Mathematical model and algorithm of operation scheduling for monitoring situation in local waters

Boris Sokolov^{1,*}, Vladimir Palitsyn² and Dmitriy Nazarov¹

¹St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences, 14th line 39, St. Petersburg, 199178, Russia

²St. Petersburg State University of Aerospace Instrumentation, Bolshaya Morskaya Str. 67A, Saint-Petersburg, 190000, Russia

Abstract. A multiple-model approach to description and investigation of control processes in regional maritime security system is presented. The processes considered in this paper were qualified as control processes of computing operations providing monitoring of the situation adding in the local water area and connected to relocation of different ships classes (further the active mobile objects (AMO)). Previously developed concept of active moving object (AMO) is used. The models describe operation of AMO automated monitoring and control system (AMCS) elements as well as their interaction with objects-in-service that are sources or recipients of information being processed. The unified description of various control processes allows synthesizing simultaneously both technical and functional structures of AMO AMCS. The algorithm for solving the scheduling problem is described in terms of the classical theory of optimal automatic control.

1 Introduction

At present, ensuring the safety of navigation of ships on inland waters of the Russian Federation is an urgent task, which is primarily due to the following factors: the number and intensity of ship movement in coastal marine areas, lakes and rivers, especially small-sized vessels used for active recreation, tourism, transportation of passengers, sports and as special means.

To date, various elements of the regional maritime security system (RMSS) have been developed, or are under development. The existing concept of the RMSS includes the following elements: - automatic monitoring systems (AMS); control systems of ship traffic; automatic identification systems; communication systems in case of disaster; a complex of terrestrial and satellite radio navigation systems; uniform database of courts and monitoring information. At the same time, as analysis shows, now, unfortunately, the automated collection and storage of monitoring information is of a local nature, there is an information inconsistency of monitoring data obtained by heterogeneous automated monitoring and control system (AMCS).

To compensate a contradiction between the existing need and to conduct operational analysis and prediction of the surface situation and the current state of the organizational and technical means ensuring the safety of navigation, methods, algorithms, techniques, software can be integrated for solving problems of analysis, planning and prediction of the surface situation on the basis of modern intellectual technologies. One of the most

important tasks, which needs to be solved to achieve a goal, is the task of joint planning and scheduling of the measuring and computing operations providing monitoring of the situation in the local water area and connected to relocation of different ship classes (further the active mobile objects (AMO)) [1-2].

According to the specifics of the structure-dynamics control problems, they belong to the class of the AMCS structure-functional synthesis problems and the problems of program construction for AMCS development [3-7].

The main disadvantage of the problems belonging to the above class is that, optimal control programs for AMCS main elements and subsystems can be implemented only when the functions and algorithms for control and information processing in these subsystems and elements are known [5-6].

We propose a dynamic interpretation of monitoring situation in local waters, which is based on results of classical control theory [8-15].

2 Conceptual model of monitoring situation in local waters

The preliminary investigations confirm that the most convenient concept for formalization monitoring situation in local waters is the concept of an active moving object (AMO). In general case, it is an artificial object (a complex of devices) moving in space (in our case in local waters) and interacting (by means of information, energy, or material flows) with other AMO and objects-in-service (OS) [1, 2].

* Corresponding author: sokolov_boris@inbox.ru

Figure 1 shows a 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).

Fig. 1. General block-diagram of AMO

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 from classical problems of mechanical-motion control. The proposed structure of AMO can be widely interpreted. It gives a common basis for description ships on inland waters. In this case we use AMO for describing both ships and their automated monitoring and control system (AMCS) including ships (in our terms – AMO), ground-based radar observation stations (GRS), data processing center (DPC).

To construct the models of AMO AMCS 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 operations are characterized by their 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.

Thus, at the conceptual level, the process of AMO AMCS 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 AMO AMCS 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 AMCS functioning.

