

# INTEGRATED MODELING OF STRUCTURE-DYNAMICS CONTROL IN COMPLEX TECHNICAL SYSTEMS

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## ABSTRACT

A concept of an active mobile object as a typical element of complex technical systems (CTS) with dynamic structures is introduced. The processes of CTS structure-dynamics control are described via a system of analytical and simulation models. General principles of joint use of these models within a simulation system were worked out. The problems of parametric and structural adaptation of the models are discussed. Theoretical results were implemented in program prototypes of computer-aided structure-dynamics control.

## INTRODUCTION

The main subject of our investigation is complex systems. That is the 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, and 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 behavior choice, complexity of development (Klir 1985).

Classic examples of complex systems are: control systems for various classes of moving objects such as surface and air transport, ships, space and launch vehicles, etc, geographically distributed heterogeneous networks, flexible computerized manufacturing (Arkhipov et al. 2004; Sokolov and Yusupov 2002; Sokolov 2003).

One of the main features of modern complex technical systems (CTS) is the changeability of their parameters and structures as 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. Under these conditions to increase (stabilize) CTS potentialities and capacity for work a structure control is to be performed. Reconfiguration is a widely used variant of the CTS structure control. Reconfiguration is a process of the CTS structure alteration with a view to increase, to keep, or to restore the level of CTS operability, or with a view to compensate the loss of CTS efficiency as a result of the degradation of its functions (Ackoff 1978; Athaus and Falb 1966; Napolitano and Swaim 1989a; Napolitano and Swaim 1989b; Sokolov and Yusupov 2004). The presented considerations led us from a narrow traditional interpretation of CTS reconfiguration to a wide interpretation within a new applied theory of CTS structure-dynamics control. Developing of this theory is one the main aims of our investigations.

## APPROACH

As applied to CTS we distinguish the following main types of structures: the structure of CTS goals, functions and tasks; the organizational structure; the technical structure; the topological structure; the structure of special software and mathematical tools; the technology structure (the structure of CTS control technology). Structure dynamics control provides transition of CTS from the current macro-state to a given one. Figure 1 illustrates possible variants of structure dynamics in a complex technical system. The problem of CTS structure-dynamics control consists of the following groups of tasks: the tasks of structure dynamics analysis of CTS; the tasks of evaluation (observation) of structural states and CTS structural dynamics; the problems of optimal program synthesis for structure dynamics control in different situations. From our point of view, the theory of structure-dynamics control will be interdisciplinary and will accumulate the results of classical control theory, operations research, artificial intelligence, systems theory, and systems analysis. The two last scientific branches will provide a structured definition of the structure-dynamics control problem instead of a weakly structured definition.

