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ARTIFICIAL INTELLIGENCE

Intelligent Robust Control of Autonomous Robot: Quantum Self-Organization of Imperfect Knowledge Bases—Experiment

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Abstract—The article discusses the information technology of a robust intelligent control system design based on quantum fuzzy inference. The application of the developed design methodology is based on the quantum self-organization of fuzzy controller's imperfect knowledge bases and leads to an increase in the robustness of intelligent control systems in unpredicted situations. The results of mathematical modeling and physical experiment are compared using the example of an autonomous robot in the form of a "cart – pole" system. Experimental confirmation of the synergetic effect existence in the robust self-organized fuzzy controller formation from a finite number of non-robust fuzzy controllers in on-line has been demonstrated. The resulting effect is based on the existence of hidden quantum information extracted from the classical states of the controller's time-varying gain coefficients processes schedule. The derived law of quantum information thermodynamics establishes the possibility to forming a thermodynamic control force due to the extracted amount of hidden quantum information and performing additional useful work, that guarantees the achievement of the control goal based on increasing the robustness of a self-organized quantum controller. At the same time, the amount of useful work performed by the control object (at the macro level) exceeds the amount of work spent (at the micro level) by a quantum self-organized controller to extract the quantum information hidden in the responses of imperfect knowledge bases without violating the second thermodynamics information law for open quantum systems with information exchange of entangled super correlated states. A concrete example of an autonomous robot is given, demonstrating the existence of a quantum self-organization synergetic effect to imperfect knowledge bases.

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INTRODUCTION

The methodology of intelligent control systems (ICS) design, based on soft computing technology, considers the structure of fuzzy controller (FC) as one of the options for effective design of conventional automatic control systems (ACS) [1, 2]. Since its appearance (1974), FC models have demonstrated an increased ability to dynamic objects control (CO), which have a poorly formalized structure or functioning under conditions of uncertainty or inaccuracy of initial information, contingencies or information risk.

The article considers the issues of ICS designing on the example of dynamically unstable CO of the "Cart – Pole (Inverted pendulum)" type using the knowledge base optimizers (KBO) on soft and quantum computations – SCOptKB^{TM} & QCOPtKB^{TM} respectively [2–4]. Description of the technology for designing a robust ICS based on quantum fuzzy inference (QFI) is introduced. The control of "Cart-Pole" type CO is one of typical problems in the control theory because the solution of this problem clearly demonstrates the ICS's quality. More in detail's description of the CO and verification of its mathematical model are considered in [5].

The main work's result is an experimental proof of the synergetic information effect's existence by quantum self-organization for imprecise FC knowledge bases due to extraction of hidden quantum information, predicted and proved by simulations in [6–9].

Industrial applications – first experimental result was obtained on a real physical object in [10] for the superconducting magnet cooling ICS's of the Mega-Science NICA collider's development project [11].

Particularly, the HW-SW platform was developed to control liquid nitrogen pressure in the superconducting magnet cryogenic system based on quantum FCs embedded in the control loop with implementation on the conventional processor's architecture. The multilevel control system includes the existed lower executive level, based on the Tango Controls system, and a new level, where the control actions are generated applying quantum FC. This provides optimal control parameters quality, such as temperature, nitrogen flow rate, speed, required pressure level and minimum control implementation complexity with proportional – integral-differential (PID) – regulators.

The operability and efficiency of the created intelligent remote-control system for the technological process of superconducting magnet cooling with guaranteed achievement of a stable superconductivity zone has been experimentally demonstrated [10]. The design of quantum FCs is based on quantum information technologies and realized using QSCIT (quantum soft computational intelligence toolkit) software developed by M.G. Mescheryakov LIT employees [11]. The possibility of the real CO knowledge base (KB) remote tuning with using remote connection of real CO with KBO on quantum computing is considered. A class of contingencies is extended to test the robustness of the developed ICS and proving the achievements of global robustness as compared to KBO based on soft computing.

The considered problem's relevance. Creating a correct algorithm for the required design level of ICS robustness is one of the actual problems of modern control systems theory. At the same time, this problem refers to a complex and poorly research area of ICS development, capable an effective and reliable functioning in conditions of risk and control contingencies. The application of intelligent computing technology in the tasks of robust control design has shown in practice an increase in the reliability of CO functioning in contingency control situations by increasing the intelligence of the lower executive level in the form of conventional ACS's structures based on conventional PID regulators, sliding mode regulators, PID^2 (2-ratio PID), fractional order regulators and many others. [12, 13].

Research Methodology. The effectiveness of the developed ICS design technology is considered on the example of ICS design issues, traditional for the control systems theory of unstable CO "Cart-Pole" type, using KBO on quantum computing.

The possibilities of dynamically unstable nonlinear control objects robust control with implementation on convenient embedded processors with the classical architecture are investigated. A design strategy for intelligent control systems based on quantum and soft computing technologies is described. In this approach mathematical formalism of quantum mechanics is used to build new algorithms of quantum control, successfully simulated on convenient computers. Algorithms applying QFI scheme—hidden quantum information is extracted from KB (including parameters of membership functions and sets of fuzzy production rules) belonging to individual FCs on which basis the new robust KB's is created. This process demonstrates a synergistic effect of quantum self-organization—a robust KB of quantum fuzzy controller is created (in on-line mode) from two unreliable KBs. This effect has a purely quantum nature and uses hidden quantum information extracted from classical states. The developed technology improves the reliability of intelligent cognitive systems that can functioning in unexpected control situations, such as the interaction of an ensemble of different robot types. An effectiveness of QFI scheme implementation on a ready programmable algorithmic solution for lower executive level control systems has been demonstrated on multiple examples of different systems [14]. The algorithms and design strategy were successfully, as noted, applied to the development of a superconducting magnet cooling ICS within the NICA project.

Technology evolution. The presented methodology of quantum self-organizing FC design and realization allows scaling and replication of this product to other types of physical CO.

An autonomous robot's simulation and physical experiment. The mathematical CO's model used in this work is described and investigated in detail in [15, 16]. In the experiment, the KBs for FC found by simulation in [7, 8, 15] were applied, and explanations are given as needed to understand the physical rigor and mathematical correctness of the obtained results interpretation.

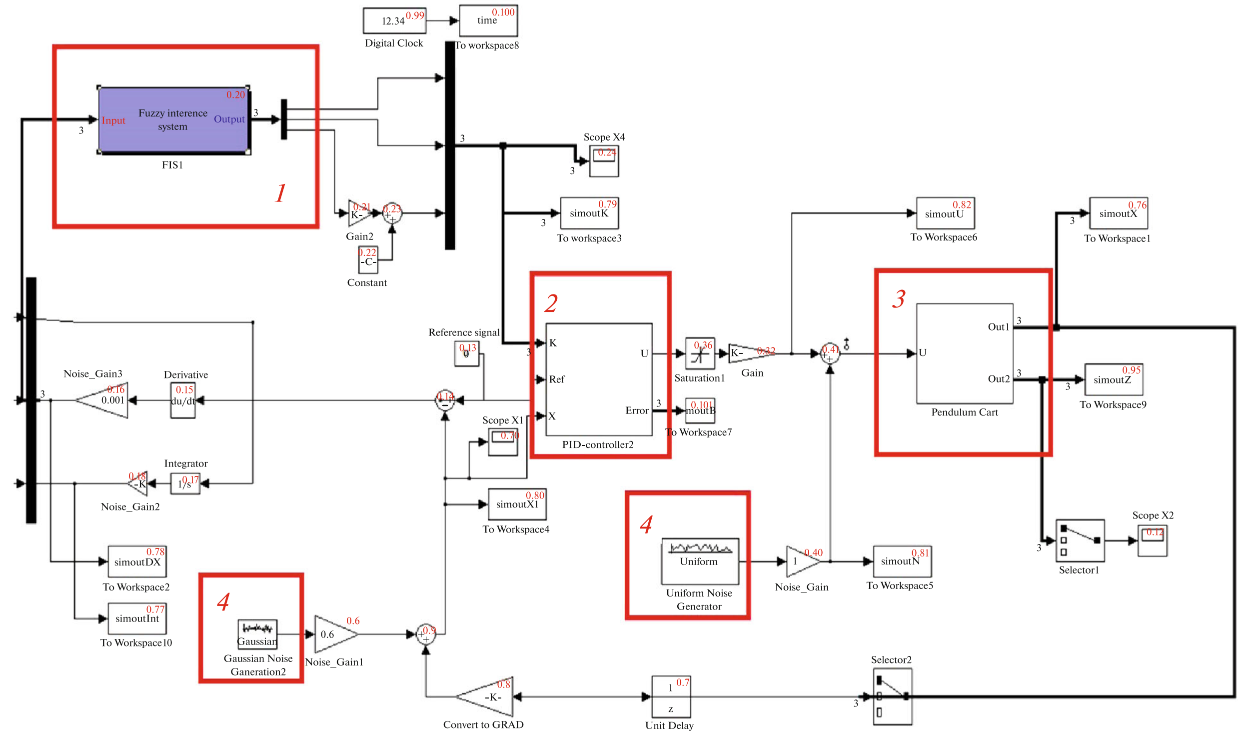


Fig. 1. Simulation model structure: *1*—QFI block; *2*—PID; *3*—CO; *4*—noise generator.

1. THE CO "CART-POLE" COMPUTER MODEL

The system has a global dynamic instability, in the absence of a control force there an unbounded growing of the deflection angle is happens, i.e. the pendulum falls.

The structure of the "Cart-Pole" computer model, man-made in the simulation environment MatLab / Simulink is shown in Fig. 1.

The model includes the PID regulator, noises in the control and measurement system, and the block that forms the regulator's signal. This computer model is used to obtain the teaching signal and to tune the KB by the soft computing means KBO – SCOptKB$^{\text{TM}}$ [2] and laws KB forming for PID – regulator coefficient gain schedule changes according to the methodology developed in [17]. As a control model for this system, the following expression to determine the control action is used:

$$u(t) = k_P(t)e(t) + k_I(t)\int_0^t e(\tau)d\tau + k_D(t)\dot{e}(t). \tag{1.1}$$

In accordance with the control scheme, a PID controller (1.1) with a global negative feedback loop is used.

1.1. System model. This type of CO is a typical (Benchmark) for testing of the robust intelligent control software toolkit. Let's consider in detail the structure of such CO model.

In Fig. 2, a model, used for testing of ICS design technologies by means of KBO, and the bench (Fig. 2, b) for experiments are represented.

The bench is equipped with various coatings for conducting experiments with the model, including contingency control situations. The stand also has a possibility to set a certain initial angle for model's launching.

As a measuring system (Fig. 2, Sensor), the model uses a board with a combination of sensors - gyroscope and accelerometer – 5 DoF (five degrees of freedom) IDG500/ADXL335.

