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Original article

Applied Quantum Soft Computing IT: SW & HW Sustainable Platform of Robust Intelligent Robotic Controllers

S. V. Ulyanov[a,b*], **A. G. Reshetnikov**[a,b], **D. P. Zrelova**[a,b]
[a] Dubna State University, Dubna, Russian Federation
Address: 19 Universitetskaya St., Dubna 141980, Moscow Region, Russian Federation
[b] Joint Institute for Nuclear Research, Dubna, Russian Federation
Address: 6 Joliot-Curie St., Dubna 141980, Moscow region, Russian Federation
[*] ulyanovsv46_46@mail.ru

Abstract

The information technology of a robust intelligent control system design based on quantum fuzzy inference is considered. The application of the developed design methodology is based on the quantum self-organization of imperfect knowledge bases of fuzzy controllers and leads to an increase in the robustness of intelligent control systems in unforeseen situations. The results of mathematical modeling and physical experiment are compared using the example of an autonomous robot in the form of an "cart - pole" system. Experimental confirmation of the existence of a synergetic effect of the formation of a robust self-organizing fuzzy controller from a finite number of non-robust fuzzy controllers in on line has been obtained. The resulting effect is based on the existence of hidden quantum information extracted from the classical states of the processes of time-varying gain coefficients schedule of regulators. 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-organizing regulator to extract quantum information hidden in the reactions of imperfect knowledge bases without violating the second information law of thermodynamics of 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 synergetic effect of quantum self-organization of imperfect knowledge bases. A generalized strategy for designing intelligent robust control systems based on quantum / soft computing technologies is described, which increase the reliability of hybrid intelligent controllers by providing the ability to self-organize. The main attention is paid to increasing the level of robustness of intelligent control systems in unpredictable control situations with demonstration by illustrative examples. A SW & HW platform and support tools for a supercomputer accelerator for modeling quantum algorithms on a classical computer are described.

Keywords: intelligent control, quantum algorithm, self-organization, knowledge base, quantum fuzzy inference

Conflict of interests: The authors declare no conflict of interets.

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Оригинальная статья

ИТ прикладных квантовых мягких вычислений: программно-аппаратная платформа робастных интеллектуальных контроллеров в робототехнике

С. В. Ульянов[1,2*], А. Г. Решетников[1,2], Д. П. Зрелова[1,2]
[1] ГБОУ ВО Московской области «Университет «Дубна», г. Дубна, Российская Федерация
Адрес: 141982, Российская Федерация, Московская область, г. Дубна, ул. Университетская, д. 19
[2] Международная межправительственная организация Объединенный институт ядерных исследований, г. Дубна, Российская Федерация
Адрес: 141980, Российская Федерация, Московская область, г. Дубна, ул. Жолио-Кюри, д. 6
[*] ulyanovsv46_46@mail.ru

Аннотация

Рассматривается информационная технология проектирования робастной интеллектуальной системы управления на базе квантового нечеткого вывода. Применение разработанной методологии проектирования основано на квантовой самоорганизации неточных баз знаний нечетких регуляторов и приводит к повышению уровня робастности интеллектуальных систем управления в непредвиденных ситуациях. Проводится сравнение результатов математического моделирования и физического эксперимента на примере автономного робота в виде системы "перевернутый маятник – движущаяся каретка". Получено экспериментальное подтверждение существования синергетического эффекта формирования робастного самоорганизующегося нечеткого регулятора из конечного числа не робастных нечетких регуляторов в реальном времени. Полученный эффект основан на существовании скрытой квантовой информации, извлекаемой из классических состояний процессов изменения во времени коэффициентов усиления регуляторов. Выведенный закон квантовой информационной термодинамики устанавливает возможность формирования термодинамической силы управления за счет извлеченного количества скрытой квантовой информации и совершения дополнительной полезной работы, гарантирующие достижение цели управления на базе повышения уровня робастности самоорганизующегося квантового регулятора. При этом количество совершенной объектом управления полезной работы (на макроуровне) превышает количество работы, затраченной (на микроуровне) квантовым самоорганизующимся регулятором на извлечение квантовой информации, скрытой в реакциях неточных баз знаний без нарушения второго информационного закона термодинамики открытых квантовых систем с обменом информацией запутанных супер-коррелированных состояний. Приведен конкретный пример автономного робота, демонстрирующий существование синергетического эффекта квантовой самоорганизации неточных баз знаний. Описана обобщенная стратегия проектирования интеллектуальных робастных систем управления, основанных на технологиях квантовых / мягких вычислений, которые повышают надежность гибридных интеллектуальных контроллеров за счет обеспечения способности к самоорганизации. Основное внимание уделено повышению уровня робастности интеллектуальных систем управления в непредсказуемых ситуациях управления с демонстрацией на наглядных примерах. Описаны программно-аппаратная платформа и инструментарий поддержки суперкомпьютерного ускорителя моделирования квантовых алгоритмов на классическом компьютере.

Ключевые слова: интеллектуальное управление, квантовый алгоритм, самоорганизация, база знаний, квантовый нечеткий вывод

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1. Introduction

For complex and ill-defined dynamic control objects that are not easily controlled by conventional control systems (such as *P*-[*I*]-*D*-controllers) — especially in the presence of fuzzy model parameters and different stochastic noises — the System of Systems Engineering methodology provides fuzzy controllers (FC) as one of alternative way of control systems design.

Soft computing methodologies, such as genetic algorithms (GA) and fuzzy neural networks (FNN) had expanded application areas of FC by adding optimization, learning and adaptation features. But still now it is difficult to design optimal and robust intelligent control system, when its operational conditions have to evolve dramatically (aging, sensor failure and so on).Such conditions could be predicted from one hand, but it is difficult to cover such situations by a single FC.Using unconventional computational intelligence toolkit, we propose a solution of such kind of generalization problems by introducing a *self-organization* design process of robust KB-FC that supported by the *Quantum Fuzzy Inference* (QFI) based on quantum soft computing ideas[1] [1].

2. Problem's Formulation

A. *Main problem and toolkit*

One of main problem in modern FC design is how to design and introduce robust KBs into control system for increasing *self-learning, self-adaptation and self-organizing capabilities* that enhance robustness of developed FC in unpredicted control situations.

The *learning* and *adaptation* aspects of FC's have always the interesting topic in advanced control theory and system of systems engineering. Many learning schemes were based on the *back-propagation* (BP) algorithm and its modifications (see, for example, [1] and their references). Adaptation processes are based on iterative stochastic algorithms.

These ideas are successfully working if we perform our control task without a presence of ill-defined stochastic noises in environment or without a presence of unknown noises in sensors systems and control loop, and so on.

For more complicated control situations learning and adaptation methods based on BP-algorithms or iterative stochastic algorithms do not guarantee the required robustness and accuracy of control.

The solution of this problem based on SCO was developed in [1]. For achieving of *self-organization* level in intelligent control system it is necessary to use QFI[2] [2]. The described *self-organizing* FC design method is based on special form of QFI that uses a few of partial KBs designed by SCO.

QFI uses the laws of quantum computing technologies and explores three main unitary operations: (i) superposition; (ii) entanglement (quantum correlations); and (iii) interference. According to quantum gate computation, the logical union of a few KBs in one generalized space is realized with *superposition* operator; with *entanglement* operator (that can be equivalently described by different models of *quantum oracle* [3]) a search of a «successful» marked solution is formalized; and with *interference* operator we can extract «good» solutions with classical *measurement* operations.

B. *Method of solution*

Proposed QFI system consists of a few KB-FCs, each of which has prepared for appropriate conditions of control object and excitations by Soft Computing Optimizer (SCO) [1]. QFI system is a new quantum control algorithm of self-organization block, which performs post processing of the results of fuzzy inference of each independent FC and produces in on-line the generalized control signal output [2].In this case the output of QFI is an optimal robust control signal, which combines best features of each independent FC outputs. Therefore, the operation area of such a control system can be expanded greatly as well as its robustness.

Robustness of control is the background for support the reliability of advanced control accuracy in uncertainty and information risk. The simulation example of robust intelligent control based on QFI is introduced.

C. *Main goal*

The main technical purpose of QFI is to supply a self-organization capability for many (sometimes unpredicted) control situations based on a few KBs. QFI produces robust optimal control signal for the current control situation using a reducing procedure and compression of redundant information in KB's of individual FCs. Process of rejection and compression of redundant information in KB's uses the laws of quantum information theory [3].Decreasing of redundant information in KB-FC increases the robustness of control without loss of important control quality as reliability of control accuracy. As a result, a few KB-FC with QFI can be adapted to unexpected change of external environments and to uncertainty in initial information.

We introduce main ideas of quantum computation and quantum information theory [3] applied in developed QFI methods. *Quantum Fuzzy Inference* ideas are introduced. Robustness of new types of *self-organizing intelligent control systems* is demonstrated.

3. SCO-structure based on soft computing

D. *KB of FC creation*

SCO uses the chain of GAs (GA_1, GA_2, GA_3) and approximates measured or simulated data (TS) about the modeled system with desired accuracy or using real robot for it. GA_1 solves optimization problem connected with the optimal choice of number of membership functions and their shapes. GA_2 searches optimal KB with given level of rules activation. Introduction of activation level of rules allows us to sort fuzzy rules in accordance with value information and design robust KB. GA_3 refines KB by using a few criteria.

Figure 2 shows the flow chart of SCO operations on macro level and combines several stages.

