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GENERALIZED METHOD OF SITUATIONAL DECOMPOSITION AND MULTIFUNCTIONAL INTELLIGENT CONTROL SYSTEMS

U. UMBETOV [1], KHU WEN-TSEN [2], P.S. BELYAEV [3], YU. SHARIPOVA[4], SEITMURATOV A.[5], SHEKEYEVA K.[6]

[1] Doctor of Technical Sciences, Professor Karaganda Industrial University, Temirtau, Republic of Kazakhstan
[2] Doctor of Technical Sciences, Professor South Kazakhstan University named after M. Auezov, Shymkent, Republic of Kazakhstan
[3] Professor of the Department of Materials and Technology, Doctor of Technical Sciences Tambov State Technical University, Tambov, Russian Federation
[4] Master of pedagogical Sciences Karaganda Industrial University, Temirtau, Republic of Kazakhstan
[5] Doctor of Technical Sciences, Professor Korkyt Ata Kyzylorda State University, Kyzylorda, Republic of Kazakhstan
[6]Doctor of Chemical Sciences, Associate Professor National Medical university named after S.D. Asfendiyarov
E-mail: uumbetov@mail.ru[1], qbcba@bk.ru[2], bps@asp.tstu.ru [3], sharipovayulia1979@mail.ru[4], angisin_@mail.ru[5], info@kaznmu.kz[6]

A fundamentally new type of automated optimal control systems, characterized as multifunctional intelligent systems, is considered. Their distinguishing feature is the ability to implement various control tasks depending on the circumstances that determine the required behavior of the control object. Such systems have a high degree of autonomy, including the ability to operate in a fully automatic mode, which increases their reliability and survivability.

The proposed generalized method of situational decomposition forms the mathematical basis of the considered control principle. Its essence lies in the fact that in order to develop control decisions in the control system, a finite set of different tasks adapted to certain situations is used. In the process of functioning, the control system independently evaluates the situations that arise and sets the necessary control task for execution.

The proposed developments seem to be extremely important and interesting from the point of view of building self-tuning control systems with increased autonomy. Such systems are relevant for complex technological processes, technological processes with variable configuration, discrete technological processes, aircraft and sea vessels, spacecraft, unmanned vehicles, multifunctional robots, including combat drones.

Keywords and phrases: Multifunctional Control, Optimal Control, Intelligent Control, Hierarchical Control System, Reliability Of Control Systems, Survivability Of Control Systems, Autonomy Of Control Systems, Control Systems For Industrial Objects Of A Discrete Type, Control Systems For Objects With A Variable Structure, Control Systems For Multifunctional Robots And Drones.

1. INTRODUCTION

At present, the traditional approach to building automated optimal control systems can be characterized as monotask, which means that in the process of operation the system implements a single control task. Meanwhile, there is an opportunity to modernize this approach. An alternative can be the multitasking principle of building control systems, in which several different control tasks are implemented within the framework of one control system at various stages of its functioning.

The mathematical basis for the functioning of control systems of this class is the proposed generalized method of situational decomposition (GMSD), which represents the development of the previously proposed method of situational decomposition [1,2] for structured control objects of a class of complex technological systems.

The essence of GMSD lies in the fact that the control system at different times generates control actions based on the solution of various control problems, taking into account the situations that arise during the operation of the control object. As a result, the control system becomes more versatile and flexible, able to automatically adapt to the emerging operating conditions. This opens up opportunities for the use of artificial intelligence, which helps to improve the overall and functional efficiency of control systems.

This property seems to be extremely important and interesting from the point of view of building self-tuning control systems with increased autonomy. Such control systems are very relevant, as they can have a wide scope of application. In particular, in complex technological processes, technological processes with variable configuration, discrete technological processes, aircraft and sea vessels, spacecraft, unmanned vehicles, multifunctional robots and combat drones. The proposed approach does not impose any special requirements regarding the structure of the management tasks used. The limitation can only be the requirement for the complete formalizability of these tasks in the sense of determinism of all structural elements. At the same time, formalization in the class of nonlinear programming problems is preferable.

The purpose of the study is to develop a scientifically based methodological apparatus for building multifunctional intelligent control systems with elements of self-organization of implemented functions. Such systems should be considered as fundamentally different from management systems with a traditional monofunctional organization, which is an obvious and undoubted scientific novelty.

