MULTIPLE-MODEL DESCRIPTION AND STRUCTURE DYNAMICS ANALYSIS OF ACTIVE MOVING OBJECTS CONTROL SYSTEM

Boris Sokolov, Rafael Yusupov, Vyacheslav Zelentsov

***Abstract**: Proposed developed concept of active moving object (AMO) was used to form statement of control problems which was investigated. Depending on the type of AMO can move and interact in space, air, on the ground, in water. In this paper AMO was interpreted as space-facilities (SF). The unified description of various control processes lets synthesize simultaneously both technical and functional structures of SF control system (CS). It is important that the presented approach extends new scientific and practical results obtained in the modern control theory to the field of space programs.*

***Keywords**: active moving object, optimal program control, multi-criteria multiple-model description applied area.*

***ACM Classification Keywords**: D.2.11 Software Architectures and F.1.1 Models of Computation.*

Introduction

One of the main features of modern complex technical systems (CTS), particularly orbital and ground-based space facilities, is the changeability of their parameters and structures caused by objective and subjective reasons at different stages of the CTS life cycle. In other words, we always come across the CTS structure dynamics in practice (Fig. 1). In Fig. 1 S^j is a number of CTS structural state. Under the existing conditions to increase (stabilize) CTS work potentialities and capacity a structure control (including the control of CTS structure reconfiguration) is to be performed.

According to the specifics of the structure-dynamics control problems, they belong to the class of the CTS structure-functional synthesis problems and the problems of program construction for CTS development.

The main disadvantage of the problems belonging to the above class is that, optimal control programs for CTS main elements and subsystems can be implemented only when the lists of functions and algorithms for control and information processing in these subsystems and elements are known.

The distribution of the functions and algorithms among the CTS elements and subsystems, in its turn depends upon the control laws actual for these elements and subsystems.

The described contradictory situation is complicated by the changes of CTS parameters and structures caused by different factors during the CTS life cycle.

Currently, the class of problems being reviewed is not examined thoroughly enough. New theoretical and practical results were obtained at the following directions of investigations:

- the synthesis of the CTS technical structure for the known laws of CTS functioning (the first direction) [Casti, 1979], [Klir, 1985], [Zvirkun, Akinfiev, Filippov, 1985], [Zvirkun, Akinfiev, 1993], [Zvirkun, 1982];

- the synthesis of programs for CTS construction and development without taking into account the periods of parallel functioning of the existing and new CTS (the third direction) [Tsurlov, 1989], [Zvirkun, Akinfiev, 1993];
- the parallel synthesis of the CTS technical and functional structures (the forth direction) [Sokolov, 1999], [Tsurlov, 1989], [Zvirkun, Akinfiev, 1993].

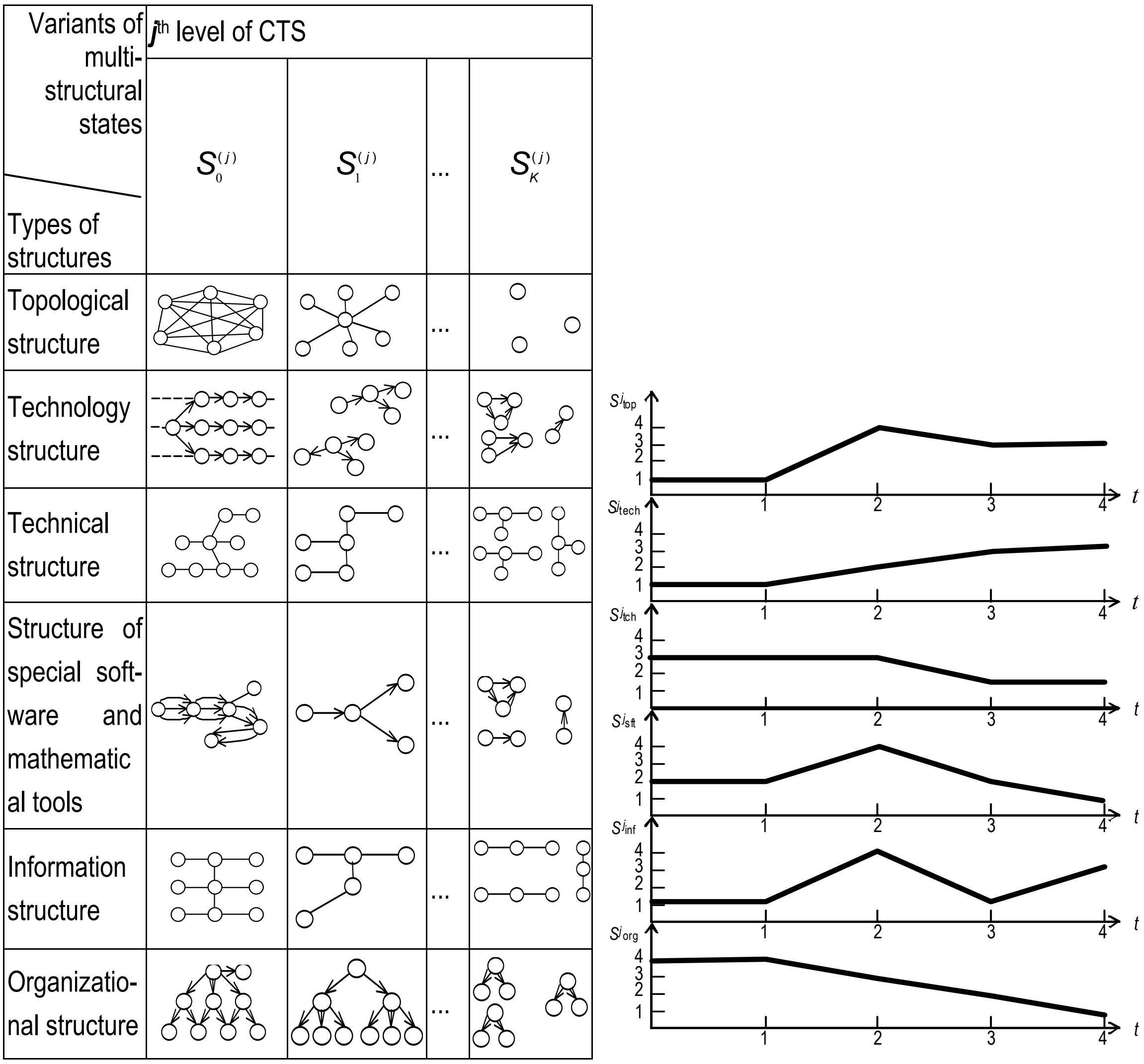


Fig. 1. Diagrams of CTS structure dynamics Possible variants of CTS structure dynamics.

Let us briefly consider the main results and state-of-the-art along the above mentioned directions of investigations.

A great deal of work regarding various problems of the CTS technical structure synthesis (the first direction of investigations) is accomplished in Russia and abroad [Casti, 1979], [Klir, 1985], [Zvirkun, Akinfiev, Filippov, 1985], [Zvirkun, Akinfiev, 1993], [Zvirkun, 1982].

