Hierarchical analytical and simulation modelling of human-machine systems with interference

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Abstract. The article considers the principles of building the analytical and simulation model of the human operator and the industrial control system hardware and software. E-networks as the extension of Petri nets are used as the mathematical apparatus. This approach allows simulating complex parallel distributed processes in human-machine systems. The structural and hierarchical approach is used as the building method for the mathematical model of the human operator. The upper level of the human operator is represented by the logical dynamic model of decision making based on E-networks. The lower level reflects psychophysiological characteristics of the human-operator.

1. Introduction

The principles of building the model of the human operator are highlighted in many different works including [1] which provides a detailed review of modern approaches to the modelling of the human operator. The analytical simulation modeling of the human-machine system uses the architecture which contains two basic components: the hierarchical analytical simulation model of the automated system managing technological processes and the human operator model. The general block diagram of such a model is shown in figure 1.

The authors of the article propose the principles of building the analytical simulation model of the human operator which takes into account the human functioning on both the physical and the psychophysiological level (the stratum of physical and psychophysiological characteristics of the human operator) as well as the level of logical output where the human controls the technological process. It is considered that these two levels must interact as the individual psychophysiological properties of the human influence his decision taking in the management process. For example, they can change the condition and the behavior of the human operator in case of emergency.

The state of the neuromuscular system of the human operator which manifests itself in the upright stability and the amplitude of unconscious micro-movements of his body plays a big role in the accurate and error-free control of complex technological objects. The control of the upright stability of the body in modern physiology is not considered to be the sum of static reflexes. The control of the upright stability includes a number of skills which are based on the interaction of dynamic sensorimotor processes of the body posture and the posture balance [1 – 4].

The relevant study of non-pharmacological methods of influencing the human psychophysiological condition in order to correct or optimize it includes photo stimulation. There is evidence [5] that rhythmical photo stimulation used together with various medications changes the muscle tone,

some mental functions and brain bioelectric activity. The work of M.A.Osipova [6] shows the possibility to use photo stimulation for the formation of certain psycho-physiological condition of the person.
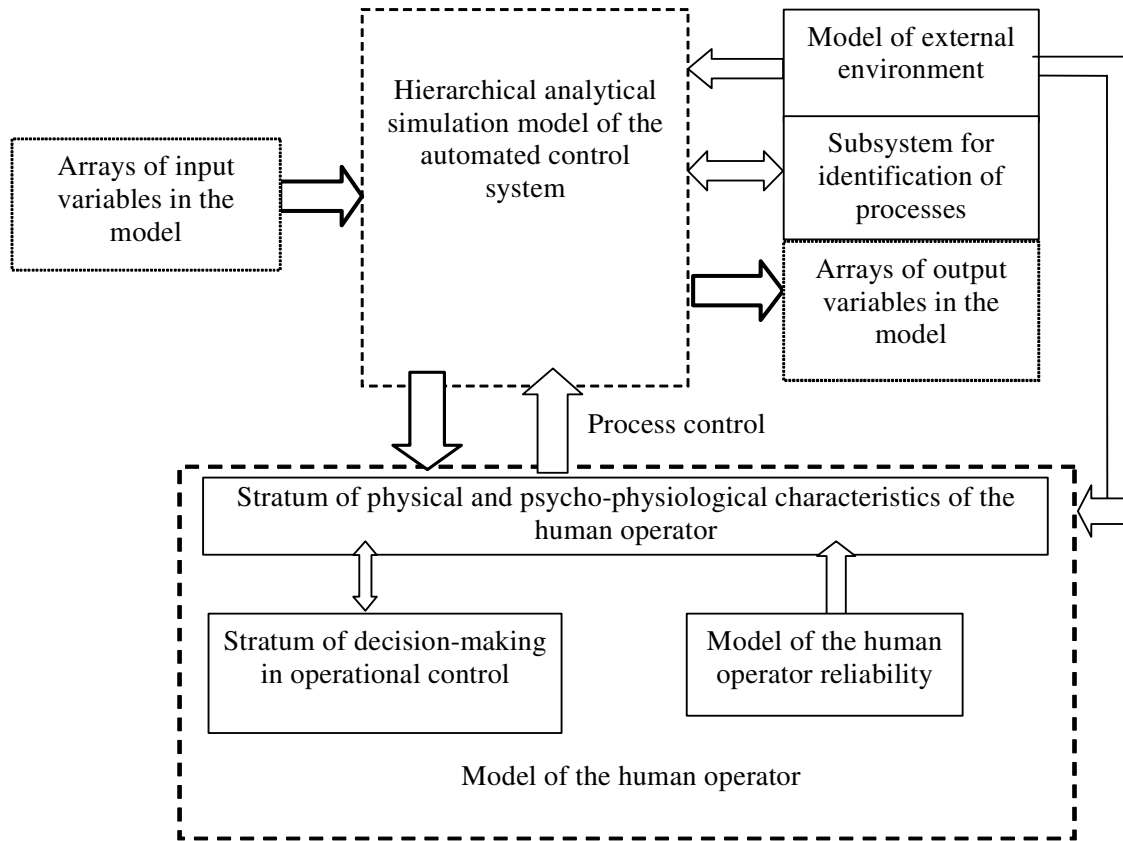

Figure 1. The general block diagram of the analytical simulation modeling of the human-machine system.