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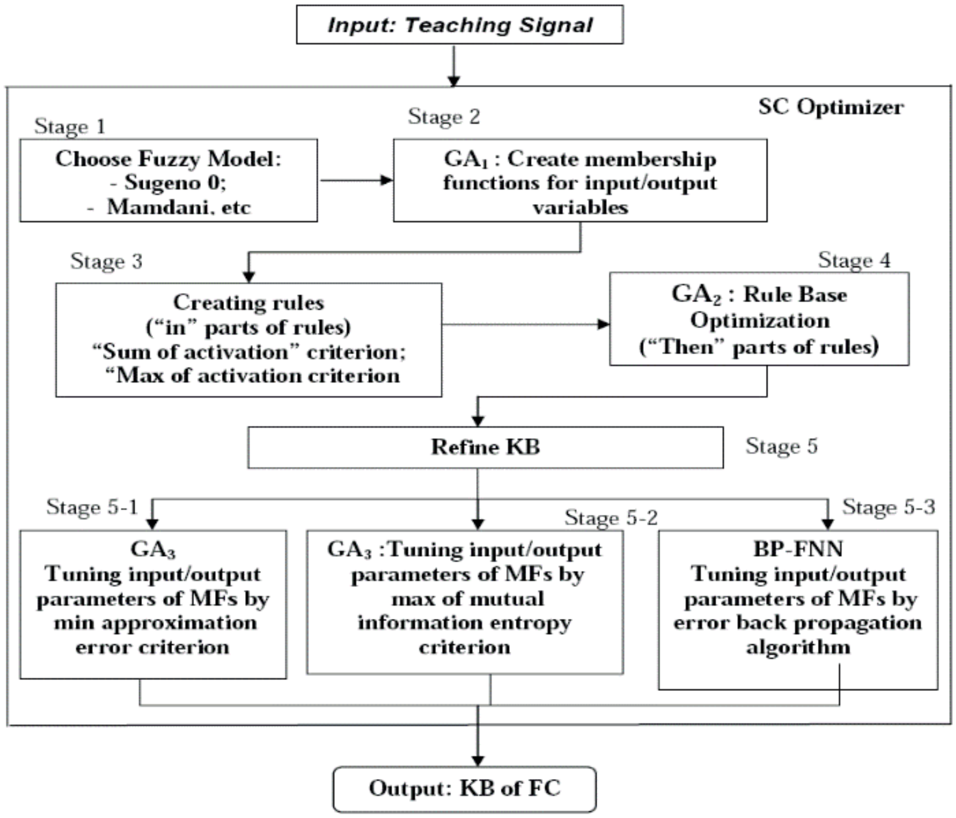
[1] Ulyanov S.V. System and Method for Control Using Quantum Soft Computing. United States Patent US-6578018B1. USA; 2003. Available at: https://patents.google.com/patent/US6578018B1/en (accessed 01.04.2023).

[2] Ibid.



F i g. 1. Flow chart of SC Optimizer

Source: Hereinafter in the article, all tables and figures are compiled by the authors.

Stage 1: *Fuzzy Inference System* (FIS) *Selection*. The user makes the selection of fuzzy inference model with the featuring of the following initial parameters: Number of input and output variables; Type of fuzzy inference model (Mamdani, Sugeno, Tsukamoto, etc.); Preliminary type of MFs.

Stage 2: *Creation of linguistic values*. By using the information (that was obtained on Stage 1), GA$_1$ optimizes membership functions number and their shapes, approximating teaching signal (TS), obtained from the in-out tables, or from dynamic response of control object (real or simulated in Matlab).

Stage 3: *Creation rules*. At this stage we use the rule rating algorithm for selection of certain number of selected rules prior to the selection of the index of the output membership function corresponding to the rules. For this case two criteria based on a rule's activation parameter called as a «manual threshold level» (TL). This parameter is given by a user (or it can be introduced automatically).

Stage 4: *Rule base optimization*. GA$_2$ optimizes the rule base obtained on the Stage 3, using the fuzzy model obtained on Stage 1, optimal linguistic variables, obtained on Stage 2, and the same TS as it was used on Stage 1. Rule base optimization can be performed by using mathematical model, or by using distance connection to real control object.

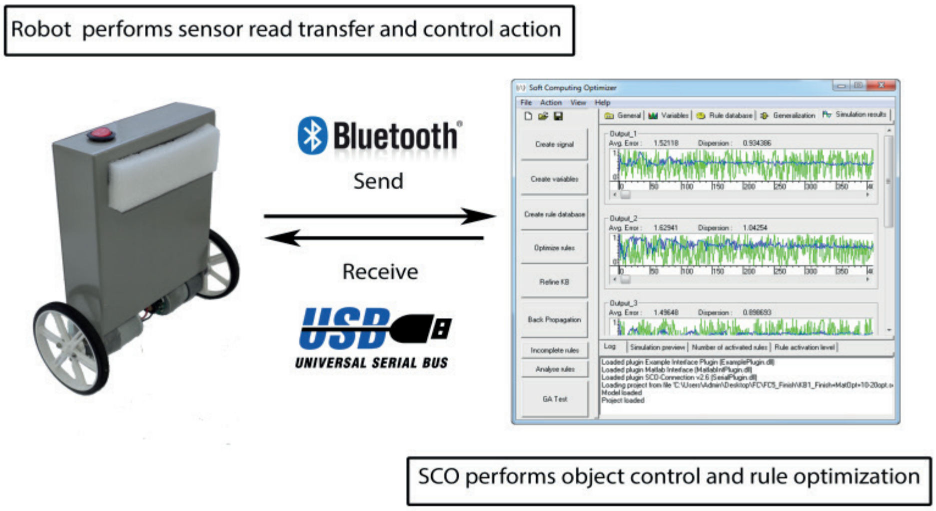
Stage 5: *Refine KB*. On this stage, the structure of KB is already specified and close to global optimum. In order to reach the optimal structure, a few methods can be used. First method is based on GA$_3$ with fitness function as minimum of approximation error, and in this case KB refining is similar to classical derivative based optimization procedures (like error back propagation (BP) algorithm for FNN tuning). Second method is also based on GA$_3$ with fitness function as maximum of mutual information entropy. Third method is realized as pure error back propagation (BP) algorithm. BP algorithm may provide further improvement of output after genetic optimization. As output results of the Stages 3, 4 and 5, we have a set of KB corresponding to chosen KB optimization criteria.

E. *Remote rule base optimization*

Remote KB optimization is performed on the fourth stage of designing FC (Fig. 1). The implementation of the physical environment connection intends to use additional equipment for the data transfer, such as radio channel, Bluetooth, WiFi or a cable connection, such as USB. Exchange of information between the management system and the SCO intended to form a KB (Fig. 2).

The control system reads the sensors and sends data to a computer for further processing. By taking input values, SCO evaluates previous decision (KB-FC) and performs fuzzy inference to check the following solutions (KB-FC). The result of the fuzzy inference is sent to the remote device. Thereafter, the control system by processing the input values generates control action.

Synchronization of SCO and control systems is based on the remote device (robot). To this end, a special program (firmware) is developed.



```
Loaded plugin Example Interface Plugin (ExamplePlugin.dll)
Loaded plugin Matlab Interface (MatlabIntPlugin.dll)
Loaded plugin SCO-Connection v2.6 (SerialPlugin.dll)
Loading project from file 'C:\Users\Admin\Desktop\FC\FC5_Finish\KB1_Finish+MatOpt+10-20opt.
Model loaded
Project loaded
```

F i g. 2. Remote rule base optimization scheme

Connection profile uses the serial port. Transmission rate in this case is 115,200 bits / sec. During operation, floats in symbolic form are passing via COM-port. Connection to SCO uses designed plug-in. Before establishing a connection to the SCO, COM port number and the check time of one solution (the number of cycles of the system to test solution) are selected.

4. QFI-structure based on quantum computing

For design of QFI based on a few KBs it is needed to apply the additional operations to partial KBs outputs that drawing and aggregate the value information from different KBs. Soft computing tool does not contain corresponding necessary operations [4].

The necessary unitary reversible operations are called as *superposition*, *entanglement* (quantum correlation) and *interference* that physically are operators of quantum computing in information processing.

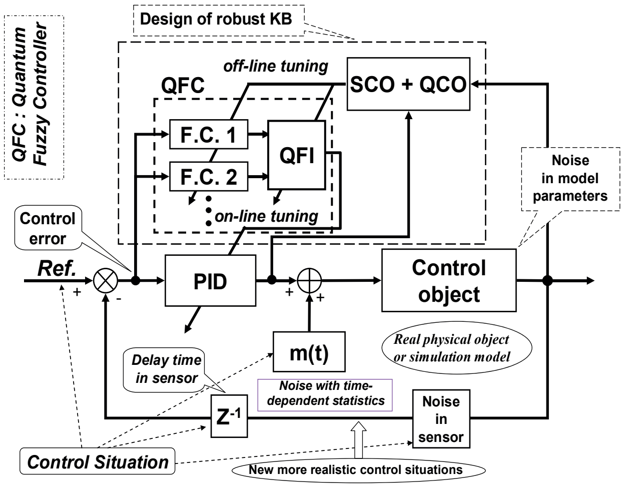
We introduce briefly the particularities of quantum computing and quantum information theory that are used in the quantum block QFI (Fig. 3) supporting a self-organizing capability of FC in robust intelligent control system (ICS).

F. *Quantum computing*

In Hilbert space the superposition of classical states $\left(c_1^{(1)}\left|0\right\rangle + c_2^{(1)}\left|1\right\rangle\right)$ called quantum bit (qubit) means that «*False*» and «*True*» are jointed in one state with different probability amplitudes, $c_i^1, i = 1,2$. If the Hadamard transform $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ is independently applied to different classical states then a tensor product of superposition states is the result:

$$\left|\psi\right\rangle = H^{\otimes n}\left|False\right\rangle = \frac{1}{\sqrt{2^n}} \otimes_{i=1}^{n} \left(\left|False\right\rangle + \left|True\right\rangle\right). \tag{1}$$

The fundamental result of quantum computation stays that all of the computation can be embedded in a circuit, which nodes are the universal gates. These gates offer an expansion of unitary operator U that evolves the system in order to perform some computation. Thus, naturally two problems are discussed: (i) Given a set of functional points $S = \{(x, y)\}$ find the operator U such that $y = U \cdot x$; (ii) Given a problem, fined the quantum circuit that solves it. Algorithms for solving these problems may be implemented in a hardware quantum gate or in software as computer programs running on a classical computer.It is shown that in quantum computing the construction of a universal quantum simulator based on classical effective simulation is possible[3] [3].



