Information Design Technology of Robust Integrated Fuzzy Intelligent Control Systems based on Unconventional Computational Intelligence: Quantum Control Algorithm of Robust KB Self-Organization

S.V. Ulyanov
MCG “*Quantum*” Ltd. Co, Moscow; **E-mail**: ulyanovsv@mail.ru

Extended abstract Engineering conventional methods of advanced control theory and the technique design of automatic control systems were formed in the past century. In particular, the background and foundations of *stochastic* learning, adaptive and self-organization control of complex dynamic systems in general, with time-dependent (variable) structure under information uncertainty conditions were developed. The next step in this direction was the principle’s development of simulation and design of fuzzy control systems under uncertainty conditions that take into account the individual specific features of the behavior of chosen trajectories without sharp defined model description of the control object (CO). This design methodology was based on the fuzzy set theory, linguistic approximation and fuzzy inference (L.A. Zadeh and others) for developing robust knowledge bases (KB) of intelligent fuzzy controllers. Within the framework of the specified methodology of control laws design based on physical approaches (information–thermodynamic and quantum–relativistic methods of describing CO and control processes), in the mid 1980s, the background of the design technique of intelligent control systems was developed.

The problem of modern advanced control In complex and essentially nonlinear dynamic models of CO with weakly formalized structure and random parameters, it is quite difficult with conventional design methods to determine an optimal structure of an automatic control system, in which, e.g., a conventional proportional–integral–differentiating (PID) controller is employed at the lower (executive) level. Especially, this difficulty reveals itself in design problems of the structures of automatic control systems in the presence of random noise different in its nature and under information uncertainty about the control goals.

Computational intelligence is one of an effective toolkit for fuzzy modeling system in design technology of robust intelligent control systems. We have developed a new quantum fuzzy modeling system (QFMS – see in details, section Overview, Quantum Modeling System) based on a new computational intelligence paradigm as quantum computing technology for design of self-organization robust KB in unpredicted control situations. Computation, based on the laws of classical physics, leads to different constraints on information processing than computation based on quantum mechanics. Quantum computers hold promise for solving many intractable problems.

But, unfortunately, there currently exist no algorithms for “programming” a quantum computer. Calculation in a quantum computer (like calculation in a conventional computer) can be described as a marriage of quantum HW (the physical embodiment of the computing machine itself, such as quantum gates and the like), and quantum SW (the computing algorithm implemented by the HW to perform the calculation). To date, quantum SW algorithms, such as Shor’s algorithm, used to solve problems on a quantum computer have been developed on an *ad hoc* basis without any real structure or programming methodology.

Important computer-scientific challenges for quantum information science are to discover efficient quantum algorithms (QAs) for interesting problems and to understand the fundamental capabilities and limitations of quantum computation in comparison to those of classical computation. The bulk of this report is concerned with the problem of discovering new QAs. Perhaps the most important open problem in the theory of quantum information processing is to understand the nature of quantum mechanical speed-up for the solution of computational problems:

What problems can be solved more rapidly using quantum computers than is possible with classical computers, and what ones cannot?

To take full advantage of the power of quantum computers, we should try to find new problems that are amenable to quantum speed-up. More importantly, we should try to broaden the range of available algorithmic techniques for quantum computers, which is presently quite limited. The first examples of problems that can be solved faster with a quantum computer than with a classical computer were *oracular*, or *black-box*, problems. In standard computational problems, the input is simply a string of data such as an integer or the description of a graph. In contrast, in the black-box model, the computer is given access to a black box, or oracle that can be queried to acquire information about the problem. The goal is to find the solution to the problem using as few queries to the oracle as possible. This model has the advantage that proving lower bounds is tractable, which allows one to demonstrate provable speed-up over classical algorithms, or to show that a given QA is the best possible.

We investigate two such ideas, quantum computation by QA gates design. In this case we are described structure of QFMS and its applications in design technology of intelligent self-organized fuzzy PID-controllers based on quantum search algorithm model as quantum fuzzy inference (QFI). Main result of quantum computing is exponential (or quadratic) speed-up in comparison to classical computation of problem. In our case we investigate the problem of global robust KB design in unpredicted control situations when the classical solution is unknown.

Let us discuss any important peculiarities of modern advanced control and its correlations with sophisticated simulation methods of computational intelligence.

1. One of the most important elements of information Hi-Tech of intelligent control system's design is the development of the methodology and the corresponding industrial software/hardware toolkit for testing and evaluating the robustness level of the designed structures. For this case robustness is considered as a measure of sensitivity to various external and internal random perturbations acting both on the CO and in the measurement channels or control loops. The topicality of the solution to this problem is dictated by practical control tasks addressed by many researchers.

An increase in the complexity of the structures of CO and difficulties in predicting unexpected (unpredicted - unforeseen) control situations only stresses the topicality of this problem and draws attention to it. Such problems are referred to as the so-called "*System of Systems Engineering*" problem that studies in a general form complex structures of automatic control systems with different levels and scales of integration and/or priority data exchange between subsystems in order to establish global (necessary and sufficient) conditions for reliable autonomous (or collective) operations of the CO in the external environments.

In the experience of designing automatic control systems, very often linearized models of CO are applied. However, under this approach, the adequacy of the relation between the physical parameters of the CO and the parameters of its linearized model is frequently lost (for details see review of **R.K. Pearson**, "*Selecting nonlinear model structures for computer control*," J. of Process Control, 2003, Vol. 13, No 1, pp. 1 – 26; the discrete approximation correctness of nonlinear functions for computer simulation is discussed in **S.V. Ulyanov**, "*Computer simulation of nonlinear and parametric systems at dynamic stochastic excitations*," In: **S.V. Ulyanov** *et all*., "*Models of Seismic Structures*," M.: Sci. Publ., 1979, Ch. 7, Item 7.5, pp. 214 – 225). In this case, in the optimization of the structure and the parameters of an intelligent control system, we consider nonlinear models of CO. Note that the effect of nonlinearities on the dynamics and on the controllability of the CO in the control laws is taken into account by the gain schedule of a fuzzy PID controller (for the acceleration of nonlinear system's simulation without redundant algebraic loops in MatLab/Simulink system, see **S.V. Ulyanov** (*Inventor*), "*System and method for simulation of nonlinear dynamic systems applicable within soft computing*," **Patent** Publ. PCT WO 2004/012098 (PCT/US2003/023666) **A**1, Intern. Publ. Date 05.02.2004).

Thus, by unconventional methods, the uncertainty effect of nonlinearities in the CO is compensated by sophisticated time-depending dynamic (control laws) of the proportionality coefficients in the classical PID controller with global negative feedback.

In practice, CO is under conditions of uncertainty connected with the effect of both external and internal random factors. The ability of automatic control system to response adequately to one or another change in the parameters of the external environments that is not given in advance in design process the automatic control system characterizes the level of learning, adaptation and robustness of processes, and the ability to learn and adapt itself. Frequently, the methods of the robust control theory are not able to solve general control problems under the presence of uncertainty described in the form of a certain stochastic process with definite (in general, unknown) statistical characteristics of probability density functions.

A number of approaches to the solution of this problem based on iterative randomized algorithms were developed. The evaluation of sensitivity and the improvement of the robustness level are reached, in particular, by using algorithms of nonlinear forming filters for reproducing realizations (informatively represented chosen trajectories) of stochastic interactions with given characteristics. In the course of optimization of the parameters of automatic control systems, this approach of stochastic simulation is used together with the method of fuzzy simulation in order to achieve the required control quality irrespective of the particular implementation of the perturbing stochastic action.

2. For Step I, we are considered the methodology of joint stochastic and fuzzy simulation of automatic control systems based on the developed tools of unconventional methods as the soft computing optimizer with the aim to test the robustness of developed KB and estimate the limiting structural capabilities of intelligent control systems. The efficiency of control processes with application of the soft computing optimizer was demonstrated by particular typical examples (Benchmarks) of models of dynamic CO under the conditions of information uncertainty about the parameters of the CO and under the presence of unpredicted (abnormal) control situations (for details, see the Section Overview & Tutorial, Simulation results).

Thus, in the connection with the fact that within the framework of the classical approach to design of automatic control systems it is not possible to improve the control quality and the robustness level of the control laws obtained, the problem of the development of methods of mathematical simulation of algorithms for intelligent control of nonlinear dynamic systems based on soft computing and software tools for their support still remains topical. It is these problems to which the developed information design technology (Step I) is dedicated.

The main point in the design of intelligent control systems is the stage of knowledge extraction and forming the corresponding KB. Thus, the design of a KB with a required robustness level (under unpredicted control situations) allows one to establish in a general form the correspondence between the conditions of functioning of the CO and the required robustness level of the intelligent control system.

In Step I of developed design technology, we focus the main attention on the description of particular results of knowledge base's design and simulating intelligent control systems with essentially nonlinear CO with a randomly time-dependent structure and control goals. In this case, the aim of this Step is to determine the robustness levels of control processes that ensure the required reliability and accuracy indices under the conditions of uncertainty of the information employed in decision-making (*learning* situations). First of all, we consider the evolution of typical structures of intelligent control systems, their specific features, advantages, and disadvantages from the point of view of design process and application of intelligent control systems.

The analysis of simulation results obtained using soft computing technologies has allowed one to establish the following fact important for design technologies of robust intelligent control systems. Designed (in the general form for random conditions) robust fuzzy controllers for dynamic CO based on the KB optimizer (Step I of the technology) with the use of soft computing can operate efficiently only for fixed (or weakly varying) descriptions of the external environments. This is caused by possible loss of the robustness property under a dramatically change of the functioning conditions of CO: the internal structure of CO, control actions (reference signal), the presence of a time delay in the measurement and control channels, under variation of conditions of functioning in the external environment, and the introduction of other weakly formalized factors in the control strategy.

