Scientific principles of coordinating the functioning of elements in a multi-level Intelligent Transportation Control System

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***Abstract*—It has been established that the description of the coordination of functioning in the Intelligent Transportation Control System (ITCS) involves the use of three levels of hierarchy. The features of the stratified system are determined. It is proposed to use the principle of multilayer when forming control decisions, when each layer is responsible for solving coherent operational problems. The functions of the three main layers of the system are determined. Describes the multilevel organizational hierarchy of the ITCS. A formalized description of the coordination of the functioning of the elements of a two-level fragment of the ITCS**

***Keywords*—Intelligent Transportation Control System, coordination, stratified system, organizational level, abstraction description level, multi-level system, Multilayer hierarchy**

One of the most important intellectual property of systems should be considered the ability to work in coordination. Such system property provides:

- solving complex problems by collective efforts;
- formation of hybrid solvers for new problems that were not considered at the stage of creating systems;
- improving the quality of control solutions (CS) due to the subsequent integration of modules with new more accurate algorithms;
- detection of errors in the CS by comparing their incoming information from different sources (systems).

Coordination of functioning can be ensured through the use of harmonized standards (for example, specifications based on OSTIS technologies) and unified principles of building intelligent systems [1–4].

In this article the key principles of the coordinated functioning of elements in a multi-level system, based on the Intelligent Transportation Control System (ITCS) example, are proposed [5, 6].

The description of the rules for coordinating functioning in the ITCS involves the using of three hierarchy levels [7]:

a) the object environment or abstraction description level (stratum);
b) complexity of generated CS level (layer);
c) organizational level (echelon).

The ITCS as a stratified system (Figure 1) is described by a family of models, each of which reflects the behavior of the system at different levels of abstraction. Each level has characteristic features, parameters, rules of behavior, patterns.

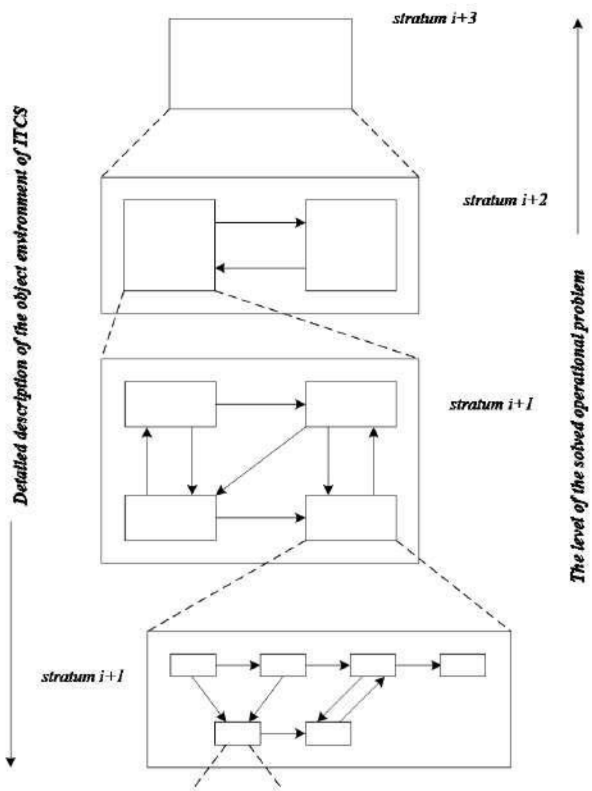

Figure 1. The relationship between the strata of the ITCS

The following features are inherent in a stratified system.

1. The choice of strata used in the ontological description of a subsystem depends not so much on the goals of the functioning of the ITCS, as on the goals of the functioning of a particular subsystem. For example, an object “marshalling yard”

in solving various operational problems will require descriptions from different points of view. For the development of a train formation plan (TFP), a station can be described only by enlarged quantitative parameters: the accumulation parameter C, the savings from running without processing t_{ec}, the limiting processing capacity N_{trans}.

When developing a train schedule (GDS), it is necessary to know the characteristics of the station's receiving and departure tracks and their layout. When managing plant operations, detailed characteristics of plant objects are required. In the above examples, the control object is considered from similar positions, which requires the consistency of descriptions in different subsystems. However, when solving the problems of "personnel work", "accounting", "repair management" approaches to the description of the "marshalling yard" will be fundamentally different.