F i g. 3. Structure of robust ICS based on QFI

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[3] Ibid.

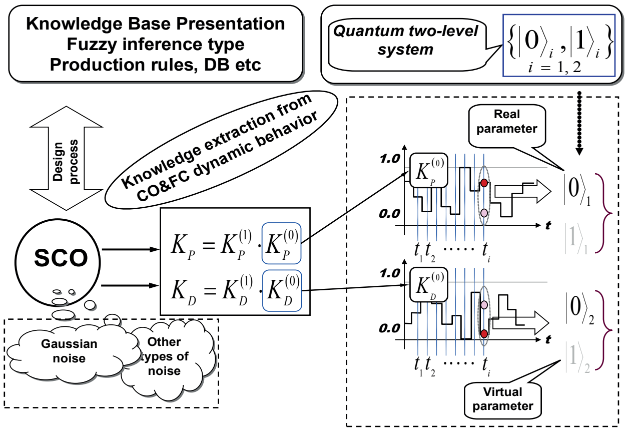
In the general form, the model of quantum algorithm computing comprises the following five stages:

- preparation of the initial state $\left|\psi_{out}\right\rangle$ (classical or quantum);
- execution of the Hadamard transform for the initial state in order to prepare the superposition state;
- application of the entangled operator or the quantum correlation operator (quantum oracle) to the superposition state;
- application of the interference operator;
- application of the measurement operator to the result of quantum computing $\left|\psi_{out}\right\rangle$.

Hence, a quantum gate approach can be used in a global optimization of KB structures of ICSs that are based on quantum computing, on a quantum genetic search and quantum learning algorithms [4].

G. *Quantum information resources in QFI algorithm*

Figure 4 shows the algorithm for coding, searching and extracting the value information from two KBs of fuzzy PID controllers designed by SCO.

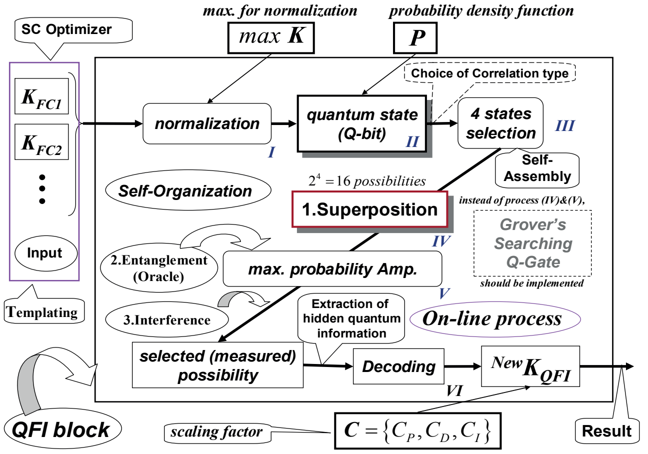


F i g. 4. Example of information extraction in QFI

Thus, the quantum algorithm for QFI (Fig. 5) the following actions are realized:

- The results of fuzzy inference are processed for each independent FC;
- Based on the methods of quantum information theory, valuable quantum information hidden in independent (individual) knowledge bases is extracted;
- In on-line, the generalized output robust control signal is designed in all sets of knowledge bases of the fuzzy controller.
- In this case, the output signal of QFI in on-line is an optimal signal of control of the variation of the gains of the PID controller, which involves the necessary (best) qualitative characteristics of the output control signals of each of the fuzzy controllers, thus implementing the self-organization principle.

Therefore, the domain of efficient functioning of the structure of the intelligent control system can be essentially extended by including robustness, which is a very important characteristic of control quality.



F i g. 5. The structure of QFI gate

The robustness of the control signal is the background for maintaining the reliability and accuracy of control under uncertainty conditions of information or a weakly formalized description of functioning conditions and/or control goals.

QFI model based on physical laws of quantum information theory, for computing use unitary invertible (quantum) operators and they have the following names: *superposition*, *quantum correlation* (entangled operators), and *interference*. The forth operator, measurement of result quantum computation is irreversible.

Optimal drawing process of value information from a few KBs that are designed by soft computing is based on following four facts from quantum information theory [2]: (i) the effective quantum data compression; (ii) the splitting of classical and quantum parts of information in quantum state; (iii) the total correlations in quantum state are «mixture» of classical and quantum correlations; and (iv) the exiting of hidden (locking) classical correlation in quantum state [3], [5].

This quantum control algorithm uses these four Facts from quantum information theory: (i) compression of classical information by coding in computational basis $\{|0\rangle, |1\rangle\}$ and forming the quantum correlation between different computational bases (Fact 1); (ii) separating and splitting total information and correlations on «classical» and «quantum» parts using Hadamard transform (Facts 2 and 3); (iii) extract unlocking information and residual redundant information by measuring the classical correlation in quantum state (Fact 4) using criteria of maximal corresponding amplitude probability.

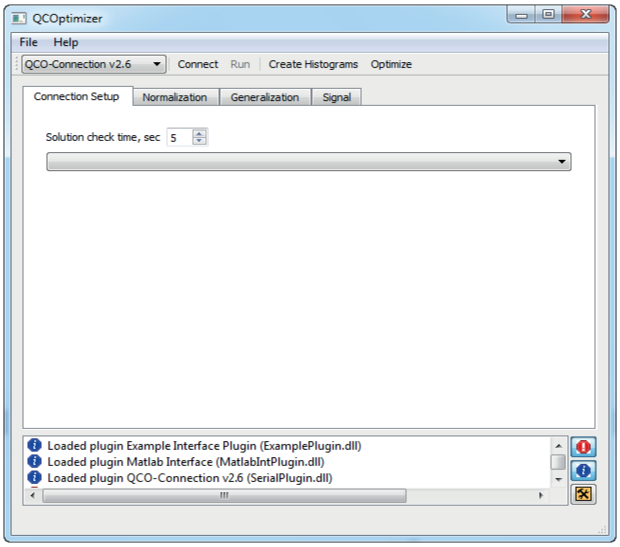
These facts are the informational resources of QFI background. Using these facts it is possible to extract an additional amount of quantum value information from smart KBs produced by SCO for design a *wise* control using compression and rejection procedures of the redundant information in a classical control signal.

Below we discuss the application of this quantum control algorithm in QFI structure.

H. *Remote quantum base optimization*

As the adjustable parameter scaling factor is used in remote quantum base optimization. Scaling factor is used in the final step of forming the gain of PID (Fig. 5).

During operation, floats in symbolic form are passed via COM-port. The control system reads the sensors and sends them to a computer for further processing. By taking the input values, the GA evaluates the previous decision, and carries a quantum fuzzy inference to check the following solutions. The result of the fuzzy inference is sent to the remote device. Thereafter, the control system by processing the input values generates control action. Connecting to QFI developed through a plug-in.Before establishing a connection to the SCO, COM port number and the check time of one solution (the number of cycles of the system to test solution) are selected (Fig. 6).