3. For Step 2, the description of the strategy of robust structure's design of an intelligent control system based on the technologies of quantum and soft computing is given. The developed strategy allows one to improve the robustness level of fuzzy controllers under the specified unpredicted or weakly formalized factors for the sake of forming and using new types of self-organization processes in the robust knowledge base with the help of the methodology of quantum computing. A particular solution of a given problem is obtained by introducing a generalization of decision making strategies in models of fuzzy inference on a finite set of fuzzy controllers designed in advance in the form of a new quantum fuzzy inference. The fundamental structure of quantum fuzzy inference model and its software toolkit in the design processes of the knowledge base of robust fuzzy controllers in on-line, as well as a system for simulating robust structures of fuzzy controllers, are described. The efficiency of applying quantum fuzzy inference is illustrated by a particular example of simulation of robust control processes by an essentially nonlinear dynamic CO with randomly time-dependent structure.

The introduction of the soft computing technology (based on genetic algorithms (GA) and fuzzy neural networks (FNN)) in design process has extended the field of efficient applications of fuzzy controllers by using new control functions in the form of learning and adaptation. However, it is very difficult to design a globally appropriate and robust structure of the intelligent control system. This limitation is especially typical of unpredicted control situations when the CO operates in unsharp or changing conditions (a failure of sensors or noise in the sensor system, the presence of a time delay in control signals or measurement, a sharp change in the structure of CO or its parameters, etc.).

In a number of practical cases, conditions of this type can be predicted, but it is difficult to realize a robust control in unpredicted situations based on the designed (for a fixed situation) KB of a fuzzy controller (even of the whole set of predicted random situations). It seems to us that one of the existing solutions is to form a finite number of KB of the fuzzy controller for the set of fixed control situations.

The question arises about *how to determine which of knowledge bases can be used at a particular time instant*. In this case, the choice of a generalized strategy to provide the opportunity to switch the flow of control signals input from different KB of the fuzzy controller and to adapt their output signal (if necessary) to the current conditions of functioning of the KB of a CO is especially important. A simple variant of solving this problem is to use the method of weighted coefficients and aggregate the output signals from each independent fuzzy controller. Regrettably, this method has limited capabilities (as simulation results have shown) since, frequently, the distribution of weighting factors has to be determined in on-line dynamics, and the search procedure has combinatorial nature.

In Step 2 of our design technology, it is shown that a solution of the problems of this type can be found based on introducing the self-organization principle in the course of designing KB of a fuzzy controller. The corresponding software toolkit is based on the developed model of quantum fuzzy inference with application of the methodology of quantum soft computing and engineering systems (System of Systems Engineering approach) using the synergetic self-organization principle. In particular, the implementation of the self-organization process of robust KB in this approach is performed using quantum generalization of fuzzy logical inference strategies in the form of quantum fuzzy inference. The structure of quantum fuzzy inference and a simulation system of robust KB for fuzzy controller, which illustrate the efficiency of application of quantum fuzzy inference, are described. The model of the developed quantum fuzzy inference is regarded as a new type of the search quantum algorithm on the generalized KB space of a fuzzy controller, and a generalized robust control signal is designed as the output result.

4. The model of quantum fuzzy inference proposed in this Step 2 harness particular individual KB of a fuzzy controller, each of which is obtained with the help of a KB optimizer for the corresponding conditions of functioning of a CO and fixed control situations in a random external environment. Particular individual KB's of a fuzzy controller are received with the help of the soft computing optimizer for given control situations and are performed in accordance with the design technology. In particular, based on a comparison of simulation results, it was shown that for sufficiently wide range of variation of parameters characterizing a given control situation, the KB optimizer yields an essential gain (compared with other software tools) in order to achieve the required robustness level of KB's. Other industrial tools for forming KB, such as the FNN ANFIS (built-in module in the Matlab simulation system) or AFM (an ST Microelectronics development), etc. have an increased sensitivity to the variation of parameters (characterizing a given control situation) compared with the KB optimizer tools and result in the loss of control robustness. As a result, in fixed control situations, fuzzy controllers with KB (designed with the help of the KB optimizer) have improved robustness, and the corresponding control laws contain less redundant information and thus are used as an input signal for quantum fuzzy inference (in accordance with the developed technology of designing robust KB).

It is worth noting that the presence of redundant information in control laws is the physical reality, which takes place because of the use in the processes of KB optimization of a random choice in the form of genetic algorithms. As well as it follows from the laws of information theory on the necessity of redundancy presence in unreliable data transmission channels with noise. This is the inevitable cost of the possibility to obtain a solution of the problem of optimal control of an essentially nonlinear CO in the conditions of uncertainty in the source information and the multi-objective nature of the optimization conditions.

In the case of an unpredicted control situation, the additional information redundancy in the control laws of the fuzzy controllers arises as the total result of the inadequate response of the CO (in the form of a new control error) and of the logically incorrect interpretation of the initialization of the corresponding production rules in the KB used by fuzzy controllers (trained only on given control situations).

5. The model of quantum fuzzy inference is a new type of the quantum search algorithm on the generalized space of structured data and, based on the methods of quantum computing theory it allows one to solve efficiently control problems that could not be solved earlier at the classical level. The developed approach is first applied in the theory and practice of intelligent control systems. In the proposed model of the quantum algorithm for quantum fuzzy inference the following actions are realized: (1) the results of fuzzy inference are processed for each independent fuzzy controller; (2) based on the methods of quantum information theory, valuable quantum information hidden in independent (individual) knowledge bases is extracted; and (3) in on-line, the generalized output robust control signal is designed in all sets of KB of the fuzzy controller.

In this case, the output signal of quantum fuzzy inference 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 very important characteristic of control quality. 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.

Now it is obvious that new sophisticated technologies must be considered and developed. Our quantum control algorithm of KB self-organization is based on special form of *quantum fuzzy inference* relative to quantum knowledge extraction from a few of KB designed by SC Optimizer tools. We are described the fundamental structure of quantum fuzzy inference and its software toolkit in the processes of KB design of robust self-organized fuzzy controllers in on-line. In particular, the functional organization of the system for simulating robust KB for fuzzy controllers that allows one to improve the efficiency of applying quantum fuzzy inference is presented.

6. The structure design of robust advanced control systems for unpredicted control situations is the corner stone of modern control theory and systems. The degree to which a control system deals successfully with above difficulties depends on the *intelligent* level of advanced control system. We will to solve the algorithmic complexity problems in advanced control system design with *unconventional sophisticated* methods of computational intelligence. The theoretical and applied roles of unconventional methods of computational intelligence in design processes of robust intelligent control systems are the following:

- The *first* theoretical purpose of the Quantum & Soft Computational Intelligence is the development of the background platform for the design of Integrated Fuzzy Intelligent Control Systems. Quantum Computational Intelligence implements basically a hierarchical quantum strategy of decision making patterned after the soft computing applications. In the important particular case, computational complexity problems in advanced control (unsolved principally by classical algorithms) are solved. For example, the design of a global robustness of advanced control system in unpredicted control situations is achieved owing to application of on-line quantum strategy of decision making relative to quantum knowledge. In advanced control system the achievement of this result with classical random search and adaptive learning algorithms is impossible.
- The *second* theoretical and applied purposes are the *know-how* implementation of the following control performance: (i) ensure the requested level of intelligent control robustness in unpredicted control situations with KB self-organization using the min-entropy principle of quantum knowledge; and (ii) support the reliability of advanced control systems in conditions of industrial disturbances with optimal thermodynamic trade-off between stability, controllability and robustness. Quantum control algorithm of KB self-organization that has developed for the task solution in item (i) is the background for the industrial applications of the optimal trade-off solutions in item (ii).
- The *third* applied purpose is a development of flexible Toolkit which can be used on problems that, generally speaking, involve the design of robust wise intelligent control in uncertain complex data and unpredicted control situations. Toolkit has programmable realization on classical computer including sophisticated fast algorithms simulation of quantum algorithms with optimal spatio-temporal computational complexity.
- The *fourth* applied purpose is the design principle realization of robust intelligent control: *Development of industrial wise intelligent controllers with physically realized simple structure for complex control objects in unpredicted control situations*.

The ultimate applications of quantum control strategies may include CO as smart macro- and micro-electromechanical systems, intelligent sensor systems (with compressing of redundant data information processing and advanced decision making), intelligent robotics and mechatronics, quantum informatics, computer science, AI security communication and information systems, including quantum algorithm modeling system for robust intelligent control design in nanotechnologies.

Background for the realization of abovementioned goals and industrial applications is the R&D results of our information design technology.

7. As mentioned above, modern CO are complex dynamic systems that characterized by information uncertainty of model structures and control goals, a high degree of freedom and essential nonlinearities, instability, distributed sensors and actuators, high level of noise, abrupt jump changes in structure and dynamics, and so on. It is the typical information resources of unpredicted control situations. Sophisticated control technologies based on new types of unconventional methods in computational intelligence has promoted automatic robust control to be at more and higher intelligent level.

The scientific background of R&D strategy was the following:

- Unconventional methods in Computational Intelligence
- Applied advanced Soft computing and Stochastic fuzzy modeling with customer constraints
- Quantum computing and quantum algorithms (operators) with a new intelligence measure
- Quantum fuzzy inference model relative to quantum knowledge extraction and self-organization
- Robust intelligent fuzzy control based on mixed classical and quantum strategies of decision making

Therefore, the main problem in intelligent control systems design is the following: how to introduce *self-learning*, *self-adaptation* and *self-organizing capabilities* into the structure of control process that enhanced robustness of developed advanced control system.

8. One of the main tasks of modern control theory is to develop and design automatic control systems that meet the three main requirements: *stability*, *controllability*, and *robustness*. The listed quality criteria ensure the required accuracy of control and reliability of operation of the CO under the conditions of incomplete information about the external perturbations and under noise in the measurement and control channels, uncertainty in either the structure or parameters of the CO, or under limited possibility of a formalized description of the control goal.

These problems are solved on the basic of developed information design technology of KB self-organization and a new computational intelligence methodology relative to quantum knowledge extraction.

Figure 1 show the main steps of our information design technology.