2. FORMULATION OF THE PROBLEM

Consider the mathematical aspects of GMSD.

Let there be some finite set of control problems of the form:

$$f_i(x_i,u_i,y_i,t) \rightarrow \max_{u_i(t)\in U_i}$$

$$U_i = \{u_i : g_i(x_i,u_i,y_i,t)=0; h_i(x_i,u_i,y_i,t)\geq 0\}, \qquad (1)$$

$$i=1,2,\dots,N$$

where t - is physical time; i - *is* the ordinal number of the task; x_i, u_i , y_i - vectors of disturbing influences, controls and outputs of the control object (CO); f_i - given scalar objective function, identified with the criterion of optimality of the CO operation; U_i - set of admissible states of CO; g_i - a given vector - valued function corresponding to the mathematical model of the CO; h_i - is a vector-valued function that sets restrictions on the admissible behavior of the CO.

For example, these can be the tasks of controlling an unmanned aerial vehicle (UAV) at the stages of takeoff, movement along a given route, performing specified maneuvers, landing, etc.

Tasks in the general case can be different and have nothing to do with each other, except that they are focused on the functioning of a single CO. This means that the goals and conditions for the functioning of the CO may be different depending on the specifics of the circumstances that need to be taken into account at the time of development of management decisions. Accordingly, the considered objective functions, mathematical models and restrictions can have a different structure.

To identify the circumstances of the operation of the CO, which require decision-making regarding the activation of the corresponding control task, we introduce an additional factor, which we will call the situation.

Under the situation in the broadest sense, we mean some generalized indicator that characterizes the state of the CO at the considered point in time. In general, some *k-th* situation at time t_k can be defined as an indicator

$$I_k(x, u, y, t_k) = I\left(\overset{o}{x},\overset{o}{u},\overset{o}{y}\right), \qquad (2)$$

where $\overset{o}{x},\overset{o}{u},\overset{o}{y}$ are specific values of input variables x , controls u and outputs y *of the* CO , respectively, generalized for all considered situations.

Let us further assume that each of the N tasks (1) has a situation of activation in the control system. In this case, index i for variables and function pointers in problems (1), it acquires the meaning of a situation pointer in the form of its ordinal number.

The activation of a specific task in the control system must be preceded by the solution of the task of recognizing a situation of the form:

$$(\overset{o}{x},\overset{o}{u},\overset{o}{y}) : \xrightarrow{R} i \text{ , } i=1,2,\ldots,N. \qquad (3)$$

The meaning of this task is to map the vector of current values of the variables *x, u, y* by means of some operator *R* to the situation number *i*.

The activated task is automatically launched and begins to be solved in relation to the current conditions, determined by the specifics of the current values of the variables taken into account.

In this case, there is a hierarchical [3,4] decision-making scheme. Its corresponding structure of the control system is shown in Figure 1. At the lower level there is a subsystem for the development of control decisions (CDS), which at each moment of time solves the control problem corresponding to the considered situation at the Shelter. At the top level, there is a coordinating body (CO), which solves the problem of recognizing situations and activates the corresponding work tasks.

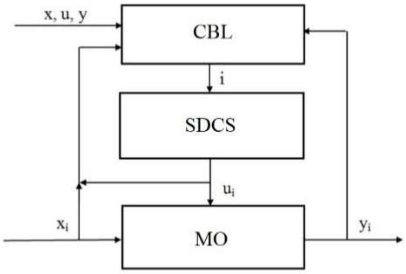

Figure 1. Structure of the multifunctional control system

The given control principle can be considered as some analogue of adaptive control. The difference lies in the fact that in this case, instead of identifying the mathematical model of the control object, the situation is identified, followed by a possible replacement of the control work task as a whole.

3. THEORY

The main problem associated with the implementation of the approach under consideration is the construction of the mapping operator *R* to identify current situations. Specifying it in an analytical form, in particular, as a function *R* (*x, u, y*), as a rule, it is not possible due to its extreme complexity, moreover, it is necessary to associate continuously changing values of the task variables with discrete values of the situation numbers. For this reason, the use of numerical procedures for the selective selection of situation features becomes the main way to specify the operator *R*.