Solution check time, sec 5

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Loaded plugin Example Interface Plugin (ExamplePlugin.dll)
Loaded plugin Matlab Interface (MatlabIntPlugin.dll)
Loaded plugin QCO-Connection v2.6 (SerialPlugin.dll)
```

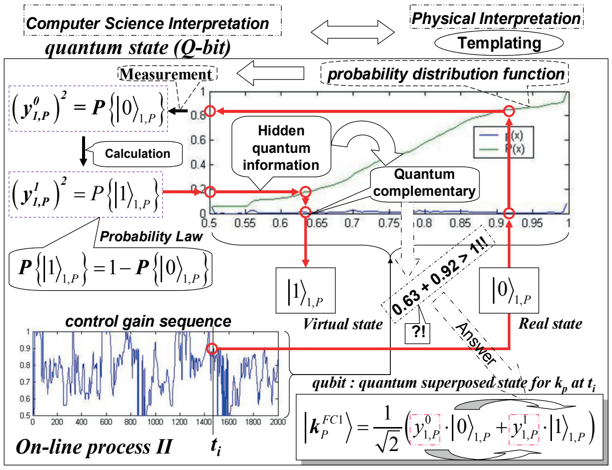
F i g. 6. Remote connection plug-in for QC Optimizer

5. KB-self-organization of FC's based on QFI

I. *Robust FC design toolkit*

The kernel of the abovementioned FC design toolkit is a so-called SCO implementing advanced soft computing ideas. SCO is considered as a new flexible tool for design of optimal structure and robust KBs of FC based on a chain of genetic algorithms (GAs) with information-thermodynamic criteria for KB optimization and advanced error back-propagation algorithm for KB refinement [1]. Input to SCO can be some measured or simulated data (called as «teaching signal» (TS)) about the modelling system. For TS design (or for GA fitness evaluation) we are used stochastic simulation system based on the control object model. More detail description of SCO is given in [1]. Below we discuss the application of this algorithm in QFI structure.Figure 3 illustrates as an example the structure and main ideas of self-organized control system consisting of two FC's coupling in one QFI chain that supplies a self-organizing capability. According to described above algorithm the input to the QFI gate is considered according (1) as a superposed quantum state $K_1(t) \otimes K_2(t)$, where $K_{1,2}(t)$ are the outputs from fuzzy controllers FC1 and FC2 designed by SCO (see, Fig. 4) for the given control task in different control situations (for example, in the presence of different stochastic noises).

The algorithm of superposition calculation is presented in Fig. 7 and described in details in [2].



F i g.7. The algorithm of superposition calculation

We discuss for simplicity the situation in which an arbitrary amount of correlation is unlocked with a one-way message. Let us consider the communication process between two KBs as communication between two players *A* and *B* (see, Figs 4 and 7) and let $d = 2^n$. According to the law of quantum mechanics, initially we must prepare a quantum state description by density matrix ρ from two classical states (KB_1 and KB_2).

The initial state ρ is shared between subsystems held by *A* (KB_1) and *B* (KB_2), with respective dimensions d,

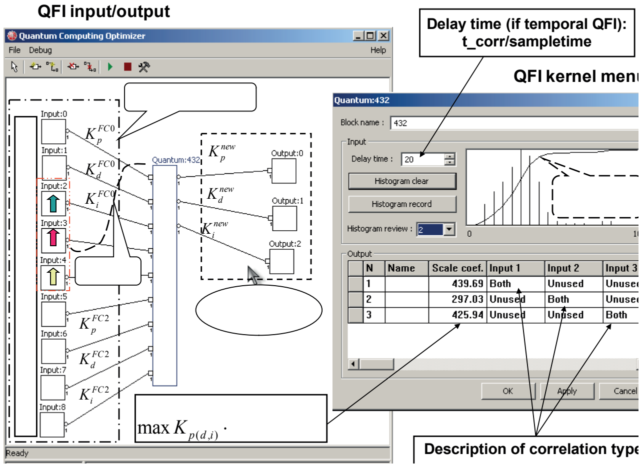
$$\rho = \frac{1}{2d} \sum_{k=0}^{d-1} \sum_{t=0}^{1} \left(\left|k\right\rangle\left\langle k\right| \otimes \left|t\right\rangle\left\langle t\right|\right)_A \otimes \left(U_t \left|k\right\rangle\left\langle k\right| U_t^{\dagger}\right)_B . \quad (2)$$

Here $U_0 = I$ and U_1 changes the computational basis to a conjugate basis $\left|\left\langle i\right| U_1 \left|k\right\rangle\right| = 1/\sqrt{d} \quad \forall\, i,k$.

In this case, *B* chooses $\left|k\right\rangle$ randomly from d states in two possible random bases, while A has complete knowledge on his state. The state (2) can arise from following scenario. *A* picks a random n-bit string k and sends B $\left|k\right\rangle$ or $H^{\otimes n}\left|k\right\rangle$ depending on whether the random bit $t = 0$ or 1. A can send t to B to unlock the correlation later. Experimentally, Hadamard transform, H and measurement on single qubits are sufficient to prepare the state (2), and later extract the unlocked correlation in ρ'. The initial correlation is small, i.e. $I_{Cl}^{(l)}(\rho) = \frac{1}{2}\log d$. The final amount of information after the complete measurement M_A in one-way communication is ad hoc, $I_{Cl}(\rho') = I_{Cl}^{(l)}(\rho) = \log d + 1$, i.e., the amount of *accessible information increase*. This phenomenon is impossible classically.

However, states exhibiting this behaviour *need not be entangled* and corresponding communication can be organized using Hadamard transform [5]. Therefore, using the Hadamard transformation and a new type of quantum correlation as the communication between a few KB's it is possible to increase initial information by unconventional quantum correlation (as the quantum cognitive process of a value hidden information extraction in on-line, see, e.g. Fig. 4).

In present report we consider a simplified case of QFI when with the Hadamard transform is organized an unlocked correlation in superposition of two KBs; instead of the difficult defined entanglement operation an equivalent quantum oracle is modelled that can estimates an «*intelligent state*» with the maximum of amplitude probability in corresponding superposition of classical states (minimum entropy principle relative to extracted quantum knowledge). Interference operator extracts this maximum of amplitude probability with a classical measurement.Figure 8 shows the structure of Quantum Computing Optimizer of robust KB-FC based on QFI [2].



Block name : 432

Input

Delay time : 20

Histogram review : 2

Output

N	Name	Scale coef.	Input 1	Input 2	Input 3
1		439.69	Both	Unused	Unuse
2		297.03	Unused	Both	Unuse
3		425.94	Unused	Unused	Both

F i g. 8. QFI-process by using QC Optimizer (QFI kernel)

Using of described QFI model to control of non-linear locally and globally unstable dynamic systems below is described.

6. Benchmark's simulation

It is demonstrated that FCs prepared to maintain control object in the prescribed conditions are often fail to control when such a conditions are dramatically changed. We propose the solution of such kind of problems by introducing a quantum generalization of strategies in fuzzy inference in on-line from a set of pre-defined fuzzy controllers by new QFI based systems. The latter is a new quantum algorithm in quantum computation without entanglement. Two Benchmarks are considered: robust control of locally and globally unstable control objects.

J. *Benchmark 1: Globally unstable control object simulation*

«Cart-pole» control object is a non-linear dissipative system. This is a typical task of control theory, they demonstrating quality of control system. Task of control is the stability of inverted pendulum in vertical position. The motion of the dynamic system «cart-pole» is described by the following equations

$$\ddot{\theta} = \frac{g\sin\theta + \cos\theta\left(\dfrac{u + \xi(t) + a_1\dot{z} + a_3 z - ml\dot{\theta}^2\sin\theta}{m_c + m}\right) - k\dot{\theta}}{l\left(\dfrac{4}{3} - \dfrac{m\cos^2\theta}{m_c + m}\right)}, \quad (3)$$

$$\ddot{z} = \frac{u + \xi(t) - a_1\dot{z} - a_2 z + ml(\dot{\theta}^2\sin\theta - \ddot{\theta}\cos\theta)}{m_c + m}, \quad (4)$$

where θ is the pendulum deviation angle (degrees); z is the movement of the cart (m); *g* is the acceleration of gravity (9.8 m/s^2); m_c is the pendulum mass (kg); *l* is the pendulum half-length (m); $\xi(t)$ is the stochastic excitation; and *u* is the control force acting on the cart (N). The equations for the entropy production rate in the control object and the PID controller have the following form, respecti

