AN INTELLIGENT SYSTEM FOR INVESTIGATIONS AND PROVISION OF SAFETY FOR COMPLEX CONSTRUCTIONS

Alexander Berman, Olga Nikolaychuk, Alexander Yurin, Alexander Pavlov

Abstract: Methodology of computer-aided investigation and provision of safety for complex constructions and a prototype of the intelligent applied system, which implements it, are considered. The methodology is determined by the model of the object under scrutiny, by the structure and functions of investigation of safety as well as by a set of research methods. The methods are based on the technologies of object-oriented databases, expert systems and on the mathematical modeling. The intelligent system's prototype represents component software, which provides for support of decision making in the process of safety investigations and investigation of the cause of failure. Support of decision making is executed by analogy, by determined search for the precedents (cases) with respect to predicted (on the stage of design) and observed (on the stage of exploitation) parameters of the damage, destruction and malfunction of a complex hazardous construction.

Keywords: computer-aided investigations, intelligent system, technical state, safety, construction, malfunction, failure, case-based reasoning.

ACM Classification Keywords: I.2.1 Applications and Expert Systems: Medicine and science, Industrial automation

Introduction

Prevention of failures in industry necessitates solution of the problem of investigation and provision of technogenic safety on all the stages of the life cycle of complex constructions: beginning from the design, construction engineering, manufacture and ending with application and utilization. The problem of safety investigations is a multi-disciplinary one. For the purpose of its solution it necessitates that knowledge and the potential of the following scientific disciples be involved: physics and mechanics of destruction, physics-chemical mechanics of materials, material engineering, reliability and safety of technologies and constructions, toxicology, foundations of design, technology of mechanical engineering, psychology, mathematics, information technologies, etc. Safety is substantially dependent on the efficiency of the systems intended for estimation and forecasting of the technical state and resource, precision of diagnostics and correct determination of the causes safety violations.

Investigation of incidents and failures, which implies description of the total cause-effect complex of their formation, is one of the main sources for acquisition of knowledge about hazards and their development [Berman, 1998].

In connection with the multi-disciplinary character of the problem of investigation and amplification of construction safety, it is necessary to provide for a coordinated activity of the researchers and the specialists, who regulate different stages of the complex systems' life cycle. This may be achieved only via elaboration of the respective computer-aided technologies intended for automation of research, which is conducted within the frames of an integrated intelligent information system and on the basis of accumulation, modeling, initial processing and efficient application of diverse information and knowledge [Berman at all, 1999].

Methodology of information support and automation of research related to technogenic safety

The methodology of computer-aided research and provision of safety properties is determined by the object's model, by the structure and functions of the process of investigation, and by the set of methods employed in the investigation.

Object's Model. Investigation and development of the recommendations related to provision of safety is based on identification and application of the regularities of the genesis, generation and development of the hazards independently of the functions and the structure of construction.

Correct determination and prediction of the causes allow us to make the objects more perfect, ground some necessary modernization, redefine the periodicity, the methods and aids needed for diagnostics and monitoring, ground the undertakings related to prevention of failures and provision of safety in case of their occurrence.

To the end of investigation of the causes of occurrence of hazardous states, we have proposed a cause-and-effect complex which determines their occurrence in the form of a model of dynamics of undesired processes. A block-diagram of dynamics of this process is shown in Fig.1. Each sequential state is conditioned by the previous one and is characterized by the some larger hazard. So, since presently our knowledge bound up with understanding sufficiency of the measures and undertakings needed for provision of reliability and safety is limited and the systems, which are intended to maintain reliability of operation and safety, are hardly ever fail-safe, malfunctions of such systems take place and provoke failures.

