APPLICATION OF DYNAMIC OBJECTS CONTROL SYSTEM USING QUANTUM- FUZZY ALGORITHMS

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Abstract: In recent years, the global food and process industries have been increasingly focused on achieving energy and resource efficiency. One of the key challenges in process automation is the development of intelligent control systems capable of ensuring high product quality while minimizing energy and material consumption. This requires the processing and analysis of large volumes of data in real time. The present study explores the application of quantum–fuzzy algorithms in the synthesis and control of complex dynamic objects operating under uncertain and nonlinear conditions. The proposed approach integrates the advantages of quantum computation, characterized by high processing speed and parallelism, with the adaptability of fuzzy logic systems for decision-making in uncertain environments. The combination of these methods enables the creation of efficient, adaptive, and energy-saving control systems for intelligent process automation.

Keywords: *quantum algorithms, superposition, correlation matrix, interference, Hadamard transform, qubit, intelligent control, dynamic object, fermenter, quality of control process, hybrid model.*

Annotatsiya: Bugungi kunda oziq-ovqat sanoatida energiya hamda resurslardan samarali foydalanish muhim yo‘nalishlardan biri hisoblanadi. Texnologik jarayonlarni avtomatlashtirish sohasidagi asosiy muammolardan biri — yuqori sifatli mahsulot ishlab chiqarishni ta’minlash bilan birga energiya va xomashyo sarfini minimallashtiruvchi intellektual boshqaruv tizimlarini yaratishdir. Ushbu maqsadga erishish uchun katta hajmdagi ma’lumotlarni real vaqt rejimida qayta ishlash va tahlil qilish talab etiladi. Mazkur maqolada kvant–qat’iymas algoritmlarini murakkab dinamik obyektlarni boshqarish jarayonlarida qo‘llash masalasi ko‘rib chiqiladi. Taklif etilgan yondashuv kvant hisoblash usullarining yuqori tezlik va parallel hisoblash imkoniyatlarini noaniq mantiq tizimlarining moslashuvchan qaror qabul qilish xususiyatlari bilan birlashtiradi. Ushbu integratsiyalashgan yondashuv avtomatik boshqaruv tizimlarining samaradorligi, barqarorligi va moslashuvchanligini oshiradi hamda texnologik jarayonlarni energiya tejamkor tarzda optimallashtirish imkonini beradi.

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Kalit so‘zlar: kvant algoritm, superpozitsiya, korrelyatsion matritsa, interferensiya, Adamara o‘zgaruvchisi, kubit, intellektual boshqarish, dinamik ob’ekt, fermentator, boshqarish jarayonining sifati, gibrid model.

Аннотация: Эффективное использование энергии и ресурсов в пищевой промышленности на сегодняшний день является одним из важнейших направлений. Одной из основных проблем в области автоматизации технологических процессов является создание интеллектуальных систем управления, минимизирующих расход энергии и сырья, обеспечивая при этом выпуск высококачественной продукции. Для достижения этой цели необходимо обрабатывать и анализировать большие объемы данных в режиме реального времени. В данной статье рассматривается применение квантово-нечетких алгоритмов в процессах управления сложными динамическими объектами. Предлагаемый подход сочетает в себе высокоскоростные и параллельные вычислительные возможности методов квантовых вычислений с гибкими свойствами принятия решений систем нечеткой логики. Такой комплексный подход повышает эффективность, устойчивость и гибкость систем автоматического управления и позволяет осуществлять энергоэффективную оптимизацию технологических процессов..

Ключевые слова: квантовые алгоритмы, суперпозиция, корреляционная матрица, интерференция, преобразование Адамара, кубит, интеллектуальное управление, динамический объект, ферментер,качество процесса управления, гибридная модель.

Introduction

Scientific research around the world is increasingly focused on improving process control systems, particularly through the integration of intelligent computational technologies in industrial and food-processing enterprises. Dynamic technological processes are inherently complex, characterized by nonlinear interactions, multivariable dependencies, and the influence of numerous internal and external disturbances. The uncertainty and interrelation of technological parameters significantly complicate the synthesis of effective control strategies.

