VERSITA

Information Technology and Management Science

doi: 10.2478/itms-2013-0001

2013 / 16

Multi-model Description of Monitoring and Control Systems of Natural and Technological Objects

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Abstract **– The paper discusses theoretical foundations of a formal description of monitoring and control systems (MTSs) that are used for the monitoring and control of various natural and technological systems (NTSs). The performed state-of-the-art analysis has demonstrated that the theory, methods and techniques related to the application of various types of models, such as mathematical, logical-algebraic, logical-linguistic, simulation and combined ones, for describing NTO MCS are widely used. On that basis, a conceptual description of NTO monitoring and control systems is proposed. It is based on a concept of NTO MCS multi-model description. The proposed general model includes particular dynamic models that describe motion control, channel control, operation control, flow control, resource control, operation parameter control, structure dynamic control, and auxiliary operation control of the considered monitoring and control system. The proposed interpretation of NTO MCS structure dynamics control processes provides advantages of applying the modern optimal control theory to NTO MCS analysis and synthesis.**

Keywords **– Models, monitoring and control systems, multi-criteria analysis, multi-model description, natural and technological objects**

I. Introduction

Within the analysis of NTS structure and dynamics, two types of systems have been researched – artifacts (technical-technological objects) and natural-ecological objects. For monitoring, control and forecasting different methodology and decision models are used – the analysis of satellite imagery, hydrologic data analysis, integration of remote sensing images, hydrologic data analysis etc. Some objects have similar models of operation both under normal and critical conditions, whereas others have unique behaviour models.

Artifacts include a variety of objects that are manmade or pertaining to a process or substance created by human technology, for example, energy production buildings (hydroelectric power stations, gas storages and wind farms), factories and manufactories (bakery, beverages, construction material, steel and other metal material, textile and garment, wood), infrastructure (bridges, bus terminals, dams, pipes, railroads, roads and train stations). In this research field, most important problems that are needed to be monitored are building settlement, shift of the soil, dilapidation, communications damage, power production, gas emission, wastewater, road wear and vibration damage.

NTSs are monitored using different remote sensing techniques for the monitoring and analysis of such natural disasters as earthquakes, volcanic eruptions, tsunamis, hurricanes, destructive cyclone, landslides, and floods. Within the analysis of NTS structure and dynamics, research was conducted on natural and ecological NTS – flood mapping systems, wildfire monitoring systems, land use monitoring systems, automatic detection of coastline change monitoring systems and forest land cover changes.

II. General Regulations

Our investigations are mainly focused on natural and technical-technological objects (NTOs) and their monitoring and control systems (MCSs). These objects and systems belong to the class of complex systems. By complex systems we mean systems that should be studied through polytypic models and combined methods. In some instances, investigations of complex systems require multiple methodological approaches, many theories and disciplines, as well as carrying out interdisciplinary researches. Different aspects of complexity can be considered to distinguish between a complex system and a simple one, for example: structure complexity, operational complexity, complexity of behaviour choice and complexity of development.

Classic examples of complex systems are: control and monitoring systems for various classes of moving objects, such as surface and air transport, ships, space and launch vehicles, etc., geographically distributed heterogeneous networks and flexible computerized manufacturing.

One of the main features of modern NTO MCSs (which are the main objects of our investigations) is the changeability of their parameters and structures due to objective and subjective causes at different stages of the NTO MCS life cycle. In other words, we always come across the NTO MCS structure dynamics in practice [1]-[5], [13]-[15], [43]-[45]. Under the existing conditions, in order to increase (stabilize) NTO MCS potentialities and capacity for work, a structure control (including control of NTO MCS structure reconfiguration) has to be performed.

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

The main features and difficulties of the problems belonging to the class above are as follows: optimal control programs for NTO MCS main elements and subsystems can only be implemented when the list of functions and algorithms for control and information processing in these subsystems and elements is known [36]-[39]. In its turn, the distribution of the functions and algorithms among the NTO MCS elements and subsystems depends upon the control laws concerning these elements and subsystems [30]-[33]. The described contradictory situation is complicated by the changes of NTO

MCS parameters and structures due to different causes during the NTO MCS life cycle.

