Conceptual and Formal Modelling of Monitoring Systems Structure-Dynamics Control

Viacheslav A. Zelentsov, Sergey Nemykin and Boris Sokolov

Abstract Elements of the methodological basis of the theory of monitoring automated (computer-aided) systems structure-dynamics control are proposed in the paper. This theory can be widely used in practice. It has an interdisciplinary basis provided by the classic control theory, operations research, artificial intelligence, systems theory and systems analysis. The proposed approaches were implemented in software prototypes. The software prototypes were developed to simulate control processes for space-facilities control system (SF CS). The unified description of various control processes allows synthesizing both technical and functional structures of SF CS simultaneously. The presented multiple-model complex, as compared with known analogues, has several advantages. It simplifies decision-making in SF CS structure dynamics management, for it allows seeking for alternatives in finite dimensional spaces rather than in discrete ones. The complex permits to reduce dimensionality of SF CS structure-functional synthesis problems in a real-time operation mode.

Keywords Monitoring automated (computer-aided) systems · Natural and technological objects · Structure-dynamics control

V.A. Zelentsov (✉) · B. Sokolov
St. Petersburg Institute of Informatics and Automation,
Russian Academy of Sciences (SPIIRAS), St. Petersburg, Russia
e-mail: v.a.zelentsov@gmail.com

B. Sokolov
e-mail: sokol@iias.spb.su

S. Nemykin
The Arsenal Design Bureau Named After M.V. Frunze Federal
State Unitary Enterprise, St. Petersburg, Russia

B. Sokolov
Saint Petersburg National Research University of Information Technologies,
Mechanics and Optics (ITMO), St. Petersburg, Russia

R. Silhavy et al. (eds.), *Automation Control Theory Perspectives in Intelligent Systems*, Advances in Intelligent Systems and Computing 466,
DOI 10.1007/978-3-319-33389-2_37

1 Introduction

The main object of our investigation is monitoring automated (computer-aided) systems (MS). Classic examples of MS are: MS for various classes of moving objects such as surface and air transport, ships, space and launch vehicles, etc., MS for geographically distributed heterogeneous networks, MS for flexible computerized manufacturing. In our paper, MS for the control of natural and technological objects (NTO) under a changing environment has been analysed [1–4].

As applied to MS we distinguish the following main types of structures: the structure of MS goals, functions and tasks; the organization structure; the technical structure; the topological structure; the structure of special software and mathematical tools; the technology structure (the structure of MS control technology) [1–3].

One of the main features of modern MS for NTO is the changeability of their parameters and structures due to objective and subjective causes at different stages of the MS life cycle. In other words, we always come across the MS structure dynamics in practice. Under these conditions, if we want to increase (stabilize) MS potentialities and capacity for work, structure control is to be performed [1].

By structure-dynamics control we mean a process of control inputs production and implementation for the MS transition from the current macro-state to a given one.

Structural and functional control in MS involves a change in system objectives; reallocation of functions, tasks, and control algorithms between different levels of the monitoring system, control of reserves; and transposition of MS elements and subsystems.

The problem of MS structure-dynamics control consists of the following groups of tasks: the tasks of structure-dynamics analysis of MS; the tasks of evaluation (observation) of structural states and MS structural dynamics; the problems of optimal program synthesis for structure-dynamics control in different situations.

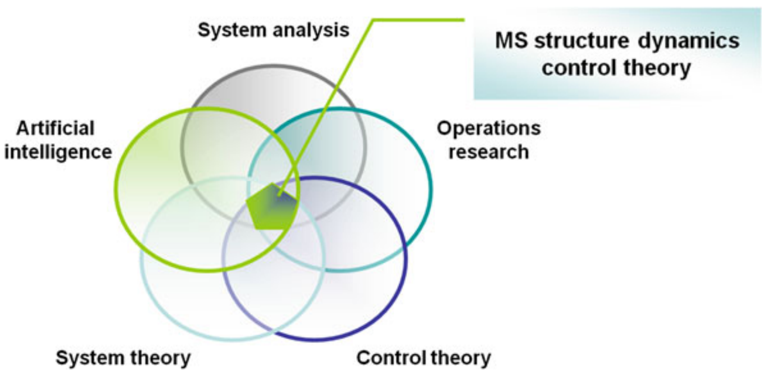

Fig. 1 The place of the theory of MS structure-dynamics control among the interdisciplinary investigations

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 [5–12]. The two last scientific directions will provide a structured definition of the structure-dynamics control problem instead of a weakly structured definition. These ideas are summarized in Fig. 1.

