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Quantum Soft Computing In Control Process Design: Quantum Genetic Algorithms And Quantum Neural Network Approaches

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QUANTUM SOFT COMPUTING IN CONTROL PROCESS DESIGN: QUANTUM GENETIC ALGORITHMS AND QUANTUM NEURAL NETWORK APPROACHES

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Abstract

A new quantum method of learning and optimization process simulation, and physical silicon implementation of quantum algorithm gates (QAG's) with applications to AI, applied informatics and robust intelligent control is discussed. R&D results in simulation and design of QAG are described. The QAG's design method on the examples as Grover's quantum search algorithm (QSA) and quantum games is illustrated. The developed analysis and synthesis of QAG's dynamic are the background for silicon circuit gate design and simulation of robust knowledge base (KB) for intelligent fuzzy controllers (FC).

Keywords: Quantum gate computing, AI-system, Quantum games, Wise robust control

1. INTRODUCTION

In [1,2] we have discussed some important applications (for example, quantum games and decision-making control processes in quantum uncertainty of information) of Quantum Soft Computing tool in AI-systems. In this report using benchmark's method, different quantum paradigms and methods of AI (on examples from quantum games) are demonstrated. Their applications in problem solution of theoretical informatics (TI) and computer science (Grover's QAG) to design intelligent robust control systems of essentially non-linear dynamic control objects (as background of intelligent robotics and mechatronics) based on Quantum Soft Computing models are described. Figure 1 shows the general structure of self-organizing intelligent control system based on Quantum Soft Computing.

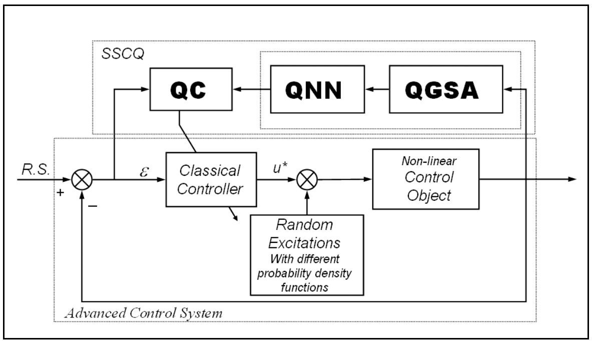

Figure 1: General structure of self organizing intelligent control system based on Quantum Soft Computing

We study a new problem in applied intelligent control system: design of a *wise* robust control laws using non-robust particular knowledge bases (KBs) that are designed with soft computing technology. This problem is correlated with the solutions of well-known Parrondo's quantum game and quantum card game without entanglement. As a result, the possibility to design a wise robust control from non-robust KBs using quantum computing without entanglement is found.

2. METHOD FOR QUANTUM ALGORITHM GATE DESIGN

Quantum computing uses four main quantum operators [2]: (i) Superposition; (ii) Entanglement; (iii) Interference; and (iv) Measurement. Superposition operator is used for junction of possible solution spaces in single unified solution space. Entanglement operator is used for searching the optimal solution as an unknown marked state. Interference and measurement operators are used for extraction of marked state with highest probability. The key point in design process of intelligent control system structures is the simulation system based on quantum algorithm gates. Table 1 shows the main idea of quantum algorithm gate design [2,3].

Name	Algorithm	Gate Symbolic Form: $\left[\underbrace{\left(Int \otimes {}^{m}I\right)}_{Interference} \cdot \underbrace{U_F}_{Entanglement}\right]^{h+1} \cdot \left(\underbrace{{}^{n}H \otimes {}^{m}S}_{Superposition}\right)$
Deutsch-Jozsa (D. – J.)	$m=1$ $S=H\ (x=1)$ $Int={}^{n}H$ $k=1$ $h=0$	$\left({}^{n}H \otimes I\right) \cdot U_F^{D.-J.} \cdot \left({}^{n+1}H\right)$
Simon (Sim)	$m=n$ $S=I\ (x=0)$ $Int={}^{n}H$ $k=O(n)$ $h=0$	$\left({}^{n}H \otimes {}^{n}I\right) \cdot U_F^{Sim} \cdot \left({}^{n}H \otimes {}^{n}I\right)$
Shor (Shr)	$m=n$ $S=I\ (x=0)$ $Int=QFT_n$ $k=O(Poly(n))$ $h=0$	$\left(QFT_n \otimes {}^{n}I\right) \cdot U_F^{Shr} \cdot \left({}^{n}H \otimes {}^{n}I\right)$
Grover (Gr)	$m=1$ $S=H\ (x=1)$ $Int=D_n$ $k=1$ $h=O\left(2^{n/2}\right)$	$\left(D_n \otimes I\right) \cdot U_F^{Gr} \cdot \left({}^{n+1}H\right)$