At present, the class of problems under review is not examined thoroughly enough. New theoretical and practical results were obtained in the following ways of the investigation:

- synthesis of the NTO MCS technical structure for the known laws of NTO MCS functioning (the first way) [1]-[5], [13], [16], [18]-[21], [35];
- synthesis of the NTO MCS functional structure; in other words, the synthesis of the control programs for the NTO MCS main elements and subsystems under the condition that the NTO MCS technical structure is known (the second way) [21]-[31], [50]-[52];
- synthesis of programs for NTO MCS construction and development without taking into account the periods of parallel functioning of the actual and the new NTO MCSs (the third way) [36]-[39];
- parallel synthesis of the NTO MCS technical structure and the functional one (the forth way) [13]-[16], [43]-[45].

III. Conceptual Description of NTO MCS

Let us outline the main results and state of the art within the mentioned ways of investigations. A great deal of work regarding various problems of the NTO MCS technical structure synthesis is accomplished worldwide.

The synthesis (choice) of NTO MCS structure (structures) was usually reduced to the following general optimization problem [36]-[39]:

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

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

$$\bar{\pi} \subset \bar{P}, \quad (2)$$

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

$$\bar{m} \subset \bar{M} \cdot \quad (4)$$

where $\bar{P}$ is a set of feasible control principles (algorithms); $\bar{F}$ is a set of interrelated functions (tasks, operations) that may be performed by the system. For each subset $\bar{\pi} \subset \bar{P}$ there is 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 NTO MCS possible elements, such as information processing and transmitting 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 conditions.

The modifications of the considered problem will concern the aspects of uncertainty and multi-criteria decision-making. The complexity of the synthesis problem (1)-(4) is mostly caused by its high dimension, i.e., by the great 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 feature complicating the problem is the integer-valued variables. The characteristics of the structure synthesis problem were thoroughly taken into account in [21]-[31], [50]-[55]. The authors proposed a hierarchical complex of analytical and simulation interconnected models as a result of decomposition and aggregation.

Various studies of structure synthesis problems confirm [43]-[45] that if NTO MCS elements and subsystems cannot manage peak data traffic, then the law of element functioning ought to be optimized (the second way of investigation).

The problems of function determination, algorithms and functioning law synthesis for hierarchical systems have been investigated by many researchers both in Russia and worldwide. The laws and algorithms of hierarchical system functioning, the problems of functional synthesis have been investigated for more than 40 years within the upcoming control theory [21]-[31]. Thus, it is reasonable to consider the particular scope of these investigations in accordance with the aims of our research. Here we view the problems of NTO MCS structure dynamics control. In the works [7]-[9], [50]-[52] the systems under consideration were called reconfigurable NTO MCS. General treatment of the term “reconfiguration” enables us to use more constructive concepts of “structure control” and “structure dynamics control”.

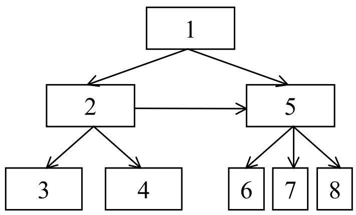

Fig. 1. Classification diagram of reconfigurable systems

Figure 1 from [7] shows the classification of NTO MCS, for which the concept of structure dynamics control was used. The numbers denote the following classes of the systems:

1 – NTO MCS with controllable structure dynamics;
2 – basic reconfigurable NTO MCS;
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 (intelligent) control.

In [50]-[51] the typical structure of a basic reconfigurable NTO MCS was introduced. The control problems for such systems were investigated most thoroughly in [7-9]; interesting fundamental and practical results were obtained in this field.

The investigations towards creation and application of integrated and especially intellectual (intelligent) systems are still at the initial phase. Various systems of multiplemode control have already been used: systems with coordination; multi-structural systems; two-region follow-up systems; control systems with changing configuration; logical-dynamic systems; multi-functional systems of automatic control; and numerous classes of systems with variable structures.

The investigations of the alternative-control and multiple-mode control systems have brought scientific and practical results comparable with those obtained for the basic reconfigurable NTO MCSs.

The systems of fault-tolerant self-recovering control can be formally treated as alternative-control and multiple-mode control systems. The particular class was formed due to the following features:

- necessity of rapid self-recovery in emergency states;
- strict requirements for exactness of state diagnostics in the case of incomplete testing;
- additional time for self-recovery of NTO MCS with a controllable structure.

The fault-tolerance approach approved in networks is widely used in the considered systems at all stages of their life cycle.

To create and put into practice fault-tolerant self-recovering control systems, the following stages should be passed through:

- survivability analysis of NTO MCS subsystems;
- analysis and design of tolerant systems;
- simulation, bench and full-scale tests of considered NTO MCS.

