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

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Abstract Toolkit applications as *Quantum Fuzzy Modeling System* (QFMS) and SW-support of robust Integrated Fuzzy Intelligent Control System (IFICS) design in unpredicted control situations are discussed from *Intelligent System of System Engineering (*SoSE*)* viewpoint. Design process of quantum control algorithms is based on Quantum Fuzzy Inference (QFI) model. QFI is a new quantum algorithm (QA) that based on combination of corresponding unitary quantum operators. QFI supports the self-organization process in design technology of robust KB. From viewpoint of computer science, QA of QFI model plays the role of the information-algorithmic and SW-platform support of self-organization design process. From viewpoint of physical background of global robustness effect in advanced control systems, QFI supports optimal *thermodynamic trade-off* between stability, controllability and robustness in self-organization process of many parts of *integrated control system*. The dominant role of self-organization in robust knowledge base (KB) design of intelligent fuzzy controllers (FC) for unpredicted control situations is demonstrated. Structure of SW-support as QFI tool is described. Effectiveness of QMS is demonstrated with Benchmark simulation results. Application of QFI to design of robust KB in fuzzy PID-controller is showed on example of robust behavior design in global unstable non-linear control objects. Quantum fuzzy controller (QFC) based on QFI is showed the increasing robustness in complex unpredicted control situations. In this case surprisingly that *robust* QFC is designed from *three* fuzzy controllers that are *non-robust* in unpredicted control situation. It is new effect in design of advanced control and in design technology of intelligent control system.

Key words: *Quantum modeling*, *self-organization*, *quantum control algorithm*, *quantum fuzzy inference* (*QFI*), *intelligent control*, *robust KB*, *nonlinear unstable control object*

1. Introduction: Design technology of robust KB based on QFI

For complex and ill-defined dynamic systems with many sub-systems that are not easily controlled by traditional control systems (such as P-[I]-D controllers) - especially in the presence of stochastic noises - the *System of Systems Engineering* methodology provides fuzzy controllers (FC) as one of alternative way of control systems design. Since their appearance, FC 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].

The complexity of problem increased for the case of integrated control systems with the necessity to design the *coordinate control* of many sub-systems as control objects with different optimization criteria [3]. 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, sensor's noises or delay, etc.). 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 [4 - 6]:

Q: *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 (see, below and [6, 7]). In this report we are proposed a solution of such kind of generalization problems based on developed design technology of Integrated Fuzzy Intelligent Control System (IFICS).

We are introduced a self-organized design process of KB-FC that supported by the *Quantum Fuzzy Inference* (QFI). Model of QFI is based on Quantum Soft Computing [5] and Self-Organization (from Synergetic and Engineering Cybernetics) ideas [6, 7].

Figure 1 shows multiple-KB design technology of robust IFICS.

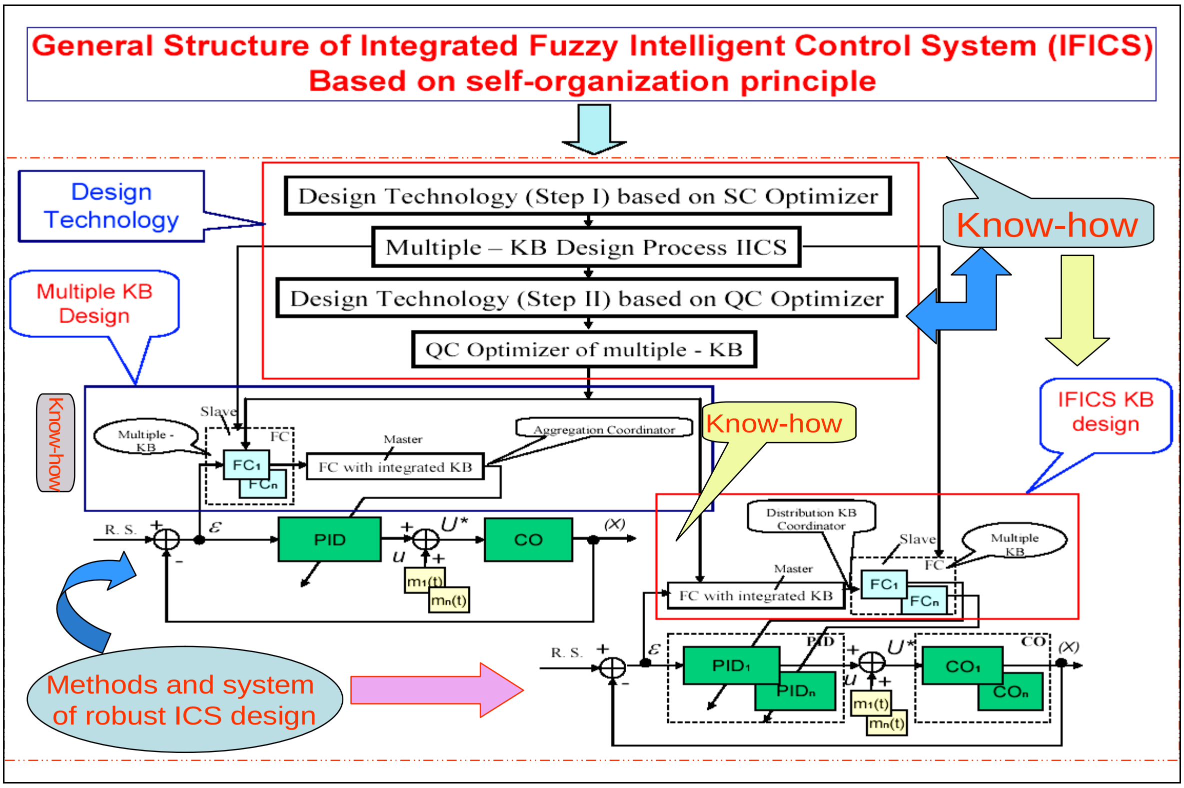


Figure 1: *Multiple-KB design technology of robust IFICS*

Remark. Important computer-scientific challenges for quantum information science are to discover efficient quantum algorithms (QAs) for interesting algorithmic problems and to understand the fundamental capabilities and limitations of quantum computation in comparison to those of classical computation [8, 9]. The bulk of this report is concerned with the problem of discovering a new *quantum robust control* algorithm for *classical* control objects. A new quantum fuzzy modeling system (QFMS) with built-in SW-support toolkit based on a new computational intelligence paradigm as quantum computing technology for design of self-organization processes for robust KB in unpredicted control situations is developed in [9]. Computational intelligence is one of an effective toolkit for fuzzy modeling system in design technology of robust IFICS. In this report we are described SW structure and concrete examples of QFMS applications in design of robust KB in IFICS. For the demonstration the power of robust KB design technology based on a new QFI model we use as Benchmark the simulation of robust control of inverted pendulum with intelligent self-organized fuzzy PID-controllers. This technology based on multiple-KB design is the kernel of IFICS design technology (see, Figure 1).

Figure 2 shows main steps of robust multiple-KB design technology in intelligent control systems that include three steps as extraction, data processing and forming of objective knowledge in KB-box of fuzzy PID-controllers. Proposed QFI system consists of a few KB-FC's (multiple-KB), each of which is prepared for appropriate conditions of control object and excitations by Soft Computing Optimizer (SCO^{TM} [1, 2]).