2 Conceptual Modelling of Structural Dynamics of Monitoring Systems for Natural and Technological Objects

Structural dynamics and control problems require innovative solutions and investigation of models to obtain them. The conceptual model represents concepts and relations between them. It is a descriptive model of a system based on qualitative assumptions about its elements and relations between them. The conceptual model is used to understand the system operation in a specific environment using natural language and naïve logic statements [10, 11]. Conceptual models play a key role in software application development. Moreover, the conceptual modelling is an important step in the simulation study.

With regard to NTO monitoring and control problems, conceptual modelling supposes the definition of a clearly formulated target set to various stages of object lifecycle under investigation; setting-up basic concepts in the area of concern and relations between these concepts; as well as definition borders between an investigated system and its environment.

The control system for natural and technological object monitoring may have a multi-level hierarchical structure. It may include control points, control stations, space and ground-based measurement equipment, and a telecommunication system. Each MS subsystem can be considered a control subsystem with respect to its inferior elements, on the one hand, and a controlled element with respect to ranking all subsystems, on the other hand.

For further specification of the structural dynamics and control problems let us introduce a subclass of control objects that represents artificially created or virtual objects (e.g., a set of devices) that could be moved in a real or virtual space and interact with other objects by information, material or energy exchange.

The object structure allows a wide interpretation, so these objects can be used for the description of natural objects, e.g., a part of land, forest area, water basins as well as ground and space facilities. They can be interpreted as different users who want to implement results of space-ground monitoring for their own goals [1, 2, 13–15]. In this case, interactions between objects could be of active or passive character.

The following basic concepts are used for the conceptual modelling of the structural dynamics of monitoring and control systems.

(a) "Operation" defines any action or a system of actions to accomplish a goal. Operations require resources, including information, material and energy exchange. Operation content is formulated by specifying parameters that define the operation results (e.g., volume, quality, and operational time), required resources as well as information, energy and material flows.
(b) Concept "Resources" includes materials, energy, production means, technical equipment, transportation tools, and finances. The operational time and personnel involved are defined as resources as well.
(c) Concept "Task" is used to describe the desirable result of actions for a specified time period. Tasks are derived from the goals and are characterised by quantitative data or parameters of the desirable results.
(d) "Flow" is characterised by current volume (level), transmission intensity, velocity of flow level variations, etc. Different types and kinds of flows are determined in real systems [3], e.g., material, energy and information flows; single-commodity and multi-commodity flows; continuous and discreet flows; homogeneous and heterogeneous flows; synchronous and asynchronous ones.
(e) "Structure" characterises stable links and interactions between system elements. The structure defines the integrity and composition of the system, and its organisation framework. Here, the following basic forms of structures [1–4, 16–18] are defined: structure of goals, functions and tasks; organisational structure; technical structure; topological structure; information support, hardware and software structure; structure of system basic elements and its subsystems at various stages of its lifecycle. Additionally, for various classes of relations between basic elements of MS, multiple constraints (i.e., space-time, technical, technological, energy, material and information) are specified for different application areas.

Furthermore, the main system function in any computer-aided control system belongs to the structure of the control subsystem that communicates with all other types of structures of other types, and each structure is related to MS objectives.

3 Formalisation of Structural Dynamics Control Problems for Monitoring Natural and Technological Objects

The structural dynamics and control problem for monitoring natural and technological objects includes the following main subgroups of tasks [1–4]: (1) control tasks of structural dynamics; (2) investigation tasks for structural dynamics under the condition of zero inputs (neither controlling nor perturbation inputs are considered); (3) investigation tasks for structural dynamics and structural control over nonzero inputs.