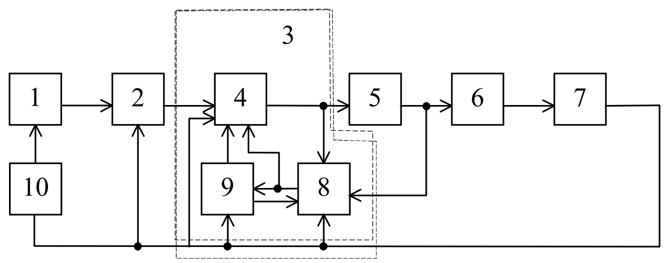

Fig. 2. Example of an aerodynamic aircraft reconfiguration system

Figure 2 from [7]-[9] shows a block diagram of an intelligent automated control system (IACS) with aerodynamic aircraft reconfiguration providing the active role of a pilot. The blocks express the following objects: 1 – the module of pilot's commands; 2 – the module of standard-mode flight control; 3 – the combined block of reconfiguration control; 4 – the active regulator and the module of control merge; 5 – the block of drives; 6 – the module implementing an aircraft aerodynamic model; 7 – the module implementing a motion model; 8 – the module of failure detection and localization; 9 – the module of control effectiveness evaluation; 10 – the module of aircraft flight monitoring.

In the case of drive faults or controller damage, module 8 detects and isolates damage, module 9 evaluates the abilities of acting control elements to produce necessary forces and moments providing the standard-mode flight. Module 4 recalculates control inputs for the drives, so control reconfiguration and self-recovery can be achieved. A survey of the scientific and practical results obtained for the systems of considered class is presented in [7]-[9], [50]-[52].

The growth of NTO MCS complexity and the increasing importance of uncertainty factors at all stages of NTO MCS functioning necessitate new approaches to control system construction.

The most perspective approach, namely, intellectual and intelligent control, has arisen within artificial intelligence investigations [10], [11], [46]-[52]. The intellectual control systems, contrary to the intelligent ones, are assumed to solve the problems of goal setting and model development. Hence, new intelligent information technologies (IITs) extend traditional analytical and simulation modelling of complex technical objects. IITs use data-driven non-algorithmic computing with intrinsic parallelism and non-determinism.

IITs include [50]-[52]: Technologies of knowledge-based and expert systems; Fuzzy logic technologies; Technologies of artificial neural networks; Case-based reasoning (CBR technologies); Technologies of natural language systems and ontology; Technologies of content-addressable memory; Technologies of cognitive mapping and operational coding; Technologies of evolutionary modelling.

An application of IITs to monitoring and control of power systems (PS) induces three lines of investigations:

- development of modelling, algorithmic, and informational tools for knowledge representation and processing;
- development of knowledge representation models in the interests of new intelligent information technologies;
- construction of new applications accumulating results of two previous items.

A recent classification of knowledge representation models is shown in Fig. 3.

It is quite reasonable to arrange the models in three groups, namely, declarative, procedural, and special (combined) ones (see Fig. 4).

Semantic networks, frames and production systems constitute the basis of general knowledge representation tools. A rapid progress of new constructions, such as multi-agent asynchronous decentralized systems and underdetermined models, can be currently detected.

These constructions are efficient for both computational and logical problems and gradually replace production languages.