The number of possible situations *N* in the general case is determined by the number of possible combinations of the components of the vectors *x*, u, y as well as the number of possible discrete values for each component of the specified vectors ${}_i$. So, if the total dimension of the vectors *x*, u, y is *n*, and the number of possible discrete values for each component is *m*, the number of situations to be taken into account will be determined by the relation

$$N=\sum_{i=1}^{n} i\cdot m\cdot\frac{n!}{i!(n-i)!}. \qquad (4)$$

Usually N turns out to be extremely large, and the specification of each situation may also require taking into account a large number of features. For this reason, the solution of the situation recognition problem (3) turns out to be significantly difficult, requiring the construction and implementation of the most complex computational algorithms. A possible way out of this difficulty is the use of expert systems and artificial intelligence methods, which leads to the intellectualization of management.

Along with this, we can limit ourselves to taking into account not all possible situations, but only typical ones, the number of which is significantly less. A typical situation is understood as one that is repetitive during the normal operation of the control object under the conditions under consideration. Emerging current situations are subject to correlation with the typical ones taken into account and, subject to certain conditions, equating them to specific typical situations.

In practice, the selection of typical situations and systems of signs for their identification does not present any particular difficulties for specialized specialists. At the same time, the sequential enumeration of feature systems provides a guaranteed identification of any typical situation taken into account, and, consequently, the current arbitrary situation equated to it.

The quality of management can be

improved by simultaneously taking into account two or more intersecting typical situations, when the emerging current situation cannot be unambiguously attributed to one of the typical ones. In this case, a mechanism should be provided for the priority consideration of signs of intersecting situations, or another mechanism. For example, the introduction of additional control tasks into consideration or the joint solution of intersecting tasks, including the multiprogramming mode, with a division into background and working ones, etc.

Management using typical situations is close to the principles of management implemented by a person. As an illustration of this statement, consider the following example.

Driving a car involves ensuring its movement at any given time in a given direction at a given speed. On the way, various situations may arise that require the driver to take various actions. At the same time, in most cases, these situations are reducible to typical ones, such as driving on a flat smooth road, driving on a poor quality road, ups and downs, winding sections, etc. optimization problem.

As a result, driving is built on the principle of “binding” the current situation to a typical and optimal action in relation to a typical situation, adjusted for the current specifics. These corrections are reduced to taking into account the current position of the car, the current mode of its movement and the current environment. This fully corresponds to how a person does it in practice.

In the case of automated control, all of the above remains valid. At the same time, taking into account corrections for the current traffic situation means entering the corresponding initial data into the control problem at the time of development of control decisions. If such input is carried out automatically to some extent, the autonomy of the control system will increase, approaching full autonomy. When providing automatic input of initial data at the moment of starting the control system, it will become a fully autonomous automatic system.

This property seems to be very important for similar control systems when used in combat drones. In particular, in UAVs, since this reduces the dependence of the device on the remote control operator, which can make it difficult to intercept control. In addition, in conditions of increased autonomy, the vulnerability of the apparatus to electronic warfare is reduced. Taken together, this contributes to an increase in the efficiency and survivability of the UAV.

4. RESULTS OF THE STUDY

The formulated approach is inherently decompositional [5], since the entire set of individual control tasks (1) can, in principle, be aggregated into one universal control task. However, it is obvious that such a task will be incommensurably more complex and dimensional in comparison with any of the number of particular tasks. Accordingly, its solution will be more time-consuming and resource - intensive, requiring the construction of a cumbersome control system with a complex architecture. Moreover, such a complication of the control system inevitably leads to a decrease in its efficiency and reliability.

The same can be said about the management of complex technological processes with the participation of a human operator. As a rule, the operator seeks to find the simplest possible control solutions using the minimum number of control organs and channels. At the same time, in each specific case, the development of a control decision is preceded by an assessment of the current situation, on the basis of which the control problem is posed and solved.

Such a task is usually tied to “bottlenecking”, i.e. to the most urgent particular problem. At the same time, the use of the full composition of available bodies and channels of control is observed more in exceptional cases than in everyday practice, moreover, this is not always possible. When making a decision, a person is guided by accumulated experience and systematized typical situations, with which he correlates emerging current situations. In this case, the accumulated experience determines the ability to recognize and identify emerging situations.