3. Multiple-model description of AMO monitoring and control processes

The main aim of our paper is to prove the need of integrated modelling and simulation for parallel structural-functional synthesis of AMO AMCS under dynamic conditions. Moreover the main idea of our approach is to use fundamental results of structural-dynamic control theory [1,2-6] for multiple-model

description of AMO AMCS planning and scheduling tasks. The dynamic interpretation of structure-dynamics control processes allows for application of the results, previously received in the theory of dynamic systems stability, ability, failure tolerance, effectiveness and sensitivity, for AMO AMCS analysis and synthesis problems [7-14].

Our investigation have shown that joint use of diverse models allows one to improve the flexibility and adaptability of AMO AMCS, as well as to compensate the drawbacks of one class of models by the advantages of the other.

We propose four interconnected dynamics models for description both ships (AMO) and their automated monitoring and control system (AMCS) including ground-based radar observation stations (GRS), data processing center (DPC).

3.1 Dynamic model of AMO motion control (Mg model)

$$M_g = \left\{ \mathbf{u}^{(g)}(t) \mid \dot{\mathbf{x}}_i^{(g)} = f_i^{(g)}(\mathbf{x}_i^{(g)}, \mathbf{u}_i^{(g)}, t), \right. \\ \mathbf{q}^{(g)}(\mathbf{x}^{(g)}, \mathbf{u}^{(g)}, t) \leq \mathbf{O}, \mathbf{h}_0^{(g)}(\mathbf{x}^{(g)}(T_0)) \leq \mathbf{O}, \quad (1) \\ \left. \mathbf{h}_1^{(g)}(\mathbf{x}^{(g)}(T_f)) \leq \mathbf{O}, i \in \tilde{M} \right\}$$

where $\mathbf{x}^{(g)} = \left\| \mathbf{x}_1^{(g)r}, \mathbf{x}_2^{(g)r}, \dots, \mathbf{x}_{m+m}^{(g)r} \right\|^T$ is a vector characterizing the state of motion for elements and subsystems of AMO AMCS, including ships (in our terms – AMO) and ground-based radar observation stations (GRS); $\mathbf{u}^{(g)} = \left\| \mathbf{u}_1^{(g)r}, \dots, \mathbf{u}_{m+m}^{(g)r} \right\|^T$ is a vector of control inputs including, in a general case, program and regulative inputs; $\mathbf{q}^{(g)}(\mathbf{x}^{(g)}, \mathbf{u}^{(g)}, t)$, $\mathbf{h}_0^{(g)}(\mathbf{x}^{(g)}(t_0))$, $\mathbf{h}_1^{(g)}(\mathbf{x}^{(g)}(t_f))$ are known vector functions used for motion constraints and end conditions. An interaction operation can be performed when each communicating object is in the interaction zone (IZ) of the other one. These zones are described by the matrix function $E(t) = \|\varepsilon_{ij}(t)\|$; $ij \in \tilde{M} = \{M \cup \bar{M}\}$.

This function was called contact potential [1, 2]. Under the above conditions, the contact potential for a pair of objects $\langle \text{AMO}_i, \text{GRS}_j \rangle$ can be obtained as follows [1]:

$$\varepsilon_{ij}(t) = \gamma_+ \left\{ R_j^{(g)} - \left| \mathbf{r}_i^{(g)}(t) - \mathbf{r}_j^{(g)}(t) \right| \right\}, \quad (2)$$

where $ij \in \tilde{M}$, $\gamma_+(\tilde{\alpha}) = 1$ if $\tilde{\alpha} \geq 0$, $\gamma_+(\tilde{\alpha}) = 0$ if $\tilde{\alpha} < 0$; $R_j^{(g)}(t)$ is IZ radius for the object B_j , $\mathbf{r}_i^{(g)}(t)$, $\mathbf{r}_j^{(g)}(t)$ are, in a general case, three-dimensional radius-vectors for B_i , B_j and are sub-vectors (together with $\dot{\mathbf{r}}_i^{(g)}(t)$, $\dot{\mathbf{r}}_j^{(g)}(t)$) of the vectors $\mathbf{x}_i^{(g)} = \|\mathbf{r}_i^{(g)}(t), \dot{\mathbf{r}}_i^{(g)}(t)\|^T$, $\mathbf{x}_j^{(g)} = \|\mathbf{r}_j^{(g)}(t), \dot{\mathbf{r}}_j^{(g)}(t)\|^T$.