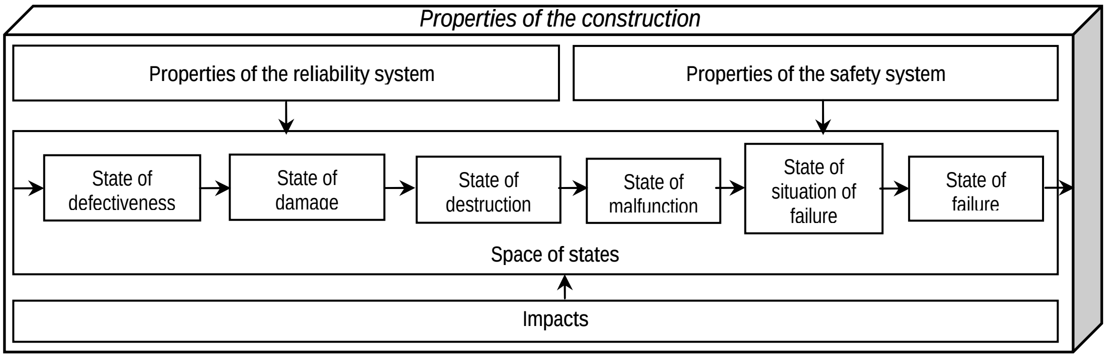

Figure.1. The cause-and-effect complex of state dynamics for the construction

According to this model, hazardous states are conditioned by properties of the designed system, by the character of impacts and by properties of systems intended to provide for reliability and safety. System's properties are characterized, for example, by i) the number of new system's components and ii) the degree of their uncertainty, iii) predictability of development of the states, iv) the level of hazard for the substances either processed or transported, v) the degree of hazard for the technological process parameters. The properties of impacts include those of mechanical, physical-chemical and biological influences, which violate safety; the rate of their development and distribution; the degree of their effect on the safe state. Properties of the safety system include, for example, observability; controllability; opportunity of state monitoring, which implies real-time information processing and realization of adequate measures for planning hazards; survivability, e.g. the operating time from the moment of occurrence of a hazardous state to the moment of transition onto another level of the hazardous state.

The structure and functions of the process of investigation. The process of investigation has a hierarchical structure. The structure of the process of investigation is conditioned by the following factors:

- the structure of the object under scrutiny: part – unit of an assembly – construction;

- the proposed structure of the state space: defect – damage – destruction – malfunction – situation of failure – failure [Berman, 1998; Berman at all, 2007];
- a set of mechanisms of occurrence and a variety of hazards which are the causes of safety violation;
- a set of scenarios bound up with development of each hazard;
- a set of variants of decisions bound up with provision of safety properties which satisfy the conditions of an acceptable risk.

The proposed structure of the model of the cause-and-effect complex is the decisive factor defining the scheme of investigation which includes consecutive investigation stages concerned with all the phases of states – from the appearance of a defect to the formation of failure. On each stage the factors are revealed, which condition and influence the frequency and consequences of hazardous states. This is necessary for the purpose of determination of the construction's rational preventive, control and protective properties, which are generalized in the concept of "property of safety". Methods and aids of provision of these properties are based on the results of such investigations.

Functions of the process of investigations correspond to the stages of decision making needed for achievement of the objectives bound up with provision of acceptable risk for all the kinds of hazardous states of constructions (Fig.2).