2. The E-network model of the interaction between the human operator and the control object

The authors have chosen the network mathematical apparatus [6 – 9] as the modeling tool as it takes into account the parallelism of processes in the system and allows building hierarchical analytical and simulation models. Besides, the network approach allows combining various modeling subsystems. After analyzing mathematical network modeling diagrams the authors chose the apparatus of E-networks as the extension of Petri-nets [8, 9]. The given approach takes into account the dynamic properties of the system being studied and allows making analytical transformations of the model parameters - token attributes.

Figure 2 shows the dynamic model of the human-machine system which describes the interaction of the human operator with the control object and takes into account the modeling of afferentation processes in the visual analyzer which in turn influence the motor functions of the person.

Token V_i is associated with each input i-variable. The intensity of tokens incoming into the model is characterized by flow $\prod_{Vi} = \lim_{\Delta t \to 0} (\frac{N_{Vi}}{\Delta t})$. The processing of the input flows is performed with E-network transition T_i which transmits data into two modes:

- token attributes are united to transmit a set of all variables with the help of one data carrier. This method reduces the load of the E-network model;

- individual data transmission. This mode processes and transmits every token at the input to the communication channel. It increases the message transmission speed and provides higher fidelity of the process model. At the same time, the load of the E-network model is increased.
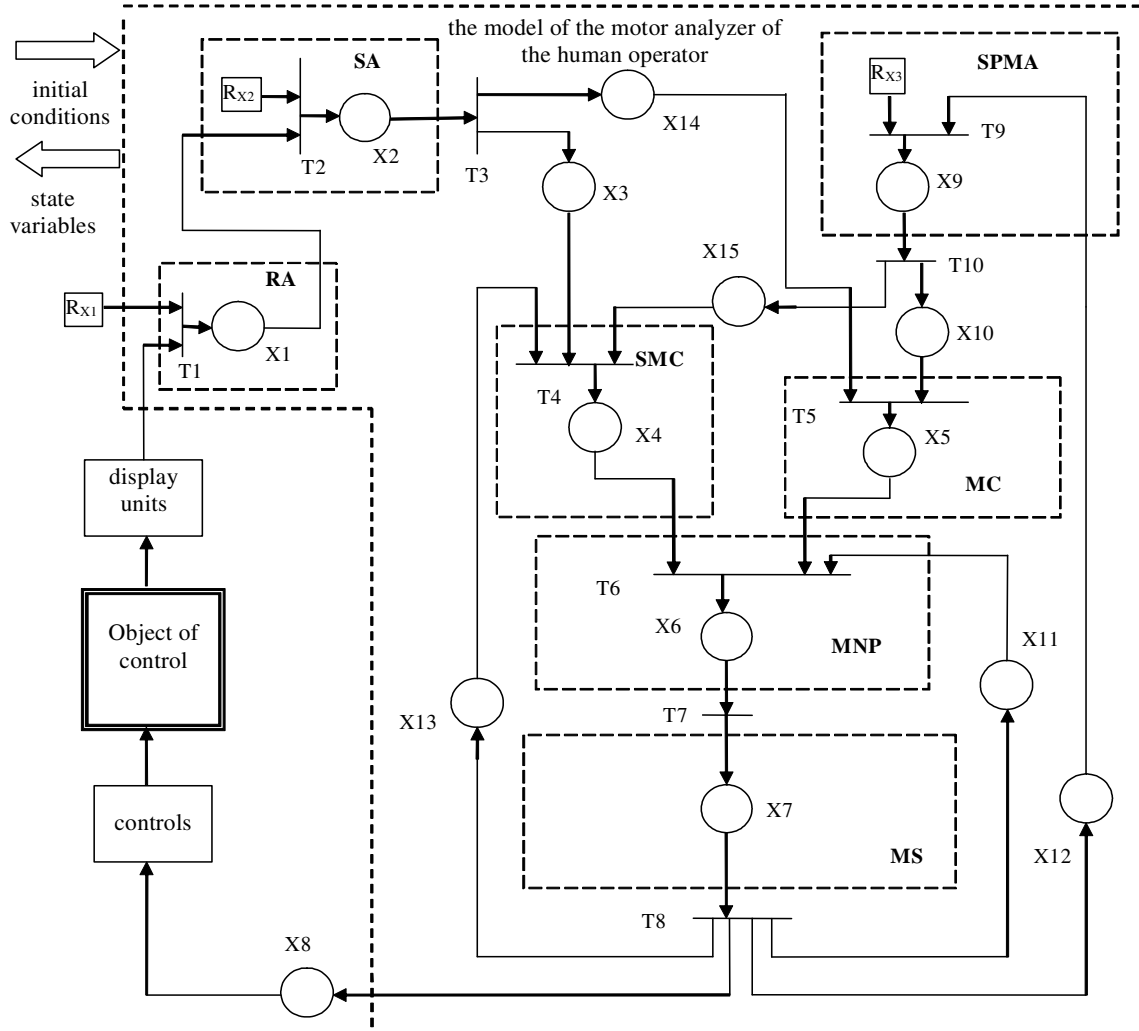

