Quantum Swarm Model of Self-Organization Process based on Quantum Fuzzy Inference and Robust Wise Control Design

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Abstract A new quantum model of self-organization in KB of fuzzy controller is discussed. The physical interpretation is introduced based on the model of the exchange and extraction of hidden information in particle swarm on quantum level of self-organization. New types of quantum correlations between particle swarm are introduced. Model of Quantum Fuzzy Inference play the role of the algorithmic support and SW-platform of developed self-organization process. This report presents a generalized design strategy of intelligent robust control systems based on quantum/soft computing technologies that enhance robustness of fuzzy controllers by supplying a KB self-organizing capability. It is demonstrated that fuzzy controllers 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 generalization of strategies in fuzzy inference 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. Benchmark simulation results are demonstrated the effectiveness of quantum approach to design of robust wise control. Based on the simulation results with Quantum Fuzzy Inference a new design principle "*Simple wise control of complex control objects*" is realized.
KEYWORDS: Robust Intelligent Control, Self-Organization, Quantum Fuzzy Inference, Quantum Soft Computing

1. INTRODUCTION

For complex and ill-defined dynamic systems that are not easily controlled by traditional 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. Advanced control system must be robust in unpredicted control situations.

Figure 1 show the general case of unpredicted control situations for fuzzy PID controller.

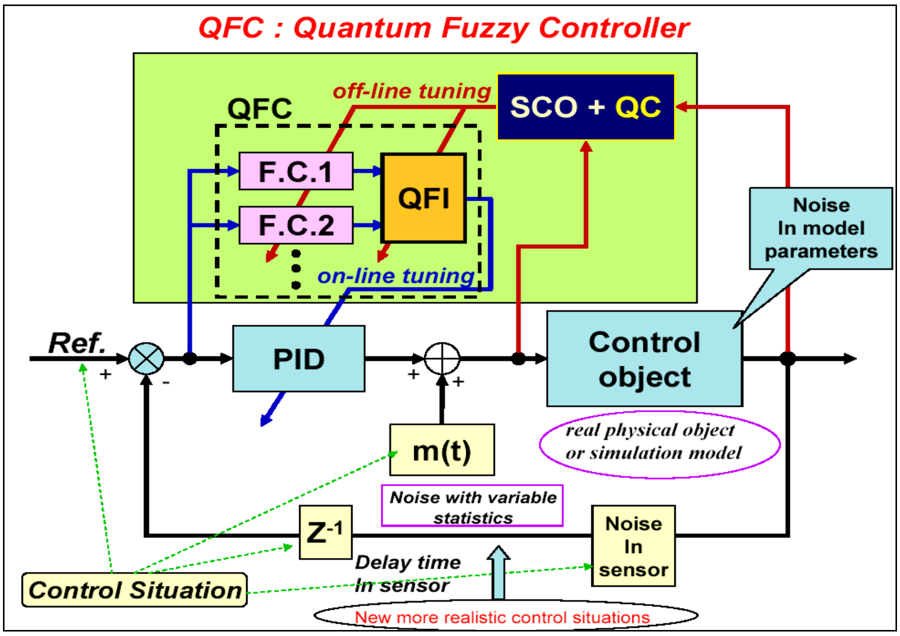


Figure 1: *Self-organized intelligent control system based on QFI*

Since their appearance, fuzzy controllers demonstrate 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. 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 good and robust intelligent control system when its operational conditions have to evolve dramatically (aging, sensor failure and so on) [1]. 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-FC) for fixed conditions of control situations, but the following question raises:

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

At this moment the most important decision is a selection of the generalization 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.

We propose the solution of such kind of problems by introducing a generalization of strategies in fuzzy inference from a set of pre-defined fuzzy controllers by new Quantum Fuzzy Inference based systems [2,3]. We stress our attention on the robustness features of intelligent control systems. Benchmark simulation results are demonstrated the effectiveness of quantum approach to design of robust wise control. Based on the simulation results with Quantum Fuzzy Inference a new design principle "*Simple wise control of complex control objects*" [3] is realized. Figure 2 show a new design principle.

