Том 3, № 2, Июнь 2008 ISSN 1819-4362

НЕЧЕТКИЕ СИСТЕМЫ и мягкие вычисления

Научный журнал Российской ассоциации нечетких систем и мягких вычислений

УДК 658.012.011.56

QUANTUM CONTROL ALGORITHM OF KNOWLEDGE SELF-ORGANIZATION IN ROBUST INTELLIGENT CONTROL SYSTEMS BASED ON QUANTUM FUZZY INFERENCE

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Поступила в редакцию 15.03.2008, после переработки 30.03.2008.

Данная статья описывает обобщенную стратегию робастного интеллектуального управления на основе технологий мягких/квантовых вычислений позволяющие повысить робастность гибридных интеллектуальных регуляторов за счет возможности самоорганизации. Предложено решение проблем за счет введения обобщенных квантовых стратегий в модель нечеткого вывода в реальном времени в виде квантового нечеткого вывода. Основное внимание уделено выявлению свойства робастности интеллектуальных систем управления на основе эффективного моделирования примеров.

This article describes a generalized design strategy of intelligent robust control systems based on quantum/soft computing technologies that enhance robustness of hybrid intelligent controllers by supplying a self-organizing capability. 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 Quantum Fuzzy Inference based systems. We stress our attention on the robustness features of intelligent control systems with the effective simulation of Benchmark.

Ключевые слова: робастное интеллектуальное управление, квантовый алгоритм управления самоорганизацией, квантовый нечеткий вывод.
Keywords: robust intelligent control, quantum control algorithm of self-organization, quantum fuzzy inference.

1. Introduction

For complex and ill-defined dynamic systems that are not easily controlled by conventional control systems (such as P-[I]-D-controllers) - especially in the presence of different stochastic noises — the System of Systems Engineering methodology provides fuzzy controllers (FC) as one of alternative way of control systems design. Since their appearance, FCs demonstrates their great applicability in cases when control object is ill-defined or it operates under unknown conditions, when traditional negative feedback based controller is failing [1, 2]. Soft computing methodologies, such as genetic algorithms (GA) and fuzzy neural networks (FNN) had expanded application areas of FC by adding 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. One of the solutions seems obvious by preparation of a separate set of knowledge bases (KB) for fixed conditions of control situations. However, the following question arose:

How to judge which KB-FC should be operational in the concrete time moment?

In decision making is most important a selection of the optimal generalized strategy which will switch the flow of control signals from different FC, and if necessary will modify their output to fit present control object conditions. For this purpose the simplest way is to use a kind of weighted aggregation of outputs of each independent FC, but this solution will fail and distribution of weighting factors should be somehow dynamically decided [2]. 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 [3, 4].

1.1 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) [2]. 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 [4]. In this case the output of QFI is an optimal robust control signal, which combines best features of the 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 environments [5].

1.2 Main goal

In this article we give a brief introduction on soft computing tools for designing independent FC and then we will provide QFI methodology. The simulation example of robust intelligent control based on QFI is introduced. The role of KB design based on QFI in the solution of System of Systems Engineering problems is also discussed.

2. Problem's formulation

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. 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 [2]. For achieving of *self-organization* level in intelligent control system it is necessary to use QFI [4].

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 [5] 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* [6]) a search of "successful" marked solution is formalized; and with *interference* operator we can extract "good" solutions together with classical *measurement* operations [7].

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 [5 - 7].

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 [6] applied in developed QFI methods. *Quantum Fuzzy Inference* ideas are introduced. Robustness of new types of *self-organizing intelligent control systems* is demonstrated.

3. 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 [8]. The necessary unitary reversible operations are called as *superposition*, *entanglement* (quantum correlation) and *interference* that physically are operators of quantum computing in information processing.

In this article we introduce briefly the particularities of quantum computing and quantum information theory that are used in the quantum block - QFI (see, Figure 1) supporting a self-organizing capability of FC in robust intelligent control system (ICS).

3.1 Quantum computing

In Hilbert space the superposition of classical states $\left(c_1^{(1)}|0\rangle + c_2^{(1)}|1\rangle\right)$ 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:

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

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.