Table 1. Structure of quantum algorithm gates

3. QUANTUM GLOBAL OPTIMIZATION BASED ON QGSA

The structure of intelligent control system includes the quantum genetic search algorithm (QGSA), (see Figure 1) as a main optimization box. Figure 2 shows the general structure of QSA as a kernel of global optimization process based on Quantum Soft Computing. The formal general structure of QGSA is described as logical set of operations [3]:

$$QGSA=\left\{C, Ev, P^0, L, [\Omega, \chi, \mu]_{GA-operators}, [Sup, Ent, Int]_{QA-operators}, \boxed{\Lambda}\right\},$$

where C is the genetic coding scheme of individuals for a given problem; Ev is the evaluation function to compute the fitness values of individuals; P^0 is the initial population; L is the size of population; Ω is the selection operator; χ is the crossover operator; μ is the mutation operator; Sup is the quantum linear superposition operator; Ent is the quantum entanglement operator (quantum super-correlation); Int is the interference operator; Λ are termination conditions that include the stopping criteria as a minimum of Shannon/von Neumann entropy and the optimum of fitness functions. The structure of QSA presented in Figure 2 is the basic model of wise control system and is described as logical set of operations in QGSA. Logical combinations of operators of QGSA create different models of optimization algorithms [4].

This approach is used as design process of robust KB of fuzzy controllers [5].

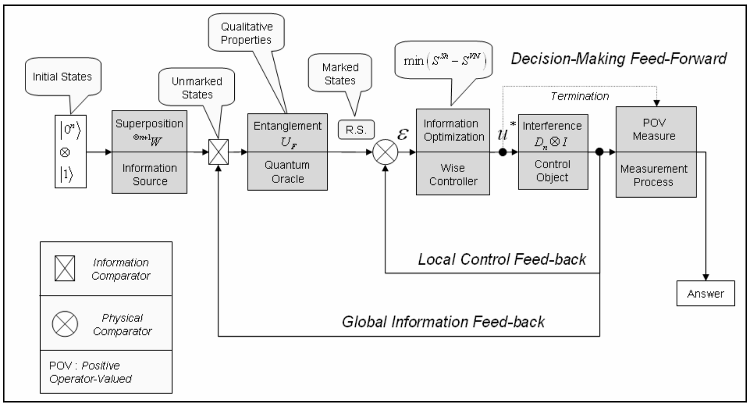

Figure 2: Self – Organizing Intelligent QSA Wise Control System

4. QUANTUM LEARNING ALGORITHMS BASED ON QNN

The structure of intelligent control system includes (Figure 1) the quantum neural network (QNN) as a main learning and approximation box. We present the algorithms necessary for the implementation of a QNN with learning and classification tasks. A complete implementation for the classification and learning algorithms is given in terms of unitary quantum gates. Such a QNN can be used to uniform complex classification tasks or to solve the general problem of binary mapping. QNN can be described by entanglement-based or by superposition-based structures [6,7]. In this report both approaches are described. We use back-propagation on QNN called quantum error back propagation algorithm (QBP) in order to introduce a learning of the network. The steepest descent method used in the BP-algorithm is taken as the learning rule. This rule is realized in quantum neural computing as the following: (i) $\theta_{l,k}^{New} = \theta_{l,k}^{Old} - \eta \frac{\partial E_{total}}{\partial \theta_{l,k}^{Old}}$; (ii) $\lambda_k^{New} = \lambda_k^{Old} - \eta \frac{\partial E_{total}}{\partial \lambda_k^{Old}}$; (iii) $\theta_k^{New} = \theta_k^{Old} - \eta \frac{\partial E_{total}}{\partial \theta_k^{Old}}$, where η is a learning coefficient and E_{total} is the squared error function $E_{total} = \frac{1}{2}\sum_p^P \sum_n^N \left(t_{n,p} - output_{n,p}\right)^2$, where P is the number of learning patterns, $t_{n,p}$ is a target signal for the n-th neuron and $output_{n,p}$ means and $output_n$ at the p-th pattern. Quantum gate of this model can be realized by the rotation gate and controlled NOT (CNOT) operations. It is safe that Hebb's rule has not been so far a natural source of powerful learning algorithms for artificial neural networks. The output of the quantum perceptron at the time t will be $\left|y\right\rangle = \sum_{j=1}^{n} \hat{w}_j(t)\left|x_j\right\rangle$ and in analogy with classical case $w_j(t+1) = w_j(t) + \mu(d-y)x_j$, let us provide a learning process as following:

$$\underbrace{w_j(t+1) = w_j(t) + \mu(d-y)x_j}_{\text{(the classical case)}} \Rightarrow \underbrace{\hat{w}_j(t+1) = \hat{w}_j(t) + \mu\left(\left|d\right\rangle - \left|y(t)\right\rangle\right)\left\langle x_j\right|}_{\text{(the quantum case)}},$$

where $\left|d\right\rangle$ is the desired output.

This learning rule drives the quantum perceptron into desired state $\left|d\right\rangle$ used for teaching. In fact, using this rule and taking the module-square difference of the real and desired outputs, it yields

$$\left\|\left|d\right\rangle - \left|y(t+1)\right\rangle\right\|^2 = \left\|\left|d\right\rangle - \sum \hat{w}_j(t+1)\left|x_j\right\rangle\right\|^2 = (1-n\mu)^2 \left\|\left|d\right\rangle - \left|y(t)\right\rangle\right\|^2.$$

Example: In the case of quantum computing, the concept of separable or non-separable classes is irrelevant, because a quantum perceptron can learn a *superposition of patterns*, which are not separable by a hyperplane. As an example of these approaches we are considering the classification task using such a quantum perceptron by a modified version of the Grover's QSA [7].

5. APPLICATION OF QUANTUM SOFT COMPUTING IN AI: QUANTUM GAMES

Table 2 describes main quantum games simulation based on quantum algorithm gate approach.

