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Adaptive remote monitoring and control system for the operation of hazardous facilities based on a risk-based approach

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Introduction. When designing technically complex industrial facilities and transport infrastructure facilities, much attention is paid to the safety of operation and maintenance. Despite all the measures taken during the development of systems, there are cases of violation of the operating rules, as well as the maintenance of a hazardous facility of inadequate quality. Non-compliance with the requirements leads to malfunctions, accidents, and in some cases, to accidents. With the development of the Internet, it becomes possible to develop devices that allow you to control a large number of parameters of technically complex devices and transfer their parameters to a single database, for subsequent processing and decision making.

Problem Statement. The article discusses the methodology of adaptive remote monitoring and control of the operation of hazardous facilities based on a risk-based approach, which is a product of the Internet of things. This is a recommendation system for making a decision on the safety of hazardous facilities based on the assessment of risk indicators taking into account the functional and linguistic criteria of the actual technical condition.

Theoretical Part. A feature of the proposed methodology is an algorithm for developing a decision on the safety of an object in real time, which provides an integrated assessment of anthropomorphic and machine data in the cloud space of the Internet using neural networks and artificial intelligence technologies, followed.

Conclusion. The main result of using the recommendation system is the reduction in accidents during the operation of a dangerous object, due to the actual reliability of remote control, which is used in the development of decisions of a precautionary nature, with a decrease in the subjective nature of human thinking.

Keywords: security, remote monitoring, control, risk-based approach, risk assessment, risk prediction, advisory decision-making systems, the Internet of things.

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Introduction. The development of legislation in the field of industrial safety, taking into account the digitalization of the economy, involves remote control of the operation of hazardous facilities. The draft Federal law on amendments to the Federal law "On industrial safety" proposes to introduce state monitoring of industrial safety based on automated collection, recording, generalization, systematization and evaluation of information using remote monitoring of hazardous production facilities [1]. The implementation of the model of state regulation in the field of industrial safety is based on a risk-based approach [1-4]. Technical progress and modern legislation impose new requirements to the safety of objects based on a risk-based approach. There is still a high accident rate at hazardous facilities. Statistics show that it is 90% related to the human factor [5, 6]. One of the promising directions for improving safety is the introduction of methods for monitoring the operation of hazardous facilities to control their technical condition, as well as the work of personnel when performing scheduled maintenance [7-9].

The aim of the research is to develop a methodology for adaptive remote monitoring and control of the operation of hazardous facilities based on a risk-based approach, which is a product of the Internet of things.

To achieve this goal, the tasks listed below are solved.

1. Creation of a mathematical apparatus for processing information about the current state of hazardous facilities, which allows predicting and assessing the risks of emergency situations, taking into account functional and linguistic parameters.

2. Development of a methodology for creating an Internet of things product in which physical objects are hazardous facilities equipped with built-in technologies for interacting with the external environment via the Internet. The new solution must have the ability to re-engineer economic and social processes (including supervisory functions), partially eliminating the need to involve human consciousness.

3. Remote formation and updating of official and production instructions for specialists operating a hazardous facility.

4. Delivery of linguistic checklists to personal mobile devices of specialists for monitoring the technical condition of the facility.

5. Performing a daily functional check of the local security system of the controlled object and transmitting the received information to the server database.

6. Creating a color visualization of the recommendation system for making decisions on the accident risk parameters of the controlled object and the indications of the local security system.

Problem Statement. The risk-based approach in control and supervisory activities provides remote impact on the objects of control of supervisory functions based on the assessment of the risk of their accidents (incidents) and the consequences of such events. One of the most promising areas in this area is the introduction of information technologies. The new solutions obtained in this way are software products that work in real time. They collect information about the current state of hazardous facilities, which allows you to predict and assess the risks of emergency situations, and transmit information about the risk of an adverse event rather than about an event that has occurred. Based on such data, it is possible to react timely to the probable danger [10-13]. The proposed information technologies are a product of the Internet of things (IOT), in which physical objects ("things") are hazardous facilities equipped with built-in technologies for interacting with the external environment. This phenomenon is capable of reconstructing economic and social processes, removing human consciousness from certain specific functions, including supervisory ones.