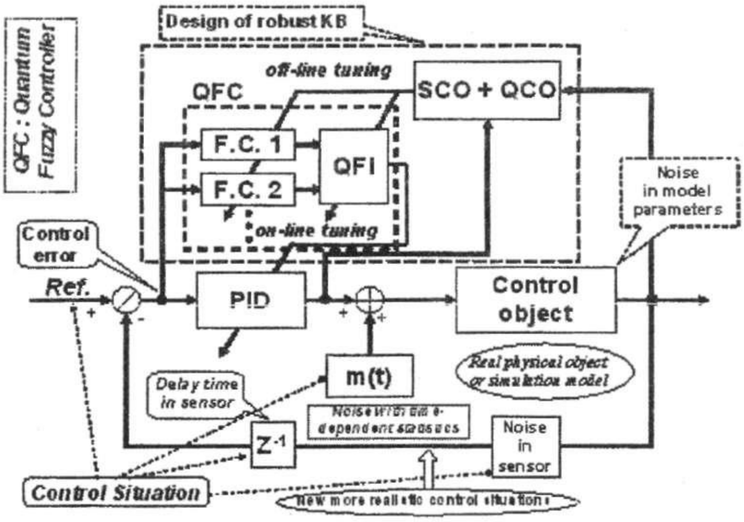


Fig. 1: Structure of robust ICS based on QFI.

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, 6, 7]. Hence, a quantum gate approach can be used in a global optimization of Knowledge Base (KB) structures of ICS's that are based on quantum computing, on a quantum genetic search and quantum learning algorithms.

3.2 Quantum information resources in QFI algorithm

Figure 2 shows the algorithm for coding, searching and extracting the value information from two KB's of fuzzy PID controllers designed by SCO.

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 [4]: (*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 [6, 9].

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.

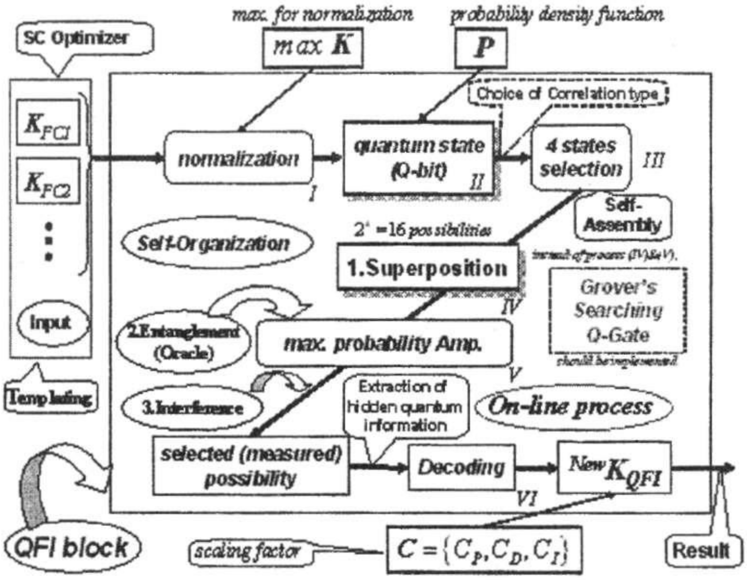


Fig. 2: The structure of QFI gate.

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

4.1 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. 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 use stochastic simulation system based on the control object model. More detail description of SCO is given in [1, 2].

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

Figure 1 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.

Figure 2 shows the structure of QFI that support and realize the quantum control algorithm of self-organization.

According to described above algorithm the input to the QFI gate is considered according Eq.(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, Figure 3) for the given control task in different control situations (for example, in the presence of different stochastic noises).

4.2 Quantum hidden information extraction in QFI

Using the four facts from quantum information theory QFI extracts the hidden quantum value information from classical KB1 and KB2 (see, Figure 3).

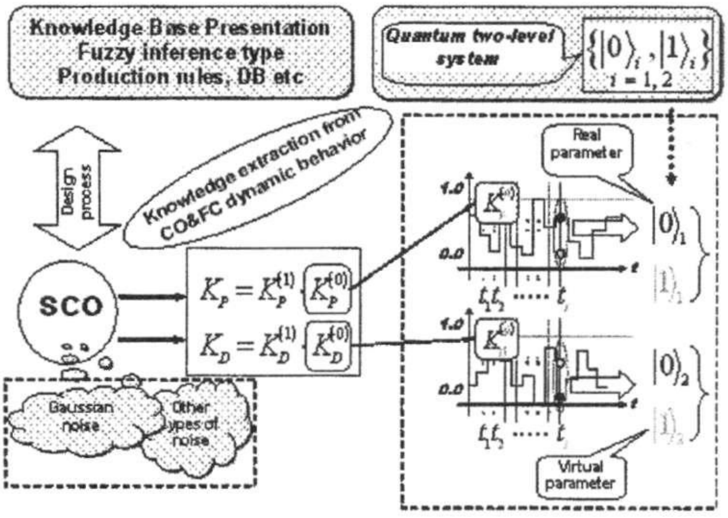


Fig. 3: Example of information extraction in QFI.