In this context, quantum–fuzzy algorithms represent a promising direction for solving multidimensional optimization and adaptive control problems. These algorithms combine the high computational efficiency of quantum computing with the robust decision-making capabilities of fuzzy logic, allowing for precise regulation of dynamic objects under conditions of uncertainty. The integration of such hybrid algorithms into process control systems enables real-time adaptation to fluctuating technological and environmental factors, thereby ensuring the stability, accuracy, and energy efficiency of production processes.

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One of the most significant challenges in automation is the creation of intelligent control systems that can optimize process parameters while reducing energy and resource consumption. The application of quantum–fuzzy approaches allows for enhanced prediction, optimization, and control of nonlinear dynamic systems, contributing to the production of high-quality products and the increased competitiveness and sustainability of industrial enterprises [1].

The controlled objects in modern industrial and technological systems are typically complex, multidimensional, and nonlinear dynamic systems characterized by strong interconnections, parameter uncertainties, and time-varying external influences. Such systems must not only provide accurate functional performance but also possess predictive and adaptive capabilities to ensure stability and reliability under fluctuating operating conditions.

The uncertainty and variability of external and internal factors make it difficult to formulate precise mathematical models of these dynamic systems. In real production environments, the nonlinearity of technological processes, modeling errors, and information noise significantly complicate the design of efficient control algorithms. Therefore, the synthesis of control systems for such objects requires the application of advanced information technologies and non-standard computational methods capable of handling uncertainty and incomplete data [2].

Traditional neural network control systems, while effective in certain contexts, face limitations related to the complexity of structural identification, sensitivity to learning parameters, and the need for large volumes of reliable data. These limitations restrict their performance when dealing with poorly defined, stochastic, or uncertain environments. Moreover, the lack of comprehensive methodologies that integrate chemical, physical, and informational dependencies of technological objects further reduces the reliability of classical modeling approaches [3].

To overcome these challenges, it is essential to develop hybrid intelligent control systems that combine quantum computing and fuzzy logic mechanisms. Quantum–fuzzy algorithms allow for adaptive learning, multidimensional data processing, and probabilistic decision-making in real time. By leveraging the superposition and entanglement properties of quantum computation, such systems can efficiently evaluate multiple control strategies simultaneously, while fuzzy inference enables reasoning under uncertainty.

Thus, taking into account the nature of dynamic objects, their nonlinear dependencies, and the need for decision-making under uncertain and incomplete information, the application of quantum–fuzzy control systems provides an effective solution for improving the accuracy, adaptability, and energy efficiency

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of technological processes. This integrated approach represents a significant step toward intelligent automation and the enhancement of overall production efficiency [4].

Research Methods and the Received Results

Scientific research across the world is increasingly aimed at improving process control systems, particularly within the food industry, through the integration of intelligent computational technologies. Modern production processes are inherently complex, influenced by numerous external disturbances and internal interdependencies among technological parameters. The uncertainty of these influences, combined with the nonlinear and multivariable nature of technological objects, significantly complicates the synthesis and implementation of effective control systems. Therefore, modern control research focuses primarily on the development of high-performance information processing methods and adaptive control algorithms that can function reliably under conditions of uncertainty [5].

One of the key challenges in process automation is the creation of highly efficient intelligent control systems capable of enhancing process quality, improving energy efficiency, and reducing resource consumption while maintaining high production standards. Leading international studies emphasize that advanced control architectures play a crucial role in increasing competitiveness, stability, and efficiency of technological systems. Intelligent control thus becomes a fundamental component in achieving sustainable and optimized production processes [6].

The controlled objects in such systems are complex, multidimensional, and nonlinear dynamic systems that require adaptive and predictive control mechanisms. These systems must respond to continuous fluctuations in external and internal conditions while maintaining operational stability. However, the variability of factors, modeling errors, and measurement noise in real technological environments make it difficult to design reliable and universal control algorithms. Consequently, the development of such systems demands the application of modern computational intelligence methods, including quantum computing, fuzzy logic, and neural modeling, which together enable high-speed data processing, self-learning, and decision-making under uncertainty.