Obviously, for the stationary (fixed) objects we have $\mathbf{r}_i(t) = \mathbf{r}_i(t_0) = \mathbf{r}_{i0}$, where $\mathbf{r}_{i0}$ is a position of an object.

3.2 Dynamic model of AMO AMCS interaction-operations (IO) control (Mo model)

$$\begin{aligned} M_o = & \left\{ \mathbf{u}^{(o)}(t) \mid \dot{x}_{i\alpha}^{(o)} = \sum_{j=1}^m \varepsilon_{ij}(t) \cdot u_{i\alpha j}^{(o)}; x_{i\alpha}^{(o)}(t_0) = 0, \right. \\ & x_{i\alpha}^{(o)}(t_f) = a_{i\alpha}^{(o)}, \sum_{i=1}^m \sum_{\alpha=1}^{s_i} u_{i\alpha j}^{(o)} \leq c_j^{(o,1)}, \\ & \sum_{j=1}^m \sum_{\alpha=1}^{s_j} u_{i\alpha j}^{(o)} \leq c_i^{(o,2)}, u_{i\alpha j}^{(o)}(t) \in \{0,1\}, \\ & \left. u_{i\alpha j}^{(o)} \left[\sum_{\tilde{\alpha} \in \Gamma_{i\alpha 1}} (a_{i\tilde{\alpha}}^{(o)} - x_{i\tilde{\alpha}}^{(o)}) + \prod_{\tilde{\beta} \in \Gamma_{i\alpha 2}} (a_{i\tilde{\beta}}^{(o)} - x_{i\tilde{\beta}}^{(o)}) \right] = 0, \right. \\ & \left. i, j = 1, \dots, m; i \neq j; \alpha = 1, \dots, s \right\}, \end{aligned} \quad (3)$$

where $x_{i\alpha}^{(o)}$ is a variable characterizing the state of interaction operation $D_{\alpha}^{(i)}$; $a_{\alpha}^{(o)}, a_{i\tilde{\alpha}}^{(o)}, a_{i\tilde{\beta}}^{(o)}$ are given amounts of work for operations $D_{\alpha}^{(i)}, D_{\tilde{\alpha}}^{(i)}, D_{\tilde{\beta}}^{(i)}$; $u_{i\alpha j}^{(o)}(t)$ is a control input, $u_{i\alpha j}^{(o)}(t) = 1$ if the operation $D_{\alpha}^{(i)}$ is being performed, $u_{i\alpha j}^{(o)}(t) = 0$ if not; $\Gamma_{i\alpha 1}, \Gamma_{i\alpha 2}$ are the sets of operations numbers for the operations that involve the object B_i and precede the operation $D_{\alpha}^{(i)}$; here $\Gamma_{i\alpha 1}$ is used for the operations connected with $D_{\alpha}^{(i)}$ by the logical “ $\wedge$ ” - (“and”-conjunction), $\Gamma_{i\alpha 2}$ is used for the operations connected with $D_{\alpha}^{(i)}$ by the logical “ $\vee$ ” (“or” - disjunction); $c_j^{(o,1)}, c_i^{(o,2)}$ are constants used for technical conditions of AMO AMCS functioning.