In this case between KB1 and KB2 (from quantum information theory of view-point) we organize a communication channel using quantum correlations that is impossible in classical communication theory [5, 7, 9]. The algorithm of superposition calculation is presented below and described in details in [5].

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, Figures 2 and 3) 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 (KB1 and KB2). The initial state ρ is shared between subsystems held by A (KB1) and B (KB2), with respective dimensions$d$,

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

Here $U_0 = I$ and U_1changes the computational basis to a conjugate basis

$$|\langle i \mid U_1 |k\rangle| = 1 \big/ \sqrt{d} \quad \forall\, i, k.$$

In this case, B chooses $|k\rangle$ 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 ρ'-bit string $k$and sends $B\,|k\rangle$ or $H^{\otimes n}\,|k\rangle$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 inρ'. 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 [9]. 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. Figure 4).In present article we consider a simplified case of QFI when with the Hadamard transform is organized an unlocked correlation in superposition of two KB's; 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 [5]). Interference operator extracts this maximum of amplitude probability with a classical measurement. Figure 5 shows the structure of Quantum Computing Optimizer of robust KB-FC based on QFI [4].

Below we discuss application of described QFI model to control of non-linear locally unstable dynamic system.

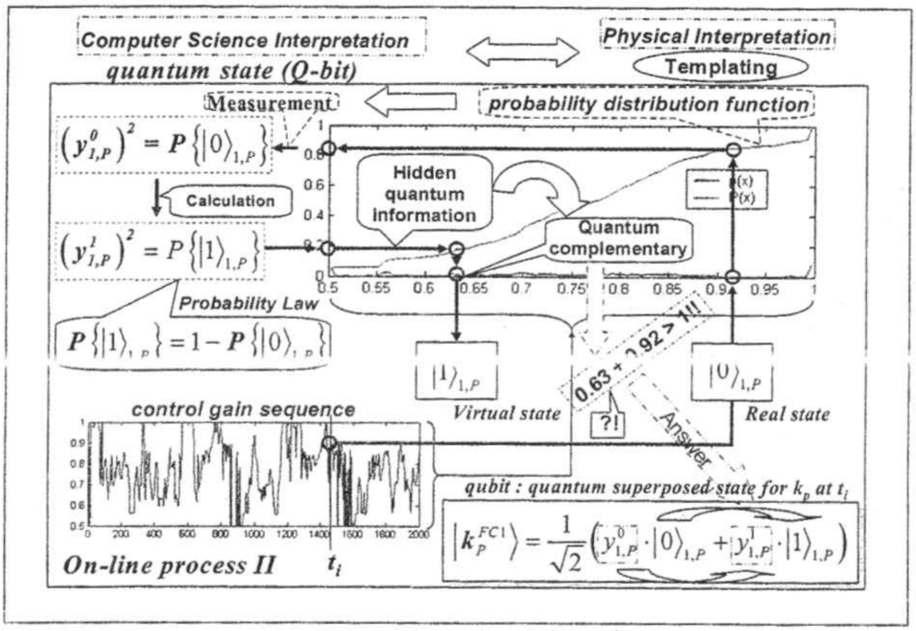
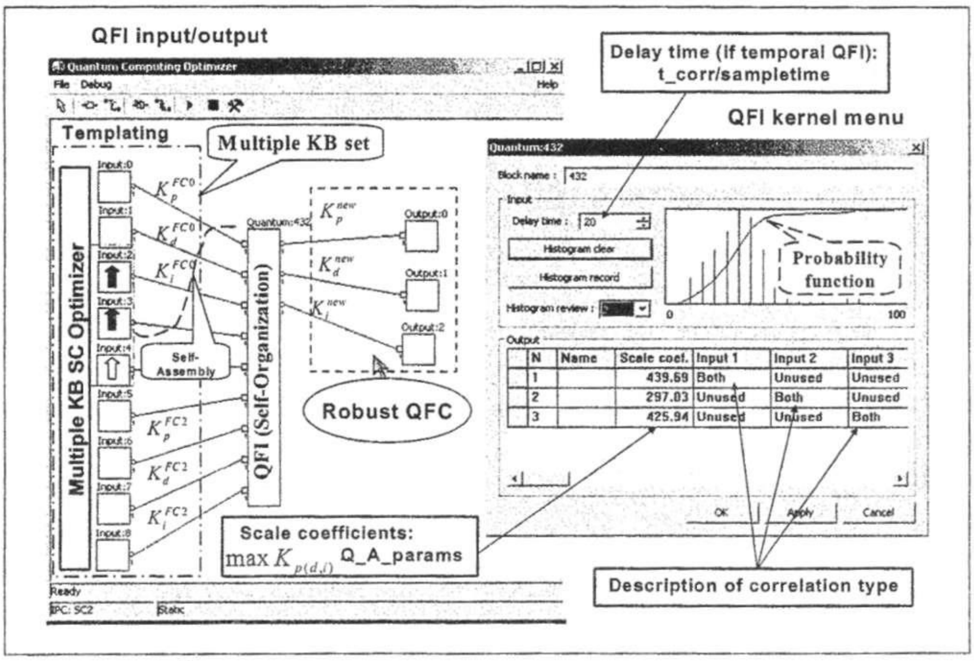


