COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 2, No. 1, 2012

# IMPROVING THE EFFICIENCY OF ELECTRONIC MONITORING SYSTEMS AT POTENTIALLY HAZARDOUS OBJECTS BASED ON OPTIMIZATION OF GROUP SENSORS

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**Abstract:** A method for improving the efficiency of electronic monitoring systems based on the usage of group sensors for detecting critical conditions at potentially hazardous objects has been described. The problem of determining the optimal Bayesian majority rule of detection for group sensors has been solved. It has been shown that for group sensors the threshold and the majority rule of detection must be optimized jointly. The task of joint optimization of the threshold and the majority rule has been solved. The estimation of an expected gain as a result of using an optimized group sensor, that shows its high detecting efficiency, has been carried out.

**Key words:** electronic monitoring system of potentially hazardous objects, group sensor, critical state of an object, critical state detection indicator.

### 1. Statement of the problem

One of the main ways of reducing eventual damage caused by potentially hazardous industrial objects of any branch of industry (power plants, transmission facilities, hydro engineering, oil, gas, and chemical objects, pipelines, etc.) is the development and creation of electronic systems for monitoring their current state as well as early detecting the critical states of objects that could become factors of man-made disasters. The global experience of running such systems faces the problem of errors while detecting critical states of potentially hazardous objects, namely omission errors and false alarms. Due to the continuous increase in the number of potentially hazardous industrial sites in different countries, the problem of increasing the efficiency of their electronic monitoring systems is becoming particularly urgent. The main priority in solving this task should be placed on reducing the errors in the early detection of critical states of potentially hazardous industrial objects. The most constructive approach to this task seems to be based on combining several primary sources of information, notably single sensors, to form a group sensor. For the group sensor, the decision about the presence or absence of the object's critical state is made on the basis of a two-step batch processing of information received from the grouped sensors. At the first stage we detect the eventual critical state by means of each of the sensors, while at the second one – by processing, analyzing, and summing up the results of the first stage. In this regard, the need to improve the effectiveness of the critical state detection using group sensors, on the one hand, and the peculiarities of monitoring the data at potentially hazardous objects, decreasing the detection efficiency, on the other hand, give rise to the task of optimization for the two-stage detection performed by the group sensor.

### 2. Analysis of recent research and publications

In [1] batching single sensors into a group and applying the majority principle of processing the information from the group of sensors was proposed to improve the effectiveness of fire detection electronic systems while making decisions on fire risk. At the same time, reducing the possibility of erroneous decisions was not considered there. In [2] using the criterion of maximum difference between the probabilities of correct and false outcome was proposed to reduce the erroneous decisions made by a group sensor. It was shown that for a fixed sensors' threshold a definite ratio exists between the number of sensors detecting the critical state and the total number of sensors. This ratio helps make the decision on the occurrence of the fire risk optimal in the terms of the selected criteria. An equation that allows choosing the optimal ratio was obtained, but the question of the threshold choice for the primary sensors and its connection with rules of majority processing for group sensors was not considered.

### 3. Problem definition and solution

The aim of our research is to increase the efficiency of electronic monitoring and detecting the critical states of potentially hazardous objects of industry on the basis of decreasing erroneous decisions by means of the joint optimization of both the threshold and the majority rule for group sensors.

We consider a group sensor with a typical structure shown in Fig. 1. On-site sensors generate and transmit information about the object, which, as a rule, is exposed to the influence of additive random factors $\varepsilon_1(t)$, $\varepsilon_2(t)$, ..., $\varepsilon_n(t)$. Initial detection is carried out at the sensor level by comparing the level of informational signal about the state of the object with an appropriate critical threshold.

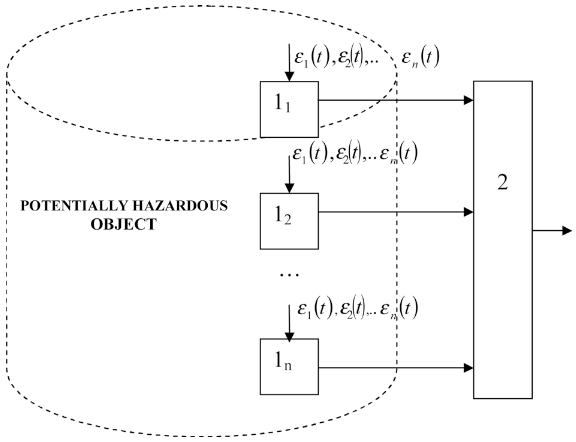



*Fig. 1. Structure of a group sensor: $1_1$, $1_2$, ..., $1_n$ – on-site sensors informing about the state of the object; 2 – a detector of the critical state of the potentially hazardous object*

The threshold tests can be performed sequentially or simultaneously at the stage of sensors $1_n$ and at the stage of the group detector 2. At the second stage a final decision on the presence or absence of the critical state of the object is rendered, and an appropriate signal is subsequently sent to the electronic monitoring system. The decision is done using the data from the first-stage detection in accordance with a specified rule.

