Models and methods for multicriteria situational flexible reassignment of control functions in man-machine systems

Alexsander Pavlov
St. Petersburg Institute of Informatics and Automation, Russian Academy of Sciences
SPIIRAS
St. Petersburg, Russia
pavlov62@list.ru

Boris Sokolov[1, 2]
[1]St. Petersburg Institute of Informatics and Automation, Russian Academy of Sciences
SPIIRAS
St. Petersburg, Russia
[2]St. Petersburg National Research University of Information Technologies, Mechanics and Optics
ITMO University
St. Petersburg, Russia
sokolov_boris@inbox.ru

Anton Pashchenko
St. Petersburg Institute of Informatics and Automation, Russian Academy of Sciences
SPIIRAS
St. Petersburg, Russia
pashchenko@mail.ru

Anatoly Shalyto
St. Petersburg National Research University of Information Technologies, Mechanics and Optics
ITMO University
St. Petersburg, Russia
shalyto@mail.ifmo.ru

Gennady Maklakov
St. Petersburg Institute of Informatics and Automation, Russian Academy of Sciences
SPIIRAS
St. Petersburg, Russia
gmaklakov@mail.bg

***Abstract*—The problem of flexible reassignment of control functions in man-machine systems at different phases of their life cycle is considered. This problem belongs to class of structural-functional problems. In the paper, we propose to solve problem of multi-criteria flexible reassignment of control functions in man-machine systems within the theory of structure-dynamics control in complex technical-organizational systems. Advantages of this theory is being elaborated by the author and of its application for the reassignment of functions are shown. For the solutions to MMS multi criteria structure-functional synthesis problems we propose a fuzzy-possibilistic approach; an approach using fuzzy logic methods and a theory of experiment design. The general procedure for problem solution is proposed.**

Keywords-man-machine systems, flexible reassignment of control functions, structure – functional synthesis, problems Introduction

I. Introduction

Analysis of the main trends for modern man-machine systems (MMS) indicates their peculiarities such as multiple aspects and uncertainty of behavior, hierarchy, structure similarity and surplus for main elements and subsystems of MMS, interrelations, variety of control functions relevant to each MMS level, territory distribution of MMS components [1-4].

One of the main features of modern MMS is the variability of their parameters and structures as caused by objective and subjective factors at different phases of the MMS life cycle. In other words, we always come across the MMS structure dynamics in practice. Under the existing conditions the MMS potentialities increment (stabilization) or degradation reducing makes it necessary to perform the MMS structures control (including the control of structures reconfiguration). There are many possible variants of MMS structure-dynamics control. For example, *they are alteration of MMS functioning means and objectives; alteration of the order of observation tasks and* *control tasks solving; redistribution of functions, of problems and of control algorithms between MMS levels; reserve resources control; control of motion of MMS elements and subsystems; reconfiguration of MMS different structures* [4-7].

According to the contents of the structure-dynamics control problems they belong under the class of the MMS structure – functional synthesis problems and the problems of program construction, providing for the MMS development. In this case, the problem of flexible reassignment of control functions in man-machine systems at different phases of their life cycle is stated and investigated within the theory of structure-dynamics control in complex technical systems.

Therefore, the problem of flexible reassignment of control functions in man-machine systems can be qualified via the following conceptual definition. We assume that multi-variant scenarios for alteration of structures in the corporate information system (CIS) are known. This first of all, concerns topological structure, technical, technological, and organizational structures of CIS. The main spatial-temporal, technical, and technological constraints for creation and development of CIS, as well as measures of its efficiency at different phases of life cycle are also assumed to be known. It is necessary to perform structure-functional synthesis of CIS make-up, including working out of best variants of control functions assignment in the considered man-machine system.

The main feature and the difficulty of the problems, belonging under the above class is a follows: optimal programs, providing for the MMS main elements and subsystems control can be implemented only when the lists of functions and of control and information-processing algorithms for these elements and subsystems are known [1,2,8-13].

In its turn, the distribution of the functions and algorithms among the MMS elements and subsystems depends upon the structure and parameters of the control rules, actual for these elements and subsystems. The described contradictory situation is complicated by the changes of MMS parameters and structures, occurring due to different causes during the MMS life cycle.