N	Game Title	Quantum algorithm gate (QAG)
1	*Prisoner's Dilemma*	$\left\|\psi_{fin}\right\rangle = G^{PrDl}\left\|\psi_{in}\right\rangle = G^{PrDl}\left\|\hat{C}\hat{C}\right\rangle = \boxed{\hat{J}^{\dagger}\left(\hat{U}_A\otimes\hat{U}_B\otimes\hat{U}_C\right)}\hat{J}\left\|000\right\rangle$
2	*Trucker's Game*	$\left\|\psi_{fin}\right\rangle = G^{Tr}\left\|00\ldots0\right\rangle = U^{\otimes n}\left\|\psi_{in}\right\rangle = \boxed{U^{\otimes n}QFT(p)}\left\|00\ldots0\right\rangle$ $=\sum_{j_0=0}^{N-1}\cdots\sum_{j_{N-1}=0}^{N-1}C_{j_0\ldots j_{N-1}}\left\|j_0\ldots j_{N-1}\right\rangle,\quad C_{j_0\ldots j_{N-1}}=\left(\frac{1}{\sqrt{N}}\right)^{N+1}\sum_{k=0}^{N-1}\omega_N^{k\cdot m},$ $m=j_0+\ldots+j_{N-1}+p,\quad QFT(p)\left\|00\ldots0\right\rangle=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}\omega_N^{k\cdot m}\left\|kk\ldots k\right\rangle$
3	*Quantum Monty Hall Problem*	$\left\|\psi_{fin}\right\rangle = G^{MHP}\left\|\psi_{in}\right\rangle = \boxed{\left(\hat{S}\cos\lambda+\hat{N}\sin\lambda\right)\hat{O}\left(\hat{I}\otimes\hat{B}\otimes\hat{A}\right)}\left\|\psi_{in}\right\rangle,\ \hat{N}=\neg\hat{S},$ $\hat{O}=\sum_{i,j,k,\ell}\left\|\varepsilon_{ijk}\right\|\left\|njk\right\rangle\left\langle\ell jk\right\|+\sum_{j,\ell}\left\|mjj\right\rangle\left\langle\ell jj\right\|,\ \hat{S}=\sum_{i,j,k,\ell}\left\|\varepsilon_{ij\ell}\right\|\left\|i\ell k\right\rangle\left\langle ijk\right\|+\sum_{i,j}\left\|iij\right\rangle\left\langle iij\right\|,$ $\left\|\varepsilon_{ijk}\right\|=1, if\ i\neq j\neq k, m=(j+\ell+1)\bmod 3, n=(i+\ell)\bmod 3,\ \lambda\in\left[0,\frac{\pi}{2}\right]$
4	*Parrondo's Paradox*	$\left\|\psi_{fin}\right\rangle = G^{Par}\left\|\psi_{in}\right\rangle = \boxed{\hat{G}^{\otimes n}}\left\|\psi_{in}\right\rangle,\quad where\ \hat{G}=\hat{B}\left(\hat{A}\otimes\hat{A}\otimes\hat{I}\right)$
5	*Card game*	$\left\|\psi_{fin}\right\rangle = \hat{G}^{Card}\left\|000\right\rangle = \left(\boxed{HU_0H}\left\|0\right\rangle\right)\otimes\left(\boxed{HU_1H}\left\|0\right\rangle\right)\otimes\left(\boxed{HU_2H}\left\|0\right\rangle\right);$ $U=U_0\otimes U_1\otimes U_2;\left\|r\right\rangle=\left\|r_0\right\rangle\left\|r_1\right\rangle\left\|r_2\right\rangle$
6	*Quantum random walk on a finite lattice*	$\left\|\psi_{fin}\right\rangle = \hat{G}^{RWalk}\left\|\psi_{in}\right\rangle = \boxed{\left(\left[Sh\right]\otimes\hat{P}_R+\left[Sh^{\dagger}\right]\otimes\hat{P}_L\right)\left(\hat{I}\otimes\hat{U}\right)}\left\|\psi_{in}\right\rangle, \left\|\psi_{in}\right\rangle=\left\|0\right\rangle\otimes\left\|\Phi_0\right\rangle$ $Sh\left\|n\right\rangle=\left\|n+1\right\rangle, Sh^{\dagger}\left\|n\right\rangle=\left\|n-1\right\rangle, Sh^L=I,\ \hat{P}_{R(L)}=\sum_{\alpha=0(M/2)}^{(M/2)-1(M-1)}\left\|\alpha\right\rangle\left\langle\alpha\right\|,$ $\hat{P}_R+\hat{P}_L=\hat{I},\ \left\|0\right\rangle=\int_{-\pi}^{\pi}\frac{dk}{2\pi}\left\|k\right\rangle, \hat{U}=\frac{1}{\sqrt{2}}\begin{pmatrix}1&1\\1&-1\end{pmatrix};\left(\hat{U}\right)_{\alpha\beta}=\frac{1}{\sqrt{M}}\exp\left\{2\pi i\frac{\alpha\beta}{M}\right\};$ $\hat{G}^{RW}\left(\left\|k\right\rangle\otimes\left\|\Phi\right\rangle\right)=\left\|k\right\rangle\otimes\left(e^{-ik}\hat{P}_R+e^{ik}\hat{P}_L\right)\hat{U}\left\|\Phi\right\rangle\equiv\left\|k\right\rangle\otimes\hat{U}_k\left\|\Phi\right\rangle$
7	*Master and Pupil (Dense coding)*	$\left\|\psi_{fin}\right\rangle=\left\|z,\alpha\right\rangle_{AB}=\hat{G}^{MP}\left\|\psi_{in}\right\rangle=\boxed{\mathcal{C}\left(U_{z,\alpha}\otimes I\right)\mathcal{C}^{\dagger}\left\|0\right\rangle_A}\left\|0'\right\rangle_B$ $=\cos(\alpha)\left\|0'\right\rangle_A\left\|0\right\rangle_B+i\sin(\alpha)\begin{bmatrix}E_z(X)\left\|0'\right\rangle_A\left\|1\right\rangle_B+E_z(X')\left\|1'\right\rangle_A\left\|0\right\rangle_B\\+E_z(XX')\left\|1'\right\rangle_A\left\|1\right\rangle_B\end{bmatrix},$ $\left\|z\right\rangle=\left\|0\right\rangle+z\left\|1\right\rangle=\left\|0\right\rangle+\left\|z\right\|e^{i\arg(z)}\left\|1\right\rangle=\left\|0'\right\rangle+\frac{1-z}{1+z}\left\|1'\right\rangle,\ E_z(\vec{\sigma})=\frac{\left\langle z\right\|\vec{\sigma}\left\|z\right\rangle}{\left\langle z\|z\right\rangle},$ $U_{z,\alpha}=\exp\left\{i\alpha\vec{\sigma}\cdot E_z(\vec{\sigma})\right\}=I\cos\alpha+i\vec{\sigma}\cdot E_z(\vec{\sigma})\sin\alpha$