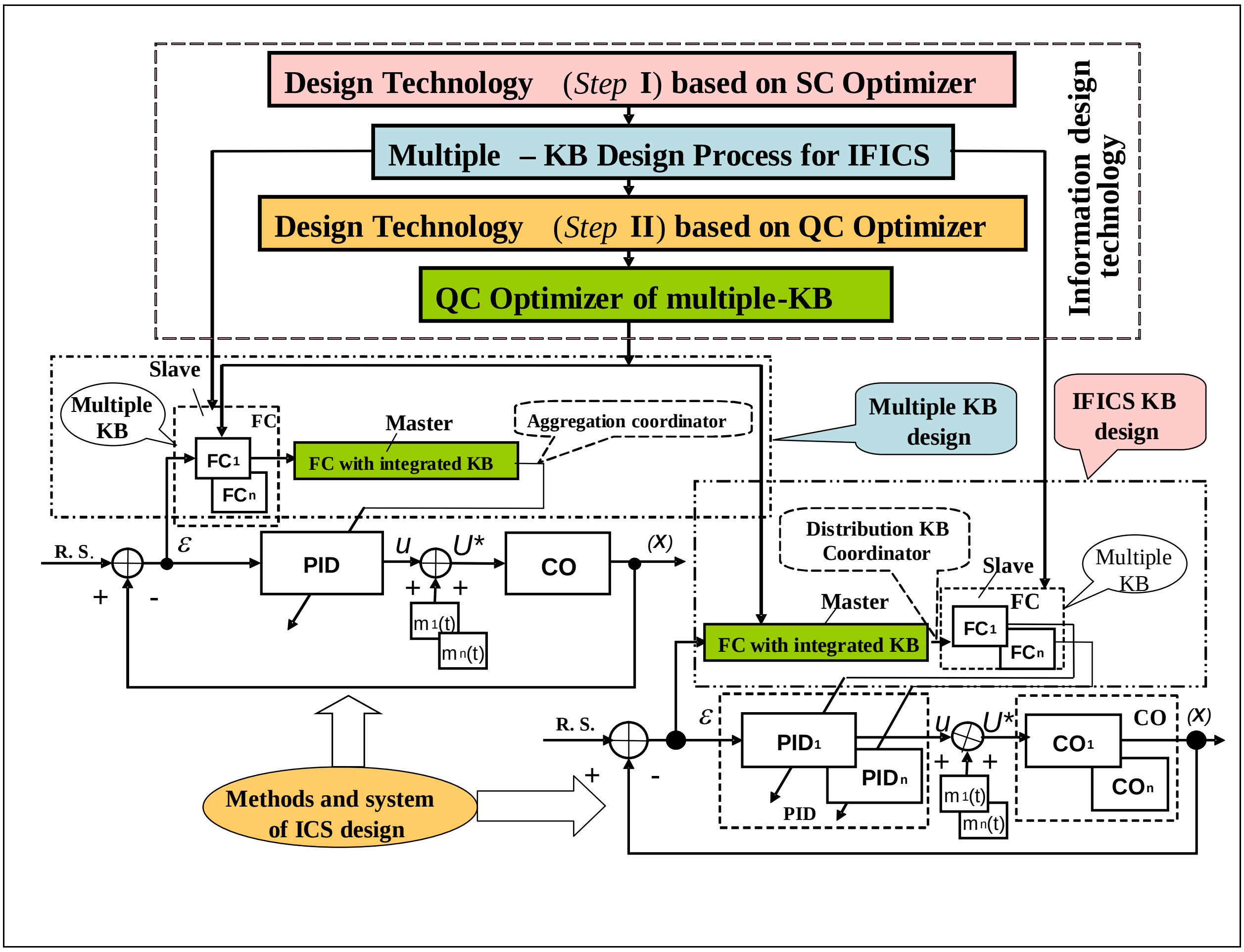


Figure 1: *Structure of information design technology of IFICS*

Figure 2 show physical sources of unpredicted control situations for systems in Figure 1.

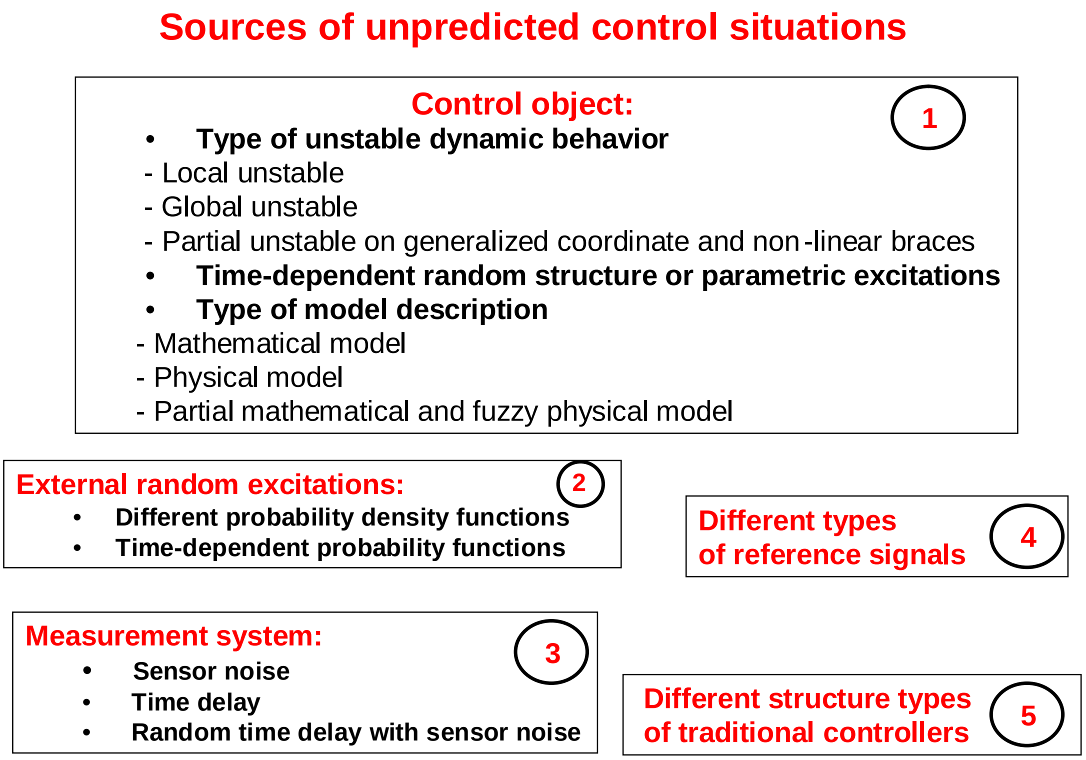


Figure 2: *Physical sources of unpredicted control situations*

Design principle of robust KB for quantum self-organized fuzzy controllers is shown in Figure 3.

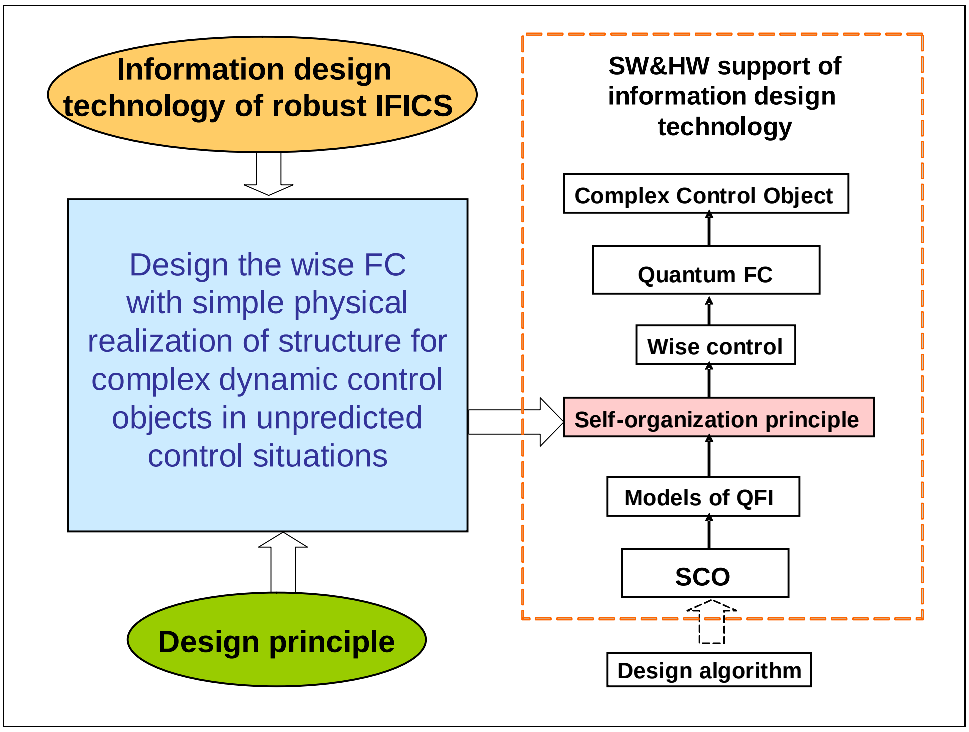
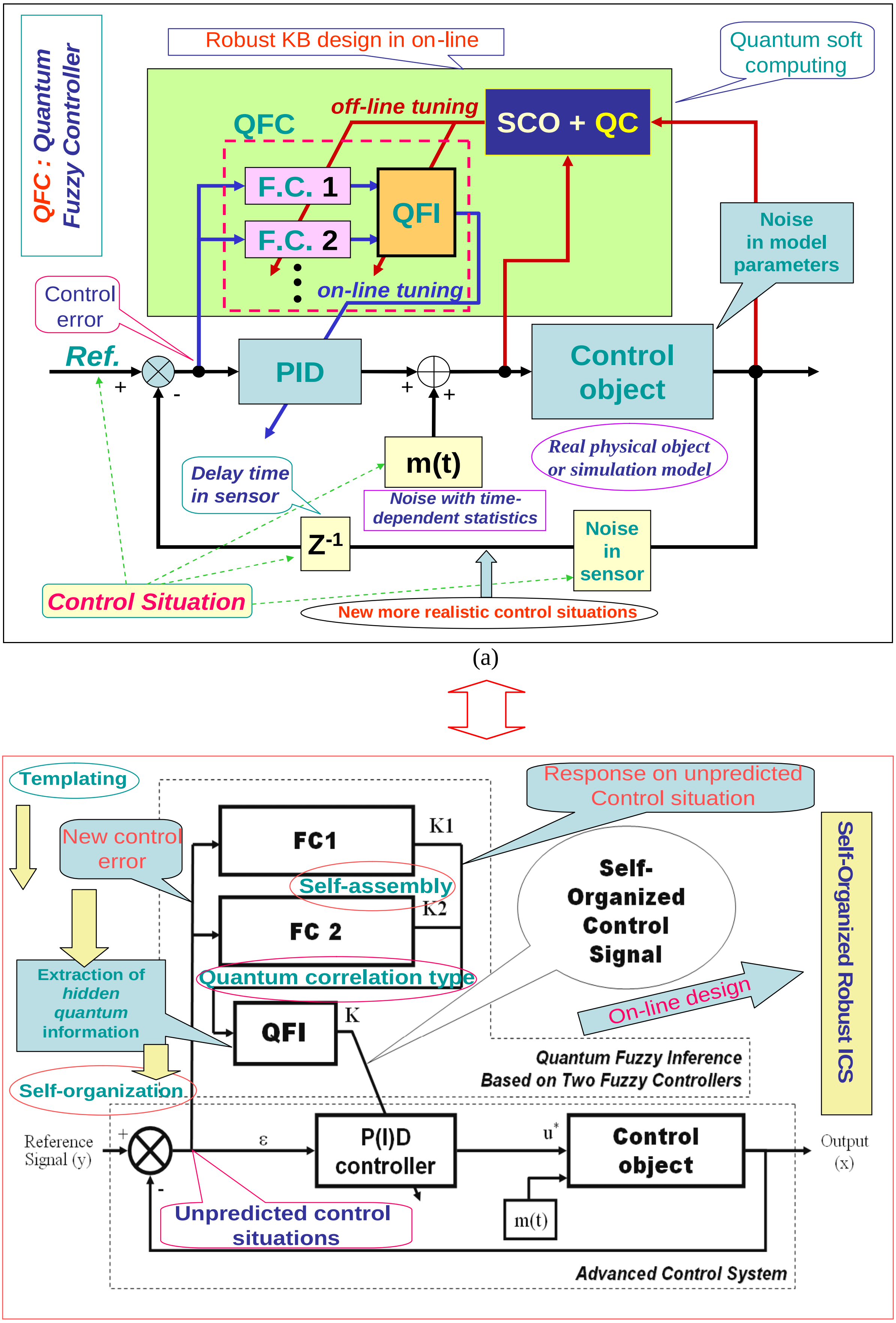