2. Ontologies of subsystems on different strata are generally not interconnected. Therefore, the laws, principles of functioning, decision rules, etc., which are used to describe a subsystem on any stratum, in the general case, cannot be deduced from the principles used in another stratum. For example, the decision rules of the subsystem "planning of shunting work" cannot be used in the subsystem "control of the work of a shunting locomotive". In this regard, in ITCS for each subsystem, its own ontology can be used. The set of ontologies of subsystems form a single ontology of the ITCS. The purpose of a unified ontology is to ensure the consistency of descriptions of private ontologies among themselves.
3. There is an asymmetric relationship between the conditions for the functioning of the ITCS on different strata. The requirements for the conditions of functioning and the decision rules of the higher subsystems act as conditions or restrictions for the lower ones. For example, the choice of the speed of shunting movement in the subsystem "planning of shunting work" is a limitation in the formation of the CS in the subsystem "control of the operation of the shunting locomotive". As a result, information (feedback) about the course of the real process and its deviations from the planned values should be transmitted to a higher level.
4. Each stratum has its own set of terms, definitions, decision rules and concepts. An elementary object of a higher stratum may be an independent subsystem on a lower one. Subsequent strata describe the internal mechanisms of the object's behavior and the principles of its functioning. The higher strata are the principles of interaction between objects. For example, a station on higher strata (for example, when developing a plan for the formation of trains) should be described in aggregate, and the emphasis is on the principles of interaction between stations. In the lower-level stratum, the station is an independent subsystem with its own principles and peculiarities of functioning. As a consequence, the study of an object in a lower stratum does not always make it possible to more effectively solve the problems of higher strata. Thus, the ITCS ontology should provide for a hierarchy of semantic relations between any two successive subsystems of the hierarchy: "subsystem behavior rules - rules of interaction between subsystems".
5. The detailing of the principles of ITCS functioning increases with the successive transition from strata of higher levels to strata of lower levels. A different detail level of control objects in digital models of subsystems belonging to different strata makes it possible to simplify the general description of ITCS, but ensure its necessary completeness.

The system of CS formation in ITCS is based on the principle of multilayer - when each layer is responsible for solving coherent operational tasks (OT), but taking into account different "powers" and detailing the final decisions (Figure 2).

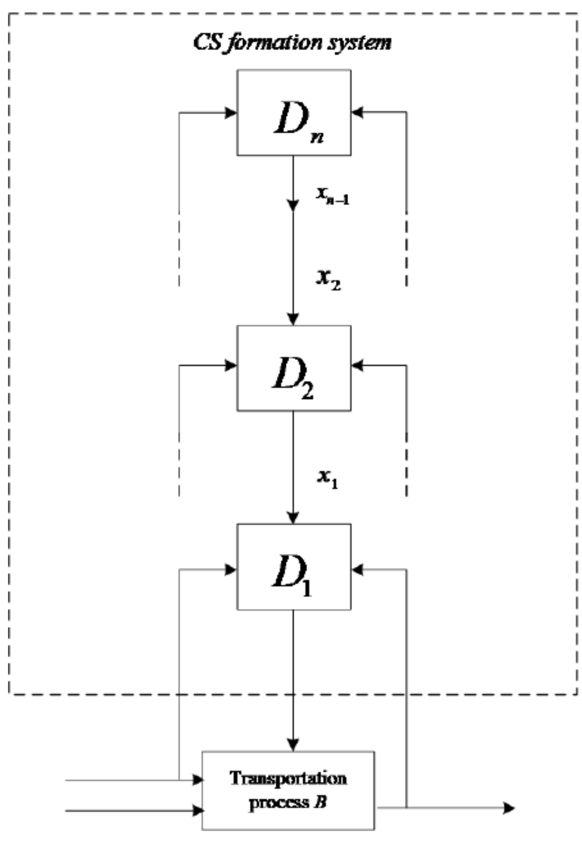

Figure 2. Multilayer hierarchy of the CS formation system in ITCS

For example, the upstream OT "TFP Development" defines a plan for the distribution of shunting work between the technical stations. OT "formation planning" at the station level, based on the established TFP, develops a shunting plan. The subordinate subsystem "control of shunting work" on the basis of a train formation plan forms shunting routes and transmits telecontrol commands to shunting locomotives.

CS in ITCS can be thought of as a family of consistently solved operational problems. Those. CS of any of the OT defines such control parameters that allow formulating the subsequent problem as fully defined and solvable. The CS of the original OT can be considered found if all associated OTs have been (or can be) resolved. For example, if within the framework of the decision OT "formation planning" it is established that the specified amount of shunting work cannot be performed (due to a shortage of track or shunting resources, etc.), the OT "development of TFP" is considered not solved and requires re-consideration.