3.3 Dynamic model of AMO AMCS channels control (Mk model)

$$\begin{aligned} M_k = & \left\{ \mathbf{u}^{(k)}(t) \mid \dot{x}_{ij}^{(k)} = \right. \\ & = \sum_{l=1}^m \Theta_{lj}(t) \frac{h_{il}^{(j)} - x_{ij}^{(k)}}{x_{lj}^{(k)}} \cdot u_{lj}^{(k)}; \\ & x_{ij}^{(k)}(t_0), x_{ij}^{(k)}(t_f) \in \mathbf{R}^+, \\ & x_{ij}^{(k)} \cdot u_{i\alpha j}^{(o)} = 0; \sum_{l=1}^m u_{lj}^{(k)} \leq 1, \\ & \left. \sum_{j=1}^m u_{lj}^{(k)} \leq 1, u_{lj}^{(k)}(t) \in \{0,1\}; i, j, l \in \tilde{M} \right\}, \end{aligned} \quad (4)$$

where $x_{ij}^{(k)}$ is the state of readjustment process for the channel $C_{\lambda}^{(i)}$; $h_{il}^{(j)}$ is a given value of the readjustment duration; it is supposed that the channel was ready to service the object GRS_l at the beginning of the readjustment and must be ready to service the object

AMO_i at the end of readjustment process; $\mathbf{R}^+$ is a set of positive real numbers; $u_{lj}^{(k)}(t)$ is a control input; $u_{lj}^{(k)}(t) = 1$ if C_j is in the readjustment state, $u_{lj}^{(k)}(t) = 0$ if not; $\Theta_{lj}(t) \in \{0,1\}$ is a given value characterizing potential ability of the channel C_j to interact with the object B_i (in our case AMO_i). It can be seen that the operation $D_{\alpha}^{(i)}$ can be started when appropriate channel is ready [$x_{ij}^{(k)}(t) = 0$], while each channel C_j at each time t can be prepared for only one object GRS_l ($l \neq j, l = 1, \dots, m$).

3.4 Dynamic model of AMO AMCS operation parameters control (Me model)

$$\begin{aligned} M_e = & \left\{ \mathbf{u}^{(e)}(t) \mid \dot{\mathbf{x}}_i^{(g)} = F_i(t) \mathbf{x}_i^{(g)}; \right. \\ & y_j^{(i)}(t) = \mathbf{d}_j^T(t) \mathbf{x}_i^{(g)} + \xi_j^{(e)}; \\ & \dot{Z}_i = -Z_i F_i - F_i^T Z_i - \sum_{j=1}^n \sum_{\alpha \in \Gamma_i} u_{i\alpha j}^{(e)} \frac{\mathbf{d}_j \mathbf{d}_j^T}{\sigma_j^2}; \\ & \left. i \neq j; i, j \in \tilde{M}; 0 \leq u_{i\alpha j}^{(e)} \leq c_{i\alpha j}^{(e)} u_{i\alpha j}^{(o)} \right\} \end{aligned} \quad (5)$$

where $\mathbf{x}_i^{(g)} = \left\| \mathbf{r}_i^{(g)T} \mathbf{r}_i^{(g)T} \right\|^T$ is a motion state vector of the AMO B_i ; the parameters $y_j^{(i)}(t)$, $j \in \tilde{M}$ of motion are cinematically associated with $x_j^{(g)}(t)$; $F_i(t)$ is a given matrix; $\xi_j^{(e)}$ denotes uncorrelated measurement errors over the channel C_j , it is asserted that $\xi_j^{(e)}$ follows normal distribution with zero expectation and the variance equal to σ_j^2 ; $D_{\alpha}^{(i)} \in D^{(i)}$; $u_{i\alpha j}^{(e)}(t)$ is a control input defining the intensity of the parameter $y_j^{(i)}(t)$ measurements; $c_{i\alpha j}^{(e)}$ is a given value of the channel C_j technical capacity for the operation $D_{\alpha}^{(i)}$; Z_i is the inverse matrix for the matrix $K_i(t)$ that is a correlation matrix for the estimation errors of the motion state variables; Γ_i is a set of subscripts for measurement operations of the AMO B_i ; $\mathbf{d}_j(t)$ is a given vector defining technical features of the measuring device (of the channel C_j); $\mathbf{b}_\gamma = \|0 \ 0 \dots 1 \dots 0 \ 0\|^T$ is an auxiliary vector used to mark a particular element number « γ » of the matrix K_i ; K_{i0} is the initial value of the matrix K_i at time $t = t_0$; $\sigma_{\gamma i}^2$ is a specified measurement accuracy for the γ -th element of the motion state vector.