From the standpoint of automated situational management, the normal course of processes can be assessed as a set of standard, i.e. typical situations for which effective response and decision-making algorithms are known and worked out. Emergency situations are considered as exceptional, requiring the search for an appropriate response algorithm and the development of a control decision. Such algorithms can be built on the basis of combined consideration of typical situations. If at the same time the constructed decision-making algorithm turns out to be effective, it is remembered, and the corresponding situation is transferred to the category of regular ones.

Thus, over time, the number of possible emergency situations is reduced, and management approaches actions in conditions of only regular situations. The latter circumstance can be attributed to the absolute merit of the management principle under consideration, and it can be characterized as self-learning management. This property is one of the criteria for intelligent control systems.

Let us note one more important aspect of the considered approach to control.

In some cases, the assessment of situations at the control object can be carried out by the values of the input variable *x (t). In* particular, this applies to process control. Usually, the need to reconfigure control systems here arises when switching from one type or batch of raw materials to another, or when the loads on process equipment change. Both are components of input disturbances in relation to the technological process as a control object.

In such cases, the set operating mode of the technological process and its control systems can remain unchanged for quite a long time. This means that *x (t)* can be identified with a piecewise constant time function and be represented by a sequence of discrete values $x(t) = x_1, \ x_2, \ \ldots, \ x_N.$ If these values are identified with the situation of making control decisions, problem (1) can be reduced to static problems of the form:

$$f_i(\overset{0}{x}_i, u_i, y_i) \to \max_{u_i \in U_i}$$

$$U_i = \left\{ u_i : g_i(\overset{0}{x}_i, u_i, y_i) = 0; h_i(\overset{0}{x}_i, u_i, y_i) \geq 0 \right\}, \qquad (5)$$

$$i=1,2,\ldots,N$$

where $\overset{0}{x}_i$ is the value of the variable x_i taken into account in the task as a given constant.

Problems (5) are obviously less complex than problem (1). However, some of them may still be quite complex. And their use in control systems will be difficult from the point of view of providing a solution time that fits into the intervals between situations that arise. In such cases, a variant is possible when the problem is solved in advance, and its result is stored in memory and, if necessary, reproduced without directly solving the control problem. You can do the same with recurring situations.

For this case, the following approach to formalization of the situation recognition problem (3) is possible.

Denote by *D the* set of situations taken into account in problem (1). Let us assume that this set admits partition into *L* subsets D_k, $k = 1, \ 2 \ \ldots, \ L,$ each of which can be associated with a certain typical situation. We evaluate each current situation for belonging to a certain set D_k, $k = 1, \ 2, \ldots, L$.

Partition of the set *D* into subsets D_k $k = 1, \ 2, \ldots, \ L$ can be carried out on the basis of the formation of a system of distinguishing features of typical situations. As such signs, in addition to the values of the components of the vector *x*, the following can be used: numbers of the components that have received an increment; the magnitude and sign of this increment; other quantitative estimates.

In the simplest case, the selected typical situations will not have intersections, i.e.

$$D_k \cap D_j = \varnothing, \quad k = 1,2,\ldots,L, \quad j = 1,2,\ldots,L, \quad k \neq j. \qquad (6)$$

This means that only separate typical situations in their pure form will take place in the management process. However, this distinction is more the exception than the rule. In a more general case, condition (6) is not satisfied, i.e., typical situations may overlap on separate grounds. Then the problem should take into account all the typical situations in which the intersection takes place.

Based on the calculation of all the distinguishing features and their subsequent comparison with the feature systems for individual typical situations, the current situation is classified as a typical one. It will correspond to a typical situation that has a match in all respects. The absence of such a typical situation will mean that the current situation belongs to intersecting typical ones, i.e. the presence of distinctive features of the current situation, which simultaneously belong to different typical situations.