Figure 3: *Design principle of robust KB for quantum self-organized fuzzy controllers*

Figure 4 show the equivalent structures of intelligent control systems that realize the self-organization principle of robust KB in unpredicted control situations.



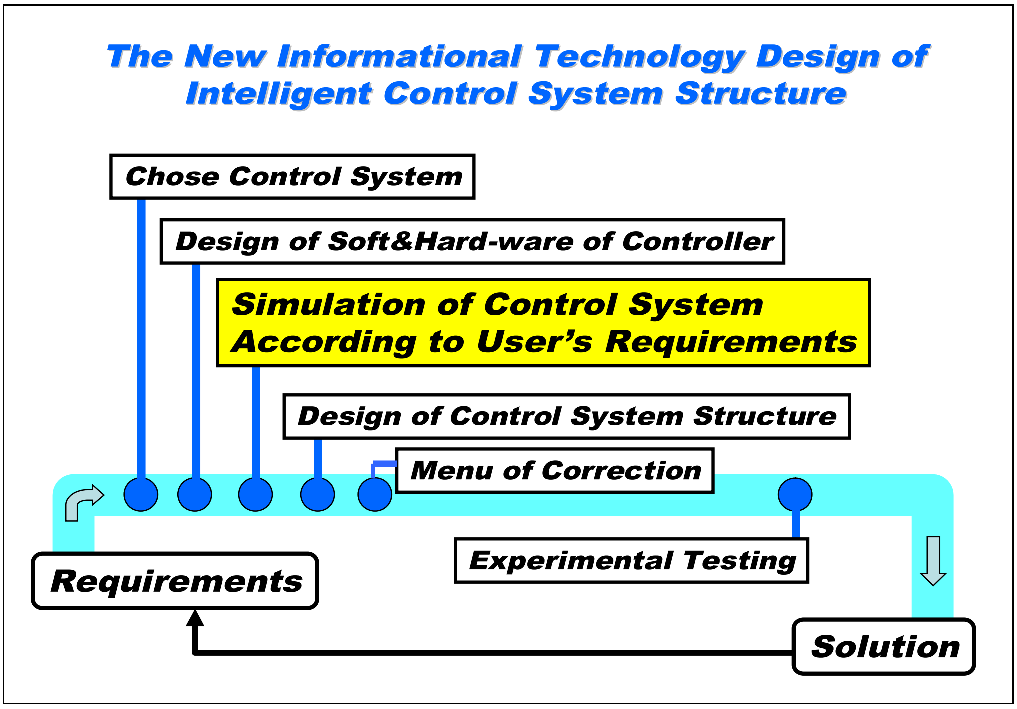
(a)

(b)

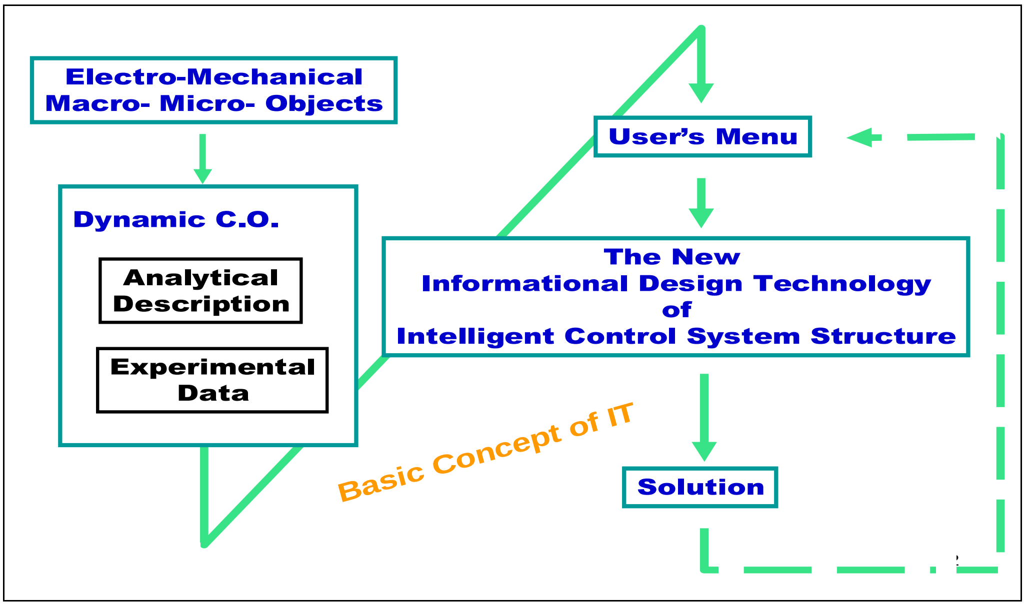
Figure 4: *Two equivalent structures of self-organized intelligent control system*

In particular *important case*, with the structure in Figure 4 the multi-objective problem can be solved using the decomposition method of multi-criteria vector as the distribution its component between different fuzzy controllers. The number of components in multi-objective vector-criterion is equivalent to the number of corresponding fuzzy controllers. The learning and KB design of these fuzzy controllers is realized with soft computing optimizer for concrete control situations using the single criteria as the fitness function of genetic algorithm for design the teaching signal of corresponding fuzzy controller. For this case, the output responses of fuzzy controllers that are learning with the different single criterion of optimization are aggregated as the solution of multi-objective problem in robust output of quantum fuzzy inference.

Figures 5 and 6 show the structure and path-way of robust KB design processes with self-organization properties.



Figures 5: *The structure of design processes*



Figures 6: *The path-way of design processes*

Figure 7 show the main menu of information design technology of robust intelligent control systems based on three types (soft computing, quantum computing, and quantum computing) of KB optimizers according to path-way of design processes in Figure 6.

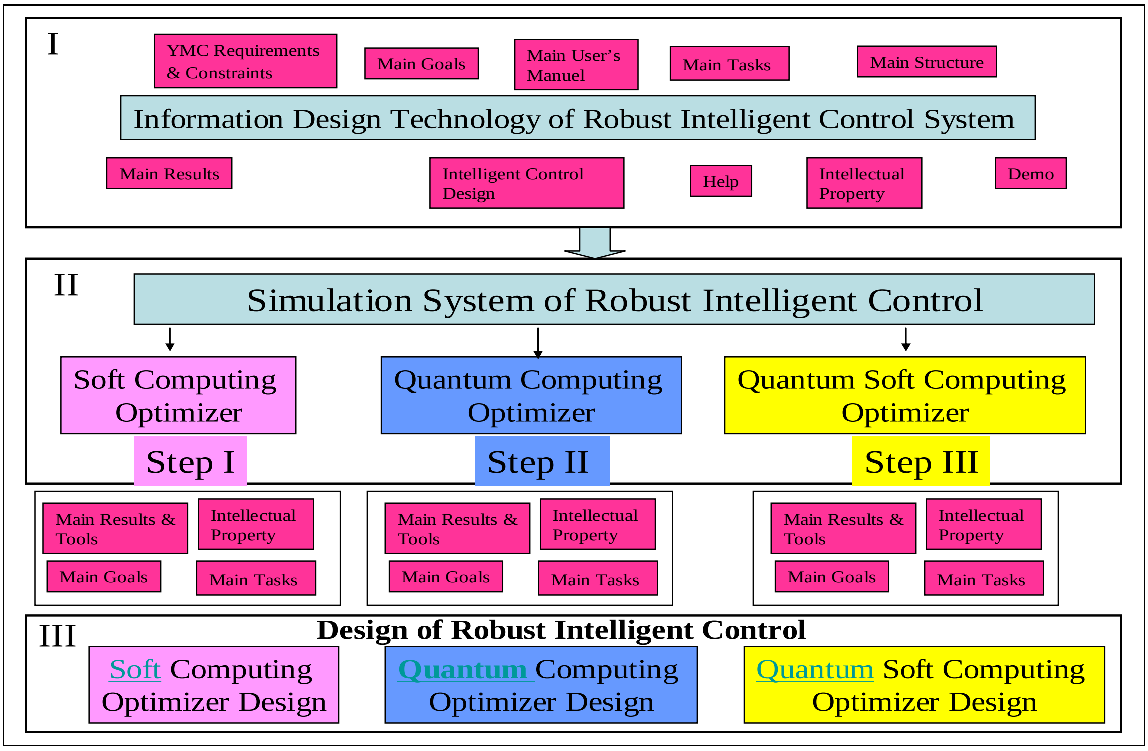


Figure 7: *The main menu of information design technology of robust intelligent control systems*

We are concentrated our attention on multiple-KB design process (see, Figure 1). QFI system is a QA 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 on-line output of QFI is an optimal robust control signal (see, Figure 8), which combines best features of the each independent FC outputs (*self-organization principle*).