Thus, each element in Figure 2 is a formative CS and can be assigned to a certain hierarchical layer. The output of an element (for example, D_2) x_1 is CS or a sequence of CS, depending on the input control x_2. At the same time, the input parameters x_2 are the CS of the parent element. In the future, in the ITCS, such a system of CS formation will be called the hierarchy of layers of CS formation, and the system itself will be called a multilayer decision-making system.

In ITCS, as a system providing CS formation in conditions of uncertainty, the hierarchy of CS formation layers is determined by the following stages:

1. Choice of the strategy that should be used in the process of CS adoption;
2. Elimination or minimization of uncertainty;
3. Search for the preferred or acceptable CS according to the given rules.

The ITCS functional hierarchy is shown in Figure 3.

1. Layer of choice: the purpose of the layer is the formation of CS m, which directly affects the subject of management (transportation process). The element forming the CS on this layer receives from the environment and higher subsystems the initial data for solving the OT and, using one or another algorithm, forms the CS. The algorithm can be defined directly as pre-formulated in the ontology of system T or indirectly using the search process.

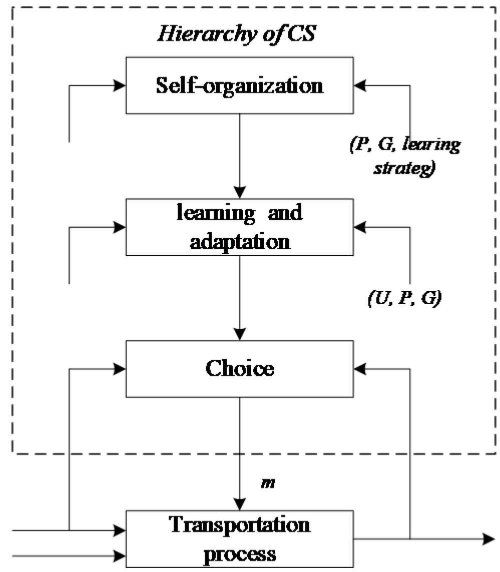

Figure 3. Functional multi-layer hierarchy CS

For this, the system specifies the output function P, the estimation function G, and the choice of the effective CS m is based on the application of the estimation function G to the function P. Using the set-theoretical approach of systems theory, the output function can be defined as a mapping P:

$$M \times U \rightarrow Y, \tag{1}$$

where M - is a set of alternative CS; Y - is the set of possible outputs; U - is a set of uncertainties that adequately reflect the lack of knowledge about the relationship between CS m and the output y.

Similarly, the estimate function G is a mapping G:

$$M \times Y \rightarrow V, \tag{2}$$

where V - is a set of parameters that can be related to the characteristics of the system's functioning quality.

If the set U consists of one element or is empty, i.e. there is no uncertainty at the output with respect to CS m, the choice can be based on optimization: find such m in M such that the value $v' = G(m', P(m'))$ is less than $v' = G(m, P(m))$ for any other CS $m \in M$.

If U is a richer set, the choice of an effective CS can be based on other principles, including those involving the introduction of additional, in addition to P and G, mappings.

Corollary 1. The search for an effective CS based on optimization approaches is a special case of search. When solving a significant number of OT, fundamentally different criteria for choosing effective CS can be used.

Consequence 2. The evaluation function G should be formed in the external, relative to the forming CS element, subsystem and be consistent with the functioning goals of higher subsystems. Otherwise, you can always find such a function G', which will allow you to define any CS as effective.

2. Layer of adaptation. The task of this layer is to concretize the set of uncertainties U , which are inherent in the layer of choice, and to narrow this set. If the system and environment are stationary, then the set U can be narrowed down to one element. However, U represents not actually existing, but assumed uncertainties. When solving new OT in ITCS, the U layer can be modified (extended), thereby assuming that certain underlying hypotheses are unfair and require adaptation to the predicted operational environment. For example, a station shunting plan is developed based on the number of locomotives available at the station (the number of locomotives is known, there is no uncertainty). However, in the process of performing the technical task, it became necessary to carry out unscheduled repairs with an indefinite time for their completion. Under such conditions, the number of shunting locomotives at the station is an undefined value.
3. The layer of self-organization. Designed to select the structure, functions and strategy for solving OT, used on the lower layers, taking into account the maximum approximation to the global goal of the system functioning. If the global goal is not achieved, the subsystem of this layer changes the functions P and G on the first layer or the adaptation (learning) strategy on the second layer.