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, which combines best features of the each independent FC outputs (*self-organization principle* [4, 6, 7]).

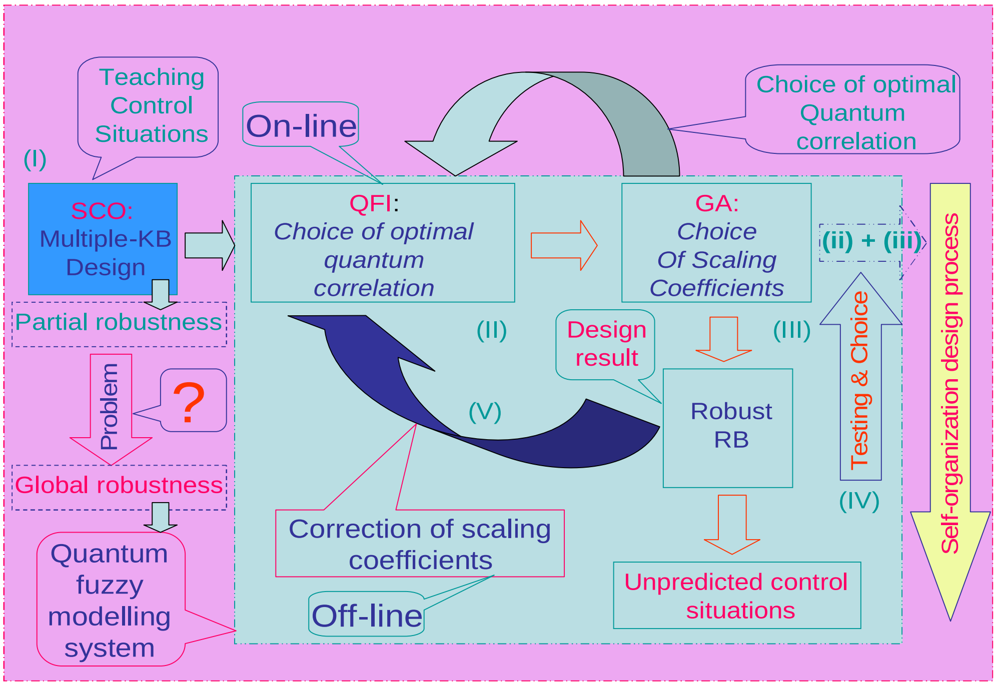


Figure 2: *Main steps of robust KB design technology*

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.

In this report we give briefly the introduction on soft computing tools for designing independent FC and then we will provide QFI methodology. The example of robust intelligent control simulation based on QFI is described. Using the simulation results with QFI a new design principle "*Simple wise control of complex control objects*" [4, 7, 9] is demonstrated.

2. SW support structure of QFI: Main block description

One of main problem in design process of robust intelligent FC is design of robust KB (KB-FC problem) [2, 10]. Many successful efforts were described in searching of solutions of robust KB design problem for concrete control objects with fixed conditions of control situation. Global robustness of this concrete KB is not achieved. Soft computing optimizer (SCO) is a new toolkit of computational intelligence based on soft computing technology [1, 10] as genetic algorithms (GA) and fuzzy neural networks (FNN). This toolkit is used for objective extraction of knowledge from dynamic behavior of complex ill-defined control object models and for design of robust KB in FC. This toolkit is based on a new type of *global intelligent feedback* [10] that can objectively extract the value information from dynamic behavior of control object and advanced controller. Information and physical criteria of control quality (*information-thermodynamic trade-off* [10] between stability, controllability and robustness) are used as fitness functions in GAs for the guarantee achievement of required level of control quality robustness. Optimization of control quality processes and required level of robustness are achieved on fixed space search of GA and depends from fitness function types. For fixed random environments (probability density functions of random environments are known) with SCO we can design robust KB for FC that does not loss robustness for many unpredicted control situations. But while random search of optimal solutions in SCO with GA created redundant information in control signals [9] the designed KB-FC can losses robustness in dramatically exchanging of control situations. Principal difficulties in searching of successful solution of this problem consist in developed toolkit of soft computing technology.

Remark. These effects are depended from fitness function's types and search space dimension of GA that are fixed before of solution searching process. Type of fitness function describes the quality of control process and can be objectively defined. Choice of dimension of search space is defined by expert and therefore it is subjective process. Both factors are strong constraints in optimization process of KB design. Robustness design of FC for unpredicted control situations can be defined as multi-objective optimization problem when robustness and choice of control fitness quality in KB-FC are depended from the description of individual unpredicted control situation. Thus in unpredicted control situations we have time-dependent vector-function criteria of control quality.

Problem: Toolkit of soft computing technology includes an algorithmically unsolved problem as constructive development of searching algorithm for design process of FC global robustness (problem of *Kolmogorov*'s algorithmic complexity of finite objects [11]).

Solution of problem. For solution of this problem we use finite number of robust KB (designed with SCO for concrete control situations with fixed random environment conditions) and self-organization principle of new robust KB design in on-line from responses of these KBs on unpredicted control situations.

Physical separation (in on-line) of KB design process on responses from partially robust KB in unpredicted control situation means the decomposition of multi-objective optimization problem on partial solution problems with different fixed criteria of optimization and final aggregation a new robust KB with quantum correlation between particular solutions of control qualities. Control laws from a new robust KB with quantum correlation are included the best partial control qualities of used KB.

Toolkit of self-organization design process of a new robust KB is QFI model [12].

Figure 3 shows the structure realization in on-line of self-organization principle in design process of robust KB based on QFI (see, Figure 1).