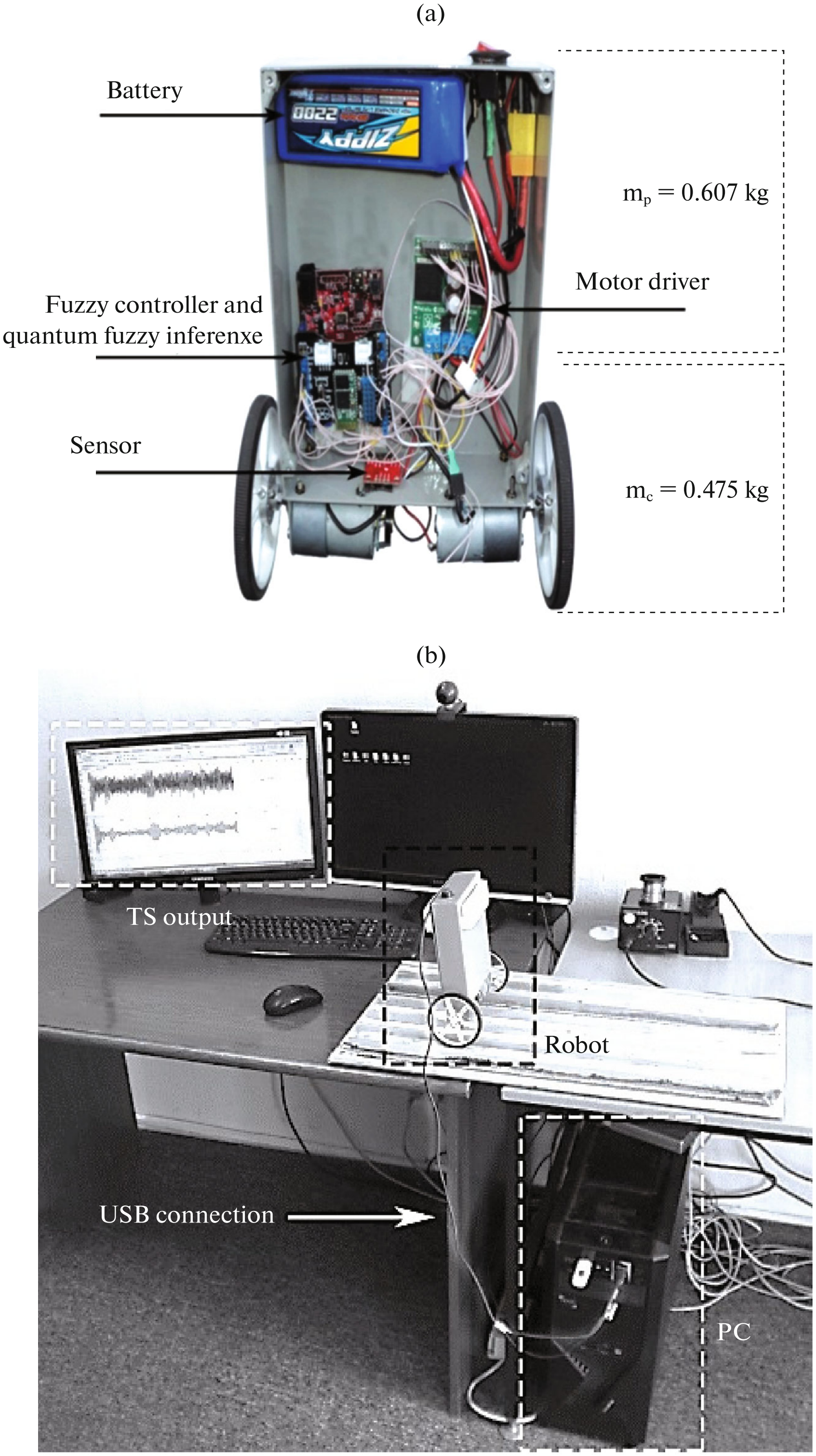


Fig. 2. “Cart-Pole” model system (a); experimental stand (b).

The core of the system is a Microchip® Chirkit microcontroller based on the PIC32MX320F128 processor. The board is equipped with a USB connector for transferring data from the processor to the computer. The USB interface is used in experiments to send and receive data (deflection angle and control value) as well as for remote tuning, which will be discussed below. Sensors are connected using analog inputs of the microcontroller.

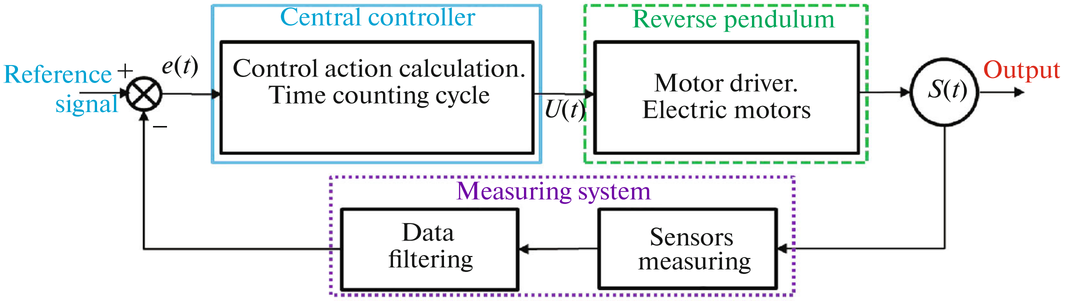
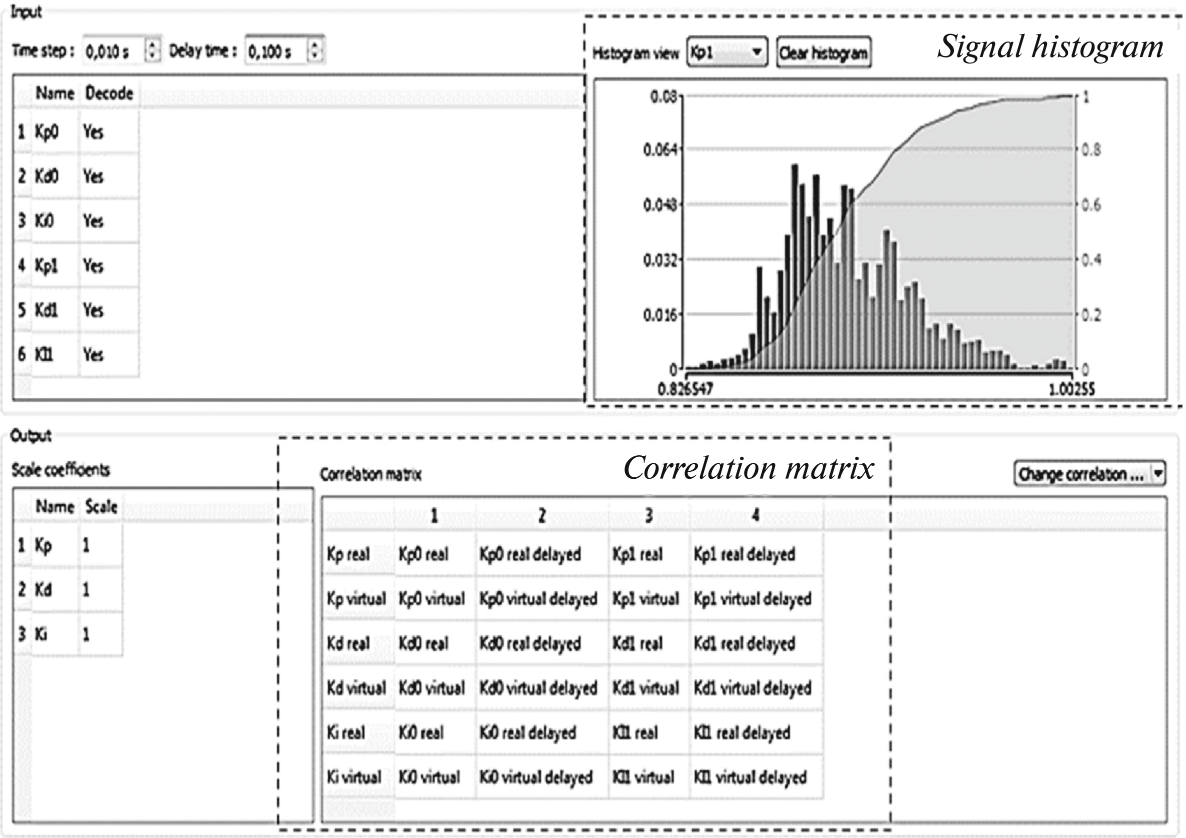


Fig. 3. Microcontroller program algorithm.



Time step: 0,010 s Delay time: 0,100 s

	Name	Decode
1	Kp0	Yes
2	Kd0	Yes
3	Ki0	Yes
4	Kp1	Yes
5	Kd1	Yes
6	Ki1	Yes

Scale coefficients

	Name	Scale
1	Kp	1
2	Kd	1
3	Ki	1

Correlation matrix

	1	2	3	4
Kp real	Kp0 real	Kp0 real delayed	Kp1 real	Kp1 real delayed
Kp virtual	Kp0 virtual	Kp0 virtual delayed	Kp1 virtual	Kp1 virtual delayed
Kd real	Kd0 real	Kd0 real delayed	Kd1 real	Kd1 real delayed
Kd virtual	Kd0 virtual	Kd0 virtual delayed	Kd1 virtual	Kd1 virtual delayed
Ki real	Ki0 real	Ki0 real delayed	Ki1 real	Ki1 real delayed
Ki virtual	Ki0 virtual	Ki0 virtual delayed	Ki1 virtual	Ki1 virtual delayed

Fig. 4. Quantum optimizer working window.

The basic functions of the model programs are shown on Fig. 3. Generally, they can be described by the following steps: measurement, filtering, control, time counting (delay).

Noting that the model's algorithm of the system shown in Fig. 3, is a particular example of ACS with feedback and is reproduced in laboratory conditions.

2. QFI DESIGN BASED ON SW TOOLKIT – QUANTUM OPTIMIZER QCOptKB$^{\mathrm{TM}}$

Control system creation on the basis of QFI is realized by use of "Quantum optimizer" software toolkit. The working window of this product is shown on Fig. 4.

Remark 1. In the bottom of Fig. 4 shows the time correlation matrix for the entangled state formation, on top – the histogram of the proportional coefficient's input signal.