At present the class of problems under review is not examined quite thoroughly. The new theoretical and practical results were obtained on the following lines of the investigation [1-10]*: the synthesis of the MMS technical structure for the known laws of MMS functioning (the first direction); the synthesis of the MMS functional structure, in other words the synthesis of the control programs for the MMS main elements and subsystems under the condition that the MMS technical structure is known (the second direction); the synthesis of programs for MMS construction and development without taking into account the periods of parallel functioning of the actual and the new MMS (the third direction); the parallel synthesis of the MMS technical structure and the functional one (the forth direction)* [12-15].

Several iterative procedures for solving of the joint problems, concerning the first and the second directions are known at present. Some particular results were obtained within the third and the forth directions of investigations. All the existing models and methods for the MMS structure – functional synthesis and for the construction of the MMS development programs can be applied during the period of the internal and external design when the time factor is not very essential.

Therefore, the development of new theoretical bases for MMS structure-functional synthesis is very important now.

II. THE APPROACH AND RESULTS

We propose to solve problem of multi-criteria flexible reassignment of control functions in man-machine systems within the theory of structure-dynamics control in complex technical-organizational systems [1]. The problem of MMS structure-dynamics control consists of the following groups of tasks: the tasks of structure dynamics analysis of MMS, the tasks of evaluation (observation) of structural states and MMS structural dynamics, the problems of optimal program synthesis for structure dynamics control in different situations.

From our point of view, the theory of structure-dynamics control will be interdisciplinary and will accumulate the results of classical control theory, operations research, artificial intelligence, systems theory, and systems analysis. The two last scientific directions will provide a structured definition of the structure-dynamics control problem instead of a weakly structured definition. Dynamic interpretation of flexible reassignment of control functions in man-machine systems problem is shown in the Fig. 1. In this figure the notion "Active Mobile Object" (AMO) generalizes features of mobile elements dealing with different complex technical systems (CTS) types [1] . Depending on the type of CTS AMO can move and interact in space, in air, on the ground, in water, or on water surface. Active Mobile Object can be regarded as multi-agent system.

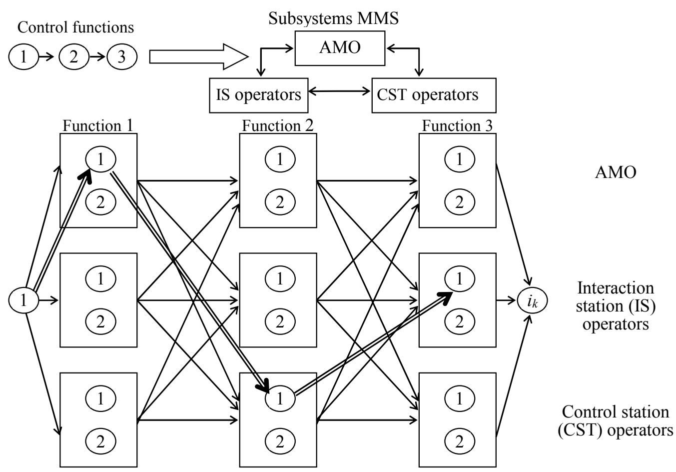

Figure 1. Graphical interpretation for problem of flexible reassignment of control functions in man-machine systems

The known approaches to flexible reassignment of control functions problems are based on the PERT description of scheduling and control problems and traditional dynamic interpretation [2,3-4,7,14]. The realization of these dynamic approaches produces algorithmic and computational difficulties caused by high dimensionality, non-linearity, non-stationary, and uncertainty of the appropriate models.

We proposed to modify dynamic interpretation of operations control processes. The main idea of model simplification is to implement non-linear technological constraints in sets of allowable control inputs rather than in the right parts of differential equations. In this case, Lagrangian coefficients, keeping the information about technical and technological constraints, are defined via the local-sections method. Furthermore, we proposed to use interval constraints instead of relay ones. Nevertheless the control inputs take on Boolean values as caused by the linearity of differential equations and convexity of the set of alternatives. The proposed substitution lets use fundamental scientific results of the modern control theory in various MMS control problems (including scheduling theory problems) [1].