$$\frac{d}{dt}S_\theta = \frac{k\dot{\theta}^2 + \dfrac{ml\dot{\theta}^3\sin 2\theta}{m_c + m}}{l(\dfrac{4}{3} - \dfrac{m\cos^2\theta}{m_c + m})}; \quad \frac{d}{dt}S_z = a_1\dot{z}^2; \quad \frac{d}{dt}S_u = k_d\dot{e}^2 \quad (5)$$

The following parameter values are determined: $m_c = 1; m = 0.1; l = 0.54 k = 0.4; a_1 = 0.1; a_2 = 5$; and the initial position $\left[\theta_0; \dot{\theta}_0; z_0; \dot{z}_0\right] = [10; 0.1; 0; 0]$ (the value of the pendulum deviation angle is given in degrees); the constraint on the control force is –0.5 < *u* < 5.0.

The specific feature of control problem for the given control object (4) is the application of one fuzzy PID controller for controlling the movement of the cart (with one degree of freedom), while the control object has two degrees of freedom.

The control goal is that the pendulum deviation angle (second generalized coordinate) reaches the given value via the implicit control using the other generalized coordinate and corresponding essentially nonlinear cross-connections with the cart movement coordinate (effect of energy transmission between the generalized coordinates).

Remark 1: *Stability Lemma for Nonlinear Systems.* Based on the relationship between thermodynamic exergy and Hamiltonian systems a fundamental stability Lemma for Hamiltonian systems formulated. The stability of Hamiltonian systems is bounded between Lyapunov and Chetaev theorems as following: Given the Lyapunov derivative as a decomposition and sum of exergy generation rate $\dot{W}$ and exergy dissipation rate $T_0\dot{S}_i$ then

$$\dot{V} = \dot{W} - T_0\dot{S}_i = \sum_{j=1}^{N} Q_j\dot{q}_j - \sum_{l=1}^{M-N} Q_l\dot{q}_l . \quad (6)$$

where Q_j is the generalized force vector and the irreversible entropy production rate can be expressed as

$$\dot{S}_i = \sum_k \mathcal{F}_k\mathcal{X}_k = \frac{1}{T_0}\sum_k Q_k\dot{q}_k \geq 0 .$$

A control law is Lyapunov optimal if it minimizes the first time derivative of the Lyapunov function over a space of admissible force controls. In general, a set of feedback gains are optimized by minimizing the regulating and / or tracking error of the conventional feedback controller while regulating to zero and / or tracking a desired reference input. The Lyapunov function is the total error energy which for most mechanical systems is equivalent to an appropriate Hamiltonian function H, as following: $V = \mathrm{H}$. Then the concept of Lyapunov Optimal follows directly from setting $\dot{W} = 0$ in (6) and maximizing $T_0\dot{S}_i$ for which the time derivative of the Lyapunov function (Hamiltonian) or the modified power (work / energy) equation is written as following:

$$\dot{V} = \dot{\mathrm{H}} = -T_0\dot{S}_i = -\sum_{j=1}^{N} Q_j\dot{q}_j = -\sum_{j=1}^{N} \mathcal{F}_j\dot{R}_j,$$

which is independent of system dynamics and is a kinematic quantity that applies to any system. Note that F_j denotes a set of forces acting on a mechanical system and $\dot{R}_j$ denotes the inertial linear velocity of the point where $\mathcal{F}_j$ and in (5) is applied. Passivity control for robotic systems follows directly from setting $\dot{W} = 0$ in (6).

Remark 2: *Information-like Lyapunov functions.* Recently, presented a rich information-like family of universal Lyapunov functions for any linear or non-linear reaction network with detailed or complex balance. Moreover, H_f are not just Lyapunov functions but information measure of the divergences: $H_f\left(c^1(t)\middle|c^2(t)\right)$ is monotonically non-increasing function of time *t* for any two kinetic curves $c^1(t)$ and $c^2(t)$ with the same value of $\sum_i c_i$. These new functions aimed to resolve "the mystery" about the difference between the rich family of Lyapunov functions (*f* - divergences) for linear kinetics and a limited collection of Lyapunov functions for non-linear networks in thermodynamic conditions.

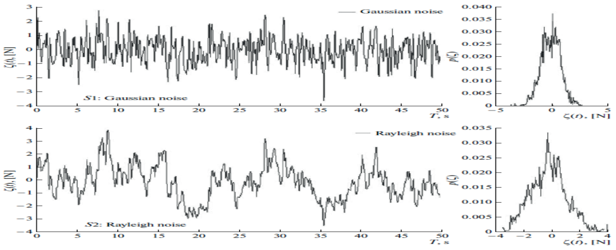
In the case of the similar initial learning conditions, the SCO with soft computing is used to design KB$_1$ of FC$_1$ for the generalized criterion of minimal mean square error:

$$\int_{t_0}^{t_{end}} \theta^2(t)\,dt + \int_{t_0}^{t_{end}} \dot{\theta}^2(t)\,dt$$

and KB$_2$ for FC$_2$ for the generalized criterion of minimal absolute error of the pendulum position:

$$\int_{t_0}^{t_{end}} \left|\,\theta(\tau)\,\right| d\tau + \int_{t_0}^{t_{end}} \left|\,\dot{\theta}(\tau)\,\right| d\tau.$$

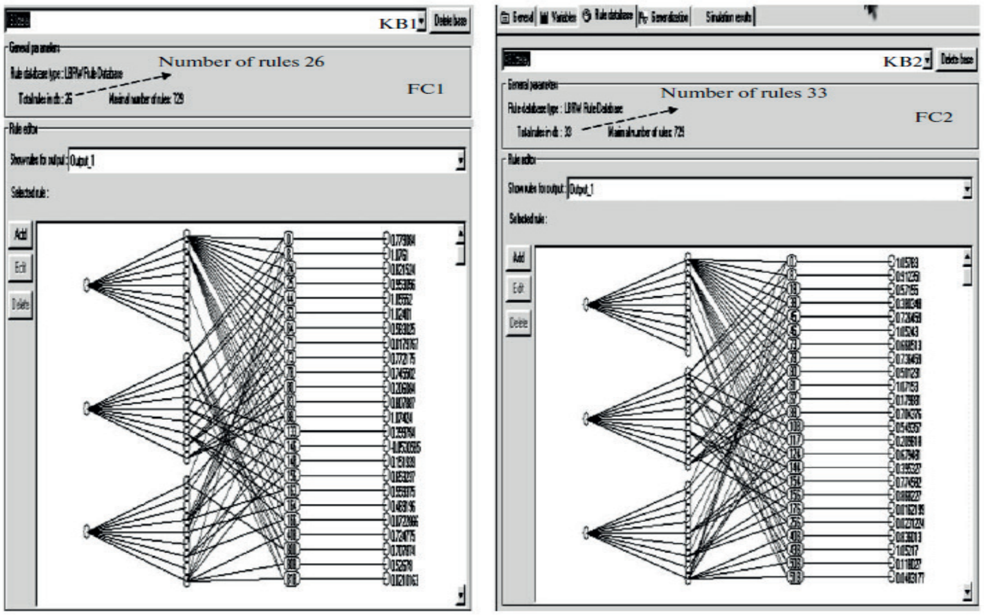
Thus, we consider the solution of the vector (multi-objective) optimization problem based on the decomposition of the KB. The Gaussian noise was used as the random signal for designing KB$_1$, and Rayleigh noise was used for forming KB$_2$ (see Fig. 9, learning situations (**S1**, **S2**), respectively).



F i g. 9. Random noise used in situations (S1, S2)

Physically the first criterion is equivalent to the total energy of the overturned pendulum and the second criterion characterizes the precision of the dynamic behavior of the control object.

Figure 10 shows KB$_1$ and KB$_2$ with the corresponding activated numbers of rules equal to 22 and 33 for a total number of rules of 729.



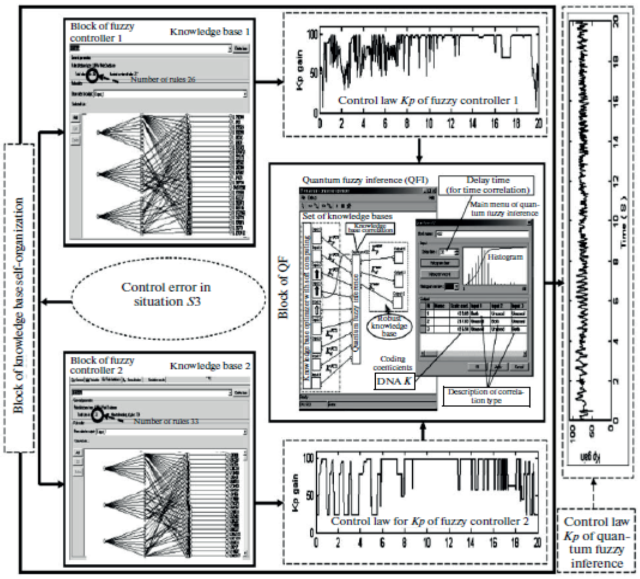
Rule database type: LBRW Rule Database
Total rules in db: 26
Maximal number of rules: 729
Show rules for output: Output_1

Rule database type: LBRW Rule Database
Total rules in db: 33
Maximal number of rules: 729
Show rules for output: Output_1

F i g. 10. Form of KB$_1$ and KB$_2$ with corresponding activated production rules

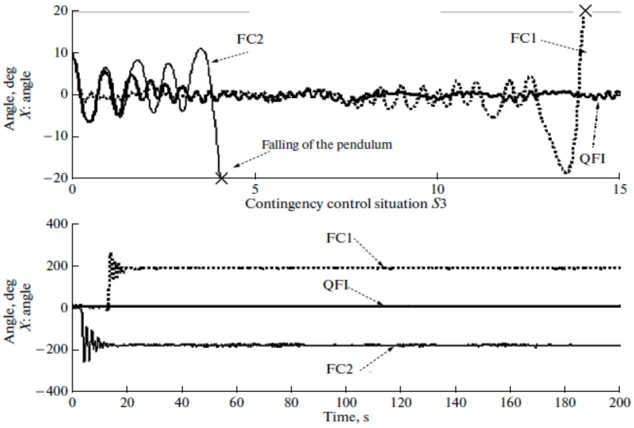
Two contingency control situations (**S3**, **S4**) were simulated; in one of them (**S3**) the new noise $\xi(t)$ was introduced, the random signal with uniform one dimensional distribution, the control error signal delay (0.03), and the noise signal in the position sensor of the pendulum (noise amplification coefficient 0.015).

Figure 11 shows the example of operation of the quantum FC for formation of the robust control signal using the proportional gain in contingency control situation **S3**. In this case, the output signals of KB$_1$ and KB$_2$ in the form of the response on the new control error in situation **S3** are received in the quantum FC. The output of the block of quantum FC is the new signal for on line control of the factor k_p .Thus, the blocks of KB$_1$ and KB$_2$, and quantum FC in Fig. 3 form the block of KB self-organization in the contingency control situation.



F i g. 11. Example of operation of the block of KB self-organization based on QFI

Figure 12 shows the dynamic behavior of the studied system «cart-pole» and the control laws of the self-organized quantum controller (QFI), FC_1 and FC_2.



F i g. 12. Dynamic motion of pole in situation S3

