Construction of automated optimal control systems with elements of artificial intelligence

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Article Info

ABSTRACT

This article examines the widespread introduction of artificial intelligence technologies, means of their implementation and support as a determining factor in the development of scientific and technological progress. On this basis, various advanced objects of various functional purposes are created, which are characterized as "smart". Their distinguishing feature is the ability to implement a "reasonable" way of functioning, taking into account the prevailing circumstances. This ability is expressed in the fact that in the object automatically, i.e., without human participation, or with minimal human participation, the most rational or optimal modes of functioning are supported, the definition of which involves the performance of operations containing signs of rational activity. This "smart" behavior of technical objects is mainly determined by the "intelligent" functioning of the control systems built into them. In particular, intelligent automated systems for optimal control. In accordance with this, the development of new approaches and methods that expand the possibilities of building such control systems should be considered as an urgent and priority task.
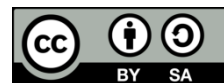
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1. INTRODUCTION

The presented method aims to address the challenges associated with constructing automated optimal control systems that incorporate elements of artificial intelligence, specifically targeting the management of highly complex technical objects such as complex technological systems (CTS). CTS control objects encompass extensive industrial facilities, including completed production units, production complexes, associations, and intricate technological processes with multiple elements, numerous operational parameters, periodic multifunctionality, variable structures, and other forms of increased complexity [1], [2].

The control problems encountered in CTS exhibit a high level of complexity due to the need to consider a vast array of parameters that exhibit intricate and diverse interrelationships. Consequently, the conventional approaches and methods used in creating automated control systems for CTS often face significant challenges, rendering them impractical or excessively resource-intensive, leading to substantial economic costs. Thus, there is an imperative to develop specialized approaches and management techniques that can alleviate or mitigate these difficulties [3].

2. THE PROBLEM STATEMENT

The mathematical basis of the proposed approach is the situational decomposition method [4], the idea of which is as follows. The task of CTS management in a general form can be formulated in the form of (1).

$$F(x, u, y, t) \rightarrow \max_{u(t)}, \boldsymbol{u(t)} \in \boldsymbol{U}, \boldsymbol{y(t)} \in \boldsymbol{Y} \tag{1}$$

If we assume that in this problem the change in perturbations x(t) has the character of a piecemeal-constant function, then in the period T, maintaining a constant value of x(t)=const, it will be equivalent to a problem of the form:

$$F(x, u, y) \rightarrow \max_{u \in U} U = \left\{ u : \begin{array}{l} g(x, u, y) = 0 \\ \\ h(x, u, y) \geq 0 \end{array} \right\} \tag{2}$$

where F is a given scalar function, identified with the criterion of optimality of the technological regime; x, u, y-vectors of disturbing influences, controls and outputs; U is the set of admissible states; g-a given vector-valued function corresponding to the mathematical model of the CTS; h is a vector-valued function that sets restrictions on technological parameters in accordance with technological regulations. The indicated assumption about the piecewise constant nature of x(t) is quite legitimate, since the main disturbing influences in the CTS arise when the quality indicators of raw materials change, or when the loads on the equipment change, which are set unchanged for a sufficiently long period. Thus, during the operation of the CTS, problem (1) can be reduced to consistently solved static problems (2).

In ordinary practice, the control system operates with a vector of control parameters u, the component composition and structure of which remain unchanged. Changes are possible only in the values of the elements of this vector. On the whole, the structure of the control problem remains unchanged (2). Thus, the development of control decisions is always based on the solution of essentially the same problem [4]–[6]. Simultaneously, an alternative approach can be adopted, involving the alteration of the initial control problem (2) during control decision-making regarding variable composition, objective function, mathematical models employed, and considered constraints. This modification aims to streamline the problem by minimizing the number of variables and transforming the objective function and constraint conditions accordingly. Despite these changes, the modified problem remains equivalent to the original. Importantly, this modification may lead to a structural transformation of the CTS control problem (2) during decision-making moments.

