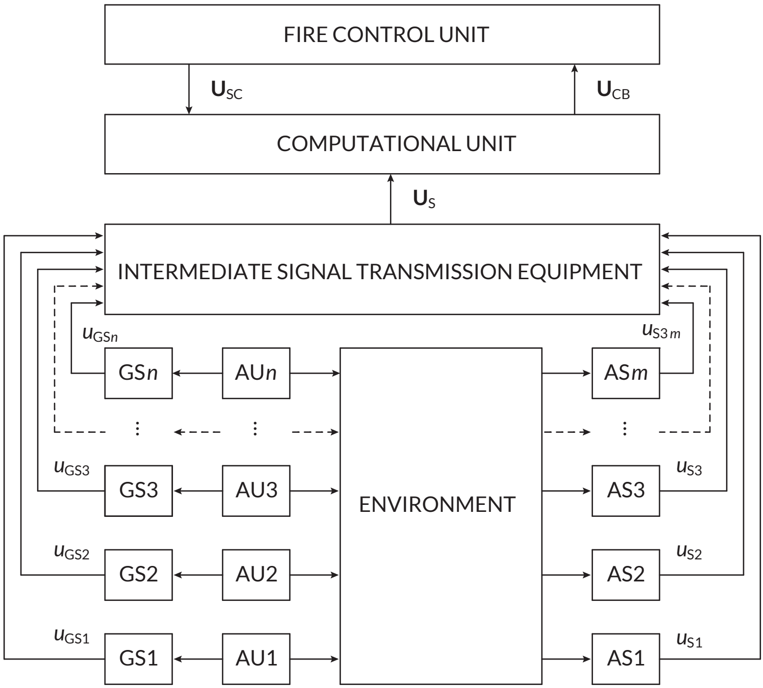

Fig. 9.1 Functional structure of the sensor system for verification of artillery gun shots

Within the firing area, *m* acoustic sensors register ballistic and muzzle waves generated by artillery shots ($m \gg n$). They are deployed using UAVs or other remote methods, ensuring a uniform spatial distribution and a minimum density that guarantees the required registration accuracy for all *n* artillery units.

For clarity, **Fig. 9.2** shows a general scheme of acoustic sensor placement in the artillery firing area for the case when the firing direction line forms an angle α

with the Oy axis. The following notations are adopted: 1 – artillery unit; 2 – target; 3 – i-th acoustic sensor ($I = 1, 2, ..., m$); x_{AU}, y_{AU} are coordinates of the artillery unit; x_t, y_t are coordinates of the target; x_i, y_i are coordinates of the i-th acoustic sensor; α is angle between the firing direction line and the Oy axis.

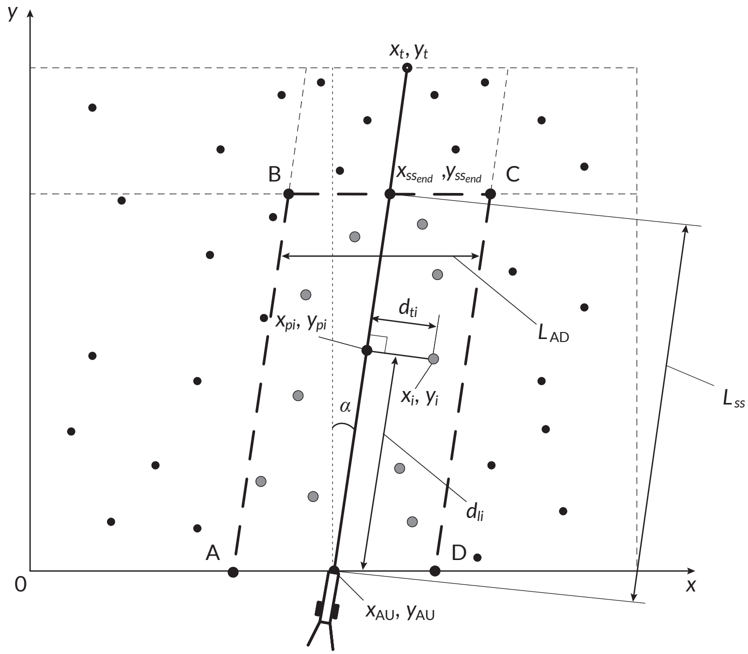

Fig. 9.2 Scheme of acoustic sensor placement in the terrain within the artillery firing area

The accuracy of registering ballistic and muzzle waves depends on the distance between the acoustic sensor and the firing direction line and is determined experimentally. In most practical cases, in order to ensure effective registration of an artillery shot, this distance should not exceed 50 m. Registration of the ballistic wave by acoustic sensors is possible only within the segment of the trajectory where the projectile moves at a supersonic velocity. Under these conditions, the selection of three acoustic sensors for registering shot parameters is carried out from the set of sensors located within parallelogram ABCD, as shown in **Fig. 9.2**.

The following notations are introduced: x_1, y_1, x_2, y_2, x_3, y_3 are the coordinates of the first, second, and third acoustic sensors selected for registering ballistic and muzzle waves from the set of sensors bounded by parallelogram ABCD; d_1, d_2, d_3 are the distances from the corresponding acoustic sensors to the firing direction line.

In this case, the width of the zone of effective registration of ballistic and muzzle waves by the sensors along AD (**Fig. 9.3**) is 100 m. The length of the ballistic wave action zone AB is preliminarily determined with respect to the specified firing range as the length of the trajectory segment over which the projectile maintains supersonic velocity. The length of this segment is calculated on the basis of mathematical and simulation models of projectile flight [11, 12], developed in accordance with the NATO STANAG 4355 standard.