The operations considered in the proposed models are sometimes executed under an interrupt prohibition. Such conditions can be stated in the additional model namely the model of auxiliary-operation control ($\mathbf{M}_b$ model). The detailed description of this model can be found in [1, 2].

The quality of AMO AMCS control processes can be evaluated through various goal functions [1, 2, 5, 6]. Let us consider some examples of these functions:

$$J_1^{(o)} = \frac{1}{2} \sum_{i=1}^m \sum_{\alpha=1}^{S_i} \left\{ \left[a_{i\alpha}^{(o)} - x_{i\alpha}^{(o)}(t_f) \right]^2 + \sum_{j=1}^m \int_{t_0}^{t_f} \xi_{i\alpha}(\tau) u_{i\alpha j}^{(o)}(\tau) d\tau \right\}, i \neq j; \quad (6)$$

$$J_5^{(e)} = \bar{b}_\gamma^T K_i(t_f) \bar{b}_\gamma, J_{6j}^{(e)} = \sum_{i=1}^m \sum_{\alpha \in I^{(j)}} \int_{t_0}^{t_f} u_{i\alpha}^{(e)}(\tau) d\tau, \quad (7)$$

where $\xi_{i\alpha}(\tau)$, $i \in \{1, \dots, m\}$, $\alpha \in \{1, \dots, S_i\}$ are monotone functions that state the penalties for the overdraft of operations' scheduled times. The functional (6) is used, firstly, when the degree of end-conditions violation should be evaluated and, secondly, when the total losses caused by the excess of operations durations are to be measured. The value of the functional $J_5^{(e)}$ characterizes the accuracy of measurement achieved for the γ -th element of the vector $\mathbf{x}_i^{(g)}$.

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

3.5 Generalized dynamic model of AMO AMCS control processes (M model)

$$M = \left\{ \mathbf{u}(t) \mid \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t); \mathbf{h}_0(\mathbf{x}(t_0)) \leq \mathbf{O}, \mathbf{h}_1(\mathbf{x}(t_f)) \leq \mathbf{O}, \mathbf{q}^{(1)}(\mathbf{x}, \mathbf{u}) = \mathbf{O}, \mathbf{q}^{(2)}(\mathbf{x}, \mathbf{u}) < \mathbf{O} \right\} \quad (8)$$

$$J_\theta = J_\theta(\mathbf{x}(t), \mathbf{u}(t), t) = \varphi_\theta(\mathbf{x}(t_f)) + \int_{t_0}^{t_f} f_\theta(\mathbf{x}(\tau), \mathbf{u}(\tau), \tau) d\tau, \theta = 1, \dots, \Theta, \quad (9)$$

where $\mathbf{x}$ is a vector of AMO AMCS generalized state, $\mathbf{u}$ is a vector of generalized control; $\mathbf{h}_0, \mathbf{h}_1$ are known vector-functions that are used for the state $\bar{\mathbf{x}}$ 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** (8) is a deterministic nonlinear non-stationary finite-dimensional differential system with a reconfigurable structure.

4. Algorithm

Computational scheme of the scheduling algorithm is as follows [1, 2, 16-18].

Step 4.1. Setting the rough decision (any valid plan) $\bar{\mathbf{u}}_g(t), t \in (t_0, t_f]$. In the special case empty plan

$(\bar{\mathbf{u}}_g(t) \equiv \bar{\mathbf{0}})$ can be selected.

Step 4.2. Integrating basic system of equations (1)–(4) with initial conditions and the $\bar{\mathbf{u}} = \bar{\mathbf{u}}_g(t)$. Vector $\bar{\mathbf{x}}_{(0)}(t)$ obtained as a result of integration. In addition, determine

(9) at $t = t_f$, which is taken as a record. Calculating the transversality condition which could be found in [8,13,14].