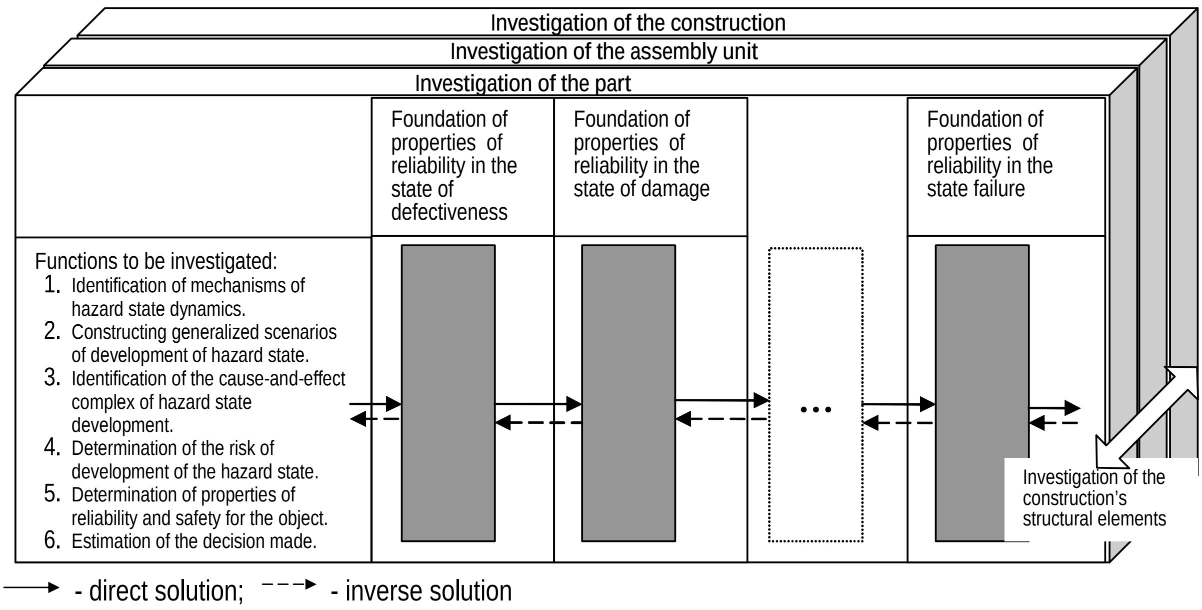

Fig.2. The structure of the process of investigation.

Methods of Investigation. In accordance with the methodology proposed, the process of investigation and provision and maintenance of safety for complex constructions is conducted with the aid of a set of methods based on the technologies of object-oriented databases, expert systems and mathematical modeling.

The process of investigation is provided by combining the methods (see Fig.3): case-based and rule-based expert systems, ontologies, methods of analytical modeling [Aamodt at all, 1994; Berman at all, 2004; Luger, 2002; Portinale at all, 2004]. In turn, before applying above methods it is necessary to perform modeling (redefining, constructing a thesaurus) of the problem domain.

Ontological systems belong to the most contemporary forms of information (data and knowledge) representation (Berman at al., 2004b). The principal intention of the ontology implies formalization and integration of information.

Ontology facilitates structuring and modeling weakly-formalized problem domains. Being grounded on the general set of terms, it determines and simplifies the semantics of formal information, facilitates its computer processing, while representing the information in the form convenient from the viewpoint of perception.

Application of the mechanism of ontology in problems of providing safety of constructions is conditioned by insufficient formalization and multi-disciplinary character of the problem under scrutiny. Its solution necessitates application of knowledge in science of materials, solid body physics, physics and mechanics of destruction, physical and chemical mechanics and strength of materials, monitoring, diagnostics and forecasting, theories of risk and safety. Furthermore, likewise in all multidisciplinary investigations, there exists the problem of knowledge coordination and development of a uniform conceptual apparatus which would provide for efficient interaction between the researchers involved in different fields of knowledge.

So, first of all, it is necessary to construct an ontology (a dictionary-type ontology) of construction safety and then formalize the main concepts from the viewpoint of the cause-and-effect complex of safety violation.