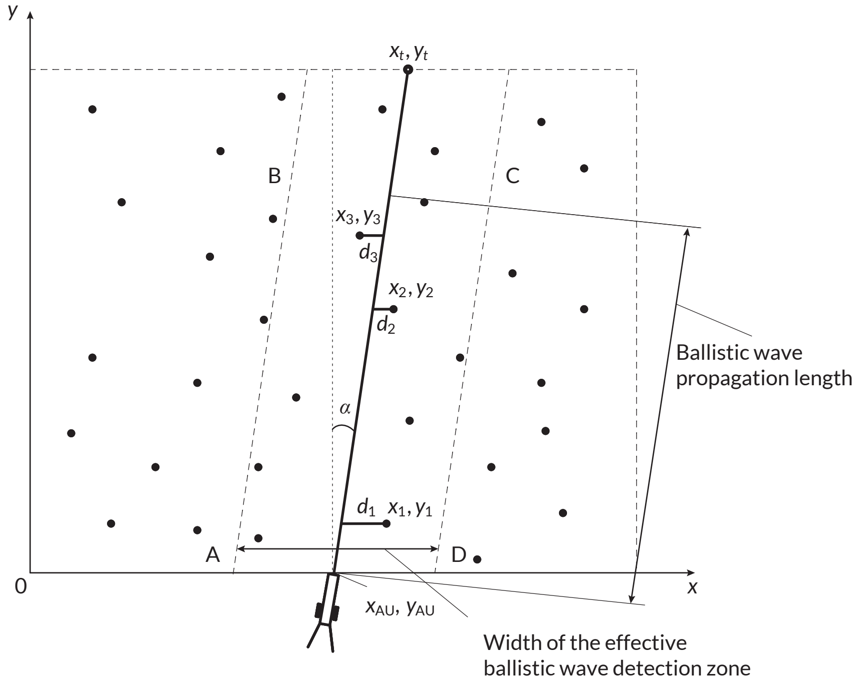

Fig. 9.3 Determination of the sensors closest to the firing direction line

Under the specified configuration, the selection of three acoustic sensors with coordinates x_1, y_1, x_2, y_2, x_3, y_3 from the available set is performed according to the minimum values of distances d_1, d_2, d_3 from the corresponding sensors to the firing direction line.

To reduce the total number of acoustic sensors in the firing area, it is advisable to arrange them in the form of three strips, as shown in **Fig. 9.4**.

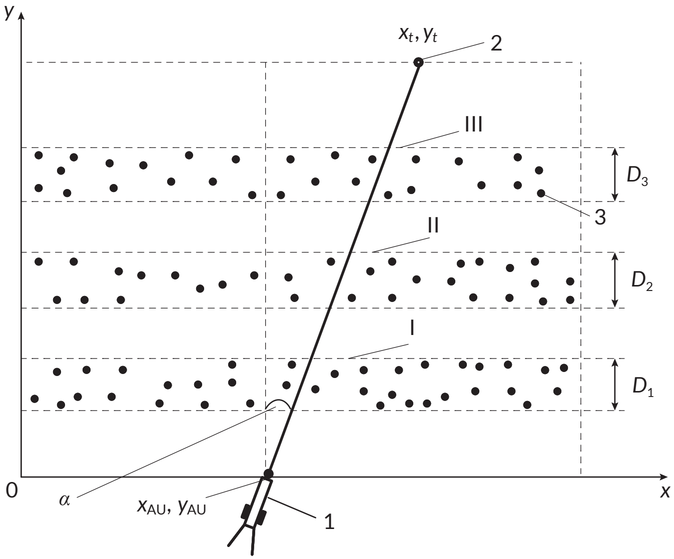

Fig. 9.4 Scheme of acoustic sensor placement in three strips within the artillery firing area

In **Fig. 9.4**, the following notations are adopted: I, II, III are the first, second, and third sensor strips; D_1, D_2, D_3 are the widths of the corresponding strips. The first, second, and third acoustic sensors for registering ballistic and muzzle waves are selected, respectively, from the first, second, and third strips. All three strips must be located within the ballistic wave action zone. Taking into account possible changes in the coordinates of artillery units and targets, the values of D_1, D_2, D_3, as well as the distances between the strips, are determined on the basis of a preliminarily estimated average firing range in the given operational area.

The intermediate equipment intended for transmitting signals from the sensors (vector $\mathbf{U}_S$) to the computing unit includes intermediate nodes and communication channels that form a specialized data transmission network. With a large number of sensors, which may reach several thousand or tens of thousands, direct transmission of signals from the measuring devices to the computing unit becomes significantly complicated. Such a scheme leads to an increase in network complexity, a decrease in its reliability, and, consequently, an increase in the overall system cost.

In order to reduce complexity and increase the reliability of the data transmission network, its structure should be formed according to a hierarchical principle using intermediate information collection nodes. Intermediate nodes of the first hierarchy level perform grouping and preliminary processing of signals from sensors and transmit them to nodes of the second level, and further to the system computing unit. Signal transmission from sensors to network nodes, as well as between individual nodes, is carried out via radio communication, while connections between upper-level nodes and the computing unit may be implemented via wired channels to improve reliability.

The formation of the hierarchical structure of the signal transmission network is carried out as follows. First, a network structure vector S of dimension j_{max} is specified, which corresponds to the total number of hierarchy levels. Each element of the vector S_j ($j = 1, ..., j_{max}$) defines the number of nodes at the j-th hierarchy level. The number of nodes S_j at each level is selected taking into account condition (9.1)

$$S_j \leq \mathrm{floor}\left(\frac{S_{j-1}}{2}\right), \tag{9.1}$$

according to which each node must have at least two inputs ($k_j \geq 2$). At the last hierarchy level, the presence of a single main node ($S_{j_{max}} = 1$), directly connected to the computing unit is assumed, while at the penultimate level the number of nodes must be not less than two ($S_{j_{max-1}} \geq 2$).

After determining the number of nodes at each hierarchy level, the number of inputs k_j for the nodes of the corresponding level is calculated on the basis of relation (9.2)

$$k_j = \frac{S_{j-1}}{S_j}. \tag{9.2}$$

If the obtained value of k_j is an integer, all nodes at this level have the same number of inputs. Otherwise, the level contains nodes with a number of inputs equal to the nearest smaller and the nearest larger integers relative to k_j, while the proportion of nodes with the larger number of inputs is determined by the fractional part of the calculated value of k_j.

After determining the number of inputs for the nodes at each hierarchy level, an appropriate hierarchical structure of the sensor signal transmission network is constructed on the basis of the formed vector S. At each j-th level, S_j nodes are created, which are successively interconnected by communication channels from the first level to the final level j_{max}. In this case, nodes of level $j - 1$ are connected exclusively to nodes of level j, taking into account the number of inputs of the latter, and the output of each node at level (j − 1) may be connected to only one input of a node at level j. After all required connections are established, the construction of the data transmission network structure is considered complete.

For clarity, three variants of signal transmission network structures are presented for the same number of primary sensors S_0 = 13. In the structure shown in **Fig. 9.5**, information is transmitted directly from the primary sensors to a single main node connected to the system computing unit.