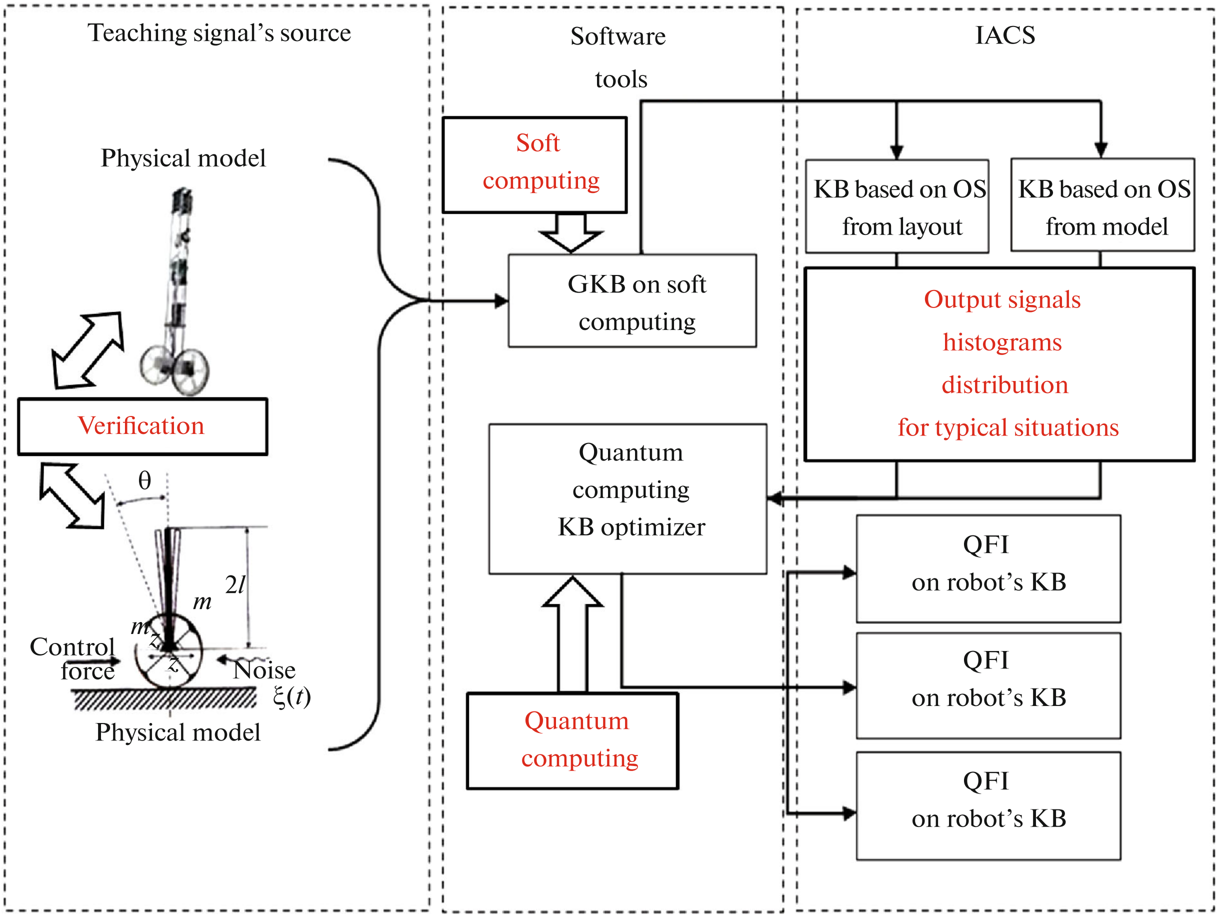


Fig. 5. QFI design technology (where IACS—intelligent autonomous control system, TS—Teaching signal, SW—software).

The technology of QFI application allows to combine several KBs into a single control system, and thus, allowing to fuzzy neural networks working in parallel, providing ICS with additional robustness.

Consider the possibility of QFI application for KB combining, obtained on the basis of different information resources. Such resources could be the measured signal on a system's operation finite time interval, which can be obtained from various sources. For example, using different mathematical models or physically measured signals of real control objects, functioning in different environments and under different initial conditions [2, 3]. A key element of such ICS is a mechanism for combining the strategies embedded in the KB. The theoretical background of QFI represented earlier were implemented and tested on the basis of various mathematical models and real control objects [4, 5]. At the same time, practice shown that to design a self-organized system, capable to functioning under extreme conditions, it is necessary to apply additional software tools for QFI design based on new types of cal-

Table 1. KB Comparison

KB, signal source, description, caption	Rules Quantity	Membership functions number	Optimization method
KB1, MathModel, FC1	245	8 × 6 × 6	Simulation
KB4, Model CO FC4	288	9 × 9 × 6	CO's TS approximation (genetic alg. - GA2)
Q-S	FC1 × FC4	–	Simulation
Q-T	FC1 × FC4	–	Simulation
Q-ST	FC1 × FC4	–	Simulation

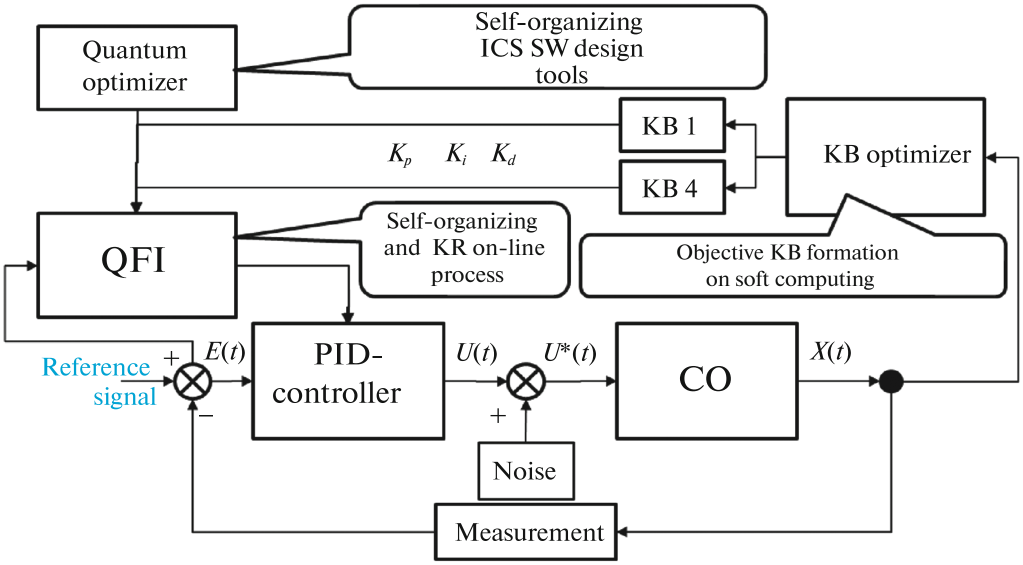


Fig. 6. Quantum FC structure.

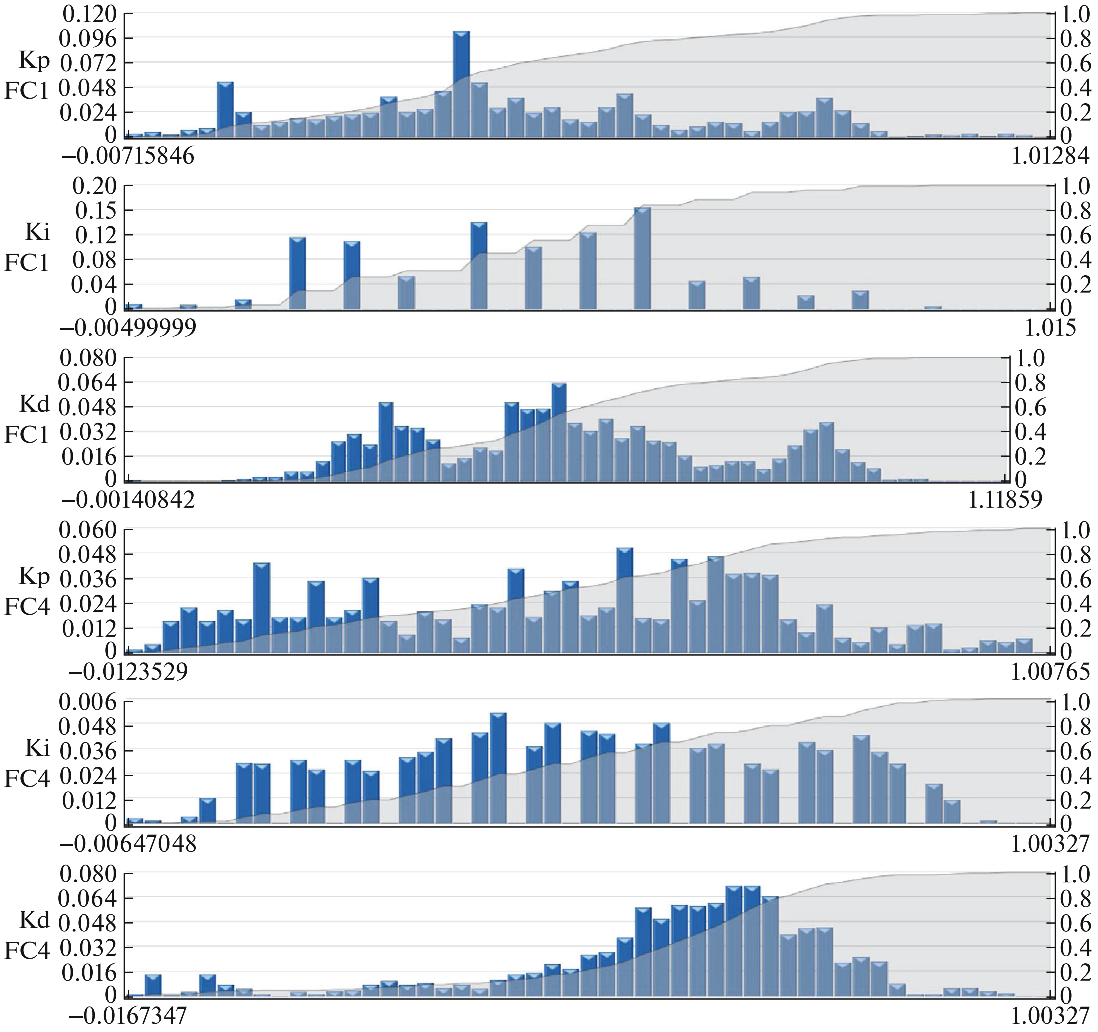
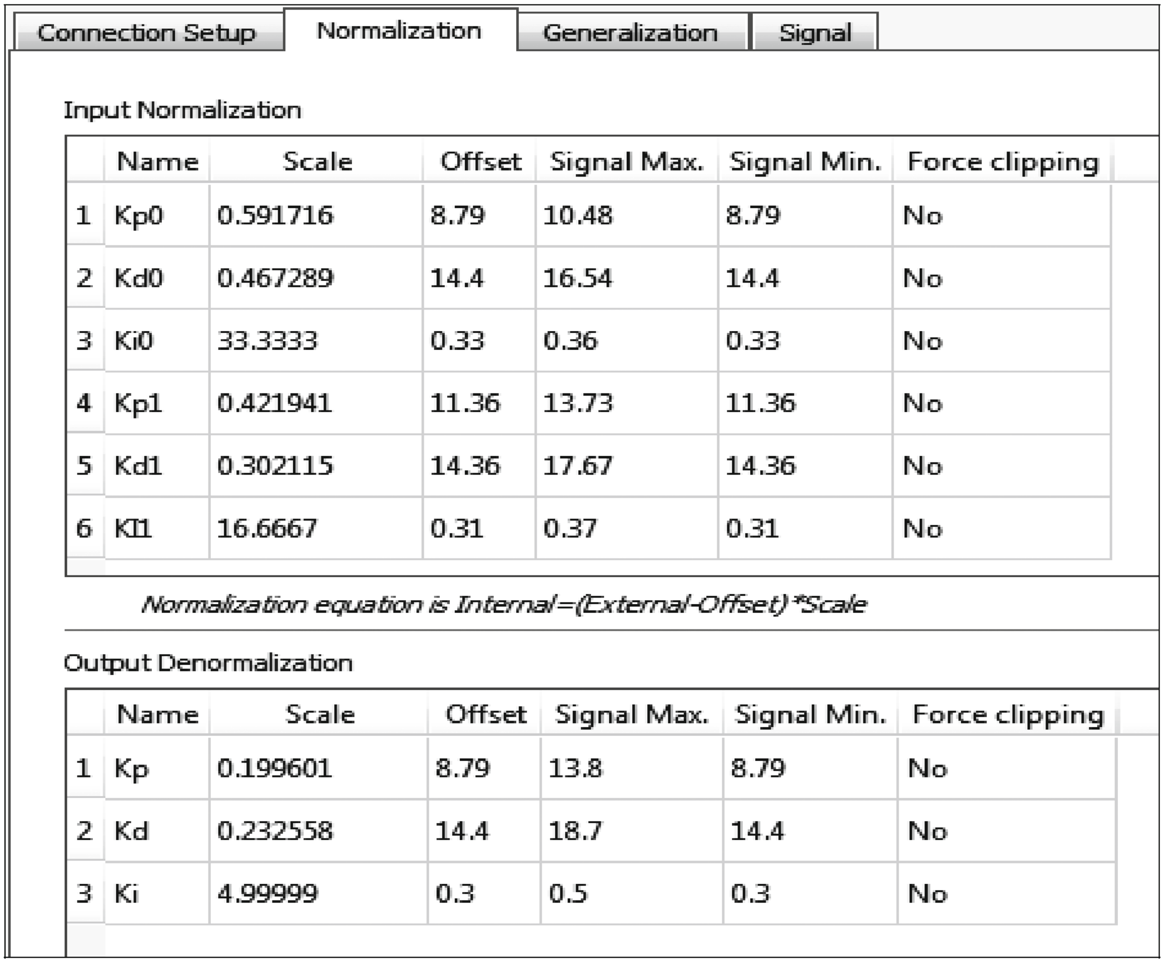