Theoretical Part. The solution to the problem of safe operation of hazardous facilities in their remote monitoring is based on digital Internet technologies integrated with mobile applications. Such products are implemented in the form of a specialized digital platform based on hardware and software tools for searching, storing, processing, providing and distributing information between platform participants. In this case, participants are primarily engineering and technical workers and maintenance personnel of a hazardous facility, the management of the operating organization, and inspectors of control and supervisory bodies. The developed digital platform must adapt to the specific features of hazardous facilities. For example, one of such platform’s components on transport should be a block that monitors, controls and informs passengers, including monitoring their health and compliance with anti-terrorist security measures.

This IT product is based on an algorithm for combinatorial interaction of elements of a recommendation system and a decision support system using functional and linguistic criteria for diagnostics of a complex security state. At the same time, the algorithm and criteria that determine the current state of safety of an object change (adapt) depending on external conditions and the identified objective causes of accidents and incidents at other hazardous facilities. This necessitates the use of artificial neural networks and machine learning algorithms to build an intelligent system that provides a transition (convolution) from an unstructured multidimensional fuzzy space of indicators that characterize the current state of object safety to a single indicator (integral indicator) that characterizes the risk of an accident (emergency situation).

Fixing the risk indicator is not in itself proof of compliance with or violation of security requirements, but indicates the possibility of such a violation and may be the basis for conducting an unscheduled inspection or other forms of control, up to the complete closure of the facility.

Decision support is relevant for complex multi-level systems (construction, transport, mechanisms, etc.). Information on assessing the state of equipment and the risk of accidents in such systems is poorly structured or not structured at all. This involves the use of large arrays of incoming data and multi-criteria schemes, complex, multi-level hierarchical event trees, and (or) nonlinear decision functions. This takes into account information received from: — sensors (functional criteria),

— service personnel and experts (linguistic criteria) [14-16].

The developed adaptive system for monitoring safety of operation of hazardous facilities based on information technologies and a risk-based approach can be used for monitoring safety in various areas, namely:

— in cranes, elevators, cable cars, escalators, lifts;

— in gas equipment [17];

— on transport — air, road, river, sea, railway;

— in industrial installations and aggregates [18].

The system under consideration and the digital platform implementing it are current innovative solutions that increase the level of industrial safety. The novelty of the proposed approach consists primarily in the introduction of devices for monitoring and controlling safety of facility operation based on a logical and linguistic model for assessing the risk of an accident or other adverse event.

Research Results. The decision on risk assessment in the operation of hazardous facilities is made based on a unique algorithm. It is a combinatorial transformation of linguistic criteria for diagnostics of the facility's security status (received from the company's specialists) and functional indicator parameters of the local security system (from the devices that the facility is equipped with). To increase the efficiency of the facilities' equipment with local security devices and to get information from them, the sensors are combined into blocks. The number of blocks and their functional purpose depends on the type of the facility and monitoring goals. For example, a vehicle safety monitoring and control device includes four main blocks that define:

— driver's status

— technical condition of the vehicle

— location, speed of movement of the vehicle, road condition and environment, compliance with traffic regulations,

— condition of passengers (cargo).

The data received from specialists and devices form a finite set of indicators (criteria). Linguistic criteria formed from human data are divided into criteria with a measurable base variable (numeric) and with an immeasurable base variable (ordinal), depending on the nature of the base variable (base set). Functional criteria generated from the data of the devices are always numeric. These linguistic and functional criteria generally form an unstructured or poorly structured fuzzy set of indicators (criteria for evaluating the object's security status). In this case the values of criteria on elements of a finite set of a hazardous facility form a matrix of estimates

$$X = \left\| x_{ij} \right\|_{n,m},$$

where $x_{ij} = k_j(a_i)$ is an assessment of the technical condition of the facility a_i on the k_j scale; n is the number of the facilities in the set $A = \{a_1, a_2, \ldots, a_n\}$; m is the number of linguistic and functional criteria (evaluation scales) in the set $K = \{k_1, k_2, \ldots, k_m\}$, which forms a criterion space, within which facilities are displayed as a set of points [19].

It should be noted that for ordinal linguistic criteria with immeasurable base variables, physical scales may not exist at all. In this case, when formalizing such criteria, some basic term sets $T = \{T_i\}$ consisting of several terms are used [20]. An example of an ordinal linguistic criterion is a criterion with the terms GOOD, MATCHES, INSUFFICIENT, or BAD.

If the initial criteria space Re^m contains linguistic variables (including ordinal ones), then the integral indicator formed as a result of transformations that characterizes the risk of an accident (abnormal situation), in general, will also be an ordinal linguistic variable L.