The problem is formulated as follows. The following data are assumed to be known: alternative system structures; an initial structural state; inputs affecting system elements and subsystems; space and time technical and technological constraints; a list of system measures to evaluate the quality of the control process, e.g., goal abilities, structural and spatial characteristics [1], and information technology abilities. Multiple criteria are introduced to evaluate structural dynamic states of the MS.

To solve the problem, first, the existence of the solution is analysed. Then controllability and stability of the MS and sensitivity of optimal solutions are investigated. Finally, the analysis, classification and sorting of MS multi-structural states are performed.

Let us introduce the following basic sets of objects and structures:

$\tilde{B} = B \cup \bar{B}$ is a set of objects, where B is a set of objects (subsystems, elements) of the MS, and $\overline{B}$ is a set of external objects interacting with the MS through information, energy or material exchange. $\tilde{C} = C \cup \bar{C}$ is a set of channels (hardware facilities) that are used by objects; D, Φ and P is a set of operations, resources and flows, correspondingly.

$G = \left\{G_\chi, \chi \in NS\right\}$ is a set of MS structural types, where the main structures are topologic (spatial) structure, technology (functional) structure, technical structure, software structures and organisational structure. To interconnect these structures, the dynamic alternative multi-graph is introduced:

$$G^t_\chi = \left\langle X^t_\chi, F^t_\chi, Z^t_\chi \right\rangle, \tag{1}$$

where χ denotes a structure type, $\chi \in NS = \{1, 2, 3, 4, 5, 6\}$, where 1 indicates a topologic structure, 2—a functional structure, 3—a technical structure, 4 and 5 indicate math and software structures, and 6 indicates an organisational structure, time point t belongs to a given set T; $X^t_\chi = \{x^t_{\chi l}, l \in L_\chi\}$ is a set of elements of structure G^t_χ that presents multi-graph vertices at time t; $F^t_\chi = \{f^t_{\langle \chi,l,l' \rangle}, l, l' \in L_\chi\}$ is a set of arcs of the multi-graph G^t_χ; the arcs represent relations between the multi-graph elements at time t; $Z^t_\chi = \{f^t_{\langle \chi,l,l' \rangle}, l, l' \in L_\chi\}$ is a set of parameters that numerically characterise these relations.

The graphs of different types are interdependent; thus, for the structural control of each particular task the following mapping should be constructed:

$$M^t_{\langle \chi,\chi' \rangle} : F^t_\chi \rightarrow F^t_{\chi'}. \tag{2}$$

The compositions of the mappings can also be constructed at time t:

$$M^t_{\langle \chi,\chi' \rangle} = M^t_{\langle \chi,\chi_1 \rangle} \circ M^t_{\langle \chi,\chi_2 \rangle} \circ \cdots \circ M^t_{< \chi'',\chi' >}. \tag{3}$$

A multi-structural state is defined as follows:

$$S_\delta \subseteq X^t_1 \times X^t_2 \times X^t_3 \times X^t_4 \times X^t_5 \times X^t_6, \quad \delta = 1, \ldots, K_\Delta \tag{4}$$

Thus, we obtain a set of MS multi-structural states:

$$S = \{S_\delta\} = \{S_1, \ldots, S_{K_\Delta}\}. \tag{5}$$

Feasible transitions from one multi-structural state to another one can be expressed as:

$$\Pi^t_{\langle\delta,\delta'\rangle} : S_\delta \to S_{\delta'}. \tag{6}$$

It is assumed that each multi-structural state at time $t \in T$ is defined by a composition (3). Hence, the problem is defined as the selection of a multi-structural state $S^*_\delta \in \{S_1, S_2, \ldots, S_{K_\Delta}\}$ and transition sequence (composition) $\Pi^{t_1}_{\langle\delta_1,\delta_2\rangle} \circ \Pi^{t_2}_{\langle\delta_2,\delta_3\rangle} \circ \Pi^{t_f}_{\langle\delta',\delta\rangle}\left(t_1 < t_2 < \cdots < t_f\right)$. The results of the selection can be presented as an optimal programme for MS transition from a given structural state to a specified one.