Traditional neural network control systems, despite their effectiveness in certain applications, often face challenges related to structure identification, overfitting, and dependence on large and accurate datasets. Moreover, classical approaches do not sufficiently account for the nonlinear chemical and physical dependencies of technological objects or the stochastic nature of external influences. This lack of systematic modeling methods limits their capability to ensure robust control under real operating conditions [7].

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In this context, the use of quantum–fuzzy algorithms offers a powerful alternative for managing dynamic objects with uncertain parameters. Quantum computation provides a framework for parallel information processing and optimization in multidimensional spaces, while fuzzy logic ensures reasoning and adaptation in the presence of incomplete or imprecise data. The hybrid integration of these approaches enables the construction of intelligent control systems that can predict, adapt, and optimize process parameters in real time.

Thus, considering the characteristics of dynamic objects and the need to make decisions under uncertain and incomplete information, the application of quantum–fuzzy control systems represents a promising direction for improving the accuracy, adaptability, and energy efficiency of technological processes. This approach provides a scientific foundation for the development of next-generation automation systems that can ensure high product quality, resource efficiency, and sustainable industrial operation [8].

Quantum computing is an alternative to classical computing. Quantum computing is based on the principle of quantum superposition. If a system has two possible ground states, then any superposition (linear combination) of these ground states is also a possible state of the system. Such quantum systems have two ground states (they are called qubits) and one state models the constant *0*, and the other *1*.

Quantum computers use quantum algorithms to perform calculations that exploit the effects of quantum mechanics, such as quantum parallelism and correlation matrices. A quantum computer operates on quantum bits. A quantum bit, or *q*-bit (qubit) for short, can be defined as a quantum system having two states respectively (*0* and *1*). However, unlike the classical case in quantum mechanics, these two states can be superimposed on each other, meaning that the most general state of a quantum bit can be written as [9]:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where: α and β - complex numbers.

A qubit can be defined as a vector of unit length in a two-dimensional Hilbert space over the field of complex numbers. and states together are the basis vector. Like all vectors, they show direction and magnitude. To write two states of qubits, bra $\langle|$ and ket$|\rangle$, Dirac notation is used. Vectors of shape $\langle|$ are called ket-vectors, and vectors of shape $|\rangle$ are called bra-vectors. The following vectors correspond to the designation ket: ket vectors corresponding to zero, the unit state of the vacubite has the following form [10]:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

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$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ when measuring the system state using the function, $|0\rangle$ probability of detection in case α^2, $\langle 1|$ probability of detection in case β^2 equals The sum of these probabilities is equal to one:

$$|\alpha|^2 + |\beta|^2 = 1$$

This relationship is called the normalization condition.

Quantum computing typically requires more than one qubit. A system consisting of several qubits is called a quantum system.

The state of a quantum system consisting of *n* qubits can be expressed by the following mathematical formula:

$$|q_1\rangle..|q_n\rangle = (\alpha_0|0\rangle + \beta_0|1\rangle) \otimes (\alpha_1|0\rangle + \beta_1|1\rangle) \otimes ... \otimes (\alpha_{n-1}|0\rangle + \beta_{n-1}|1\rangle)$$

Once a qubit is measured, the previous state of the coefficients α and β that describe its previous state disappears.

So the n-qubit is expressed as:

$$|\Psi\rangle = \sum_{k=0}^{2^n-1} \alpha_k |k\rangle$$

Considering that the states of the qubit can be expressed as follows, a mathematical expression is formed.

The Hadamard operator (*H*) is used to create cases of superposition. The Hadamard operator has a matrix form:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

The behavior of the operator H on an arbitrary qubit can be described by the following formula:

$$H|\Psi\rangle = \frac{\alpha+\beta}{\sqrt{2}}|0\rangle + \frac{\alpha-\beta}{\sqrt{2}}|1\rangle$$

In the geometric interpretation of the qubit on the Blox sphere, it is clear that the action of the Hadamard operator on the qubit in the $|0\rangle$ state, expressing $\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$, transfers it to a state between the $\langle 0|$ and $\langle 1|$ states.

