Secondary similarity criteria in intelligent information technologies for optimal system control*

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Abstract

The paper considers approaches to determining secondary criteria and similarity indicators in modeling and optimal control of complex technical systems. It is shown that these criteria can be interpreted as informative features and used in intelligent information technologies, in particular in decision support systems, adaptive control algorithms, and digital twins. An algorithmic approach to integrating secondary similarity criteria into intelligent systems for optimizing the operating modes of energy and other technical objects is proposed. The study examines the mathematical formulation of optimal control problems in which objective functions and constraints are represented as polynomial expressions. Similarity criteria are derived from normalization of these expressions, and secondary criteria are introduced as ratios of primary criteria. Their invariance properties are analyzed for both defined and uncertain systems. Similarity indicators are also considered as scale-based analogues that enable parametric coordination between real objects and their digital models. A structured algorithm for integrating these criteria into intelligent information technologies is described. The approach reduces the dimensionality of optimization problems, increases the stability of control algorithms, and forms reference modes in digital twins. The results apply to optimal control of energy systems and other complex technical objects.

Keywords

intelligent information technologies, secondary similarity criteria, similarity indicators, optimal control, decision support systems

1. Introduction

1.1. Background and motivation

The modern development of intelligent information technologies necessitates the creation of effective methods for analysis [1], modelling [2], and optimal control of complex technical systems [3–5]. Problems related to adaptive control [6, 7], digital twins [8, 9], and decision support systems [10, 11], where the information interpretation of system state parameters plays a key role, are of particular relevance.

In the theory of similarity and modeling, similarity criteria are widely used, which allow establishing correspondence between real processes and their mathematical models. At the same time, secondary similarity criteria are important in optimal control problems, which determine stable relationships between the components of objective functions and constraints [12, 13].

In this work, secondary similarity criteria and indicators are considered not only as mathematical characteristics, but as elements of intelligent information technology that can be used to form algorithms for optimal and adaptive control of system states.

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1.2. Problem statement and relevance

An important feature of secondary similarity criteria is their ability to integrate heterogeneous information about the system state, operating conditions, and external influences into a unified formal representation. This makes it possible to reduce the dimensionality of control problems and to identify invariant relationships that remain stable under changes in system parameters. Such properties are especially valuable in the analysis of complex, nonlinear, and poorly formalized systems, where classical control approaches become ineffective or computationally expensive [14, 15].

In intelligent information technologies, secondary similarity criteria can be interpreted as informational indicators that reflect the degree of correspondence between current system states and reference or optimal regimes. On this basis, decision-making mechanisms can be formed that adapt control actions in real time, taking into account uncertainty, incomplete data, and dynamic changes in the environment [16–18]. This approach is particularly relevant for the development of adaptive control systems and digital twins, where continuous comparison between a physical object and its virtual model is required.

The use of secondary similarity criteria also contributes to improving the robustness and stability of optimal control algorithms. By embedding these criteria into objective functions and constraint systems, it becomes possible to ensure coordinated changes of control variables and system parameters, preventing critical deviations and undesirable operating modes [19, 20]. As a result, control strategies based on similarity principles demonstrate increased reliability and flexibility in comparison with traditional methods.

Thus, the consideration of secondary similarity criteria as elements of intelligent information technology opens up new opportunities for the synthesis of optimal and adaptive control systems. Their application allows not only to improve the accuracy of system simulation and state assessment, but also to create knowledge-oriented control algorithms capable of self-adjustment and learning [1, 2, 21]. This determines the relevance of further research aimed at developing methods for constructing and using secondary similarity criteria in modern intelligent control systems.

2. Related works

2.1. Similarity measures and criteria in control systems

The concept of similarity between dynamical systems has been explored in several recent studies. Wang and Meng [1, 5] proposed a data-driven framework for learning and control based on behavioral similarity between heterogeneous systems, establishing a theoretical foundation for similarity-based control without direct system identification. Pirastehzad, van der Schaft, and Besselink [11] introduced a (γ,δ)-similarity concept for non-deterministic linear systems, providing a rigorous comparison framework for uncertain systems. This approach aligns with the secondary similarity criteria proposed in our work, which also aim to capture invariant properties of optimal system states.

In the context of optimization, Huang and Wang [20] developed a similarity measure between functions with applications to statistical learning and optimization, demonstrating that similarity metrics can guide parameter selection and improve algorithm performance. Akdağ and Can [6] applied Pythagorean fuzzy similarity measures for tuning controller parameters, showing that similarity-based decision-making can effectively handle uncertainties in stable and time-delayed unstable plants.