Figure 2. The E-network model of the interaction between the human operator and the control object which takes into account the influence of light stimuli on the motor analyzer (RA – receptor apparatus, SA – sensory analyzer, SPMA - the central part of the motor analyzer, SMC - subcortical motor center, MC - motor cortex, MNP - motor neuron pool, MS - muscular system).

Further on, the token passes through the E-network model. It results in physical variable transformation according to the specified laws of system functioning, the structural - parametric model setup and the simulation process activation.

3. Fuzzy model of decision-making in operational control

In order to build the behavior model of the human operator [5, 11] who controls the technological processes at the upper level we propose to use fuzzy production rules $R : X \rightarrow Y$. Input variables X are the input and output data arrays which the operator sees on his monitor. Output variables Y are the control commands executed by the operator to perform the current task

$$Rule_i : \text{ if } x_1 = R_1 \wedge x_2 = R_2 \wedge ..., \text{ then } y_1 = B_1 \wedge y_2 = B_2 \wedge ... \tag{1}$$

The array of technical parameters in the system at time x_i is used as input variables. According to the input data the correctness of the conditional statement is checked with each fuzzy (linguistic) variable f_i. Then according to fuzzy production rules $Rule_i$, function $f_{Bk}(y_k)$ is activated and the defuzzification begins.

As a consequence, the fuzzy output system gives the result as a number of controlling actions $B(y)$ of the operator. Figure 3 shows the fuzzy logical output principles of the controlling actions of the operator which were described above.
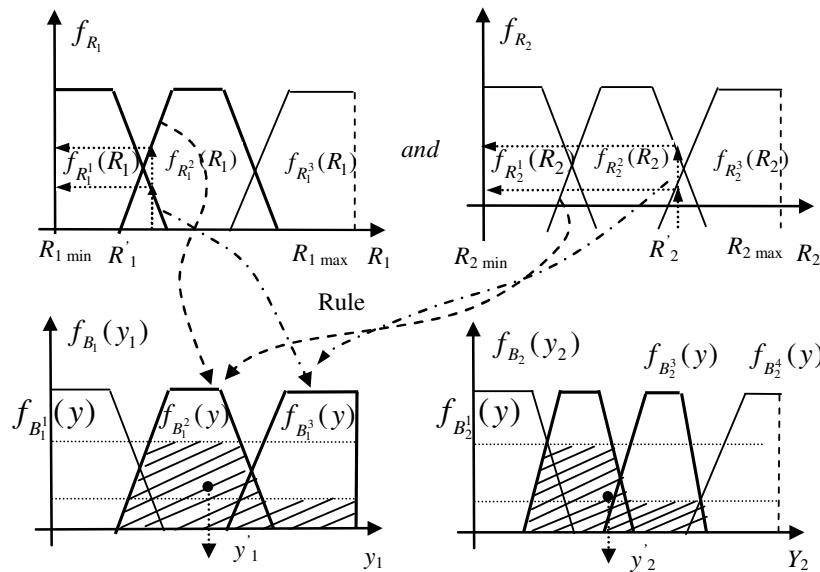

Figure 3. The procedure of performing the controlling actions of the human operator.

Dynamic properties of the human operator are taken into account by the subsystem of the lower level (figure 1) To solve this problem, the method of identifying human reactions and the postural stability of the human body is used. The processes of the dynamic properties of the human operator have been studied and modelled under the conditions of photo stimulation.

Rhythmic light signals given sequentially at the frequency of 0.2, 0.5, 1, 2, 3, 5, 10 Hz for 30 seconds each were used as input stimuli affecting the postural stability indirectly through the visual analyzer.

Stabilography time realizations in array format *(X, Y, Z)* were used as experimental data, where *X* is the projection of the trajectory of the body centre (BC) in the sagittal plane, *Y* is the projection of the trajectory of the BC in the frontal plane, *Z* is the amplitude of the BC pressure on the stabilographic platform.