The interpretation of the object structural dynamics process is given in Fig. 2. Multi-graphs $G^{t_1}_\chi$ and $G^{t_1}_{\chi_1}$ describe dynamics of functional and technical structures, where $\Gamma^{t_1}_\chi$ and $\Gamma^{t_1}_{\chi_1}$ present object functional and technical structures at moment t_1.

Our investigations have shown that the development of the programme for optimal structural dynamics and control in the monitoring systems includes two stages. At the first stage, a set of feasible multi-structural macro-states is generated, so the structural and functional synthesis of a new system is performed in accordance with an actual or forecasted state of the control object. At the second stage, a single macro-state is selected, and an adaptive plan that specifies the transition of the monitoring system to the selected macro-state as well as provides system stable operations in the intermediate macro-states is designed. The construction of the transition programme is formulated as a multi-level multi-stage optimisation problem [1].

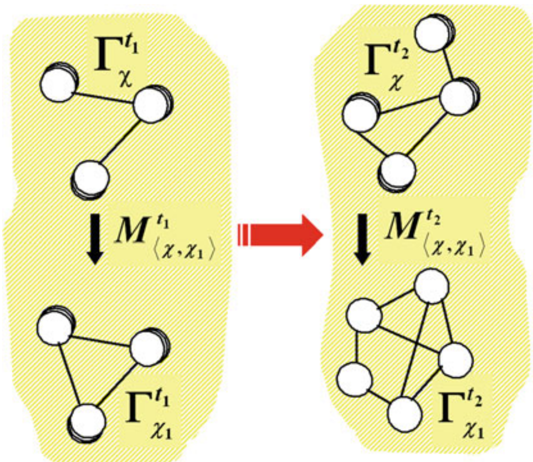

Fig. 2 Structural changes in the system

Well-known approaches to solving the problem are based on the PERT description of scheduling and control problems and the process dynamic interpretation [7, 10, 19]. The implementation of these approaches results in algorithmic and computational difficulties caused by high dimension, non-linearity, non-stationary and uncertainty of appropriate models.

4 Modern Optimal Control Theory Application in Monitoring and Control of Natural and Technological Objects

Let us introduce the following modification of the dynamic interpretation of monitoring and control processes. The main idea of the model simplification is to implement non-linear technological constraints in sets of feasible 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 section method [1–4, 14, 15, 20]. Furthermore, interval constraints instead of relay ones can be used. Nevertheless, the control inputs take on Boolean values caused by the linearity of differential equations and convexity of a set of alternatives. The proposed substitution enables the use of fundamental scientific results of the modern control theory in various monitoring and control problems of natural and technological systems.

As provided by the concept of a multiple model description, the proposed general model includes the dynamic models of [1–5]: system motion control (M_g model); channel control (M_k model); operation control (M_o model); flow control (M_n model); resource control (M_p model); operational parameter control (M_e model); structural dynamic control (M_c model); and auxiliary operation control ($M\nu$ model).

Procedures of structural dynamics problem solution depend on the variants of transition and output function (operators) implementation. Various approaches, methods, algorithms and procedures of a coordinated choice through complexes of developed heterogeneous models have been developed by now.

The control problem of structural dynamics of monitoring and control systems has some specific features in comparison with classical 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 have been studied.

These variants are associated with the tasks of the model quality selection and reduction of its complexity. Decision-makers can select an appropriate level of the model thoroughness in the interactive mode. The level of thoroughness depends on the input data, external conditions, and required level of solution validity.

Classification and analysis of perturbation factors having an influence upon operation of MS were performed. Variants of perturbation-factors descriptions were considered for MS models. In our opinion, a comprehensive simulation of uncertainty factors with all adequate models and forms of description should be used during investigation of MS. Moreover, the abilities of MS 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 MS functioning should include the following phases [1, 2, 4]:

(a) Determining scenarios for MS environment, particularly determining of extremely situations and impacts that can have catastrophic results.
(b) Analysis of MS 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.
(c) Repetition of item b for the main extremely situations and estimation of guaranteed results of MS operation in these situations.
(d) Computing of general (integral) efficiency measures of MS structure-dynamics control.