2.2. Similarity in digital twins and model validation

Recent works have emphasized the importance of similarity metrics for validating digital twins and ensuring model fidelity. Tang, Zhuang, and Zhang [8] proposed an evaluation framework for domain-specific digital twin platforms, addressing key challenges in assessing twin validity. Abdessadak et al. [9] provided a systematic review of digital twin technology and artificial intelligence in energy systems, highlighting the role of similarity indicators in model synchronization.

Lugaresi et al. [15] focused on online validation of digital twins for manufacturing systems, presenting a methodology for measuring similarity between real and simulated data streams. Ding et al. [17] conducted a comprehensive review of digital twins in smart industries, covering concepts, trends, and challenges. Colarusso et al. [18] introduced a “Predicted In-Sync Digital Twin” for fast decision-making, leveraging similarity-based predictions to reduce latency.

2.3. Similarity indicators for optimization and control

The use of similarity indicators in control optimization has been investigated from various perspectives. Lefebvre [22] explored probabilistic control and majorisation of optimal control, providing theoretical insights into how similarity relationships can simplify complex optimization problems. Hromatko et al. [23] demonstrated direct transfer of optimized controllers to similar systems using dimensionless Model Predictive Control, showing that similarity indicators can significantly reduce computational effort.

Kargaran et al. [10] provided an analytical derivation of alarm similarity measures, which can be interpreted as informational features for decision support systems. Fan [12] and Badra et al. [14] explored similarity measure learning for case-based reasoning and analogical transfer, linking similarity theory to machine learning and intelligent decision-making.

While these works provide valuable contributions, most focus on specific applications or single aspects of similarity. Our study addresses the gap by proposing a unified approach to defining and integrating secondary similarity criteria as informational features in intelligent control systems. Unlike existing methods, our framework derives criteria directly from the structural properties of the optimization problem, making them interpretable, invariant, and applicable across different system classes.

3. Proposed methodology

3.1. Statement of the optimal control problem in the context of intelligent information technologies

In the development of intelligent information technologies, a key challenge lies in ensuring the efficient and adaptive operation of complex technical and socio-economic systems. Such systems are typically characterized by a large number of interrelated parameters, nonlinear dynamics, uncertainty in external influences, and conflicting performance criteria. Intelligent control methods aim to process heterogeneous information, support decision-making, and dynamically adjust system behavior in order to achieve predefined goals while respecting operational constraints [19, 20].

From this perspective, the use of optimal control theory provides a rigorous mathematical framework for modeling and solving decision-making problems in intelligent systems. By formalizing system behavior through objective functions and constraints, it becomes possible to systematically evaluate alternative control strategies and identify the most effective one according to selected technical and economic indicators. This approach enables the integration of optimization procedures into intelligent information technologies, ensuring rational resource utilization, improved system performance, and robustness under varying operating conditions.

Let us formulate the optimal control problem as follows [1, 7]:

minimize

$$f(x)=\sum_{i=1}^{m_1} a_i \prod_{j=1}^{n} x_j^{\alpha_{ji}}, \qquad (1)$$

under the conditions

$$g_k(x)=\sum_{i=m_k+1}^{m_{k+1}} a_i \prod_{j=1}^{n} x_j^{\alpha_{ji}} \le G_k, \quad k=\overline{1,h}, \quad x_j>0, \qquad (2)$$

where $f(x)$ – is some generalized technical and economic indicator of the process that is being optimized; $g(x)$ – is a limitation that establishes the permissible area of process research; a_i, a_{ji}, G_k – constant coefficients determined by the properties of the system; x_j – variable parameters of the system, the values of which are optimized; m_1 – number of members of the target function; m – the total number of members of the target function and constraints; n – number of shifters; h – number of restrictions.

Within the framework of intelligent information technologies, the task (1) and (2) is considered as the basis for forming an information model of the system state, where each member of the objective function and constraints can be interpreted as a separate information component [4].

The similarity criteria obtained by normalizing the members of the objective function, in this case, play the role of weight coefficients that characterize the significance of individual factors in the process of making an optimal decision.

In expressions (1) and (2), for the convenience of further analysis, a continuous indexation of the components of the objective function and constraints is adopted.