As a mathematical model the radial basis neural network (RBN) is used as it approximates the processes with sufficient (given) accuracy. The fragment of experimental data $x(t)$ are shown in figure 4.

4. Physical and physiological characteristics of the human operator
The block diagram of the longitudinal (sagittal plane) and transverse (frontal plane) channels of the human body stabilization and control (reflex arcs) is shown in figure 5. These channels have two inputs [10] through which they are exposed to two types of input actions:

- Kinematic ($\Delta\varphi_d$ - disturbances and $\Delta\varphi_c$ - control);
- Dynamic (M^d - disturbances and M^c - program management).

The feedback in the channels of stabilization and control of the upright position of the person is described by transfer functions of three blocks:

- the afferent block obtaining information using mechanoreceptors and performing afferent function - $W_1(p)$;
- the correction block of information processing in the CNS and the brain cortex which performs intermediate function - $W_2(p)$;
- the execution block of the neuro-muscular reaction of the muscles in the back, hips, feet, legs and other body parts of the motor block performing efferent function - $W_3(p)$ [3].
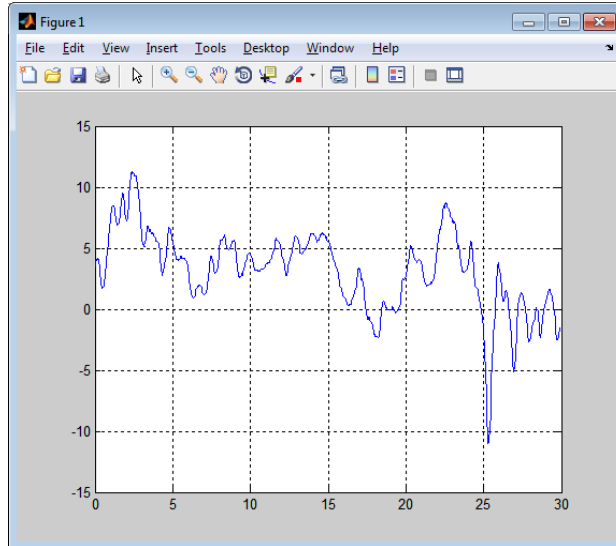

Figure 4. The stabilogram projections of $x(t)$.

Disturbances in this system will be represented by random deviation angle $\Delta\varphi'$ of the human body; difference moment ΔM, effecting the human body; feedback moment M^F; the increment of body rotation angle $\Delta\varphi$.
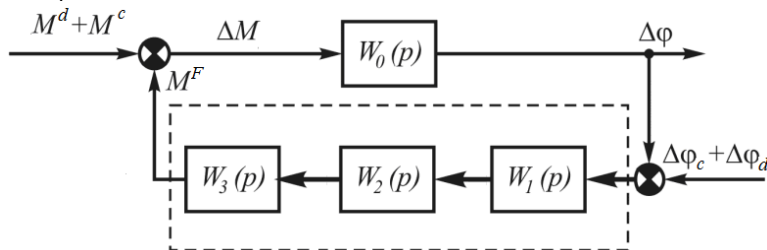

Figure 5. The block diagram of the channel of the human body balance system.

We propose to determine mathematical operators and their parameters with the help of the neural network identification procedure. The radial basis network can be used to identify the neural network.

Figure 6 illustrates the result of the radial basis network performance, where approximation is done with the help of the superposition of the bell-shaped radial basis functions.
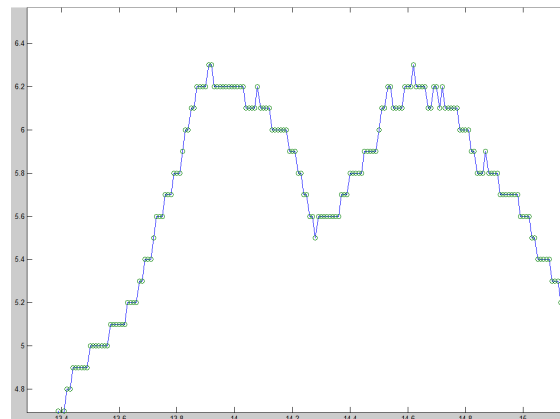
Figure 6. Stabilogram projections $x(t)$ modelling result (values calculated with the help of RBN are circled).

5. Conclusion

The present work illustrates the opportunity of using the E-network as the mathematical apparatus of modelling heterogeneous interacting processes. The authors propose two-layer mathematical models of the operator realizing the output of logical decision-making and simulating the dynamic properties of a human operator. The last task is performed using the neural network identification. The introduced concept can be used for the creation of computer simulators, technical system design and implementation.

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