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Abstract— The paper considers the problem of automatic identification of typical functional structures in functional networks that describe human-machine interaction in ergatic control systems. The models are used for automatic reduction of functional networks and form the basis of the software package for modeling human-machine interaction.

Keywords— ergonomics, ergatic system, human-operator, human-machine, reliability, modeling, information technology cybersecurity, critical system

I. INTRODUCTION

The fourth industrial revolution despite significant achievements in the field of artificial intelligence [1], as well as robotics and automation of technological processes, transport systems [2-5], education [6-9] and the provision of various services, caused the appearance of so-called critical systems [10, 11] (at a high cost of errors and failures).

Unfortunately, the number of accidents (despite a successful application of cybernetics in production) and the risks to human life and health are increasing [11].

The avalanche-like increase in the number of network attacks and cybercrimes exacerbate traditional problems of unreliability of automated control systems [12].

The low efficiency of a large number of automated control systems is often associated with the "human factor"[2, 13-14].

II. PROBLEM STATEMENT

More than 80 percent of accidents in automated control systems are caused by errors of a human operator [3, 10, 13-16].

This is due to ignoring the principles of ergonomic support and adapting automation to the features of the human operator [16-18].

Solving the human factor problems in the tasks of automated control of technological processes, repelling cyberattacks and minimizing losses from cybercrimes is possible due to [11, 16-18]:

- system analysis of an automated system as an ergatic (man-machine) complex (with the study of features of technical, and information support, software, individual characteristics of operators, and processes of man-machine dialogue);
- assessment of the time-variety reliability indicators of alternative activity algorithms;
- solving a set of optimization problems.

Moreover, the main problem is the one of constructing an activity model [11, 17, 18] which, on the one hand, takes into account all the specific features of a person and system, and on the other hand, provides:

- prompt receipt of estimates of error-freeness and resource consumption indicators, including time;

- variant analysis of alternative methods of information processing and management.

To solve these problems within the man-system approach [19], it was proposed to use the apparatus of functional networks [19-21] to describe a man-machine dialogue.

Such a functional network (FN) compares favorably with other network models, for example [22], in the following:

- it allows not only describing the logic of the process, but also evaluates the time-variety reliability characteristics of the man-machine interaction;
- it takes into account the specific characteristics of a person as well as software and hardware.

The essence of the procedures for evaluating indicators of human-machine interaction is as follows [19-21, 23, 24]:

- actions and operations of the system functioning process are distinguished [24];
- typical functional units (TFU) are put in accordance with actions and operations [19];
- logical-functional relationships between TFUs are established and a process model is formed (the array of TFUs and the relationships between them form a model in the form of FN) [19];
- typical functional structures (TFS) are searched for and then replaced by equivalent TFUs with the same indicators of performance and resource consumption [19-21].

The last procedure repeats many times until the complete “collapse” of FN.

The variety of possible connections between TFUs and, as a rule, the large dimensions of networks cause problems [19-21, 23]:

- high complexity of “manual counting”;
- for automated modeling systems, the complexity of the procedures for translating the algorithm structures, presented graphically or in words, in a machine-oriented form;
- difficulties in the implementation of procedures for complete automation of calculations (without human intervention) associated with the appointing the equivalent indicators and a phased reduction in network dimension.

To solve the problems of ensuring reliability and cybersecurity of ergatic control systems, which are usually solved in real time, an instant calculation of situational behavior options is required. In this regard we supplement the well-known models [19-21, 23, 24] by a new functional network description language (FNDL) for FN [25] which provides the convenience of entering information in a computer.

However, in order to provide a fully automatic mode of calculations, the models that allow recognition of TFS and

implementation of automatic reduction of FN should supplement this language [19-21].

Thus, the objective of this study is to develop models of recognition of TFS for automatic evaluation of time-variable reliability indicators of man-machine interaction [19-21].

III. RESULTS

A. Statement of the problem of automatic estimation of the time-variety reliability characteristics using the functional network description language

Let us describe the essence of the problem using Fig. 1 example, where:

a – an example of a FN (describes a fragment of the activity of the operator of a computer system for controlling a gas pumping station of a gas main, studied and modeled by Viktor Koshara, a graduate student of Sumy State University);

b – a description of the FN in the language [25] (automatically generated by the computer system [11, 23] in the dialogue mode with the ergonomist);

c – a necessary sequence of steps for reducing the FN (should be carried out automatically).