Fig. 7. Input QFI coefficients histograms from fuzzy controllers FC1 and FC4.



Input Normalization

	Name	Scale	Offset	Signal Max.	Signal Min.	Force clipping
1	Kp0	0.591716	8.79	10.48	8.79	No
2	Kd0	0.467289	14.4	16.54	14.4	No
3	Ki0	33.3333	0.33	0.36	0.33	No
4	Kp1	0.421941	11.36	13.73	11.36	No
5	Kd1	0.302115	14.36	17.67	14.36	No
6	KI1	16.6667	0.31	0.37	0.31	No

*Normalization equation is Internal=(External-Offset)*Scale*

Output Denormalization

	Name	Scale	Offset	Signal Max.	Signal Min.	Force clipping
1	Kp	0.199601	8.79	13.8	8.79	No
2	Kd	0.232558	14.4	18.7	14.4	No
3	Ki	4.99999	0.3	0.5	0.3	No

Fig. 8. QFI window. Normalization and denormalization of the physical model's signal.

culations, such as quantum soft computing [3]. The general methodology of QFI design is presented in Fig. 5.

In this context, we can identify three types of QFI based on different sources:

—KBs derived from mathematical models;

—KBs found using a physically measured control signal;

—joint application of different information resources.

The research has shown that the best quality of control belongs to quantum controllers (QC) based on different information resources [2].

Furthermore, to QFI developing the KB1 & KB4 will uses, in accordance with the soft computing KB optimizer's technology [7, 8, 13] (Fig. 6).

A comparison of the given KBs is considered in Table 1.

Prior to creating QFI, it is necessary to obtain histograms of the FCs output signals distribution (amplification factors) (Fig. 7).

For this purpose, a series of experiments and simulations in a typical control situation are carried out. Using the obtained values of gain coefficients during simulation and model operation, an array of data is formed to build histograms of fuzzy PID controllers gain coefficients. Histograms are constructed automatically when data are loaded into the quantum optimizer. Further these histograms are used in the QFI algorithm to form virtual states (Fig. 7).

The histograms of gain coefficients obtained experimentally are used in the experimental models, and the histograms of gain coefficients, founded by mathematical simulation are used in the QFI for-

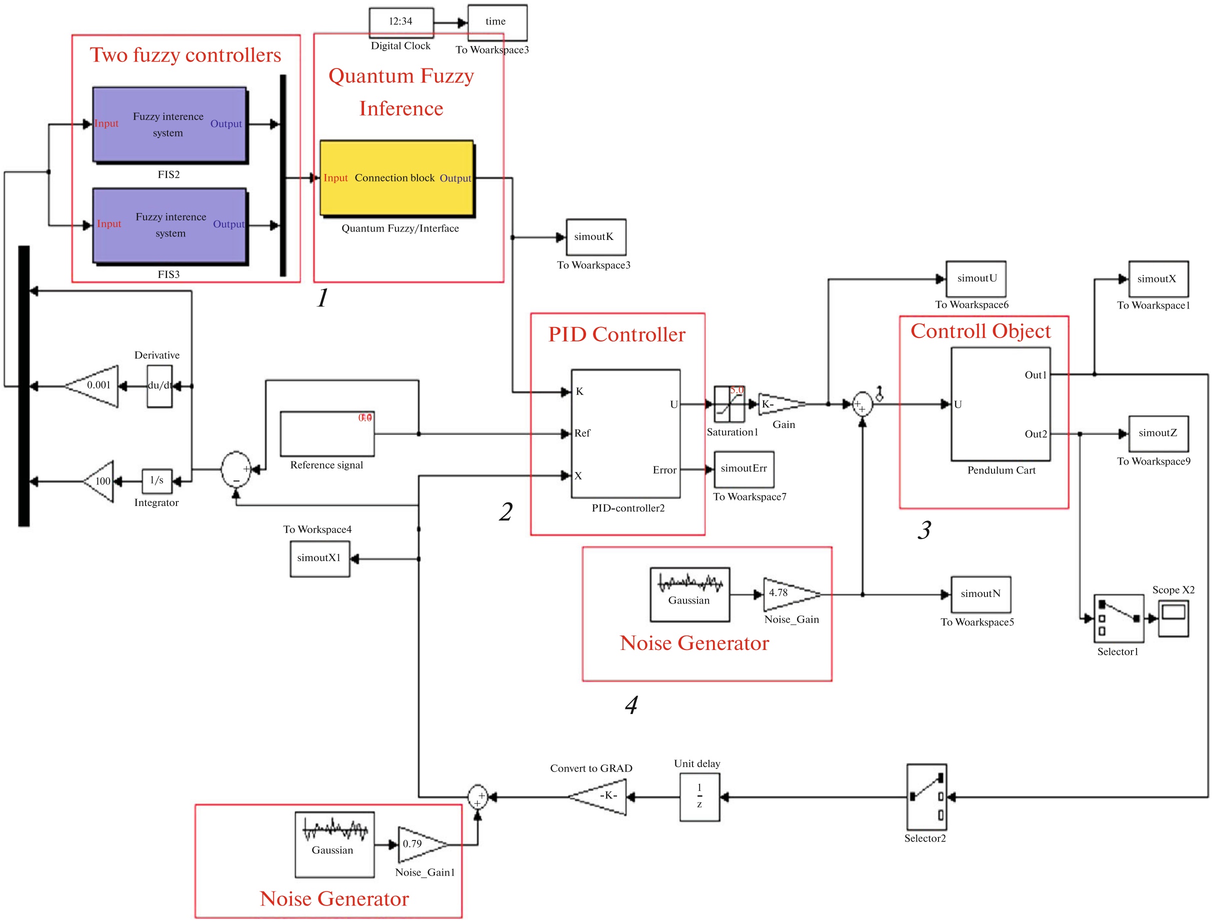


Fig. 9. Simulation System Structure in MatLab/Simulink environment: *1*—QFI unit; *2*—PID controller; *3*—Control object (CO); *4*—Noise generators.

mation to simulate the robot's control. Figure 7 shows the histograms of the coefficients obtained from FC1 and FC4.

After creating a new regulator's model and loading data into the quantum optimizer, a type of quantum correlation between gain coefficients is chosen. Formation of entangled states is performed on the basis of selected correlation matrix, which is displayed in the optimizer working window (Fig. 4).

Table 2. Control situations and mathematical models parameters

CO parameters	Typical situation (C1)	Contingent (C2)
Initial angle	0	0
Initial velocity	1	1
Cart weight	0.56	0.56
Pendulum weight	0.63	0.63
Pendulum length	0.05	0.07
Pin Friction	3.55 + normalized noise – int= 0.01, ampl=0.35	3.73 + normalized noise – int= 0.01, ampl=0.35
Wheel friction	3.63 + Gaussian noise 15%	3.63 + Gaussian noise 15%
Elasticity	5.54	5.54
Control noise	Uniform [–2.15 2.15], intensity 0.48	Uniform [–2.15 2.15], intensity 0.48
Measurement system Noise	Amplitude 0.22, Gaussian noise, intensity 0.01	Amplitude 0.32, Gaussian noise, intensity 0.01
Control delay	0.015	0.035