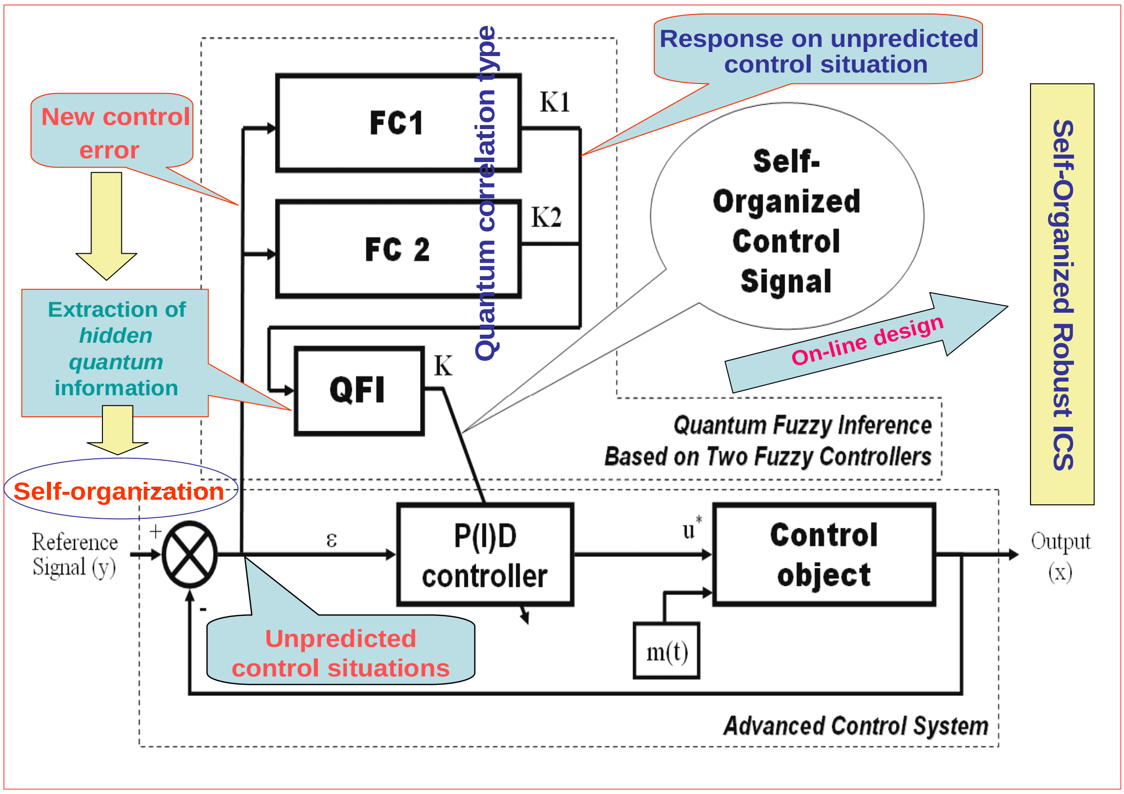


Figure 3: *Self-organization design process of robust KB based on QFI*

Figure 4 shows Simulink model in MatLab simulation of QFI from Figure 3.

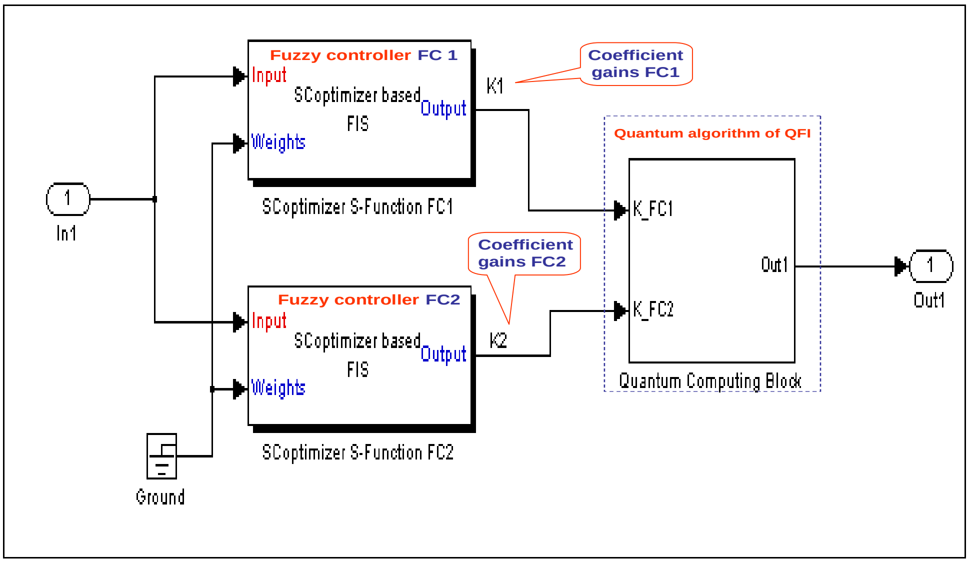


Figure 4: *MatLab Simulink model of* QFI

Figure 5 shows main steps of QFI that are used in SW-support of self-organization principle in design process from Figure 4.

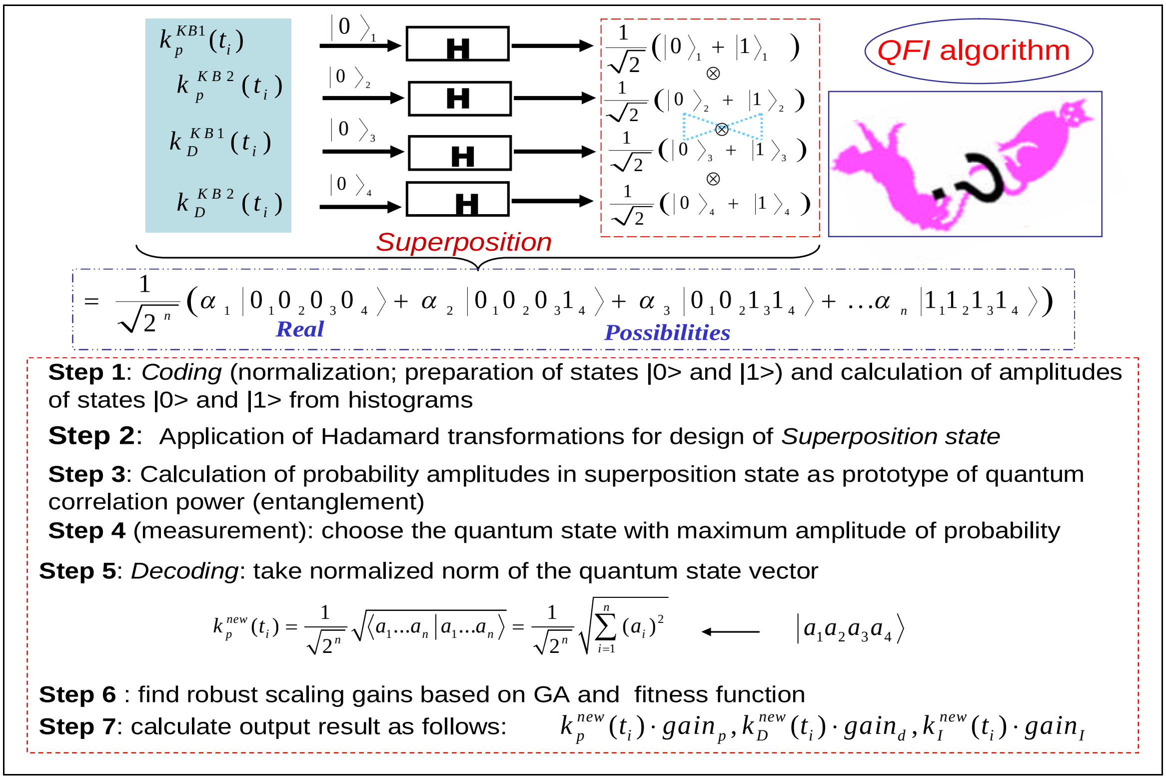


Figure 5: *Main steps in QA of QFI*

Physical meaning and role of QFI in SW-support of self-organization principle in design process is described in details in [9, 12]. In this section we will consider briefly steps in QFI of SW-support.

Step 1: *Coding*. QFI is QA. According to QA theory first step is coding of inputs with searching possible solution. In our case we must doing the following sub-steps: (i) normalization of control signals (in our case coefficient gain schedule from two KBs with different amplitude values); (ii) preparation of states $(|0\rangle,|1\rangle)$; and (iii) calculation of amplitude probabilities of quantum states $(|0\rangle,|1\rangle)$.