The synthesis (selection) of a CTS structure (structures) was usually reduced to the following general optimization problem [Zvirkun, Akinfiev, Filippov, 1985], [Zvirkun, 1982]:

$$\bar{S}\left\{\left[\bar{f}\subset\bar{F}(\bar{\pi})\right]\bar{R}\left[\bar{m}\subset\bar{M}\right]\right\}\to extr\,, \tag{1}$$

$$\bar{\pi}\subset\bar{P}\,, \tag{2}$$

$$\bar{f}\subset\bar{F}(\bar{\pi})\,, \tag{3}$$

$$\bar{m}\subset\bar{M}\,, \tag{4}$$

where $\bar{P}$ is a set of feasible control principles (algorithms); $\bar{F}$ is a set of interrelated functions (tasks, operations) that can be performed by the system. For each subset $\bar{\pi}\subset\bar{P}$ there exists the set $\bar{F}(\bar{\pi})$ the realizations sufficient for the given principles (algorithms) should be chosen from, i.e., it is necessary to choose $\bar{f}\subset\bar{F}(\bar{\pi})$; $\bar{M}$ is a set of CTS possible elements such as information processing and transceiving facilities, control units, service terminals, etc; the map $\bar{R}$ takes $\bar{F}$ to $\bar{M}$.

It is stated that the optimal map $\bar{F}$ returns an extremum to some objective function (functions) $\bar{S}$ under given constraints.

The modifications of the considered problem concern the aspects of uncertainty and multi-criteria decision-making.

The complexity of the synthesis problem (1)–(4) is mainly caused by its high dimensionality that is by the number of variables and constraints in the detailed problem statement. That is why the methods of decomposition, aggregation and sub-problem coordination are widely used. Another peculiarity complicating the problem is the integer-valued variables.

The features of the structure synthesis problem were thoroughly considered in the works [Zvirkun, Akinfiev, Filippov, 1985], [Zvirkun, Akinfiev, 1993], [Zvirkun, 1982]. The authors proposed a multi-level interrelated complex of analytical and simulation models based on decomposition and aggregation approach.

Studies on structure synthesis problems (1)–(4) confirm [Zvirkun, Akinfiev, Filippov, 1985], [Zvirkun, Akinfiev, 1993], [Zvirkun, 1982] that when CTS elements and subsystems cannot manage peak data traffic, then the law of elements functioning ought to be optimized (the second direction of investigations).

The laws and algorithms of hierarchical system functioning, as well as problems of functional synthesis have been investigated in Russia and abroad for more than 40 years within the developing control theory [Athaus, Falb, 1966], [Bryson, Yo-Chi, 1969], [Moiseev, 1974], [Pontriagin, etc., 1961], [Singh, Titli, 1978], [Tsypkin, 1971], [Vasil'ev, 2001]. Therefore, it is reasonable to consider the particular scope of these investigations in accordance with the aims of this paper. Here we discuss the problems of CTS structure-dynamics control.

Fig. 2 from [Doganovskii, Oseranii, 1990] shows the classification of CTS, the concept of structure dynamics control was applied to. The numbers denote the following classes of the systems: 1 — CTS with controllable structure dynamics; 2 — basic reconfigurable CTS; 3 — systems with coordinate-parametric control (SCPC); 4 — systems with active controllable technologies (SACT); 5 — integrated active-control systems (IACS); 6 — systems of alternative control and multiple-mode control; 7 — systems of fault-tolerant self-recovering control; 8 — systems of intellectual control.

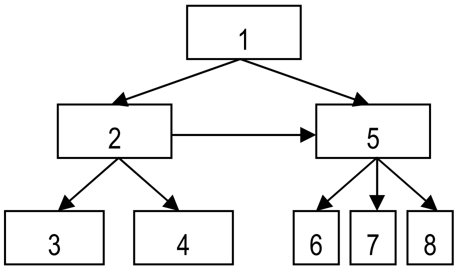


Fig. 2. Classification diagram of reconfigurable systems.

The control problems for basic reconfigurable CTS were the best investigated ones. Interesting fundamental and practical results were obtained in this field [Bryson, Yo-Chi, 1969], [Napolitano, Swaim, 1989], [Ohtilev, Sokolov, Yusupov, 2006], [Van der Velde, 1984].

The investigations towards creation and application of integrated active-control systems are still at the initial phase, especially for the systems of controllable structure dynamics with intellectual control elements. These systems are functioning under mutable objectives and external perturbation actions that can be purposeful and/or not purposeful [Fleming, Richel, 1975], [Gupta, Sinka, 1996], [Ohtilev, Sokolov, Yusupov, 2006], [Russell, Norvig, 1995], [Shannon, 1975], [Oreu, Zeigler, Elzas, 1984], [Sokolov, 1999], [Tsypkin, 1971], [Vasil'ev, 2001], [Yusupov, Rozenwasser, 1999].

The growth of CTS complexity along with the increasing importance of uncertainty factors at all stages of CTS functioning necessitates new approaches for control-system construction.

The most perspective approach, namely, intellectual control has arisen within artificial-intelligence investigations [Gupta, Sinka, 1996], [Russell, Norvig, 1995], [Vasil'ev, 2001].

Fig. 3 presents the multilevel scheme of CTS control.

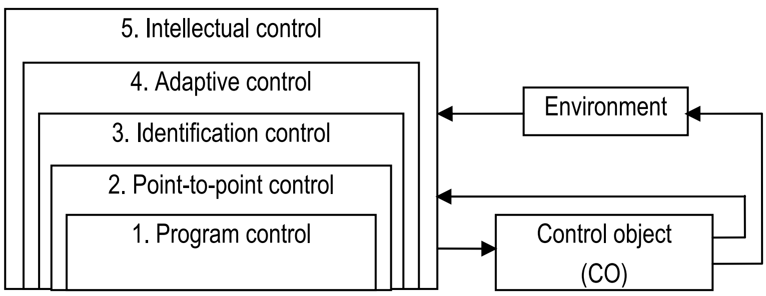


Fig. 3. Multilevel structure of CTS control processes.

Fig. 4, 5 from [Vasil'ev, 2001] show respectively the sources of intellectual control and the relations of scientific disciplines forming the theory of intellectual control. The work [Vasil'ev, 2001] gave a detailed analysis of intellectual-control investigations that have been carried out in Russia and abroad during the last 30 years. The most interesting recent scientific and practical results in the field of CTS control were received on the basis of production languages with fuzzy rules and by means of neural networks [Gupta, Sinka, 1996], [Russell, Norvig, 1995], [Vasil'ev, 2001].

To accomplish the analysis of state-of-the-art CTS structure-dynamics control let us briefly consider the third and the forth directions of structure synthesis that were mentioned at the beginning of the section.

There are several works [Casti, 1979], [Klir, 1985], [Zvirkun, Akinfiev, 1993] related to theoretical basics for the synthesis of CTS development programs. Several iterative procedures for particular structure-functional synthesis problems concerning the early stages of CTS life cycle are currently known. Nevertheless, the obtained results do not conform to dynamics of the environment at the CTS operating stage when the time factor is rather important [Sokolov, 1999]. As well, the peculiarities of distributed CTS are not considered thoroughly enough for the operation phase.

Therefore, the development of new theoretical bases for CTS structure-dynamics control is very important now. 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. These ideas are summarized in Fig. 6 that is a modification of Fig. 5 for the subject of this paper.

Here, as the first step to the new theory, we introduce conceptual and formal description of CTS structure dynamics. The interpretation of the constructed models concerns SF control systems.

