Mathematical models for description of human-machine interaction in automated systems

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December 29, 2020

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***Abstract*—The task of functional network description formalization for operator activity algorithm in automated systems is examined. The method of functional networks description is developed.**

Keywords—automated system, man-machine, interaction, algorithm of functioning; functional network.

I. Introduction

The effectiveness of automated systems depends significantly on the consideration of the so-called "human factor" [1-6]. Creation by Professor Gubinsky A.I. scientific school "The effectiveness, quality and reliability of systems" man - technology - environment "was in fact a revolution in ergonomics, which allowed to find approaches to the formalization and optimization of the human-operator [7-9].The activity of the human-operator [7-9] is specified by the functional network (FN), but there are big problems associated with the convenience of entering the structure of this FN into the computer for the purposes of the subsequent simulation of human-machine interaction.

II. Statement of the task

FN is used by many authors to model human activities and assess risks in different systems:

• in information processing systems [7, 10-12];

• in the systems of computer production management and decision support systems [7, 9, 10, 13-17];

• in e-learning systems [7, 10, 18-20];

• in space systems [7, 8].

The FS is a very convenient model, because it allows [7-10, 21]:

• describe human activities and computer operations;

• assess the accuracy and time of implementation of activities;

• to set and solve optimization problems.

FN is more convenient than Petri networks [7, 22] and other network models, because allows not only to describe the process, but to evaluate it.

However, in order to evaluate the FN indicators, it is necessary to "collapse", i.e. carry out a reduction. For this, one should be able to recognize typical blocks of operations in the description. And then – to change them by one operation with equivalent characteristics.

Until now, this is done manually. Unfortunately, until today, we could not automate the folding procedures. The main problem is the recognition of typical blocks of operations.

Disadvantages of manual recognition:

• great labor intensity;

• errors of recognition;

• high time consumption.

However, this is unacceptable when the management tasks in complex systems are being solved [1-6, 23].

In connection with these problems, we define the task. The purpose of this work is to develop an approach to the development of a language describing the FN, which allows:

– describe (in a form convenient for entering into the computer) FN including:

- operations algorithm of operation – typical functional units (TFU);
- communication between operations (TFU);
- characteristics of operations;
- typical blocks of operations – type functional structures (TFS);
- rules for identifying TFS;
- rules for converting (reducing) the FN;
- models for calculating the indicators at the steps of reduction;

– to ensure automatic reduction and evaluation indicators of FN.

III. RESULTS

A. Models development for describing and evaluating FN in general

By a functional network formalized description, we mean the representation of the algorithm for the functioning of the human machine system (HMS) by a structural formula consisting of two sets elements M_1 and M_2:

M_1 – an elements set of the FN description, with the help of which a functional network description of the activity algorithm is constructed, taking into account events leading to the generation, detection and errors elimination (including various types);

M_2 – a types set of links (description operations) between elements of the FN description. This elements set are relations between the elements of the particular FN description (order, outputs and transitions).

Then we obtain a FN description model in general form:

$$O_{FS} ::=< E_{FS}, S_{FS} >, \quad (1)$$

where: E_{FS} – a description elements subset from the set M_1, $E_{FS} \in M_1$;

S_{FS} – a subset of operations describing the set M_2, $S_{FS} \in M_2$.

Estimating a functional network process is also given by elements of two sets M_3 and M_4:

M_3 – an evaluation elements set; probabilistic and cost characteristics, with the help of which the quality of the elements performance of the FN description is assessed;

M_4 – an estimation operations set, that is, operations on the evaluation elements, by means of which the probability-time characteristics of the HMS operation entire algorithm are calculated. To the set M_4 we refer the library of known mathematical models for calculating the performance indicators of typical functional structures and replacing them by equivalent standard functional units with one error in mind and developed models for accounting for errors of various types. We introduce a one-to-one correspondence: first, between the description elements of M_1 and the estimation elements from M_3; secondly, between the description operations of M_2 and the estimation operations from M_4. This makes it possible to quantify the HMS operation algorithm by a formal procedure: it is sufficient to describe the operation algorithm by the sets M_1 and M_2, and then to identify and replace each description operation from the set M_2 by the corresponding estimated operation from the set M_4.