The outcome of this transformation should enable effective resolution of the modified problem using conventional methods, within a control system that does not impose stringent requirements on computing device performance. This allows for a form of problem decomposition (2), as it is reduced to a set of simplified problems solved independently. This decomposition, implemented in a temporal manner rather than spatially, should not be misconstrued as directly incorporating the time factor in the problem. Instead, it merely reflects the subsequent modification of the control problem [7], [8].

During the process of control decision-making, the proposed method focuses on analyzing and taking into account the various scenarios that can occur within the CTS. In this context, the term "situation" refers to a general quality of the existing state as well as the degree to which the CTS can be controlled at any particular instant. It is possible to define it by a range of state coordinate values, the elements that have undergone incremental changes, the magnitude and sign of these changes, the degree of correspondence between calculated and actual CTS state parameters, and the level of compliance with current restrictions. By conducting an analysis of the current circumstances, one can more easily determine the relevant variables for the CTS control problem, as well as the structure of the objective function, the model, and the constraint conditions. As a consequence of this, variables that are deemed to be insignificant are eliminated, and the objective function, mathematical model, and constraints are appropriately modified and simplified. This ultimately leads to a general reduction in the complexity of the control problem. In contrast to traditional decomposition methods [9]–[11], the proposed method does not impose any specific requirements on the structure of the control problem, the objective function, or the conditions that are taken into account, which is one of the most significant advantages of the method. Therefore, this method can be used to solve virtually any optimal control problem; the most important requirement, however, is the capability to recognize and distinguish between the various developing circumstances that exist within the control object.

3. METHOD

Let's delve into the essence of the proposed approach, known as the situational decomposition method or situation decomposition. Drawing an analogy to dynamic programming [12], this method also

entails transforming a dynamic control problem into a series of sequentially solved specific static problems. However, unlike classical decomposition methods, these specific problems do not pertain to the control of individual subsystems within the CTS. Moreover, they do not manifest as elements of a recurrent equation, as seen in dynamic programming. Instead, these partial problems represent an equivalent modification of the overall static control problem and arise from its simplification by eliminating insignificant variables. As a result, the number of variables considered decreases, and the objective function and constraint conditions are simplified accordingly [13], [14].

Consequently, the original static control problem (3) is transformed into a collection of simpler partial subtasks, each corresponding to a specific situation within the CTS. A key challenge emerges in recognizing these situations within the control object to address the corresponding specific problems effectively. The issue of scenario recognition can be considered as a coordination challenge, whereas each individual difficulty can be viewed as a problem of localized control.

The challenge of situation recognition can, in general, be stated as follows:

$$(\overset{o}{x}, \overset{o}{u}, \overset{o}{y}) : \overset{R}{\to} i, \overline{D_i} \tag{3}$$

where $\overset{o}{x}, \overset{o}{u}, \overset{o}{y}$ -values that are particular to the input variables x, controls u, and outputs y of the CTS, in that order; i-situation number; D_i-the set of variables of the control problem (2), taken into account in the i-th situation, $Di \subset D = X \cup U \cup Y$; X, U, Y-sets of variables x, u, y, respectively; R is the operator for mapping a vector $\left(\overset{o}{x}, \overset{o}{u}, \overset{o}{y}\right)$ into a pair $i, \overline{D_i}$. The significance of this issue lies in the fact that the vector of the current values of the variables x, u, and y at the time when the control decision is being made, by means of the operator R, is mapped into the situation with the number i and the set of variables $\overline{D_i}$ of problem (2), which are relevant to the circumstance that has the number i. The values of the functions f, g, and h are not taken into consideration because the values of their arguments *x, u,* and *y* are the only thing that can determine those function values. When the *i*-th scenario is taken into consideration, a specific control problem for the CTS can be expressed as the form.