In ITCS, as a multi-echelon system, the concept of hierarchy implies that:

1. The system consists of a family of clearly interacting subsystems;
2. Some of their subsystems are forming CS;
3. The forming CS elements are arranged hierarchically in the sense that some of them are controlled by other (superior) elements (Figure 4).

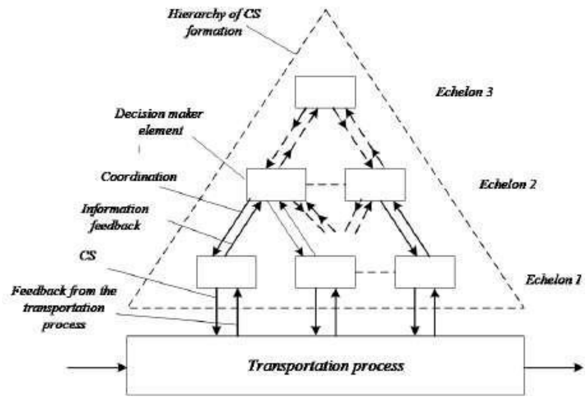

Figure 4. Multilevel organizational hierarchy of ITCS

The presence of many subsystems that have the right to form the CS implies the possibility of the functioning "conflicting" goals existence. In addition, the goals of functioning can be not only "conflicting", but also form "coalitions". Traditionally, such systems are considered as multi-agent, but this approach leads to an oversimplification of the system description (functional connections between elements of the same level, target parameters of functioning set by higher subsystems, etc. are neglected). In addition, conflicts between elements of the same echelon are not resolved within one hierarchical level, but through the intervention of an element of a higher level.

Considering ITCS as a multi-level multi-purpose system, it should be borne in mind that the upper level elements determine the purposeful activity of the lower level elements, but do not completely control it. Subordinate elements forming CS should have the freedom to form and choose CS. In some cases, the CS chosen by the lower level may differ from the choice of the higher level element. For example, when generating a predictive GDS, the route of receiving a train to a station is determined. However, in the subsystem "Managing the operation of a technical station" in view of the availability of more complete information (information awareness), a different reception path can be chosen (for example, due to the presence of a train on the initial track with which operations for non-decoupling car repair are performed).

At the same time, in the interest conflict event arising between elements of one or different echelons, the priority in the choice of SD remains with the element of a higher level. Let's consider the coordination of functioning on the example of a two-tier fragment of ITCS. The choice of such a fragment is explained by the following reasons:

1. This is the simplest type of system in which all significant properties of multilevel systems are manifested;

2. Any more complex multi-level system can be built from two-level by hierarchical unification.

Fragment ITCS contains upstream control elements C_0 and downstream C_1, C_2, ..., C_n of various control levels, the control object for which is the transportation process B_1, B_2, ..., B_n. (Figure 5).

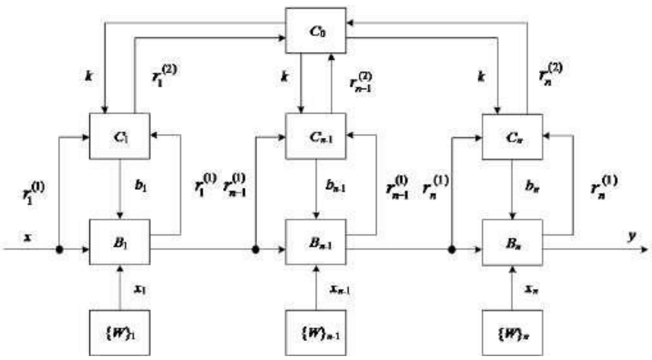

Figure 5. Diagram of management coordination in ITCS

Bodies of the control system C_1, C_2, ..., C_n act on the control objects B_n through the implementation of the SD b_k ($b \in B_k$ to the set of admissible SD) and receive information about the progress of the SD implementation on the control objects $r_n \in R_n^{(1)}$ (where $R_n^{(1)}$ – is the set of information messages of the 1st level).