For tasks (1) and (2), two types of similarity criteria are possible depending on the selected base. According to the method of integral analogues, similarity criteria are determined by dividing all members of the equation by one of them. If we choose, for example, the *l*-th member as the base, then we obtain similarity criteria of the form:

$$\pi_i=\frac{a_i \prod_{j=1}^{n} x_j^{\alpha_{ji}}}{a_l \prod_{j=1}^{n} x_j^{\alpha_{jl}}}. \qquad (3)$$

If we take $f(x)$ as the basis, then the similarity criteria will have the form:

$$\pi_i=\frac{a_i \prod_{j=1}^{n} x_j^{\alpha_{ji}}}{f(x)}. \qquad (4)$$

In the last case, the similarity criteria, which refer to the objective function, contain weight coefficients and characterize the contribution of each member to the value of the optimality criterion. Similarity criteria, which refer to constraints, characterize the sensitivity of the optimality criterion. It is assumed that $\lambda_k = \sum_{i=m_k+1}^{m_{k+1}} \pi_i$ are the normalized Lagrange multipliers of the k-th constraint [8].

It is obvious that the second form of similarity criteria is mainly used in optimal control problems, since they are more informative in this case. Especially when the similarity criteria are determined for the extreme value of the optimality criterion according to problem (1) and (2). In this case, each similarity criterion shows which particle the corresponding member of the objective function contributes to the optimal value of the optimality criterion.

From the expressions of the form (4), a system of equations relative to variables x_j can be formed from which, under the condition of optimality, optimal values are determined. x_{j0}. This is the so-called inverse problem of criterion programming [16].

Depending on the form of the target function expression and constraints, as well as the ratio of the number of members m and the number of variables n, the given problem is solved by different algorithms. When problem exists in an analytical form, i.e. known coefficients a_i, a_{ji}, then two cases are possible: $s = m - n + 1 = 0$; $s = m - n + 1 > 0$.

In (1) and (2) there may be known indicators of the degree a_{ji}, which determine the nature of the dependences f and g, and the coefficients a_i are unknown or partially known, or given by the possible range of existence.

In this article, algorithms for solving analytically formulated problems with a measure of complexity $s = 0$ and $s > 0$ are considered.

3.2. Definition of secondary similarity criteria as information features

The optimal values of the similarity criteria for problem in formulas (1) and (2) are determined from the conditions of orthogonality and normalization:

$$\boldsymbol{\alpha}\boldsymbol{\pi} = \mathbf{b}, \tag{5}$$

where

$$\boldsymbol{\alpha} = \begin{vmatrix} \alpha_{11}\,\alpha_{12}\;\alpha_{13} \ldots \alpha_{1m} \\ \alpha_{21}\,\alpha_{22}\,\alpha_{23} \ldots \alpha_{2m} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ \alpha_{n1}\,\alpha_{n2}\,\alpha_{n3} \ldots \alpha_{nm} \\ 1 \quad 1 \ldots 0 \;\ldots 0 \end{vmatrix}; \quad \boldsymbol{\pi} = \begin{vmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \ldots \\ \pi_m \end{vmatrix}; \quad \mathbf{b} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ \ldots \\ 1 \end{vmatrix}.$$

In the last row of the matrix $\boldsymbol{\alpha}$, the number of units is equal to the number of terms in the target function (1), namely m_1. If the system of equations (5) is defined ($s = 0$), then the similarity criteria can be found by Kramer's rule:

$$\pi_i = \frac{\|\boldsymbol{\alpha}\|_i}{\|\boldsymbol{\alpha}\|} = \|\boldsymbol{\alpha}\|^{-1} \sum_{t=1}^{n+1} b_t \|\boldsymbol{\alpha}_{ti}\|, \quad i = \overline{1,m}, \tag{6}$$

where $\|\boldsymbol{\alpha}\|$ – determinant of the matrix $\boldsymbol{\alpha}$ of the system of equations (5); $\|\boldsymbol{\alpha}\|_i$ – the determinant of the matrix $\boldsymbol{\alpha}$, in which the vector of free terms $\mathbf{b}$ is written instead of the i-th column;

$\|\boldsymbol{\alpha}_{ti}\|$ – algebraic additions written on the *i*-th column of the matrix $\boldsymbol{\alpha}$, in which instead of the *i*-th column a vector of free terms **b** is written.