Figure 6 shows sub-step (i) of coding process in MatLab.

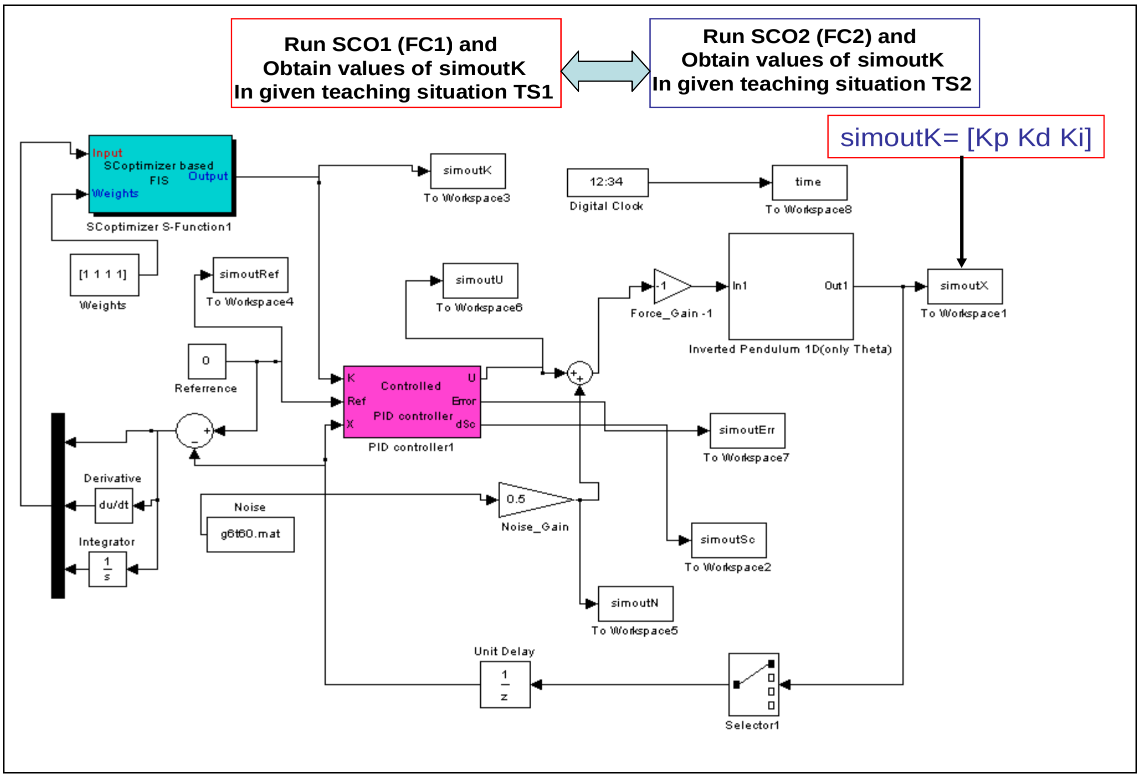


Figure 6: *Coding* (*normalization*; *preparation of states* $\left(|0\rangle,|1\rangle\right)$)

Figure 7 shows normalization process.

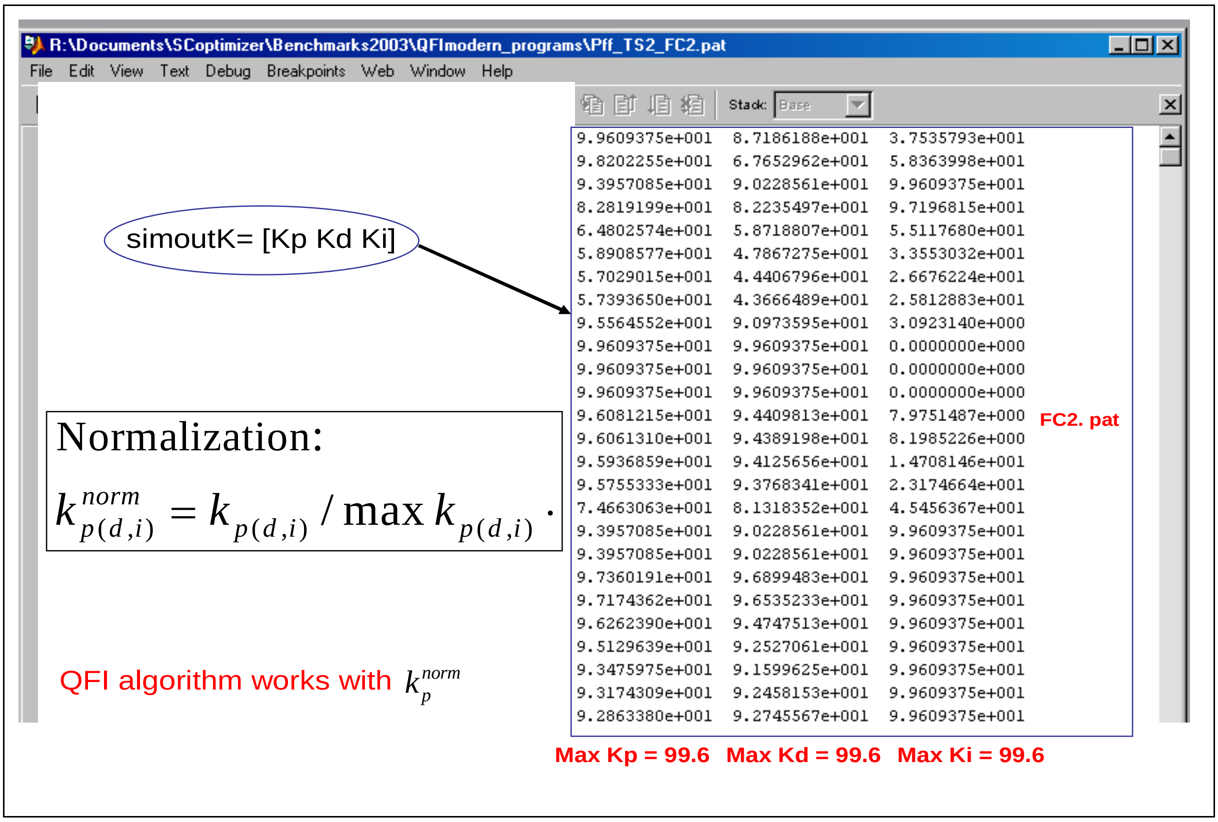
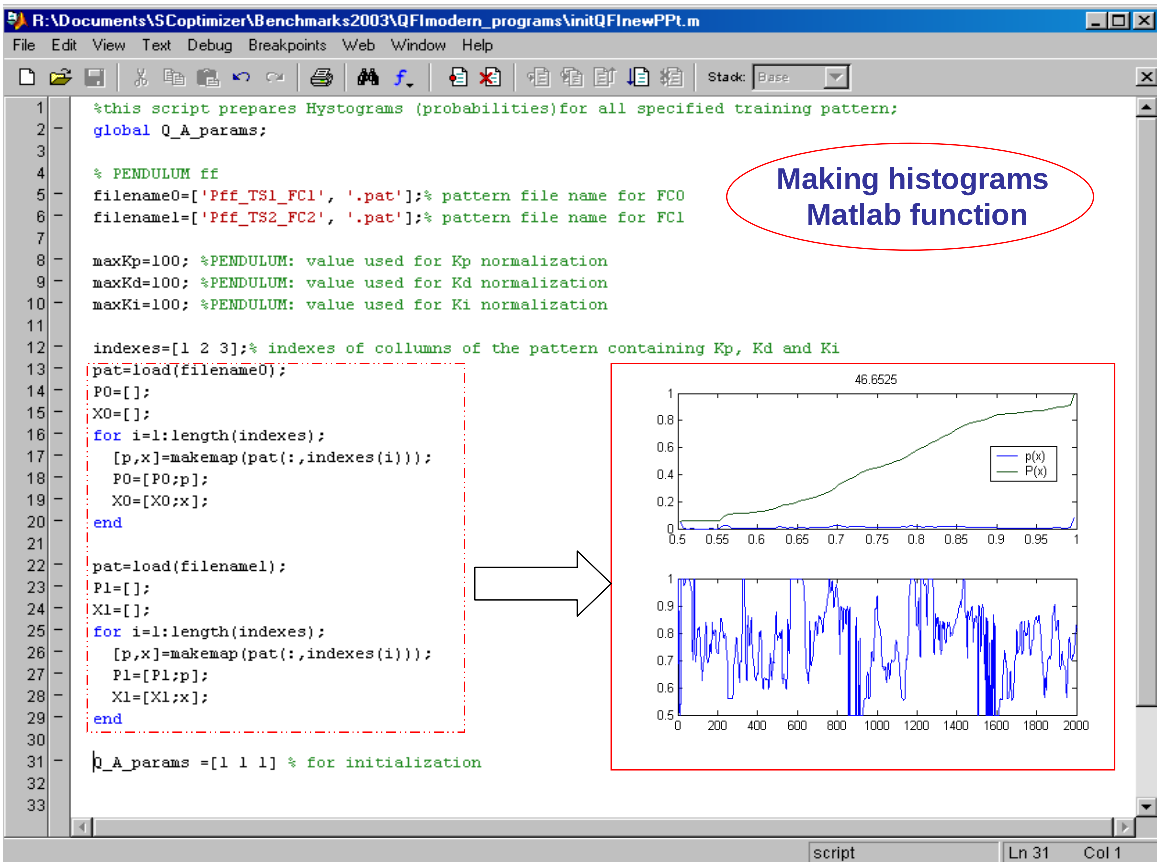