$$Fi(xi,ui,yi) \to \max ui \in Ui \subset U$$
$$U_i = \left\{ u_i : \begin{array}{l} g_i(x_i, u_i, y_i) = 0 \\ \\ h_i(x_i, u_i y_i) \geq 0 \end{array} \right\} \quad \cup Ui = U, \, i=1,2,...,N, \tag{4}$$

where *i* is the number of the circumstance that is occurring right now; *N* is the total number of situations that could occur; y_i, x_i, and u_i are modified vectors of the CTS's inputs, controls, and outputs, respectively; modified objective function is denoted by "Fi". Because of the different functions, U_i represents an updated version of the possible solutions to the issue. g_i, h_i; the collection of possible solutions to the general problem is denoted by the letter U. The solutions to problems three and four are assumed to involve a two-level structure. As a consequence of this, the CTS control system that is used to implement it gains a structure with two levels [15]–[17].

Here, CTSi, i=1, 2,...,N, represents modified CTSs corresponding to the i-th situations, where CB denotes the coordinating body, and CS is a control system tasked with solving the modified control problem for the CTS. Within this control system, CB evaluates the current situation i within the CTS by identifying it from the set of considered situations {1,2,...,N}. It then constructs the structure of the modified problem (4) based on the original problem (2) by excluding variables of minor significance. The component-wise composition of the vectors x_i, u_i, y_i in problem (4) may differ and represent, in each unique case $\overline{D_i}$, a subset of the complete set of variables D. The modified vectors x_i, u_i, y_i formed in this manner, encompass only the most effective components relevant to the specific situation being considered.

The aforementioned control principle can be understood as being comparable to adaptive control [18], which similarly involves a change to the control problem. On the other hand, adaptive control restricts the scope of the alteration to the mathematical representation of the control object, and it only puts it into action when there is a reduction in the model's accuracy. The structure of the model and the management duties, in their whole, continue to be the same; the only thing that changes are the parameters of the model, which are modified by adjusting the coefficients of the variables. The situational decomposition method, on the other hand, differs by identifying the situation within the control object instead of focusing on the mathematical model of the control object. Subsequently, the original control problem is replaced with a modified problem tailored to the specific situation. In this case, the structure of the modified control problem (4) can vary across its components. As a result, the control system responsible for solving this problem adopts a variable structure [19].

The identification of situations at the control object requires the formulation and solution of the problem of their recognition. The content and method of solving this problem depend on the specifics of the object under consideration, as well as the criteria used, according to which the situations to be taken into account during control are differentiated. It is essential to recognize that the reduction of the CTS control issue (2) to a particular subproblem (4) with fewer variables, simpler circumstances, and an objective function invariably leads to some level of coarsening. This is one of the reasons why it is necessary to recognise this fact. In the general case, we are unable to provide a guarantee that the solutions to issues (2) and (4) would completely coincide with one another. It is only feasible for there to be a coincidence up to a certain margin of error. Therefore, when examining the similarities between problems (2) and (4), it is important to keep in mind that they both occur within certain limitations and may be evaluated utilizing a wide variety of indicators that comply with the standards.

Despite this, the actual implementation of situational decomposition is not hampered in any way by the reality in question. When dealing with actual control systems, it is generally unnecessary to pinpoint the precise value that is optimal. Instead, it is often sufficient to use an approximation of the optimal solution, which is represented by an arbitrary point within a given proximity of the optimal solution. As a result, the solution will invariably be imperfect in some way. In this regard, it is permissible for there to be a difference in the solutions to issues (2) and (4) so long as that difference does not go beyond a certain threshold. A very accurate solution to the control problem is not necessary since the execution of results at the control object utilizing automatic control systems and technical executive devices always entails an error that is greater than the error in solving the control problem [10], [20]. In addition, achieving a highly accurate solution to the control problem is not required.

The method of situational decomposition that was proposed is fundamentally different from the traditional decomposition methods in that it involves a single unique (local) control problem, which can also modify its structure. This is one of the ways in which it differentiates itself from traditional decomposition methods. In addition to this, it does not rule out the possibility of applying the principles of decentralized administration to the object that has been modified. As a direct consequence of this, a combined control system is produced, which in turn implements a space-time decomposition of the CTS control issue [21].