When FN collapses, the calculation procedure should be carried out using computational models for probability of error-free execution, mathematical expectation, and variance of a random run-time value [19].

B. Functional network reduction algorithm

Let us reduce the process of reducing the FN dimension to manipulation of the line descriptions of FN, TFS, and TFU:

1. Present the operator’s activity algorithm in the form of a functional network;
2. Describe in a tabular (line) form the constructed O_{FS} network, using the elements and description operations developed in models [8, 9]:

$$O_{FS} = \langle \{o_{e_j}, te_j, N_j, \{V_{j_l}, L_{j_l}\} | l=1,2,\eta_j, [k_{c_j}]\} | j=1,2,\dots,n \rangle \quad (1)$$

3. Assign value 1 to the enlargement substitution number and to the TFS count: $k=1; m=1$;
4. Create a temporary description of the functional network with the name of O_{FS_l} in accordance with formula (1) in a tabular form. In the description of the given FN, select the lines describing the sequence of work operations and place them in the FN description with the name O_{FS_l} ;
5. In the description of the FN with the name O_{FS_l} , replace each group of lines describing the sequence of work operations with a line describing the equivalent TFU;
6. Create a description of the protocol for the process of reducing the dimension of the FN, PR_{FS} , in the FNDL, and place the lines of the protocol description for step $k = 1$. In the original description of the FN with the name

O_{FS} , replace the selected lines describing the sequence of work operations with the lines describing the equivalent TFUs. Delete all lines from the description of O_{FS_I} ;

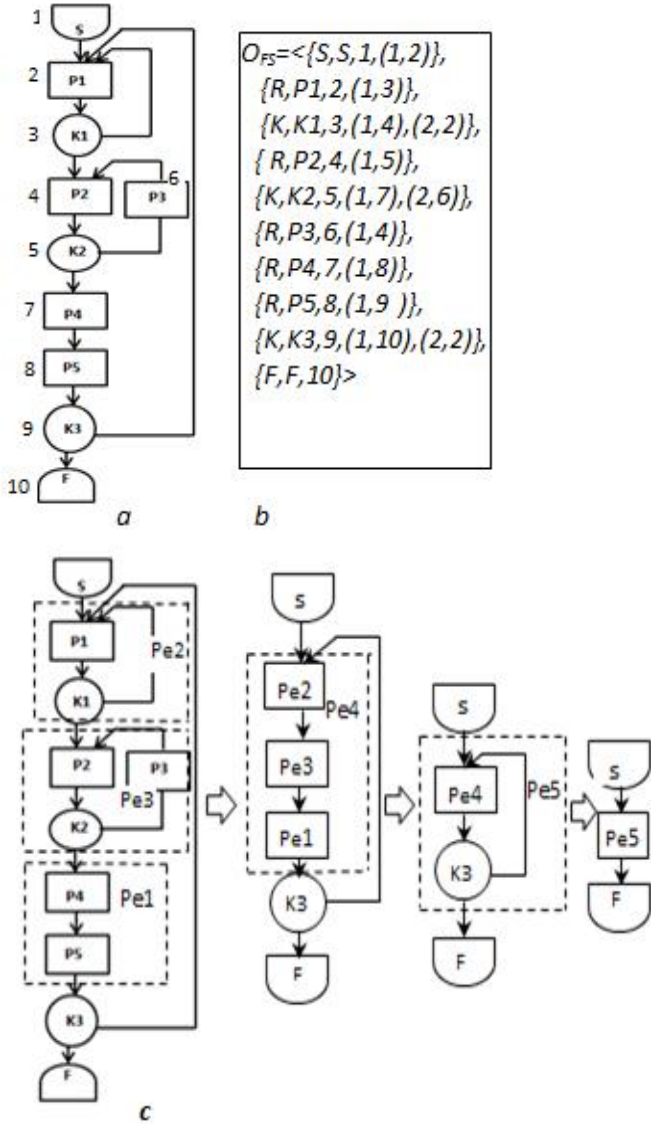


Fig. 1. Illustration of the problem of using the FN description language for reduction: a - functional network (graph model); b - functional network in the FNDL; c - desired sequence of reduction steps.

where: O_{e_j} - the j -th description element in the FN structure; te_j - designation of TFU in the structure of the algorithm, with an element of description O_{e_j} ; n - the number of description elements in the structure of the algorithm; $N_j, \{V_{j_i}, L_{j_i}\}$ - a descriptive operation corresponding to the j -th element of the FN description. This indicates a transition of type V_{j_i} from TFU with description element O_{e_j} and number N_j to TFU with

number L_{j_i} ; η_j is the number of types of transitions corresponding to the j -th element of description; k_{e_j} is a limit on the number of repetitions in a cycle.