As provided by the concept of MMS multiple-model description the proposed general model includes the particular dynamic model: dynamic model of MMS motion control; dynamic model of MMS channel control; dynamic model of MMS operations control; dynamic model of MMS flows control; dynamic model of MMS resource control; dynamic model of MMS operation parameters control; dynamic model of MMS structure dynamic control; dynamic model of MMS auxiliary operation control.

Procedures of structure-dynamics problem solving depend on the variants of transition and output functions (operators) implementation. Various approaches, methods, algorithms and procedures of coordinated choice through complexes of heterogeneous models are developed by now.

MMS structure-dynamic control problem has some specific features in comparison with classic optimal control problems. The first feature is that the right parts of the differential equations undergo discontinuity at the beginning of interaction zones. The considered problems can be regarded as control problems with intermediate conditions. The second feature is the multi-criteria nature of the problems. The third feature is concerned with the influence of uncertainty factors. The fourth feature is the form of time-spatial, technical, and technological non-linear conditions that are mainly considered in control constraints and boundary conditions. On the whole the constructed model is a non-linear non-stationary finite-dimensional differential system with a re-configurable structure. Different variants of model aggregation were proposed [1-2]. These variants produce a task of model quality selection that is the task of model complexity reduction. Decision-makers can select an appropriate level of model thoroughness in the interactive mode. The level of thoroughness depends on input data, on external conditions, on required level of solution validity.

The proposed interpretation of MMS structure dynamics control processes provides advantages of modern optimal control theory for MMS analysis and synthesis Methodological and methodical basics for the theory of structure-dynamics control were developed. Methodological basics include the methodologies of the generalized system analysis and the modern optimal control theory for MMS with re-configurable structures. The methodologies find their concrete reflection in the corresponding principles. The main principles are the principle of goal programmed control; the principle of external complement; the principle of necessary variety; the principles of multiple-model and multi-criteria approaches; the principle of new problems. The dynamic interpretation of structure-dynamics control processes lets apply the results, previously received in the theory of dynamic systems stability and sensitivity, for MMS analysis problems.

The multiple-model description of MMS structure-dynamics control processes is the base of comprehensive simulation technologies and of simulation systems. We assume the simulation system to be a specially organized complex. This complex includes: simulation models (the hierarchy of models); analytical models (the hierarchy of models) for a simplified (aggregated) description of objects being studied; informational subsystem that is a system of data bases (knownledge bases); control-and-coordination system for interrelation and joint use of previous elements and interaction with the user (decision-maker).

Existence of various alternative descriptions for MMS elements and control subsystems gives an opportunity of adaptive models selection (synthesis) for program control under changing environment. Therefore, we considered two general actual problems of the MMS structure-dynamics investigation. They were :

- •the problem of selection of optimal MMS structure-dynamics control programs at different states of the environment;
- •the problem of parametric and structural adaptation of models describing MMS structure-dynamics control.

The formal statement and decomposition of structural and parametric adaptation tasks were worked out for models of MMS structure-dynamics control (SDC). Here the adaptive control should include the following main phases:

- •parametric and structural adaptation of MMS structure-dynamics control (SDC) models and algorithms to previous and current states control subsystems (CS) of CIS, and of the environment;
- •integrated scheduling of MMS operation (construction of SDC programs);
- •simulation of MMS operation, according to the schedules, for different variants of control decisions in real situations;
- •structural and parametric adaptation of the schedule, control inputs, models, algorithms, and SCS programs to possible (predicted by simulation) states of SO, CS, and of the environment.

During our investigations the main phases and steps of a program-construction procedure for optimal structure-dynamics control in MMS were proposed.

At the first phase forming (generation) of MMS allowable multi-structural macro-states is being performed. In other words, a structure-functional synthesis of a new MMS make-up should be fulfilled in accordance with an actual or forecasted situation. Here the first-phase problems come to MMS structure-functional synthesis.

At the second phase, a single multi-structural macro-state is being selected, and adaptive plans (programs) of MMS transition to the selected macro-state are constructed. These plans should specify transition programs, as well as programs of stable MMS operation in intermediate multi-structural macro-states. The second phase of program construction is aimed at a solution of multi-level multi-stage optimization problems.