The procedure for replacing the description operations with their estimated analogs in the study of a formalized FN will be called the folding or FN reduction (by analogy with the FN graphical representation reduction). This procedure is based on the use of typical functional units and structures. Then we obtain a FN model estimation in general form:

$$C_{FS} =< C_{EFS}, C_{OFS}, \mathrm{Pr}_{FS} >, \quad (2)$$

where: C_{EFS} – an estimation elements subset from the set M_3, $C_{EFS} \in M_3$;

C_{OFS} – a estimation operations subset from the set M_4, $C_{OFS} \in M_4$;

Pr_{FS} – reduction protocol FN model.

Define the description elements values, evaluation elements and description operations used to represent the functional network and other objects.

B. FN elements description

With the help of the description elements (the set elements M_1), the TFU designations (the functionaries of the basic and additional and composers of auxiliary and service), the TFU name and the equivalent TFU name in the structure of the activity algorithm. Functionaries correspond to real operations or a person's actions, work operations of technological equipment, computer hardware and software in the analyzed functioning algorithm, and composers to certain interrelationships of operations and logical functions.

The designations of functioning some units, taken to denote the FN elements, their names are given in Table 1.

TABLE I. THE DESCRIPTION ELEMENTS FOR DESIGNATION OF THE FUNCTIONING BASIC TYPICAL UNITS

Number	Description element definition	Application for description
1	*R*	Working operation
2	*A*	Alternative operation
3	*K*	Operation control function
4	*Z*	Delay operation

As the description elements for specifying the TFU name and equivalent TFU in the structure of the activity algorithm, we will use symbol sequences that indicate the TFU type or equivalent TFU and the number of this TFU in the algorithm structure:

«*P1*», «*P2*»,…, «*Pn*», «*K1*», «*K2*»,…, «*Pe1*»,… .

C. The estimation elements set

Elements of this group are used as variables for setting values of quality indicators of descriptive elements from the set M_1. A variable, like in mathematics, is an object with a name and meaning. The name is used to indicate the quality score. The variable gets a specific value in the process of setting the value to the evaluation elements (elements of the set M_3), i.e. probabilistic and temporal characteristics, with the help of which the quality of descriptive elements performance is evaluated.

Variables examples and their use are shown in Table 2.

D. TFU Model

A formalized description of a functional unit is an element of the description from the set M_1, together with the corresponding elements of the evaluation from the set M_3.

Then the i-th model functional unit will look like:

$$Fe_i ::=< o_{e_i}, \{c_{e_{ij}}\} | \; j = 1,2,\dots m_i >, \quad o_{e_i} \in M_1, c_{e_{ij}} \in M_3 \tag{3}$$

where: Oe_i – the i-th description element of the set M_1;

Ce_{ij} – j-th evaluation element (j-th quality indicator) of the i-th item from the set M_1;

m_i – the evaluation elements number related to the i-th descriptive element.

TABLE II. – EVALUATION ELEMENTS

Number	Evaluation element designation	Application for setting values
1	B^1	TFU error-free execution probability
2	B^0	TFU erroneous execution probability
5	M_T	Expected value of execution time
6	D_T	Execution time dispersion
7	K^{11}	The conditional probability that the operation under test, if actually performed correctly, will be recognized as correct
8	K^{00}	The conditional probability that the operation to be checked, if actually performed incorrectly, will be recognized as incorrect

Using the obtained functional unit model in general form (formula 3), as well as the description elements and estimation defined above, we will describe some functional units (Table 3).

E. The relationships description between FN elements

The connections between the FN elements are specified by the elements of the set M_2, that map how connected and in which sequence the operation units are performed.

TABLE III. THE FUNCTIONAL UNITS' DESCRIPTION

TFU number	TFU contents	TFU model
1	Working	$Fe_1=<R,B^1,B^0,[M_T,D_T],[\overline{C},[D(C)],[\overline{W},D(W)]>$
2	Alternative	$Fe_2=<A,A_i,A_{ij},[M_T,D_T],[\overline{C},D(C)],[\overline{W},D(W)]>$
3	Function monitoring	$Fe_3=<K,K^{11},K^{10},K^{00},K^{01},[M_T,D_T],[\overline{C},D(C)],[\overline{W},D(W)]>$
4	Delay	$Fe_4=<Z,[M_T,D_T],[\overline{C},D(C)],[\overline{W},D(W)]>$

Elements of this group are generally denoted by N_j, V_{jl}, L_{jl} variables with lower indices, used in models to define relationships between functional structures elements and a functional network, and take integer values. The use of these variables:

N_j – the serial TFU number in the algorithm structure;

V_{jl} – the transition possible type after the TFU execution with the number N_j;

L_{jl} – TFU number executed after the TFU execution with the number N_j, if a type transition occurs V_{jl}.