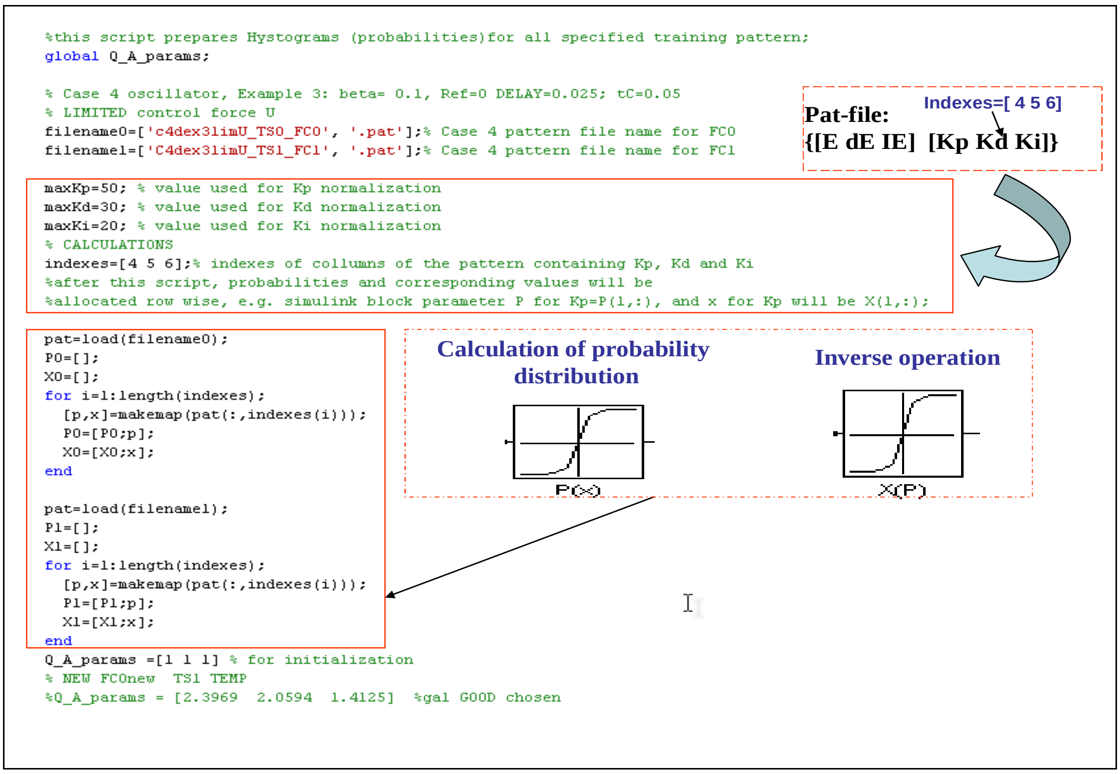
Figure 7: *Normalization*

[For normalization task, we use the patterns FC1.pat and FC2.pat from FC1 and FC2 performances in TS1 and TS2 control situations, correspondently]

Step 2: *Superposition state design*. For this case in MatLab the following functions for calculations of probability distributions and inverse operations are demonstrated in Figure 8a,b. In this case we make histograms using standard MatLab function.



(a)



(b)

Figure 8: *Making histogram MatLab function*

Figure 9 shows computation process of values of coefficient gains K corresponding to quantum states $(|0\rangle, |1\rangle)$, and its amplitude probabilities from histograms in Figure 8.