Algorithms of parametric and structural adaptation for MS 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 proposed interpretation of MS structural dynamics and its control processes provides advantages of applying the modern optimal control theory for the analysis and synthesis of monitoring and control systems. During the performed investigations, the main classes of structural dynamics problems have been defined. They are as follows: the analysis of structural dynamics of mobile objects and its diagnosis; observation, multi-layer control problems; synthesis of generalised states of monitoring and control systems; generation of optimal transition programmes providing the transition from a given system structural state to feasible (or optimal) one.

Methodology for structural dynamics control developed in [1–4, 13–16, 20] includes the methodology of a general system analysis and the modern optimal control theory for monitoring and control systems with re-configurable structures. As stated above, the solutions are based on principles of goal-programmed control, external complement, multi-scale variety, multiple-models and multi-criteria decision analysis [9–12]. The dynamic interpretation of the structural control allows applying known results from the theory of dynamic systems (in particular, stability and sensitivity analysis in optimal control) to the analysis of monitoring and control systems of natural and technological objects (see Table 1).

Table 1 Practical use of theoretical results in the analysis of monitoring systems

№	Qualitative analysis of space facility control processes	Practical implementation of the results
1	The existence of the solution in a control problem	Adequacy analysis of the system process description in control models
2	Controllability and attainability conditions for a control system	Reliability analysis of the planning time interval (major factors of object goal setting and IT abilities)
3	Conditions for uniqueness of optimal controls in scheduling problems	Analysis of the possibility to obtain optimal schedules for MS functioning
4	Necessary and sufficient optimality conditions for control problems	Preliminary analysis of an optimal control structure and scheduling algorithms
5	Conditions for solution reliability and sensitivity	Reliability and sensitivity analysis of control processes regarding perturbation effects and alterations in a system structure

5 Summary

Methodological and methodical basis of the theory of MS structure-dynamics control has been developed. 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 an interdisciplinary basis provided by the classic control theory, operations research, artificial intelligence, systems theory and systems analysis. The dynamic interpretation of MS reconfiguration process provides strict mathematical base for complex technical-organizational problems that were never formalized before and have high practical importance. The proposed approaches were implemented in software prototypes. The software prototypes were developed to simulate control processes for space-facilities control system (SF CS). The unified description of various control processes allows synthesizing both technical and functional structures of SF CS simultaneously. The presented multiple-model complex, as compared with known analogues, has several advantages. It simplifies decision-making in SF CS structure dynamics management, for it allows seeking for alternatives in finite dimensional spaces rather than in discrete ones. The complex permits to reduce dimensionality of SF CS structure-functional synthesis problems to be solved in a real-time operation mode. Moreover, it enables us to establish the dependence relation between control technology applied to spacecrafts and the results of their use according to the main goal. 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. This statement is exemplified by an analysis of SF CS information-technological abilities and goal abilities. All theoretical results and conclusions of this research are explored and validated via simulation on the basis of the prototype software developed by the authors.

The MS structure-dynamics control methodological and methodical basis was implemented in research project 2.1/ELRI -184/2011/14 “Integrated Intelligent Platform for Monitoring the Cross-Border Natural-Technological Systems” (INFROM) as part of “Estonia-Latvia-Russia Cross-Border Cooperation Programme within European Neighborhood and Partnership Instrument 2007-2013”.

Acknowledgements The research is supported by the Russian Foundation for Basic Research (grants 15-07-08391, 15-08-08459, 16-57-00172-Бел_а, 16-07-00779, 16-08-01068, 16-07-01277), grant 074-U01 supported by Government of Russian Federation, Program “5-100-2020” supported by Government of RF, Department of nanotechnologies and information technologies of the RAS (project 2.11).