The list of transitions possible types and the corresponding values of the variable V_{jl} are given in Table 4.

TABLE IV. APPLICATION OF THE VARIABLE VJL

Variable value Vj_l	Use to specify the transition type
1	The transition to TFU in the structure of the algorithm following the given in the main algorithm direction
2	Transition to the TFU, which follows the current TFU "operation control" in case of operation erroneous execution
3	Transition to the TFU following the current TFU "performance check" in case of operation erroneous execution
4	Transition to the TFU of the continuation of the cycle following the current TFU
5	The transition to the TFU, which follows the current TFU and signifies the exit from the cycle

In the elements group of the links assignment we add the variable kc, which means the restriction on the number of repetitions in the cycle.

F. TFS Model

A functional structure formalized description is a description operation from the set M_2, that defines the relations between several description elements, together with the corresponding valuation operations from the set M_4. Then the i-th model functional structure will look like:

$$Fs_i ::=<\{o_{e_{ij}}, N_{ij}, \{V_{ij_l}, L_{ij_l}\} \; | \; l=1,2,..\eta_{i_j}, [k_{c_j}]\} | \; j=1,2,..k_i\}, o_{ee_i}, \{y_{i_m}\} | \; m=1,2,..z_i> \tag{4}$$

where: Oe_{ij} – j-th description element of the i-th functional structure;

k_i – number of description elements of the i-th functional structure;

k_{cj}- restriction on the repetitions number in a cycle;

$\{N_{ij}, \{V_{ijl}, L_{ijl}\} | l=1,2,\dots,\eta_{ij}\} \in M_2$ – a links subset (description operation) corresponding to the j-th description element the of the i-th functional structure.

Denotes the transition V_{ijl} from the functional unit with the descriptive element Oe_{ij} and the number N_{ij}, to the functional unit with the number L_{ijl};

η_{ij} – number of transitions types corresponding to the *j*-th descriptive element of the *i*-th functional structure;

Oee_i – description element of the equivalent functional unit of the *i*-th functional structure;

$\{y_{im}\}$ – *m*-th the valuation operation of the *i*-th functional structure used to determine the *m*-th quality index of equivalent TFU, $\{y_{im}\} \in M_4$;

z_i – evaluation operations number of the *i*-th functional structure.

Using a functional structure model (formula 4) defined in general form, as well as the descriptive, estimated elements and elements of the task of descriptive operations defined above, we give the functional structures description (TFS models examples are in Table 5).

TABLE V. EXAMPLES OF THE FUNCTIONAL STRUCTURES DESCRIPTION

TFS number	TFS designation	TFS model
1	Fs_{RR}[a]	Fs_{RR} =<{R,1,(1,2)},{R,2,(1,3)},..., {R,n,(1,n+1)},R,{B,MT,DT}>
2	Fs_{RK}[b]	Fs_{RK} =<{R,1,(1,2)},{K,2,(1,3),(2,1)}, R,{B,M_T,D_T}>
3	Fs_{CRF}[c]	Fs_{CRF} =<{R,1,(1,2)},{C_F,2,(4,1),(5,3),k_c}, R,{B,M_T,D_T}>

a. Consistent execution of work operations.

b. Cyclic FN "Working operation with monitoring of operation without limit on the number of cycles".

c. *n*-fold repetition of the work operation with acceptance for all successful outcomes.