The possibility assignment equation is necessary to establish a quantitative correspondence between the feature of an object (the ordinal linguistic variable L) and the property S, which the object may possess to a vague (indefinite) degree [20]. In this case, the property S represents the state of the object that determines the safety of its operation. It is important to emphasize that the uncertainty of the presence of this property in an object is not probabilistic, but possible. The possibility assignment equations for linguistic variables are based on the following principle.

The general statement P that defines the linguistic variable L is written as: L is G, where L — m-ary variable in the criterion space Re^m (m is the number of criteria that form the criterion space Re^m and are included in the linguistic variable L corresponding to the general concept of accident risk during object operation); G is a fuzzy relation in the base space $X = X_1 \ldots X_m$ between subsets S_i ($i = 1, \ldots, m$) describing individual properties that determine the object's safety state. Then the distribution of possibilities associated with the m-ary variable L will be determined by the equation:

$$\Pi_L = G,$$

where Π_L is the distribution of possibilities associated with the linguistic variable L.

This equation is a formalized expression of a complex linguistic concept — "the risk of an accident (emergency) during the operation of an object". Thus, a fundamental problem of fuzzy set theory arises — the problem of assigning numerical estimates to subjective properties. The main method for solving this problem is to construct membership functions of object belonging to a fuzzy set [19]. When introducing membership functions to the risk assessment model, we use the axiomatic structure proposed in [20] for the fundamental measurement of fuzziness. According to the definitions and theorems introduced there, the resulting values of the membership function are bounded from below by the number assigned to the a_{min} object or its equivalence class $[a_{min}]$, and from above by the value assigned to the a_{max} object or its equivalence class $[a_{max}]$. Here a_{max} is an object whose membership function indicates that it definitely has the property S; a_{min} is an object that definitely does not have the property S.

The evaluated property S splits the region A with the physical media $X(A)$ into three subdomains I_0, I_1, and F. Two "regions of indifference" I_0 and I_1 are formed by objects in the equivalence classes $[a_{min}]$ and $[a_{max}]$, respectively. The membership function for the" fuzzy area" F is usually constructed by formally specifying the security properties of specific objects.

Then in the system under consideration, for the ordinal linguistic variable ACCIDENT RISK, it is proposed to use three basic elementary terms corresponding to the subdomains I_0, I_1 and F, and two additional terms that are visualized as a color scale of indicators (table 1). The color of the hazard indication does not require decoding, it is intuitive to the manager, the personnel operating the facility, and is available to the controlling authorities. The object's belonging to one of the three main terms entered (fuzzy sets) is determined by the values of the so-called risk indicators.

Table 1

Determining whether an object belongs to one of the main fuzzy sets based on the values of risk indicators

Terms of the linguistic variable for assessing the risk of an accident at the facility	**Risk indicators**	
Acceptable risk level — operation of the facility is allowed as normal	Green	$u \leq u_{min}$ $a_i \geq s\ [a_{max}]$
Increased risk level — operation of the facility is allowed under increased control	Yellow	$u_{max} < u < u_{min}$ $[a_{max}] > s\ a_i > s\ [a_{min}]$
Critical risk level — operation is prohibited (as an exception, it is possible to perform single operations under strict control)	Red	$u > u_{min}$ $a_i \leq s\ [a_{min}]$
Risk level is not deftermined due to a system failure (malfunction)	Black	u — not determined
The facility is not operated	White	

As risk indicators, it is proposed to use the values of the universal variable which is entered when setting elementary terms in accordance with the requirements listed below [19].

1. Each term is described by a fuzzy subset of the set of values of the universal variable u from the interval [0,1].

2. The assembly of all elements of the term set covers completely the set of values of the base variable *X(A)* and the corresponding interval [0, 1] of the universal variable u.

3. Membership functions of elementary terms are constructed in the interval scale using *(L-R)* approximation or other methods [21, 22].

Taking into account these requirements, the membership functions of term sets describing the property of object operation safety are defined by the function

$$\mu D = 1 - u^{\gamma}.$$

If the risk indicator $u = 0$, then there is no risk and the operation of the object is absolutely safe. If the risk indicator $u = 1$, then the risk is critical and the operation of the object should be stopped.

The degree indicator γ determines the weak order on the $a_i a_j$ interval in the region A and determines the nature of the change in the membership function as the risk indicator increases. For $\gamma > 1$, the same deviations of the risk indicator lead to a greater increase in the membership function μ_D in the area close to zero than in the area close to one. In this case, if the risk indicator is low, its deviations do not significantly change the membership function of the object belonging to the safe area. If the value of the risk indicator is high, then its deviation changes this function much more.