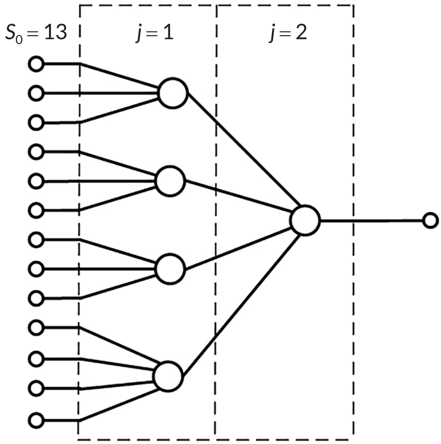

Fig. 9.5 Typical two-level hierarchical structure of sensor signal aggregation

In the limiting case j_{max} = 1, the hierarchical structure degenerates into a single-level scheme, where signals from all sensors S_0 are directly transmitted to the main node. As the number of hierarchy levels increases ($j_{max} > 2$), the network structure is expanded in a similar manner by successive grouping of lower-level nodes and connecting them to higher-level nodes.

Thus, the presented scheme reflects a general approach to the formation of hierarchical data transmission structures, within which the specific number of levels is determined by requirements for scalability, transmission delays, and computational load.

For the presented structures, the vectors **S** are defined by expressions (9.3) and (9.4), respectively:

$$\mathbf{S} = \{4,1\}, \tag{9.3}$$

$$\mathbf{S} = \{5,2,1\}. \tag{9.4}$$

Depending on the current fire tasks, the fire control unit transmits to the computing unit the signal vector $\mathbf{U}_{SC}$, which contains the coordinates of the designated targets. Based on the vectors $\mathbf{U}_S$ (from the sensor signal transmission network) and $\mathbf{U}_{SC}$, the computing unit performs verification of artillery shots, taking into account random disturbances, and determines the coordinates of projectile impacts on the surface.

In addition, before each shot, the computing unit identifies three sensors from the available set of measuring devices that are most suitable for registering the ballistic and muzzle waves. The results of these calculations, including the coordinates of projectile impacts and the selected sensors, are transmitted to the fire control unit in the form of the signal vector $\mathbf{U}_{SC}$. The task of selecting the three optimal sensors during artillery shot verification is solved using the method described in the following subsection.

9.3 Method for registering the coordinates of an artillery projectile impact with the surface

The proposed approach makes it possible to determine three acoustic sensors that are the most suitable for registering the ballistic wave during the verification of artillery shots, based on the known current coordinates of the target, the artillery unit, and all functioning acoustic sensors located within the firing area.

The target coordinates are received from the fire control unit in accordance with the assigned fire mission. The current coordinates of the artillery unit and each acoustic sensor are determined using their built-in navigation systems.

At the initial stage, on the basis of the target and artillery unit coordinates, the firing range L_s and the angle α with respect to the *Oy* axis (**Fig. 9.3**) are determined, after which the equation of the firing direction line for the current shot is formed. The values of L_s and α are calculated using relations (9.5) and (9.6), and the equation of the firing direction line in the form of the general equation of a straight line in the plane is written as (9.7) [13–15]:

$$L_s = \sqrt{\left(x_t - x_{AU}\right)^2 + \left(y_t - y_{AU}\right)^2}, \tag{9.5}$$

$$\alpha = \arcsin\left(\frac{x_t - x_{AU}}{L_s}\right), \tag{9.6}$$

$$a_{ls}x + b_{ls}y + c_{ls} = 0, \tag{9.7}$$

where a_{ls}, b_{ls}, c_{ls} are the coefficients of the firing direction line equation.

In this case, the angle α can take values in the range from −90° to 90° and is measured clockwise. The coefficients of the straight-line equation a_{ls}, b_{ls}, c_{ls} are determined using expressions of analytical geometry [13] or on the basis of the least squares method using the known coordinates of the target and the artillery unit [16].

In order to significantly reduce the computational burden when selecting the three most appropriate acoustic sensors, it is expedient at the initial stage to select, from the total number of functioning sensors, only those located within the zone of possible registration of the ballistic and muzzle waves of the current artillery shot. This zone is bounded by parallelogram ABCD (**Fig. 9.3**).

The width AD should be specified depending on the accuracy of registration of ballistic and muzzle waves by acoustic sensors and, as a rule, should not exceed 100 m. The length AB is defined as the length of the projectile flight segment with supersonic velocity (supersonic segment) L_{SS}, which is calculated on the basis of the preliminarily determined firing range L_s using formula (9.5) [11, 12].

To determine the zone of possible registration of ballistic and muzzle waves and for the subsequent selection of sensors located within this zone, it is necessary to determine the coordinates of points A, B, C, and D, as well as the equations of the four straight lines passing through the corresponding pairs of these points.

The coordinates of points A and D are determined on the basis of the current coordinates of the artillery unit AU using expressions (9.8) and (9.9), respectively:

$$x_{\mathrm{A}} = x_{\mathrm{AU}} - \frac{L_{\mathrm{AD}}}{2}; y_{\mathrm{A}} = y_{\mathrm{AU}}, \tag{9.8}$$

$$x_{\mathrm{D}} = x_{\mathrm{AU}} + \frac{L_{\mathrm{AD}}}{2}; y_{\mathrm{D}} = y_{\mathrm{AU}}, \tag{9.9}$$

where L_{AD} is the length of segment AD.

The coordinates of points B and C are determined on the basis of the coordinates of the point on the firing direction line at which the projectile loses its supersonic velocity, using expressions (9.10) and (9.11):

$$x_{\mathrm{B}} = x_{ss_{end}} - \frac{L_{\mathrm{BC}}}{2}; y_{\mathrm{B}} = y_{ss_{end}}, \tag{9.10}$$

$$x_{\mathrm{C}} = x_{ss_{end}} + \frac{L_{\mathrm{BC}}}{2}; y_{\mathrm{C}} = y_{ss_{end}}, \tag{9.11}$$

where $x_{ss_{end}}$, $y_{ss_{end}}$ are the coordinates of the corresponding point, and $L_{\mathrm{BC}} = L_{\mathrm{AD}}$.