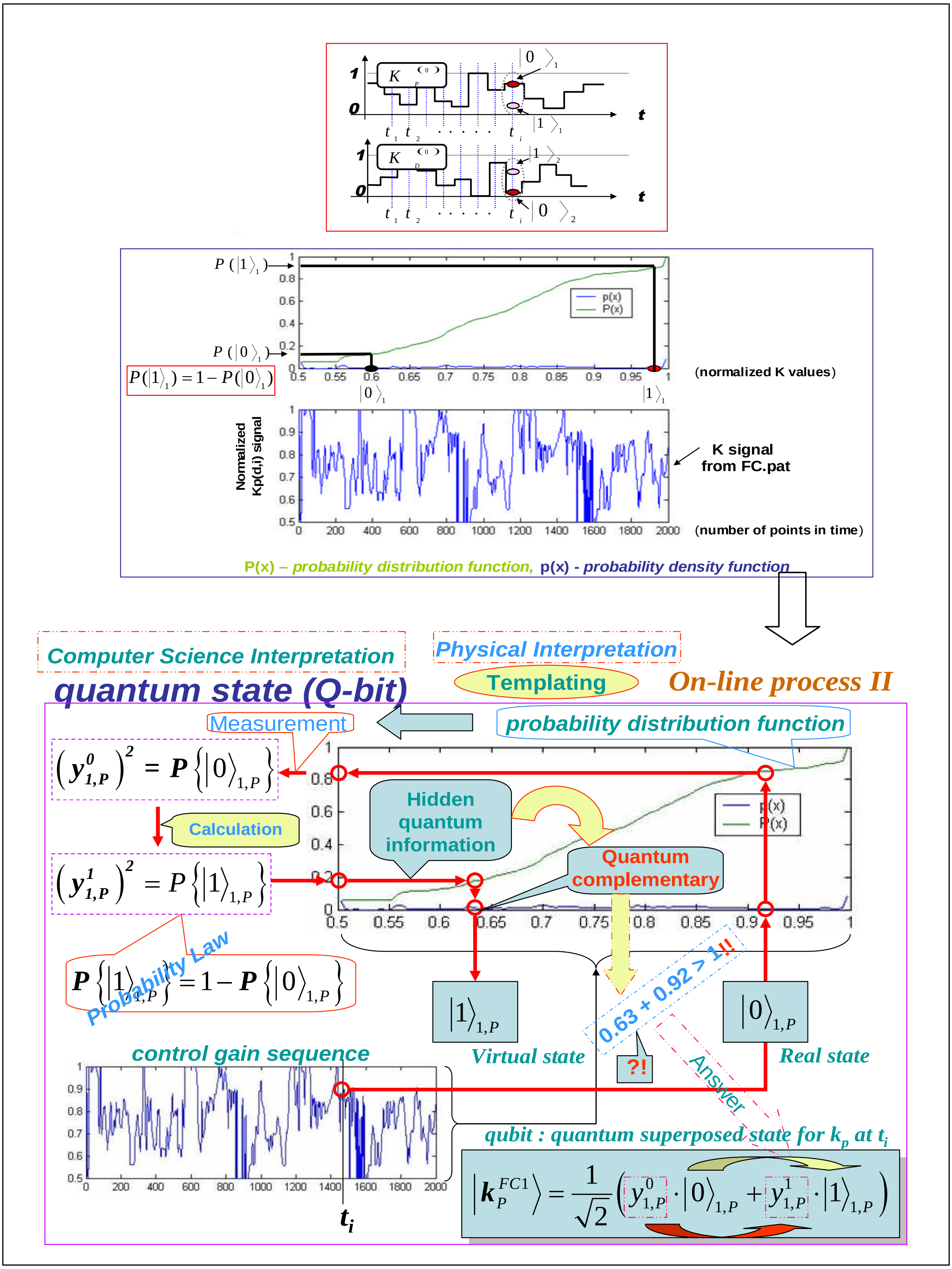


Figure 9: *Calculation of values of K corresponding to quantum states* $|(|0\rangle, |1\rangle)$, *and its amplitude probabilities*

Figure 10 shows final design of quantum state: $\frac{1}{\sqrt{2}}\left(a|0\rangle+b|1\rangle\right)$, $a^2+b^2=2$.

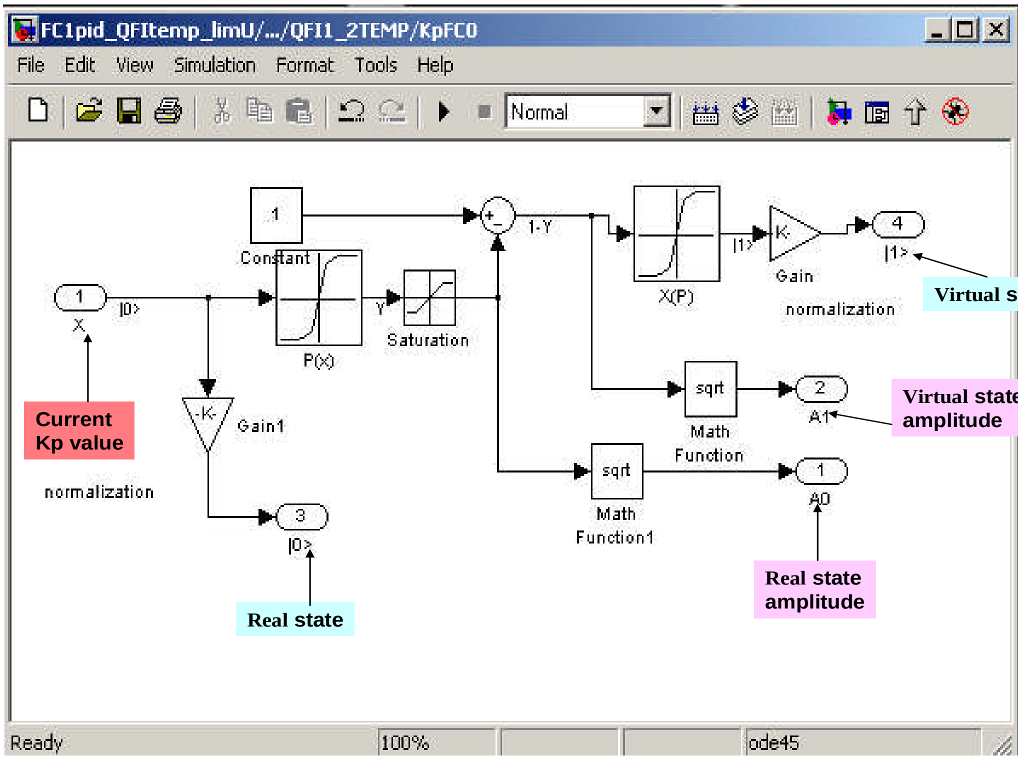


Figure 10: *Design of quantum states*

Figures 11 and 12 are demonstrated principles of final superposition state design including the types of quantum correlation [12] (see below, Figure 14, where these ideas are implemented in Matlab Simulink block).