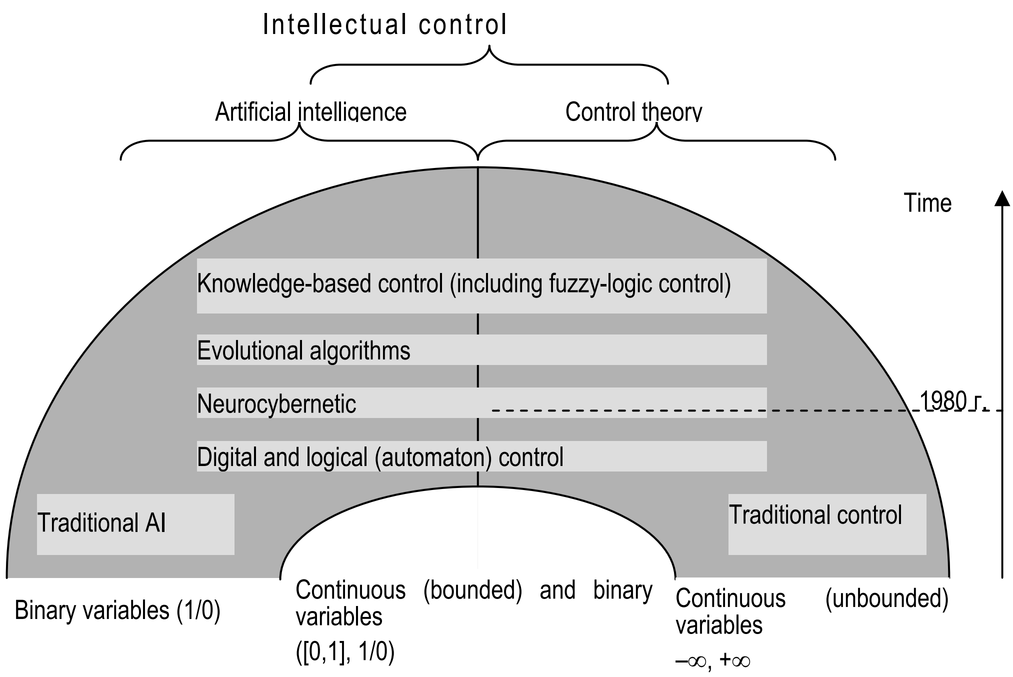


Fig. 4. Two main sources of intelligent control.

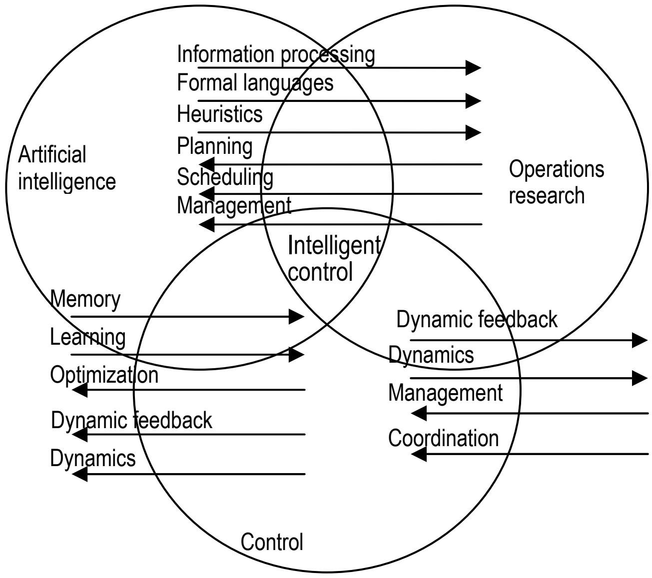


Fig. 5. Intellectual control as a scope of investigations.

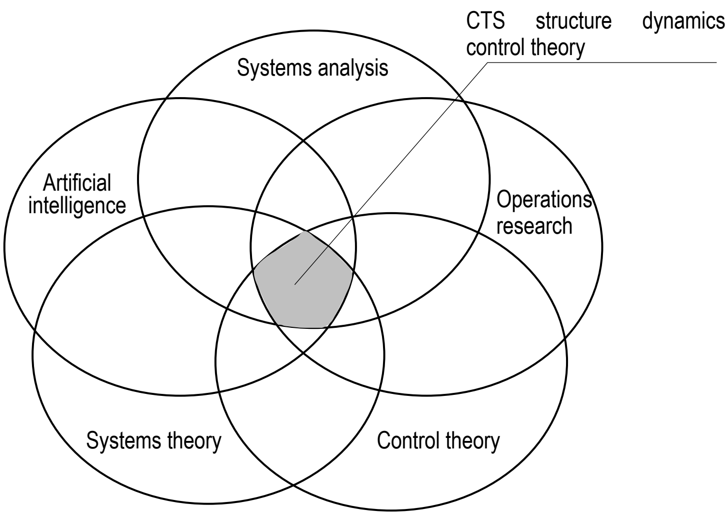


Fig. 6. The theory of structure-dynamics control as a scope of interdisciplinary investigations.

The complex of SF program-control models is discussed in this paper. These models give unified technology for an analysis and optimization of various processes concerning spacecraft information receiving, transferring and processing. The main advantage of the constructed models is that the structural and functional constraints for SF control process are defined explicitly. By now, the prototype programs realizing models were developed and used for evaluation of SF CS abilities and for planning of SF CS operation.

II. CONCEPTUAL MODEL FOR CONTROL PROCESSES OF ORBITAL AND GROUND-BASED SPACE FACILITIES

Under the orbital space facilities (OSF) a group of spacecrafts having a common mission is meant. The ground-based space facilities (GSF) are hardware-software complexes supporting spacecraft functioning at the phase of orbital flight. These complexes are the parts of ground-based control systems (GCS) such as control centers (CC) for spacecrafts of different missions, control stations (CST), OSF-interacting stations (IS), central control station (CCS), and telecommunication system (TS) providing for communication between enumerated elements. The groups of OSF and GSF form the SF control system (SF CS).

In Fig. 7 the generalized structure of SF CS is shown. The following notation was used: HSC is a unified hardware-software complex for control automation; the symbols ○ denote spacecrafts of some group; the symbols ⊗ denote objects-in-service (OS). The last are sources or recipients of information being processed, they can be moving or stationary, and in particular, they can represent some water, ground, or space areas that are interesting for the recipients. OS can change their state during the information, material, or energy interactions with OSF.

The preliminary investigations confirm that the most convenient concept for the formalization of SF control processes is the concept of an active moving object (AMO). In general case, it is an artificial object (a complex of devices) moving in space and interacting (by means of information, energy, or material flows) with other AMO and OS [Sokolov, 1999], [Sokolov, Kalinin, 1995].

Fig. 8 shows general structure of AMO as an object being controlled. It is seen that AMO consists of four subsystems relating to four processes (functioning forms): moving, interaction with OS and other AMO, functioning of the main (goal-oriented) and auxiliary facilities, resources consumption (replenishment).

The four functions of AMO are quite different, though the joint execution of these functions, the interaction being the main one, provide for AMO new characteristics. Thus, it becomes a specific object of investigation, and AMO control problems are strictly different than classical problems of mechanical-motion control. The proposed structure of AMO can be widely interpreted. It gives a common basis for description of OSF, GSF, and OS.