Thus, the coordinates of the point on the firing direction line at which the projectile loses its supersonic velocity are calculated on the basis of the determined length of the projectile flight segment with supersonic velocity L_{ss}, the angle α, and the current coordinates of the artillery unit using expressions (9.12) and (9.13), respectively:

$$x_{ss_{end}} = x_{\mathrm{AU}} + L_{ss} \sin\alpha, \tag{9.12}$$

$$y_{ss_{end}} = y_{\mathrm{AU}} + L_{ss} \cos\alpha. \tag{9.13}$$

Next, the equations of the four straight lines passing through the following point pairs are determined: 1) A and B; 2) D and C; 3) A and D; 4) B and C. To simplify the calculations, it is expedient to represent the equations of these lines in the form of straight-line equations with slope coefficients:

$$y = a_{\mathrm{AB}} x + b_{\mathrm{AB}}, \tag{9.14}$$

$$y = a_{\mathrm{DC}} x + b_{\mathrm{DC}}, \tag{9.15}$$

$$y = a_{\mathrm{AD}} x + b_{\mathrm{AD}}, \tag{9.16}$$

$$y = a_{\mathrm{BC}} x + b_{\mathrm{BC}}, \tag{9.17}$$

where a_{AB}, b_{AB}, a_{DC}, b_{DC}, a_{AD}, b_{AD}, a_{BC}, b_{BC} are the coefficients of the equations of the corresponding straight lines. These coefficients are determined using well-known relations of analytic geometry [13] or by applying the least squares method based on the coordinates of points A, B, C, and D [16].

After that, on the basis of the line equations (9.14)–(9.17) and their determined coefficients, conditions (9.18) are formulated, according to which a sequential verification of all functioning acoustic sensors of the system is carried out using their coordinates. There is:

$$\begin{cases} x_i \ge \dfrac{y_i - b_{\mathrm{AB}}}{a_{\mathrm{AB}}}; \\ x_i \le \dfrac{y_i - b_{\mathrm{DC}}}{a_{\mathrm{DC}}}; \\ y_i \ge a_{\mathrm{AD}} x_i + b_{\mathrm{AD}}; \\ y_i \le a_{\mathrm{BC}} x_i + b_{\mathrm{BC}}. \end{cases} \tag{9.18}$$

If the coordinates of the i-th sensor satisfy conditions (9.18), it lies within the zone of possible registration of the ballistic and muzzle waves of an artillery shot and can be selected as one of the three most suitable sensors.

After performing this sorting procedure, all sensors that satisfy conditions (9.18) are numbered and selected for further calculations aimed at determining the three most appropriate measuring devices for registering the ballistic and muzzle waves. Acoustic sensors that do not fall within the region bounded by parallelogram ABCD are not used at subsequent stages of the method.

At the following computational stages of the proposed method, only three sensors are selected from the set of preselected sensors as being the most suitable for registering the ballistic and muzzle waves. To select these three acoustic sensors, all preselected sensors are evaluated according to the following parameters.

The first parameter that significantly affects the suitability of an acoustic sensor for high-quality registration of the ballistic and muzzle waves is its position along the firing direction line. This position is determined by the distance d_l from the artillery unit to the point on the firing direction line that is closest to the given sensor.

For more accurate verification of artillery shots, it is advisable to register the ballistic and muzzle waves over the second half of the projectile flight segment with supersonic velocity and as close as possible to its end [17, 18]. In addition, all three acoustic sensors should be placed uniformly along the firing direction line to ensure reliable registration of the ballistic and muzzle waves at three distinct points. At the same time, the third sensor should not be located too close to the point with coordinates $x_{ss_{end}}$, $y_{ss_{end}}$, at which the projectile loses its supersonic velocity, since the position of this point is determined with a certain error. In such a case, the sensor may be positioned outside the supersonic flight segment of the projectile. Therefore, as optimal distances from the artillery unit to the first, second, and third sensors along the firing direction line, it is reasonable to preliminarily adopt the following values: $d_{l1\text{opt}} = 0.5L_{ss}$; $d_{l2\text{opt}} = 0.7L_{ss}$; $d_{l3\text{opt}} = 0.9L_{ss}$.

Thus, when selecting the most suitable first, second, or third acoustic sensor, it is necessary, for each i-th sensor located within the zone of possible registration of the ballistic and muzzle waves (ABCD), to calculate the parameter d_{li} and compare its value with the corresponding predefined optimal value $d_{l1\text{opt}}$, $d_{l2\text{opt}}$ or $d_{l3\text{opt}}$.

At the same time, the distance d_{li} for the i-th acoustic sensor is calculated on the basis of the coordinates of this sensor and the obtained general equation of the firing direction line (9.7) as follows. First, the coordinates x_{pi}, y_{pi} of the point on the firing direction line that is closest to the i-th sensor are determined using expressions (9.19) and (9.20) [13–15]:

$$x_{pi} = \frac{b_{ls}\left(b_{ls}x_i - a_{ls}y_i\right) - a_{ls}c_{ls}}{a_{ls}^2 + b_{ls}^2}, \tag{9.19}$$

$$y_{pi} = \frac{a_{ls}\left(a_{ls}y_i - b_{ls}x_i\right) - b_{ls}c_{ls}}{a_{ls}^2 + b_{ls}^2}. \tag{9.20}$$

Subsequently, using the obtained coordinates x_{pi}, y_{pi} and the known coordinates of the artillery unit x_{AU}, y_{AU}, the distance d_{li} is directly calculated using formula (9.21)

$$d_{li} = \sqrt{\left(x_{pi} - x_{\mathrm{AU}}\right)^2 + \left(y_{pi} - y_{\mathrm{AU}}\right)^2}. \tag{9.21}$$

Another equally important parameter used to select the most suitable acoustic sensors is the distance d_t from a sensor to the nearest point on the firing direction line, which is defined as the length of the perpendicular drawn from the sensor location to the firing direction line. The smaller the value of this distance, the higher the accuracy of registering the ballistic and muzzle waves of the shot, and, accordingly, the more suitable the sensor is considered. Therefore, the optimal configuration for all acoustic sensors (first, second, and third) used for shot verification is their placement directly on the firing direction line ($d_{t1\mathrm{opt}} = d_{t2\mathrm{opt}} = d_{t3\mathrm{opt}} = 0$).