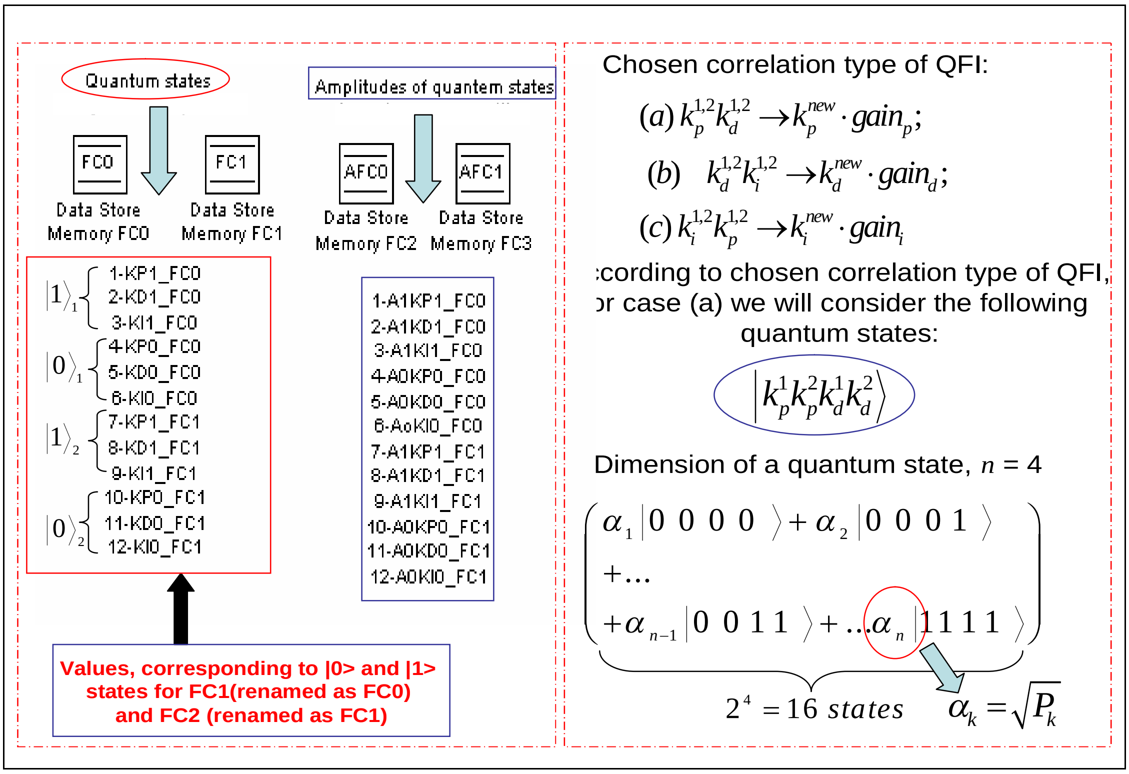


Figure 11: *Design of quantum superposition with different types of quantum correlations*

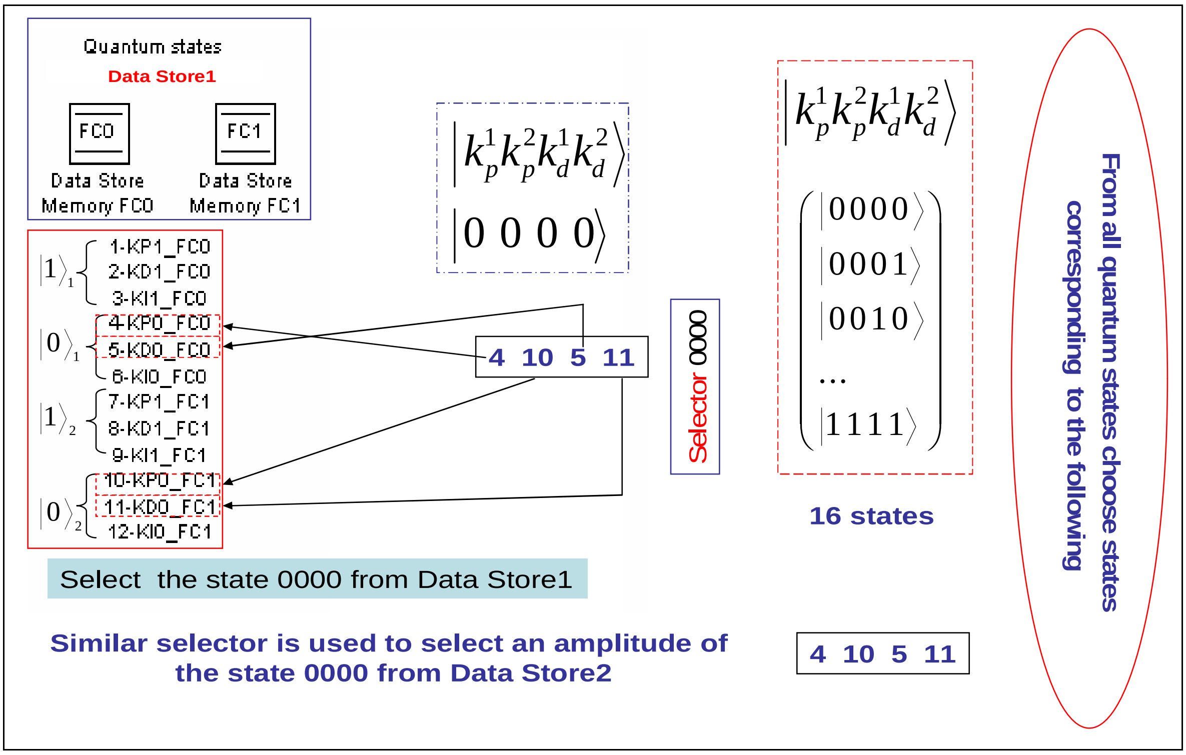


Figure 12: *Making superposition of quantum states*

Step 3: *Computation of amplitude probabilities in superposition state*. Figure 13 shows the calculation process of amplitude probabilities in superposition state.