This form of computational models allows us to generalize the stages associated with the representation of modeling algorithms and express them as formal problems that can be solved on the basis of these models.

Thus, it is possible to build models of various technological processes in the dynamic sphere of control. With this approach, speed and accuracy are key, ensuring process quality increases and efficiency remains at a high level [11].

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According to the above equation, the first part of the design is the entangled state operator describing the quantum algorithmic cell - type U_F, which physically describes the qualitative properties of the function being studied. The received signals are normalized by dividing the current values of the $[0,1]$ control signals by their previously known maximum values (*maxK*). Probability density functions are determined. They are integrated and, based on the current state of the input control signals, probability distribution functions are obtained, which make it possible to determine the virtual states of the control signals to form a superposition using the Hadamard operator [13].

The law of probability is expressed as follows:

$$p(|0\rangle) + p(\langle 1|) = 1$$

where $p(|0\rangle)$– probability of the current real state; $p(\langle 1|)$ - probability of the current virtual state. The current real state of the virtual state is determined from the law of conservation of probabilities.

The superposition of a quantum system “real state-virtual state” has the following form:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(\sqrt{p(|0\rangle)} \times |0\rangle + \sqrt{(1 - p(|0\rangle))} \times |1\rangle\right)$$

As you can see, the use of quantum algorithms can significantly reduce the time spent on solving the problem of detecting nonlinear objects.

In addition, it should be noted that the proposed quantum algorithms make it possible to move to a new method of processing experimental information. The main advantage of this method is the ease of interpretation of the results obtained and its high speed [14].

The analysis of the developed control architecture demonstrates that the operation of neuro-fuzzy controllers can be effectively enhanced by incorporating quantum algorithms. In such hybrid systems, quantum algorithms may serve either as independent control modules or as optimization mechanisms for determining the most suitable parameters of the controller. Considering the existence of a conventional control loop in the technological system, quantum algorithms are here employed primarily to identify the optimal values of correction coefficients and fine-tune control parameters to ensure adaptive, stable, and energy-efficient regulation.

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Within this framework, the control system can include not only a classical PID controller but also a range of non-standard adaptive controllers whose functionality is expanded through the integration of quantum computational elements. The design accounts for both variations in the process parameters and changes in the composition of the material flow, allowing the system to maintain high robustness under dynamic and uncertain conditions [15].

Based on the theoretical analysis and modeling results, a quantum tuner synthesis algorithm was developed. The proposed algorithm includes the following main stages:

1. Determination of the input and output variables of the quantum–fuzzy controller, defining the linguistic structure of the control model.

2. Computation of normalization coefficients for the quantum regulator to ensure accurate signal scaling within the fuzzy inference system.

3. Implementation of logical quantum control modules for each linguistic variable, aimed at suppressing fluctuations, minimizing transient time, and improving overall efficiency.

4. Selection of optimal tuning parameters to reduce static and dynamic errors in the control process.

Using the proposed quantum computational approach, it becomes possible to construct a stable control model even under non-stationary conditions, where the characteristics of the technological object and influencing factors vary over time [16].

As a practical example, the developed methodology was applied to the fermentation process temperature control system in a champagne production unit. Traditional automatic control systems in such technological processes are typically limited to maintaining a constant temperature and are unable to account for the interdependence of multiple influencing factors and the uncertainty of system parameters, resulting in reduced product quality [17].

To evaluate the effectiveness of the developed quantum-based control algorithms, a simulation model of the quantum parameter tuning system was implemented in MATLAB. Computational experiments were conducted under conditions of external disturbances and parameter uncertainties. The simulation results confirmed the high accuracy, adaptability, and robustness of the proposed quantum–fuzzy control strategy in maintaining optimal process parameters during ammonia synthesis [18].

First, a relevance function was formed based on the linguistic input-output variables and their optimal parameters were determined. Below is a computer model of a quantum temperature control system in a technological device, implemented using the MATLAB program (Fig. 1).