One of the main opportunities of the proposed method of MMS SDC program construction is that besides the vector of program control we receive a preferable multi-structural macro-state of MMS at final time. This is the state of MMS reliable operation in the current (forecasted) situation. The combined methods and algorithms of optimal program construction for structure-dynamics control in centralized and non-centralized modes of MMS operation were developed too. The main combined method was based on joint use of the successive approximations method and the "branch and bounds" method. A theorem characterizing properties of the relaxed problem of MMS SDC optimal program construction was proved for a theoretical approval of the proposed method. An example was used to illustrate the main aspects of realization of the proposed combined method.

Classification and analysis of perturbation factors having an influence upon operation of a complex technical system were performed. Variants of perturbation-factors descriptions were considered for MMS SDC models. In our opinion, a comprehensive simulation of uncertainty factors with all adequate models and forms of description should be used during investigation of MMS SDC. Moreover, the abilities of MMS management should be estimated both in normal mode of operation and in emergency situations. It is important to estimate destruction "abilities" of perturbation impacts. In this case the investigation of MMS functioning should include the following phases [4-7,10-11]:

- •determining of scenarios for MMS environment, particularly determining of extremely situations and impacts that can have catastrophic results.
- •analysis of MMS operation in a normal mode on the basis of a priori probability information (if any), simulation, and processing of expert information through theory of subjective probabilities and theory of fuzzy sets.
- •repetition of item b for the main extremely situations and estimation of guaranteed results of MMS operation in these situations.
- •computing of general (integral) efficiency measures of MMS structure-dynamics control.
- •algorithms of parametric and structural adaptation for MMS SDC models were proposed. The algorithms were based on the methods of fuzzy clusterization, on the methods of hierarchy analysis, and on the methods of a joint use of analytical and simulation models

The most important step when estimating the effectiveness of MMS structure-functional synthesis is the construction stage of the generalized indicator for quality structure-dynamic control. At present, a wide variety of methods for solving multi-criteria evaluation of the efficiency of a MMS have been developed [1-2,14-16]. These tasks are usually per-formed as a form of convolution for private assessments, integrated to a scalar characteristic of quality. We refer to these methods: constructing an additive convolution multiplicative convolution functions of distance, the minimum function, and so on.

One of the main drawbacks of the convolution of vector indices is ignoring the possibility of mutual compensation of assessments by functions with different criteria. Key features and relevant issues related to the solution of problems of multi-criteria evaluation, tend to have a computational and conceptual character. Additional in-formation from the decision maker (the expert) is needed for a correct solution to the construction of a convolution.

Depending on the specific problem of estimating the efficiency of a MMS, the private parameters are usually a non-linear influence on each other and on the whole integral indicator. On the other hand, the calculation of the resulting figure allows us to determine that the efficiency of the layer is complicated by inaccurate and illegible interval values of private indicators (in the general case, private indicators are de-fined by the linguistic variables).

For the solutions to MMS multi criteria structure-functional synthesis problems we propose a fuzzy-possibilistic approach; an approach using fuzzy logic methods and a theory of experiment design [1,14].

From the perspective of a fuzzy-possibilistic approach, the private indicators efficiency of the layer can be represented in the form of fuzzy events. Then, the task of estimating the efficiency of the MMS is to construct the integral index, which is an operation on the fuzzy events with private indicators and their impact on the assessment of the MMS's effectiveness.

To take into account the non-linear nature of the impact of these private indicators of the management areas on the effectiveness of the generalized index of the MMS, as well as a fuzzy-possibilistic approach of private indicators, we propose the construction of a generalized index using fuzzy-possibilistic convolution. Fuzzy-possibilistic convolution is based on fuzzy measures and fuzzy integrals, and allows us the flexibility to take into account the non-linear nature of the influence of private indicators. The method of multi-criteria evaluation of the efficiency of a MMS consists of the following steps [14]:

Step 1: Construction of the evaluation function for different subsets of indicators of the MMS by normalizing private fuzzy indicators.