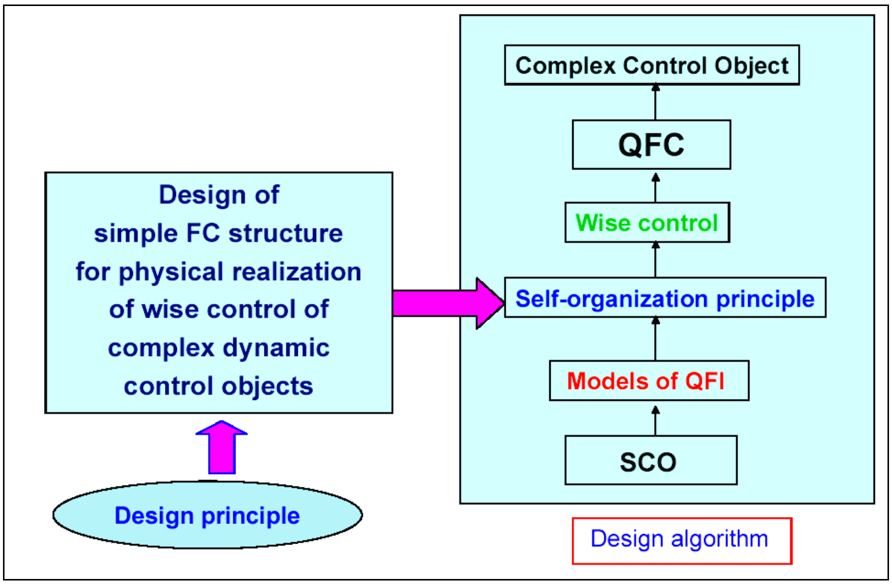


Figure 2: *Design principle of robust KB for quantum self-organized FC*

We propose a solution of such kind of generalization problems by introducing a *self-organization* design process of KB-FC that supported by the *Quantum Fuzzy Inference* (QFI) based on Quantum Soft Computing ideas [2].

Figures 3, 4 and 5 show the main structure of quantum model of self-organization process that biologically inspired by swarm behavior of pedestrians, colony ants, birds, fishes and so on.

A new quantum model of self-organization in KB of fuzzy controller is discussed. The physical interpretation is introduced based on the model of the exchange and extraction of hidden information in particle swarm on quantum level of self-organization. New types of quantum correlations between particle swarm are introduced. 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. QFI system is a quantum algorithm block, which performs post processing of the results of fuzzy inference of each independent FC and produces the generalized control signal output. 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 signal is the background for support the reliability of control accuracy in uncertainty environments.