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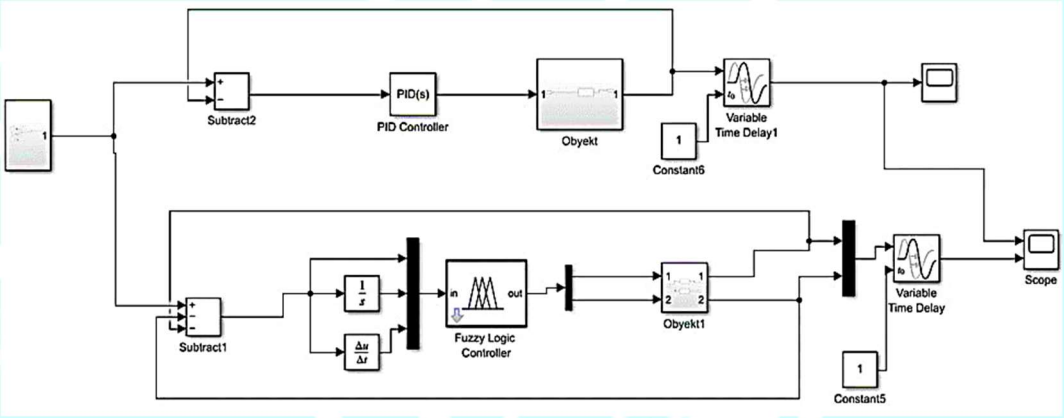


Fig. 1. Computer model of an ammonia synthesis process control system.

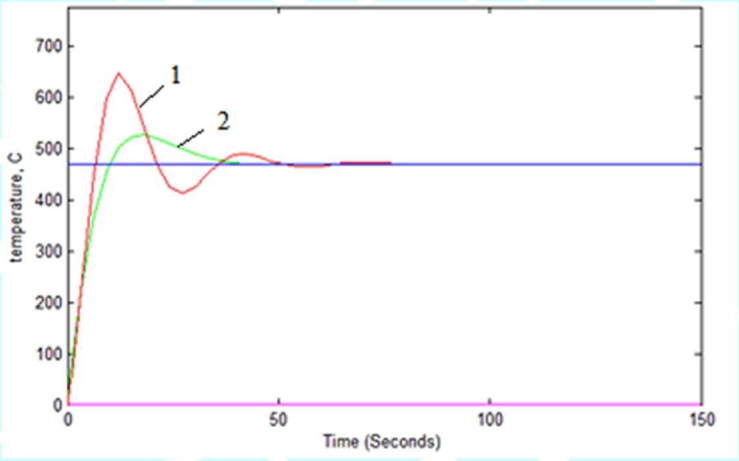


Fig. 2. Graph of the process of the hybrid automatic control system: 1- Classic PID controller; 2-quantum fuzzy controller.

As evidenced by the transient response graph, the control system integrated with a quantum–fuzzy controller demonstrates stable operation even under the influence of external disturbances. The controller effectively transfers the dynamic object from one steady state to another within a short transition period, ensuring smooth response characteristics without overshoot or oscillatory deviations [19].

The results of simulation experiments confirm that the proposed quantum–fuzzy control structure maintains a high degree of stability, adaptability, and control accuracy under uncertain and varying external conditions. The hybrid quantum mechanism dynamically adjusts the control parameters in real time, compensating for external perturbations and process nonlinearities. As a result, the system consistently achieves the required quality of regulation, minimizing steady-state error and ensuring robust performance of the controlled technological object [20].

Conclusion

The transient response analysis shows that the quantum–fuzzy controller ensures stable operation under external disturbances, achieving fast and smooth transitions with minimal overshoot. Simulation results confirm that the controller maintains robust stability and high control quality under uncertainty. By integrating

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quantum computation into fuzzy inference, the system adapts control parameters in real time, improving dynamic performance. In the fermentation process, temperature deviation decreased by 1.9 %, demonstrating the practical efficiency of the hybrid quantum–fuzzy control in maintaining optimal conditions and enhancing process quality.

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