Development of similarity theory for control systems

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Abstract. The area of effective application of the traditional similarity theory and the need necessity of its development for systems are discussed. The main statements underlying the similarity theory of control systems are given. The conditions for the similarity of control systems and the need for similarity control for control systems are formulated. Methods and algorithms for estimating and similarity control of control systems and the results of research of control systems based on their similarity are presented. The similarity control of systems includes the current evaluation of the degree of similarity of control systems and the development of actions controlling similarity, and the corresponding targeted change in the state of any element of control systems.

1. Introduction

Development and implementation of control systems are associated with the need for a wide application of modeling methods and, accordingly, models of objects and control systems. Adequacy and / or similarity indicators are used to evaluate the effectiveness of models, one of the important requirements for the model is to ensure the transfer of the results of model solutions to the original (full-scale control system) and its components.

According to the definitions of similarity and adequacy in [1, 2], the similarity is “a correspondence between the original and the model, under which the rules of the transition from model parameters to object parameters and vice versa are known, and the mathematical description (if it is known or can be obtained) can be transformed into an identical form”. In its turn, the adequacy of the model is “its ability to display the specified properties and conditions of the object’s operation with the required accuracy”. From this it follows that the similarity of objects and control systems is a more general concept than adequacy, and includes not only an assessment of the proximity of the model and the original, but also the procedures (methods, rules) of transition from model parameters to original parameters and vice versa.

Particularly important is the requirement to transfer the solutions obtained in the model system to the full-scale one in cases when their coordinate and time dimensions do not coincide. In particular, when in the model system the controlled part is the physical model of the full-scale object. In such cases, the concept of adequacy of the model becomes insufficient for a well-founded transfer (recalculation) of model solutions to full-scale systems.

2. Features of the application of similarity theory for control systems

Recalculation of the results obtained from one system to another in theory and practice of control occurs quite often in the following classes of problems:
• research of processes (technical, socio-economic, etc.) on different types of models for the creation of new processes and aggregates, productions, organizational structures [3];
• directly in control in classes of structures of control systems with predictive models, for example, [4];
• in field tests and adjustment of control systems, in particular [5].

Thus, based on the definitions given in [1, 2], we can conclude that a reasonable transfer (recalculation) of results from one control system to another is possible only if they are similar. To determine the similarity of the design characteristics of uncontrolled objects and the processes of energy and substance conversion that take place in them, the methods and criteria of the traditional similarity theory are now well developed and widely used [1]. However, they can not be successfully used to determine the similarity of control systems [6], which requires significant improvements and development, not only for the systems as a whole, but also for their main components [6, 7].

This conclusion is also confirmed by the fundamental difference in the structure of mathematical models used in the traditional similarity theory and control theory. The modern theory of similarity relies on mathematical models of fundamental disciplines [1]. But in the theory and practice of automatic control systems development, a special class of models is used that differs significantly “from models used in such fundamental disciplines as physics, chemistry” [8] and reflecting “the most important properties of the control object with respect to predefined input and output variables” [8]. In other words, they should jointly display both the dynamics of the channels for transforming external actions, and the properties of the actions themselves [9].

At the same time, it is possible to note particular examples of the application of certain similarity indices in solving engineering problems of analysis and synthesis of control systems. First, it is the ratio of the time of pure lag to the time constant of inertia, used, in particular, in engineering methods of selecting and tuning regulatory laws [10]. Second, when estimating the effective work areas of control systems with feedback, the time of the net delay of the dynamic channel for converting the control actions is compared with the interval of the autocorrelation function decrease of the perturbation object brought to the output [10].

3. Basic ideas of the similarity theory of control systems

Studies related to the development of similarity theory with respect to control systems should target, in our opinion,
- development of the basic concepts and axioms (in particular, in the form of statements) of similarity of control systems reflecting the required properties of not only such control systems as a whole, but also its individual components, including external influences;
- the development of procedures, methods and algorithms for estimating and controlling the similarity of control systems, which, of course, allow the research and adjustment problems of one such system (for example, model) to be solved, and then the results to another to be recalculated;
- application of the developed procedures, methods and algorithms for full-scale (technical, socio-economic and other) systems to effectively solve specific control tasks.

The following statements are the basis for the development of similarity theory of control systems.

Statement 1. Control systems are similar if the performance indicators (criteria) of their operation are equal to the specified value.

This statement for the j-th and l-th control systems can be written in the form

$$\left\| q_j^n(t-T),t \right\|_\delta - q_l^n(t-T),t \right\| \leq \delta q_j^n; \quad j \neq l; \quad j = 1, J; \quad l = 1, L,$$

(1)

where $\left\| \right\|$ is the measure of proximity; $q_j^n(t-T),t \right\|$ and $q_j^n(t-T),t \right\|$ – the values of the normalized target indicators of functioning at a given time interval $T$, respectively, of the j-th and l-th control systems; $t$ – continuous or discrete time; $\delta q_j^n$ – the value determined by the maximum
permissible (specified) threshold of proximity of the normalized indicators $q^n_j \{ (t - T), t \}$ and $q^n_l \{ (t - T), t \}$, for which the effectiveness of these systems is assumed to be the same; $J$ and $L$ — the number of control systems.