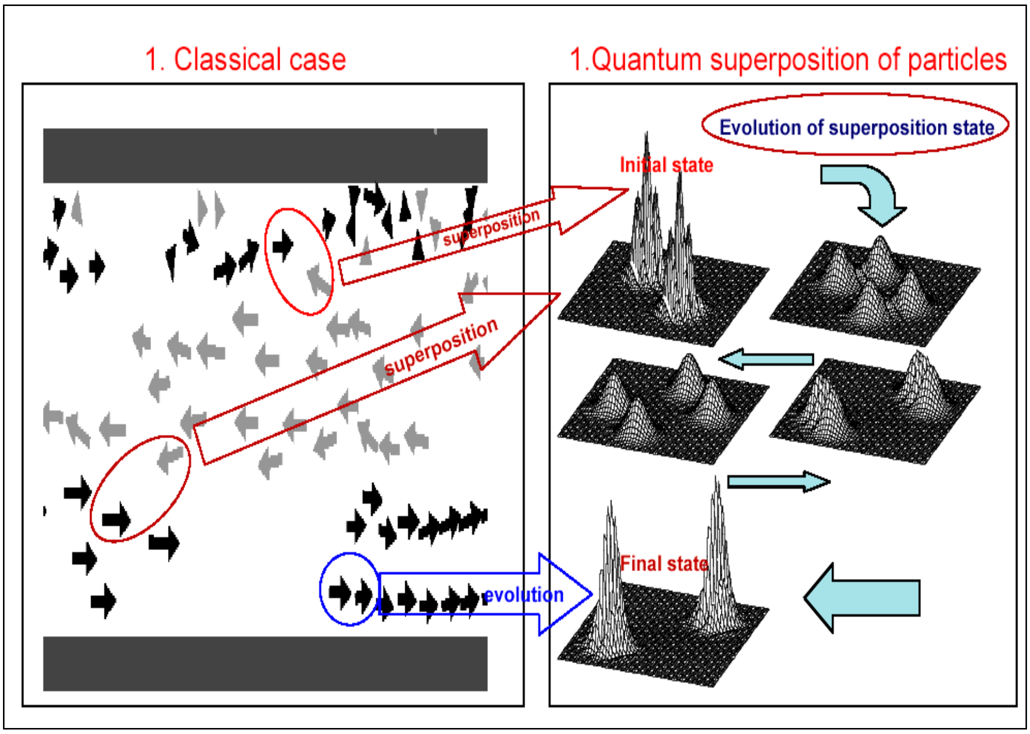


Figure 3: *Superposition evolution in quantum swarm self-organization*

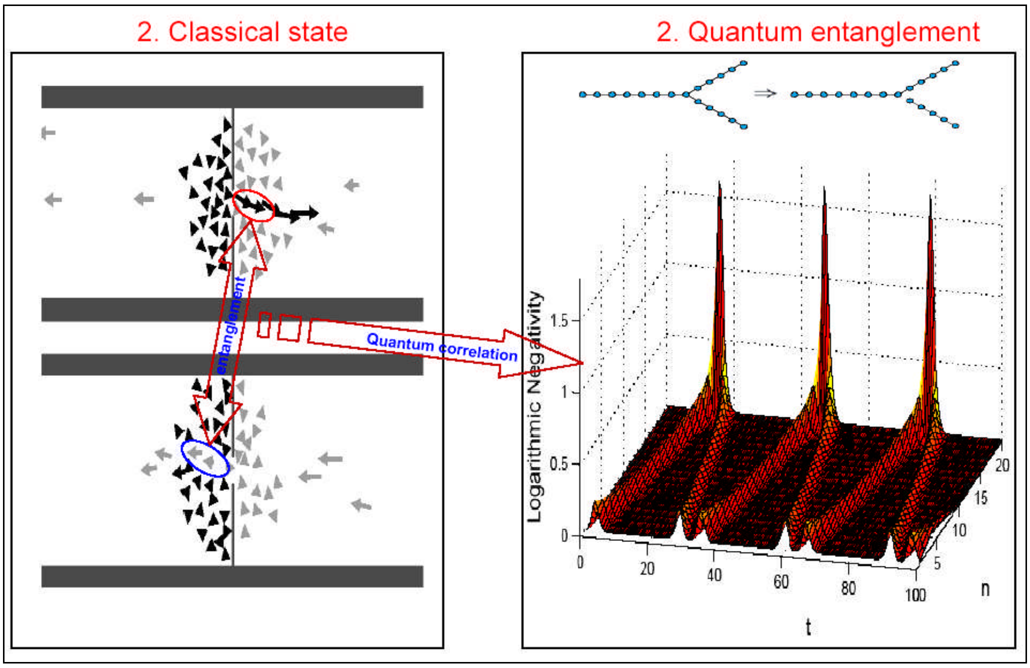


Figure 4: *Entanglement evolution in quantum swarm self-organization*

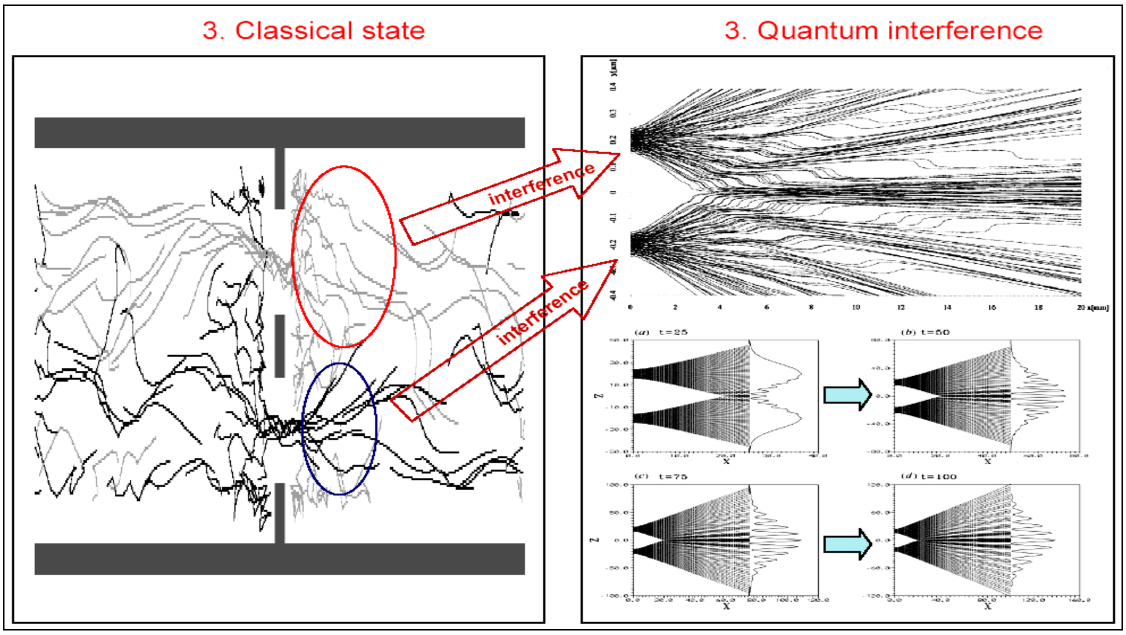


Figure 5: *Interference evolution in quantum swarm self-organization*

In this report we give a brief introduction on soft computing tools for designing independent FC and then we will provide QFI methodology, and the simulation example of robust intelligent control based on QFI.

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. 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 sensor 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 Soft Computing Optimizer (SCO) was developed in [1].

For achieving of *self-organization* level in intelligent control system it is necessary to use QFI. 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 [2, 4] and explores three main unitary operations [4]: (i) superposition; (ii) entanglement (quantum correlations); and (iii) interference. According to quantum gate computation [2, 4], the logical union of a few KBs in one generalized space is realized with *superposition* operator; with *entanglement* operator (that can be described by different models of *quantum oracle* [4]) a search of "successful" marked solution is formalized; and with *interference* operator we can extract "good" solutions together with classical *measurement* operations.

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. 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 [2 - 6] applied in developed QFI methods. *Quantum Fuzzy Inference* ideas are introduced. Robustness of new types of *self-organizing intelligent control systems* is demonstrated.

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

3. DESIGN OF SELF-ORGANIZING FUZZY CONTROLLER BASED ON QFI

The kernel of the abovementioned FC design tools 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].

Figure 6 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 [3].