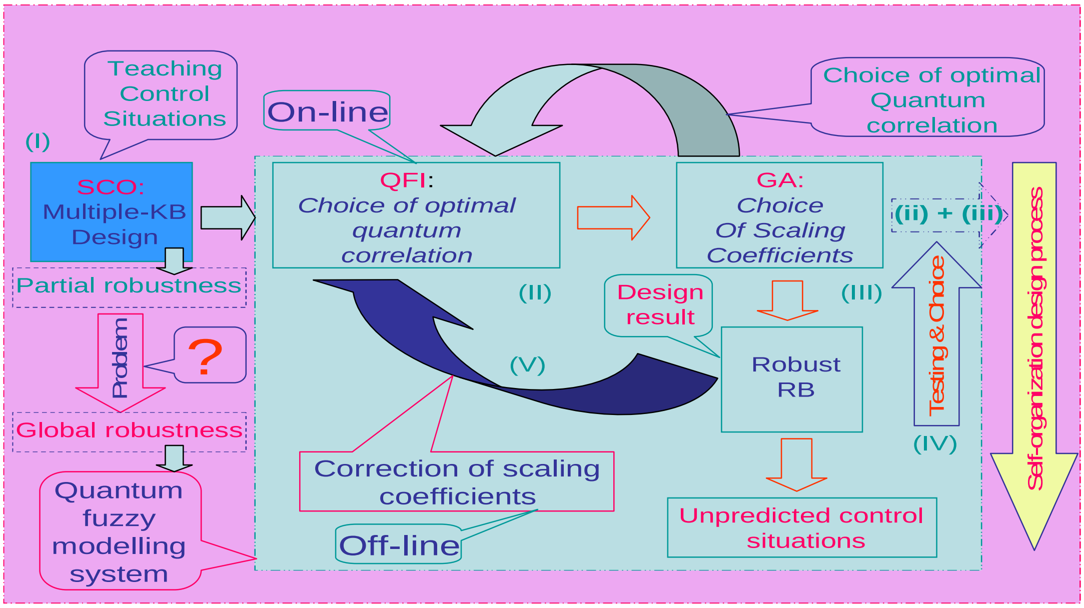


Figure 8: *Main steps of robust KB design technology*

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. Using the simulation results with QFI a new design principle "*Simple wise control of complex control objects*" was demonstrated.

9. The self-organized systems have different physical nature but can be described in general form based on developed quantum control algorithm of self-organization (see in details, Self-organization, pdf). Analysis of self-organization models gives us the following results. Models of self-organization are included natural *quantum* effects and based on the following *information-thermodynamic* concepts: (i) macro- and micro-level interactions with information exchange (in Agent Based Models micro-level is the communication space where the inter-agent messages are exchange and is explained by increased entropy on a micro-level); (ii) communication and information transport on micro-level ("quantum mirage" in quantum corrals); (iii) different types of quantum spin correlation that design different structure in self-organization (quantum dot); (iv) coordination control (swam-bot and snake-bot).

Natural evolution processes are based on the following steps: (i) templating; (iii) self-assembling; and (iii) self-organization.

According quantum computing theory in general form every QA includes the following unitary quantum operators: (i) superposition; (ii) entanglement (quantum oracle); (iii) interference. Measurement is the fourth classical operator. [It is irreversible operator and is used for measurement of computation results].

Quantum control algorithm of self-organization that developed below (see, Figure 9) is based on QFI models.

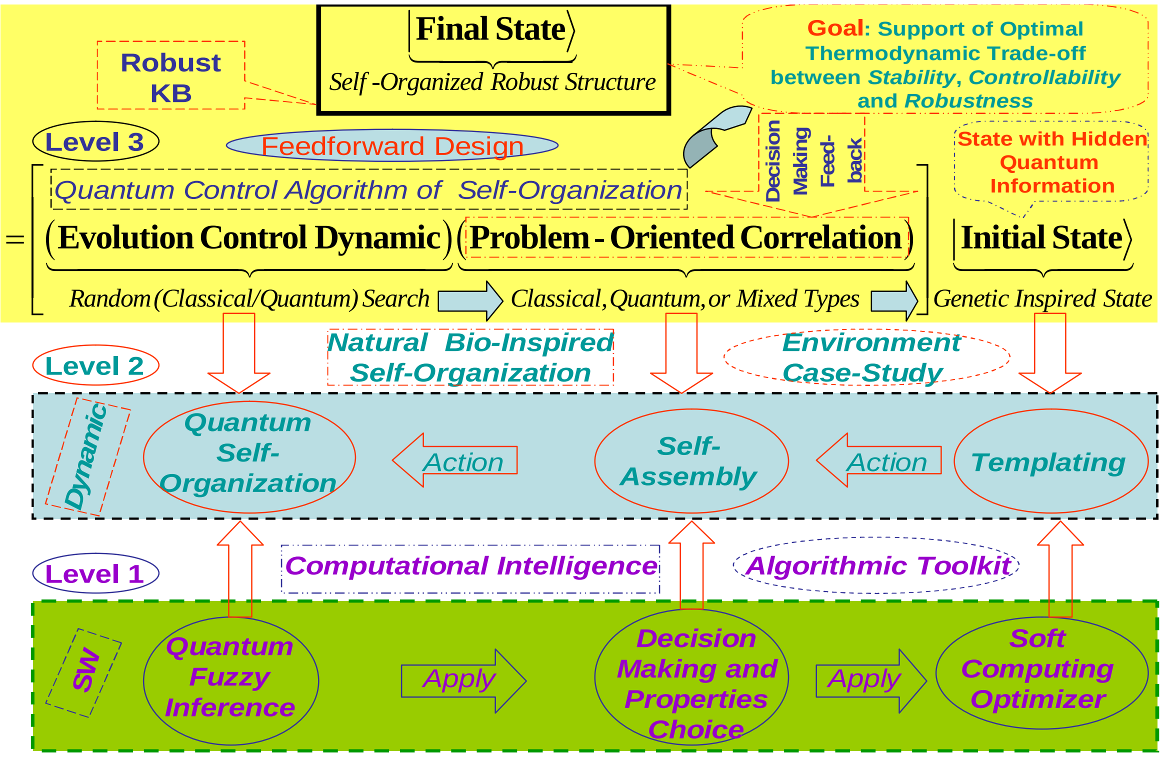


Figure 9: *General structure of quantum control algorithm of KB self-organization*

QFI includes these concepts of self-organization and has realized by corresponding quantum operators. Structure of QFI that realize the self-organization process is developed. QFI is one of possible realization of quantum control algorithm of self-organization that includes all of these features: (i) superposition; (ii) selection of quantum correlation types; (iii) information transport and quantum oracle; and (iv) interference. With *superposition* is realized *templating* operation, and based on macro- and micro-level interactions with information exchange of active agents.

Selection of quantum correlation type organize *self-assembling* using power source of communication and information transport on micro-level. In this case the type of correlation defines the level of *robustness* in designed KB of fuzzy controller. *Quantum oracle* calculates intelligent quantum state that includes the most important (value) information transport for *coordination* control. *Interference* is used for extraction the results of coordination control and design in on-line robust KB.

Figure 10 show the structure of QFI algorithm.

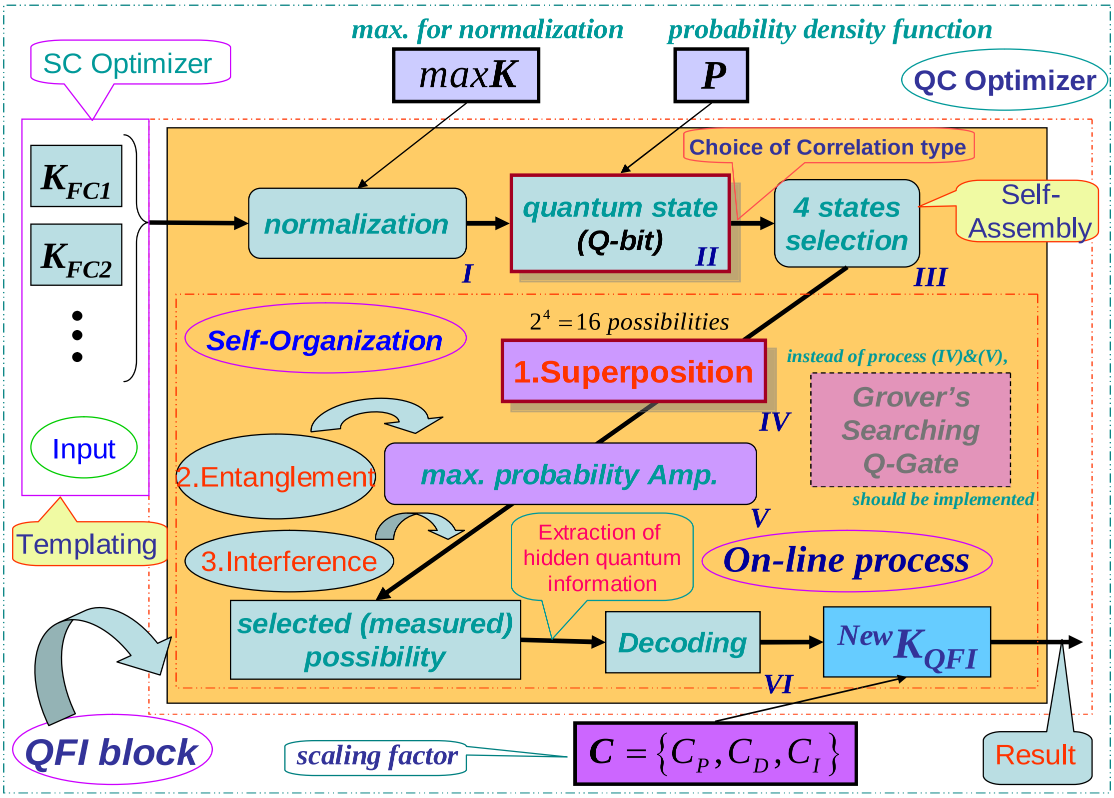


Figure 10: *Structure of QFI algorithm*

The developed QA of self-organization is applied to design of robust KB of fuzzy controller in unpredicted control situations. Main operations of developed QA and concrete examples of QFI applications are described (see in details, RobustICS, pdf).