Step 2: Conduction of an expert survey to find the coefficients of the importance of individual indicators.

Step 3: Construction of fuzzy measures (Sugeno λ-measures), which characterize the importance of the various subsets of the MMS.

Step 4: Calculation of the integral indicator of the efficiency of the MMS based on fuzzy convolution of private indicators using a fuzzy integral evaluation function from subsets of indicators from fuzzy measures.

If the coefficients of efficiency of a MMS is given by linguistic variables (LV) the scale of linguistic assessments should be mentioned with the importance of the criteria and with the method of information convolution. To implement this approach, we propose a combined method for solving the problem of multi-criteria evaluation of the efficiency of a MMS using the fuzzy method, and a theory of experiment planning for the flexible convolution of indicators.

The efficiency of a MMS is an estimated set of indicators, or linguistic variables. A set of several indicators with the corresponding values of the terms of the decision-maker's view, characterizes the resulting indices expressing a general view of the MMS's performance. LV-knowledge, in general terms, can be represented by production rules.

To construct the integral indicator it is necessary to translate the values of each parameter to a single scale [-1, 1]. The extreme values of the linguistic variable's ordinal scale are marked as -1 and +1, the point of "0" corresponds to the linguistic definition of the middle of the scale, according to the physical meaning of this indicator.

In accordance to the theory of experiment planning, to build the convolution matrix of indicators it is necessary to build an expert survey of extreme values of particular indicators that reflect the expert opinion in the form of production models (e.g. If indicator 1 is set to "high", indicator 2 is set to "low", ... indicator n has a value of "low", then the integral indicator is rated as "below average").

To determine the coefficients of the importance of the convolution of indicators, taking into account the impact of both individual performance and the impact of sets of two, three, and so on, indicators, an orthogonal expert survey plan is formed. The polynomial coefficients are calculated according to the rules adopted in the theory of experimental planning. Averaged scalar multiplications of the respective columns of the orthogonal matrix and vector values of the resulting indicator are calculated.

Let us show implementation of proposed procedure with the help of example.

Let's the effiency of functioning of the human-machine systems (HMS) evaluate by three private indicators $F = \{f_i, i = 1,2,3\}$. Assume that the three scenarios $\{w_1, w_2, w_3,\}$ of development (HMS) are evaluated, evaluation results are shown in Table 1 (step 1 of method).

TABLE I. PRIVATE EVALUATIONOF SCENARIOUS OF DEVELOPMENT HMS

Indicators	w_1	w_2	w_3
f_1	0.33	0.44	0.22
f_2	0.33	0.17	0.5
f_3	0.14	0.28	0.56

According to the theory of planning experiment for the construction of the convolution is necessary to build matrix of the expert poll in extreme values of indicator f_1 (Table 2).

TABLE II. RESULTS OF AN EXPERT POLL (SIMPLE RULES)

Rule	f_1	f_2	f_3	f_{res}
1	Low	Low	Low	0
2	High	Low	Low	0,2
3	Low	High	Low	0,6
4	High	High	Low	?
5	Low	Low	High	0,4
6	High	Low	High	?
7	Low	High	High	?
8	High	High	High	1

Estimates of the expert of an integrated indicator $f_{res} = A_{resi}$ in simple rules 2, 3, 5 are presented in Table 2 (step 2 of method).

For definition of estimates of integrated indicators in difficult rules taking into account opinions of the expert for simple rules we will calculate the parameter λ^* of an indistinct measure of Sugeno, having solved the equation (step 3 of method)

$$\frac{(1+0.2\lambda)(1+0.6\lambda)(1+0.4\lambda)-1}{\lambda} = 1 \Rightarrow 0.048\lambda^2 + 0.44\lambda + 0.2 = 0$$

Roots of the equation are equal respectively $\lambda_1^* \approx -0.48$, $\lambda_2^* \approx -8.69$. The second solution does not satisfy the condition, $-1 < \lambda < \infty$, therefore, $\lambda^* \approx -0.48$.