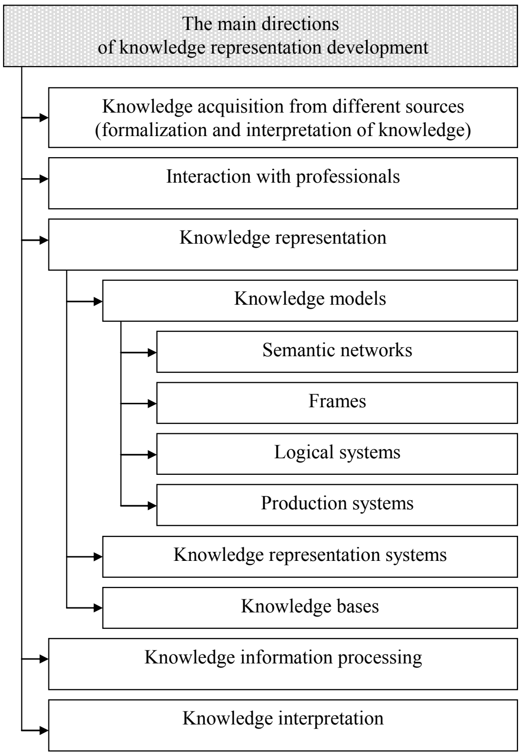

Fig. 3. Classification of knowledge representation NTO MCS models

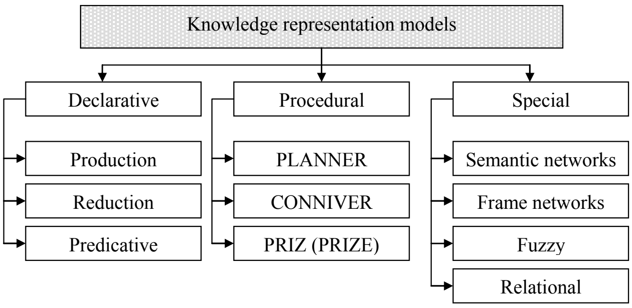

Fig. 4. Groups of knowledge representation NTO MCS models

There are the following tendencies in the influence of new knowledge representation models upon the IIT.

1) A transition from classical calculations to a decentralized asynchronous parallel data-driven computational process.

2) Active object technologies. These technologies extend the object-oriented programming to a development framework for the construction of autonomous interacting active objects.

3) The priority of models rather than of algorithms. Some predictions foretell that in 10-15 years algorithms will go the way of assemblers and object coding.

4) Parallelism. The complexity of imperative program multi-sequencing up to now reduces the development of multi-processor architectures. Within the IIT, the parallelism is not a problem but a natural feature.

The above-mentioned tendencies confirm the significance of new knowledge representation models.

Possible ways of inter-model integration for intelligent information technologies are summarized in Table i (see [53]).

Finally, let us briefly consider the third and the forth ways of structure synthesis mentioned at the beginning of the section. There are several studies devoted to theoretical bases of NTO MCS development control [37]-[43]. Nevertheless, the dynamics of environment at the NTO MCS operating stage when the time factor is rather important is not considered thoroughly enough [37]-[46]. The results of the investigations under consideration should be summarized to construct the theory of structure dynamics control.

Let us introduce the following modification of dynamic interpretation of operation monitoring and control processes in NTO MCS. The main idea of model simplification is to implement non-linear technological constraints in sets of allowable control inputs rather than in the right parts of differential equations. In this case, Lagrangian coefficients, keeping the information about technical and technological constraints, are defined via the local section method. Furthermore, interval constraints instead of relay ones could be used.

TABLE I

HYBRID MODEL SYSTEMS

The method of computational intelligence and its applications	**Combination**		
	two methods	**three methods**	**four methods**
Fuzzy-deduction systems. Fzelips 6.04 Matlab	Fuzzy neural networks	Fuzzy probabilistic neural networks	Fuzzy probabilistic neural networks with the genetic algorithm (*)
Neural networks. Neurosolution 3.0	Fuzzy-and-probabilistic deduction systems Guru	Probabilistic neural networks with the genetic algorithm (*)	–
Probabilistic reasoning. Expert system Prospector	Fuzzy-deduction system with genetic algorithm	Fuzzy neural networks with genetic algorithm. Fungen 1.2	–
Genetic algorithms. Professional Version 1.2	Probabilistic neural networks Trajan 2.1 Matlab	Fuzzy-and-probabilistic deduction systems with the genetic algorithm (*)	–
NeuroGenetic Optimizer	Neural networks with the genetic algorithm	–	–
	Probabilistic deduction systems with the genetic algorithm	–	–

(*) A hybrid is not constructed or described

Nevertheless, the control inputs take on Boolean values caused by the linearity of differential equations and convexity of the set of alternatives. The proposed substitution enables the use of fundamental scientific results of the modern control theory in various NTO MCS monitoring and control problems (including scheduling theory problems). As provided by the concept of NTO MCS multiple model description, the proposed general model includes the following particular dynamic models: dynamic model of NTO MCS motion control (Mg model); dynamic model of NTO MCS channel control (Mk model); dynamic model of NTO MCS operation control (Mo model); dynamic model of NTO MCS flow control (Mn model); dynamic model of NTO MCS resource control (Mp model); dynamic model of NTO MCS operation parameter control (Me model); dynamic model of NTO MCS structure dynamic control (Mc model); and dynamic model of NTO MCS auxiliary operation control (M_v model).

