Fuzzy cognitive map of pre-emergency prediction

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Abstract. The state of a technically complex object (TCO) during its operation is determined by means of a set of parametric sensors making it possible to determine dynamics features of both the external production environment and object operation parameters. The sensors output signals can display the presence of short-run, step-type and other loads, changes in the structure of the signal random component, and also they make it possible to forecast the approach of the operating mode to the pre-emergency situation. The monitoring system development is possible on a conceptual basis of fuzzy cognitive maps. This approach allows not to make the mathematical tools used complex and to simulate the TCO control process. The system approach realization method to designing in terms of fuzzy cognitive maps allows to develop scenarios of monitoring and control system operation, to evaluate the information value of conclusions based on the results of individual sensors signals processing.

1. Introduction

A technically complex object (TCO) pre-starting procedure is connected with the analysis of readings of parametrical sensors performing the measuring conversion of physical quantities of different nature. The influence of operation objective conditions, the environment, the adjustment of task, any of which can result in a pre-emergency situation, reveals itself during preparation for the operating mode and during the object movement. Effects of temperature and time drift of sensors characteristics together with equipment wear, electromagnetic noise, vibrations, changes in the external physical environment, operational adjustment, revision of the TCO control objective may appear in the sensors output signals during the work [1]. System approach to TCO designing makes it possible to bring the incoming information flows into a single system, to set priorities or the degree of an indicator significance, to determine cause-effect relationships and to draw final conclusions for the management of an object. Elements of the system here are not only physically existing sensor output signals that have passed analog-to-digital conversion, but also virtual components: the results of checking the properties of signals in program modules, the results of logical rules execution. Despite of some elements virtuality the system approach can be fully implemented in the TCO control system model. TCO control system is a stable structure with specifically defined relationships between the elements and the state of the system can be assessed. The factor of building the control system serves to provide the ability to control the object both in decision support mode and in automatic mode.

2. Research objective and its practical significance

The subject area of the research has been to control the state of the moving object in difficult running conditions. The possibility of fast changes of operating regime, structural vibrations, anomalous detector's readouts, which are caused by obstacles and collisions, has been taken into account.

The set of readouts of acceleration transducer, linear velocity sensor, angular velocity transmitter and shock pick-up has submitted the information for drawing up a logical conclusion on the current state of the moving object. The concept of object control system on the basis of fuzzy cognitive map has enabled to apply the flexible control approach and to choose the solution from the vast area of feasible solutions.

The goal of the work is to build a model reflecting the process of TCO work monitoring with the ability to predict transition to pre-emergency condition because of a number of reasons or because of a combination of reasons. To achieve the goal we propose a model of monitoring system for TCO condition, operating on short time segments while controlling motion process and during preparatory stage.

The implementation tool of the model is a fuzzy Cognitive Map [2] (Fuzzy Cognitive Map, FCM), which meets the research objective and system approach to solving problems. The elements of the control system are the factors of FCM represented as vertices of an oriented graph. The factors are characterized by a numeric level and are connected by arcs of the oriented graph, the arcs weights reflect the causal relationship intensity. The factors that do not depend on other ones (within the control system under consideration) refer to the state of the external environment and other circumstances which cannot be influenced on during the TCO operating.

The research experience has made it possible to improve the fundamentals of using fuzzy numbers and conclusions [3, 4] and to obtain self-adjusting maps with improved accuracy [5]. There appeared research area using fuzzy logic with indefinite relations (neutrosophic logic [6]). Methods for reducing FCM complexity [7] and methods for generating FCM models based on evolutionary genetic algorithms [8, 9, 10] are proposed.

The practice of FCM applying is constantly enriched with new examples: production of biofuels, food and pharmaceutical products [11]; making political and engineering decisions [12]; modeling of public opinion formation by the mass media [13]; time series forecasting [14]. There appeared scientific works on the dynamic assessment of complex system risks taking into account the priority of the factors [15]. The prospects of applying the FCM toolkit proved by a variety of publications is simultaneously combined with deficiency of ready-made solutions for creation and operation of engineering systems, in particular, systems for TCO controlling. So, there appeared the necessity to develop own FCM model and to verify with its help the possibility in principle to control TCO having many dynamic state parameters.

Tasks for the safe operation of TCO and the sequence of procedures for processing and analyzing data are depicted in the form of a diagram in Figure 1. Security policies require well-timed prediction of the TCO pre-emergency condition. Critical changes in the mode of the object operation can occur on a short interval of time series.