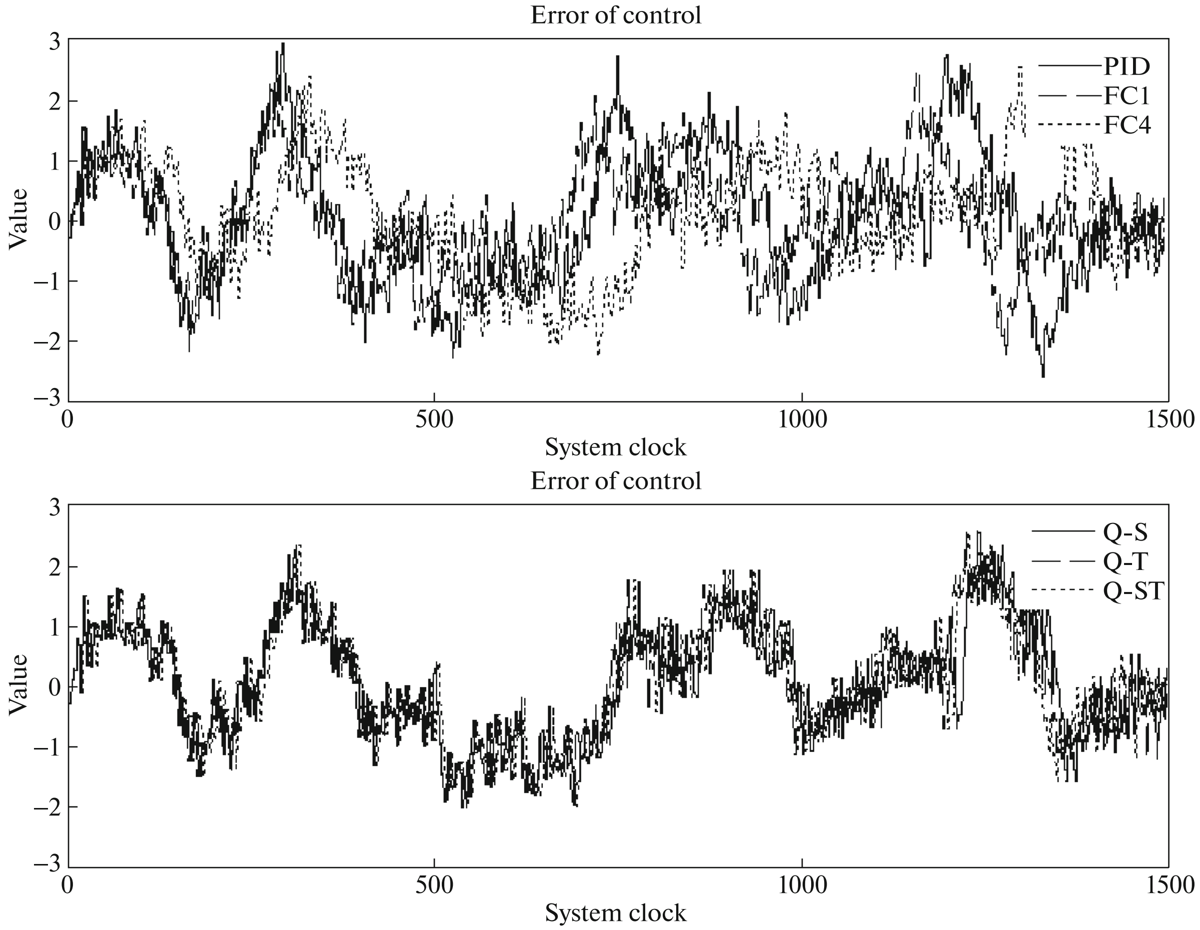


Fig. 10. Mathematical model deviation angle. Typical control situation (C1). Simulation.

At the next step the corresponding maximum and minimum values for QFI's input and output signals are set up in a special program window (Fig. 8).

In the final designing step, the scaling factors of the QFI output signals are adjusted using the genetic algorithm (GA) and the mathematical model to select the best solution.

3. THE AUTONOMOUS ICS's SIMULATION AND EXPERIMENT BASED ON THE QFI

Proceed to the practical application of the developed QFI model for the formation of the PID controller's gain coefficients control processes. Let's consider the classical problem of the "Cart-Pole" system stabilization for the mathematical and real model's which are given in [7, 13, 15, 16].

Description of the mathematical simulation and physical experiment results in two control situations:

—in the first (typical) situation (C1) the control signal delay is standard – 0.015 s;

—in the second contingency (C2) the control signal delay is 0.035 s. (increased about 3 times).

Table 2 shows the parameters of the mathematical simulation for C1 and C2.

Remark 2. The dimensions of physical quantities in Table 2 are given in the SI system and the form of (m, s, m/s, N) for displacement, time, velocity and force, respectively. Noises are generated by the forming filters and no additional information about the noise characteristics is required, since noises are used only to forming of the FC's robust KB.

Figure 9 shows the structure of the simulation system performed in the *MatLab/Simulink* environment.

The simulation results of regulators in a typical control situation are illustrated in Figs. 10 and 11.

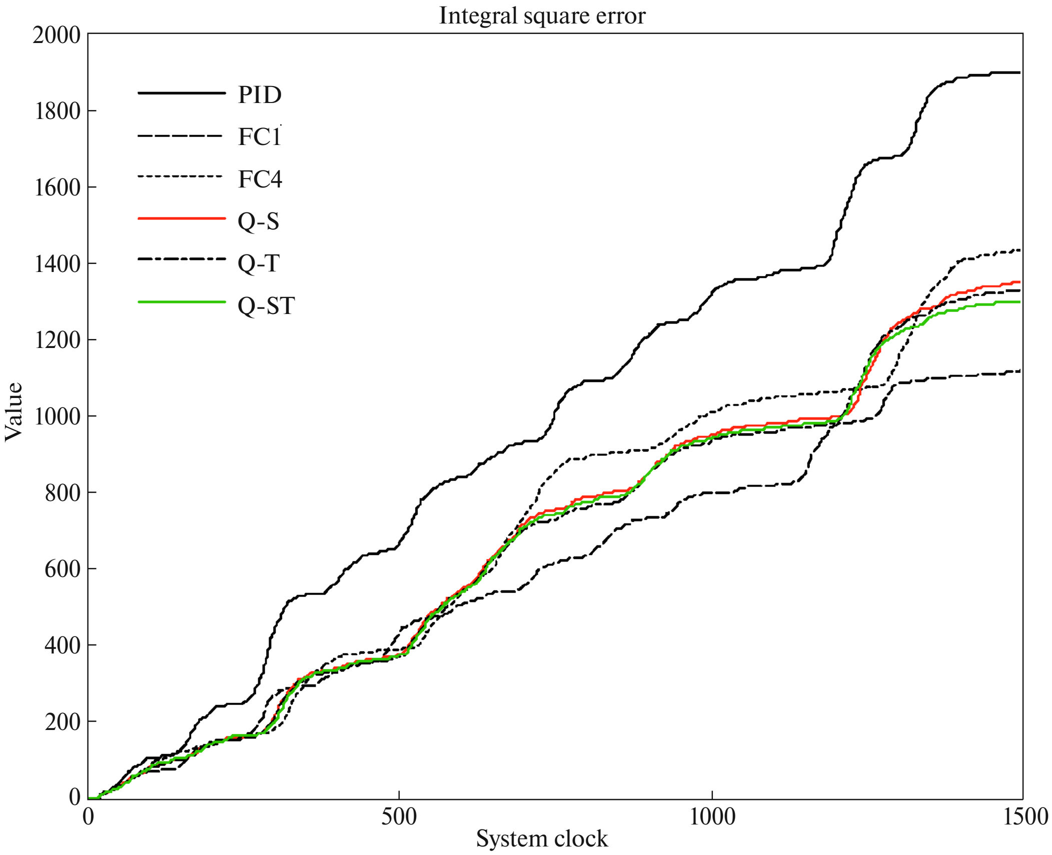


Fig. 11. Quadratic error integral. Typical control situation (C1). Simulation.

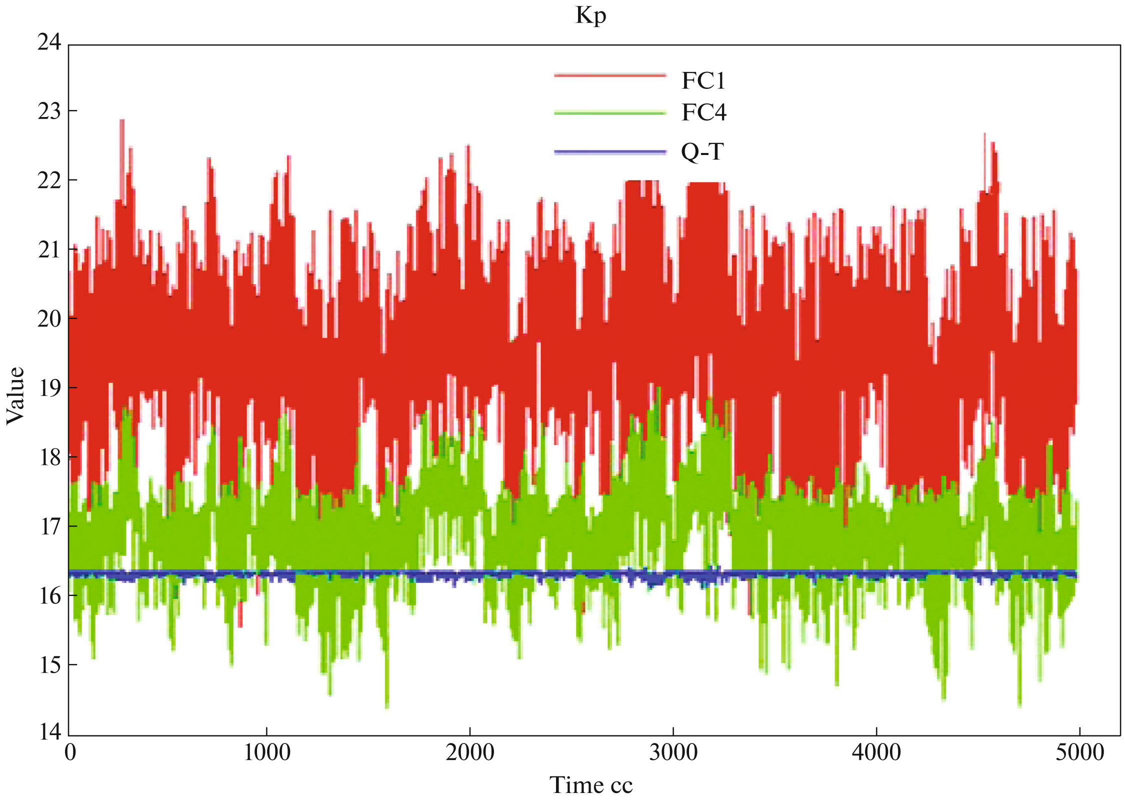
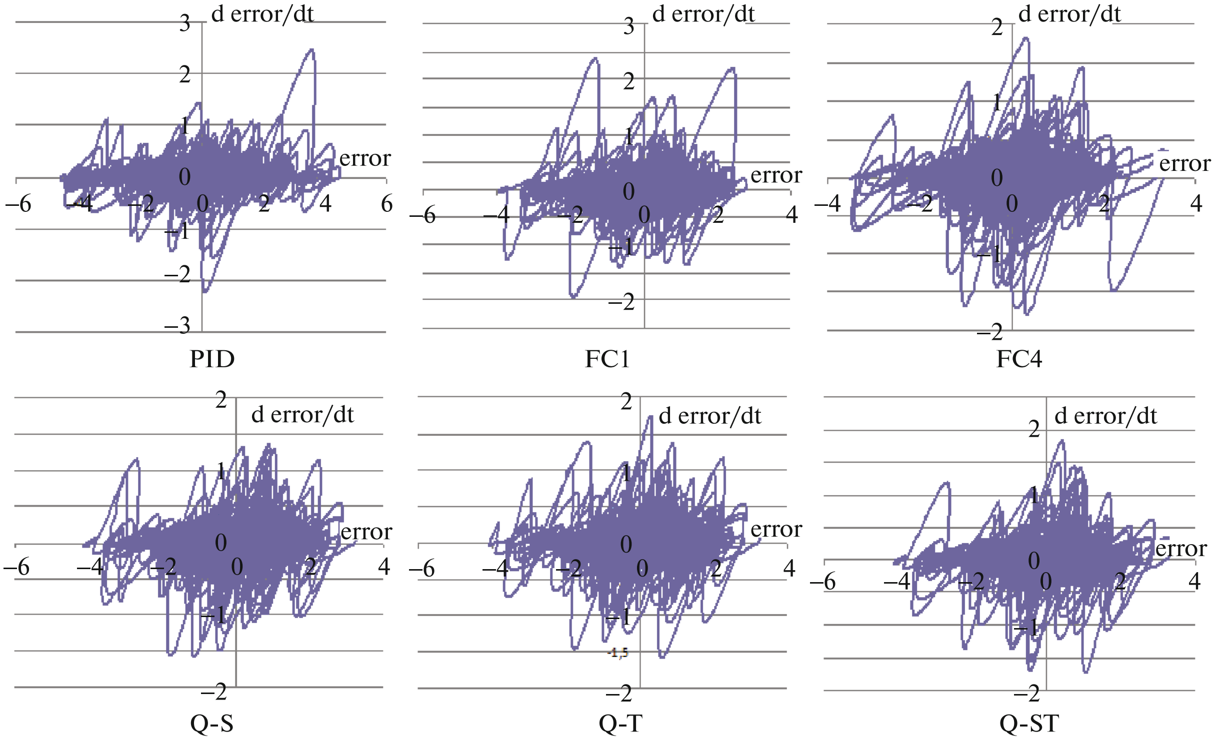


Fig. 12. Proportional gain. Input and output QFI’s values. Simulation in a typical control situation C1.