As above mentioned, QFI block (see, Figure 1) is based on three main quantum operators of quantum computing: superposition of classical states, entanglement, interference, and classical measurement. According to described above algorithm the input to the QFI block is considered as a superposed quantum state $K_1(t)\otimes K_2(t)$, where $K_{1,2}(t)$ are the outputs from fuzzy controllers FC-1 and FC-2 designed by SCO for the given control task in different control situations (for example, in the presence of different stochastic noises).

The algorithm of superposition calculation is described in [3]. Using the four facts from quantum information theory [3, 4] QFI extracts the value information from KB-1 and KB-2. In this case between KB-1 and KB-2 (from quantum information theory point of view) we organize a communication channel using quantum correlations that is impossible in classical communication theory.

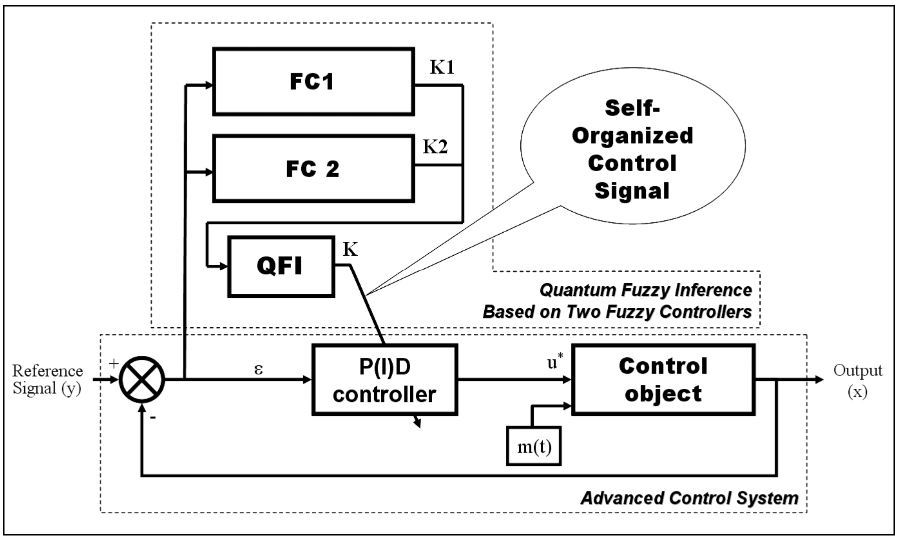


Figure 6: *Main structure of intelligent self-organized control system*

In present report we consider a simplified case of QFI when an unlocked correlation in superposition of two KB's is organized with the Hadamard transform; the entanglement operation is modelled as quantum oracle that can estimates a maximum of amplitude probability in corresponding superposition of classical states. Interference operator extracts this maximum of amplitudes probability with a classical measurement (see, details in [3]).

Figure 7 show the role of different types of quantum correlations in QFI model.

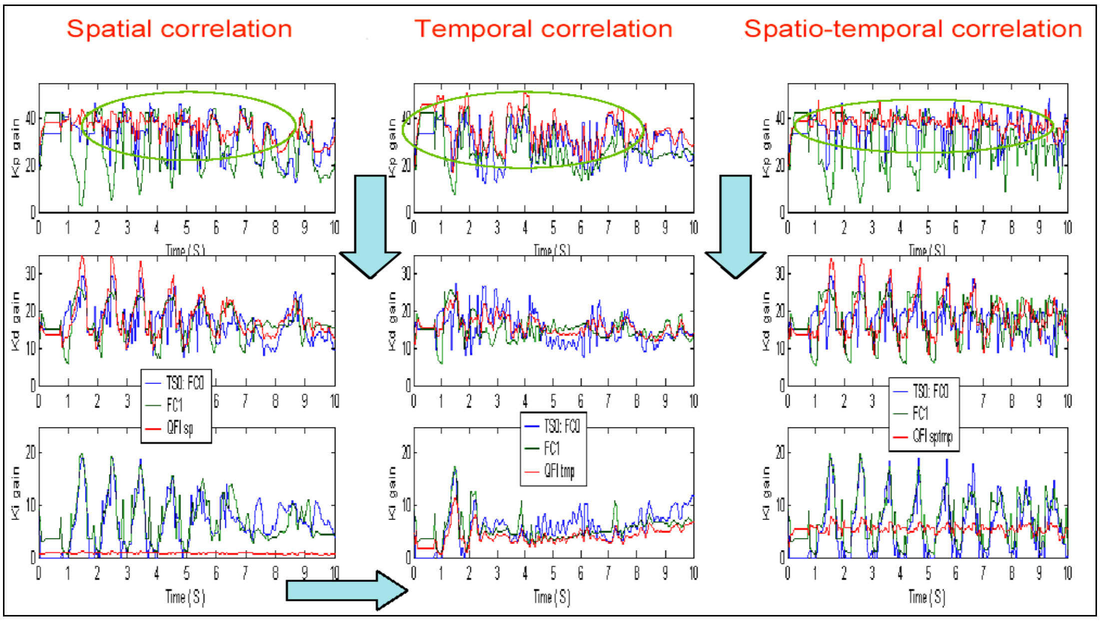


Figure 7: *Control law comparison for different types of quantum correlation in QFI*

Below we use temporal quantum correlation and discuss application of described QFI model to design robust intelligent control of essentially non-linear *locally unstable* dynamic system.