To construct the models of AMO (SF or OS) control we should firstly formulate the goal of its functioning. This goal is to be related to the interaction between other AMO and OS. Secondly, the sequence of operations that lead to the specified goal should be determined. Each operation is characterized by its parameters. Some of parameters describe the results of the operation performance (amount of work, quality, duration, resource consumption, etc), the others present the characteristics of material or information flows necessary to perform the operation.

The conceptual model of SF control can be presented by means of state (macro-state) diagrams. Fig. 9 shows the fragment of a diagram for transition from SF general states. The following notations were used: 1 — execution of SF goal tasks; 2 — reserve state of SF; 3 — SF technical service and repair; 4 — SF motion for the goal tasks; 5 — SF motion after goal-tasks execution. In [Sokolov, 1999], [Sokolov, Kalinin, 1995] other examples of diagrams are presented.

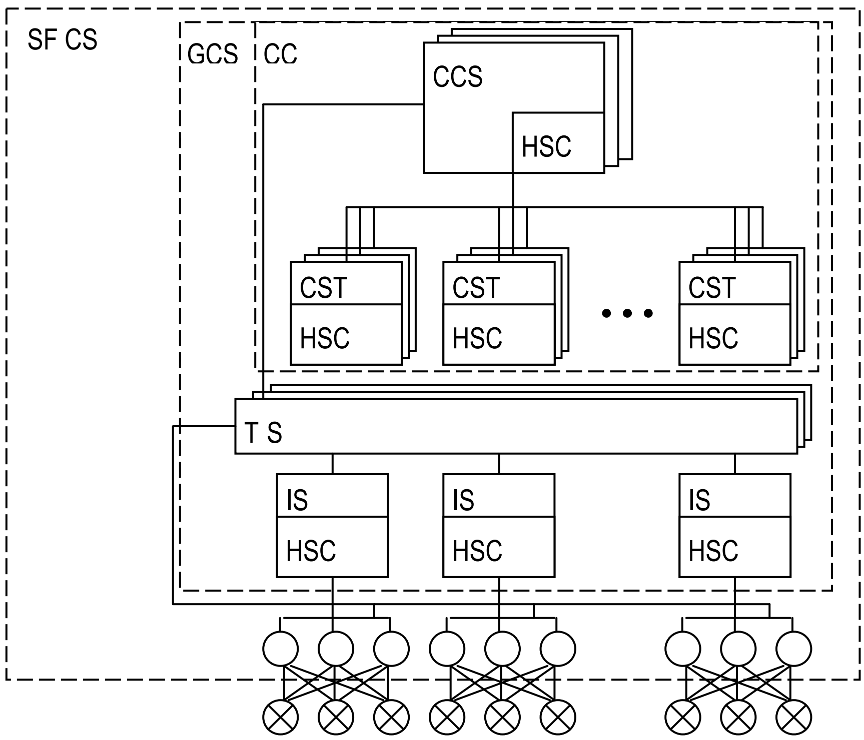


Fig. 7. The generalized technical and organizational structure of SF CS.

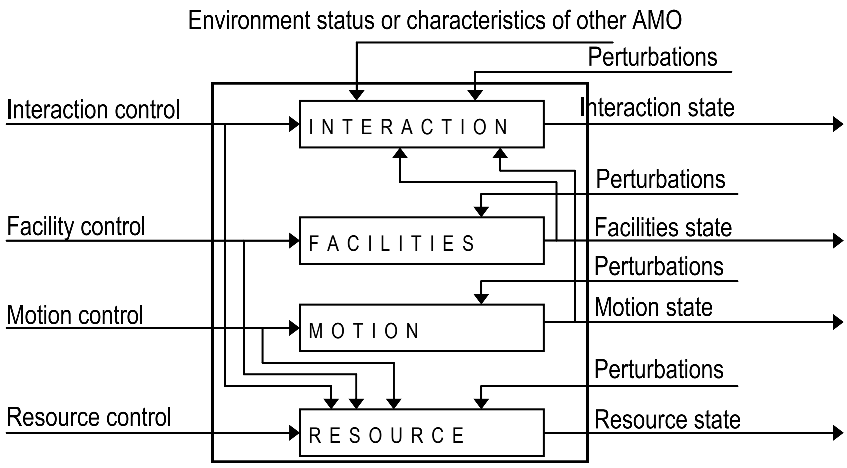


Fig. 8. General block diagram of AMO.

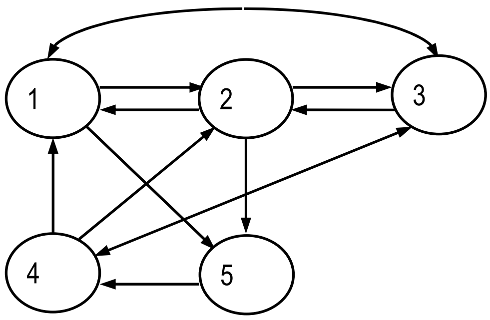


Fig. 9. The fragment of general-state transition diagram.

Thus, at the conceptual level, the process of SF functioning can be described as a process of operation execution, while each operation can be regarded as a transition from one state to another one. Meanwhile, it is convenient to characterize the SF state by the parameters of operations.

The particular control models are based on the dynamic interpretation of operations and the previously developed particular dynamic models of AMO functioning.

III. Multiple-model description of space-facilities control processes

A. Set-theory based model

In accordance with the proposed conceptual model of SF control, let us introduce the following basic sets and structures:

$B=\{B_i, i\in M=\{1,\dots,m\}\}$ is a set of objects (subsystems, elements) that are embodied in SF CS and are necessary for its functioning;

$\bar{B}=\{\bar{B}_i, i\in \bar{M}=\{1,\dots,\bar{m}\}\}$ is a set of external objects, (subsystems, elements) interacting with SF CS (the interaction may be informational, energy or material);

$\tilde{B}=B\cup\bar{B}$ is a set of the considered objects;

$\tilde{C}=C\cup\bar{C}=\{C_1,C_2,\dots,C_m\}\cup\{\bar{C}_1,\bar{C}_2,\dots,\bar{C}_{\bar{m}}\}$ is a set of channels that are used by SF and OS for interaction;

$C=\{C_\lambda^{(i)},\lambda\in\Lambda_i, i\in M\}$ is a set of channels (hardware facilities) that exist on the considered SF;

$D=\left\{D^{(c)}\cup D^{(i)}, i\in M\right\}$ is a set of SF CS operations;

$D^{(i)}=\left\{ D_\alpha^{(i)},\alpha\in K_i^{(o)}=\{1,\dots,s_i\} \right\}$ is a set of interaction operations with the object B_i;

$D^{(c)}=\left\{\{D_{iwf\eta_1}^{(c,1)}\}\cup\{D_{iwf\eta_1}^{(c,2)}\}\cup\{D_{iwf}^{(c,3)}\}, i\in M, w\in NW^{(i)}, f\in NF^{(w)}, \eta_1\in NH_1\right\}$ is a set of SF CS macro-operations;

$\{D_{iwf\eta_1}^{(c,1)}\}$ is a set of macro-operations for the object B_i and its macro-state S_{iwf} at the control cycle η_1; the sets of subscripts $M=\{1,\dots,m\}$, $NW^{(i)}=\{1,\dots,K_W^{(i)}\}$, $NW^{(w)}=\{1,\dots,K_F^{(w)}\}$, $NH_1=\{1,\dots,E_H\}$ are respectively used for the macro-states of the object B_i, for the place numbers of objects B_i in the macro-state «*w*», for the control cycles of the object B_i;