Fig. 4: The algorithm of superposition calculation.



Block name : 432

Input

Delay time : 20

Histogram review :

Output

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

Fig. 5: QFI-process by using QC Optimizer (QFI kernel).

5. Benchmark simulation

5.1 Control object's model simulation

Consider the following model of control object as nonlinear oscillator:

$$\ddot{x} + \left[2\beta + a\dot{x}^2 + k_1 x^2 - 1\right]\dot{x} + kx = u(t) + \xi(t), \qquad (3)$$

where $\xi(t)$is a stochastic excitation with an appropriate probability density function. The system, described by Eq.(3) have essentially nonlinear dissipative components and appears different types of behaviour: if $\beta = 0.5$ (other parameters, for example,$\alpha = 0.3; k_1 = 0.2; k = 5$), then dynamic system motion is asymptotically stable; if $\beta = -1$ (other parameters is the same as above), then the motion is locally unstable. Consider an excited motion of the given dynamic system under hybrid fuzzy PID-control. Let the system be disturbed by a *Rayleigh* (*non Gaussian*) noise. The stochastic simulation of random excitations with appropriate probability density functions is based on nonlinear forming filters methodology developed in [2].

FC1 *design*: The following model parameters: $\beta = 0.5$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$ and initial conditions [2.5] [0.1] are considered. Reference signal is: $x_{ref} = 0$. K-gains ranging area is [0, 10]. By using SC Optimizer and teaching signal (TS) obtained by the stochastic simulation system with GA [1, 2]) or from experimental data, we design KB of FC 1, which optimally approximate the given TS (from the chosen fitness function point of view).

FC2 *design*: The following *new* model parameters: $\beta = -1$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$ are used. Initial conditions are the same: [2.5] [0.1]. *New* reference signal is as following: $x_{ref} = -1$; K-gains ranging area is [0, 10].

In modelling we are considered with developed toolkit (see, Figure 5) different unforeseen control situations and compared control performances of FC1, FC2, and self-organized control system based on QFI with two FC's. In Table 1 four different control situations are described.

For *Environments* 2 and 4 (see, Table 1), Figures 6 - 8 show the response comparison of FC1, FC2 and QFI-self-organized control system. *Environment* 2 for FC1 is an unpredicted control situation. Figure 9 shows responses of FC's on unpredicted control situation: a *dramatically new* parameter $\beta = -\ 0.1$(R1 *situation*) in the model of the control object (3) and with the similar as above Rayleigh external noise. *Environment* 4 and R1 situation are presented also unpredicted control situations for both designed FC1 & FC2.

5.2 Result analysis

Simulation results show that with QFI it is possible from two non-robust KB's outputs to design the optimal robust control signal with simple wise control laws of PID coefficient gain schedule in unpredicted control situations. The latter is despite the fact that in Environments 2 & 4 FC1 and in R1 situation both FC1 & FC2 lose robustness.

Physically, it is the employment demonstration of the minimum entropy principle relative to extracted quantum knowledge [4, 5]. As to the viewpoint of quantum game theory we have *Parrondo*' paradox: from two classical KBs - that are not winners in different unforeseen environments - with QFI toolkit we can design one

Table 1: Learning and unpredicted control situation types.