- 7. Check the number of lines in the description of given functional network with the name O_{FS} , describing TFUs: $i = \text{number of TFU}$;
- 8. If $i = 1$, go to 24, otherwise go to 9;
- 9. Increase the TFS counter by 1: $m = m + 1$;
- 10. In the description of the FN with the name O_{FS} , select a sequence of lines representing the m -th TFS and place it in the description of the FN with the name O_{FS_I} ;
- 11. If the number of lines in the description of the FN with the name O_{FS_I} is empty, then go to 19; if not, replace the lines describing the m -th TFS in O_{FS_I} with the lines describing the equivalent TFUs;
- 12. Increase the collapse step by 1: $k = k + 1$. In the description PR_{FS} of the process protocol of decreasing the dimension of FN, add entries describing the protocol of folding $m-x$ TFS;
- 13. In the original description of the FN with the name O_{FS} , the records describing the selected m -th TFS should be replaced by the records with the description O_{FS_I} , representing the equivalent TFUs;
- 14. Delete all lines from the O_{FS_I} description;
- 15. In the description of the FN with the name O_{FS} , select the lines representing the sequences of working TFUs and place them in the description of the functional network with the name O_{FS_I} ;
- 16. If the number of lines in the description of the FN with the name O_{FS_I} is empty, then go to 19, otherwise replace the records representing the sequences of working TFUs by the records equivalent to TFUs;
- 17. Increase the collapse step by 1: $k = k + 1$. In the description PR_{FS} of the process protocol of reducing the dimension of the FN, add entries describing the protocol of folding the sequences of working TFUs
- 18. In the original description of the FN with the name O_{FS} , replace the selected lines describing the sequence of work operations with lines describing equivalent TFUs. Delete all lines from the O_{FS_I} description;
- 19. Check the number of lines in the description of the FN with the name O_{FS} , describing TFUs: $i = \text{the number of TFU}$. If $i = 1$, go to 24, otherwise go to 20;
- 20. Check the condition "Are there more TFS?". If "Yes", then increase the TFS counter by one: $m = m + 1$, otherwise go to step 22;
- 21. Go to step 10;
- 22. Check the number of lines in the description of the FN with the name O_{FS} ;

- 23. If $i > 1$, check the description of FN;
- 24. The end of the process of reducing the FN dimension.

The main complexity of the described procedure is the identification of collapsible fragments of the functional network, i.e. TFS, and replacing them with equivalent TFUs. Therefore, we describe this process separately.

C. Model recognition rules for typical functional structures

At each reduction step, certain states characterize FN. To describe them, we introduce the following notation:

k – a step of the process reducing the FN dimension, $k \in \mathbb{N}$;

$f_k = f(k)$ – state of the functional network at the k -th step of the process;

G_f – a set of functional network states in the process of reduction, $f_k \in G_f$; $k_0 = 0$ – initial step in the process of reducing the FN dimension;

$f_0 = f(k_0)$ – initial state of the functional network, $f_0 \in G_f$;

G_α – a set of rules for recognizing collapsible fragments of a functional network;

$\alpha_j \in G_\alpha$ – detection rule in the structure of the algorithm of the j -th TFS for reducing;

$u_k = u(k)$ – collapse protocol at the k -th step of the process.

Then the process of reducing the FN dimension can be represented by two mappings:

- Transitional mapping $R: (k; k_0, f, \alpha) \rightarrow f(k)$ to form the state of the FN $f(k) \in G_f$, achieved at the step $k \in \mathbb{N}$. The mapping is carried out by applying the rules for identifying TFS $\alpha \in G_\alpha$ (at the initial step $k_0 = 0$, the initial state of the FN structure is $f_0 = f(k_0)$, $k_0 \in \mathbb{N}$).
- Display of the output $u(k) = \eta(k, f(k))$ to form the FN reduction protocol.