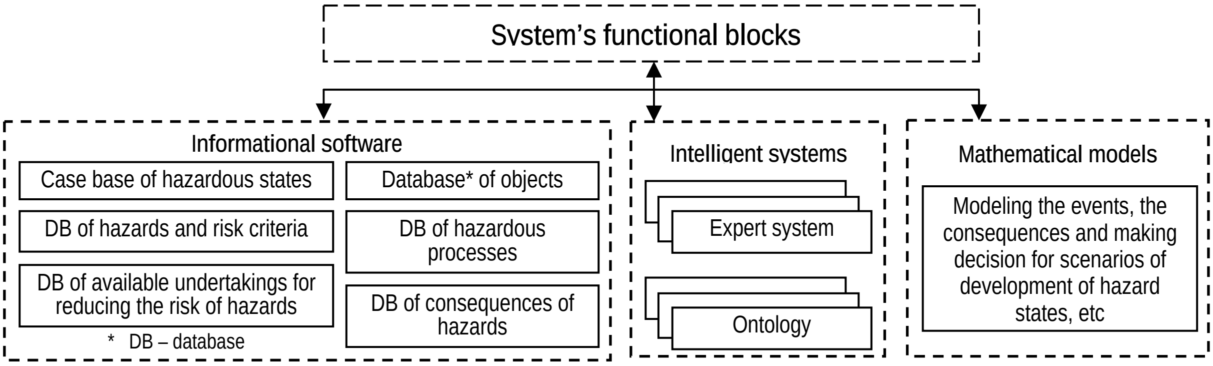

Figure.3. The architecture of the system for investigation and provision of reliability and safety of the constructions.

The formalized concepts form a taxonomy of concepts which inherit the properties of general concepts. Such abstract concepts as defect, damage, destruction, malfunction, situation of failure, failure have been decomposed into definite concepts. The ontology elaborated is supposed to be used as a knowledge base for the system proving for safety.

Case-based reasoning provides for solving the problems on the basis of precedents (cases), while using accumulated experience, i.e. the decisions made earlier [Aamodt at all, 1994]. According to this methodology, the process of solving the problem represents a sequence of stages related to finding (retrieval) some analogs and reuse of the information contained in them.

Furthermore, knowledge (apparatus) of different scientific and engineering disciplines is concentrated with respect to these precedents. So, each precedent represents some systematized and classified information on the causes of possible or actual damages and destruction of the construction, which condition either probable or actual (real) violation of safety (failure).

The precedent includes the following information: project and actual exploitation conditions; a sequence of the states, which could lead to the state under scrutiny, while including the properties of these states; causes of the state; the organizing-technical genesis of the state; the structural genesis of the state; consequences of the state; the decision made to prevent the undesirable state; etc.

The construction has a hierarchical structure, each element of which is characterized by a state. The relation "part–total" between the structural elements conditions the cause-effect relations between their technical states: a part, which represents an element of an assembly unit, may be the cause of the undesirable state for the assembly unit; etc.

Proceeding from this assumption, it is possible to state that there exists a hierarchical space of precedents. Furthermore, each precedent (case) corresponds to a set of indices, which represent a brief description of one of the declarative aspects of the precedent: for example, either structural belonging of the object (involved in the incident) or its technical state. Depending on the complexity of description (some available hierarchy of properties and a type of criteria: determined/logical) the indices (descriptors) represent either binary sequences (…01001…) or some sets of corteges ({…, P_i , …}, $P_i = \langle n, v, w, r \rangle$, where n is the property's name; v is its value; w is the importance (or information weight) of the property; r is the restriction imposed on the band of values – the restriction determines the band of values within the frames of which the property's value can determine the value of the measure of similarity; in the case when the property's value occurs outside of this band of values the value of the similarity measure is 0).

Presence of the given set of indices allows us to apply elements of the procedure of sequential solutions [Zhuravlev at all, 1989] in the process of finding solution. Finding (retrieval) of the precedents with respect to separate indices and groups of indices (from the set of indices) allows one not only to substantially increase the search algorithm's computational power (and, therefore, complexity of the process of investigations) at the expense of restricting the number of vain (irrelevant) comparison and search operation, but also to concentrate attention of the researcher on some important aspects of the technical state dynamics.

Selection of precedents on each of the stages in the procedure of sequential solutions is conducted in accordance with a global measure (estimate) of similarity/closeness of descriptions of the precedents. This measure is computed as a distance between the precedents in the space of criteria (features). The distance is computed using both the Minkovsky metrics [Bergmann, 2002] (1), which is a generalization of the so called "city district metrics" (which is used in processing of binary vectors) and the Euclidean distance (used in processing some sets of corteges):

$$dist_{Minkowsi,p}(\overline{x}, \overline{y}) = (\sum_{i=1}^{n} \left| x_i - y_i \right|^p)^{1/p} \qquad (1)$$

The parameter p determines whether it behaves like the so called "city district metrics"($p = 1$) or like the Euclidean distance.