Then an expert estimate of the integral indicator for 4 rule will equal $G_\lambda(p_4) = \frac{(1+0.2\lambda^*)(1+0.6\lambda^*)-1}{\lambda^*} \approx 0.742$, for 6 rule will equal $G_\lambda(p_6) = \frac{(1+0.2\lambda^*)(1+0.4\lambda^*)-1}{\lambda^*} \approx 0.5616$, for 7 rule will equal $G_\lambda(p_7) = \frac{(1+0.6\lambda^*)(1+0.4\lambda^*)-1}{\lambda^*} \approx 0.8848$.

Calculation of coefficients of a polynom is made by the rules accepted in the theory of planning of experiments for what average scalar products of the corresponding columns of an orthogonal matrix on a vector of values of a resultant indicator are calculated. The received results are given below in Table 3.

TABLE III. CALCULATION OF COEFFICIENTS OF AN INTEGRATED INDICATOR

$f_0 * f_{res}$	$f_1 * f_{res}$	$f_2 * f_{res}$	$f_3 * f_{res}$	$f_1 * f_2 * f_{res}$	$f_1 * f_3 * f_{res}$	$f_2 * f_3 * f_{res}$	$f_1 * f_2 * f_3 * f_{res}$	Calc.
0	0	0	0	0	0	0	0	0
0,2	0,2	-0,2	-0,2	-0,2	-0,2	0,2	0,2	0,2
0,6	-0,6	0,6	-0,6	-0,6	0,6	-0,6	0,6	0,6
0,742	0,742	0,742	-0,742	0,742	-0,742	-0,742	-0,742	0,742
0,4	-0,4	-0,4	0,4	0,4	-0,4	-0,4	0,4	0,4
0,5	0,562	-0,562	0,562	-0,562	0,562	-0,562	-0,562	0,562
1	-0,885	0,885	0,885	-0,885	-0,885	0,885	-0,885	0,885
1	1	1	1	1	1	1	1	1
λ_0	λ_1	λ_2	λ_3	λ_{12}	λ_{13}	λ_{23}	λ_{123}	
0,549	0,077	0,258	0,163	-0,013	-0,0081	-0,0274	0,0014	

Thus, convolution of indicators in our case has the following look

$$f_{res} = 0.549 + 0.077 f_1 + 0.258 f_2 + 0.163 f_3 - 0.013 f_1 f_2 - 0.0081 f_1 f_3 - 0.0274 f_2 f_3 - 0.0014 f_1 f_2 f_3$$

Estimate efficiency of scenarios of development of HMS $\{w_1, w_2, w_3,\}$. For this purpose we will transfer the estimates given in Table 1 to a scale [-1,1] (Table 4).

TABLE IV. RESULTS OF SCALING OF PRIVATE ESTIMATES

Indicators	w_1	w_2	w_3
f_1	-0.34	-0.12	-0.56
f_2	-0.34	-0.66	0
f_3	-0.72	-0.44	0.12

The calculated values of a resultant indicator of efficiency of scenarios of development of HMS $\{w_1, w_2, w_3,\}$ will equal $f_{res}(w_1) = 0.307$, $f_{res}(w_2) = 0.288$, $f_{res}(w_{31}) = 0.525$.

III. CONCLUSION

Methodological and methodical basis of the theory of MMS structure-dynamics control is developed by now. This theory can be widely used in practice (including the integrated modeling and simulation for structure dynamic control and monitoring of computer distributed networks). It has interdisciplinary basis provided by classic control theory, operations research, artificial intelligence, systems theory and systems analysis. The dynamic interpretation of MMS reconfiguration process provides strict mathematical base for complex technical-organizational problems that were never formalized before and have high practical importance. We proposed to modify dynamic interpretation of operations control processes. The main idea of model simplification is to implement non-linear technological constraints in sets of allowable control inputs rather than in the right parts of differential equations. In this case, Lagrangian coefficients, keeping the information about technical and technological constraints, are defined via the local-sections method. Furthermore, we proposed to use interval constraints instead of relay ones. Nevertheless the control inputs take on Boolean values as caused by the linearity of differential equations and convexity of the set of alternatives. The proposed substitution lets use fundamental scientific results of the modern control theory in various MMS control problems (including scheduling theory problems).