So, the key points of defining the membership function are:

— conversion of the basic variables *X(A)* to the universal variable **u** defined on the interval [0, 1];

— determination of the values of the risk indicator u_{max} and u_{min}, which determine whether the object belongs to one of the three defined in table 1 main terms.

The stated functions of the logical-linguistic model of accident risk assessment in the operation of hazardous facilities are proposed to be implemented on the basis of a specialized digital platform developed with the use of neural network technologies.

In this system, the linguistic diagnostics of the technical condition of the object must use the knowledge, skills and abilities of a person, because it is almost impossible to cover all the parameters that characterize safety of operation of dangerous technical objects with instrument control methods. In addition, in real time it allows you to take into account constantly incoming information about the causes of accidents at similar facilities and changes in regulatory documentation.

Linguistic diagnostics of technical condition of the object in combination with instrument diagnostics create a synergistic effect. It manifests itself in a significant increase in the accuracy of diagnostics of the condition and assessment of risk of an emergency at the facility by reducing the degree of uncertainty. This is due to the mutual influence of all diagnostic parameters on each other in the process of machine learning using neural networks [23].

At the machine learning stage, the specialist makes adjustments to the algorithm for assessing risk of a possible accident and to the generated checklists based on visual prompts in the mobile app. This allows the system to learn how to automatically correct checklist templates by entering new diagnostic parameters. The block of forming linguistic criteria and corresponding checklists is based on the technologies of recommendation systems.

Of course, the structure of data collection in natural language is limited. The main requirement here is the clarity of the operator's answers to questions in the checklists. At the same time the proposed approach allows us to quantify typical non numeric responses: "a little bit", "a little", "recently", "long ago".

For example, the list of checklist questions that reflect the requirements of Federal Standards and Regulations on Industrial Safety (by type of equipment) depends on the type of the controlled facilities and the specific production situation. Common checklists include questions about the service life of the equipment, the latest industrial safety examination of the object and the last maintenance, the availability of insurance, the manufacturer of the work, etc. Special questions on the checklist for specific equipment, for example, relate to the assessment of the wearing of the flange surface and the rolling of the wheel; the presence of cracks on the drums, in the welds and the base metal; the level of wear of the drum stream along the profile, etc.

When training an artificial neural network, at this stage, responses are recognized using Natural Language Processing (NLP) technology and multicluster categorization of their content. In this case, a set of corresponding linguistic criteria is formed in the criteria space Re^m. In the end, machine learning allows the system to predict the time when the limit values of existing diagnostic parameters will occur. To do this, an approximation curve is constructed using a special algorithm, the training of which is corrected for each subsequent diagnostic operation.

Thus, the software for machine learning and adaptation of the security monitoring system uses modern algorithms based on neural networks that allow implementing the proposed approach taking into account operating modes, real weather conditions and non-standard situations [24-27].

For example, Fig. 1 schematically shows the interaction of participants, software and hardware parts of the digital platform of the proposed remote monitoring system for object security, which is based on the technical proposals of the patent [28].