$\{D^{(c,2)}_{iwf\eta_1}\}$ is a set of auxiliary operations;

$\{D^{(c,3)}_{iwf}\}$ is a set of macro-operations for B_i transitions from the macro-state $S_{iw'f''}$ to the macro-state S_{iwf};

$\Phi = \left\{\{\Phi S^{(i)}_{\pi}\} \cup \{\Phi N^{(i)}_{\mu}\}, i \in M, \pi \in K^{(p,1)}_i = \{1,\ldots,k^{(p,1)}_i\}, \mu \in K^{(p,2)}_i = \{1,\ldots,k^{(p,1)}_i\}\right\}$ is a set of SF CS resources;

$\Phi S^{(i)} = \left\{ \Phi S^{(i)}_{\pi}, \pi \in K^{(p,1)}_i \right\}$ is a set of non-storable resources of the object B_i;

$\Phi N^{(i)} = \left\{ \Phi N^{(i)}_{\mu}, \mu \in K^{(p,2)}_i \right\}$ is a set of storable resources of the object B_i;

$P = \left\{\{P^{(i)}_{<\alpha',\rho>}\} \cup \{P^{(i,j)}_{<\alpha,\rho>}\}, i \in M,\ \alpha' \in K^{(o)}_i, \nu \in K^{(o)}_{<i,j>}, \rho \in K^{(n)}_i\right\}$ is a set of SF CS flows;

$P^{(i)} = \left\{\{P^{(i)}_{<\alpha',\rho>}\}, i \in M, \alpha' \in K^{(o)}_i, \rho \in K^{(n)}_i\right\}$ is a set of flows (energy flows, material flows, and information flows) produced by or necessary for the object B_i;

$P^{(i,j)} = \left\{ P^{(i,j)}_{<\alpha,\rho>}, i, j \in M, \rho \in K^{(n)}_i\right\}$ is a set of flows (energy flows, material flows, and information flows) produced when the objects B_i and B_j interact;

$G = \left\{ G_{\chi}, \chi \in NS\right\}$ is a set of SF CS structural types, where the main types of structures are the topologic (spatial) structure, the technology (functional) structure, the technical structure, the structures of mathematical and software tools, and the organizational structure.

To interconnect the structures let us consider the following dynamic alternative multi-graph (DAMG):

$$G^t_{\chi} = \left\langle X^t_{\chi}, F^t_{\chi}, Z^t_{\chi} \right\rangle, \tag{5}$$

where the subscript χ characterizes the SF CS structure type, $\chi \in NS = \{1,2,3,4,5,6\}$ (here 1 indicates the topologic structure, 2 indicates the functional structure, 3 indicates the technical structure, 4 and 5 indicate the structures of mathematical and software tools, 6 indicates the organizational structure, the time point *t* belongs to a given set T; $X^t_{\chi} = X^t_{\chi} = \{x^t_{\chi l}, l \in L_{\chi}\}$ is a set of elements of the structure G^t_{χ} (the set of DAMG vertices) at the time point t; $F^t_{\chi} = \{f^t_{<\chi,l,l'>}, l, l' \in L_{\chi}\}$ is a set of arcs of the DAMG G^t_{χ}; the arcs represent relations between the DAMG elements at time t; $Z^t_{\chi} = \{f^t_{<\chi,l,l'>}, l, l' \in L_{\chi}\}$ is a set of parameters that characterize relations numerically.

The graphs of different types are interdependent, thus, for each particular task of SF CS structure–dynamics control the following maps should be constructed:

$$M^t_{<\chi,\chi'>} : F^t_{\chi} \to F^t_{\chi'}, \tag{6}$$

compositions of the maps can be also used at time *t*:

$$M^t_{<\chi,\chi'>} = M^t_{<\chi,\chi_1>} \circ M^t_{<\chi,\chi_2>} \circ \ldots \circ M^t_{<\chi'',\chi'>}. \tag{7}$$

A multi-structural state can be defined as the following inclusion:

$$S_\delta \subseteq X_1^t \times X_2^t \times X_3^t \times X_4^t \times X_5^t \times X_6^t, \quad \delta = 1,\dots,K_\Delta . \tag{8}$$

Thus we obtain the set of SF CS multi-structural states:

$$S = \{S_\delta\} = \{S_1,\dots,S_{K_\Delta}\} . \tag{9}$$

Allowable transitions from one multi-structural state to another one can be expressed by means of the maps:

$$\Pi^t_{<\delta,\delta'>} : S_\delta \to S_{\delta'} . \tag{10}$$

Here we assume that each multi-structural state at time $t \in T$ is defined by a composition (7).

Now the problems of SF CS structure dynamics control can be regarded as a selection of a multi-structural state $S_\delta^* \in \{S_1, S_2,\dots,S_{K_\Delta}\}$ and of a transition sequence (composition) $\Pi^{t_1}_{<\delta_1,\delta_2>} \circ \Pi^{t_2}_{<\delta_2,\delta_3>} \circ \Pi^{t_f}_{<\delta',\delta>}$ $(t_1,< t_2 < \dots < t_f)$, under some criterion of effectiveness. The results of the selection can be presented as the optimal program for SF CS structure dynamics control. This program guides the system from a given multi-structural state to the specified one.

Along with the set $\{S_\delta\}$ of multi-structural states let us introduce two additional sets which are necessary for the description of SF CS structure dynamics. We shall use the set $\{S_{\chi\omega}\}$ of structural states (for structures of the type G_χ) and the set $\{S_{iwf}\}$ of macro-states (for the object B_i). Here $\chi \in NS = \{1,\dots,K_s\}$, $\omega \in N\Omega^{(\chi)} = \{1,\dots,K_\Omega^{(\chi)}\}\}$, $w \in NW^{(i)} = \{1,\dots,K_W^{(i)}\}$, $f \in NF^{(w)} = \{1,\dots,K_F^{(w)}\}$.

All the presented models can be interrelated into a generalized model.