The value of this distance d_{ti} for the i-th acoustic sensor can be calculated based on the coordinates of the given sensor x_i, y_i and the obtained general equation of the firing direction line (9.7) using expression (9.22) [13–15]

$$d_{ti} = \frac{\left|a_{ls}x_i + b_{ls}y_i + c_{ls}\right|}{\sqrt{a_{ls}^2 + b_{ls}^2}}. \tag{9.22}$$

The third parameter that must also be taken into account when selecting the three most suitable acoustic sensors is the value of their probability of failure-free operation $P(t)$. Even if the i-th sensor has a sufficiently favorable location (in terms of the parameters d_{li} and d_{ti}) within zone ABCD, but its probability of failure-free operation is low, selecting it for registering ballistic and muzzle waves would be impractical. This is because there is a relatively high risk of sensor malfunction and, consequently, failure to complete the entire verification procedure for the current shot.

In practice, the reliability of any element is determined by two components: the probability of failure-free operation under random failures $P(t)$ and the probability of failures due to wear $P_w(t)$. Random failures are described by an exponential law, according to which the reliability, or probability of failure-free operation $P(t)$, is determined by the expression

$$P(t) = e^{-\lambda t}, \tag{9.23}$$

where λ is the intensity (rate) of random failures.

During the period of normal equipment operation, the failure intensity for the exponential law is a constant value. When wear begins, the failure intensity starts to increase, and in addition to random failures, wear-out failures also occur. These wear-related failures are usually described by a normal distribution

$$P_w(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_t^{\infty} e^{-(t-M)^2/2\sigma^2} dt, \tag{9.24}$$

where M is the mean value of the element lifetime taking wear into account, and σ is the standard deviation of the lifetime from its mean value, which is defined as

$$\sigma = \sqrt{\frac{\sum (t-M)^2}{N}}, \tag{9.25}$$

where N is the number of failures over the time interval t.

Moreover, the combined probability of failure-free operation of an element, taking into account both sudden failures and wear-out failures, over the period from $t = 0$ (when the element is new) to time t, is calculated as

$$P(t) = e^{-\lambda t} P_w(t). \tag{9.26}$$

Thus, in the process of selecting the most suitable sensors for recording the ballistic and muzzle waves of a shot, the probability of failure-free operation $P_i(t)$ for each i-th acoustic sensor is determined using expression (9.26), depending on the operating time t and based on the known values λ_i, M_i, and N_i.

For a comprehensive assessment of the suitability of acoustic sensors for recording ballistic and muzzle waves, it is expedient to formulate an integrated dimensionless suitability criterion J, which properly accounts for all three considered sensor parameters (d_{li}, d_{ti}, and P_i). Accordingly, the suitability criterion J_i for each i-th sensor is defined as

$$J_i = f\left(d_{li}, d_{ti}, P_i\right). \tag{9.27}$$

Since the considered parameters d_{li}, d_{ti}, and P_i used to assess sensor suitability differ in their physical nature, vary significantly in absolute magnitude, and may be computed with certain uncertainties, formalizing their interrelation within a single criterion based on strict mathematical dependencies is a rather challenging task. Therefore, to calculate the current value of the criterion J_i with proper consideration of each of the above-mentioned sensor parameters (d_{li}, d_{ti}, and P_i), it is expedient to employ the mathematical apparatus of fuzzy logic theory. This approach enables effective aggregation of expert knowledge and experimental data, approximation of arbitrary nonlinear multidimensional relationships, and construction of linguistic models of complex objects and processes [19–21].

For convenience of calculations, it is reasonable to assume that the acoustic sensor suitability criterion J varies within the range from 0 to 1. The closer the calculated value of the criterion J_i is to 1, the more suitable the i-th sensor is considered.

Since three most suitable sensors must be selected to record the ballistic and muzzle waves of each shot, the criterion J_i for each i-th sensor should be calculated three times (J_{i1}, J_{i2}, J_{i3}), taking into account the role in which the sensor is assumed to be used, namely as the first, second, or third sensor. Subsequently, the maximum of the obtained values (J_{i1}, J_{i2}, or J_{i3}) is used to determine the final suitability of the given sensor J_{if}, with its assignment to a specific role (first, second, or third sensor). Thus,

$$J_{if} = \max\{J_{i1}, J_{i2}, J_{i3}\}. \tag{9.28}$$

After that, based on the value of the final suitability J_{if}, the given i-th acoustic sensor is assigned to one of three groups: potential first, second, or third sensors. For example, for the i-th acoustic sensor the following suitability criterion values were calculated for its use as the first, second, and third sensor: $J_{i1} = 0.791$; $J_{i2} = 0.215$; $J_{i3} = 0.42$. Since the value J_{i1} is the largest among those obtained, this sensor is preliminarily assigned to the group of potential first sensors with the corresponding suitability $J_{if} = 0.791$.

Thus, for all sensors located within the possible ballistic and muzzle wave registration zone ABCD, the suitability criterion J is calculated three times, taking into account their possible use as the first, second, or third sensor. The largest of the obtained values determines the final suitability J_{if}, after which the sensors are distributed among the three corresponding groups.

At the final stage of the method, in the established groups of potential first, second, and third sensors, the most suitable first, second, and third sensors are selected according to the maximum suitability values J_{best1}, J_{best2} and J_{best3}. These acoustic sensors are the three sensors that will be used to register the ballistic and muzzle waves of the current artillery shot.

Based on the above, the steps of the method for determining three acoustic sensors for registering the ballistic and muzzle waves of an artillery shot are presented below:

Step 1. Method initialization. At this stage, all initial data required for the verification of artillery shots are obtained. The number and coordinates of all operational acoustic sensors within the artillery firing zone are determined, and the values of parameters used in subsequent calculations are fixed: the width of the possible ballistic and muzzle wave registration zone L_{AD}; the optimal distances from the artillery unit to the first, second, and third sensors along the firing direction line d_{l1opt}, d_{l2opt}, d_{l3opt}; and the current values of the sensors' probability of failure-free operation $P(t)$.

The width of the zone AD, L_{AD}, should be set according to the accuracy of wave registration (in most practical cases $L_{AD} = 100$ m). The optimal distances d_{l1opt}, d_{l2opt}, d_{l3opt} are specified as functions of the length of the supersonic flight segment. The values of $P(t)$ are determined based on their known parameters λ, M, N and the operating time t. Before starting the calculations, the current coordinates of the target x_t, y_t and the artillery unit x_{AU}, y_{AU} are also recorded.