Taking into account the values of the components of vector **b**, the last expression will be rewritten:

$$\pi_i = \|\boldsymbol{\alpha}\|^{-1} \|\boldsymbol{\alpha}_{n+1,i}\|, \quad i = \overline{1,m}, \tag{7}$$

Let us now use expression (7) and write the secondary similarity criterion as the ratio of the *p-th* hand *q*-th similarity criteria:

$$\pi_{pq} = \pi_p / \pi_q = \|\boldsymbol{\alpha}_{n+1,p}\| \|\boldsymbol{\alpha}_{n+1,q}\|^{-1}, \tag{8}$$

It can be seen from (7) and (8) that under the condition $m = n + 1$, both similarity criteria and secondary similarity criteria are determined only by the degree of parameters x_j [5].

A special case, when a certain parameter x_j is included only in two terms of the equation - *p*'s and *q*'s. In this case, the orthogonality condition will be written for the parameter x_j:

$$\alpha_{jp}\pi_p + \alpha_{jq}\pi_q = 0. \tag{9}$$

From the last equation, it means that the secondary similarity criterion is:

$$\pi_{pq} = \pi_p / \pi_q = -\alpha_{jq}\ \alpha_{jp}^{-1}. \tag{10}$$

Note that expression (10), unlike (8), can also be used when the system of equations (5) is uncertain (in criterion programming, this corresponds to a problem with a complexity measure $s = m - n + 1 > 0$). This means that secondary criteria can be determined when studying both canonical and non-canonical models.

In the context of intelligent control, secondary similarity criteria can be interpreted as information features that characterize the optimal state of the system. Their constancy for optimal regimes allows using these ratios as invariants, on the basis of which control rules or training samples for intelligent algorithms are formed [7, 22].

Of particular practical value are secondary criteria that determine the optimal ratios between parameters, since they can be used for:

1. Reducing the dimensionality of the optimization problem.
2. Increasing the stability of control algorithms.
3. Forming reference modes in digital twins.

In the tasks of optimal control of the states of intelligent information technology systems, similarity indicators can be used instead of similarity criteria, which are determined by the scales of quantities included in formulas (1) and (2). The use of them provides certain advantages. In particular, the optimal control system becomes more rational due to the fact that the similarity criteria are not determined relative to the parameters x_j, and regarding control parameters u_j, which optimize system states and are functionally related to x_j. The above applies to optimal control systems with a reference model. In this case, it is necessary to establish the similarity between the original system and its model in the control system, as well as the numerical relationship between the control parameters of the original u_{jop} and models u_{jM}.

3.3. Definition of secondary similarity criteria as information features

Similarity indicators of each member of the problem in formulas (1) and (2) are defined as:

$$\mu_i = \frac{\mu_{a_i} \prod_{j=1}^{n} \mu_{x_j}^{\alpha_{ji}}}{\mu_f} = 1, \tag{11}$$

where $\mu_{a_i}, \mu_{x_j}, \mu_f$ – scale coefficients of the corresponding quantities.

Similarity criteria are determined by formula (6), but since in this case they are calculated in the differential system of relative units, the vector **b**, unlike (5), will be equal to:

$$\mathbf{b} = \begin{vmatrix} b_1 \\ b_2 \\ \ldots \\ b_n \\ 1 \end{vmatrix}, \tag{12}$$

where $b_j = \frac{\partial f / \partial x_j}{f_o / x_{jo}}, \quad j = \overline{1, n}$.

Thus, it is not possible to obtain a simple expression similar to (10) for determining secondary similarity criteria.

As is known [2], in relation to establishing the similarity of processes, similarity criteria and indicators of similarity are considered equivalent. However, as can be seen from (11), the ratio of similarity criteria of individual members of the mathematical model of the process and the corresponding indicators of similarity is not equivalent. It can be assumed that if parametric similarity is manifested through the relationship of similarity criteria, then it can also be established through the relationship of similarity indicators [23].

Provided that the target function relative to the control parameters is approximated by a polynomial of the form (1):

$$F(u) = \sum_{i=1}^{m_1} a_i \prod_{j=1}^{n} u_j^{\alpha_{ji}}. \tag{13}$$

Similarity indicators for control parameters u_j write in the form:

$$\mu_{u_j} = \prod_{i=1}^{m} \mu_{a_i}^{\frac{\|\boldsymbol{\alpha}_{ji}\|}{\|\boldsymbol{\alpha}\|}}, \quad j = \overline{1, n}, \tag{14}$$

where $\boldsymbol{\alpha}_{ji}$ – algebraic complements of elements a_{ji}, which are taken with the opposite sign.