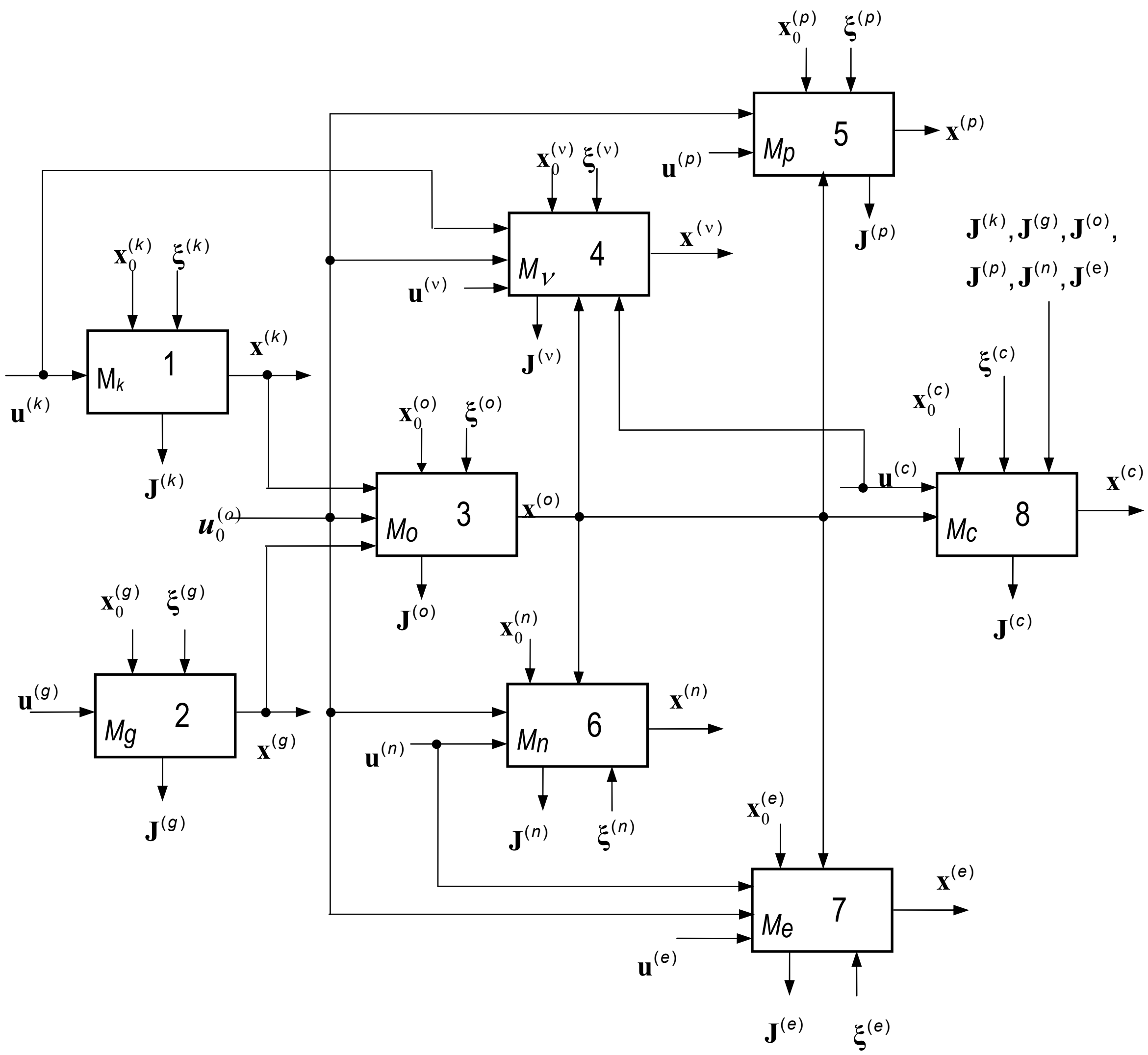
B. Generalized dynamic model of SF CS control processes (*M* model)

$$M = \left\{\mathbf{u}(t) \mid \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u},t); \mathbf{h}_0(\mathbf{x}(t_0)) \le \mathbf{O}, \mathbf{h}_1(\mathbf{x}(t_f)) \le \mathbf{O}, \mathbf{q}^{(1)}(\mathbf{x},\mathbf{u}) = \mathbf{O}, \mathbf{q}^{(2)}(\mathbf{x},\mathbf{u}) < \mathbf{O}\right\}, \tag{11}$$

$$J_\theta = J_\theta\left(\mathbf{x}(t),\mathbf{u}(t),t\right) = \varphi_\theta\left(\mathbf{x}(t_f)\right) + \int_{t_0}^{t_f} f_\theta\left(\mathbf{x}(\tau),\mathbf{u}(\tau),\tau\right) d\tau,\ \theta = 1,\dots,\Theta , \tag{12}$$

where $\mathbf{x} = \| \mathbf{x}^{(g)\mathrm{T}}, \mathbf{x}^{(o)\mathrm{T}}, \mathbf{x}^{(k)\mathrm{T}}, \mathbf{x}^{(p)\mathrm{T}}, \mathbf{x}^{(n)\mathrm{T}}, \mathbf{x}^{(e)\mathrm{T}}, \mathbf{x}^{(c)\mathrm{T}}, \mathbf{x}^{(v)\mathrm{T}} \|^{\mathrm{T}}$ is a vector of SF generalized state, $\mathbf{u} = \| \mathbf{u}^{(g)\mathrm{T}}, \mathbf{u}^{(o)\mathrm{T}}, \mathbf{u}^{(k)\mathrm{T}}, \mathbf{u}^{(p)\mathrm{T}}, \mathbf{u}^{(n)\mathrm{T}}, \mathbf{u}^{(e)\mathrm{T}}, \mathbf{u}^{(v)\mathrm{T}}, \mathbf{u}^{(v)\mathrm{T}} \|^{\mathrm{T}}$ is a vector of generalized control; $\mathbf{h}_0, \mathbf{h}_1$ are known vector-functions that are used for the state $\mathbf{x}$ end conditions at the time points $t = t_0$ and $t = t_f$; the vector-functions $\mathbf{q}^{(1)}, \mathbf{q}^{(2)}$ define the main spatio-temporal, technical and technological conditions for the SF functioning process.

On the whole the constructed model M (11) is a deterministic nonlinear non-stationary finite-dimensional differential system with a reconfigurable structure. Fig. 10 shows the interconnection of models M_g , M_o , M_k , M_p , M_n , M_e , M_c , M_v , embodied in the generalized model. In Fig. 10 the additional vector-function $\xi = \| \xi^{(g)\mathrm{T}}, \xi^{(o)\mathrm{T}}, \xi^{(k)\mathrm{T}}, \xi^{(p)\mathrm{T}}, \xi^{(n)\mathrm{T}}, \xi^{(e)\mathrm{T}}, \xi^{(c)\mathrm{T}}, \xi^{(v)\mathrm{T}} \|^{\mathrm{T}}$ of perturbation actions is introduced. This function describes the impact of the environment upon the SF functioning.



M_g — dynamic model of CTS motion control; M_k — dynamic model of CTS channel control;

M_o — dynamic model of CTS operations control; M_n — dynamic model of CTS flow control;

M_p — dynamic model of CTS resource control; M_e — dynamic model of CTS operation parameters control;

M_c — dynamic model of CTS structure dynamic control; M_ν — dynamic model of CTS auxiliary operation control

Fig. 10. The scheme of model interconnection.

IV. Methods and algorithms for evaluation of SF CS information-technological and goal abilities

One of the important problems in SF CS structure dynamic control is the evaluation of goal abilities, i.e., potential of the system to perform its missions in different situations. Thus, the preliminary analysis of information and technological and goal abilities (GA and ITA) of SF CS can be used to obtain reasonable means of the objects $B_j, j = 1,..,m$ exploitation under different conditions.

The numerical estimations of SF CS GA and ITA should be based on the system of measures. These measures can be regarded as characteristics of SF CS potential effectiveness. The GA measures characterizing different levels of SF CS are interrelated and have a hierarchical structure.

The leading role of information and technological aspects of the goal-abilities (GA) evaluation is a result of the influence of the technology structure (the structure of SF CS control technology) upon the other SF CS structures (organizational structure, technical structure, etc.) [Casti, 1979], [Klir, 1985], [Moiseev, 1974], [Roy, 1996], [Sokolov, 1999].

So the information and technological abilities (ITA) of a system ought to be evaluated first of all. These abilities can be measured as SF CS capacities [Sokolov, 1999].

The following measures are to be evaluated: the total number of objects in a given macro-state over a fixed time period or at a fixed point of time (this characteristics can be obtained with the model M_c); the total number of working operations performed over a fixed time period $\sigma = (t_0, t_f)$ or by the time point t .