Environment 1: Rayleigh noise; Ref signal = 0; *Model parameters*: $\beta = 0.5$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$	**Environment 2**: Rayleigh noise; Ref signal = - 1; *Model parameters* : $\beta = -1$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$
Environment 3: Gaussian noise; Ref signal = -0.5; *Model parameters*: $\beta = -1$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$	**Environment 4**: Gaussian noise; Ref signal = +0.5; *Model parameters*: $\beta = -1$; $\alpha = 0.3$; $k_1 = 0.2$; $k = 5$

winner as a wise control signal using quantum strategy of decision making (without entanglement).

This effect in robust control was described also in [10] on other examples of unstable control systems (details on http://www.qcoptimizer.com).

6. Conclusions

1. SCO allows us to model different versions of KBs of FC that guarantee robustness for fixed control environments.
2. The QFI block enhances robustness of FCs using a self-organizing capability and hidden quantum knowledge.
3. Designed FC based on QFI achieves the prescribed control objectives in many unpredicted control situations.
4. Using SCO and QFI we can design *wise control* of essentially non-linear stable and, especially of unstable dynamic systems in the presence of information uncertainty about external excitations and in presence of dramatically changing control goal, model parameters, and emergency.
5. QFI based FC requires minimum of initial information about external environments and internal structures of a control object adopted a computing speed-up and the power of quantum control algorithm in KB-self-organization [4].

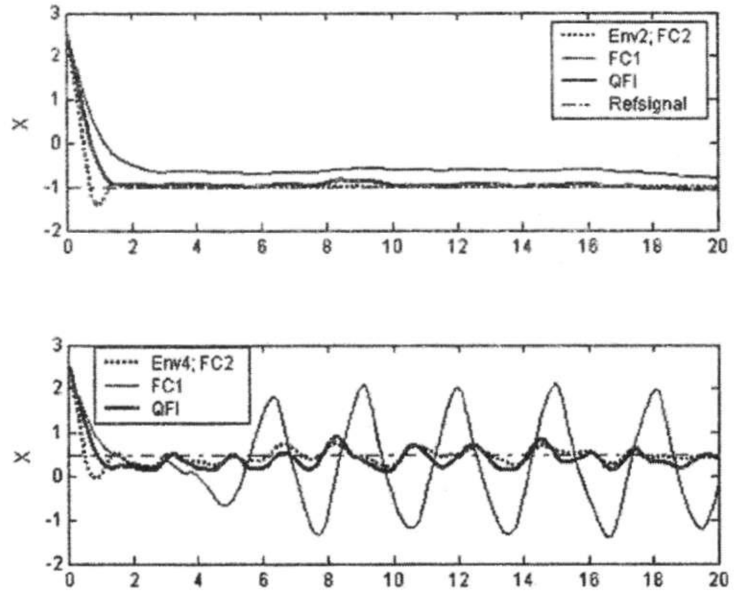


Fig. 6: Motion under different types of control.

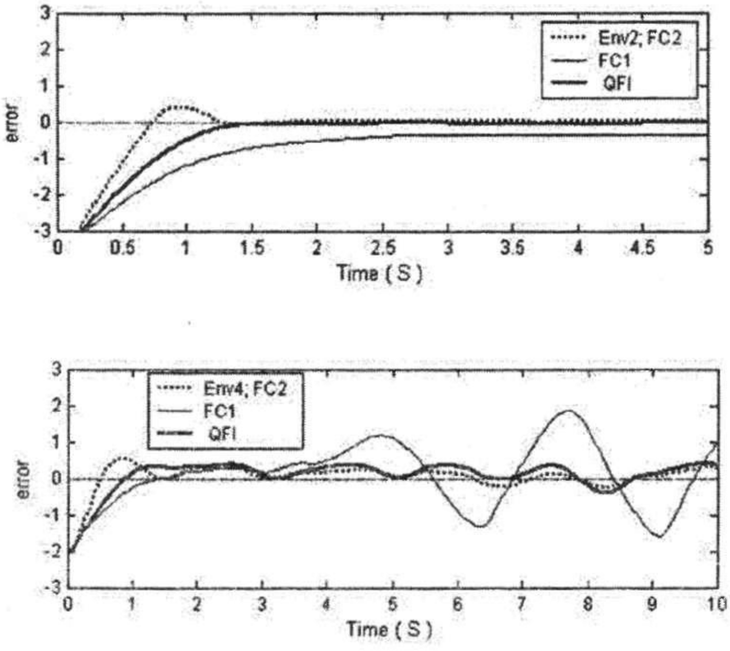


Fig. 7: Control error in different types of control.