9. Example. *QFI application in robust KB design*: *Intelligent control of "cart - pole" system*. Let us consider fuzzy control problem of "*Cart - Pole*" system as intelligent control Benchmark. This system is described by the following equation of motion:

$$\ddot{\theta} = \frac{g\sin\theta + \cos\theta\left(\frac{+(u+\xi(t)) + \{+a_1\dot{z} + a_2 z\} - ml\dot{\theta}^2\sin\theta}{M+m}\right) - k\dot{\theta}}{l\left(\frac{4}{3} - \frac{m\cos^2\theta}{M+m}\right)}, \tag{9.1a}$$

$$\ddot{z} = \frac{u + \xi(t) + \{-a_1\dot{z} - a_2 z\} + m\ell\left(\dot{\theta}^2\sin\theta - \ddot{\theta}\cos\theta\right)}{M+m}, \tag{9.1b}$$

where θ and z are generalized coordinates (angle of pole and position of cart, correspondingly); $u(t)$ is control force; and $\xi(t)$ is random excitation. The pendulum is planar and the cart moves under an applied horizontal force *u*, constituting the control, in a direction that lies in the plane of motion of the pendulum. The cart has mass *M*, the pendulum has mass *m* and the center of mass lies at distance *l* from the pivot (half the length of the pendulum). The position of the pendulum is measured relative to the position of the cart as the offset angle θ from the vertical up position.

Eq. (9.1) shows that considered system has two degree of freedom but it is possible control this system with *one* fuzzy controller that design optimal control force *u*. The "*cart-pole*" system has very complex dynamic. The stable state of considered system is depends from initial states and in this report is considered as a resource of *new unpredicted control situations*.

Figure 11 shows the advanced control system structure with resource of unpredicted control situations.

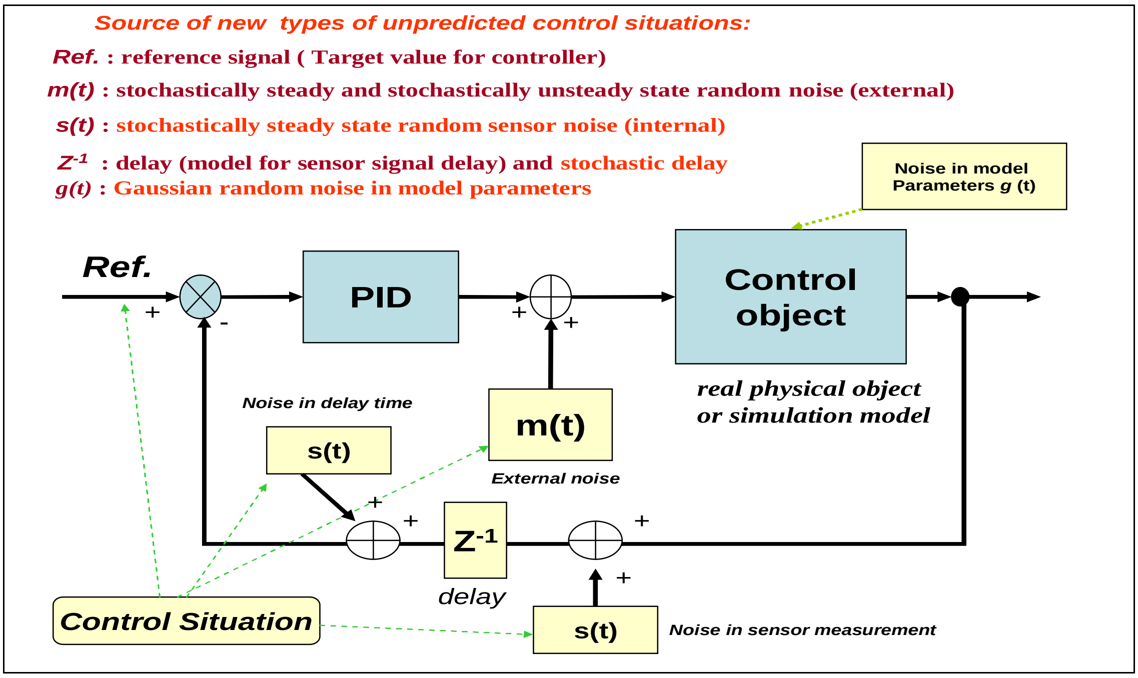


Figure 11: *Advanced control system with resource of unpredicted control situations*

Figure 12 shows MatLab Smulink model simulation of unpredicted situations for "*cart-pole*" system (9.1). Figure 13 shows control laws obtained as result of QFI in Figure 4 with scaling gains = [1 1 1] for pendulum control model without consideration cart position.

Let us consider now the problem of robust intelligent control design for system (9.1) in unpredicted situations according to structures on Figure 11 (see, Table 1).

Table1: *Unpredicted control situations*

New 1	New 2	New 3	New 4	New 5	New 6
S1 (*in legend*)	**S1***b* (*in legend*)	**S2***a* (*in legend*)	**S2***c* (*in legend*)	**S3***c* (*in legend*)	**S4** (*in legend*)
New Rayleigh noise as r4_1t200.matx Gain=1; Sensor noise Gain = 0.01; Delay = 0.003; TS-model parameters; TS initial conditions	New Rayleigh noise as r4_1t200matx Gain = 1; Sensor noise Gain = **0.015**; Delay = **0.004** ; TS-model parameters; TS initial conditions	New Rayleigh noise as r4_1t200matx Gain=1; Sensor noise Gain = 0.015 ; Delay=**0.003**; Model parameters (a1 = **0.08**); TS initial conditions	New Rayleigh noise as r4_1t200matx Gain = 1; Sensor noise Gain = 0.015 ; Delay = **0.004** ; Model parameters (a1 = **0.08; a2=4**);TS initial conditions	Uniform noise u3t200matx Gain = 0.8; Sensor noise Gain=0.01 ; Delay=0.003 ; Model parameters (a1 = **0.06; a2=3; k= 0.2**); TS initial conditions	Mixed noise r3_u3200matx Gain = 1; Sensor noise Gain = **0.02** ; Delay= **0.006** ; TS-model parameters; TS initial conditions are used

9.1. *Robust intelligent control of "cart-pole" system in unpredicted control situations*. Table 1 shows different types of unpredicted control situations for the system (9.1).

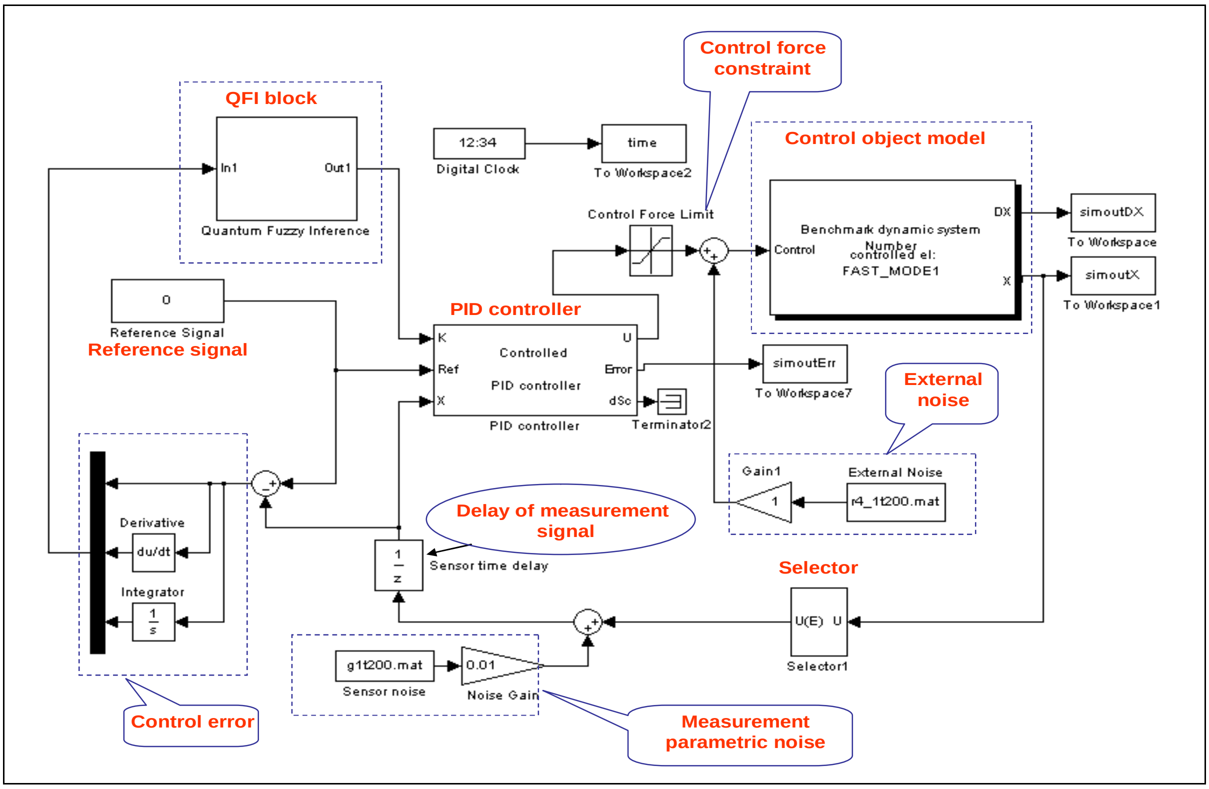


Figure 12: *MatLab Simulink model for simulation of intelligent control for system* (9.1) *in unpredicted control situations*

We will consider situation *New* 2 from Table 1 as example of a new unpredicted control situation. With SCO four KB for different types of noises $\xi(t)$ was designed (see, Figure 14).