Step 4.3. Integrating the conjugate system of equations

$$\dot{\psi}_l = -\frac{\partial H}{\partial x_l} + \sum_{\alpha=1}^{I_1} \eta_\alpha(t) \frac{\partial q_\alpha^{(1)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t))}{\partial x_l} + \sum_{\beta=1}^{I_2} \rho_\beta(t) \frac{\partial q_\beta^{(2)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t))}{\partial x_l}, l = 1, \dots, \tilde{n} \quad (10)$$

Where, H – Hamiltonian [13,14], η_α and ρ_β could be found from

$$\rho_\beta(t) q_\beta^{(2)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t)) \equiv 0, \beta = 1, \dots, I_2,$$

$$\text{grad}_{\bar{\mathbf{u}}} H(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t), \bar{\psi}(t)) = \sum_{\alpha=1}^{I_1} \eta_\alpha(t) \text{grad}_{\bar{\mathbf{u}}} q_\alpha^{(1)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t)) + \sum_{\beta=1}^{I_2} \rho_\beta(t) \text{grad}_{\bar{\mathbf{u}}} q_\beta^{(2)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t)),$$

where $\bar{\psi}(t)$ is a general vector of the conjugate system of equations, $q_\alpha^{(1)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t))$ and $q_\beta^{(2)}(\bar{\mathbf{x}}(t), \bar{\mathbf{u}}(t))$ – components of given system of constraints, from $t = t_f$ to $t = t_0$ with $\bar{\mathbf{u}} = \bar{\mathbf{u}}_g(t)$. At $t = t_0$ we get a first approximation of $\bar{\psi}_i(t_0)$. This completes the iteration $r = 0$.

Step 4.4. From the moment t_0 control $\bar{\mathbf{u}}^{(r+1)}(t)$ is sought ($r = 0, 1, 2, \dots$ – number of iterations) based on the maximization of the Hamiltonian $H(\bar{\mathbf{x}}^*(t), \bar{\mathbf{u}}^*(t), \bar{\psi}^*(t))$ [2]. Simultaneously the main system of equations is integrated. Thus at any given time there is a dynamic decomposition of the main tasks for several mathematical programming problems: linear programming, assignment problems [4].

The iterative optimization process ends when the following conditions are satisfied: $|J^{(r+1)} - J^{(r)}| \leq \varepsilon$. Thus $\bar{\psi}(t_0)$ defines vector of associative values of dynamic priority $\bar{\zeta}$ for each operation $D_K^{(i)}$ [2,3].

5 Conclusion

The constructed general model has a form of linear (bilinear as regards the model **Mk**) 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 $\mathbf{u}^{(o)}$ of the model **Mo**. This vector determines the sequence of interaction operations and fixes AMO AMCS resources allocation. The applied procedure of solution adjustment was called in [5,10-12] resource coordination.

The model complex **M** evolves and generalizes the dynamic models of scheduling theory [2-4,6,15]. The main distinctive feature (as apposed to [3]) 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 [2]. In [5-6] more complicated iterative procedure was suggested to obtain Lagrangian coefficients. Furthermore instead of relay constraints $u_{i\alpha j}^{(o)}(t) \in \{0,1\}$, less strict ones $u_{i\alpha j}^{(o)}(t) \in [0,1]$ can be considered. This substitution allows for the use of fundamental scientific results of the modern control theory [8,13,14] in various AMO AMCS control problems (including scheduling theory problems).

Computational investigation [2] showed that the use of the AMO AMCS 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 AMO AMCS control processes establishes dependence relations between control technology and the goals of AMO AMCS. For example, the methods of optimal-control theory applied to the models **Mo**, **Me** help to estimate the degree of interdependency between quality of spacecraft operating according to a specified purpose and such technological aspects of AMO management as AMCS 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 multi-criteria analysis of the factors influencing upon the objective results of AMO AMCS operating.