Table 2. Quantum gates of quantum games and quantum algorithms.

Main example as Parrondo's effect and its role in simulation of intelligent robust control are described.

6. APPLICATION OF QAG-APPROACH IN INTELLIGENT CONTROL: ENTANGLEMENT FREE CONTROL ALGORITHM

As above mentioned the QGSA can be described in Figure 2 as a wise control system. Let us consider the application of this system to design of robust wise KB of intelligent control systems. We consider the non-linear van der Pol oscillator: $\ddot{x}+\left(x^2-1\right)\dot{x}+x=u\left(t\right)+\xi\left(t\right)$, as the control object model, where $u\left(t\right)=k_P e+k_D\dot{e}$ is PD-controller and $\xi\left(t\right)$ is an external noise. In general case, the coefficient gains $\left\{k_P,k_D\right\}$ in PD-controller are created by Soft Computing technology using stochastic simulation and are non-robust to different types of external excitations or changing of structure parameters.

6.1. Quantum simulation of robust control laws. The *problem* is consists in design of robust coefficient gains $\left\{k_P,k_D\right\}$ in PD-controller using the particular information about these coefficient gains created by soft computing technology.

Simulation results of coefficient gain's schedule of fuzzy PD-controller are produced with superposition operator in Quantum block from two KB's created by Soft Computing. In Quantum block the entanglement is not used [5]. Figure 3 shows the simulation results of control object dynamic with different KBs for the case of telegraph references signal. The results of simulation demonstrate the high performance of quantum fuzzy PD-controller: minimum of entropy production and maximum of control accuracy.

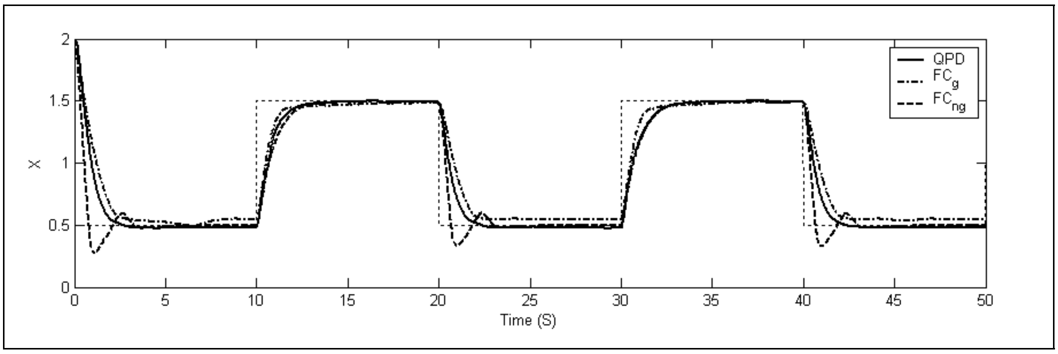

Figure 3: Simulation results of van der Pol dynamics system control, result under Gaussian excitation

This effect is similar to Parrondo's effect in game theory (see Table 2, Item 4) with classical-quantum strategies where two loser games can create one winner game with using maximal entanglement. But in our case the quantum strategy of wise controller is without entanglement in quantum control algorithm.

6.2. Investigations of wise control robustness. The investigation of intelligent control robustness is the main *problem* of modern control system theory. Figures 3 and 4 show the simulation results of dynamic behavior for different stochastic excitations and different cases of KB's in fuzzy PD-controllers. In both cases (of Gaussian and non-Gaussian random excitations) the quantum strategy of coefficient gains scheduling in wise fuzzy Q-PD-controller has the highest robustness in comparison with dynamic behavior of control object with other two fuzzy PD-controllers (FC1 and FC2).