4. Benchmark simulations

4.1 Nonlinear oscillator model with sizable nonlinear dissipative components and control situations Consider the following model of control object as nonlinear oscillator with sizable nonlinear dissipative components: $\ddot{x}+\left[2\beta+a\dot{x}^2+k_1x^2-1\right]\dot{x}+kx=u(t)+\xi(t)$, where $\xi(t)$ is fixed type of a stochastic excitation with an appropriate probability density function. Consider excited motion of the given dynamic system under fuzzy PID-control. The system can be disturbed by different types of stochastic noises, for example by *Rayleigh* (*non Gaussian*) noise or *Gaussian* noise, or uniformly distributed noises. Simulation algorithm is considered in [3] and used in this section. As mentioned above, still now it is difficult to design good and robust intelligent control system, when its operational conditions have to evolve dramatically (aging, sensor failure or sensor noise, sensor time delay and so on). In order to consider more realistic control situations and design wise robust control, we include in our control chain emulation blocks of sensor's time delay, sensor noises and noises in model parameters. The structure of the new type of unpredicted control situations is shown in Figure 8.

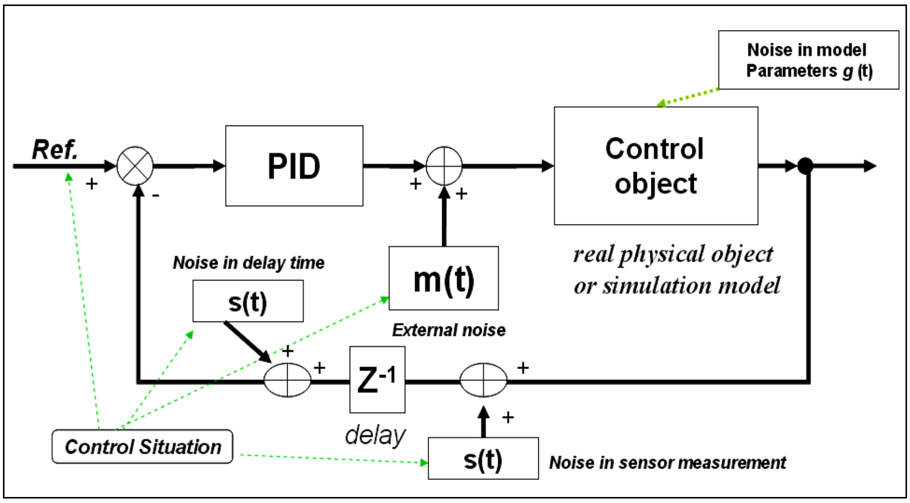


Figure 8: *The structure of the new type of control situations*

Consider the process of smart control design for the given benchmark. At first, design two KB for two FC's in two teaching control situations, and then investigate self-organization property based on QFI. Let us consider for simplicity (FC-1) as (FC0) and (FC-2) as (FC1) (see, Figure 6).

FC0-design. The following model parameters $\beta = 0.1; \alpha = 0.3; k_1 = 0.2; k = 5$ and initial conditions [2.5] [0.1] are considered. Reference signal is $x_{ref} = 0$. K-gains ranging area is [0, 50]. External stochastic noise is a *Rayleigh noise***.** These control conditions are denoted as *TS0*.

FC1-design. The following model parameters $\beta = 0.1; \alpha = 0.3; k_1 = 0.2; k = 5$ and initial conditions [2.5] [0.1] are considered. Reference signal is $x_{ref} = 0$. K-gains ranging area is [0, 50]. External stochastic noise is a *Gaussian noise***.** These control conditions are denoted as *TS1*.

By using SC Optimizer and teaching signal (obtained by the stochastic simulation system with GA [1]), we design KB of FC0 and KB of FC1, which optimally approximate the given teaching signals (from the chosen fitness function point of view). For the given control object the following control time denoted as sample time C = 0.05 *sec* and simulation time denoted as sample time c = 0.025 are chosen. We also introduced the limitation on applied control force as follows: $|u| \leq 20$ (N). Sensor delay time t_{ds} = 0.001 *sec***.**

4.2. Investigation of self-organization property of QFI for the given control object

Consider now the behavior of the control object in a new control situation S2 (as an unpredicted one) represented as following: new external noise as a uniformly distributed noise, sensor noise with gain = 0.02, time delay = 0.001 *sec*, and new time-dependent reference signal as a step signal (see a curve denoted as REF in Figure 5). We will test the robustness of intelligent control in unpredicted control situations using self-organization principle.

Case 1: *Unpredicted control situation S2*. Figures 9 shows results of dynamic motion comparison under three types of control FC0, FC1 and under Quantum Fuzzy Controller (QFC) based on QFI for the new control situation S2. *Spatio-temporal* quantum correlation is used in QFI model simulation. Calculation of spatio-temporal quantum correlation is described in [3] (see Figure 7).