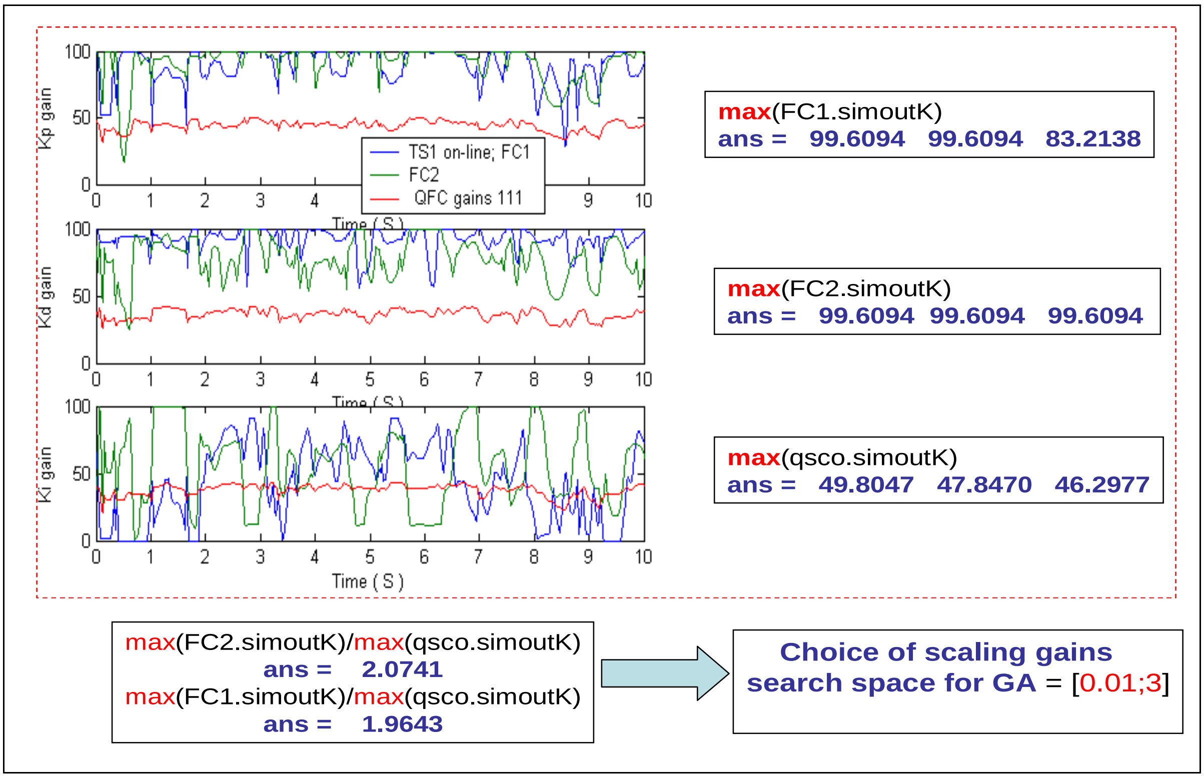


Figure 13: *Simulation results of control laws of fuzzy controller and quantum fuzzy controller*

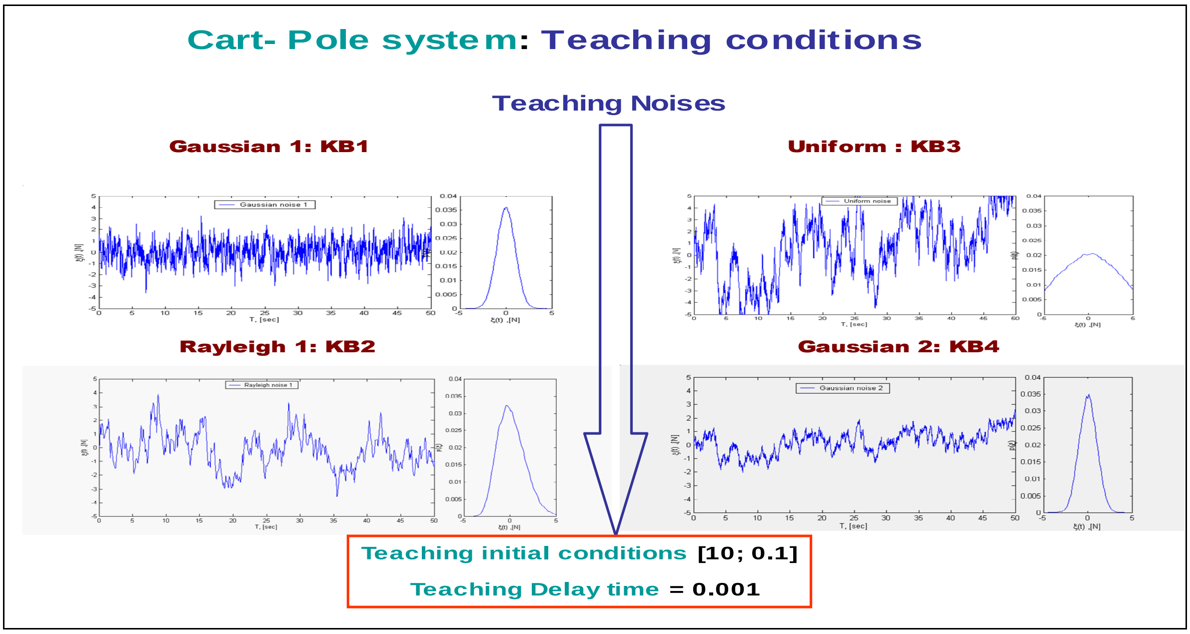


Figure 14: *Teaching conditions*

Figure 15 shows dynamic behavior of considered control system in new unpredicted control situation for cases with *two* (2KB) and *three* (3KB) KB in QFI.

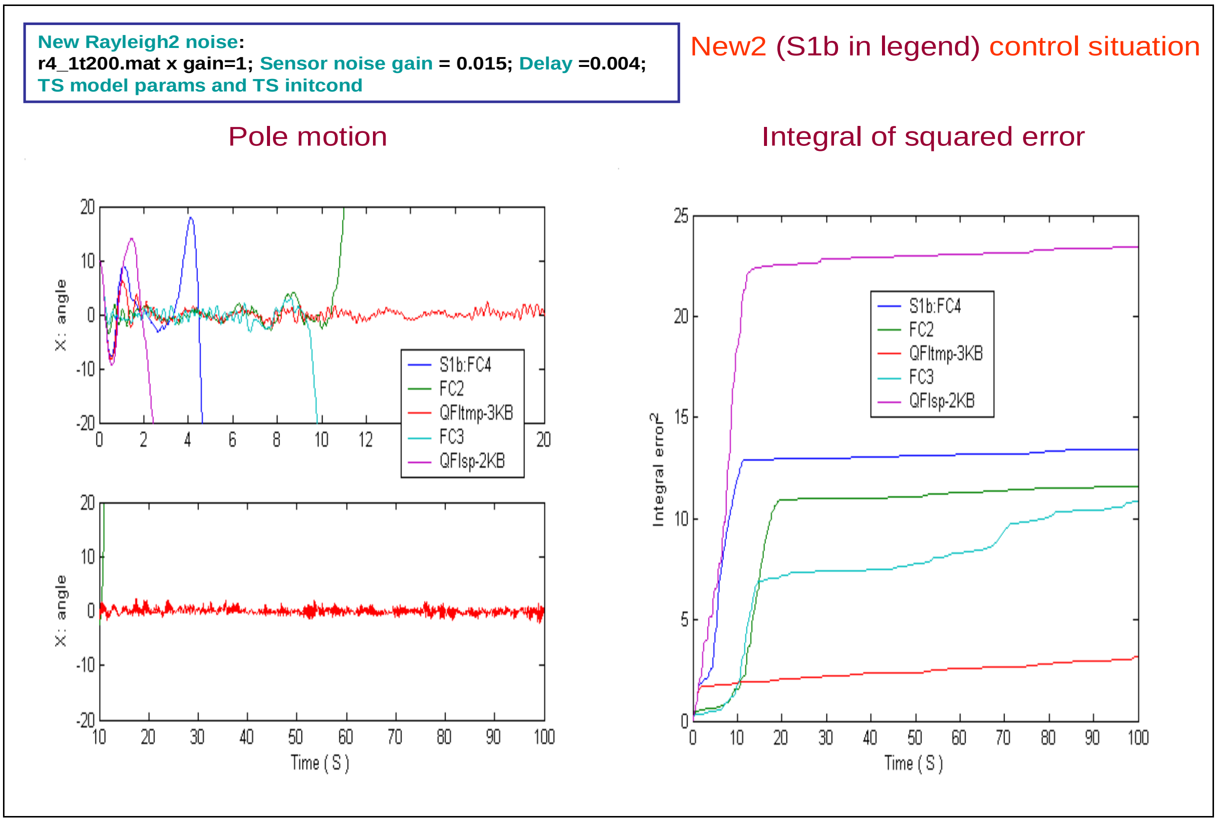
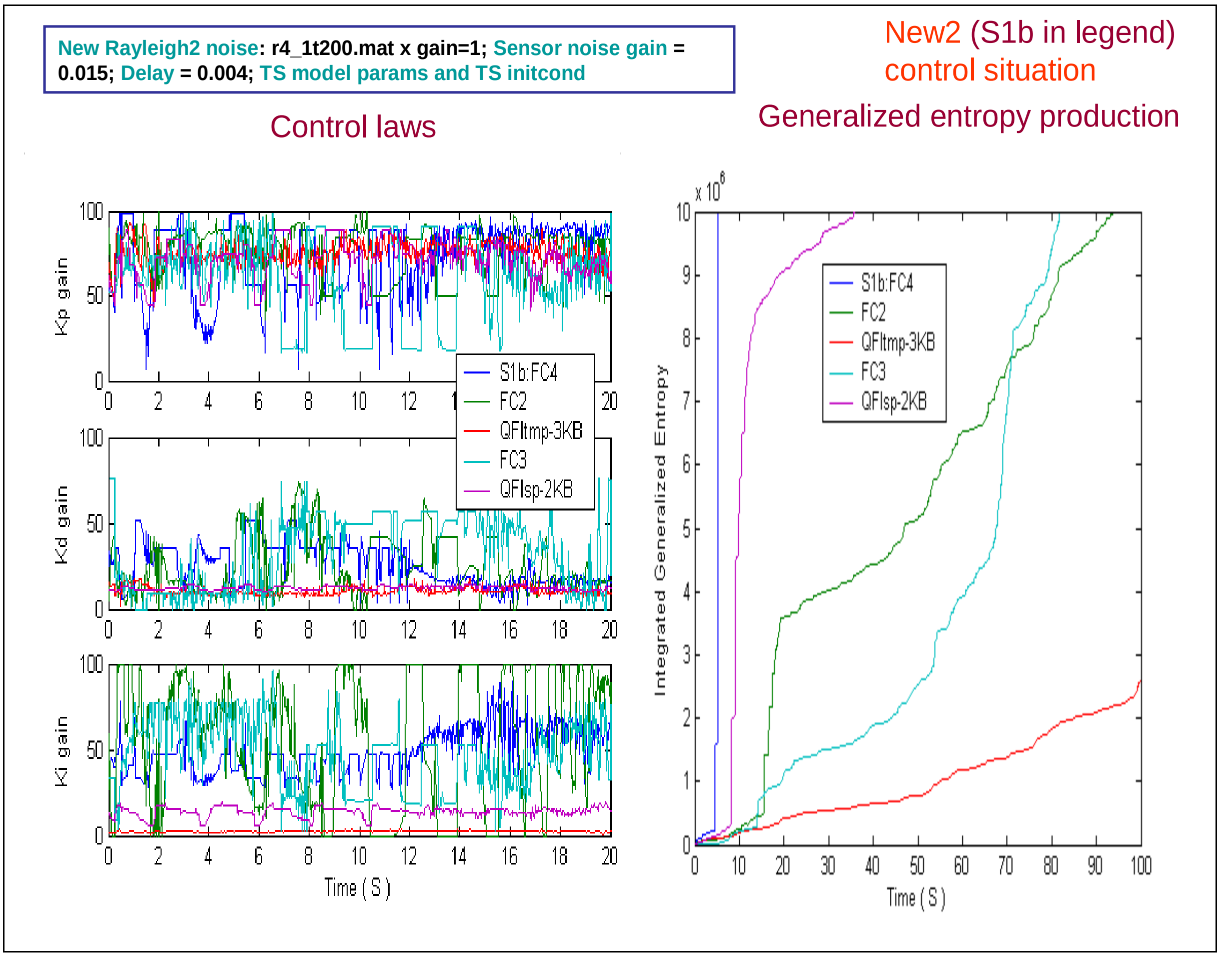