The random nature of the object's critical states, as well as interfering factors recorded by on-site sensors at the primary stage, cause two types of failures:

type I – skipping the presence of a critical state;

type II – a false alarm in the absence of a critical state.

It is evident that the errors of the primary sensor detection can cause the corresponding error detection made by the group sensor.

Let the error probability of type I be the magnitude of $\alpha$ and the error probability of type II – $\beta$ at the stage of the initial detection (at the level of sensors) for a fixed threshold. Then the error probability $p_\alpha$ of type I (skipping) for the group sensor, characterized by the lack of detection of the critical state for more than $n-k$ of sensors in a group, while it actually exists, is determined by the value

$$p_\alpha = 1 - \sum_{i=k}^{n} C_n^i (1-\alpha)^i \alpha^{n-i}, \qquad (1)$$

The error probability $p_\beta$ of type II (false alarm) characterizes the detection of a critical state by at least $k$ sensors, when it is actually absent, and can be determined by the value

$$p_\beta = \sum_{i=k}^{n} C_n^i \beta^i (1-\beta)^{n-i}. \qquad (2)$$

Taking into account the equations (1) and (2), the optimization of the majority ratio "$k/n$" for detecting the critical state in the second stage of detection (device 2, Fig.1) in general should be carried out according to the Bayesian criterion, which determines the mean risk of erroneous solutions

$$\begin{aligned} L &= Ap_\alpha + Bp_\beta = \\ &= A - \sum_{i=k}^{n} C_n^i \left[ A(1-\alpha)^i \alpha^{n-i} - B\beta^i (1-\beta)^{n-i} \right] \to \min_k \end{aligned} \qquad (3)$$

where $A$, $B$ are generalized weighting coefficients: $A \geq 0$, $B \geq 0$. The weighting coefficients $A$, $B$ can be determined by the probabilities of various events related to the errors, by the value of damage caused by the errors, as well as by the multiplication of damage and the probabilities of the associated events. The task of minimizing the Bayesian risk (3) is equivalent to maximizing

$$\sum_{i=k}^{n} C_n^i \left[ A(1-\alpha)^i \alpha^{n-i} - B\beta^i (1-\beta)^{n-i} \right] \to \max_k. \qquad (4)$$

Let the probability of correct detection of a critical state exceed the probability of a false alarm $1-\alpha > \beta$. Following [2], the maximum of the equation (4) can be reached at a value $k$ equal to the top of the nearest to $x_0$ integer, but not larger than $n$. The sought value $x_0$ is given by

$$x_0 = \frac{\ln\frac{B}{A} + n\ln\frac{1-\beta}{\alpha}}{\ln\left(\frac{1-\alpha}{\beta}\cdot\frac{1-\beta}{\alpha}\right)}. \qquad (5)$$

Considering the expression (5), it is evident that the number $k$ of sensors detecting the critical state of an object in the group sensor, which is required for an optimal solution in terms of minimum Bayes risk (3), depends on the probability of sensor errors, as well as values $A$ and $B$ of generalized weighting coefficients. The choice of generalized weighting coefficients and their impact on the optimal number of sensors at fixed values of $\alpha$ and $\beta$ was the subject of [3].

It should be noted that the probability of sensor errors $\alpha$ and $\beta$ significantly depends on the statistics of critical states of hazardous objects, taking into account interfering factors and selected thresholds. In this regard, it is important to solve jointly the task of sensors thresholds' selection and that of processing rules selection, i.e. the rules that are responsible for the analysis of initial results while making decision by the detector.