The application software for structure-dynamics control in MMS was developed. Operability of the software was shown for a space navigation system. The software was applied to construction of control programs for ground-based elements of the system and for navigation spacecraft's structure-dynamics. The considered system is a part of a space-facilities control system that is a classic example of MMS. A multiple-model description of the system, scheduling algorithms for ground-based technical facilities, and algorithms of flexible reassignment of control functions among navigation spacecraft's, interaction ground station and control station were proposed. Different variants of these dynamic distributions were ranked with the help of suggested multi-criteria procedure.

ACKNOWLEDGMENT

Research carried out by the grant of the Russian Science Foundation (Project No. 16-19-00199).

REFERENCES

[1] Ohtilev, M.Yu., Sokolov, B.V., Yusupov, R.M. 2006. Intellectual Technologies for Monitoring and Control of Structure-Dynamics of Complex Technical Objects. Moscow, Nauka, 410 p. (in Russian)

[2] Zaychik E, Sokolov B, Verzilin D. Integrated modeling of structure-dynamics control in complex technical systems 19 th European Conference on Modeling and Simulation ESMS 2005, "Simulation in Wider Europe", June 1-4, 2005, Riga, Latvia, Proceedings, Riga Technical University, 2005. – pp. 341-346

[3] Skurihin V.I., Zabrodsky V.A., Kopeychenko Yu.V. Adaptive control systems in machine-building industry. – M.: Mashinostroenie, 1989 (in Russian).

[4] Rastrigin L.A. Modern principles of control for complicated objects. – M.: Sovetscoe Radio, 1980 (in Russian).

[5] Bellmann R., 1972. Adaptive Control Processes: A Guided Tour. Princeton Univ. Press, Princeton, New Jersey.

[6] Rastrigin L.A. Adaptation of complex systems. – Riga: Zinatne, 1981 (in Russian).

[7] Fleming, W.H., Richel R.W., 1975. Deterministic and stochastic optimal control. Springer-verlag, Berlin, New York.

[8] Obbink, M., Gürkök, H., Bos, D.P.O., Hakvoort, G., Poel, M., Nijholt, A.: Social interaction in a cooperative brain-computer interface game. In: Proceedings of 4th International ICST Conference on Intelligent Technologies for Interactive Entertainment, 2012, pp. 183–192.

[9] Nijholt, A.: Towards multimodal, multi-party, and social brain-computer interfacing. In: Camurri, A., Costa, C. (eds.) INTETAIN 2011. LNICST, vol. 78, pp. 12–17. Springer, Heidelberg (2012)

[10] Poli, R., Cinel, C., Matran-Femandez, A., Sepulveda, F., Stoica, A.: Towards cooperative brain-computer interfaces for space navigation. In: Proceedings of the International Conference on Intelligent User Inteljaces (lUI), pp. 19–22, Santa Monica, CA, USA (2013)

[11] Pope, A.T., Bogart, E.H., Bartolome, D.S.: Biocybernetic system evaluates indices of operator engagement in automated task. Biol. Psychol. 40(1–2), 187–195 (1995)

[12] Moore Jackson, M., Mappus, R.: Applications for brain-computer interfaces. In: Nijholt, A., Tan, D. (eds.) Brain-Computer Interfaces: Applying our Minds to Human-Computer Interaction, pp. 89–103. Springer-Verlag London Ltd., London (2010)

[13] 16. Leeb, R., Lee, F., Keinrath, C., Scherer, R., Bischof, H., Pfurtscheller, G.: Brain– computer communication: motivation, aim, and impact of exploring a virtual apartment. IEEE Trans. Neural Syst. Rehab. Eng. 15, 473–482 (2007)

[14] Petrosjan, L.A., and N.A. Zenkevich, 1996. Game Theory. World Scientific Publ., Singapure, London.

[15] Roy, B., 1996. Multi-criteria Methodology for Decision Aiding. Kluwer Academic Pulisher, Dordreeht.

[16] Nilsson F, Darley V. On complex adaptive systems and agent-based modeling for improving decision-making in manufacturing and logistics settings. Int. Journal of Operations and Production Management, 2006, Vol. 26(12), pp. 1351-1373.