Figure 15: *Comparison of dynamic behavior of system* (9.1) *in new unpredicted control situation* (**New 2**) *for cases with two and three KB in QFI*

Figure 16 shows the results of simulation of control laws for coefficient gain schedule and loss of resource in considered intelligent control system (rate increasing of generalized entropy production).


New Rayleigh2 noise: r4_1t200.mat x gain=1; Sensor noise gain = 0.015; Delay = 0.004; TS model params and TS initcond

New2 (S1b in legend) control situation

Control laws

Generalized entropy production

Figure 16: *Results of simulation of control laws for coefficient gain schedule and loss of resource in considered intelligent control system* (*increasing of generalized entropy production*)

Results of simulation show that winner is **QFC** with minimum of generalized entropy production and robust KB designed from *three* individual KB controllers.

Thus QFI supports optimal *thermodynamic trade-off* between stability, controllability and robustness in self-organization process (from viewpoint of physical background of global robustness in intelligent control systems). Also important the new result for design of advanced control system that all other controllers (FC1, FC2, FC3, FC4 and QFC with KB designed from *two* KB) are failed but **QFC** (based on KB of these controllers) is demonstrated increasing robustness. It is the new *Parrondo*’s game effect in design of intelligent control systems.

Conclusions

- QFI model supports the self-organization process in design technology of robust KB with optimal *thermodynamic trade-off* between *stability*, *controllability* and *robustness* in intelligent control processes of unpredicted control situations.
- Structure of SW-support as QFI toolkit is developed.
- Effectiveness of QMS is demonstrated with Benchmark simulation results.
- Application of QFI to design of robust KB in fuzzy PID-controller is described on example of robust behavior design in global unstable and local non-linear control objects.
- Quantum fuzzy controller (QFC) based on QFI is demonstrated the increasing robustness in complex unpredicted control situations.

- For global unstable control object *robust* QFC is designed from three fuzzy controllers that are *non-robust* in unpredicted control situation.
- New design effect (the new *Parrondo*'s game effect) in advanced control theory and design technology of intelligent control system is showed.
- Effectiveness of quantum control application with new design principle "*Simple wise controller for complex control objects*" in classical control systems is demonstrated.

10. Main publications with the free access are the following:

- L.V. Litvintseva, I.S. Ulyanov, K. Takahashi, S.V. Ulyanov and T. Hagiwara, "*Soft computing optimizer for intelligent control system design*: *The structure and applications*," **Systemics, Cybernetics and Informatics** (USA), 2003, Vol. 1, № 5, pp. 91 – 96. (pdf)
- L. V. Litvintseva, S. V. Ulyanov and S. S. Ulyanov, "*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*," **J. of Computer and Systems Sciences Intern**., 2006, Vol. 45, № 5, pp. 744 – 771. (pdf)
- L.V. Litvintseva, K. Takahashi, I.S. Ulyanov and S.S. Ulyanov, *Intelligent robust control design based on new types of computations*. **Part 1**: *New soft computing technology of KB-design Benchmarks of smart control simulation for nonlinear dynamic systems*. Università degli Studi di Milano, Polo Didattico e di Ricerca di Crema Publ., Italy, Vol. 60, 2004. (pdf)
- L. V. Litvintseva, I.S. Ulyanov, S. V. Ulyanov and S. S. Ulyanov, "*Quantum fuzzy inference for knowledge base design in robust intelligent controllers*," **J. of Computer and Systems Sciences Intern**., 2007, Vol. 46, № 6, pp. 908 – 961. (pdf)
- S. V. Ulyanov, L. V. Litvintseva, K. Takahashi and S. S. Ulyanov, "*Self-organization principle and robust wise control design based on quantum fuzzy inference*," In: **Proceedings of International Conference** (ICSCCW' 2005), Antalya, Turkey, 2005, pp. 54 – 80. (pdf)
- L. V. Litvintseva, S. V. Ulyanov, K. Takahashi and T. Hagiwara, "*Design of self-organized robust wise control systems based on quantum fuzzy inference*," In: **Proceedings of World Automation Congress** (WAC'2006) - *Soft Computing with Industrial Applications* (ISSCI'2006). Budapest, Hungary, Vol. 5, 2006. (pdf)
- S.V. Ulyanov, L.V. Litvintseva and S.S. Ulyanov, **"***Quantum swarm model of self-organization process based on quantum fuzzy inference and robust wise control design*," In: **Proc. 7th International Conference on Application of Fuzzy Systems and Soft Computing** (ICAFS'2006), Siegen, Germany, 2006, pp. 10 – 19. (pdf)
- S.V. Ulyanov, L.V. Litvintseva, I.S. Ulyanov and S.S. Ulyanov, "*Design technology of robust KB for integrated fuzzy intelligent control based on quantum fuzzy inference: Inverted pendulum as benchmark of quantum fuzzy control in unpredicted control situations*," In: **Proceedings 4th Intern. Conference on Soft Computing, Computing with Words and Perceptions in System Analysis, Decision and Control** (ICSCCW' 2007). Antalya, Turkey, 2007. pp. 218 – 237. (pdf)
- S.V. Ulyanov, "*Quantum control algorithm of robust KB self-organization process based on quantum fuzzy inference*," In: **Proceedings 4th Intern. Conference on Soft Computing, Computing with Words and Perceptions in System Analysis, Decision and Control** (ICSCCW' 2007). Antalya, Turkey, 2007. pp. 27 – 86. (pdf)

11. Detail description of our technology engineering platform is given in the following Chapter 6 of book's publication (see, Section Publications, Lecture Notes, Vol. 82 (pdf)):

Chapter 6: *Information design technology of integrated fuzzy intelligent control systems in unpredicted control situations based on quantum control algorithm of self-organization*

Content

Introduction: *Role of unconventional computational intelligence in design technology of robust advanced control systems at unpredicted control situations*

Part 1: *Theoretical and Applied Background of Information Design Technology*

- Structure analysis of automatic control systems relative to knowledge extraction and action
- Interrelations between of intelligent control performance and computational intelligence
- New physical law of robust intelligent control: Thermodynamic trade-off between stability, controllability and robustness
- Stochastic fuzzy simulation system and soft computing design of robust knowledge base in individual (multiple) control situations
- Quantum control algorithm of self-organization for the design of robust knowledge base in unpredicted control situations
- Min-entropy principle of quantum knowledge extraction from classical knowledge sources
- Structure of quantum fuzzy inference based on the min-entropy principle of quantum knowledge

Part 2: *Structure of Information Design Technology*

- Principles and structure of robust control design process
- Steps of design process
- Soft computing optimizer in design process of robust multiple knowledge bases
- Quantum computing optimizer in self-organization design process of robust knowledge base in unpredicted control situations
- Software menu of Information Design Technology
- Computer Aided Engineering System based on Information Design Technology
- Examples of Benchmark simulation using SW of Soft & Quantum Computing Optimizers

Appendix 1: Physical models of self-organization and its main characteristics
Appendix 2: Models of quantum fuzzy inference and its main characteristics
Appendix 3: Background of min-entropy principle relative to quantum knowledge