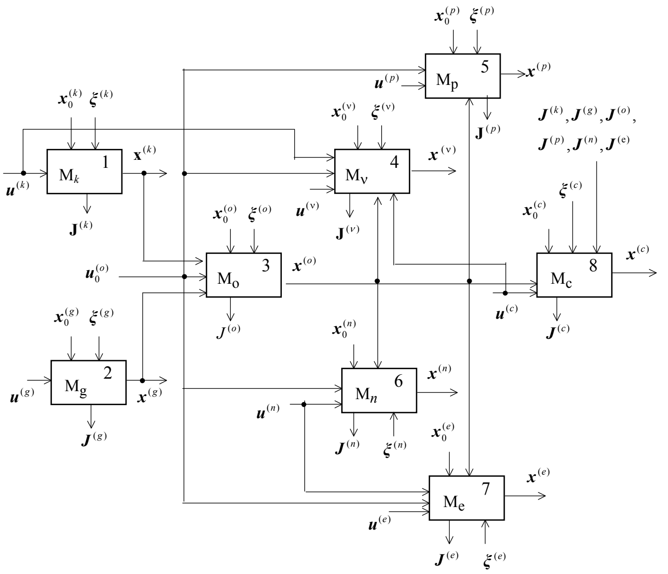

Fig. 5. The groups of knowledge representation NTO MCS models

Figure 5 illustrates a possible interconnection of the models. Procedures of structure dynamics problem solving depend on the variants of transition and output function (operators) implementation. Various approaches, methods, algorithms and procedures of coordinated choice through complexes of heterogeneous models have been developed by now. The NTO MCS structure dynamics control problem has some specific features in comparison with classic optimal control problems.

The first feature is that the right parts of the differential equations undergo discontinuity at the beginning of interaction zones. The considered problems can be regarded as control problems with intermediate conditions.

The second feature is the multi-criteria nature of the problems.

The third feature is concerned with the influence of uncertainty factors.

The fourth feature is the form of time-spatial, technical, and technological non-linear conditions that are mainly considered in control constraints and boundary conditions. On the whole, the constructed model is a non-linear non-stationary finite-dimensional differential system with a re-configurable structure. Different variants of model aggregation were proposed. These variants produce a task of model quality selection that is the task of model complexity reduction. Decision-makers can select an appropriate level of model thoroughness in the interactive mode. The level of thoroughness depends on: input data, external conditions, and required level of solution validity.

IV. Conclusion

The proposed interpretation of NTO MCS structure dynamics control processes provides advantages of applying the modern optimal control theory to NTO MCS analysis and synthesis. During the performed investigations, the main classes of NTO MCS structure dynamics problems have been defined. These problems include: MCS structure dynamics analysis problems; MCS structure dynamics diagnosis, observation, multi-layer control problems; problems of MCS generalized structural state synthesis and the choice problems of optimal transition programs providing the transition from a given NTO MCS structural state to an allowable (optimal) structural state. Methodological and methodical foundations for the theory of structure dynamics control have been developed that include: the methodologies of the generalized system analysis and the modern optimal control theory for NTO MCS with re-configurable structures. The methodologies find their concrete reflection in the corresponding principles. The main principles are: *the principle of goal programmed control; the principle of external complement; the principle of necessary variety; the principles of multiple model and multi-criteria approaches; the principle of new problems*. The dynamic interpretation of structure dynamics control processes allows application of results, previously received in the theory of dynamic system stability and sensitivity, to NTO MCS analysis problems.

Acknowledgments

The described research has been supported by the Russian Foundation for Basic Research (grants 11-08-01016, 11-08-00767, 12-07-13119-ofi-m-RGD, 12-07-00302, 13-07-00279, 13-08-00702, 13-08-01250), by the Department of Nanotechnologies and Information Technologies of the RAS (project 2.11), and by ESTLATRUS projects 1.2./ELRI-121/2 011/13 "Baltic ICT Platform" and 2.1/ELRI-184/2011/14 "Integrated Intelligent Platform for Monitoring the Cross-border Natural-Technological Systems" as part of the Estonia-Latvia-Russia Cross-border Cooperation Program within European Neighbourhood and Partnership Instrument 2007–2013.