G. FN model of operator activity algorithm

Taking into account the description elements and description operations introduced in the models (3) and (4), the structural formula (1) of the functional network representation by elements of the sets M_1 and M_2 will look like:

$$O_{FS} ::=< \{o_{e_j}, te_j, N_j, \{V_{j_l}, L_{j_l}\} \\ \left| l = 1,2,...,\eta_j, [k_{c_j}]\}\right| j = 1,2,...,n >, \quad (5)$$

where: Oe_j – *j*-th element of the description in the structure of the activity algorithm;

te_j – the designation in the algorithm structure of the functional unit with the description element Oe_j;

n – the number of the description elements in the algorithm structure;

$\{N_j, \{V_{jl}, L_{jl}\}$ – descriptive operation corresponding to the *j*-th element of the functional network description. Denotes a type - V_{jl} transition from a functional unit to a description element Oe_j and number N_j, to the functional unit with the number L_{jl};

η_j – transition types number corresponding to the *j*-th description element;

k_{cj} – restriction on the repetitions number in a cycle.

CONCLUSION

Human activity in computer systems is conveniently described using FN.

The main problem of automating the ergonomic modeling of complex human-machine systems is the inability to automatically analyze the FN.

The analysis of the FN elements was performed.

This allowed us to develop models of:

- typical functional units;
- typical functional structures;
- complete FN, which describes the activities of human-operator.

Such models represent a language for describing the algorithm of human activity, which is convenient for entering into a computer.

The language is constructed in such a way, that it allows to automically identify typical functional structures and carry out the reduction of FN.

The developed models allowed to create a computer program [24] for assessing the reliability of the human-operator.

The computer program was used in the design process for systems of various purposes [12, 17, 25, 26] and was showed its effectiveness.

REFERENCES

[1] Rothmorea, P. The implementation of ergonomics advice and the stage of change approach [Text] / P. Rothmorea, P. Aylwardb, J. Karnon // Applied Ergonomics. 2015. – V. 51. – P. 370–376. doi: 10.1016/j.apergo.2015.06.013

[2] Cacciabue, P. C. Human error risk management for engineering systems: a methodology for design, safety assessment, accident investigation and training [Text] / P. C. Cacciabue // Reliability Engineering & System Safety. 2014. – V. 83(2). – P. 229 – 269. doi: 10.1016/j.ress.2003.09.013

[3] Dul, J. A strategy for human factors/ergonomics: developing the discipline and profession [Text] / J. Dul, R. Bruder, P. Buckle, P. Carayon, P. Falzon, W. S. Marraset // Ergonomics. 2012. – V. 55(4). – P. 377–395. doi: 10.1080/00140139.2012.661087

[4] Bentley, T. A. The role of organisational support in teleworker wellbeing: A socio-technical systems approach [Text] / T. A. Bentley, S. T. T. Teo, L. McLeod, F. Tana, R. Bosua, M. Gloet //Applied Ergonomics. 2016. – V.52. – P. 207–215. doi: 10.1016/j.apergo.2015.07.019

[5] De Felice, F. Methodological Approach for Performing Human Reliability and Error Analysis in Railway Transportation System [Text] / F. De Felice, A. Petrillo // International Journal of Engineering and Technology. 2011. – V. 3(5). – P. 341–353.

[6] Sedov, V.A. The fuzzy model of ships collision risk rating in a heavy traffic [Text] / V.A.Sedov, N.A.Sedova, S.V.Glushkov// In Proc. of the 22nd International Conference on Vibroengineering. 2016. – P. 453–458.

[7] Adamenko, A.N., Asherov, A.T., Berdnikov, I.L. et al. Information controlling human-machine systems: research, design, testing, Reference book, Gubinsky, A.I. & Evgrafov, V.G., eds., Mechanical Engineering, Moscow, 1993.-528 p. (In Russian)

[8] Popovich, P.R. Ergonomic support of astronauts' activities /P.R. Popovich, A.I. Gubinskiy, G.M. Kolesnikov.-M.: Mechanical Engineering, 1985.-272p. (In Russian)

[9] Chabanenko, P.P. Research of the safety and efficiency of the functioning of systems “human – technics” by ergonomic networks /P.P. Chabanenko.- Sevastopol, Academy of naval forces named after P. S. Nahimov, 2012.-162p. (In Russian)

[10] Anokhin, A. Education and professional development of ergonomists in Russia [Text] / A. Anokhin, I. Gorodetskiy, V. Lvov, P. Paderno // In Proc. of International Conference in Applied Human Factors and Ergonomics 2014 and the Affiliated Conferences, 2014. – P. 1017–1024.