In ITCS, the objective of good governance is formulated as follows:

– the subsystem of the higher level C_0 should form such CS $\{k_i\}$ so that at the lower level subsystems C_1, C_2, ..., C_n form operational tasks and optimal local SD $\{b_n\}$ in relation to the global quality function Y;
– subsystems C_1, C_2, ..., C_n solving problems of local optimization should provide an extremum of the quality function Y.

The model of ITCS functioning from the point of view of set theory describes the SP as

$$B_n: L_k \times X \rightarrow Y, \quad (3)$$

where X – is the set of perturbations of the external object environment affecting the controlled process.

The model of functioning of the control element C_i can be described by a functional of the form

$$C_i: K \times B_n \rightarrow L_k, \quad (4)$$

and the model of the coordinator K is implemented in the form

$$C_0: R_n^{(2)} \rightarrow K, \quad (5)$$

where $R_n^{(2)}$ – set of second level information signals.

The implementation of the control loop in ITCS includes information coming through feedback channels ($R_n^{(2)}$). Feedback information enters the control bodies and provides the formation of an array of data on the state of control objects. Feedback allows you to form dependencies between a set of control decisions L_k and changes in the parameters of control objects B_n, i.e.

$$x_i: L \times W \times Y_n \rightarrow R_n^{(2)}, \quad (6)$$

where W - is the set of all possible factors influencing the result of solving the control problem; Y_n - set of effective outputs of transportation processobjects in the considered subsystem.

The function coordinating control actions coming from the upper control level is defined as

$$F(L) \rightarrow x_0: K \times R_n^{(2)} \times L, \quad (7)$$

where K - is a set of coordinated actions.

At the lower control level, the tasks of coordinating subprocesses to be solved can be optimization. In this regard, it is expedient to consider any local problem as a pair (g_i;x_i), where g_i - is a given local objective function; x_i - a predetermined set of input actions X. In this case, we can assume that g_i it is determined by the output function of the process B_n and the local quality function G_i:

$$g_i(x_i) = G_i(x_i, B_n(x_i)). \quad (8)$$

The solution to the local optimization control problem in the ITCS subsystem is the element $x_i \in X$, which determines the minimization condition

$$g_i(x_i) = \min g_i(x_i). \quad (9)$$

In ITCS, the implementation of the principle of coordinating the activities of subsystems is based on:

– for top-level subsystems - on “coordination of interaction”;
– for subsystems of a lower level - on “unleashing interaction”.

To implement coordination in ITCS, it is proposed to use a modified method for obtaining the quality function for lower-level elements by means of operators for evaluating the indirect effect of the implementation of CS.

In order to obtain the global optimum of the function Y in accordance with the method of coordinating “untied” interactions, the elements of the lower level must maximize their quality functions both in terms of local controls and in interactions. Subsystem C_0 should form coordinating CS k_w^j so as to balance interactions

$$\sum_{j=1}^{n} y_{jf}^{i} = u_{if}; \sum_{j=1}^{n} y_{jw}^{i} = u_{iw}, \quad (10)$$

where u_{if}, u_{iw} – optimal parameters of subsystem functioning adopted at the upper control level; y_{jf}^{i}, y_{jw}^{i} – optimal performance parameters selected by the corresponding subsystems at the lower control levels.

The use of the above principles made it possible to create and introduce into industrial operation a number of intelligent systems on the Belarusian Railway: "Shift-daily planning of cargo work" - the system allows you to develop detailed agreed work plans for three levels of management and more than 100 objects of management;

"Linking the formation with the train schedule" - the system allows to solve a new operational problem due to the coordinated interaction of the systems "train planning", "station work planning" and "development of the train schedule". Detailed coordinated plans are being developed for two management levels and about 20 objects of management.

Harmonized OSTIS standards and uniform principles for coordinating the functioning of intelligent systems can be used to build intelligent systems in other areas of knowledge. In the future, this will allow the creation of intelligent systems that have interdisciplinary knowledge and are able to form CS for various fields of activity.

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Научные принципы координации функционирования элементов в многоуровневой интеллектуальной системе управления перевозочным процессом

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Установлено, что описание координации функционирования в интеллектуальной системе управления перевозочным процессом предполагает использование трех уровней иерархии. Определены особенности стратифицированной системы. Предложено при формировании управляющих решений использовать принцип многослойности, когда каждый слой отвечает за решение связных эксплуатационных задач. Определены функции трех основных слоев системы. Описана многоуровневая организационная иерархия ИСУПП. Приведено формализованное описание координации функционирования элементов двухуровнего фрагмента ИСУПП.

Received 04.05.2021