Case 2: *Unpredicted control situation R1*. Consider now a new unpredicted control situation as following**:** (i) a new external noise; (ii) a new sensor noise; (iii) a new sensor time delay; and (iv) a new model parameter. New Rayleigh noise; Delay time of sensor = 0.0125 *sec*; Sensor noise gain = 0.02 ; REF=0; New model parameter Beta = − 0.1; modeling time t = 200 *sec*.

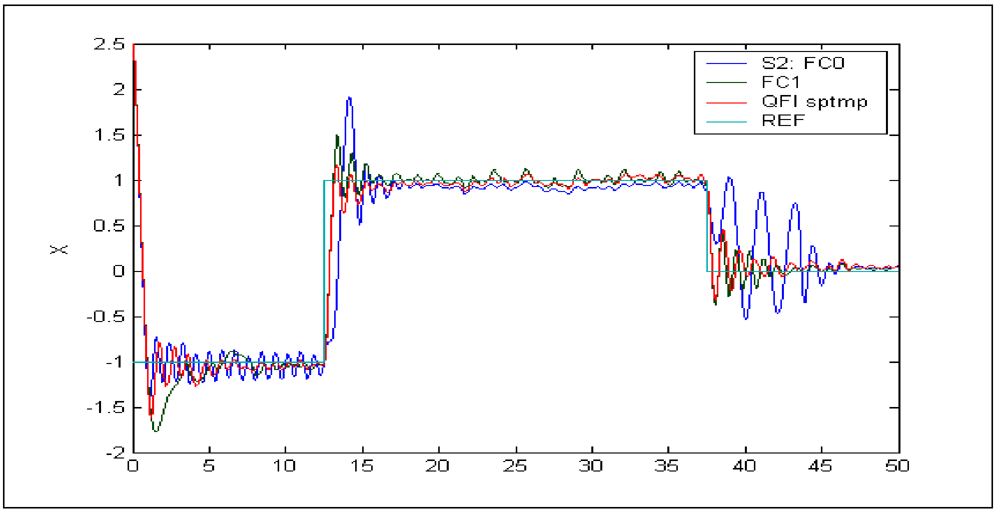
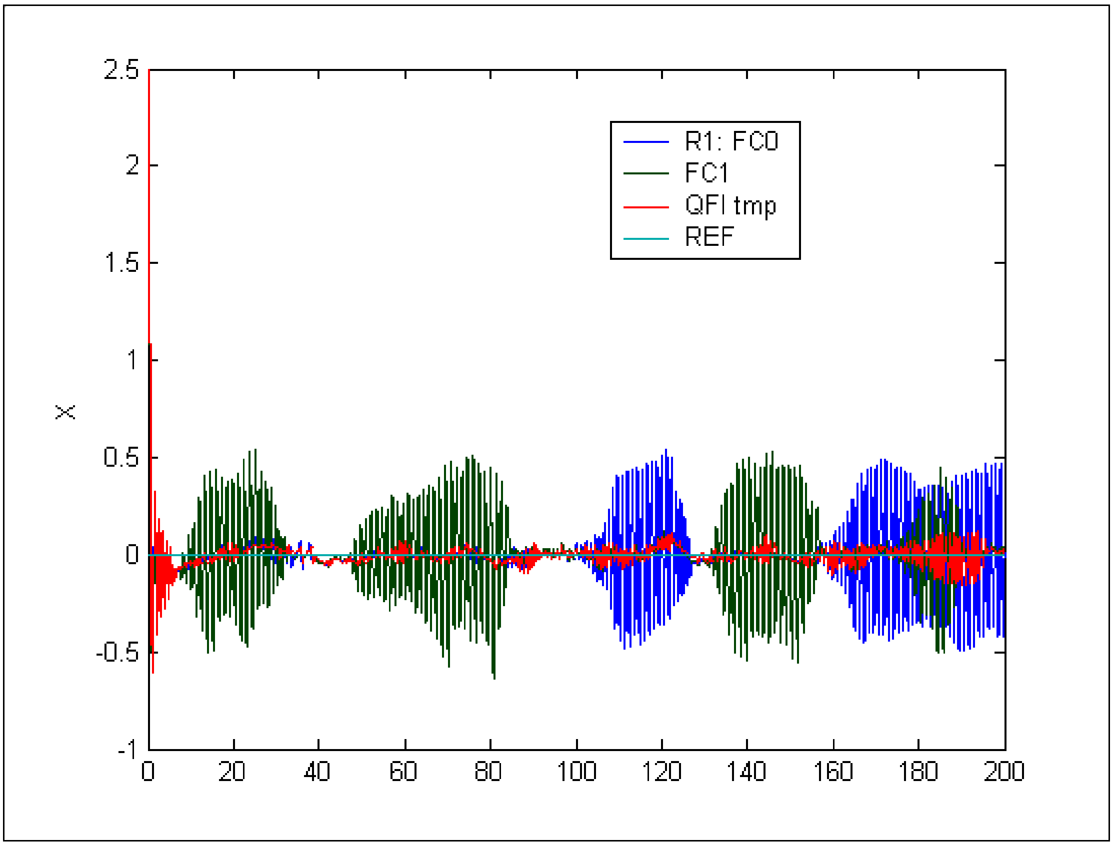
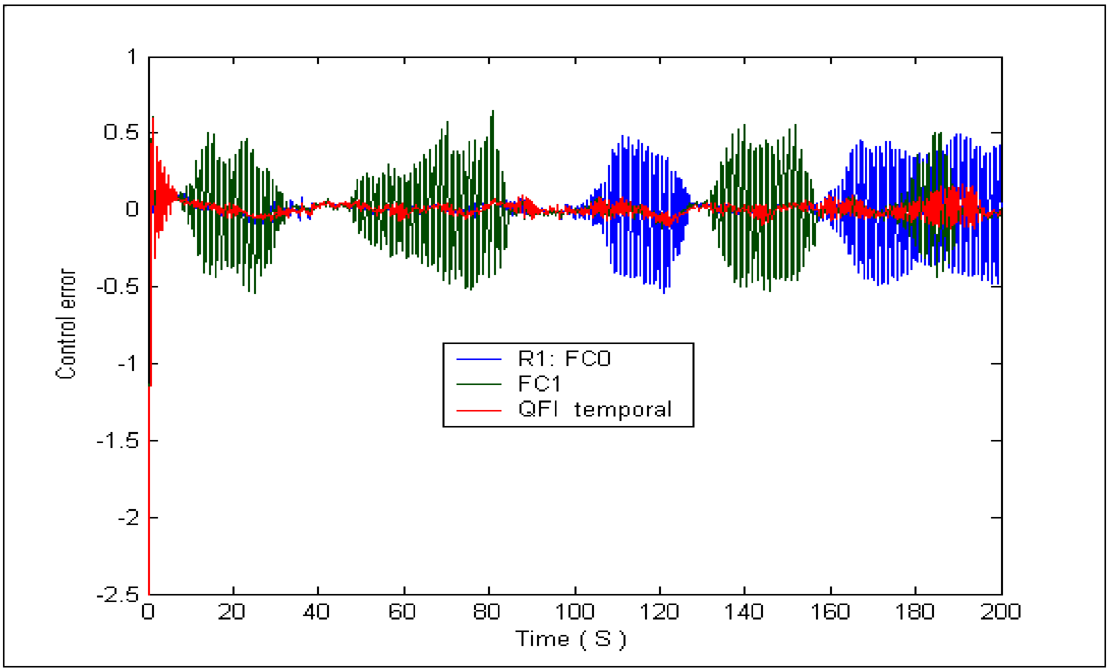