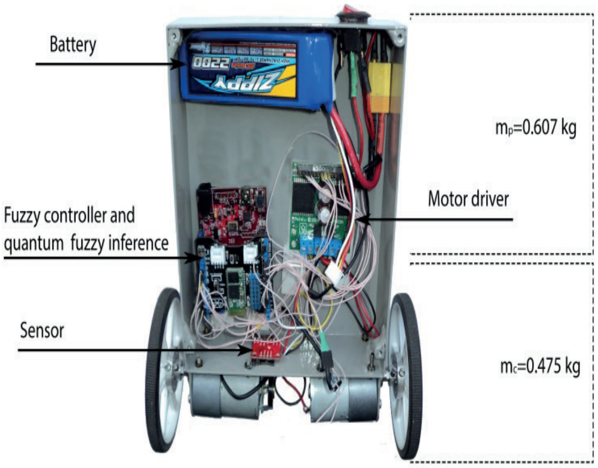
Remark. The following notation is used in Fig. 12 and below: $x = \theta$ is the angle of pendulum deviation from the given position; *z* is the cart position; the quantum FC is based on the spatial correlation.

The results of simulation (Fig. 12) demonstrate that the dynamic control object in contingency control situations (**S3**) for the control of FC_1 (FC_2) loses stability, and for the control of quantum FC the control system possesses the property of robustness and achieving the control goal is guaranteed. According to the results of simulation (Fig. 12), the required amount of control for the given criteria in contingency control situations (**S3**) for the control of FC_1 and FC_2 also is not achieved, while in the case of control of the quantum FC the control system possesses the required amount of control. This yields that two non robust fuzzy controllers can be used to design in on line the robust fuzzy controller using quantum self-organization; the KB of this robust FC satisfies both quality criteria.

Therefore, the decomposition of the solution to the above multi-objective optimization problem for the robust KB in the contingency control situation into partial solutions to optimization sub-problems physically can be performed in on line in the form of separate responses of the corresponding individual KBs optimized with different fixed cost functions and control situations.

The aggregation of the obtained partial solutions in the form of the new robust KB is performed based on the quantum FC containing the mechanism of formation of the quantum correlation between the obtained partial solutions.As a result, only responses of the finite number of individual KBs containing limiting admissible control laws in the given contingency situations are used.

The control laws of variation of the gains of the fuzzy PID controller formed by the new robust KB have a simpler physical realization, and as a result they possess better characteristics of individual control cost function for the contingency control situation.For experimental testing a physical model of robot (Fig. 13) is used.



F i g. 13. Mobile robot configuration

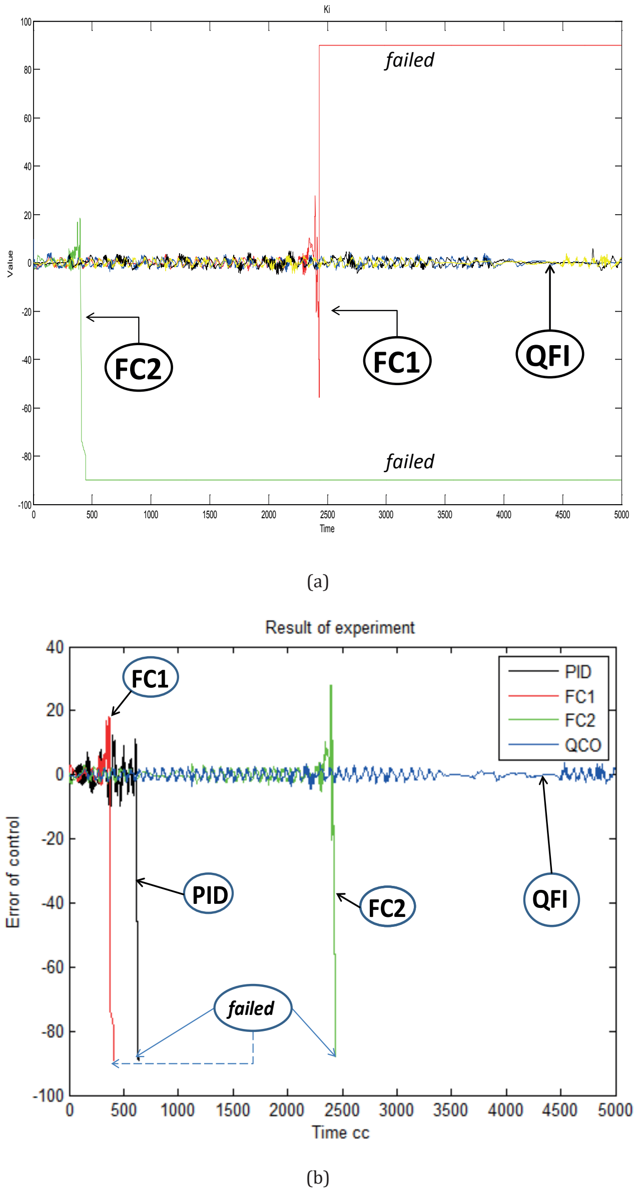
Three situations of control are tested.First situation images simple situation.The second situation use uniform noise in control channel, Gaussian noise in wheel friction and delay of control action — 0.01 s.

And the third situation have delay of control action equal 0.03s. Simulation and experimental results (for the complex situation 3) are shown on Fig. 14.

PID controller as FC_1 and FC_2 do not reach the goal in unpredicted situation.But quantum FC based on these fuzzy controllers, successful in unpredicted situation. For experiments and modeling we use QFI with temporal correlation, between FC_1 and FC_2.

Thus, the output signal of the quantum FC represents the on line optimal control signal for variation of the gains of the fuzzy PID controller which includes the necessary (best) qualitative characteristics of output control signals of each of the fuzzy controllers with priority and dominating component among the control quality criteria.

Therefore, the generalized self-organization principle [4], [6-9] is realized.



(a)

(b)

F i g. 14. Control error. Unpredicted situation: (a) modeling; (b) experiment on physical model

K. *Benchmark 2: Remote rule base optimization*

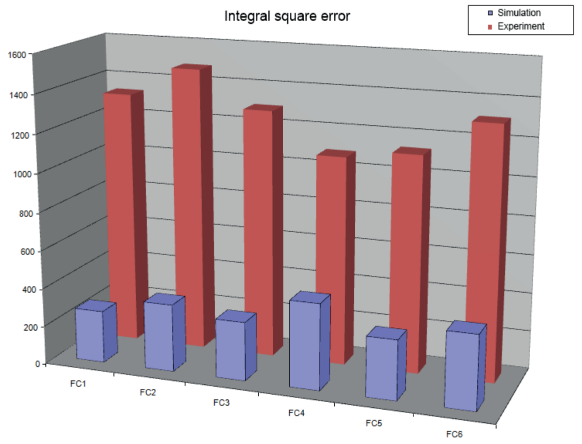
To compare method of remote rule optimization on the real control object with method using Matlab simulation for optimization we created 6 KB-FC.

	TS Source	**Optimization method**	**Rules count**
FC1	Math. model	Math. modelling	125
FC2	CO (GA-PID)	Math. modelling	125
FC3	Math. model	Remote connection	125
FC4	CO (GA-PID)	Remote connection	125
FC5	Math. model	Math. modeling + Remote connection	125
FC6	CO (GA-PID)	Remote connection + Math. modeling	125

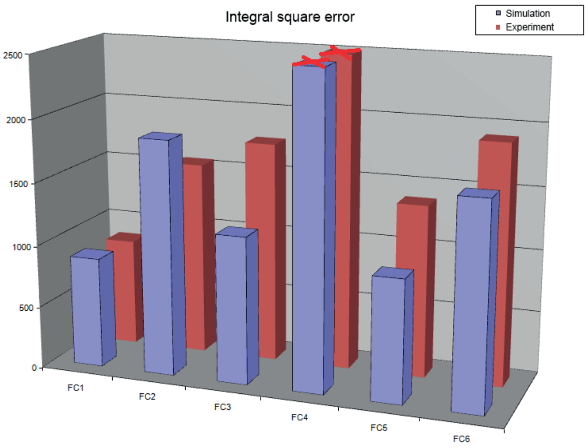
Experiment and modeling were performed in two control situations.The first situation (S1) is typical for the control system (the initial angle equals to 1). The goal is to maintain the pendulum in equilibrium (0° angle of deflection). It should be noted that KB optimization held in this control situation.

The second situation is unexpected (S2). The initial angle equals to 5°. This situation characterizes the perturbation caused by external influences on CO.

Figure 15 shows a comparison of integrals of squared error for all regarded regulators in a typical situation of control:



F i g. 15. Integral square error. Typical situation: Simulation and experiment



F i g. 16. Integral square error. Unpredicted situation: Simulation and experiment

The lower is integral square error level, the better controller works. Consider the results of simulation and experiment in unpredicted situation of control:

Figure 16 shows a comparison of integrals of squared error for all regarded regulators in an unpredicted situation of control.

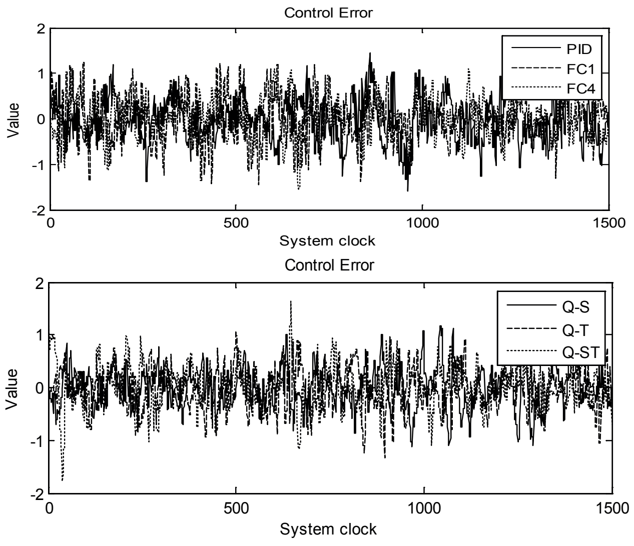
L. *Benchmark 3: Remote quantum base optimization*

Let's compare the PID controller, fuzzy controllers FC$_1$ and FC$_4$, and QFI controllers based on different correlations: Quantum-Space (Q-S), Quantum-Time (Q-T), Quantum-Space-Time (Q-ST). These QFI controllers are optimized using remote connection.

Mathematical modeling and physical experiments took place in two control situation:

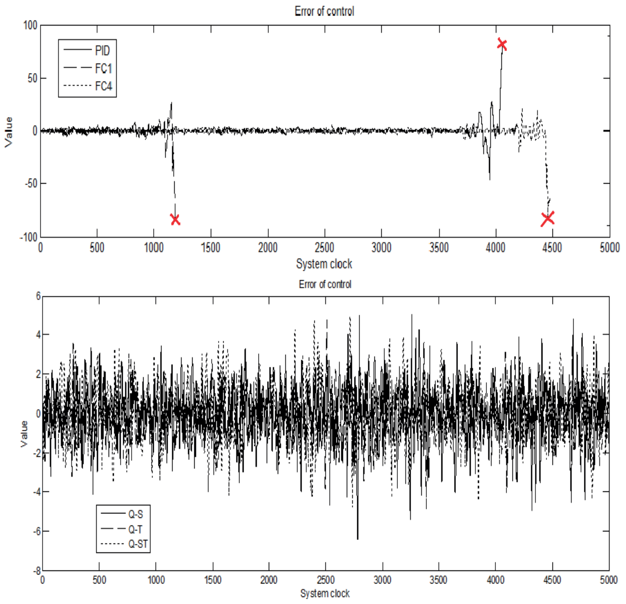
- in the first (typical) situation (S1), the delay of control is standard as 0.015 sec;
- in the second unpredicted situation (S2), the delay of the control as 0.035 sec.

From Figs 17 and 18 it can be seen that KB optimization using a remote connection with quantum optimizer can improve the quality of control in a typical and unpredicted situation.



F i g. 17. Control error. Typical situation of control (Experiment)

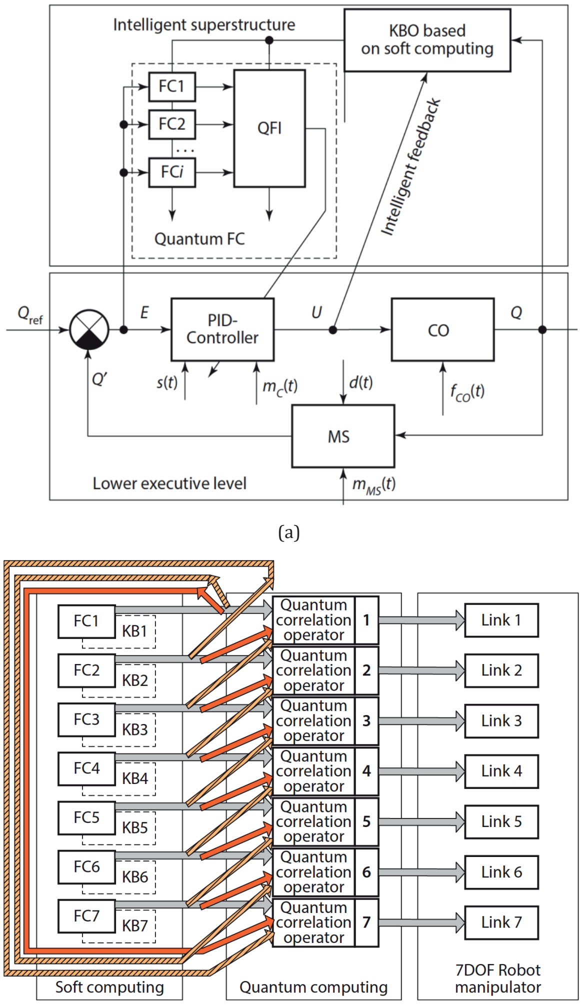
Related works. Quantum computing approaching in robot path planning, emotion design, navigation, learning, decision making was applied also in [10-24] etc. Our approach is based on quantum self-organization of knowledge bases using responses of fuzzy controllers on unpredicted situations in on line.



F i g. 18. Control error. Unpredicted situation of control (Experiment)

7. Smart Robotic Manipulator: Quantum supremacy in intelligent control

The seven degrees of freedom (7 DoF) and seven-link robotic manipulator is described in this part. Due control object is complex, ICS for 7 DoF manipulator is constructed with using decomposition principal. Seven independent FCs (FC1 – FC7) are used for control each of manipulator link. The decomposition of control allows reducing complexity of constructing ICS. However, character of ICS somewhat reduced due to independence of seven FCs (Fig. 19).