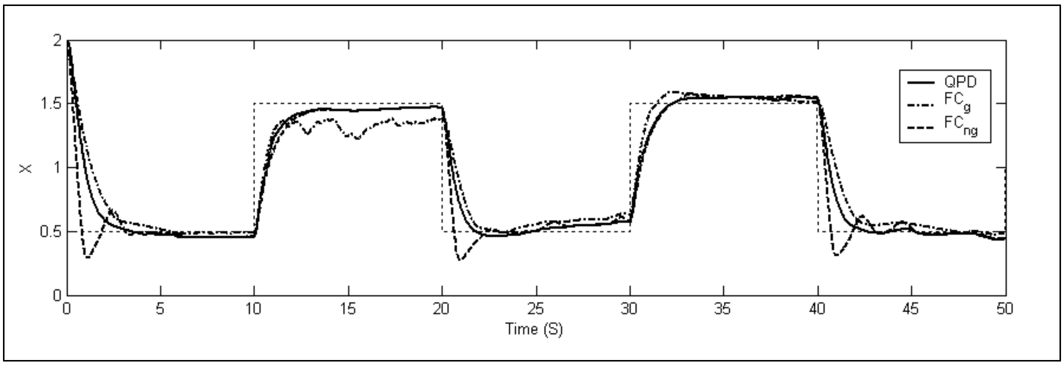

Figure 4: Simulation results of van der Pol dynamics system control, result under Non-Gaussian excitation

7. CONCLUSIONS

We demonstrate the power of high information design technology approach to the investigation of intelligent robust control systems of essentially non-linear dynamic control objects (intelligent robotics and mechatronics) with high performance based on Quantum Soft Computing models. We describe the new effect in design of robust intelligent KB control systems: Design of wise robust KB fuzzy controller using two non-robust KBs created by soft computing technology. This effect includes the *Parrondo*'s effect and quantum control algorithms without using the entanglement in quantum strategy. Efficient simulation system is based on fast algorithms [8].

8. REFERENCES

[1] B.N. Petrov, S.V. Ulyanov, I.I. Goldenblat and G.M.Ulanov, Control problems of relativistic and quantum dynamic objects: Information and thermodynamics approaches, Science Publ., M., 1982.

[2] S. Ulyanov, F. Ghisi, S. Panfilov, V. Ulyanov, I. Kurawaki and L. Litvintseva, Simulation of quantum algorithms on classical computers, Universita degli Studi di Milano, Polo Didatico e di Ricerca di Crema, Note del Polo, Vol. 32, 2000, 132 p.; F. Ghisi and S. Ulyanov, "The information role of entanglement and interference operators in Shor's quantum algorithm gate dynamics", *Journal of Modern Optics*, Vol. 47, No 12, 2000, pp. 2079-2090.

[3] US patent 6,578,018 B1, System and method for control using quantum soft computing, (*Inventor*: S. V. Ulyanov), Filled 27/07/1999, Date of publication 10/07/2003.

[4] K.-H. Han, J.-H. Kim, "Quantum-inspired evolutionary algorithm for a class of combinatorial optimization," *IEEE Trans. Evolutionary Computation*, Vol.6, No 6, 2002, pp. 580-593.

[5] S.V. Ulyanov, K. Takahashi, S.A. Panfilov, L.V. Litvintseva, I.S. Ulyanov, A.V. Yazenin, "Quantum soft computing via robust control: classical efficient simulation of wise quantum control in nonlinear dynamic systems based on quantum game gates", Proc. of Second International Conference on Soft Computing, Computing with Words and Perceptions in System Analysis, Decision and Control (ICSCCW 2003), Antalya, Turkey, 2003, pp.11-41.

[6] N. Kouda, N. Matsui, H. Nishimura, "Image compression by layered quantum networks," *Neural Proceedings Letters*, Vol. 16, No 1, 2002, pp. 67-80.

[7] M. Andrecut, M.K. Ali, "A quantum neural network model," *Intern. J. Modern Physics C*, Vol.13, No 1, 2002, pp. 75-88.

[8] S.A. Panfilov, K. Takahashi, I.S. Ulyanov, "Fast quantum algorithms for quantum soft computing and simulation of robust intelligent robust control systems", Proc. of WAC 2004, this issue.