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Functional Networks for Modeling and Optimization Human-Machine Systems

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Abstract The article examines the issues of reliability or human-machine systems and modeling of human-machine interaction. The classification of models for describing human activity and its interaction with a machine is carried out. The advantages of functional networks for ergonomics are show. The description of the mathematical apparatus of functional networks is given. The characteristics of the models for describing, evaluating and optimizing the algorithms of the human operator's activity when they work with automaton are given. Examples of models for control systems for complex objects of different types are given. A computer system for modeling and optimizing the activities of operators of control systems is described. The tasks are set for improving the theory and practice of functional networks, associated with the development of situational control models and intelligent analysis of data on the reliability of the human operator. The results will be useful for finding ergonomic reserves for increasing the reliability of automated systems.

Keywords Reliability • Simulation ^Ergonomics • Man-machine system Activity algorithm • Optimization.

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1 Introduction

intelligence, the expected complete exclusion of man from the field of computerized production did not occur [1, 2]. Moreover, the importance of his role and the intensity of his activities in this area in connection with the growth of responsibility and the cost of mistakes are constantly increasing [3, 4].

2 Problem Statement

The catastrophic consequences of ignoring the human factor for critical systems [5, 6] actualize the task of designing ergonomic measures [7, 8]. The traditional problems of ergonomics are [9-11]: anthropometry, biomechanics, psychophysiology, perception of information, memory, thinking, safety, prevention of musculoskeletal disorders and risk of various diseases, etc. However, a number of scientists [10, 12-14] notes that despite the importance of these and other local tasks, in the conditions of a new stage in the development of ergonomics—«ergonomics of the information space»—complex tasks of organizational ergonomics come to the fore, that is, the tasks of modeling and optimizing the activities of operators taking into account all significant factors. In this regard, we define the goal of this work: to describe the methodology of modeling by functional networks of operators' activities (little presented in the English-language scientific literature), taking into account the structures of human-machine interaction and the entire range of influencing factors.

3 Results

3.1 History and Methodology of Modeling Human-Machine Systems by Functional Networks

The founder (1963) of the functional-structural theory [14-16] of ergo-technical systems was Anatoly Ilyich Gubinsky (1931-1990), a military sailor, Doctor of Technical Sciences, Professor, Captain 1st Rank, the first president of the Soviet Ergonomic Association. The impetus for his research in the field of ergonomics was the experience gained during his service in the navy: in 1959 A.I. Gubinsky took part in the first voyage of a nuclear submarine cruiser to the North Pole. By 1981, under the leadership of professor A.I. Gubinsky, the scientific direction «Efficiency, quality and reliability of human-technology systems» was finally formed [14-16].

Ergonomic associates (doctors of sciences) Vladimir Evgrafov, Yuri Grechko, Valentin Kobzev, Evgeny Tsoi, Mikhail Grif, Evgeny Pavlov (Russia); Akiva

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Asherov, Pavel Chabanenko, Alexander Burov, Georgy Kozhevnikov, Sergey Shtovba (Ukraine); Alexander Rothstein (Israel), Marjan Wlodarczyk (Poland) and many others not only participated in the development of principles and models for the evaluation and optimization of man-machine systems, but also tested them on systems of various purposes and in various fields [13, 16, 17]:

marine fleet;
aviation and astronautics;
control systems for technological processes of various types;
enterprise management systems;
training systems.

To model and evaluate such logically complex systems, it is in principle impossible or difficult to use existing network and other models [18, 19], for example:

- logical systems (formal grammars, Petri networks, etc.);
- algebraic systems (Markov and semi-Markov processes);
- language-algebraic systems (antecedent networks, PERT, GERT, etc.).

This is due to the fact that these models have common drawbacks: the impossibility of describing the complex logic of human interaction with technology and (or) the impossibility of obtaining an assessment of the reliability and timeliness of the performance of activity processes. Therefore, a fundamentally new type of model was developed—a functional network (FN), which describes and allows to evaluate the process of human-machine interaction. FN is a work graph, the vertices of which correspond to operations, and the arcs correspond to relations between operations, and (or) an event graph (events describe, for example, the processes of occurrence and elimination of errors or failures). To describe the process of interaction, typical functional units (TFU) are used: functionaries that correspond to real operations and actions, and composers necessary to establish logical and functional links between functionaries.