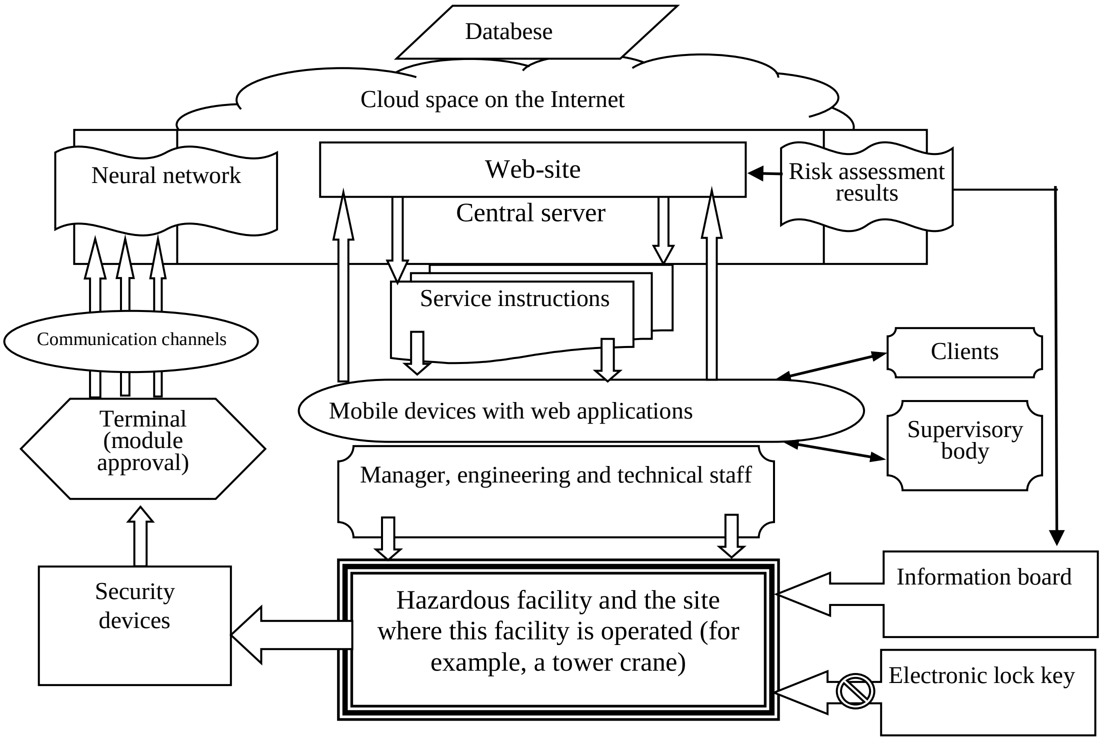

Fig. 1. Block diagram of the digital platform

The database of the digital platform is uploaded to the Internet cloud space. It is accessed via a web site hosted on a central server. An unlimited number of registered users (with personal passwords and usernames) work with the system. Data is provided according to the degree of administration and level of confidentiality. Log in to the database is from individual mobile devices (computers, tablets, mobile phones, etc.) of managers, engineers, service personnel, customers, and representatives of the Supervisory authorities.

The central server uses neural networks to process information and requests from monitoring devices and personal mobile devices [29].

When creating and updating the database, the content of relevant legislative acts is taken into account. It is possible to create a selection of keywords from these texts, which are used to create checklists, and then production and job descriptions. These documents prescribe actions to assess the condition of the object, the safety of which is confirmed by the formation of linguistic indicators of the technical condition of the object. Instructions are delivered via the web application to individual mobile devices of registered users.

The information received by the server is processed using neural networks according to the risk assessment algorithm (described above and based on the theory of fuzzy sets by L.A. Zade). The user's mobile device receives the result of the calculation — the value of the risk indicator expressed in color (a color scale with three main and two additional colors is used).

Conclusion. The proposed system is the first fully combined digital solution built using technologies of recommendation systems (formation of linguistic safety criteria) and decision support systems (assessment of risk indicators for the operation of hazardous technical facilities). The features of this system:

— real-time integration of human and machine data,

— accounting for all available information,

— risk assessment and assistance to the operator in making decisions using several algorithms based on neural networks of the so-called artificial intelligence and Internet of things technologies.

Implementation of the system on the basis of the considered digital platform allows you to get the following advantages:

— to process information about the current state of hazardous facilities;

— to predict and assess the risks of emergency situations, taking into account functional and linguistic parameters;

— to remotely communicate to specialists service and production instructions updated to reflect changes in the legal framework;

— to send checklists to specialists' personal mobile devices for monitoring the technical condition of the object;

— to perform daily functional check of the local security system of the controlled object using checklists and transmit the received information to the server database;

— to recommend specialists to make decisions on safe operation based on color indicators;

— to record the received information in the database in accordance with the object identification and its location on the electronic map;

— to create an Internet of things product in which physical objects are dangerous objects equipped with built-in technologies for interacting with the external environment via the Internet.

Thus, the solution allows you to unify and systematize the requirements of the supervisory authorities for construction equipment, operation of machines, technological equipment and make recommendations based on objective data taken at the site.

The developed methodology is applicable for monitoring objects in remote and hard-to-reach regions.

The recommendation system is designed to reduce accidents when operating a hazardous facility. The result is achieved due to the actual reliability of remote control, since the role of subjective human thinking is limited in the development of preventive solutions.

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A. V. Panfilov — assessment of the studied issue and the relevance of the research, participation in shaping the original concept, making the results of the study. O. A. Bakhteyev — participation in the design of block-diagram digital platform. V. V. Deryushev — development of the study methodology. A. A. Korotkiy — synthesis of research results, formulation of conclusions.