The procedures for analyzing short time series should be fully automated, in order for the violation of the structure of the time series to be detected in "real time". Procedures for assessing the adequacy and accuracy of the time series model can be standard. The prediction of a possible TCO pre-emergency condition should be presented in a user-friendly form which easy-to-use as a component of decision support system.

3. Methodology

The functional stability and operability of the control system using FCM mathematical apparatus have been researched.

One of the approaches to constructing a model of relations development scenarios is the construction of a fuzzy cognitive map, a variant of which is shown in Figure 1. Causal dependence in the form of arcs of the oriented graph from left to right reflects the logical chains: "change in the structure of the sensor output signal" - "test result" - "output". The arcs of graph directed from right to left correspond to the "subjective" part of the cause-effect relationships, they depend on the adjustment of the TCO operation mode, when the influence of the corresponding causative factors decreases significantly.

The factors included in the model are characterized by initial level, the change of which is possible during the functioning of the system, as well as by relations with other factors with different intensity of links. In addition, the model contains exogenous concepts that have no reason to change within the simulated system, but have such reasons in the external environment of TCO applying. The scheme shows that the factors e_1 to e_4 refer mainly to real external reasons, and e_5 to e_7 refer to "subjective" reasons that can be adjusted by changing the TCO's operating mode. The feedback in the system shown between e_{22} and e_{13}, e_{14}, e_{15} demonstrates the possibility of the adjustment.