Let the statistical data recorded for the object's state $T$ at the input of a sensor for a fixed period of time be described by a Gaussian probability density. We assume that the critical state of an object is determined by the value $Tp$ of its current state. In this case, the additive mixture $T = Tp + \varepsilon$ occures at the input of the sensors threshold device, where $\varepsilon$ is an independent component representing random factors, characterized by a zero mean and dispersion $\sigma^2$. If the critical state of the object does not exist, the mixture $T = \varepsilon$ occures at the input, being conditioned only by the influence of random factors. We assume that the statistics of the observed state $T$ of a potentially hazardous object in case when the critical state exists is determined by the density $P_1(T) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(T-Tp)^2}{2\sigma^2}}$, and in its absence by – $P_0(T) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{T^2}{2\sigma^2}}$. Then the probability $\alpha$ and $\beta$ of erroneous detection for sensors with given threshold $u$ is determined accordingly:

$$\alpha(u) = \int_{-\infty}^{u} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(T-Tp)^2}{2\sigma^2}} dT \text{ and}$$

$$\beta(u) = \int_{u}^{\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{T^2}{2\sigma^2}} dT . \qquad (6)$$

Taking into account (6) the mean Bayesian risk of the solution for the group sensor is determined by the functional

$$L\ (k,n,u) = Ap_{\alpha}(k,n,u) + Bp_{\beta}(k,n,u) \to \min_{n,k,u}, \quad (7)$$

where $p_{\alpha}(k,n,u) = 1 - \sum_{i=k}^{n} C_n^i \left(1-\alpha(u)\right)^i \alpha(u)^{n-i}$ and $p_{\beta}(k,n,u) = \sum_{i=k}^{n} C_n^i \beta^i(u) \left(1-\beta(u)\right)^{n-i}$.

In general, the optimization for the group sensor according to the Bayesian criterion (7) must be carried out jointly for the number $n$ of the sensors in the group, for the threshold $u$ set for them, and for the required number $k$ of sensors detecing the critical condition in such a group. In practice, the total number $n$ of sensors in the group is usually fixed. Therefore, the threshold values $k$ and $u$ are the subjects for joint optimization.

Fig. 2 shows the typical shape of the surface in the space of threshold values $k$ and $u$, defined by the functional (7) for the fixed number of sensors $n = 20$. The data are obtained through the statistical observation of a critical state of an object, which is characterized by the value $Tp = 30$ (relative units) and the mean-square value $\sigma = 15$ (relative units) of interfering factors.

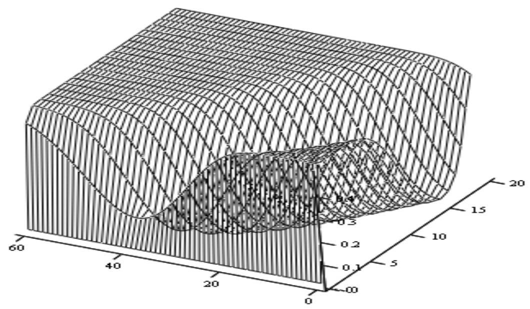
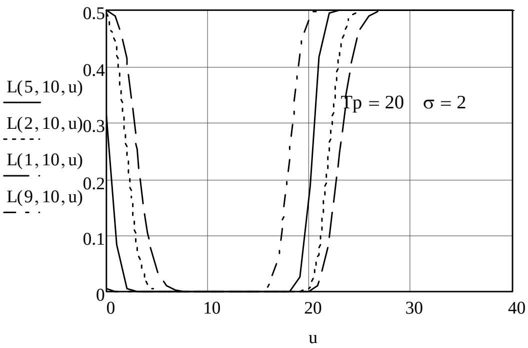


*Fig. 2. Dependence of mean risk in the space of threshold values $k$ and $u$*

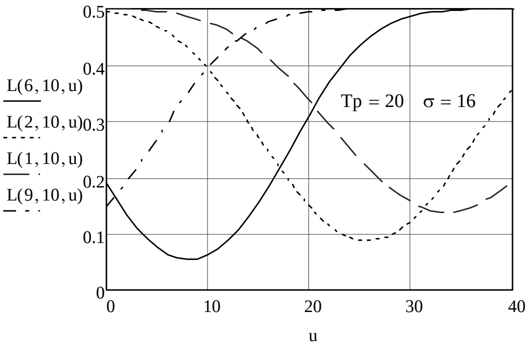
The data represented show that for the group sensor the minimum of the mean risk (7) depends on the majority ratio "$k/n$" and the threshold value $u$ set for sensors. Therefore, the joint optimization of the ratio "$k/n$" and the threshold $u$ set for sensors should be applied to create an optimal sensor group.

Following (7), the threshold value $u$ is determined by the statistics of the critical states and interfering factors. It means that the solution of optimization task for the group sensor generally depends on the statistical observation of the critical state. Fig. 3 shows dependencies that illustrate this fact. The curves in Fig. 3a correspond to a change of the sensor threshold $u$ under the conditions of a negligible level of interfering factors for the different ratios "$k/n$" when the total number of sensors in the group is $n = 10$; the curves in Fig. 3b correspond to the situation with a significant level of interfering factors (if compared to the level corresponding to the critical state of the object observed).