The research is supported by the Russian Science Foundation (project № 17-11-01254).

References

1. V.N. Kalinin, B.V. Sokolov, International Journal of Difference Equations, **21**(5) (1985)
2. V.N. Kalinin, B.V. Sokolov, Automation and Remote Control, **48**(1-2) (1987)
3. I.N. Zimin, Yu.P. Ivanilov, Zh. Vychisl. Mat. Mat. Fiz., **11**(3) (1971)
4. M.Y. Okhtilev, B.V. Sokolov, R.M. Yusupov, *Intellectual Technology of Complex-Technical-Object Structural-Dynamic Monitoring and Control* (Moscow, "Nauka", 2014)
5. D. Ivanov, B. Sokolov, International Journal of Production Research, **51**(9) (2013)
6. D. Ivanov, B. Sokolov, Journal of Scheduling, **15**(2) (2012)
7. M. Athans, P.L. Falb. *Optimal control: An introduction to the theory and its applications* (New York San Francisco, CA, Sidney, NSW: McGraw-Hill 1966).
8. F. Werner, Y. Sotskov (Eds.), *Sequencing and Scheduling with Inaccurate Data*. (Nova Publishers, 2014)
9. E. Khmelnitsky, K. Kogan, O. Maimom, International Journal of Production Research, **10**(35) (1997)
10. J.G. Kimemia, T.I. Gershwin, IIE Transactions, **15** (1983)
11. K. Kogan, E. Khmelnitsky, International Journal of Production Research, **3** (1996)
12. K. Kogan, E. Khmelnitsky. *Scheduling: control-based theory and polynomial-time algorithms*. (Dordrecht, Kluwer 2000)
13. E.B. Lee, L. Markus, *Foundations of optimal control theory*. (Wiley & Sons, New York 1967)
14. D. Tabak, B.C. Kuo, *Optimal control by mathematical programming*. (Prentice Hall, NY 1971)
15. H. Ye, R. Liu, Transportation Research Part B: Methodological, **93** (Part A) (2016)
16. F.L. Chernousko, A.A. Lyubushin, Optimal Control Applications and Methods, **3**(2) (1982)
17. A. Alabyan, V. Zelentsov, I. Krylenko, S. Potryasaev, B. Sokolov, R. Yusupov, SPIIRAS Proceedings, **41**(4) (2015)
18. I.A. Krylov, F.L. Chernousko, Zh. Vychisl. Mat. Mat. Fiz., **12**(1) (1972)
19. F. Werner, Y. Sotskov (Eds.), *Sequencing and Scheduling with Inaccurate Data*. (Nova Publishers, 2014)
20. E. Khmelnitsky, K. Kogan, O. Maimom, International Journal of Production Research, **10**(35) (1997)
21. J.G. Kimemia, T.I. Gershwin, IIE Transactions, **15** (1983)
22. K. Kogan, E. Khmelnitsky, International Journal of Production Research, **3** (1996)
23. K. Kogan, E. Khmelnitsky. *Scheduling: control-based theory and polynomial-time algorithms*. (Dordrecht, Kluwer 2000)
24. E.B. Lee, L. Markus, *Foundations of optimal control theory*. (Wiley & Sons, New York 1967)
25. D. Tabak, B.C. Kuo, *Optimal control by mathematical programming*. (Prentice Hall, NY 1971)
26. H. Ye, R. Liu, Transportation Research Part B: Methodological, **93** (Part A) (2016)
27. F.L. Chernousko, A.A. Lyubushin, Optimal Control Applications and Methods, **3**(2) (1982)
28. A. Alabyan, V. Zelentsov, I. Krylenko, S. Potryasaev, B. Sokolov, R. Yusupov, SPIIRAS Proceedings, **41**(4) (2015)
29. I.A. Krylov, F.L. Chernousko, Zh. Vychisl. Mat. Mat. Fiz., **12**(1) (1972)