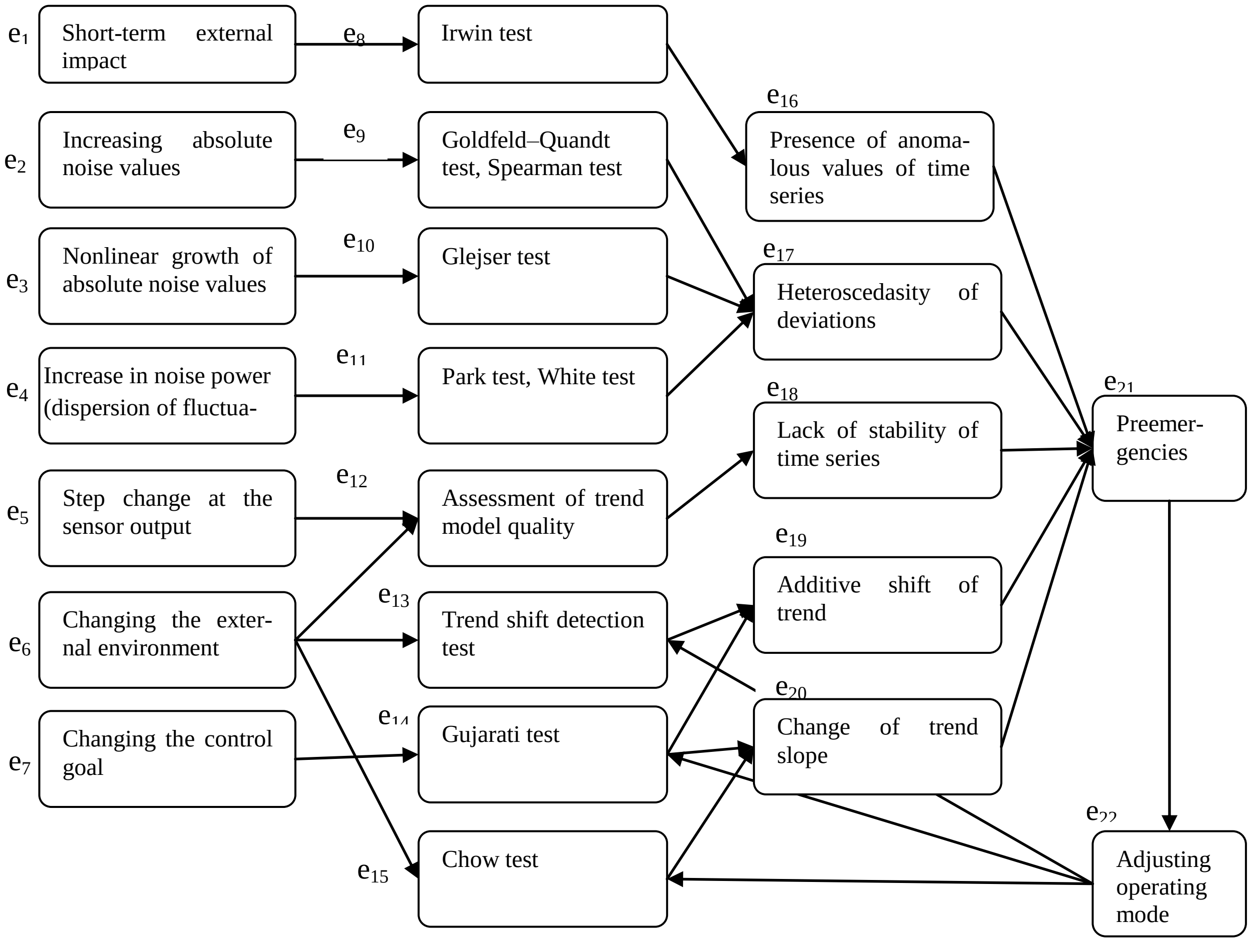

Figure 1. Fuzzy cognitive map.

The modeling is performed with the help of the method that is characterized by simplicity of implementation, the one that was used by Guillermo Ochoa de Aspuru in his Java application [16]:

$$L_i^{(k)} = \frac{1}{n} \sum_{j=1}^{n} L_{ij}^{(k-1)},$$

$$L_{ij}^{(k-1)} = E_{ij} \left(L_j^{(k-1)} - L_i^{(k-1)} \right) I_{ij} \Big/ 100,$$

$$i = \overline{1,n} \qquad j = \overline{1,n}.$$

k is an iteration number;

$L_{ij}^{(k)}$ - level of factor i in the range from 0 to 100;

$L_{ij}^{(k-1)}$ - result of factor j influence on factor i;

E_{ij} - direction of influence, which takes on values -1 or 1;

I_{ij} - the intensity of causal connection, which takes on a value in the range from 0 to 100.

4. Technology of the experiment and the results obtained

The instrument of the experiment was the Java-based modeling application which can be found on Guillermo Ochoa de Aspuru's website [16] and which functions in the Internet Explorer environment.

Levels of factors and intensity of effects are estimated in conventional units in the range from 0 to 100 and appear as a result of processing experts' opinions. The values of the intensity of effects are presented in Table 1.

Table 1. The intensity of effects.

Dependent factor	Causal factor	Intensity of effect
$\mathbf{e_{21}}$	$\mathbf{e_{16}}$	75
		100
	$\mathbf{e_{17}}$	75
		100
	$\mathbf{e_{18}}$	75
		100
	$\mathbf{e_{19}}$	75
		100
	$\mathbf{e_{20}}$	75
		100
$\mathbf{e_{22}}$	$\mathbf{e_{21}}$	75
		100
other effects		50

As follows from Table 1, several variants of the intensity of effects with the factors-causes are considered for the factors e_{21} and e_{22} in the experiment. The inventory of factors is created in the main dialog box of the program, and the values of the intensities of the relationships (effects) and the initial values of the factor levels are input in the editor window.

The iterative process of the map transition to a new stable state stopped in accordance with the zero norm of correction between state vectors of the factors at neighboring iterations (run until convergence).

The research results using a cognitive map have been obtained as iteration processes results (Convergence reached), the processes convergence has been achieved in all cases.

5. Analysis of the experiments results

The final states of the factors of Fuzzy cognitive map are shown in Table 2. The columns correspond to the experiments numbers.

Table 2. Examples of resulting factors states.

	1	**2**	**3**	**4**	**5**	**6**	**7**
$\mathbf{e_1}$	0	0	0	0	100	0	100
$\mathbf{e_2}$	0	0	0	0	100	0	100

e_3	0	0	0	0	100	0	100
e_4	0	50	50	100	100	0	100
e_5	0	0	0	0	100	100	0
e_6	0	0	0	0	100	100	0
e_7	0	0	0	0	100	100	0
e_8	0	0	0	0	100	0	100
e_9	0	0	0	0	100	0	100
e_{10}	0	0	0	0	100	0	100
e_{11}	0	50	50	100	100	0	100
e_{12}	0	0	0	0	100	100	0
e_{13}	0	0	0	0	100	100	0
e_{14}	0	0	0	0	100	100	0
e_{15}	0	0	0	0	100	100	0
e_{16}	0	0	0	0	100	0	100
e_{17}	0	16	16	33	100	0	100
e_{18}	0	0	0	0	100	100	0
e_{19}	0	0	0	0	100	100	0
e_{20}	0	0	0	0	100	100	0
e_{21}	0	3	3	6	100	60	40
e_{22}	0	3	3	6	100	60	40
K	2	8	8	8	12	12	11

The column numbers correspond to the experiments numbers that are listed below.