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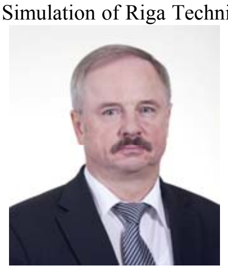

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Boriss Sokolovs, Mihails Ohtiļevs, Semjons Potrjasajevs, Jurijs Merkurjevs. Dabas un tehnoloģisko objektu monitoringa un daudz-modeļu vadības sistēmu apraksts

Rakstā tiek apspriesti tādu monitoringa un vadības sistēmu formālās aprakstīšanas teorētiskie pamati, ko lieto dažādu dabas un tehnoloģisko objektu monitoringa un vadības uzdevumu risināšanai. Šeit monitoringa un vadības objekti ietver sevī, no vienas puses, dabas objektus un procesus, kas ir būtiski svarīgi dotajā teritorijā realizējamo sociālo un saimniecisko procesu īstenošanai (piemēram, plūdi, meža ugunsgrēki, krastu erozija, zemes lietošana, meža izciršana un atjaunošana, akvatorijas piesārņošana), tā arī sarežģītus tehnoloģiskus objektus un procesus (piemēram, hidro- un siltumelektrostacijas, transporta mezgli, tilti, cauruļvadi, ražošanas procesi). Tika veikta šīs zināšanu sfēras stāvokļa analīze, kas nodemonstrēja dažādu modeļu klašu teorijas, metožu un algoritmu pielietošanu dabas un tehnoloģisko objektu monitoringa un vadības sistēmu aprakstīšanai. Piemēram, šim klašu lokam pieder analītiski, loģiski-algebriski, loģiski-lingvistiski, simulācijas un kombinētie modeļi. Minētās analīzes rezultātā tiek piedāvāts dabas un tehnoloģisku objektu monitoringa un vadības sistēmu konceptuāls modelis, kas balstās uz dabas un tehnoloģisku objektu monitoringa un vadības sistēmu daudzmodeļu aprakstīšanas koncepciju. Piedāvātais monitoringa un vadības sistēmu vispārīgs modelis ietver sevī apskatāmas monitoringa un vadības sistēmas atsevišķus dinamiskus modeļus, kas apraksta tās kustību, kanālus, operāciju veikšanu, plūsmas, resursus, parametrus, struktūru un papildu operāciju vadību. Dotā formālisma pielietošanas rezultātā dabas un tehnoloģisku objektu monitoringa un vadības sistēmu dinamikas aprakstīšanai, rodas iespēja pielietot mūsdienu vadības teorijas metodes un līdzekļus, lai risinātu dabas un tehnoloģisku objektu monitoringa un vadības sistēmu analīzes un sintēzes uzdevumus.

Борис Владимирович Соколов, Михаил Юрьевич Охтилев, Семен Алексеевич Потрясаев, Юрий Анатольевич Меркурьев. Многомодельное описание систем мониторинга и управления природными и технологическими объектами

В статье рассматриваются теоретические основы формального описания систем мониторинга и управления, используемых для решения задач мониторинга и управления различными природными и технологическими объектами. При этом рассматриваемые объекты мониторинга и управления включают как объекты и процессы природного характера, существенно важные для реализации осуществляемых на данной территории социальных и хозяйственно-экономических процессов (например, разливы рек, лесные пожары, эррозия берегов, землепользование, вырубка лесов, загрязнение акваторий), так и сложные технологические объекты и процессы (например, гидро- и тепловые електростанции, транспортные узлы, мосты, трубопроводы, производственные процессы). Выполненный анализ современного состояния данной области знаний продемонстрировал широкое применение для описания систем мониторинга и управления природными и технологическими объектами теории, методов и алгоритмов, относящихся к различным классам моделей. В частности, в числе указанных классов присутствуют аналитические, логико-алгебраические, логико-лингвистические, имитационные и комбинированные модели. На основе указанного анализа предложена концептуальная модель систем мониторинга и управления природными и технологическими объектами, базирующаяся на концепции многомодельного описания систем мониторинга и управления природными и технологическими объектами. Предложенная обобщенная модель систем мониторинга и управления включает частные динамические модели управления движением, каналами, выполнением операций, потоков, ресурсов, параметрами, структурой и вспомогательными операциями рассматриваемой системы мониторинга и управления. В результате использования данного формализма для описания динамики поведения систем мониторинга и управления природными и технологическими объектами возникает возможность применения методов и средств современной теории управления для решения задач анализа и синтеза систем мониторинга и управления природными и технологическими объектами.