4. RESULTS AND DISCUSSION

The primary challenge in implementing the proposed method lies in constructing a mapping operator, denoted as R, to identify current situations. It is typically difficult to specify this operator analytically, particularly in the form of a function R (x, u, y), as it is challenging to establish patterns connecting continuously changing variable values with discrete situation numbers. As a result, numerical procedures are commonly employed to selectively extract situation features when specifying the operator R. This results in the necessity for complicated computational schemes or the development of expert systems because the number of possible scenarios is typically very large, and the thorough definition of each scenario necessitates taking into consideration a great deal of information. When this occurs, an intelligent component is included into the system that is being controlled.

Another challenge involves determining the composition of significant variables $\overline{D_i}$, to be considered in the modified problem (4) for each situation number i. This selection process entails assessing the sensitivity of output variables y_i to changes in control variables u_i permitted in the i-th situation, given a specific value of x_i. It may also involve solving an additional problem of identifying the optimal structure of the CTS model. To address these challenges, it is suggested to focus on typical situations rather than considering all possible situations. Typical situations are those that systematically arise in the behavior of the CTS and possess clearly distinguishable features. The use of typical situations is predicated on the concept that, under actual production conditions, it is frequently possible to conduct an analysis of the CTS and to systematize typical scenarios related to control decisions. This is the reasoning behind the use of typical situations. Furthermore, the totality of the conceivable scenarios can be broken down into subsets in such a way that the circumstances of the present can, to an error margin that is deemed to be acceptable, be interpreted as corresponding to individual examples of typical scenarios or combinations of these scenarios.

It is possible to predefine modified control problems (4) for each and every typical scenario by taking into account only the important variables and conditions imposed by the restrictions. Additionally, attribute systems can be constructed to identify each specific typical situation. Sequentially enumerating these attribute systems ensures the identification of the current typical situation. When the current circumstance cannot be unambiguously linked to one of the typical situations, the quality of management can be improved by examining two or more typical scenarios simultaneously. In such circumstances, there should be a mechanism in place to identify common factors for crossing situations. This would allow for the formation of the variable composition of the modified control problem, which would involve adding the

private variables of the relevant situations that are being taken into consideration. In real CTS control systems, the need to develop and implement control decisions is most often associated with the occurrence of disturbing influences, which are caused by a change in the values of the quality indicators of the processed raw materials, or by a change in the loads on technological equipment, identified with the input parameters. In accordance with this, the assessment of situations can be carried out by the values of the input variable x. For this case, the following version of the situational decomposition is proposed.

Let the behavior of the CTS in time allow it to be considered as a sequence of stationary states of the CTS in space $X \times U \times Y$. Each stationary state of the CTS corresponds to a certain vector (x, u, y), where $x \in X, u \in U, y \in Y$. The accepted assumption means that the disturbing effect x(t) has the nature of a piecewise constant function and can be represented by a sequence of discrete values $x(t) = x_1, x_2, \dots, x_N$. If these discrete values x(t) are identified with the moments of making control decisions, problem (1) can be reduced to a sequence of partial static problems of the form

$$f(x_i, u, y) \to \max_u \quad \begin{matrix} x_i \in X, \quad u \in U, \quad y \in Y, \\ i = 1, 2, \dots, N, \end{matrix} \qquad (5)$$

where N is the number of situations to be considered.

Problems (5) are completely autonomous, since they are not related to each other. Therefore, they can be formulated as

$$f(x_i, u_i, y_i) \to \max_{u_i} \quad \begin{matrix} \boldsymbol{x_i \in X, \quad u_i \in U, \quad y_i \in Y,} \\ \boldsymbol{i = 1, 2, \dots, N.} \end{matrix} \qquad (6)$$

Each of the problems (6) can be interpreted as a particular or local control problem for the CTS for the i-th situation, determined by the value xi. Thus, the original CTS control problem (1) turns out to be reduced to N particular problems (6) for the situations taken into account by inputs. The problems stated in (6) represent specific variations of the general static CTS control problem (2). It should be acknowledged that certain problems may be considerably intricate, posing challenges in terms of ensuring timely decision-making within the intervals between the considered situations. Addressing these complexities, it may be feasible to pre-solve the problem and store the solution in the computer's memory. This way, when required, the solution can be retrieved without directly solving the control problem. This approach is particularly suitable for recurring situations.