PID FC1 FC4

Q-S Q-T Q-ST

Fig. 13. Simulated controllers phase portraits.

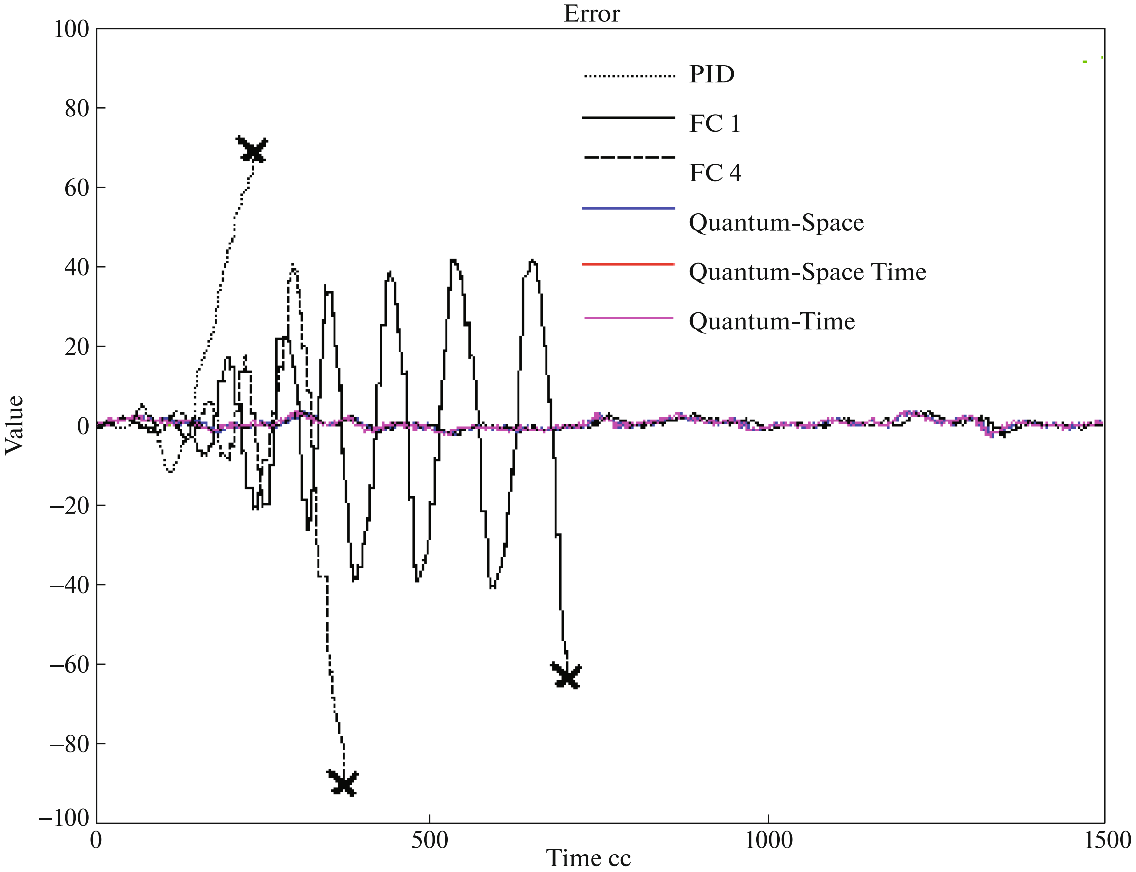


Fig. 14. Mathematical model deviation angle. Contingency control (C2). Simulation.

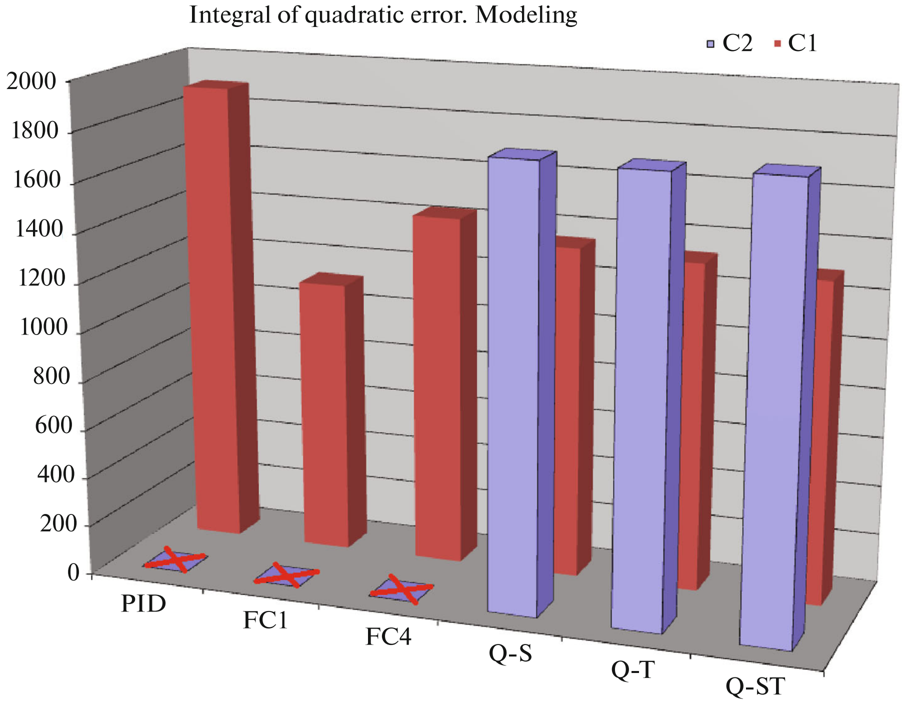


Fig. 15. Quadratic error integral. Contingency and typical control situations. Simulation (where FC1-FC4 are fuzzy controllers, and abbreviations: Q—quantum, S(Space)—spatial, T(Time)—temporal, ST(SpaceTime)—spatiotemporal correlations.

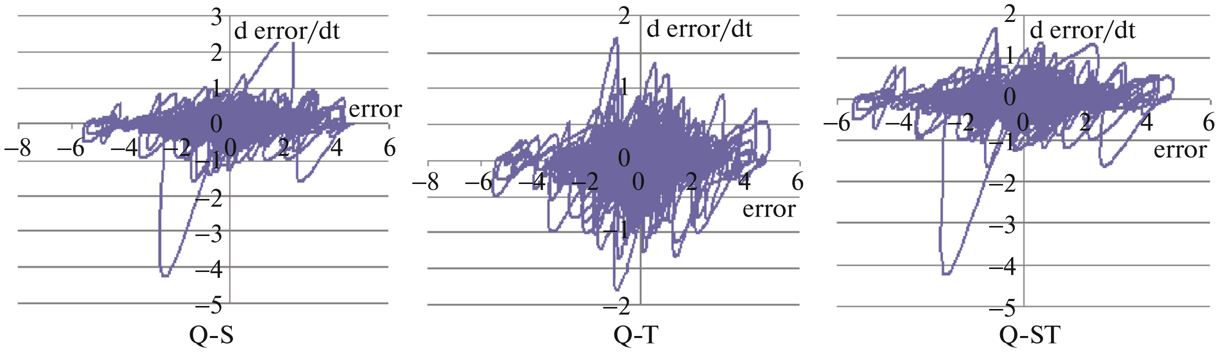


Fig. 16. Mathematical model's phase portraits with quantum fuzzy controllers in a control contingency (C2). Simulation.

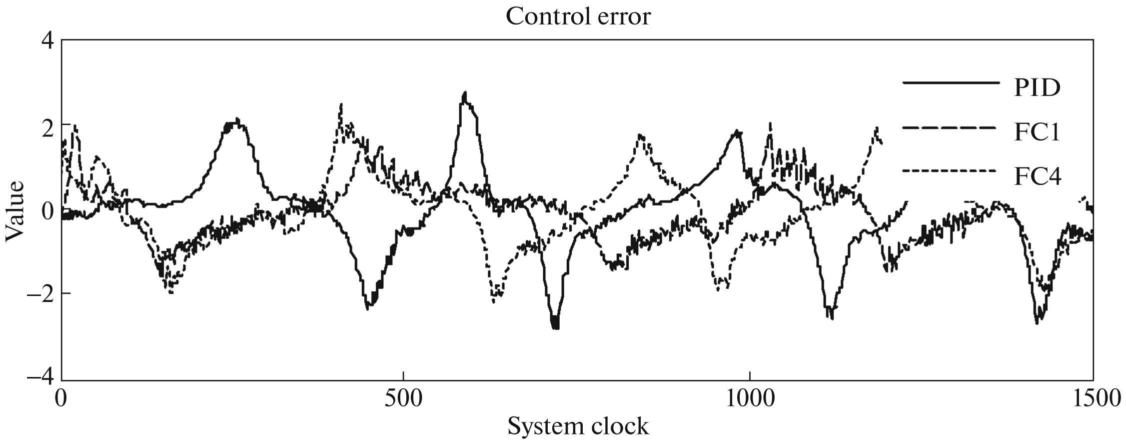


Fig. 17. Physical model deviation angle. Typical control situation (C1). Experiment.