The introduction into the alphabet of the FN apparatus of operations of control of functioning and operability allows, in contrast to other network methods, to simulate the processes of loss of stability of functioning due to errors and failures. FN can describe cyclic processes (loops), both with a limitation on the number of repetitions, and without this limitation. The logic for executing parallel operations is wider than in GERT, and allows to implement the functions of logic algebra «AND», «OR», «XOR» both at the input and at the output of the parallel structure. To assess the reliability (accuracy, timeliness) and resource consumption, a set of analytical expressions was obtained for the most common structures, the so-called typical functional structures (TFS). If in 1991 the base of models contained models for 18 TFS, then in 2020 it contains models for 55 TFS.

An assessment of the quality of the execution of the entire algorithm of human-machine interaction is obtained by sequential iterative combining of TFU into TFS (by «folding» of TFU).

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3.2 Solution of Ergonomics Problems by Methods of Functional Networks. Automating Modeling in Ergonomics

After the death of A.I. Gubinsky in 1990, the collapse of the USSR and the general crisis in science, work within the framework of the scientific school was suspended. In 1997, we resumed research within the framework of Russian-Ukrainian cooperation in connection with the urgent need to develop decision support systems to find ergonomic reserves for the effectiveness of new generation automation systems. The effectiveness of assessment and optimization models based on FN for solving typical problems of ergonomics has been proven [16, 17, 20]:

- *Er*j—distribution of functions between man and technology (choice of the degree of automation);
- Er_2—determination of the number of personnel and the distribution of functions between operators;
- Er_3—design of information models (interfaces);
- Er_4—design of operator activity algorithms;
- Er_5—design of working conditions and certification of workplaces.

A need arose to solve a number of fundamentally new problems at a new level, due to the fact that in order to make decisions on-line, FN must be analyzed quickly and automatically, excluding human participation. To do this, a new computer-optimized FN description language and its automatic parsing method were developed [20, 21]. This and a number of other new models form the basis of the simulating qualimetric complex of human-machine interaction (Table 1).

Table 1 The main subsystems of th e dating qualimetric complex

Subsystem	Model types	Solvable tasks	Source
1. Storage (formation, taking into account influencing factors) of the initial data on the reliability and duration of operations	Databank, predictive model (neural network, fuzzy logic, etc.)	Er_1-Er_4	[21]
2. FN assessment, variant analysis	TFU, TFS, FN description language, FN analysis mode	Er_1-Er_4	[21]
3.FN optimization	Single-criteria and multi-criteria tasks (task bank contains 56 models)	Er_1-Er_4	[22]
4.Assessment of physical and psychological factors of the environment, assessment of the workplace	Normative, expert, fuzzy models; integral scores	Er_s	[23]
5. Ergonomic expertise	Bank of models for the formation and processing of expert assessments	Er_1-Er_5	[24]

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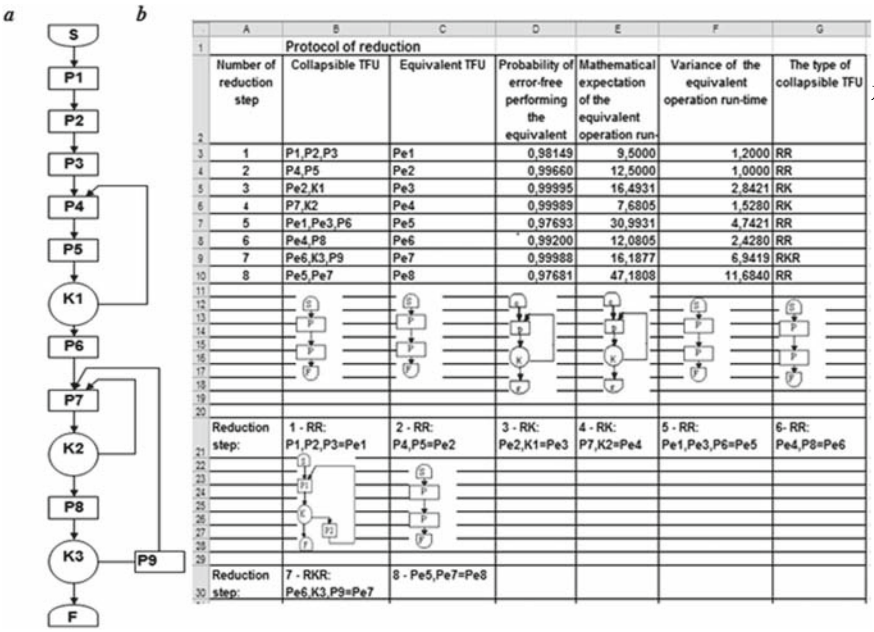
An example of the results of calculating reliability (for a flexible production system), performed using the software package, is shown in Fig. 1.