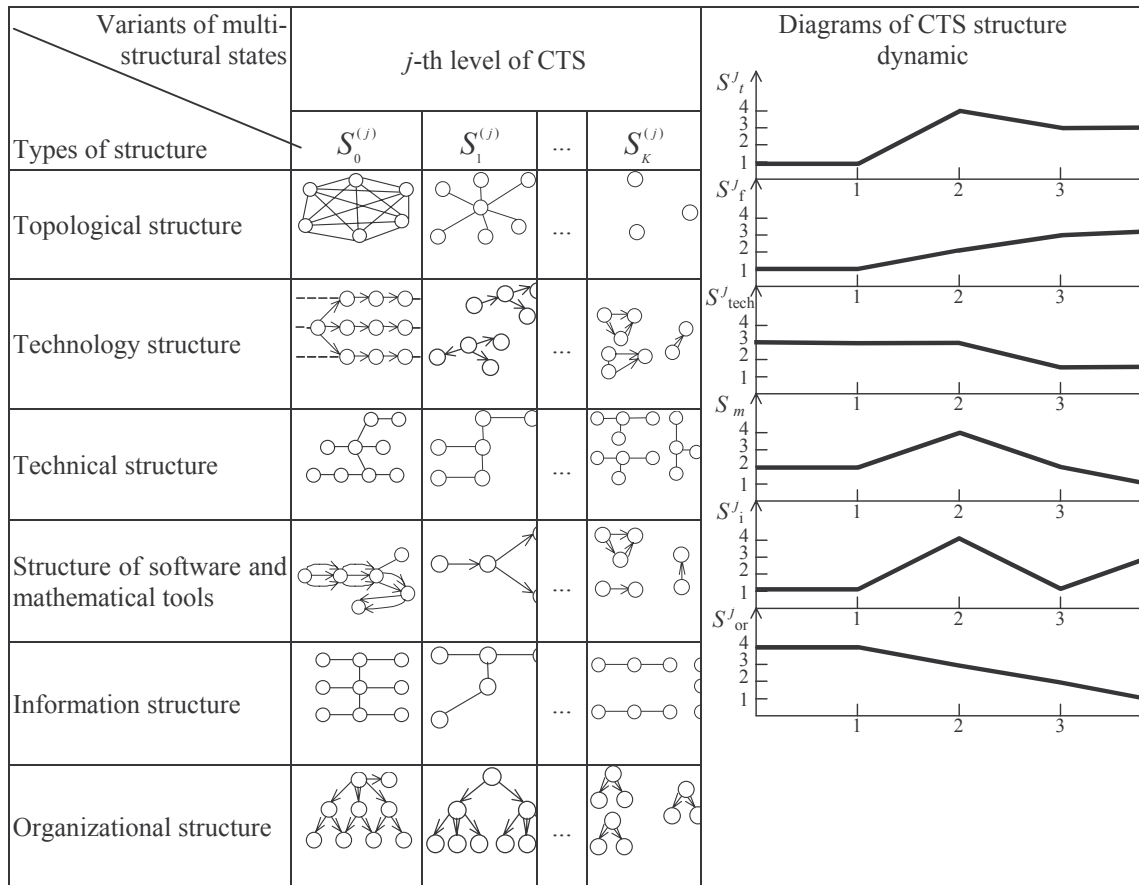


Figure 1: Possible variants of structure dynamics in complex technical systems

Today different methods and models are used for solving the problems of CTS structure-dynamics control. The known approaches to these problems are based on the PERT description of scheduling and control problems and traditional dynamic interpretation. The realization of these dynamic approaches produces algorithmic and computational difficulties caused by high dimensionality, non-linearity, non-stationary, and uncertainty of the models (Klir 1985; Athaus and Falb 1966; Siliak 1990).

We proposed to modify dynamic interpretation of operations control processes. The main idea of model simplification is to implement non-linear technological constraints in sets of allowable control inputs rather than in the right parts of differential equations. In this case, Lagrange coefficients, keeping the information about technical and technological constraints, are defined via the local-sections method. Furthermore, we proposed to use interval constraints instead of relay ones. Nevertheless the control inputs take on Boolean values as a result of the linearity of differential equations and convexity of the set of alternatives (Sokolov 2003). The proposed substitution lets use fundamental scientific results of the modern control theory in various CTS control problems (including scheduling theory problems).

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

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

CTS structure-dynamic control problem has some specific features in comparison with classic optimal control problems (Ackoff 1978; Athaus and Falb 1966; Okhtilev 2004; Siliak 1990). The first feature is that the right parts of the differential equations undergo discontinuity at the beginning of interaction zones (communication intervals). 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 the input data, external conditions, and required level of solution validity. The proposed interpretation of CTS structure dynamics control processes provides advantages of modern optimal control theory for CTS analysis and synthesis.

## RESULTS

The preliminary investigations confirm that the most convenient concept for the formalization of CTS control processes is the concept of an active mobile 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, control system (AMO CS) and objects-in service (OS). The 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, and 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. In general, AMO functioning includes informational, material, and energy interaction with OS, with other AMO, and with the environment. Along with the interaction, the facilities functioning, resource consumption (replenishment), and AMO motion are to be considered via functioning models (Sokolov 2003). The notion "Active Mobile Object" generalizes features of mobile elements dealing with different CTS types. Depending on the type of CTS the active mobile objects can move and interact in space, in air, on the ground, in water, or on water surface. Active Mobile Object can be also regarded as multi-agent system. The main classes of CTS structure dynamics problems include: AMO structure-dynamics analysis problems; AMO structure-dynamics diagnosis, observation, multi-layer control problems; problems of AMO generalized structural states synthesis and the problems of programs construction for a transition from a given CTS structural state to an allowable (optimal) structural state. Methodological and methodical basics for the theory of structure-dynamics control were developed. Methodological basics include: the methodologies of

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

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

The components of the simulation system were the main parts of the developed program prototypes during our investigation. The processes of AMO structure-dynamics control are hierarchical, multi-stage and multi-task ones. The structure of simulation system conforms the features of control processes. There are three groups of models in SIS: models of AMO CS and OS functioning (the 1st subsystem of SIS); models of evaluation (observation) and analysis of structural states and AMO CS structure-dynamics (the 2nd subsystem of SIS); and decision-making models for control processes in AMO CS (the 3rd subsystem of SIS).