These dependencies show the necessity of the correcting the threshold level for the group of sensors. The higher the level of interfering factors is, the stronger the correction should be. For example, for the considered optimal ratio "$k = 6/n = 10$" the optimal threshold at the level of interfering factors $\sigma = 16$ should be of an order $Tp/2$. When the selected threshold equals to the level $Tp$ of the critical state, the probability of complete detection error is about 6 times greater. With the lower level of interfering factors the gain is more significant.




*a)*



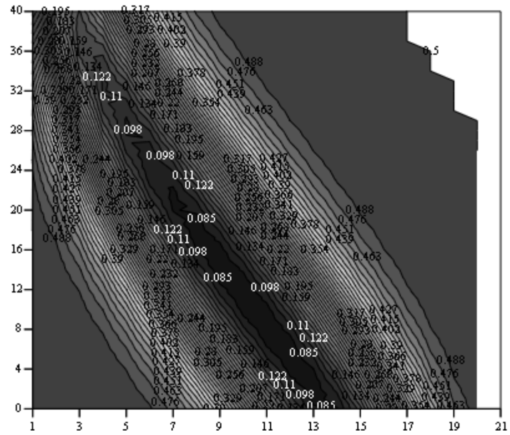

*b)*

*Fig. 3. The dependence of a mean risk value on the threshold value $u$ for different ratios "$k/n$" and levels of interfering factors*

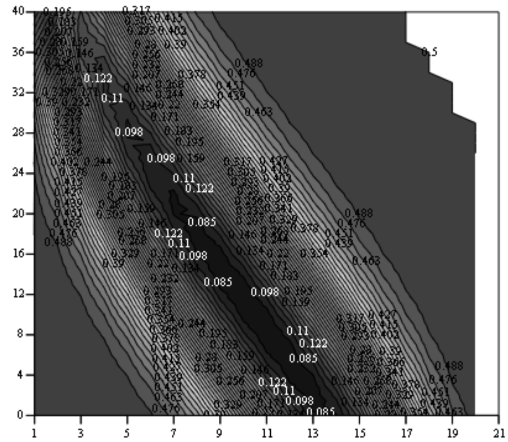
The typical shape of the cross-sections of the mean risk functional (7) (when the object's critical state is observed) characterized by the values of $Tp/\sigma$ equal to 0.8, 1.0 and 2.0 is shown in Fig. 4 a, b, c, respectively.

The value $Uo$ corresponds to the result of a joint optimization for the parameters $k$ and $a = u$ of the threshold. The functionals of the probabilities of correct critical state's detection and of a false alarm for considered group sensors are denoted with $D(\cdot)$ and $LT(\cdot)$. For comparison, in Fig. 5 the values of the probabilities of the correct detection $D(Tp)$ and of the false alarm $\beta(Tp)$ for a single sensor, the dependencies of the mean risk functionals $R5(\cdot)$ and $L5(\cdot)$ on the parameter $u = a$ for the sensor group with optimized threshold $Uo$, and those for sensors with a fixed threshold, corresponding to given values $D(Tp)$ and $\beta(Tp)$, are shown.

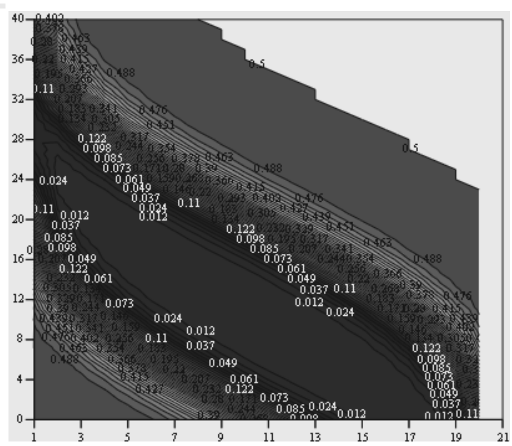
Key indicators of detection quality under considered conditions for the group sensor optimized only for the threshold $k$, and for the sensor group optimized for the thresholds $k$ and $u = a$, when the total number of sensors in a group is equal to 20, are presented in Fig. 5 a, b, c.



a)



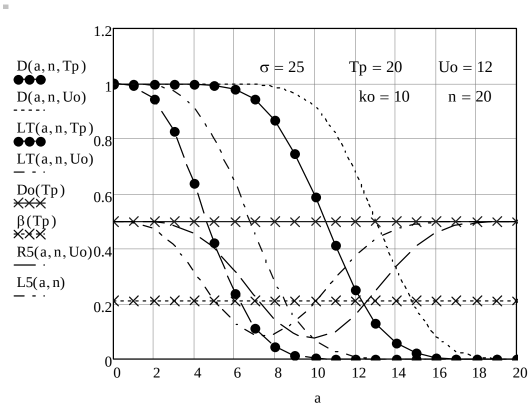
b)