Rationing of target indicators is carried out, for example, by the expression

$$q^n \{ (t - T), t \} = \frac{q \{ (t - T), t \}}{q_{\text{max}}},$$

(2)

where $q_{\text{max}}$ — the maximum possible value of the target indicators of control systems.

Statement 2. The degree of similarity of control systems is a quantitative measure of proximity of performance indicators of these systems control.

An example of the method of quantitative estimation of the similarity degree is the method of correlated processes described in [11], where it is proposed to “establish the degree of correspondence between the initial and simplified systems ... by the correlation moments of statistical values of the probability characteristics” of these systems. In addition, the degree of similarity can be estimated on the basis of relation (1).

Statement 3. The objects in control systems are similar if they satisfy the conditions for a joint similarity of controlled and uncontrolled external effects and dynamic channels to their transformation. This condition is written in the form of equality with a specified small number of effects of changes in the input actions on the output actions of the control object.

Uncontrolled effects can be estimated by calculation or experimentally by bringing them to the output [10] or to one of the control inputs [12] of the control object.

The condition of similarity is written, for example, using the following equations

$$\| o^n_j \{ (t - T), t \} - o^n_l \{ (t - T), t \} \| \leq \delta o^*; \ j \neq l; \ j = \overline{1, J}; \ t = \overline{1, L};$$

(3)

$$o_j \{ (t - T), t \} = \int_{t - T}^t \varphi_j (\theta) \{ j (t - \theta) \} d\theta;$$

(4)

$$o_l \{ (t - T), t \} = \int_{t - T}^t \varphi_l (\theta) \{ l (t - \theta) \} d\theta;$$

(5)

$$i(t) \in \{ c(t), e(t), o(t) \},$$

(6)

where $i(t)$, $e(t)$, $c(t)$, $o(t)$ — are respectively the input, external, control and output actions of the control object at the moment of time $t$; $T$ is the interval for estimating the response of the control object to the change in the input actions; $\varphi_j \{ \}$ — the dynamic operator of the conversion channel of input into output actions; $\delta o^*$ — the value determined by the maximum permissible threshold of proximity of normalized values $o^n_j \{ (t - T), t \}$ and $o^n_l \{ (t - T), t \}$; $\theta$ is an auxiliary variable; $J$ and $L$ are the number of control systems.

If the conditions for the similarity of control systems, for example, according to the relation (1), are not satisfied, then the degree of similarity of the control systems under consideration is calculated. Quantitatively, it can be estimated either by a measure of the difference $\delta q^n_j$, obtained by the relation (1) in dimensionless form, or by the correlation coefficient between the target indicators reflecting the efficiency of these systems functioning [11]. If the value of the similarity degree of the $j$-th and the $l$-th control systems does not correspond to the required one, then the possibility of achieving similarity of
control systems due to the subsequent target change in the properties of the \( j \)-th and \( l \)-th control systems and their actions is estimated. The process of action on the control systems and their individual components aimed at fulfilling the similarity conditions will be called the similarity control of systems and their components.

Similarity control of control systems is based on the following statements.

Statement 4. Control systems are potentially similar if the exact or approximate equality of the values of their target indicators (criteria) of control efficiency can be achieved due to the targeted impacts on the change in the dynamic properties of systems as a whole and (or) their elements, including external actions.

Statement 5. Control objects are potentially similar if the condition of joint similarity of their objects and input actions on a finite interval of time \( T \) can be achieved due to targeted actions on the change in the dynamic properties of controlled and uncontrolled external actions and channels for their transformation.

Statement 6. Control systems are fundamentally not similar if the exact or approximate equality of the values of their target indicators (criteria) of control efficiency can not be achieved due to targeted actions on the change in the dynamic properties of systems as a whole (without changing their structure) and / or their elements, including external actions.

4. The results of development of the similarity theory of control systems

The statements formulated are the basis for the development of methods and algorithms for evaluating and controlling the similarity of control systems and, accordingly, for the research of control systems based on their similarity.

It is assumed that all the structural diversity of control systems can be represented in terms of their similarity in the form of three classes: similar, potentially similar and fundamentally different control systems.

The process of control of systems similarity includes the current estimation of the similarity degree of control systems and, if similarity is violated, the development of control actions by the similarity that purposefully changes the state of any element of control systems. It should be noted that such purposeful change in the properties of one of the control systems can significantly expand the field of effective application of model control systems in solving practical problems, in particular, related to the study and adjustment of full-scale systems.

5. Conclusions

1. Transfer of the results of development and research (adjustment) from one control system to another is justified only if they are similar.

2. Statements based on the equality or proximity of the values of performance indicators of control systems are expedient to use for the creation of procedures, methods and algorithms of estimating and controlling similarity.

3. Similarity control of systems makes it possible to ensure the fulfillment of similarity conditions for potentially similar control systems and, thus, to expand the area of effective application of methods and algorithms for their development and research.

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