Step 2. Performing initial calculations. Based on the coordinates of the target x_t, y_t and the artillery unit x_{AU}, y_{AU}, the firing range L_s, the angle α relative to the Oy axis, and the length of the supersonic flight segment L_{SS} are determined. At the same time, the equation of the firing direction line for the current shot is formed, and its coefficients a_{ls}, b_{ls}, c_{ls} are calculated in accordance with (9.5)–(9.7).

Step 3. Determination of the possible registration zone of the ballistic and muzzle waves of the current shot ABCD. At this stage, using expressions (9.8)–(9.13), the coordinates of points A, B, C, D, as well as the point $x_{ss_{end}}$, $y_{ss_{end}}$ at which the projectile loses supersonic velocity, are determined. Then, the equations of the four boundary lines of zone ABCD are constructed according to (9.14)–(9.17).

Step 4. Sorting of sensors within the ABCD zone. From the total set of operational sensors, only those which coordinates satisfy the conditions (9.18) are selected. The selected sensors are numbered and used in subsequent calculations, where as all other sensors are not used in the following stages of the method.

Step 5. Calculation of the parameter d_{li}. For each i-th sensor located within the ABCD zone, the distance d_{li} from the artillery unit to the point on the firing direction line closest to the sensor is calculated using formula (9.21), with the coordinates x_{pi}, y_{pi} determined according to expressions (9.19) and (9.20).

Step 6. Calculation of the parameter d_{ti}. For each selected sensor, the distance d_t from the sensor to the firing direction line is determined using formula (9.22).

Step 7. Determination of the parameter $P_i(t)$. For each i-th sensor within the ABCD zone, the probability of failure-free operation $P_i(t)$ is calculated according to expression (9.26).

Step 8. Calculation of the comprehensive suitability criterion J_i. Based on the parameters d_{li}, d_{ti}, and $P_i(t)$ for each sensor, the criterion J_i is computed three times (J_{i1}, J_{i2}, J_{i3}) according to expression (9.27), taking into account the potential use of the sensor as the first, second, or third. The calculation is performed using the previously developed fuzzy logic model.

Step 9. Assignment of sensors to groups. For each *i*-th sensor, the final suitability J_{if} is determined according to expression (9.28), after which all sensors are classified into three groups of potential first, second, and third sensors.

Step 10. Selection of the best first, second, and third sensors. Within each of the three formed groups, one sensor with the maximum suitability values J_{best1}, J_{best2}, J_{best3} is selected. The selected sensors are used to register the ballistic and muzzle waves of the current artillery shot.

After completion of Step 10, the search for the optimal acoustic sensors is considered complete, and the selected three sensors can be used to verify the current artillery shot and to register the coordinates of the projectile impact point.

9.4 Development of a fuzzy model for calculating the suitability criterion of acoustic sensors for registration of ballistic and muzzle waves of a shot

According to the fuzzy approximation theorem [22], any mathematical relationship can be approximated by a system based on fuzzy logic. This makes it possible to represent complex "input–output" relationships in the form of a set of natural-language rules of the type "IF …, THEN …", formalized using the theory of fuzzy sets, without the need to employ complex analytical models, in particular differential and integral equations [19]. Modern fuzzy models, which are characterized by interpretability and logical transparency, can be constructed on the basis of various fuzzy inference mechanisms, enabling effective use of expert knowledge as well as learning based on experimental data sets and objective functions similar to those used in neural networks [20, 21]. These features make fuzzy models and systems flexible, universal, and promising for solving problems related to modeling complex objects and processes.

For the simultaneous calculation of three values of the composite suitability criterion J_{i1}, J_{i2}, and J_{i3} for each *i*-th acoustic sensor, taking into account its possible use as the first, second, or third sensor, a fuzzy model is proposed, which should have the structure shown in **Fig. 9.6**.

In **Fig. 9.6**, the following notations are used: FM denotes the fuzzy model for calculating the suitability criterion; FB is the fuzzification block; FIL is the fuzzy logical inference block; DB is the defuzzification block; RB is the rule base; K_{d1}, K_{d2}, K_P are normalization coefficients used to convert the input variables of the model d_{li}, d_{ti}, and P_i into relative units with respect to their maximum values; d^*_{li}, d^*_{ti} and P^*_i are the normalized values of the corresponding input variables of the fuzzy model.

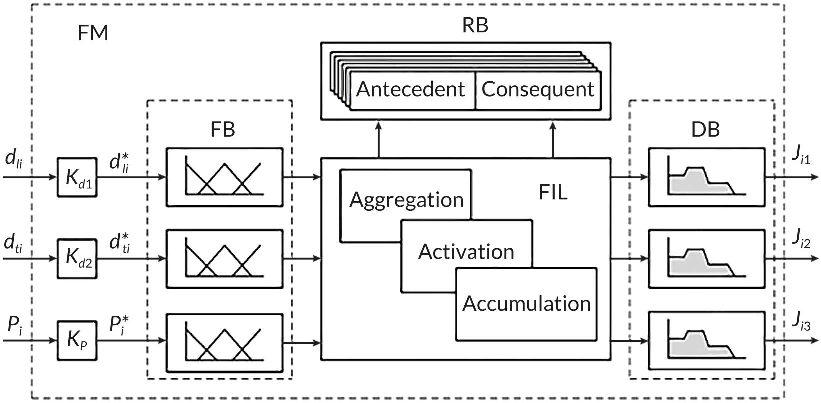

Fig. 9.6 Structure of the fuzzy model for calculating the values of the acoustic sensor suitability criterion

As shown in **Fig. 9.6**, the proposed model has three output variables (J_{i1}, J_{i2}, J_{i3}), each of which represents the suitability of the *i*-th acoustic sensor as the first, second, or third sensor, respectively, depending on the input parameters d_{li}, d_{ti}, and P_i in accordance with the developed rule base.

In this case, for the fuzzy model with the proposed structure (**Fig. 9.6**), it is advisable to choose the Mamdani type of fuzzy logical inference [23], which provides sufficient efficiency with a relatively simple synthesis and tuning procedure [21].

The fuzzification block determines the degrees of membership of the numerical values of the input variables d_{li}, d_{ti}, and P_i to the corresponding fuzzy linguistic terms of the fuzzy model [20]. The fuzzy logical inference block implements aggregation, activation, and accumulation operations based on the rule base. The defuzzification block converts the resulting fuzzy set into a crisp numerical value of the output variable J_i [23].