1. Zero states of factors mean the system elements operation in the normative state and the absence of conclusion about a pre-emergency situation. The iterative process consists of two iterations.

2. Noise power increase (deviation variance) is represented by e4 equal to 50, and this was revealed with the help of the Park and White tests (e_{11}). The pre-emergency situation factor e_{21} has level 3. It is recommended to increase the intensity of cause-effect relationships. The iterative process consists of 8 iterations.

3. The intensity of effect between e_{21} and concepts-causes equal to 75, between e_{22} and e_{21} equal to 75, with other unchanged conditions. The concept level of the pre-emergency situation e_{21} has not changed. The pre-emergency situation factor e_{21} has level 3. The iterative process consists of 8 iterations.

4. Noise power increase (deviation variance) is represented by e_4 factor, its status is estimated as 100. The state of pre-emergency factor e_{21} has increased to 6. The iterative process consists of 8 iterations.

5. All the factor-causes from e_1 to e_7 are active and have the value of 100. The intensity of effect between e_{21} and the factor-causes is 100, between e_{22} and e_{21} is 100, with other conditions unchanged. All other factors reach the level of 100. The iterative process is completed within 12 iterations.

6. The only factor-reasons that are active are those from e_5 to e_7 and they have the value of 100. A pre-emergency situation reasons are related with the task of TCO moving, it is possible to adjust them.

The factor-causes from e_1 to e_4 have the value 0. The state of pre-emergency situation factor e_{21} has reached 60. The iterative process is completed within 12 iterations.

7. The situation that is reverse to the previous one. The only factor-causes that are active are those from e1 to e_4 and they have the value of 100. The factor-reasons from e5 to e7 have the value 0. The state of pre-emergency situation factor e_{21} has changed to 40. The iterative process is completed within 11 iterations.

6. Practical significance

The authors carry out research and development in predicting pre-emergency situations for technically complex objects.

Produced fuzzy cognitive map (Figure 1**)** allowed to develop the conception of the functioning complex computer system (CCS) prediction of emergency on the basis of analysis of structural instabilities and inhomogeneities of time series [17]. This determines CCS purpose, tasks, functions and principles of functioning, which allows defining the directions of works on its creation, use and development.