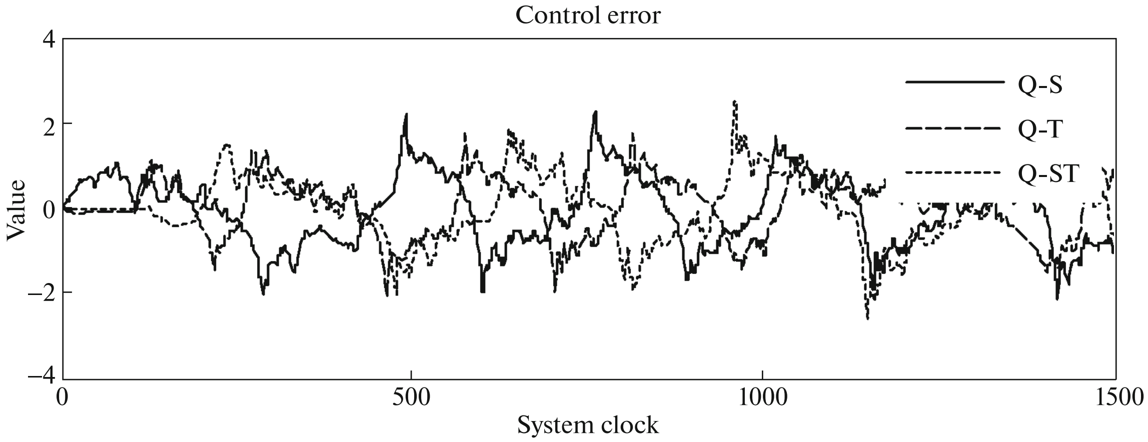


Fig. 18. Physical model deviation angle. Typical control situation (C1). Experiment.

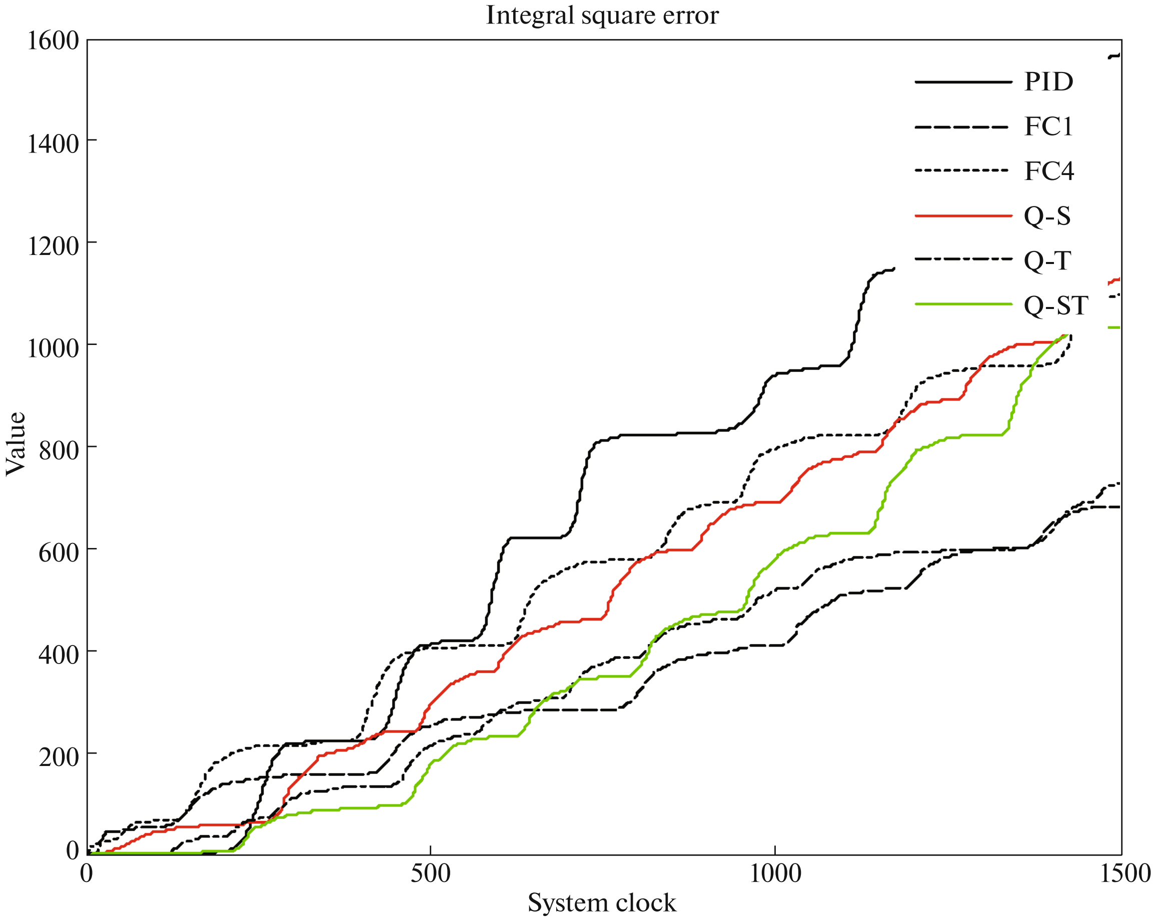
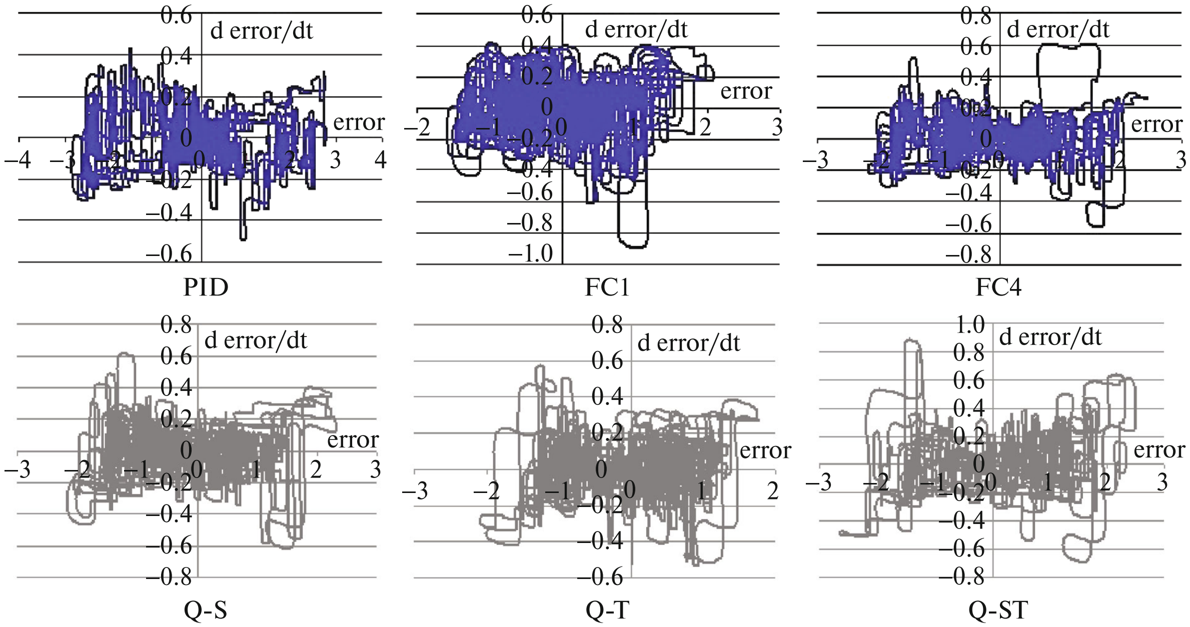


Fig. 19. Quadratic error integral. Typical control situation (C1). Experiment.

Consider the relationship between the input and output values of the QFI on the example of the proportional gain coefficient. Figure 12 shows the input values of the QFI (gain FC1 and FC4) and the output value of the proportional QFI gain coefficient under temporal correlation.

Figure 13 shows the phase portraits of the simulated systems.

Next, Fig. 14 shows the results of the simulation in a contingency control situation.



PID FC1 FC4

Q-S Q-T Q-ST

Fig. 20. Controllers phase portraits in a typical control situation (C1). Experiment.

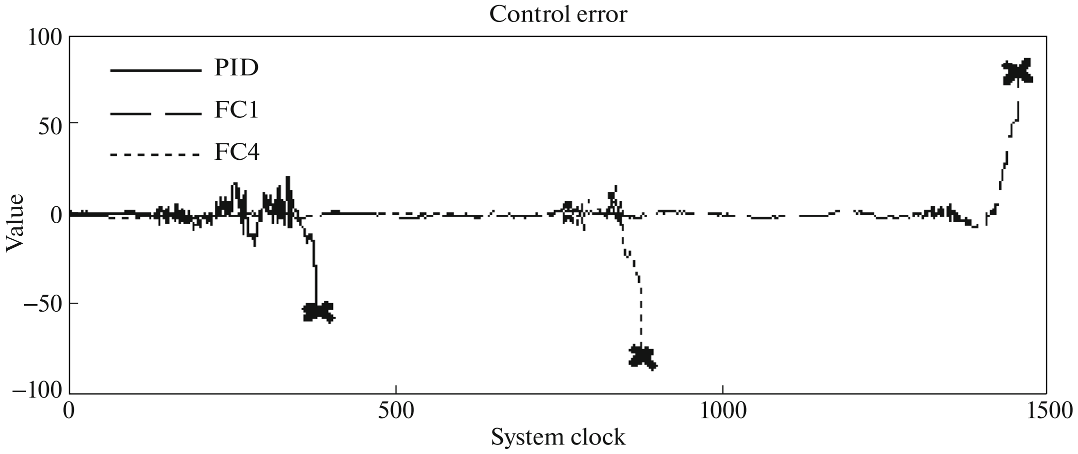


Fig. 21. Physical model deviation angle. Contingency control (C2). Experiment.

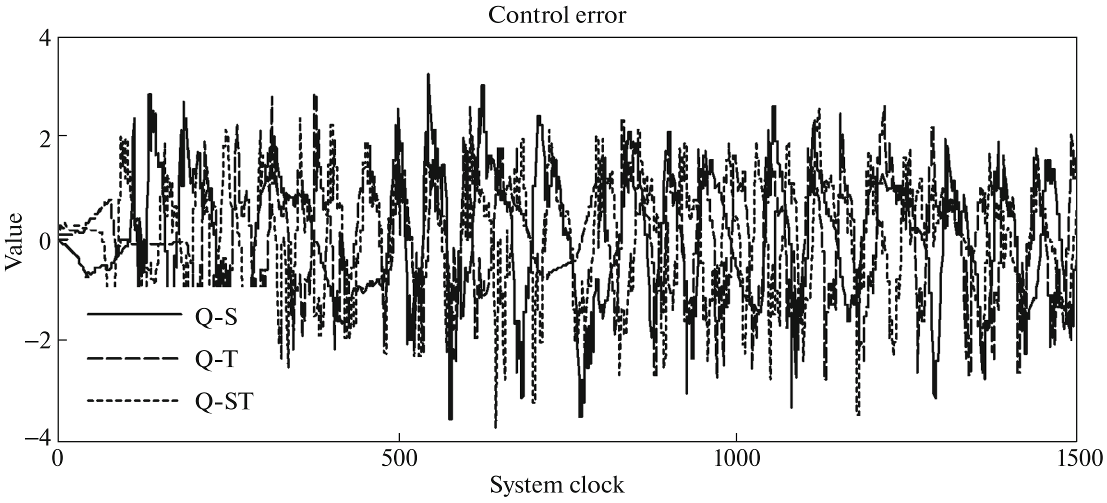


Fig. 22. Physical model deviation angle. Contingency control (C2). Experiment.