[11] Tortorella, G. L. Lean manufacturing implementation: an assessment method with regards to socio-technical and ergonomics practices adoption [Text] / G. L. Tortorella, L. G. L. Vergara, E. P. Ferreira //The International Journal of Advanced Manufacturing Technology. 2016. – P. 1–12.

[12] Lavrov, E. Ergonomics of IT outsourcing. Development of a mathematical model to distribute functions among operators [Text] / E. Lavrov, N. Pasko, A. Krivodub, N. Barchenko, V. Kontsevich //Eastern European Journal of Enterprise Technologies. 2016. – N.4 (80). – P. 32-40.

[13] Yang, J., Yang, M., Wang, W., and Li, F. Online application of a risk management system for risk assessment and monitoring at NPPs. Nuclear Engineering and Design, vol. 305, 2016.- P. 200-212.

[14] Hassnain, A., Yu, Y., Shahzad, M. A., Ammar, M. A., and Ansari, T. Q. Available recovery time prediction in case of an accident scenario for NPP component. Progress in Nuclear Energy, vol. 97, 2017.- P. 115-122.

[15] Xu, P., Wang, J., Yang, M., Wang, W., Bai, Y., and Song, Y. Analysis of operator support method based on intelligent dynamic interlock in lead-cooled fast reactor simulator. Annals of Nuclear Energy, vol. 99, 2017.- P. 279-282.

[16] Li, P. C., Zhang, L., Dai, L. C., and Li, X. F. Study on operator's SA reliability in digital NPPs. Part 1: The analysis method of operator's errors of situation awareness. Annals of Nuclear Energy, vol. 102, 2017.-P. 168-178.

[17] Lavrov, E. Mathematical models for the distribution of functions between the operators of the computer-integrated flexible manufacturing systems [Text] / E. Lavrov, N. Pasko, A. Krivodub, // In Proc. of the International Scientific Conference TCSET'2016, 2016. – P. 72–77.

[18] Burov, O. Combination of Usability Evaluation of E-Learning Tools and Ergonomic Expertise [Text] / O. Burov, O. Tsarik // In Proc. of the National Aviation University, 2014. – N. 2 (59). – P. 136–140.

[19] Burov, O. Ergonomic evaluation of e-learning systems [Text] / O. Burov, O. Tsarik // Presented at Zastosowania Ergonomii, Poland, 2013.

[20] Lavrov, E. Organizational Approach to the Ergonomic Examination of E-Learning Modules [Text] / E. Lavrov, O. Kupenko, T. Lavryk, N. Barchenko //Informatics in education, 2013. –V. 12. – N. 1. – P.105 – 123.

[21] Grif M. G. Methods of desingning and modeling of man–machine systems [Text] / M. G. Grif, O. Sundui, E. B. Tsoy // In Proc. of International Summer workshop Computer Science 2014, 2014. – P. 38–40.

[22] Drakaki M., Tzionas P. Manufacturing Scheduling Using Colored Petri Nets and Reinforcement Learning //Applied Sciences. – 2017. – T. 7. – №. 2. – P. 136. doi:10.3390/app7020136

[23] Havlikovaa, M. Human Reliability in Man-Machine Systems [Text] / M. Havlikovaa, M. Jirglb, Z. Bradac // Procedia Engineering. 2015. – V. 100, P. 1207 – 1214. doi.org/10.1016/j.proeng.2015.01.485

[24] Lavrov E.A., Pasko N.B. The certificate of registration of copyright for the work "Computer program" Computer technology modeling discrete human-machine interaction", № 45262, 21.08.2012. (In Ukrainian).

[25] Lavrov, E. Development of Adaptation Technologies to Man-Operator in Distributed E-Learning Systems [Text] / E. Lavrov, N. Barchenko, N. Pasko, A. Tolbatov // Proceedings of 2nd International Conference on Advanced Information and Communication Technologies-2017 (AICT-2017), Lviv, Ukraine, July 4-7, 2017.– P. 83-87

[26] Lavrov, E. Cybersecurity of Distributed Information Systems. The Minimization of Damage Caused by Errors of Operators During Group Activity [Text] / E. Lavrov, N. Pasko, A. Tolbatov, V. Tolbatov// Proceedings of 2nd International Conference on Advanced Information and Communication Technologies-2017 (AICT-2017), Lviv, Ukraine, July 4-7, 2017.– P. 83-87.