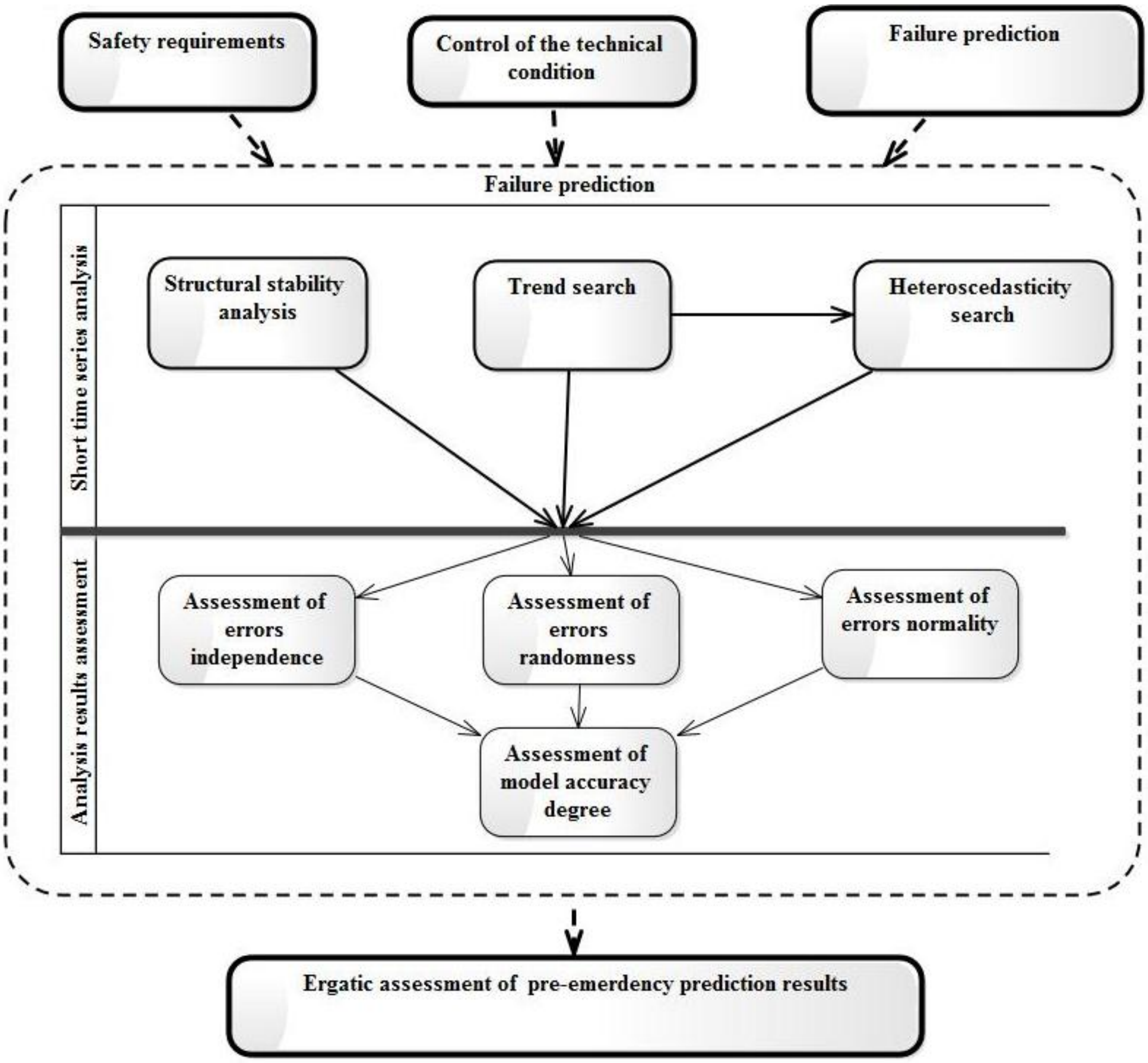

Figure 2. Conception of the functioning construction of CCS prediction of emergency situations.

In the process of developing CCS for forecasting an emergency situation on the basis of an analysis of time series [18], the following principles should be guided:

- parallelism (provides reduction of processing time, collection and analysis of initial information and execution of the very definition of the possibility of an emergency);

- continuity (the principle that operates after the very process of determining the possibility of an emergency situation and making corrections, as necessary, ensuring systematic collection and processing of additional information) [19];

- directness (reflects a strictly expedient, regulated transfer of information on the shortest path);

Within the framework of such CCS, in order to forecast an emergency, time series should be conducted through several stages of analysis:

- determination of the structural instability of time series and the search for anomalies in it [20-22];

- determination of the presence of a trend in time series [23-26];

- study of the change in the dispersion of the residual component of the time series (revealing heteroscedasticity).

At each of the stages considered, an assumption is made about a future change in the process. At the end of all stages, a general assumption is made about the occurrence of an emergency.

7. Conclusions

Within the framework of the application of fuzzy cognitive map as unified formal model of forecasting the occurrence of an emergency on the basis of the analysis of time series, the following elements are consolidated:

- discrete mathematical models of time series;
- a complex of mathematical models of structural inhomogeneities of time series;
- a complex of mathematical models of structural instabilities of time series;
- conditions for the optimal application of each model;
- generalized conception of TCO emergency situation prediction based on the analysis of the time series structure.

Experiments 2-4 prove the importance of adjusting the control system sensitivity both via the factors levels and intensities of cause-effect relations. It is disputable that there is the relation between the factors levels of the pre-emergency factor e_{21} having values 60 and 40 corresponding to experiments 6 and 7. Despite this the testing of the model demonstrates its adequacy in a wide sense, since there are no discrepancies between finite steady states of the system and fundamental concepts in the subject area.

To achieve functional stability and efficiency of the monitoring system is possible only with the complex approach to threat evaluation of approaching to the pre-emergency situation. Fuzzy cognitive maps tools used here are rather fruitful in terms of covering related subject areas [6]. It is not associated with a significant increase in the complexity of the algorithm with the complexity of parametric sensor equipment.

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