Next, the main procedures for synthesizing the fuzzy logical model for calculating the suitability criterion of acoustic sensors are considered in detail.

The normalization coefficients of the model K_{d1} and K_{d2} are determined by expressions (9.29) and (9.30):

$$K_{d1}=\frac{1}{L_{ss}},\tag{9.29}$$

$$K_{d2}=\frac{2}{L_{AD}}.\tag{9.30}$$

This makes it possible to convert the current values of the input variables d_{li} and d_{ti} into relative units with respect to their maximum values ($d_{li\max} = L_{ss}$; $d_{ti\max} = L_{AD}/2$).

Since the probability of failure-free operation P_i for each i-th acoustic sensor varies within the range [0, 1], and the operating range of this variable is assumed to be the interval [0.75, 1], the normalization coefficient K_P in this case is equal to 1. Sensors with a current value of $P_i(t) < 0.75$ are not admitted to further evaluation.

For the input (d_{li}, d_{ti}, P_i) and output (J_{i1}, J_{i2}, J_{i3}) variables of the fuzzy model, sets of linguistic terms have been defined, which are presented in **Table 9.1**.

The triangular membership function of a linguistic term, illustrated here for the variable d_{li}, is defined by expression (9.31):

$$\mu(d_{lj})=\begin{cases}0, & \text{when } d_{li}\le a;\\ \dfrac{d_{li}-a}{b-a}, & \text{when } a<d_{li}\le b;\\ \dfrac{c-d_{li}}{c-b}, & \text{when } b<d_{li}<c;\\ 0, & \text{when } d_{li}\ge c,\end{cases}\tag{9.31}$$

where a, b, c are adjustable parameters of the function, subject to the condition $a \le b \le c$. The graphical representation of the linguistic terms for the input and output variables of the fuzzy model with the specified parameters is shown in **Fig. 9.7**.

Table 9.1 Linguistic terms of the fuzzy model for calculating the values of the suitability criterion

Fuzzy model variables	Number of linguistic terms	Selected linguistic terms	Type of membership functions of linguistic terms
d_{li}	5	VS – very short; S – short; M – medium; LN – long; VLN – very long	triangular
d_{ti}	3	S – short; M – medium; LN – long	triangular
P_i	3	L – low; A – average; H – high	triangular
J_{i1}, J_{i2}, J_{i3}	7	VL – very low; L – low; BA – below average; A – average; AA – above average; H – high; VH – very high	triangular

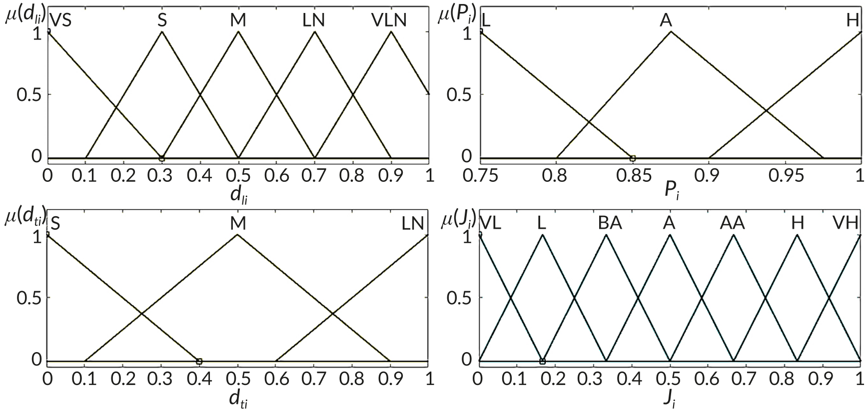

Fig. 9.7 Linguistic terms (with specified parameters) for the input and output variables of the fuzzy model

As can be seen from **Table 9.1** and **Fig. 9.7**, the same sets of linguistic terms are used for the three output variables J_{i1}, J_{i2} and J_{i3}.

The rules of the proposed fuzzy model for calculating the acoustic sensors' suitability criterion are formulated as follows:

$$\text{IF "}d_{li}=LT_{dl}\text{" AND "}d_{ti}=LT_{dt}\text{" AND "}P_i=LT_P\text{"}$$
$$\text{THEN "}J_{i1}=LT_{J1}\text{" AND "}J_{i2}=LT_{J2}\text{" AND "}J_{i3}=LT_{J3}\text{",} \tag{9.32}$$

where LT_{dl}, LT_{dt}, LT_P, LT_{J1}, LT_{J2}, LT_{J3} are specific linguistic terms of the input and output variables.

For example, the first rule of RB is expressed as:

$$\text{IF "}d_{li}=\text{VS" AND "}d_{ti}=\text{S" AND "}P_i=\text{L"}$$
$$\text{THEN "}J_{i1}=\text{VL" AND "}J_{i2}=\text{VL" AND "}J_{i3}=\text{VL".} \tag{9.33}$$

The total number of rules in the rule base is determined by the number of all possible combinations of the linguistic terms of the input variables d_{li}, d_{ti}, and P_i, which equals $5{\cdot}3{\cdot}3 = 45$.

In the proposed fuzzy model, the aggregation and activation procedures are performed using the "min" operation [19]. After these operations, during the accumulation stage, the truncated membership functions are combined to obtain the final fuzzy subset of the output variable. This procedure uses the "max" operation.

The final stage of the calculations is defuzzification, which involves converting the membership function of the output linguistic variable into its precise (numerical) value. In this case, the center of gravity method [20] is chosen as the defuzzification technique for the fuzzy model.

To illustrate the nonlinear relationships realized by the developed fuzzy model, the corresponding characteristic surfaces are shown in **Fig. 9.8**. In particular, **Fig. 9.8** shows the dependencies of the acoustic sensor suitability criterion J_i on the model input variables d_{li} and d_{ti} at a fixed failure-free operation probability $P_i = 0.95$. The resulting surfaces reflect the coordinated influence of the geometric parameters of sensor placement on their suitability as the first, second, or third sensors in the system.