The simulation system also includes: system of control, coordination and interpretation containing user interface and general control subsystem, local systems of control and coordination, subsystem of data processing, analysis, and interpretation for planning, control and modeling, subsystem of modeling scenarios formalization, subsystem of software parametric and structural adaptation, subsystem of recommendations producing for decision-making and modeling.

The data-ware includes databases for AMO states, for AMO CS states and general situation, for SO states and data bases for analytical and simulation models of decision-making and AMO CS functioning.

Existence of various alternative descriptions for CTS elements and control subsystems gives an opportunity of adaptive models selection (synthesis) for program control under changing environment.

Therefore we considered two general actual problems of the CTS structure-dynamics investigation, namely the problem of selection of optimal CTS structure-dynamics control programs at different states of the environment and the problem of parametric and structural adaptation

of models describing CTS structure-dynamics control. The formal statement and decomposition of structural and parametric adaptation tasks were worked out for models of CTS structure-dynamics control (SDC). Here the adaptive control should include the following main phases: parametric and structural adaptation of structure-dynamics control (SDC) models and algorithms to previous and current states of objects-in-service, of control subsystems, and of the environment; comprehensive scheduling of CTS operation (construction of SDC programs); simulation of CTS operation, according to the schedules, for different variants of control decisions in real situations; and structural and parametric adaptation of the schedule, control inputs, models, algorithms, and SDC programs to possible (predicted via simulation) states of SO, CS, and of the environment.

To implement the proposed concept of adaptive control let us consider two groups of parameters for CTS SDC models and algorithms: parameters that can be evaluated on the basis of real data available in CTS and parameters that can be evaluated via simulation models for different scenarios of future events.

The adaptation procedures can be organized in two blocks (models), namely SIS external adapter and SIS internal adapter.

As regards the CTS SDC models constructed previously, the following parameters belong to the first group and can be evaluated through the external adapter: the values of end conditions of the SDC models; technical and technological characteristics of CTS elements and subsystems [for example, computer speed, amount of random-access memory, maximal (minimal) intensity of resource consumption (regeneration), carrying capacity of data link channels]; and probabilistic characteristics and values of real and observed random processes.

The second group of parameters being evaluated through the internal adapter includes such characteristics as: redundancy rate for reserving of different type (functional, time, hardware/software, and informational reserving); priority of CTS SDC quality measures; and parameters defining the variants of compensation for trajectory deviations (violations of the schedule) in the simulation models.

When the parametric adaptation of SCS does not provide simulation adequacy then the structural transformations can be needed. Two main approaches to structural model adaptation are usually distinguished.

The first approach lies in the selection of a model from a given set. The model must be the most adequate to SO and CS. The second approach stands for CTS SDC model construction of elementary models (modules) in compliance with given requirements.

The second approach provides more flexible adjustment of SO and CS for particular functioning conditions. However, the first one is faster and can be effective if the application knowledge base is sufficiently large.

Both approaches need active participation of system

analysts and decision-makers who interact with SIS and consider hard-formalizing factors and dependences within the general procedure of CTS SDC program selection.

The structural adaptation of SCS takes a certain period of time, when the following main activities should be done: selection or construction (synthesis) of CTS SDC models meeting given requirements; selection or construction (synthesis) of CTS SDC algorithms for given conditions and given control problems; synthesis of software and data-ware for given control problems; and adjustment of SCS parameters for current and predicted states of SO and CS (parametric adaptation). Sometimes it is useful to adjust models and algorithms that are not currently used in CTS control processes, it will provide fast utilization of additional models when they are needed. The considered adaptation should be based on the results of CTS SDC simulation.

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

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

The general algorithm of the CTS structure-functional synthesis includes the following main steps.

Step 1. Gathering, analysis, and interrelation of input data for the synthesis of CTS multi-structural macro-states. Construction or correction of the appropriate models.

Step 2. Planning of a solving process for the problem of the CTS macro-states synthesis. Estimation of time and other resources needed for the problem.

Step 3. Construction and approximation of an attainability set for dynamic system. This set contains indirect description of different variants of CTS pattern (variants of CTS multi-structural macro-states).

Step 4. Orthogonal projection of a set defining macro-state requirements to the attainability set.

Step 5. Interpretation of output results and their transformation to a convenient form for future use (for example, the output data can be used for construction of adaptive plans of CTS development).

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

The general algorithm of problem solving should include the following steps.

Step 1. Input data for the problem are being prepared and analyzed in an interactive mode. During this step a

structural and parametric adaptation of models, algorithms, and special software tools of simulation system is being fulfilled to the past and to the current states of the environment, of object-in-service, of control subsystems embodied in existing and developing CTS. For missed data simulation experiments with SIS models or expert inquest can be used.