If the parametric similarity exists between the control parameters p and q, then they must have the same indicators of similarity. Taking into account (14), this condition will be written:

$$\mu_{pq} = \frac{\mu_{u\,p}}{\mu_{u\,q}} = \frac{\prod_{i=1}^{m} \mu_{a_i}^{\|\boldsymbol{\alpha}_{pi}\|\|\boldsymbol{\alpha}\|^{-1}}}{\prod_{i=1}^{m} \mu_{a_i}^{\|\boldsymbol{\alpha}_{qi}\|\|\boldsymbol{\alpha}\|^{-1}}} = 1, \tag{15}$$

which, after simplification, will take the form:

$$\mu_{pq} = \prod_{i=1}^{m} \mu_{a_i}^{(\|\boldsymbol{\alpha}_{pi}\| - \|\boldsymbol{\alpha}_{qi}\|)\|\boldsymbol{\alpha}\|^{-1}} = 1. \tag{16}$$

It follows from the last expression that when there is a parametric similarity in the investigated process, then, in order for it to be preserved in the model of this process, the condition must be fulfilled:

$$\|\boldsymbol{\alpha}_{pi}\| = \|\boldsymbol{\alpha}_{qi}\|. \tag{17}$$

That is, the corresponding algebraic complements of the parameters of the same name in the original process and in the model must be the same.

Similarity indicators are useful in intelligent control systems with a reference model, where it is necessary to ensure consistency between the original process and its digital model. In this case, the indicators play the role of large-scale information parameters that allow automatic adjustment of control effects [24–26].

3.4. Definition of secondary similarity criteria as information features

The proposed algorithm (Fig. 1) is designed to extract similarity-based informational features and integrate them into intelligent control and decision support systems. The algorithm consists of the following sequential stages. Each stage performs a specific function related to data preprocessing, feature extraction, similarity assessment, and decision synthesis.

At the first stage, a mathematical model of the considered process is formulated in the form of an optimization problem. The objective function and system constraints are defined according to expressions (1) and (2), which describe the target performance criteria and admissible operating conditions of the system.

At the second stage, similarity criteria are defined for both the objective function and the constraints. These criteria characterize the degree of correspondence between different system states and serve as a basis for further dimensional and structural analysis.

At the third stage, the dimensional matrix of the model variables is analyzed. Based on this analysis, secondary similarity criteria are computed. These criteria are derived from the relationships between dimensionless groups and reflect invariant properties of the modeled process.

At the fourth stage, the obtained secondary similarity criteria are interpreted as informational features of the optimal system state. These features provide a compact and meaningful representation of the system behavior in the vicinity of the optimum.

At the fifth stage, the extracted informational features are integrated into an intelligent control algorithm or a decision support system. At this stage, the features are used for state evaluation, control synthesis, or decision-making under uncertainty.