Parallel with the enumerated measures of ITA the following measures of GA can be used: the total possible number of objects-in-service (OS) over the time period σ; the total time that is necessary for the execution of all interaction operations with OS. If the uncertainty factors are considered (the stochastic, probabilistic, or fuzzy models can be applied) the measures of GA can be evaluated as: the expectation (or the fuzzy expectation) of the number of serviced objects by a given time point; the probability (its statistical estimation) of successful service for the given objects.

Similar measures can be proposed for ITA estimations, for example the expectation of the number of objects in a given macro-state, the probability of technological operations fulfillment.

The problem of SF CS GA and ITA evaluation and analysis can be solved on the basis of structure dynamics control models (the model *M* and its components M_o , M_k , M_n , M_e , M_g , M_ν , M_c , M_p .

These models have a form of nonstationary finite-dimensional differential dynamic systems (NFDDS) with reconfigurable structures. So the problem of GA and ITA evaluation can be regarded as a problem of NFDDS controllability analysis. The latter problem, in its turn, can be solved by the NFDDS attainability set $D(t, T_0, \boldsymbol{x}(T_0))$, construction. If the attainability set is obtained, the solvability of the previously stated boundary problems for structure-dynamics control (SDC) can be checked in accordance with the sets of initial X_0 and final X_f states $(\boldsymbol{x}(T_0) \in X_0, \boldsymbol{x}(T_f) \in X_f)$, with the considered period of time, with time-spatial, technical, and technological constraints.

Moreover, the problems of SF SDC stated in the section III can be formulated as follows:

$$J'_{об}(\mathbf{x}(\cdot)) \to \min_{\mathbf{x}(\cdot)\in D(t_f, t_0, \mathbf{x}(t_0))} , \qquad (13)$$

where $D(t_f, t_0, \mathbf{x}(t_0))$ is the attainability set of the dynamic system (model) M ; $J'_G(\mathbf{x}(\cdot))$ — is the initial functional (12) transformed to the form of Mayer's functional. It is important that the alteration of objective functional does not imply the recalculation of the attainability set $D(t_f, t_0, \mathbf{x}(t_0))$. If the dimensionality of SF CS SDC problem is high, then the construction of the attainability sets becomes a rather complicated problem. Therefore, the approximations of $D(t_f, t_0, \mathbf{x}(t_0))$ ought to be used [Chernousko, Zak, 1985], [Moiseev, 1974], [Sokolov, 1999].

Now we introduce the algorithm of $D(t_f, t_0, \mathbf{x}(t_0))$ construction. The boundary points of the set $D(t_f, t_0, \mathbf{x}(t_0))$ are obtained as the solutions of the optimal control problems [Moiseev, 1974]:

$$J''_G(\mathbf{x}(\cdot)) = \mathbf{c}^{\mathrm{T}}\mathbf{x}(t_f) \to \min_{\mathbf{u}\in Q_p(\mathbf{x})}, \tag{14}$$

where $\mathbf{c}$ is a vector such that $|\mathbf{c}| = 1$. For a given vector $\mathbf{c}$ we obtain the optimal control $\mathbf{u}^*(t)$, the appropriate state vector $\mathbf{x}^*(t_f)$ that is equal to some boundary point of $D(t_f, t_0, \mathbf{x}(t_0))$, and the hyperplane $\mathbf{c}^{\mathrm{T}}\mathbf{x}^*(t_f)$ $\mathbf{c}^{\mathrm{T}}\mathbf{x}^*(t_f)$ to $D(t_f, t_0, \mathbf{x}(t_0))$ at the point $\mathbf{x}^*(t_f)$.

Let $\overline{\overline{\Delta}}$ be the number of different vectors $\mathbf{c}_{\overline{\beta}}$, $\overline{\beta} = 1,\ldots,\overline{\overline{\Delta}}$, then the external approximation $D^+(t_f, t_0, \mathbf{x}(t_0))$ of the set $D(t_f, t_0, \mathbf{x}(t_0))$ is a polyhedron whose faces lie on the corresponding hyperplanes, the internal approximation $D^-(t_f, t_0, \mathbf{x}(t_0))$ of $D(t_f, t_0, \mathbf{x}(t_0))$ is a polyhedron whose vertices are the points $\mathbf{x}^*_{\beta}(t_f)$, i.e., $D^-(t_f, t_0, \mathbf{x}(t_0)) = Co(\mathbf{x}_1(t_f),\ldots,\mathbf{x}_{\overline{\overline{\Delta}}}(t_f))$. The bigger $\overline{\overline{\Delta}}$, the better approximation of the attainability set $D(t_f, t_0, \mathbf{x}(t_0))$ can be obtained. It can be proved [Sokolov, 1999] that the value $\overline{\overline{\Delta}}$ is defined by the total number of possible interruptions for CTS interaction operations over a given time period (t_0, t). To obtain D^+, D^- Krylov and Chernousko's method was used [Moiseev, 1974]. Instead of the vector $\mathbf{c}$ the vector $\boldsymbol{\psi}(t_0)$ of conjugate variables is to be varied.

Conclusion

The constructed general model has a form of linear (bilinear as regards the model M_k) nonstationary finite-dimensional differential dynamic system with reconfigurable structure. The solutions obtained in the presented multiple-model complex are coordinated by the control-inputs vector $u^{(o)}(t)$ of the model M_o. This vector determines the sequence of interaction operations and fixes SF resources allocation. The applied procedure of solution adjustment was called in [Mesarovic, Takahara, 1975], [Moiseev, 1974], [Tsurlov, 1989] resource coordination.

The model complex M evolves and generalizes the dynamic models of scheduling theory [Moiseev, 1974], [Wanguer, 1969]. The main distinctive feature (as apposed to [Moiseev, 1974]) of the complex is that nonlinear technological constraints are actualized in the convex domain of allowable control inputs rather than in differential equations. Therefore, Lagrangian coefficients keeping the information about technical and technological constraints can be defined explicitly using the local-sections method [Pontriagin, etc., 1961]. In [Moiseev, 1974] more complicated iterative procedure was suggested to obtain Lagrangian coefficients. Furthermore instead of relay constraints $u_v \in \{0,1\}$, $v \in \{1,\ldots,n\}$ (here n is the dimensionality of the control vector u) less strict ones $u_v \in [0,1]$ can be considered. This substitution lets use fundamental scientific results of the modern control theory [Athaus, Falb, 1966], [Bryson, Yo-Chi, 1969], [Fleming, Richel, 1975], [Moiseev, 1974], [Pontriagin, etc., 1961] in various SF control problems (including scheduling theory problems).

Computational investigation [Sokolov, 1999] showed that the use of the SF dynamic models entails considerable dimensionality decrease for control problems to be solved in a real-time operation mode. Recurrence description of models allows parallel computations accelerating problem solving.

The proposed original description of SF control processes establishes dependence relations between control technology and the goals of SF CS. For example, the methods of optimal-control theory applied to the models M_o, M_e, M_n help to estimate the degree of interdependency between quality of spacecraft operating according to a specified purpose and such technological aspects of space-system management as SF resource allocation, trajectory measurement schemes, and information-flow routing methods. Consequently, the optimal programs for resource allocation, for flow routing, and trajectory measurements can be obtained.