Step 2. Planning of comprehensive modeling of adaptive CTS control and development for the current and forecasted situation; planning of simulation experiments in SIS; selection of models, selection of model structure; determination of methods and algorithms for particular modeling problems, selection of models and model structure for these problems; estimation of necessary time.

Step 3. Generating via comprehensive modeling, of feasible variants of CTS functioning in initial, intermediate, and required multi-structural macro-states; introducing of the results to a decision-maker; preliminary interactive structure-functional analysis of modeling results; producing of equivalent classes of CTS multi-structural macro-states.

Step 4. Automatic putting into operation of data of CTS functioning variants; analysis of constraints correctness; final selection of aggregation level for CTS SDC models, and for computation experiments aimed at CTS SDC program construction.

Step 5. Search for optimal CTS SDC programs for transition from a given multi-structural macro-state to a synthesized one and for stable CTS operation in intermediate multi-structural macro-states.

Step 6. Simulation of program execution under perturbation impacts for different variants of compensation control inputs received via methods and algorithms of the real-time control.

Step 7. Structural and parametric adaptation of the plan and SIS software to possible (forecasted through simulation models) states of SO, CS, and of the environment.

Here CTS structural redundancy should be provided for compensation of extra perturbation impacts. After reiterative computation experiments the stability of constructed CTS SDC plan is being estimated.

Step 8. Introducing of comprehensive adaptive planning results to a decision-maker; interpretation and correction of these results.

One of the main opportunities of the proposed method of CTS SDC program construction is that besides the vector of program control we receive a preferable multi-structural macro-state of CTS at final time. This is the state of CTS reliable operation in the current (forecasted) situation.

The combined methods and algorithms of optimal program construction for structure-dynamics control in centralized and non-centralized modes of CTS operation were developed too.

The main combined method was based on joint use of the successive approximations method and the “branch

and bounds” method. A theorem characterizing properties of the relaxed problem of CTS SDC optimal program construction was proved for a theoretical approval of the proposed method.

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

- Determining of scenarios for CTS environment, particularly determining of extremely situations and impacts that can have catastrophic results.

- Analysis of CTS operation in a normal mode with the help of a priori probability information (if any), simulation, and processing of expert information through the theory of subjective probabilities and theory of fuzzy sets.

- Repetition of the previous item for the main extremely situations and estimation of guaranteed results of CTS operation in these situations.

- Computing of general (integral) efficiency measures of CTS structure-dynamics control.

Algorithms of parametric and structural adaptation for CTS SDC models were proposed. The algorithms were based on the methods of fuzzy clusterization, on the methods of hierarchy analysis, and on the methods of a joint use of analytical and simulation models.

The SDC application software for structure-dynamics control in complex technical systems was developed. It included elements for the above-mentioned 1st subsystem of SIS. External simulation software was inevitable at the current stage of our investigations. Specificity of AMO CS can be efficiently described via the terms of the queuing theory. Thus the use of the General Purpose Simulation System (GPSS world by Minuteman Software) was rather reasonable as it includes all necessary elements for such description. The embedded programming language under simulation (PLUS) provided a more flexible adjustment of simulation models to the input data. However, the processes of AMO operation and control differ from the typical servicing processes that are usually simulated via GPSS. The main distinction is that the control operations are executed according to previously obtained plans (SDC programs). Thus, the process of plan implementation under the presence of perturbation impacts should be simulated.

Characteristics of AMO control processes were arranged in a sequence of matrices containing the information about the control subsystems, the interaction zones (intervals of communication with

AMO), and the control operations. Systems of servicing facilities were automatically built via the PLUS language according to the contents of the matrices. The use of the GPSS models helped to evaluate reliability of the SDC programs.

## CONCLUSIONS

Methodological and methodical basics of the theory of CTS structure-dynamics control are developed by now. This theory can be widely used in practice. It has interdisciplinary basis provided by classic control theory, operations research, artificial intelligence, systems theory and systems analysis. The dynamic interpretation of CTS reconfiguration process provides strict mathematical base for complex technical-organizational problems of high importance that were never formalized before and have high practical importance.

The proposed approach to the problem of CTS structure reconfiguration control in the terms of general context of CTS structural dynamics control enables the following: common goals of CTS functioning to be directly linked with those implemented (realized) in CTS control process; a reasonable decision and selection (choice) of adequate consequence of problems solved and operations fulfilled related to structural dynamics to be made; and a compromise distribution (trade-off) of a restricted resources appropriated for a structural dynamics control to be found voluntary.

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