On the left, Fig. 1 shows the algorithm of the operator's activity using the symbols accepted in the scientific school of A.I. Gubinsky [14-17]: rectangle—working operation (mandatory for a technological process), circle—an operation of checking the correctness of the technological process (introduced to increase error-free). On the right, Fig. 1 shows how a specially designed computer program identifies typical functional structures in the activity algorithm, substitutes human reliability characteristics into the corresponding formulas, and replaces the found structures with single operations with equivalent characteristics *(Pe$_i$* designating an equivalent operation that replaced a certain typical functional structure in the *i*-th step). The presented process of folding typical structures consists of 8 steps. In the last step, the desired error-free probability values and runtime statistics are obtained. All necessary calculations are carried out completely automatically, which allows an ergonomist or manager not to waste time on them. Assessments can be obtained for different initial data (taking into account differences in equipment, working conditions, operator skills, etc.) and different activity structures, while providing a graphical display of existing dependencies and the possibility of choosing a rational option.



Number of reduction step	Collapsible TFU	Equivalent TFU	Probability of error-free performing the equivalent	Mathematical expectation of the equivalent operation run-	Variance of the equivalent operation run-time	The type of collapsible TFU
1	P1,P2,P3	Pe1	0,98149	9,5000	1,2000	RR
2	P4,P5	Pe2	0,99660	12,5000	1,0000	RR
3	Pe2,K1	Pe3	0,99995	16,4931	2,8421	RK
4	P7,K2	Pe4	0,99989	7,6805	1,5280	RK
5	Pe1,Pe3,P6	Pe5	0,97693	30,9931	4,7421	RR
6	Pe4,P8	Pe6	0,99200	12,0805	2,4280	RR
7	Pe6,K3,P9	Pe7	0,99988	16,1877	6,9419	RKR
8	Pe5,Pe7	Pe8	0,97681	47,1808	11,6840	RR

Fig. 1 Operator's activity in managing an automated warehouse module of a flexible production system: **a** model, **b** process and results of automatic calculation

3.3 Tasks of Development of Theory and Practice of Modeling of Activity by Functional Networks

Prospects for the further development of the FN theory lie in the gradual removal of a number of assumptions and limitations, in particular, in the creation and development of:

- managed FN (for models of «flexible» activity and situational management);
- FN with queues (for polyergatic systems with flows of requests);
- FN with models of identification and control of the state of operators;
- FN with time-varying initial data (taking into account tempo tension, emotional state, working conditions, etc.);
- fuzzy FS (fuzzy structure of activity, fuzzy models of the formation of initial data, fuzzy optimization);
- progressive methods of entering information about the FN (voice input, input using a smartphone, etc.).

4 Conclusions

The posed problem of integrated modeling of human-machine interaction (taking into account the structures of activity; working conditions; characteristics of operators, equipment and software) can be solved within the framework of the proposed set of models based on the theory of functional networks.

The advantages of this approach: qualimetric modeling using indicators of error and timeliness, the ability to take into account ergonomic norms and restrictions, the possibility of variant modeling and optimization, as well as economic justification and the choice of ergonomic measures.

The scientific novelty of the proposed approach lies in the fact that, in contrast to the known methods, as a rule, qualitative (intuitive) or focused on the study of local indicators, the proposed methodology is based on the use of formal models for describing, evaluating and optimizing activities that allow using all available data on the influence of various factors.

The reliability is confirmed by extensive testing of models in the design and operation of automated systems in industry, agriculture, transport and education.

Acknowledgements The authors dedicate this article to the memory of their teacher - the first president of the Soviet Ergonomic Association, Doctor of Technical Sciences, Professor Anatoly Ilyich Gubinsky (1931-1990, St. Petersburg, Russia), who was the founder of the scientific school «Efficiency, quality and reliability of man-machine systems» and who first formulated the ideas that formed the basis of our study.

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