Memorization and automatic reproduction of ready-made solutions in relation to specific situations can be considered as the ability of a control system to self-learning, which is one of the manifestations of the property of intelligence. In the overall scenario, the potential number of situations N can be significantly large, as it depends on the dimension of the vector x, the various combinations of its components x_i, and the discrete values that each component can assume. Suppose the dimension of the vector x is n, and there are m possible discrete values for each component x_i. In that case, the total number of situations to consider will be influenced by the ratio.

$$N = \sum_{i=1}^{n} i \cdot m \cdot \frac{n!}{i!(n-i)!}. \qquad (7)$$

As you can see, even for insignificant values of n and m, the number of possible situations N will be quite large. In CTS control problems, which are characterized by large dimensions and significant ranges of possible values of variables, the number of situations can turn out to be so large that their complete accounting will turn into an intractable problem that complicates the practical application of the method under consideration. In such cases, the way out of the difficulty can be the use of typical situations, which were mentioned above [17], [18].

In the context being discussed, a typical situation is characterized by the effectiveness of only a specific subset of the control vector components u. In other words, only these components have a tangible impact on the state of the CTS and are considered as variables, while the remaining components are treated as constants. This simplifies the solution to the STS management task. It is evident that managing using typical situations aligns with the principles of human management. To formalize the coordination problem of situation recognition, the following approach can be adopted. Let D represent the set of situations considered in problem (2), each corresponding to its own composition of effective variables. Suppose that the set D can be divided into L subsets D_k, where k=1, 2, ..., L, representing typical situations. All current situations are

assessed for their belonging to a specific set D_k, and problem (7) is replaced by an equivalent problem for the typical situation D_k.

The division of set D into subsets D_k, where k=1, 2, ..., L, can be carried out in various ways, such as based on the formation of a system of distinctive features of typical situations. These distinctive features can include the values of the vector variable components, the indices of the components that experienced changes, the magnitude and direction of these changes, and other quantitative assessments. In the simplest case, distinct typical situations will have no intersections, i.e.,

$$D_k \cap D_j = \emptyset, \text{ for } k=1, 2, ..., L; j=1, 2, ..., L; k \neq j \tag{8}$$

This implies that during the management process, only certain pure typical situations will occur. However, such a clear distinction between typical situations is the exception rather than the norm. In general, condition (8) is not satisfied, meaning that for some current situations, there may be indications that correspond to different typical situations. In such cases, all typical situations for which an intersection occurs must be taken into account in the specific problem at hand.

Calculating all of the distinctive elements of the current scenario and comparing them with the systems of indicators for individual usual circumstances is the first step in determining whether or not the current circumstance falls into the category of a typical one. When all of the indicators are consistent with one another, it will correspond to a specific typical scenario. The absence of such a typical situation shows that the current circumstance belongs to overlapping typical situations, which are situations in which there are differentiating qualities that simultaneously belong to multiple separate typical situations. When this is taken into consideration, the coordination problem can be stated as identifying the differentiating elements of the current situation that correspond to distinct typical circumstances, and then proceeding to combine the situations that cross. This is the most general case of the problem. The following is one possible way to phrase this task:

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

$$\exists k = 1,2,\dots,L; \ p_s \in P_k, s = 1,2,\dots,S \Rightarrow d = 1; \ b_{ks} = 1; \ a_k = 1$$

$$\bar{D} = \cup \bar{D}_j, j = 1,2,\dots,L \tag{9}$$

d, b_{ks} and a_j are auxiliary variables used as indicators; p_s is the s-th sign of the situation; P_k is the set of distinguishing features of the k-th typical situation; D⁻ represents the set of effective variables considered in the modified control problem; $\bar{D}_i$ - represents the intersecting sets of typical situations where $a_j \neq 0$.