Various combinations and interactions of particular control models forming the general model M is the basis for detailed multicriteria analysis of the factors influencing upon the objective results of SF operating.

This research described in this paper is partially supported by grants of Russian Foundation for Basic Research (RFBR) (11-07-00302-a, 10-07-00311-a, 11-08-01016-a, 11-08-00767-a, 12-07-00302). Saint-Petersburg Scientific Center RAS (SPIIRAS project 2012), and the Program of Fundamental Investigation of the Department of Nanotechnologies and Information Technologies RAS (project № 2.11), Program ESTLATRUS project 2.1/ELRI-184/2011/14.

Bibliography

[Athaus, Falb, 1966] Athaus, M., Falb P.L. Optimal control: An Introduction to the Theory and Its Applications. McGrow-Hill Book Company. New York, San Francisco, Sidney, 1966.

[Bryson, Yo-Chi, 1969] Bryson, A.E., and Yo-Chi Ho. Applied optimal control: Optimization, Estimation and Control. Waltham Massachusetts, Toronto, London, 1969.

[Casti, 1979] Casti, J.L.. Connectivity, Complexity and Catastrophe in Large-Scale Systems. Wiley-Interscience, New York and London, 1979.

[Chernousko, Zak, 1985] Chernousko, F.L., Zak, V.L. On Differential Games of Enasion from Many Pursuers // J. Optimiz. Theory and Appl. 1985. Vol.46, N 4. P.461-470.

[Doganovskii, Oseranii, 1990] Doganovskii S.A. Oseranii N.A. Automatic Restructurable Control Systems // Measurement, Cheek, Automation, 1990, N 4 (90). P.62-80 (in Russian).

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

[Gupta, Sinka, 1996] Intelligent Control Systems: Theory and Applications / Eds. M.M. Gupta, N.K. Sinka. N.Y.: IEEE Press, 1996.

[Klir, 1985] Klir, G.J. Architecture of Systems Problem Solving. Plenum Press, New York. 1985.

[Mesarovic, Takahara, 1975] Mesarovic M.D. and Y. Takahara. General Systems Theory: Mathematical Foundations. Academic Press, New York, Can Francisco, London, 1975.

[Moiseev, 1974] Moiseev, N.N. Element of the Optimal Systems Theory. – Moscow: Nauka, 1974 (in Russian).

[Napolitano, Swaim, 1989] Napolitano M.R., Swaim R.L. A New Technique for Aircraft Flight Control Reconfiguration // Proc. AIAA Guidance, Navigation and Control Conf., 1989. Pt 1, p.1-9.

[Ohtilev, Sokolov, Yusupov, 2006] Ohtilev, M., Sokolov, B., Yusupov, R. Intelligent technologies of monitoring and control. Moscow, Nauka, 2006. 410 p. (in Russian).

[Oreu, Zeigler, Elzas, 1984] Simulation and Model-Based Methodologies: An Integrate View/Ed. by T.I. Oreu, B.P. Zeigler, M.S. Elzas: NATO Series (F), Vol.10 Springer-Verlag Berlin Heidelberg, New York, 1984.

[Pontriagin, etc., 1961] Pontriagin, L.S., etc. Theory of Optimal Process. – Moscow: Fizmatgiz, 1961 (in Russian).

[Roy, 1996] Roy, B. Multicriteria Methodology for Decision Aiding. Kluwer Academic Pulisher, Dordrecht, 1996.

[Russell, Norvig, 1995] Russell, S.J., Norvig, P. Artificial Intelligence: A Modern Approach. Prentice-Hall, Inc., A Simon & Schuster Company, Upper Saddle River, New Jersey, 1995.

[Shannon, 1975] Shannon, R.E. Systems Simulation. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1975.

[Siliak, 1990] Siliak, D.D. Decentralized Control of Complex Systems, Academic Press, New York, 1990.

[Singh, Titli, 1978] Singh, M., and A. Titli. Systems: Decomposition, Optimization and Control, Pergamon Press, Oxford, 1978.

[Sokolov, 1999] Sokolov, B.V., Complex Operations Scheduling and Structure Control in Automation Control Systems of Active Moving Objects. RF. Department of Defense, 1999 (in Russian).

[Sokolov, Kalinin, 1985] Sokolov, B.V., Kalinin V.N., A Dynamic Model and an Optimal Scheduling Algorithm for Activities with Baus of Interrupts // Automation and Telechanics, 1985, N 1, pp.106-114 (in Russian).

[Sokolov, Kalinin, 1995] Sokolov, B.V., Kalinin V.N., Multi-model Approach to the Description of the Air-Space Facilities Control Process // Control Theory and process, 1995, N 1, pp.149-156 (in Russian).

[Tsurlov, 1989] Tsurlov, V.I., Dynamic Problems of large Dimension. – Moscow: Nauka, 1989 (in Russian).

[Tsypkin, 1971] Tsypkin, Y.Z. Adaptation and Learning in Automatic System. Academic Press. New York, 1971.

[Van der Velde, 1984] Van der Velde W.E. Control System Reconfiguration // Proc. American Control Conf., 1984, v.3. P.1741-1745.

[Vasil'ev, 2001] Vasil'ev, S.N., From Classical Control Problems to Intelligent Control // Control theory and process, 2001. N 1. P.5-22. N 2. P.5-21.

[Wanguer, 1969] Wanguer, H.M. Principles of Operations Research. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1969.

[Yusupov, Timofeev, 1994] Yusupov R., Timofeev A. Intellectual systems of automated control // Engineering Cybernetics, 1994. N 5.Pp.211-224 (in Russian).

[Yusupov, Rozenwasser, 1999] Yusupov R., Rozenwasser E. Sensitivity of Automatic Control Systems. CRS. Press, London, New York, 1999.

[Zvirkun, Akinfiev, Filippov, 1985] Zvirkun, A.D., and Akinfiev V.K., Filippov V.A., Simulation Modeling in the Problems of Complex Systems Structure Synthesis. – Moscow: Nauka, 1985 (in Russian).

[Zvirkun, Akinfiev, 1993] Zvirkun, A.D., and V.K. Akinfiev, Structure of the multi-level systems (synthesis and development). – Moscow: Nauka, 1993 (in Russian).

[Zvirkun, 1982] Zvirkun, A.D., Basis of Complex Systems Structure Synthesis. – Moscow: Nauka, 1982 (in Russian).

Authors' Information

Boris Sokolov – Doctor of Sciences (Tech), Prof., Honored scientist of Russian Federation; Deputy-Director for Research of St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS), 14th line, 39, St.Petersburg, 199178; e-mail: sokol@iias.spb.su.

Major Fields of Scientific Research: Development of research fundamentals for the control theory by structural dynamics of complex organizational-technical systems.

Rafael Yusupov – Doctor of Sciences (Tech), RAS Correspondent member, Honored scientist of Russian Federation; Director of St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS), 14th line, 39, St.Petersburg, 199178; e-mail: yusupov@iias.spb.su.

Major Fields of Scientific Research: Control theory, informatics, theoretic basics of informatization and information society, information security

Vyacheslav Zelentsov – Doctor of Sciences (Tech), Prof.; Leading Researcher of St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences (SPIIRAS), 14th line, 39, St.Petersburg, 199178; e-mail: v.a.zelentsov@gmail.com .

Major Fields of Scientific Research: Decision-making in complex systems.