References

1. Okhtilev, M.Y., Sokolov, B.V., Yusupov, R.M.: Intellectual Technologies of Monitoring and Controlling the Dynamics of Complex Technical Objects, 409p. Nauka, Moskva (2006)
2. Ivanov, D., Sokolov, B., Kaeschel, J.: A multi-structural framework for adaptive supply chain planning and operations with structure dynamics considerations. Eur. J. Oper. Res. **200**(2), 409–420 (2010)
3. Ivanov, D.A., Sokolov, B.V.: Adaptive Supply Chain Management, 269p. Springer, London (2010)
4. Sokolov, B., Ivanov, D., Fridman, A.: Situational modelling for structural dynamics control of industry-business processes and supply chains. In: Sgurev, V., Hadjiski, M., Kacprzyk, J. (eds.) Intelligent Systems: From Theory to Practice, pp. 279–308. Springer, London (2010)
5. Norenkov, I.P.: The approaches to designing of automation systems. Inf. Technol. **2**, 2–9 (1998)
6. Ackoff, R.L.: The Art of Problem Solving. Wiley-Interscience, New York (1978)
7. Aframchuk, E.F., Vavilov, A.A., Emel’yanov S.V., et al.: In: Emel’yanov, S.V. (ed.) Technology of System Modelling. Mashinostroenie, Moscow (1998)
8. Casti, J.L.: Connectivity, Complexity and Catastrophe in Large-Scale Systems, 203p. Wiley-Interscience, New York (1979)
9. Gigch, J.: Applied General Systems Theory. Harper and Row, New York (1978)
10. Peregudov, F.I., Tarrasenko, F.P.: Introduction to Systems Analysis. Vysshaya Shkola, Moscow (1989)
11. Peschel, M.: Modellbilding für Signale und Systeme. Verlag Technik, Berlin (1978)
12. Shannon, R.E.: Systems Simulation, 387p. Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1975)
13. Romanovs, A., Lektauers, A., Soshko, O., Zelentsov, V.: Models of the monitoring and control of natural and technological objects. Inf. Technol. Manage. Sci. **16**, 121–130 (2013)
14. Merkuryev, Y., Sokolov, B., Merkuryeva, G.: Integrated intelligent platform for monitoring the cross-border natural-technological systems. In: Proceedings of the 14th International Conference on Harbour Maritime and Multimodal Logistics M&S, HMS 2012. 19–21 Sept 2012, Vienna, Austria, pp. 7–10 (2012)
15. Merkuryeva, G.V., Merkuryev, Y.A., Lectauers, A., Sokolov, B.V., Potryasaev, S.A., Zelentsov, V.A.: Advanced river flood monitoring, modeling and forecasting. J. Comput. Sci. **10**, 77–85 (2015)
16. Sokolov, B.V., Okhtilev, M.Y., Zelentsov, V.A., Maslova, M.A.: The Intelligent monitoring technology based on integrated ground and aerospace data. In: Proceedings of the 14th

International Conference on Harbour Maritime and Multimodal Logistics M&S, HMS 2012. 19–21 Sept 2012, Vienna, Austria, pp. 112–117 (2012)
17. Arnott, D.: Decision support systems evolution: framework, case study and research agenda. Eur. J. Inf. Syst. **13**(4), 247–259 (2004)
18. Intelligent Systems in Cybernetics and Automation Theory. In: Proceedings of the 4th Computer Science On-line Conference 2015 (CSOC2015), Vol 2: Intelligent Systems in Cybernetics and Automation Theory. Advances in Intelligent Systems and Computing, vol. 348 (2015)
19. Skurikhin, V.I., Zabrodskii, V.A., Kopeichenko, Yu.V.: Adaptive Control Systems for Manufacturing. Mashinostroenie, Moscow (1989)
20. Petuhova, J., Lektauers, A., Zelentsov, V.: Classification of natural-technogenic objects in remote sensing applications. In: Proceedings of the 14th International Conference on Harbour Maritime and Multimodal Logistics M&S, HMS 2012. 19–21 Sept 2012, Vienna, Austria, pp. 91–95 (2012)