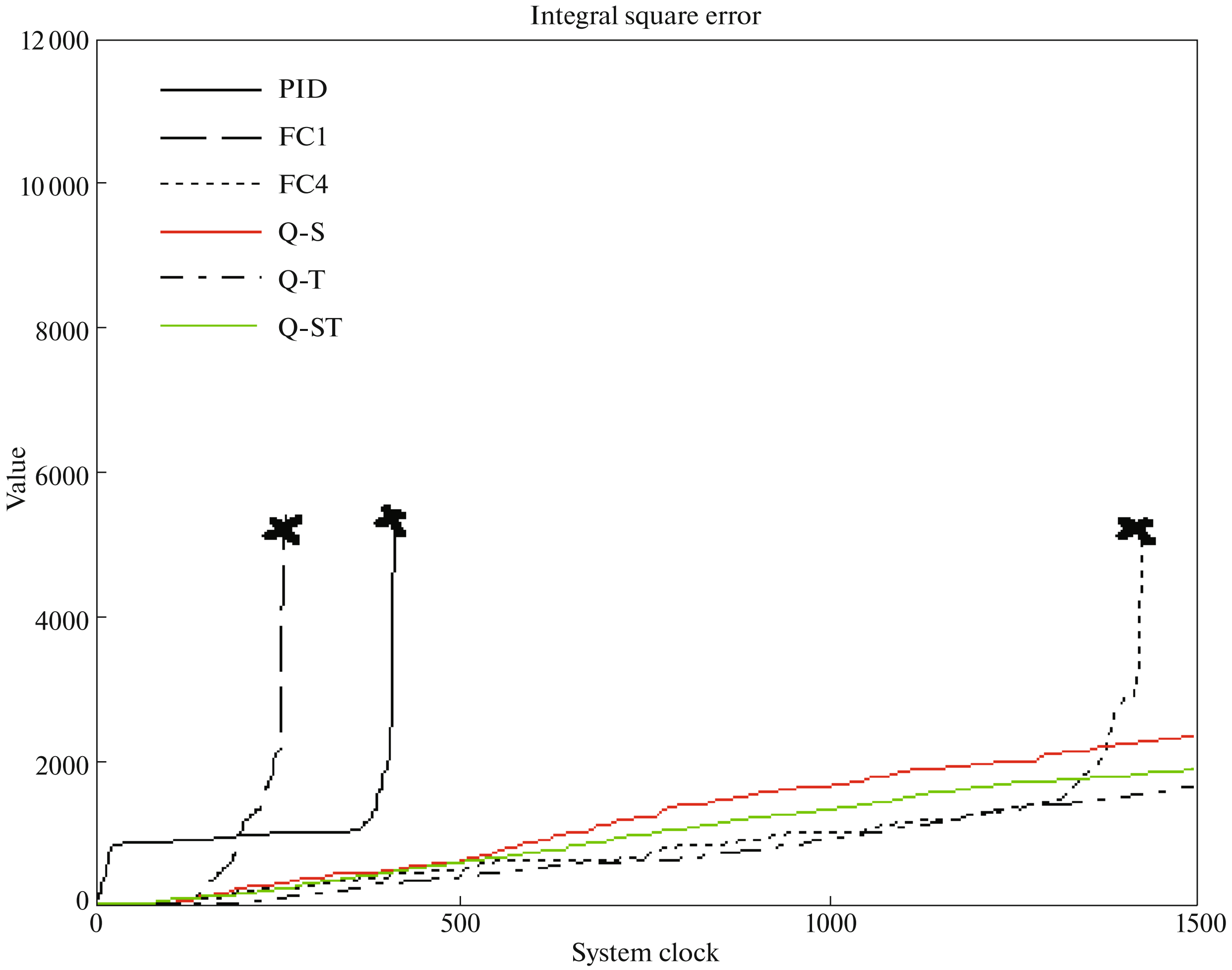


Fig. 23. Quadratic error integral. Contingency control (C2). Experiment.

Figure 15 describes a general diagram of the quadratic modeling error integral.

In Fig. 14, it can be seen that the value of the QC integral error is located between the fuzzy controllers that formed the QFI.

A physical experiment was performed on a real CO in a typical control situation. Figures 16–20 show the experimental results.

An experiment on a real CO in contingency control situation (C2) is conducted. Figures 21–25 shown these experimental results.

As the simulation and experiment modeling results show, the developed methodology of combining control strategies allows to cope effectively with the control tasks even in extreme situations in which the FCs, underlying of the QFI, does not coping. It is important to note that the QFI-based control system is inherited the best of the control quality characteristics from the KB FC, adding the self-organization ability.

Remark 3. Shown results essentially differ from known in literary sources [18–33] there are not exists the experimental results checking of quantum computations efficiency application on the real physical CO's.

Thus, the effectiveness and necessity of quantum computations application and control algorithms not only for quantum systems, but for classical CO's as well is shown. The effect of imprecise KB's quantum self-organization discovered in [6–9] due to extraction of hidden quantum information is experimentally successful verified and established in experiments for many complex poorly formalized and weakly structured physical CO's.

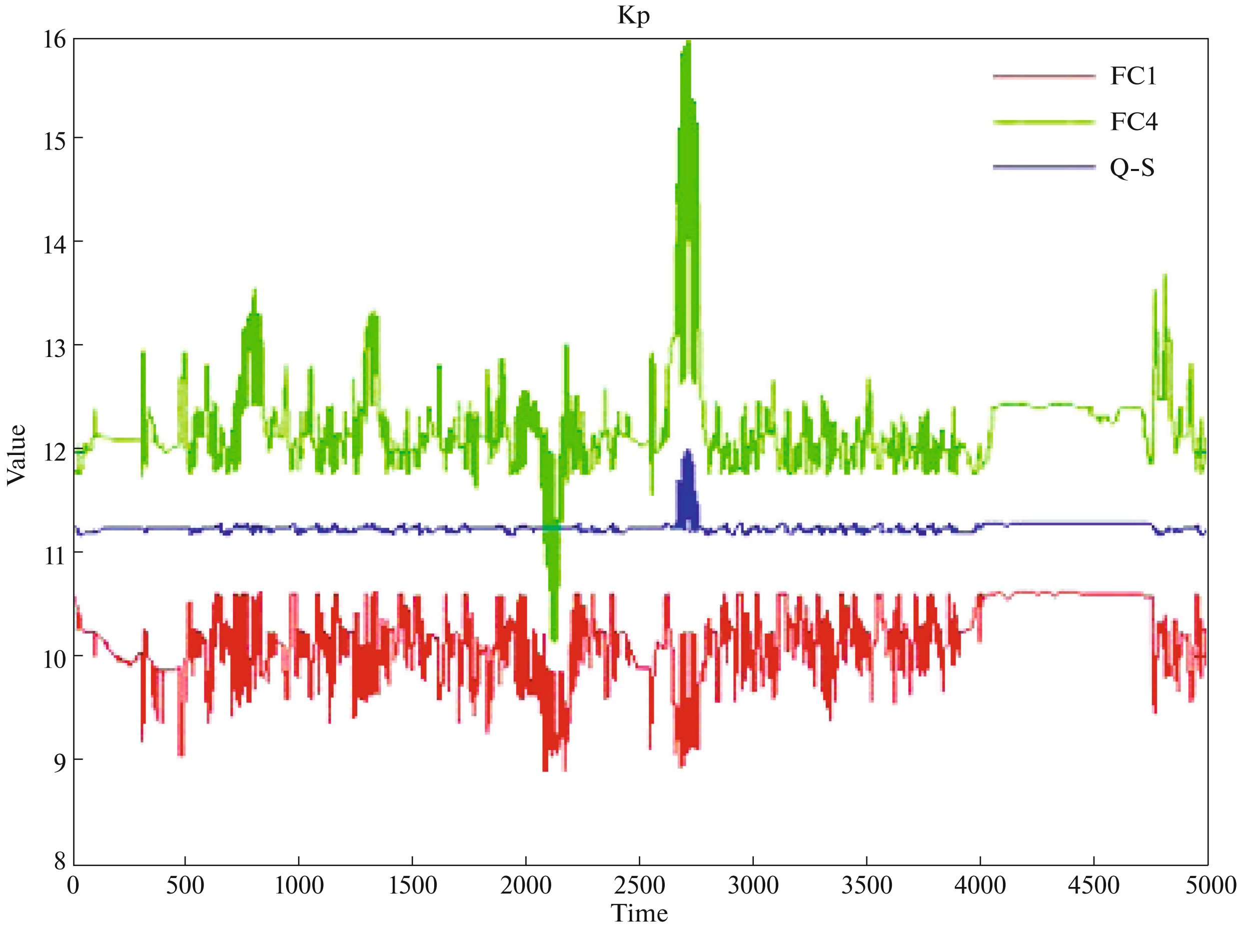


Fig. 24. Quantum controllers proportional gain based on KBs from mathematical and physical models. Experiment in contingency situation.

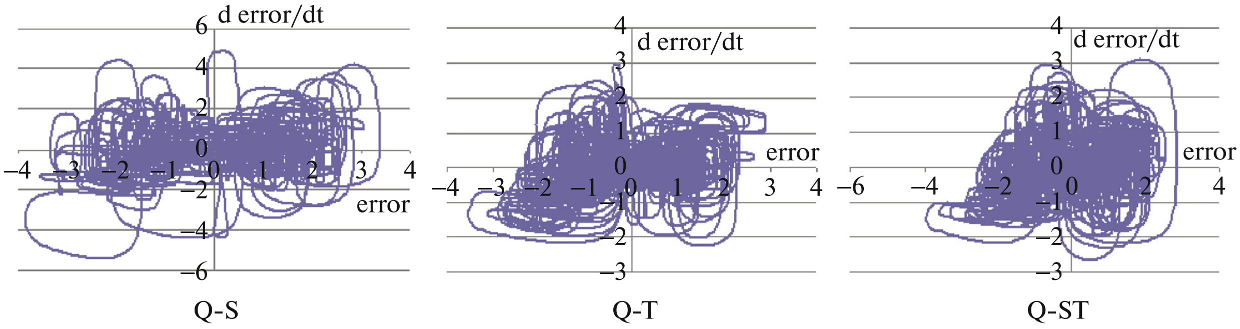


Fig. 25. Quantum fuzzy controller's phase portraits in a contingency situation. Experiment.

CONCLUSIONS

The technology of quantum KB optimizer application provides the system with additional robustness property only with application of algorithmic software. The conducted experiments shown that the intelligent control allows to perform adjustments even the complex control objects with several feedback loops. It is demonstrated that quantum FC in real conditions and real physical CO's copes with the task of a complex CO controlling at a sufficiently high level, where the classical regulator and FC does not have the required quality of control. The established effect confirms the realization of the KB's quantum self-organization principle by using the QFI algorithm developed in [3, 4, 6, 7]. The application of quantum computing on a classical processor in on line is shown. The simulations and experiments results prove usefulness and efficiency of hidden quantum information extracted from classical states of gain coefficients in control processes [34, 35].

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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