Taking into account this circumstance, the coordination problem (3) for the most general case can be formulated as the problem of determining the distinguishing features of the current situation that belong to different typical ones, followed by the union of intersecting situations. This problem can be formulated as follows

$$d = 0;\ a_j = 0;\ j = 1,2,...,L;$$

$$\exists k = 1,2,...L;\ p_s \in P_k;\ s = 1,2,...,S \Rightarrow$$

$$\Rightarrow d = 1; b_{ks} = 1; a_k = 1, \tag{7}$$

$$\overline{D} = \bigcup \overline{D}_j, \quad j = 1,2,...,L, \tag{8}$$

where d, b_{ks} and a_j - auxiliary variables used as indicators; ps – s - th sign of the situation; P_k– a set of distinguishing features of the k - th typical situation; $\overline{D}$ is the set of variables taken into account in the modified control problem; $\overline{D}_i$ are intersecting sets of typical situations for which $a_j \neq 0$.

In the absence of intersecting features, the problem is reduced to a sequential enumeration of systems of features of typical situations P_k in order to find a system that completely coincides with the features of the current situation. This problem can be formulated as

$$d = 1 \Rightarrow \sum_{s=1}^{S} b_{ks} \to \max_k, k = 1,2,...,L$$

$$,$$

$$\overline{D} = D_{k^*} \tag{9}$$

The solution to this problem is $k = k^*$, for which the sum of significant features of a typical situation $\sum_{s=1}^{S} b_{ks}$ is maximum.

The multifunctional control algorithm based on the generalized situational decomposition method is shown in Figure 2.

At the time of the start of the control system, initial values are entered as initial data for the complete set of variables that have the meaning of the parameters of the operation of the control object for the entire period of control.

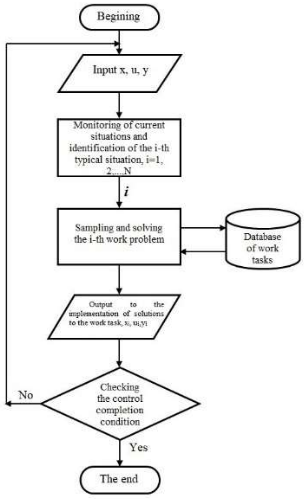

Figure 2 - Algorithm of multifunctional control

Based on the analysis of the initial data, the starting control task is determined and put into execution. Further, in the course of the functioning of the control object, on the basis of monitoring its operating parameters, there is a periodic analysis of current situations in order to identify the occurrence of the considered typical situations. When the fact of the occurrence of a typical situation is revealed, the database of management work tasks is accessed and the corresponding work task is put on the working execution.

The results of solving the working tasks of management are sent for implementation to the bodies or devices for executing control decisions. After that, the control completion condition is checked. When this condition is met, further control is terminated, resulting in the termination of the functioning of the control object.

Otherwise, the current values of the functioning parameters are used to update the considered initial data, and the entire cycle of development and implementation of control decisions is repeated.

For the joint solution of problems (1), (7) - (9) within the framework of this algorithm, in terms of identifying typical situations, artificial intelligence methods can be effective. In this case, the control system using them will be fully multifunctional and intelligent.

5. CONCLUSION

A fundamentally new approach to the construction of automated optimal control systems has been developed. Its distinctive feature is the implementation of several different control tasks within a single control system, due to which the effect of multifunctionality is achieved. As a result, the functionality of control systems is significantly expanded. Prerequisites are being created to reduce their number at complex control objects, which helps to reduce the costs of their creation, operation and maintenance. As a result, the efficiency of control systems as a whole increases. At the same time, the emerging opportunities for using elements of artificial intelligence improve the quality of management, bringing it closer in content to the actions of a human specialist. These features should be considered as strong positive characteristics that are difficult to achieve or even unattainable in management systems with a traditional monofunctional organization.

As a relative negative point, we can note the need to complicate the management system by including an intellectual element in its structure that implements situational analysis and activation of the work task necessary for current management. At the same time, this complication of the system is more than covered by the achieved end effects of multifunctional intelligent control.

The proposed approach and method were tested and tested by means of computer simulation. As a control object, a model chemical -technological process of industrial multi-stage extraction [6] with a variable structure was considered, which allows the inclusion of a different number of extraction stages depending on the quality indicators of the processed raw materials and the load on the reactor equipment. Process management assumed the possibility of three typical situations, to which the current working situations were adapted.

The results of experimental studies confirmed the validity of the proposed developments and showed their effectiveness. It should be noted that the evaluation of the effectiveness of the presented developments in comparison with known published analogues is not possible, due to the lack of such.

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