The essence of this problem lies in determining if there exists a k-th typical situation, characterized by the features defined by the set P_k, that coincides with the features of the current situation p_s. The number of coinciding features is calculated while simultaneously keeping track of the number of the typical situation [19], [20]. In this case, all typical situations that exhibit the specified coincidence of signs are taken into consideration. The set of effective variables $\bar{D}$ for the modified control problem is formed by combining the sets of effective variables for the intersecting typical situations $\bar{D}$.

If there are no features that cross with one another, then the solution to problem 7 is to perform a sequential enumeration of systems of features of typical circumstances Pk in order to locate a system that completely matches the features of the current scenario. The following is one possible way to phrase this task:

$$d = 1 \Rightarrow \sum_{s=1}^{S} b_{ks} \to \max_k, k = 1,2,\dots,L; \bar{D} = D_{k^*} \tag{10}$$

The solution to problem (8) is given by k = k*, where the sum of significant features of a typical situation $\sum_{s=1}^{S} b_{ks}$ is maximum. Accordingly, the set of variables considered for the modified control problem is D_{k^*}. The local low-level problem corresponding to the general control problem (2) and modified according to the specific typical situation can be represented as:

$$F_i(x_i, u_k, y_i) \to \max_{u_k \in U_k} \ U_k = \left\{ u_k : \begin{matrix} g_k(x_i, u_k, y_i) = 0 \\ h_k(x_i, u_k, y_i) \geq 0 \end{matrix} \right\} \cup U_k = U \ , i = 1,2,\dots,N \tag{11}$$

where i represents the number of the current situation, k is the number of a typical situation, $i \in \{1,2,\dots,N\}; k \in \{1,2,\dots,L\}$. The presented method for solving problem (2) can be characterized as a

decomposition method based on typical situations. Therefore, the control system that implements this method resembles a decentralized situational control system.

The method can be viewed as projecting the original problem onto the subspace of equivalent subproblems for specific situations or projecting the set of feasible solutions U of the original problem onto the subsets U_k, where k=1, 2, ..., L. In this sense, an analogy can be drawn with the coordinate-wise search method in nonlinear programming, also known as the Gauss-Seidel method [8]. The essence of this method lies in solving a multidimensional optimization problem by sequentially solving simple one-dimensional problems resulting from the projection of the original problem into a one-dimensional subspace. In the considered case, a similar technique is employed, with the only difference being that the original problem is projected into different subspaces of lower dimension each time [21]–[25]. It is abundantly clear that if issue (2) is convex, it will continue to be convex in whatever subspace of the variable space that the problem utilizes. As a consequence of this, the possibility of a solution that is free from ambiguity is ensured. In the event that the required property of the problem is not satisfied, the solvability of the problem, both in its initial formulation and in any modified equivalent formulation, is contingent on the efficacy of the algorithms that are applied. In situations like these, efficient algorithms that can handle multi-extremal issues should be utilized; alternatively, the problem should be solved multiple times using a variety of distinct starting points.

5.   CONCLUSION

The proposed method of situational decomposition offers a means to develop efficient automated optimal control systems for CTC-class industrial facilities. These control systems incorporate elements of artificial intelligence, as they consider the prevailing circumstances at the controlled object when generating control decisions in each specific case. Consequently, it is unnecessary to utilize the complete set of control object parameters, only those that are effective in the given situation are considered. As a direct consequence of this, it is possible to drastically reduce the total number of variables in the resultant control problem in comparison to the total number of variables in the initial problem. Because the control problem has been simplified in this way, the number of computational resources that are needed to locate a solution has been cut down. In the end, it improves the overall quality as well as the efficiency of the management process while simultaneously minimizing the overall costs that are associated with the creation and operation of an automated control system. The validity of the suggested method has been established through the use of computer simulations of a control system that is based on the situational decomposition method. These studies have also shown that the proposed method is highly effective.

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