The search within a hierarchical space may be both ascending (bottom – up) (i.e. from a part to a construction) and descending (top to bottom). In the first case, the problem of forecasting is solved in the process of investigation; in the second cease, the problem of genesis is solved.

Consider the sequence of stages (steps) in the search algorithm intended for finding precedents in the process of solving the problem of genesis. This problem can be solved on the stage of exploitation of the object, when some malfunction of the construction has already taken place, external manifestations of the malfunction are obvious, and it is necessary to find out the causes of this malfunction.

Step 1. The user describes the object of investigation, i.e. the failed construction, while taking into account initial exploitation conditions (values) and external manifestations of malfunction, and then automatically forming the initial set of indices needed for the description.

Next, search for the analogs with respect to the indices, which describe structural belonging of the failed construction and external manifestations of malfunction is sequentially conducted. The result of the procedure of finding (retrieval) is a list of similar precedents ordered according to the estimate of closeness (similarity) of the descriptions. This list allows one to analyze the malfunctions having similar indicators and make a preliminary decision related to investigation of causes of the malfunction, for example, a decision on testing all the assembly units (or parts), which have been indicated in the list as possible causes of malfunction.

Step 2. Having obtained additional information in the form of a list of similar construction malfunctions, the user continues the process of investigation – determines the genesis of the malfunction. The structural genesis of malfunctions of all constructions is the malfunction of one of the assembly units (or parts) included in some or another construction. A set of possible structural genesises of construction's malfunctions is formed in the process of investigation of these assembly units (parts). The procedure of finding (retrieval) proceeds to the next level in the hierarchy of the space of precedents (cases), to the level of precedents describing the malfunctions of assembly units (or parts).

In turn, already on the given level, there takes place the search of analogs with respect to external manifestations of some malfunction, the result of which are some precedents containing the description of the most probable cause of the malfunction for the assembly unit. Having chosen the most close description of the malfunction (and, consequently, the most probable failed assembly unit), the user redefines the actual conditions of its exploitation and external manifestations of its malfunction.

Step 3. Since the object of investigation represents itself a hierarchical structure, and the process of investigation represents a sequential and goal-oriented search of analogs in the hierarchical space of precedents, after finding the analogs at the level of precedents, which describe malfunctions of assembly units, there follows the search for the precedents at the next level, i.e. at the level of precedents, which describes malfunctions of parts. At the given level, the search (retrieval) of analogs is conducted with respect to the indices, which describe external manifestations of damage, destruction and malfunction of the part, and on account of information of actual conditions of its exploitation and initial defectiveness (conditioned by the technology of manufacture). Such a description of this step is given in [Nikolaychuk at al, 2006].

Only on the given step the user reaches the beginning of the chain of the structural genesis of malfunction and obtains the possibility to "assign" and analog, i.e. to choose the most close precedent. As a result of this "assignment", attribution of the solution, which is contained in the analog, to a new precedent, which characterizes the current situation, takes place. The solution contains a description of the organizing-technical causes of malfunction for the part as well as a description of undertakings, which are needed to prevent any malfunctions of the part in future.

Step 4. As soon as the cause of the part's malfunction has been determined, the algorithm turns back to the stage of finding out the malfunction for the assembly unit. On this stage, the organizing-technical genesis of malfunction of the part is inherited by the assembly unit. The part in the structural genesis is fixed, which caused the malfunction of the assembly unit. Noteworthy, after "assigning" the analog, we obtain the total chain of the cause-effect complex in the form of a set of precedents: the part's precedent – the assembly unit's precedent – the construction's precedent. On each of the levels, the precedent contains information on the cause of malfunction and the undertakings needed. So, the undertakings, which need to be conducted for the assembly unit, are inherited from a similar precedent of malfunction for some assembly unit and are redefined by the user on account of the definite characteristics of the problematic situation.