The mappings R and η are defined by the sets of rules for replacing TFS with equivalent TFUs and mathematical models for determining performance quality indicators of equivalent TFUs, respectively. At the same time, the change in the state of the functional network at the step of the reduction process, depending on the initial recognition rules, the TFS is represented by the iterative formula:

$$f_{k+1} = f_k \circ \bar{a}_k, \quad (2)$$

where: f_k is the state of the functional network at the k -th step of the collapse process, represented in the line (tabular) form by formula (1), using the functional network description language;

$\bar{a}_k = (\alpha_1, \alpha_2, \dots, \alpha_m)_k$ is generalized vector of rules for recognizing TFS in the structure of the functioning algorithm at the k -th step of the collapse process,

α_j is the rule of identification in the structure of the algorithm of the j -th TFS for reduction, $m=18$. The recognition

rules for TFS are defined by predicates whose operands belong to the sets of description elements and description operations and are used to describe the functional network (formula 1).

In order to approximate model (2), and considering the state of the functional network f_k , represented in the line form by formula (1), we study the map $R: f_k, \alpha_k \rightarrow f_{k+1}$ as a sequence of expressions giving a line description corresponding to the state of the functional network f_k (we denote the description as O_{FS_k}) to a line description, corresponding to the state of the functional network f_{k+1} (we denote the description as $O_{FS_{k+1}}$).

Similarly, by PR_{FS_k} we denote a line description containing the collapse process protocol, corresponding to the k -th step of the process, and by $PR_{FS_{k+1}}$ – the collapse process protocol, corresponding to the $k+1$ -th process step. Then the process of reducing the dimension of the FN can be filed as a sequence of iterative formulas applied to the descriptions.

The descriptions O_{FS_1} and O_{FS_E} , having the same composition of elements in the description line as the description O_{FS_k} , are taken to select lines representing TFS from the O_{FS_k} relation and to represent equivalent TFUs, respectively.

Recognition and selection of collapsible fragments of the functional network of the j -th TFS are performed by the selection function from the O_{FS_k} description under the condition α ($TimesWhere(O_{FS_k}, \dots, \alpha_j)$), which contains operations for comparing different attributes with each other. The α_j rule depends on the type of TFS.

Replacement of collapsible fragments of the functional network of TFS with equivalent TFUs is carried out by sequential execution of the difference (*Minus*), update (*Update*) and union (*Union*) operations on the descriptions $O_{FS_{k+1}}$, O_{FS_1} , O_{FS_2} and O_{FS_E} . The O_{FS_E} description is generated based on the O_{FS_1} description defined by the execution of the $TimesWhere(O_{FS_k}, \dots, \alpha_i)$ function. At the same time, one O_{FS_E} description record corresponds to each TFS represented in O_{FS_1} . The values of the attributes of this record, which determine the performance indicators of the equivalent TFU, are calculated according to known models [19].

To display the protocol of the FN dimension reduction process, a description of PR_{FS_k} is taken, which, in addition to attributes whose values are performance quality indicators of equivalent TFUs, contains attributes for the values of the collapse step, the designation of equivalent TFUs, and the list of collapsible TFUs.

Thus, formula (2) is approximated as a sequence of iterative formulas over the specified descriptions:

$$\left. \begin{aligned} O_{FS_1} &= TimesWhere(O_{FS_k}, \alpha_1, O_{FS_k}, \alpha_2, \dots, \alpha_i); \\ O_{FS_2} &= Minus(O_{FS_k}, O_{FS_1}); \\ O_{FS_E} &= Update(O_{FS_1}); \\ O_{FS_{k+1}} &= Union(O_{FS_2}, O_{FS_E}); \\ PR_{FS_{k+1}} &= Union(PR_{FS_k}, O_{FS_E}); \end{aligned} \right\} \quad (3)$$

The ellipsis symbol in the first formula means that the number of designations (o_1, o_2, \dots) of the O_{FS_k} description depends on the type of recognized TFS in the algorithm structure.

Here are examples of the rules for generating the O_{FS_1} description for some TFS (Table 1).

D. Approximation and analysis of the results

The developed TFS recognition models to ensure the FN reduction procedure are the basis of the "Computer technology for modeling discrete man-machine interaction" software package [11, 23], which has been tested in modeling ergatic systems for various purposes [9, 11, 23-25]. Herewith, the assessment is carried out automatically (see Fig. 2 for the activity algorithm shown in Fig. 1).