Figure 9: *Dynamic motion of CO in comparison under three types of control*: *FC0, FC1 and Quantum Fuzzy Controller (QFC) based on QFI*

Figures 10(a), 10(b) show the results of the comparison of dynamic object and control error behavior under three types of control: FC0, FC1 and Quantum Fuzzy Controller (QFC) based on QFI in unpredicted control situation R1. *Temporal* quantum correlation is used in QFI simulation. Figures 11 and 12 shows the comparison of control performance for different types of performance criterion.



(a)



(b)

Figure 10: *Comparison of dynamic control object behavior under three types of control*
(a) *dynamic behavior of control object* ; (b) *dynamic behavior of control error*

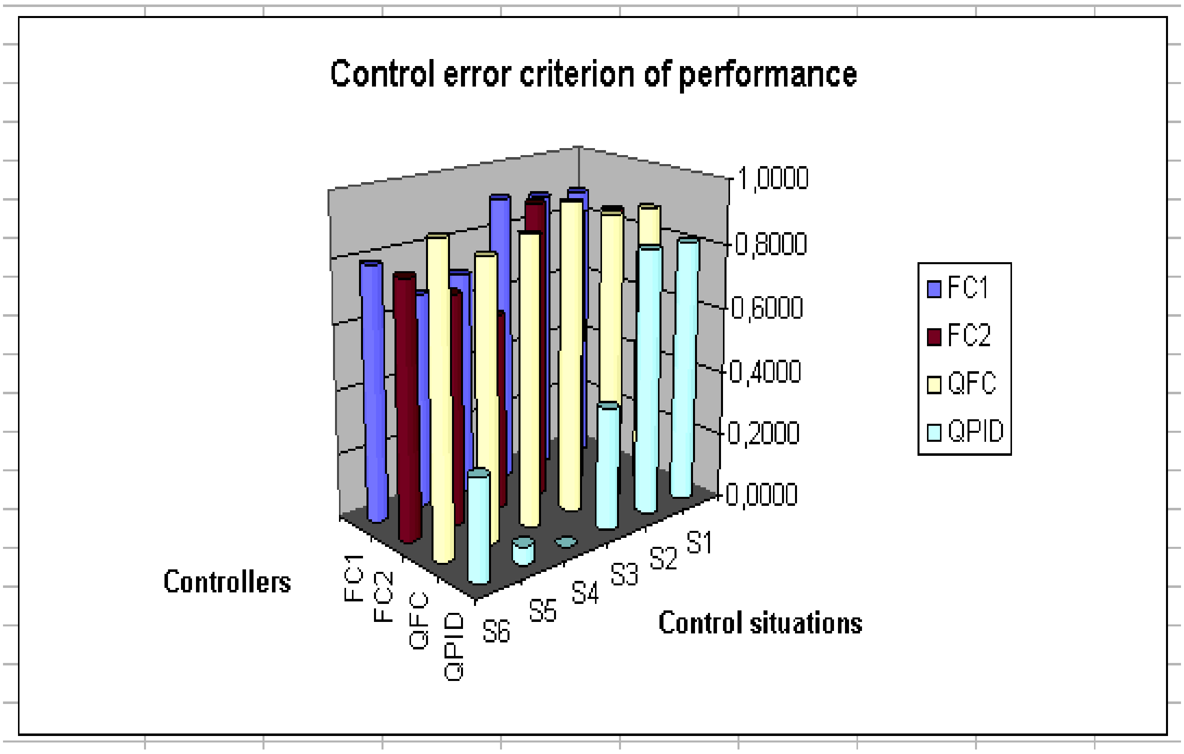


Figure 11: *Performance comparison based on integral square control error criterion*

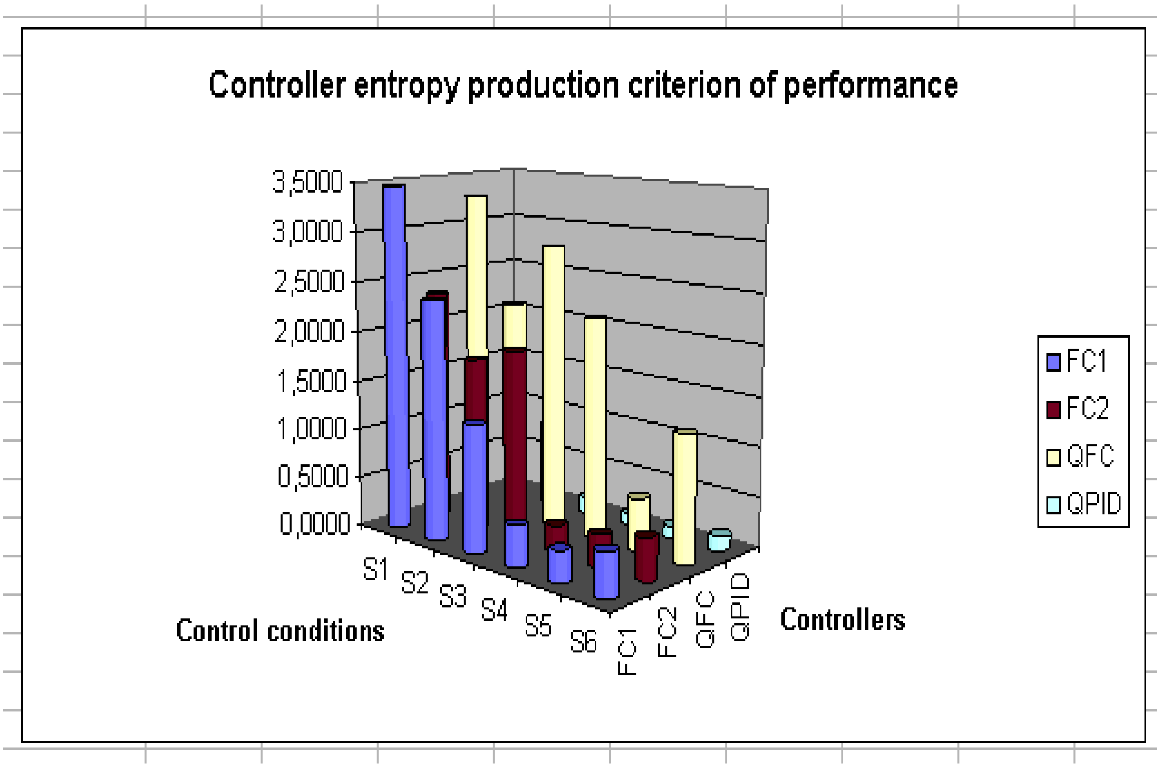


Figure 12: *Performance comparison based on controller entropy production criterion*

5. CONCLUSIONS

1. SCO allows us to model different versions of KBs (multiple KB) of FC that guarantee robustness for fixed control environments.
2. *Self-organization* principle in quantum FC in on-line regime is introduced.
3. The QFI block enhances robustness of FC using a self-organizing capability.

4. Designed quantum FC achieves the prescribed control objectives in many unpredicted control situations: The *reliability* of intelligent control system based on QFI is increased in unpredicted control situations.
5. 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 of changing reference signals (control goal), and model parameters.
6. Control laws based on QFI are simple for the physical realization.
7. QFI based FC requires minimum of the initial information about external environments and internal structure of control object model.
8. On-line process for extraction of the value information for wise control and in design of the unified robust KB in quantum FC is used.

6. REFERENCES

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