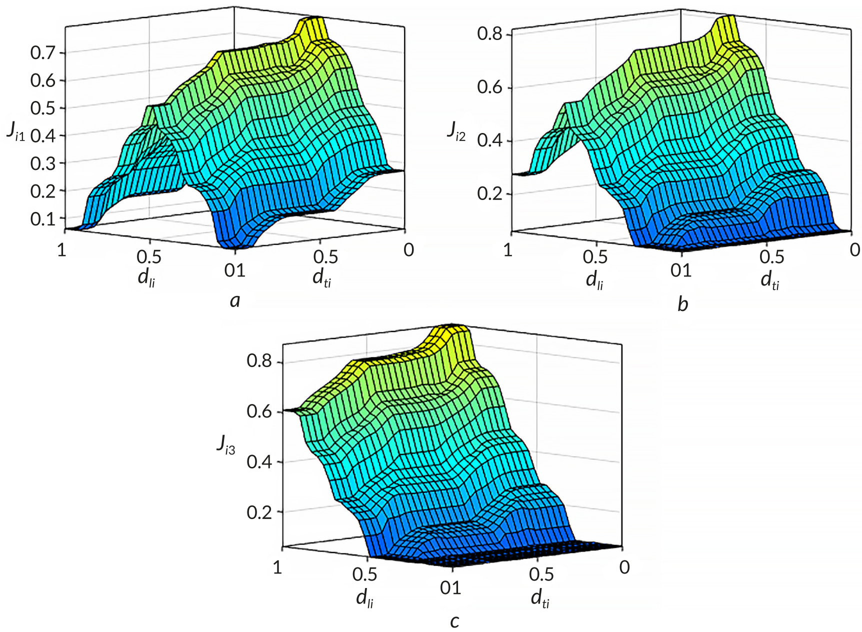

Fig. 9.8 FM characteristic surfaces: *a* – $J_{i1} = f(d_{li}, d_{ti})$; *b* – $J_{i2} = f(d_{li}, d_{ti})$; *c* – $J_{i3} = f(d_{li}, d_{ti})$

Similar characteristic surfaces were also obtained for the pairs of input variables (d_{ti}, P_i) and (P_i, d_{li}) at fixed values of the third variable. In all considered cases, the coordinated nature of the changes in the suitability criterion values is preserved, which confirms the correctness of the formulated rule base and the adequacy of the constructed fuzzy model.

To validate the correct functioning of the proposed fuzzy model, **Table 9.2** presents the results of calculating the suitability criterion of acoustic sensors depending on different values of the input variables d_{li}, d_{ti}, and P_i.

As can be seen from **Table 9.2**, the developed fuzzy model correctly determines the suitability of acoustic sensors as the first, second, and third sensors (J_{i1}, J_{i2}, J_{i3}) depending on the current values of the input variables d_{li}, d_{ti}, and P_i. In the first three rows of **Table 9.2**, the values of d_{li} in relative units are close to the optimal distance from the first sensor to the artillery unit along the firing line ($d_{l1opt} = 0.5L_{ss}$). Therefore, in these rows, the highest suitability value corresponds to J_{i1}. In turn, in rows 4–6, the highest suitability value corresponds to J_{i2}, as the respective d_{li} values are closest to the optimal distance for the second sensor, $d_{l2opt} = 0.7L_{ss}$. A similar dependence is observed in rows 7–9 for the third sensor.

Table 9.2 Results of calculating the suitability criterion values of acoustic sensors based on the proposed fuzzy logic model

No.	Input variables			Output variables		
	d_{li}	d_{ti}	P_i	J_{i1}	J_{i2}	J_{i3}
1	0.5	0.5	0.875	0.667	0.333	0.0523
2	0.54	0.133	0.91	0.725	0.591	0.301
3	0.48	0.32	0.86	0.651	0.353	0.0608
4	0.7	0.04	0.93	0.568	0.844	0.568
5	0.71	0.6	0.82	0.237	0.404	0.288
6	0.67	0.1	0.79	0.165	0.296	0.0593
7	0.9	0.03	0.915	0.166	0.536	0.836
8	0.92	0.43	0.95	0.159	0.443	0.776
9	0.86	0.21	0.89	0.274	0.546	0.65
10	0.05	0.98	0.76	0.054	0.054	0.054

The suitability of a given sensor is also significantly influenced by the parameters d_{ti} and P_i, which is reflected in the corresponding changes in the values of J_{i1}, J_{i2}, and J_{i3} in rows 1–9. Moreover, to fully verify the functionality of the developed fuzzy model, the tenth row of **Table 9.2** contains input variable values that are unacceptable for the first, second, and third sensors of the system. In this case, the suitability values J_{i1}, J_{i2}, and J_{i3} calculated by the model are very low, indicating that the corresponding sensors are unsuitable for performing the artillery shot verification process. This also confirms the correct functioning of the developed fuzzy model.

9.5 Conclusions

This chapter has examined an approach for selecting acoustic sensors to register the ballistic and muzzle waves of an artillery shot under conditions of random disturbances. The proposed method is aimed at improving the reliability of acoustic information used in subsequent stages of artillery shot verification and in determining the coordinates of the projectile impact point.

It has been shown that the sensor selection problem is best considered as a multi-criteria task, taking into account the spatial arrangement of measurement points relative to the firing direction line, measurement errors, and the probability of their operational status. To formalize this problem, a fuzzy logic model is employed, which allows for a coordinated consideration of these factors and provides an integrated assessment of the suitability of each sensor.

Computational experiments conducted on two artillery shot examples with different parameters confirmed the effectiveness of the proposed approach. In both cases, three sensors were selected from the available sets of acoustic sensors, providing the most favorable conditions for accurately registering the ballistic and muzzle waves of the current shot. The resulting sensor configurations demonstrate consistency with the physical characteristics of acoustic wave propagation and the geometry of the firing.

Thus, the results presented in this chapter indicate the feasibility of applying the proposed method to form an optimal subsystem of acoustic measurements. This provides a basis for improving the accuracy and robustness of subsequent artillery shot verification procedures under random disturbances and can be used as a component of the corresponding methods and models discussed in the following chapters of the monograph.

Conflict of interest

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.

Use of artificial intelligence statement

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Volodymyr Demidenko: Conceptualization, Methodology, Development of sensor selection framework, Writing – original draft.

Yevhenii Dobrynin: Data acquisition, Processing of acoustic signals, Validation of results.

Maksym Maksymov: Computational modeling, Analysis of sensor configurations, Algorithm implementation.

Ruslan Riaboshapka: Visualization of results, Technical support of field experiments, Writing – review & editing.

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