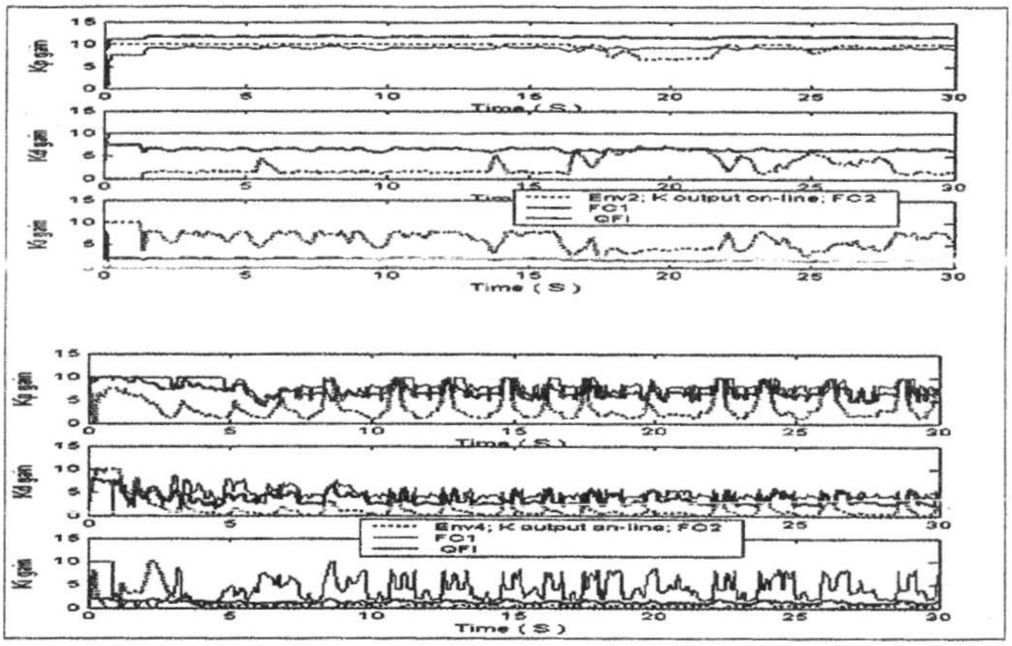


Fig. 8: Control laws in different types of environments.

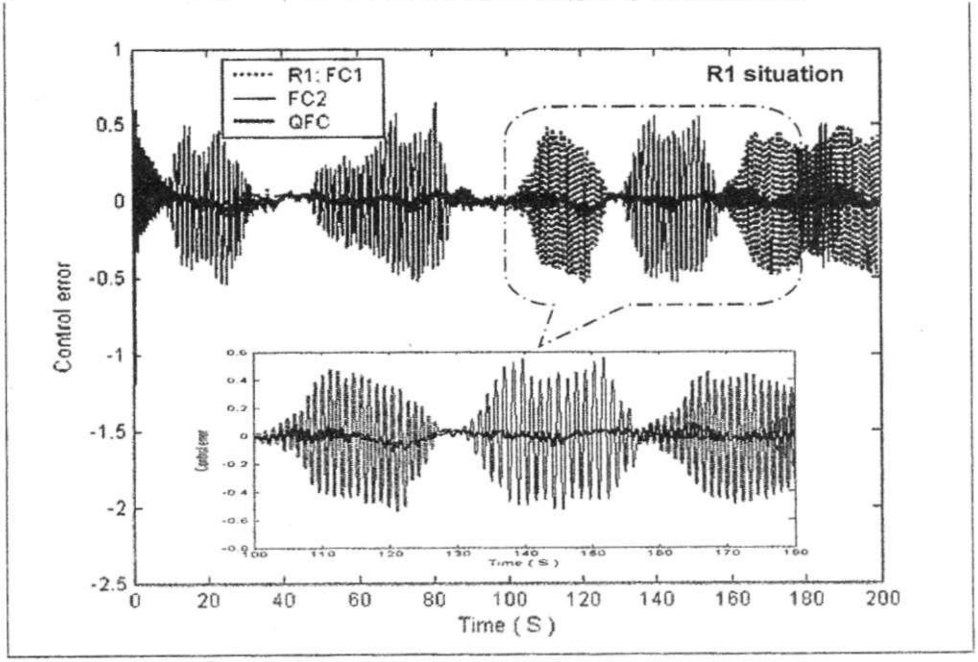


Fig. 9: Control error in unpredicted control situation.

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