Step 5. As soon as the cause of the assembly unit's malfunction has been determined, the algorithm turns back to the stage of finding out the malfunction for the construction on the whole. On this stage, the organizing-technical cause of malfunction of the assembly unit is inherited by the construction. The assembly unit in the structural genesis is fixed, which caused the malfunction of the construction. The undertakings, which need to be conducted for the construction, are inherited from a similar precedent of malfunction for some other construction and are redefined by the user on account of the definite characteristics of the problematic situation.

Therefore, it appears possible to determine (trace) the whole chain of genesis for the malfunction. Before the moment of "assigning" an analog, the user can turn back to the previous step, input additional information and repeat the search (retrieval) of analogs.

Application of analogs in many cases necessitates adaptation of available solutions, what may be implemented by the concretization, which implies qualitative redefining the description of the precedent, refining the parameters and their values.

The problem of genesis of states for a failure situation or a failure is solved by the case-based method likewise in the problem of genesis of construction malfunction considered above.

The rule-based reasoning provides for solving problems of investigation on the basis of models of the cause-effect complex of occurrence of malfunctions and failures. A corresponding rule-based model has been developed, where the object concepts and relations between them have been transformed into the production rules of CLIPS [Nikolaychuk at all, 2006].

The mathematical models. In the problem domain under scrutiny, side by side with weakly formalized knowledge, there are separate aspects of the technical state dynamics which are described by analytical models, for example, by models of growth of micro-cracks, variation of material hardness, variation of residual stress (strains) in the part, etc. So, in the process of describing the process of variation of the technical state, it is necessary to combine rule-based models (and/or case-based model) and analytical models, when the latter complement and redefine the values of separate parameters of these knowledge models.

Application (Intelligent System)

Implementation of the system is conducted by component-wise assembly of the systems designed by the team [Berman at all, 2006]. Each component represents an autonomous module having some internal memory and a unified interface. The internal memory provides the user with the opportunity to input some information needed for modification of the basic functionality, its adjustment to the specificity of a definite problem domain. The unified interface represents a set of properties and the methods needed for obtaining a description of a component and for controlling it.

In the process of design of these components it was necessary to isolate the employed knowledge of some problem domain from the knowledge of the object domain; the component has to know "how" the information is processed, but not "what" is definitely processed. When some purchased software is employed, the implementation of a component consists in design of a controlling module for this software. The unified interface gives the possibility of programmed control of a component, what provides for the possibility of dynamic integration of the system's components into a joint system.

Presently, we have elaborated a prototype of intelligent system intended for determination of causes of malfunctions and failures in the oil-chemical industry [Berman at all, 2006], which includes the following components: component for modeling (description) of an object domain, which provides for integration of the information on the object domain [Berman at all, 2004a]; case-based and rule-based expert systems [Nikolaychuk at all, 2006]; modules, which implement mathematical functions. Furthermore, there are databases, which contain information on the constructions, degradation processes, consequences and undertakings oriented to neutralization of the impact. The knowledge base of the case-based expert system contains information on 250 malfunctions and failures which have taken place at different oil-chemical enterprises. The rule base of the rule-based expert system includes the rules for the relationships between degradation processes, causes and the related undertakings. Mathematical models intended for computing the rate of cracking development and corrosion have been developed.

Conclusion

Provision of predicted technical state, estimation of the possible hazard of the object's destruction and the expected damages (detriment) acquires special importance at the stages of design of technical devices intended to be applied under special, extreme conditions, for example, under water or in space. It acquires importance also in connection with the necessity of all the more increased degree of automation and informatization of all the life cycle stages of complex constructions performed on the basis of adaptive and intelligent control systems.

Development of computer-aided systems of automation and informatization of research, which imply storage, initial processing, modeling and efficient application of diverse information and knowledge within the frames of one integrated intelligent information system, ensures coordinated activity of researchers and specialists in solving multi-disciplinary problems of investigation and increase of safety of the complex constructions on various stages of their life cycle.

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