	A	B	C	D	E	F	G
1	Protocol of reduction						
2	Number of reduction step	Collapsible TFU	Equivalent TFU	Probability of error-free performing the equivalent operation	Mathematical expectation of the equivalent operation run-time	Variance of the equivalent operation run-time	The type of collapsible TFU
3	1	P4, P5	Pe1	0,98861	0,7000	0,1500	RR
4	2	P1, K1	Pe2	0,99997	7,1787	1,5762	RK
5	3	P2, K2, P3	Pe3	0,99992	10,6807	3,5137	RKR
6	4	Pe2, Pe3, Pe1	Pe4	0,98850	18,5994	5,2399	RR
7	5	Pe4, K3	Pe5	0,99970	19,9807	14,4868	RK
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19	Reduction step:	1 - RR: P4, P5=Pe1	2 - RK: P1, K1=Pe2	3 - RKR: P2, K2, P3=Pe3	4 - RR: Pe2, Pe3, Pe1=Pe4	5 - RK: Pe4, K3=Pe5	

Fig. 2. Example protocol of functional network reduction

IV. CONCLUSION

It is convenient to describe the activities of the human operator in automated systems using FN. The main problem of automation of modeling complex ergatic systems is the impossibility of automatic analysis and reduction of FN.

A formal description of the FN in the FN description language made it possible to formulate the rules for recognizing TFS in the FN structure in order to reduce it automatically.

Thus, the posed and solved task of recognizing TFS allows us to automatically evaluate the reliability of man-machine interaction.

The developed models form the basis of a computer program for assessing the reliability of man-machine interaction options. The computer program was used in the design and operation of systems for various purposes and confirmed the constructiveness of the described models.

TABLE I. EXAMPLES OF RULES FOR THE FORMATION OF OFS_1 DESCRIPTION

Content of typical functional structure	TFS diagram	Model (The symbols "o1", "o2", "o3" are used to indicate of OFS_1 description)
.Consistent implementation of operations, F_{SRR} :		$O_{FS_1} = TimesWhere (O_{FS_k} o_1, O_{FS_k} o_2, a_1)$ <p>here:</p> $a_1 = ((o_1.o_{e_j} = "R" \wedge o_1.N_j = o_1.L_{j_1} - 1) \wedge (o_2.o_{e_j} = "R" \wedge o_2.N_j = o_1.N_j + 1 \wedge o_2.L_{j_1} = o_2.N_j + 1)) \vee ((o_1.o_{e_j} = "R" \wedge o_1.L_{j_1} = o_1.N_j + 1) \wedge (o_2.o_{e_j} = "R" \wedge o_2.N_j = o_1.N_j - 1 \wedge o_2.L_{j_1} = o_2.N_j + 1))$
Cyclic functional structure "An operation with action control without restrictions on the number of cycles", F_{SRK} :		$O_{FS_1} = TimesWhere (O_{FS_k} o_1, O_{FS_k} o_2, a_2)$ <p>here:</p> $a_2 = ((o_1.o_{e_j} = "R" \wedge o_1.N_j = o_1.L_{j_1} - 1) \wedge (o_2.o_{e_j} = "K" \wedge o_2.N_j = o_1.N_j + 1 \wedge o_2.L_{j_1} = o_2.N_j + 1 \wedge o_2.L_{j_2} = o_1.N_j)) \vee ((o_1.o_{e_j} = "K" \wedge o_1.L_{j_1} = o_1.N_j + 1 \wedge o_1.L_{j_2} = o_1.N_j - 1) \wedge (o_2.o_{e_j} = "R" \wedge o_2.N_j = o_1.L_{j_2} \wedge o_2.L_{j_1} = o_2.N_j + 1))$
Functional structure "An operation with action control and without restrictions on the number of cycles", F_{SRKI}		$O_{FS_1} = TimesWhere (O_{FS_k} o_1, O_{FS_k} o_2, a_3)$ <p>here:</p> $a_3 = ((o_1.o_{e_j} = "R" \wedge o_1.N_j = o_1.L_{j_1} - 1) \wedge (o_2.o_{e_j} = "K" \wedge o_2.N_j = o_1.N_j + 1 \wedge o_2.L_{j_1} = o_2.N_j + 1 \wedge o_2.L_{j_2} > o_2.N_j + 1)) \vee ((o_1.o_{e_j} = "K" \wedge o_1.L_{j_1} = o_1.N_j + 1 \wedge o_1.L_{j_2} > o_1.N_j + 1) \wedge (o_2.o_{e_j} = "R" \wedge o_2.N_j = o_1.N_j - 1 \wedge o_2.L_{j_1} = o_2.N_j + 1))$

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