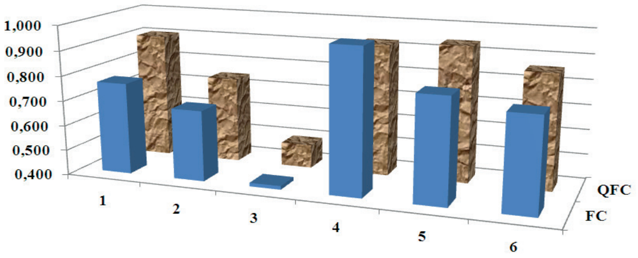


(a)

(b)

F i g. 19. (a) The structure of 7DoF manipulator ICS; (b) The application of the correlation of three neighboring FC

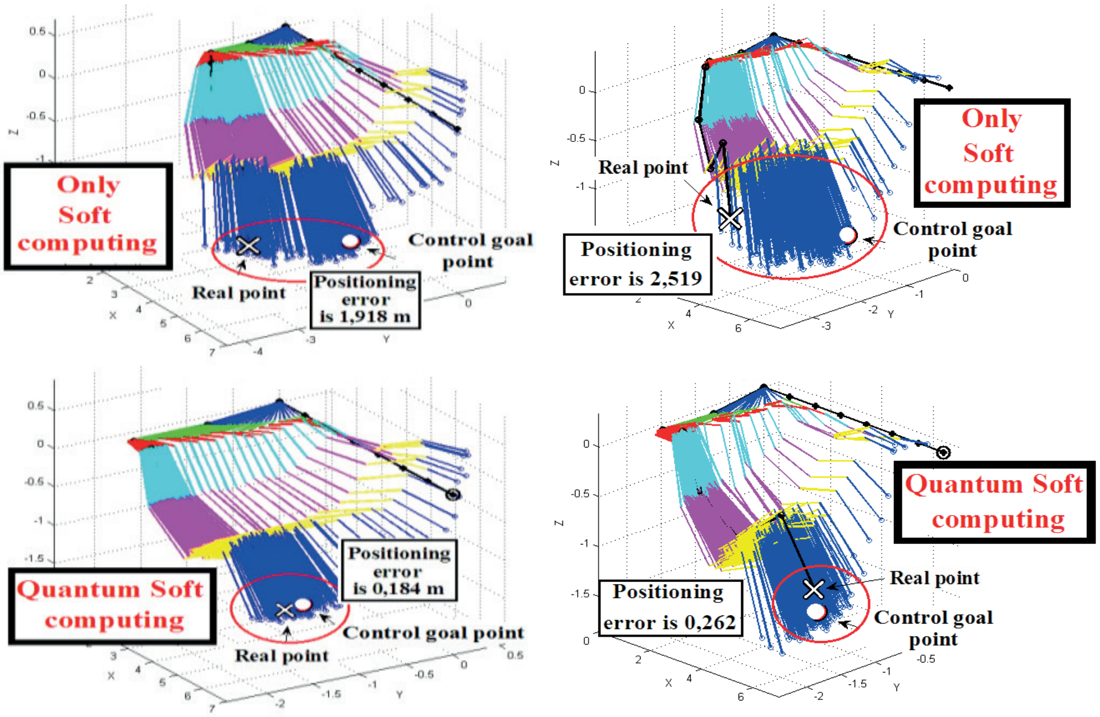
QFI unit introduction allows improving ICS behavior by self-organization of independent KBs in FC1 – FC7. The correlation of three adjacent fuzzy KBs (the information FC *i*, *i* + 1 and *i* + 2 is used to control the *i*-th link of the manipulator, as shown on Fig. 19(b). Consider the first internal unpredicted situation – the random noise in the control channel (see, the signal $s(t)$ on Fig. 19). Comparison of manipulator behavior for control system based on soft computing and based on quantum soft computing in performance criteria terms is shown in Fig. 20 (on the base results of sixty-five experiments).



F i g. 20. Manipulator behavior with random noise in the control channel: FC – based on soft computing, QFC – based on quantum soft computing

The results are demonstrating if ICS is used with QFI gate (see, Fig. 19 (a)), all of evaluation of performance criteria improve (expect “One iteration time”).

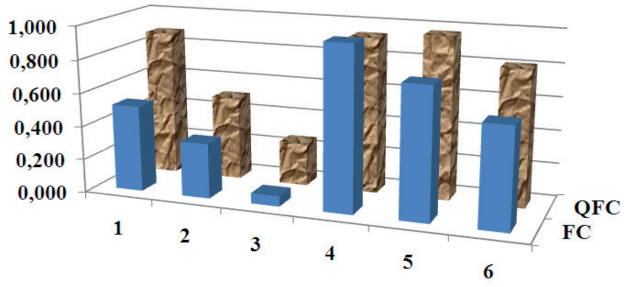
The one of cases is shown in Fig. 21 (a). Positioning accuracy is better if used ICS with QFI unit (in this case positioning error is 0.184 m). Positioning error is 1.918 m, if used ICS without QFI unit.



(a) (b)

F i g. 21. (a) Manipulator behavior with random noise in the control channel, (b) Manipulator behavior with random noise in the measurement system

Consider the second internal unpredicted situation – random noise in the measurement system (see, the signal $d(t)$ and «Sensors», Fig. 19(a)). Comparison of manipulator behavior for control system based on soft computing and based on quantum soft computing in performance criteria terms is shown in Fig. 22.



F i g. 22. Manipulator behavior with random noise in the measurement system

The results are demonstrating if ICS is used with QFI unit, all of evaluation of performance criteria improve (expect “One iteration time”). The one of cases is shown in Fig. 21 (b). Positioning accuracy is better if used ICS with QFI unit (in this case positioning error is 0.262 m). Positioning error is 2.519 m, if used ICS without QFI unit. Thus, the positioning accuracy ten times increased with QFI application in the comparison with the using case of soft computing and these facts demonstrate the quantum supremacy of described methods of robust control design [25].

Conclusion

- New circuit implementation design method of quantum gates for fast classical efficient simulation of search QAs is developed. Benchmarks of design application as Grover’s QSA and QFI based on QGA demonstrated.
- Applications of QAG approach in intelligent control systems

with quantum self-organization of imperfect knowledge bases are described on concrete examples. Quantum supremacy on robotic Benchmarks demonstrated.

- Results of controller's behavior comparison confirm the existence of synergetic self-organization effect in the design process of robust KB on the base of imperfect (non-robust) KB of fuzzy controllers: from two imperfect KB with quantum approach a robust KB can be created using only quantum correlation. In classical intelligent control based on soft computing toolkit this effect impossible to achieve.
- Described approach opens new prospects for application of the model of quantum FC as the particular variant of the quantum self-organization algorithm in multi-objective control problems for the control object with weakly formalized structure and large dimensionality of the phase space of control parameters, application of experimental data in the form of the learning signal without development the mathematical model of the control object. These facts present a great advantage which is manifested as the possibility of design of control with required robustness in on line.

References

[1] Litvintseva L.V., Ulyanov S.V., Ulyanov S.S. Design of robust knowledge bases of fuzzy controllers for intelligent control of substantially nonlinear dynamic systems: II. A soft computing optimizer and robustness of intelligent control systems. *Journal of Computer and Systems Sciences International.* 2006;45(5):744-771. https://doi.org/10.1134/S106423070605008X

[2] Litvintseva L.V., Ulyanov S.V. Quantum fuzzy inference for knowledge base design in robust intelligent controllers. *Journal of Computer and Systems Sciences International.* 2007;46(6):908-961. https://doi.org/10.1134/S1064230707060081

[3] Nielsen M.A., Chuang I.L. Quantum Computation and Quantum Information: 10th Anniversary Ed. Cambridge: Cambridge University Press; 2010. 702 p. https://doi.org/10.1017/CBO9780511976667

[4] Ulyanov S.V. Self-organization of robust intelligent controller using quantum fuzzy inference. In: 2008 3rd International Conference on Intelligent System and Knowledge Engineering. Xiamen, China: IEEE Computer Society; 2008. p. 726-732. https://doi.org/10.1109/ISKE.2008.4731026

[5] DiVincenzo D.P., Horodecki M., Leung D.W., Smolin J.A., Terhal B.M. Locking classical correlation in quantum states. *Physical Review Letters*. 2004;92(6);067902. https://doi.org/10.1103/PhysRevLett.92.067902

[6] Ulyanov S.V., Litvintseva L.V., Panfilov S.A. Design of self-organized intelligent control systems based on quantum fuzzy inference: intelligent system of systems engineering approach. In: 2005 IEEE International Conference on Systems, Man and Cybernetics, Waikoloa. HI, USA: IEEE Computer Society; 2005. Vol. 4. p. 3835-3840. https://doi.org/10.1109/ICSMC.2005.1571744

[7] Ulyanov S.V. Self-Organized Intelligent Robust Control Based on Quantum Fuzzy Inference. In: Mller A. (ed) Recent Advances in Robust Control – Novel Approaches and Design Methods. Ch. 9. InTech; 2011. p. 187-220. https://doi.org/10.5772/17189

[8] Ulyanov S.V. Quantum soft computing in control processes design: Quantum genetic algorithms and quantum neural network approaches. In: Proceedings World Automation Congress. Seville, Spain: IEEE Computer Society; 2004. p. 99-104. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1439352 (accessed 01.04.2023).

[9] Mishin A., Ulyanov S. Intelligent Robust Control of Dynamic Systems with Partial Unstable Generalized Coordinates Based on Quantum Fuzzy Inference. In: Batyrshin I., Sidorov G. (eds.) Advances in Soft Computing. MICAI 2011. *Lecture Notes in Computer Science.* Vol. 7095. Berlin, Heidelberg: Springer; 2011. p. 24-36. https://doi.org/10.1007/978-3-642-25330-0_3

[10] Dong D., Chen Z.-L., Chen Z.-H., Zhang C.-B. Quantum mechanics helps in learning for more intelligent robots. *Chinese Physics Letters*. 2006;23(7):1691-1694. https://doi.org/10.1088/0256-307X/23/7/010

[11] Lukac M., Perkowski M. Inductive learning of quantum behaviors. *Facta Universitatis*. 2007;20(3):561-586. https://doi.org/10.2298/FUEE0703561L