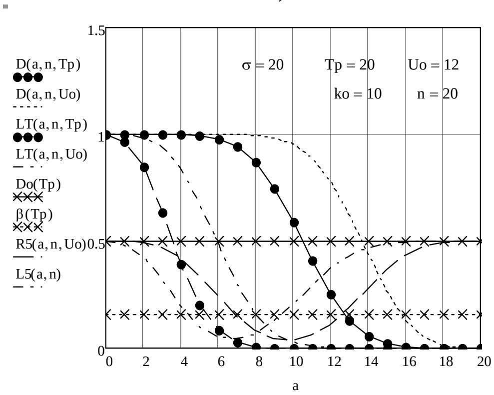
c)

*Fig. 4. The cross-sections of the mean risk functional (7) under various conditions of observation of the critical state*

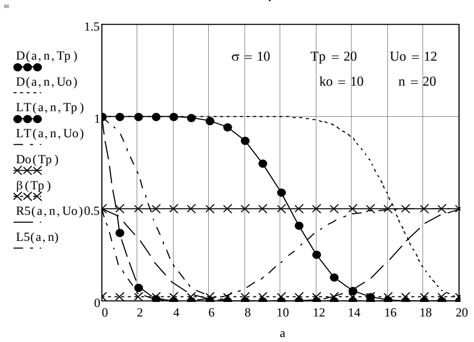
The analysis of the dependencies in Fig. 5 makes it evident that the indicators of detection quality in the group sensor optimized for the threshold value $k$ and the threshold $u = a$ substantially increase with increasing the ratio $Tp/\sigma$. For example, the probabilities of the correct detection and of the false alarm for the group sensor optimized for two parameters with ratio $Tp/\sigma = 1$ are respectively 0.954 and 0.026.




a)




b)




c)

*Fig. 5. Detection characteristics of a group sensor for different observation conditions*

Similar detection characteristics of the sensor group, optimized only for the parameter $k$, are respectively 0.942 and 0.029, and those of a single sensor – 0.5 and 0.159. While assuming the ratio $Tp/\sigma = 2$, the probabilities of the correct detection and of the false alarm for the group sensor optimized for two parameters are 0.999 and $2,504 \cdot 10^{-5}$ respectively, and those for the group sensor optimized only for the value $k$ are 0.999 and $9,691 \cdot 10^{-4}$ respectively. The provided data indicate that in the case of the group sensor optimized jointly for both the thresholds $k$ and $u = a$ the value of false alarm probability is by an order lower while the value of correct detection probability does not change and is equal to 0.999. At the same time the increase of the value $Tp/\sigma$ brings an even greater gain in the considered critical state detection indicators.

### 7. Conclusion

A method for improving the effectiveness of electronic monitoring and detecting the critical states of potentially hazardous objects, based on the usage of group sensors and on the Bayesian optimization of the threshold and of the majority rule of detection, has been described. For a group sensor with a fixed threshold the optimization problem of the Bayesian rule of detection has been solved. It has been shown that for the group sensors the threshold and the rule of detection must be optimized jointly. The task of joint optimization of the threshold and the majority rule for the group sensor has been solved. The dependence of the threshold and of the rule of detection under various conditions of observation has been investigated. The quantitative estimation of an expected gain as a result of the joint optimization of the threshold and of the rule of detection, that shows high efficiency of group sensors, has been carried out.

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## ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ЕЛЕКТРОННИХ СИСТЕМ МОНІТОРИНГУ ПОТЕНЦІЙНО НЕБЕЗПЕЧНИХ ОБ'ЄКТІВ НА ОСНОВІ ОПТИМІЗАЦІЇ ГРУПОВИХ СЕНСОРІВ ВИЯВЛЕННЯ

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Описано метод підвищення ефективності систем моніторингу потенційно небезпечних об'єктів на основі використання групових сенсорів для виявлення критичних станів. Вирішено завдання визначення оптимального байесівського мажоритарного правила виявлення для групових сенсорів. Показано, що для групових сенсорів поріг і мажоритарне правило виявлення повинні оптимізуватися спільно. Вирішено завдання сумісної оптимізації порогу та мажоритарного правила виявлення. Проведено оцінку очікуваного виграшу в показниках виявлення при використанні оптимізованого таким чином групового сенсора, яка показала його високу ефективність виявлення.

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