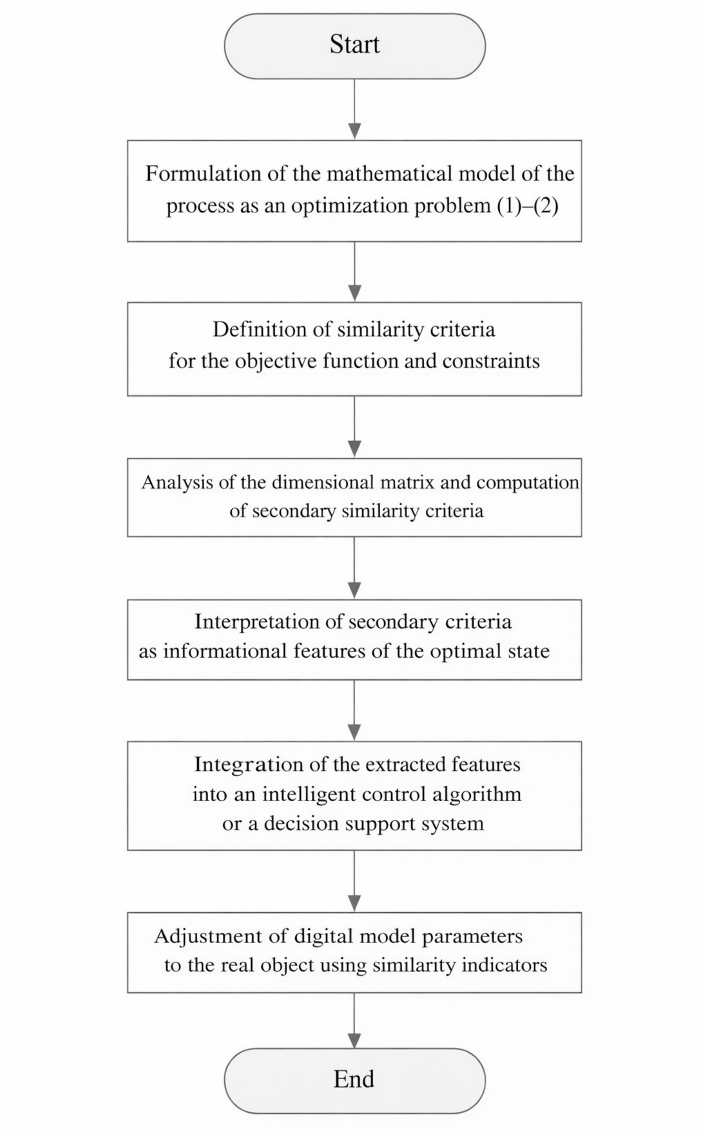

Figure 1: Proposed algorithm and its description.

At the final stage, similarity indicators are employed to adjust the parameters of the digital model to the real object. This adjustment ensures consistency between the model and the physical system and improves the accuracy of control and prediction results.

The modular structure of the algorithm ensures flexibility and scalability, allowing it to be adapted to different classes of control objects and varying volumes of input information.

The use of similarity indicators is especially effective in adaptive systems, where control parameters change in real time based on the analysis of the current state of the system.

4. Discussions

4.1. Definition of secondary similarity criteria as information features

The fact that secondary similarity criteria depend primarily on the exponents of system variables provides a significant practical advantage. These criteria can be computed before solving the optimization problem, enabling a preliminary qualitative analysis. This allows designers to identify the dominant components of the objective function and focus system-identification efforts on the most critical parameters. Conversely, criteria with very small values indicate candidates for model simplification, reducing complexity without sacrificing accuracy.

4.2. Definition of secondary similarity criteria as information features

The analysis reveals that similarity criteria and similarity indicators serve distinct but complementary purposes. The criteria provide a static, structural description of the optimal operating point – answering what the significance of each component is. The indicators, incorporating scaling factors, offer a dynamic mechanism for comparing different states or systems – answering how to adjust control parameters to maintain the desired similarity. This suggests a two-tiered control strategy: use criteria for strategic planning and indicators for real-time tactical adjustments, which is particularly relevant for digital twins.

4.3. Definition of secondary similarity criteria as information features

Embedding secondary criteria into control algorithms enhances robustness by providing interpretable invariants. When parameters deviate from nominal values, the sensitivity interpretation of the criteria allows controllers to preemptively adjust strategies, contrasting with purely data-driven methods that require retraining. Future work should focus on experimental validation in real systems (e.g., energy grids) and extension to multi-agent distributed control, where secondary criteria could enable autonomous system-of-systems coordination.

5. Conclusions

This paper substantiates the feasibility of using secondary similarity criteria as informative features within intelligent information technologies for optimal control of complex technical systems. It is shown that such criteria, derived from the normalization and interrelation of objective function components and constraints, reflect invariant properties of optimal system states.

The proposed interpretation of secondary similarity criteria as informational features enables a reduction in the dimensionality of optimization problems and increases the robustness of intelligent control algorithms. It has been demonstrated that, under certain structural conditions of the optimization model, secondary similarity criteria depend only on the exponents of system parameters, which allows their application in both canonical and non-canonical control models.

Similarity indicators are shown to be an effective tool for ensuring parametric consistency between real objects and their digital models. Their use is particularly relevant for intelligent control systems with reference models and digital twins, where maintaining similarity between the physical process and its model is critical for adaptive and predictive control.

An algorithm for integrating secondary similarity criteria and similarity indicators into intelligent control and decision support systems has been developed. The algorithm provides a systematic procedure for extracting invariant informational features and embedding them into adaptive and self-learning control structures.

The proposed approach can be applied to a wide range of practical problems, including intelligent control of energy systems, electrical networks, and other complex cyber-physical objects. Future research will focus on the experimental validation of the proposed methods and their extension to distributed and multi-agent intelligent control systems.

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Declaration on Generative AI

AI tools were used solely as translation and proofreading aids. All content was originally authored by the submitting party.

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