[12] Kagan E., Ben-Gal I. Navigation of Quantum-Controlled Mobile Robots. In: Topalov A. (ed.) Recent Advances in Mobile Robotics. Ch. 15. InTech; 2011. p. 220-311. https://doi.org/10.5772/25944

[13] Bannikov A., Egerton S., Callaghan V., Jonson B.D., Shaukat M. Quantum computing: Non-deterministic controllers for artificial intelligent agents. In: Lopez-Cozar R., et al. Workshop Proceedings of the 6th International Conference on Intelligent Environments. Vol. 8. Amsterdam Netherlands: IOS Press; 2010. p. 109-118. https://doi.org/10.3233/978-1-60750-638-6-109

[14] Chatzis S.P., Korkinof D., Demiris Y. A quantum-statistical approach toward robot learning by demonstration. *IEEE Transactions on Robotics.* 2012;28(6):1371-1381. https://doi.org/10.1109/TRO.2012.2203055

[15] Kouda N., Matsui N. An examination of qubit neural network in controlling an inverted pendulum. *Neural Processing Letters.* 2005;22(3):277-290. https://doi.org/10.1007/s11063-005-8337-2

[16] Panella M., Martinelli G. Neurofuzzy networks with nonlinear quantum learning. *IEEE Transactions on Fuzzy Systems*. 2009;17(3):698-710. https://doi.org/10.1109/TFUZZ.2008.928603

[17] Chen F., Hou R., Tao G. Adaptive Controller Design for Faulty UAVs via Quantum Information Technology. *International Journal of Advanced Robotic Systems.* 2012;9(6):256. https://doi.org/10.5772/53617

[18] Gyongyosi L., Imre S. Quantum Cellular Automata Controlled Self-Organizing Networks. In: Salcido A. (ed.) Cellular Automata – Innovative Modelling for Science and Engineering. Ch. 6. InTech; 2011. p. 113-152. https://doi.org/10.5772/15750

[19] Kim Y.H., Kim J.H. Multiobjective quantum-inspired evolutionary algorithm for fuzzy path planning of mobile robot. In: IEEE Congress on Evolutionary Computation (CEC 2009). Trondheim, Norway: IEEE Computer Society; 2009. p. 1185-1192. https://doi.org/10.1109/CEC.2009.4983080

[20] Masood A. A Perspective on Whether Robot Localization Can be Effectively Simulated by Quantum Mechanics. *International Journal Of Multidisciplinary Sciences And Engineering*. 2021;3(9):15-18. Available at: https://www.ijmse.org/Volume3/Issue9/paper3.pdf (accessed 01.04.2023).

[21] Dong D., Chen C. Quantum robot: Structure, algorithms and applications. *Robotica.* 2006;24(4):513-521. https://doi.org/10.1017/S0263574705002596

[22] Chen C., Dong D. Quantum intelligent mobile system. Quantum Inspired Intelligent Systems. *Studies in Computational Intelligence.* 2008;121:77-102. https://doi.org/10.1007/978-3-540-78532-3_4

[23] Nedjah N., Coelho L.d.S., Mourelle L.d.M. (eds.) Quantum Inspired Intelligent Systems. *Studies in Computational Intelligence.* Vol. 121. Berlin, Heidelberg: Springer; 2008.156 p. https://doi.org/10.1007/978-3-540-78532-3

[24] Kim S.S., Choia H.J., Kwak K. Knowledge extraction and representation using quantum mechanics and intelligent models. *Expert Systems with Applications*. 2012;39(3):3572-3581. https://doi.org/10.1016/j.eswa.2011.09.047

[25] Ulyanov S.V. Quantum Fuzzy Inference Based on Quantum Genetic Algorithm: Quantum Simulator in Intelligent Robotics. In: Aliev R., Kacprzyk J., Pedrycz W., Jamshidi M., Babanli M., Sadikoglu F. (eds.) 10th International Conference on Theory and Application of Soft Computing, Computing with Words and Perceptions – ICSCCW-2019. ICSCCW 2019. *Advances in Intelligent Systems and Computing*. Vol. 1095. Cham: Springer; 2020. p. 78-85. https://doi.org/10.1007/978-3-030-35249-3_9

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About the authors:

Sergey V. Ulyanov, Professor of the Department of System Analysis and Management, Institute of System Analysis and Management, Dubna State University (19 Universitetskaya St., Dubna 141980, Moscow Region, Russian Federation); Chief researcher of the Meshcheryakov Laboratory of Information Technologies, Joint Institute for Nuclear Research (6 Joliot-Curie St., Dubna 141980, Moscow region, Russian Federation), Dr. Sci. (Phys.-Math.), Professor, **ORCID: https://orcid.org/0000-0001-7409-9531**, ulyanovsv46_46@mail.ru

Andrey G. Reshetnikov, Associate Professor of the Institute of System Analysis and Management, Dubna State University (19 Universitetskaya St., Dubna 141980, Moscow Region, Russian Federation); Senior researcher of the Meshcheryakov Laboratory of Information Technologies, Joint Institute for Nuclear Research (6 Joliot-Curie St., Dubna 141980, Moscow region, Russian Federation), Cand. Sci. (Tech.), **ORCID: https://orcid.org/0000-0003-2528-5201,** agreshetnikov@jinr.ru

Daria P. Zrelova, Postgraduate Student of the Institute of System Analysis and Control, Dubna State University (19 Universitetskaya St., Dubna 141980, Moscow Region, Russian Federation); Research assistant of the Meshcheryakov Laboratory of Information Technologies, Joint Institute for Nuclear Research (6 Joliot-Curie St., Dubna 141980, Moscow region, Russian Federation), **ORCID: https://orcid.org/0000-0002-7146-2494**, zrelova@jinr.ru

All authors have read and approved the final manuscript.

Об авторах:

Ульянов Сергей Викторович, профессор кафедры системного анализа и управления Института системного анализа и управления, ГБОУ ВО Московской области «Университет «Дубна» (141982, Российская Федерация, Московская область, г. Дубна, ул. Университетская, д. 19); главный научный сотрудник Лаборатории информационных технологий имени М.Г. Мещерякова, Международная межправительственная организация Объединенный институт ядерных исследований (141980, Российская Федерация, Московская область, г. Дубна, ул. Жолио-Кюри, д. 6), доктор физико-математических наук, профессор, **ORCID: https://orcid.org/0000-0001-7409-9531**, ulyanovsv46_46@mail.ru

Решетников Андрей Геннадьевич, доцент кафедры геоинформационных систем и технологий Института системного анализа и управления, ГБОУ ВО Московской области «Университет «Дубна» (141982, Российская Федерация, Московская область, г. Дубна, ул. Университетская, д. 19); старший научный сотрудник Лаборатории информационных технологий имени М.Г. Мещерякова, Международная межправительственная организация Объединенный институт ядерных исследований (141980, Российская Федерация, Московская область, г. Дубна, ул. Жолио-Кюри, д. 6), кандидат технических наук, **ORCID: https://orcid.org/0000-0003-2528-5201,** agreshetnikov@jinr.ru

Зрелова Дарья Петровна, аспирант Института системного анализа и управления, ГБОУ ВО Московской области «Университет «Дубна» (141982, Российская Федерация, Московская область, г. Дубна, ул. Университетская, д. 19); стажер-исследователь Лаборатории информационных технологий имени М.Г. Мещерякова, Международная межправительственная организация Объединенный институт ядерных исследований (141980, Российская Федерация, Московская область, г. Дубна, ул. Жолио-Кюри, д. 6), **ORCID: https://orcid.org/0000-0002-7146-2494**, zrelova@jinr.ru

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