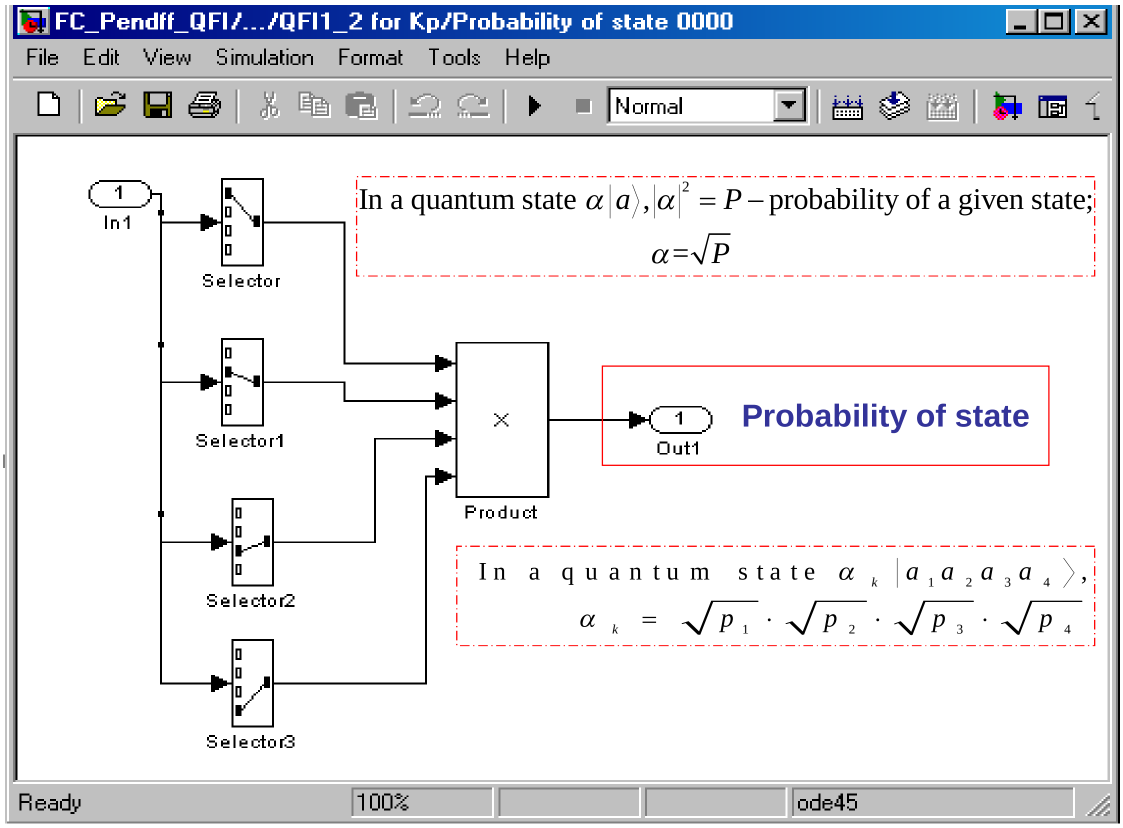


Figure 13: *Calculation of amplitudes of quantum states*

Steps 4 and *5*: *Choose of classical state with maximum amplitude probability and decoding*. Figure 14 shows these processes in Matlab Simulink block implementation.

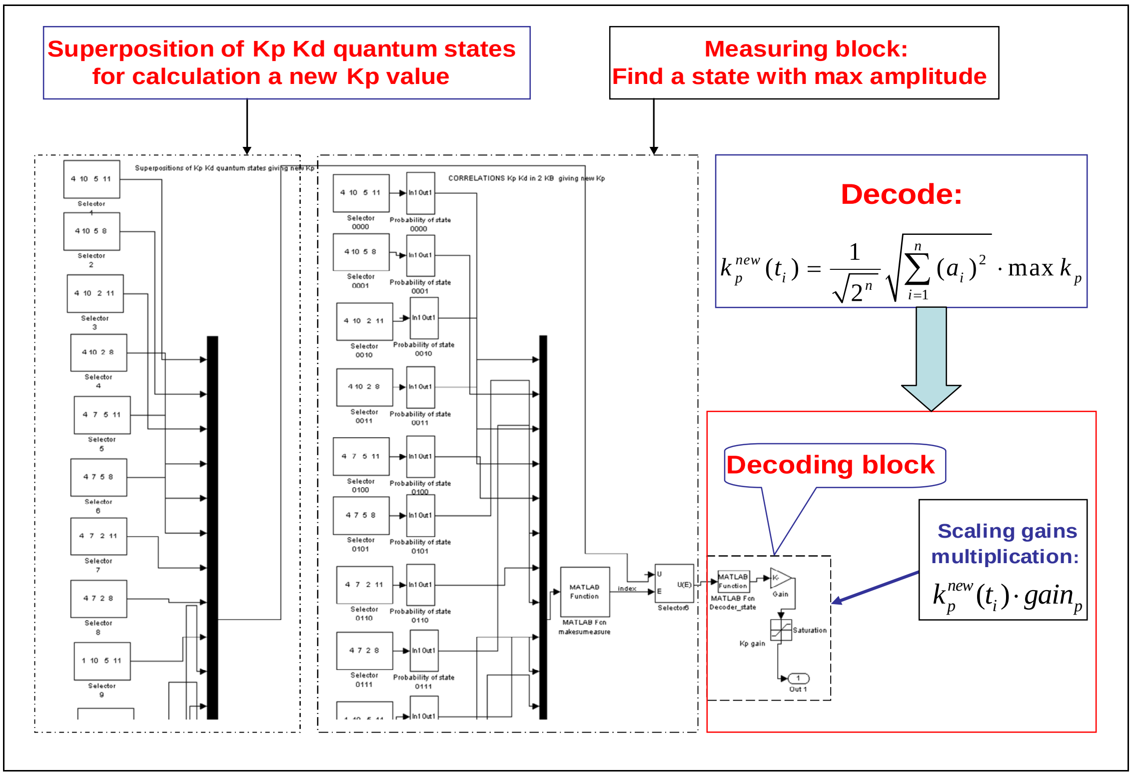


Figure 14: *Make superposition of quantum states, measurement and decode*
[Quantum Fuzzy Inference Block (hidden layer 3)]

Step 6: *Search of robust scaling gains*. Figure 15 shows the searching process of robust scaling gains using GA with different fitness functions.

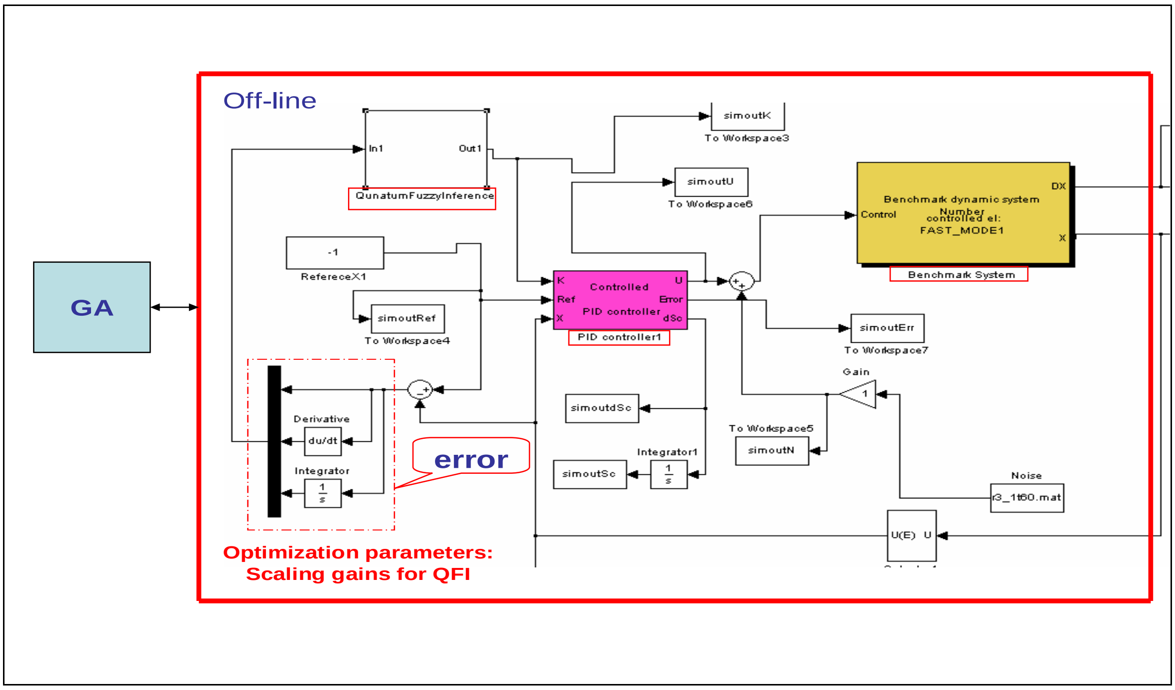


Figure 15: QFI *with* GA *for optimal choice of scaling gains*
[Fitness function: min control error or others]

Figure 16 shows final QFI process by using QC Optimizer (QFI kernel) (Steps 1-7 in Figures 4 and 5).

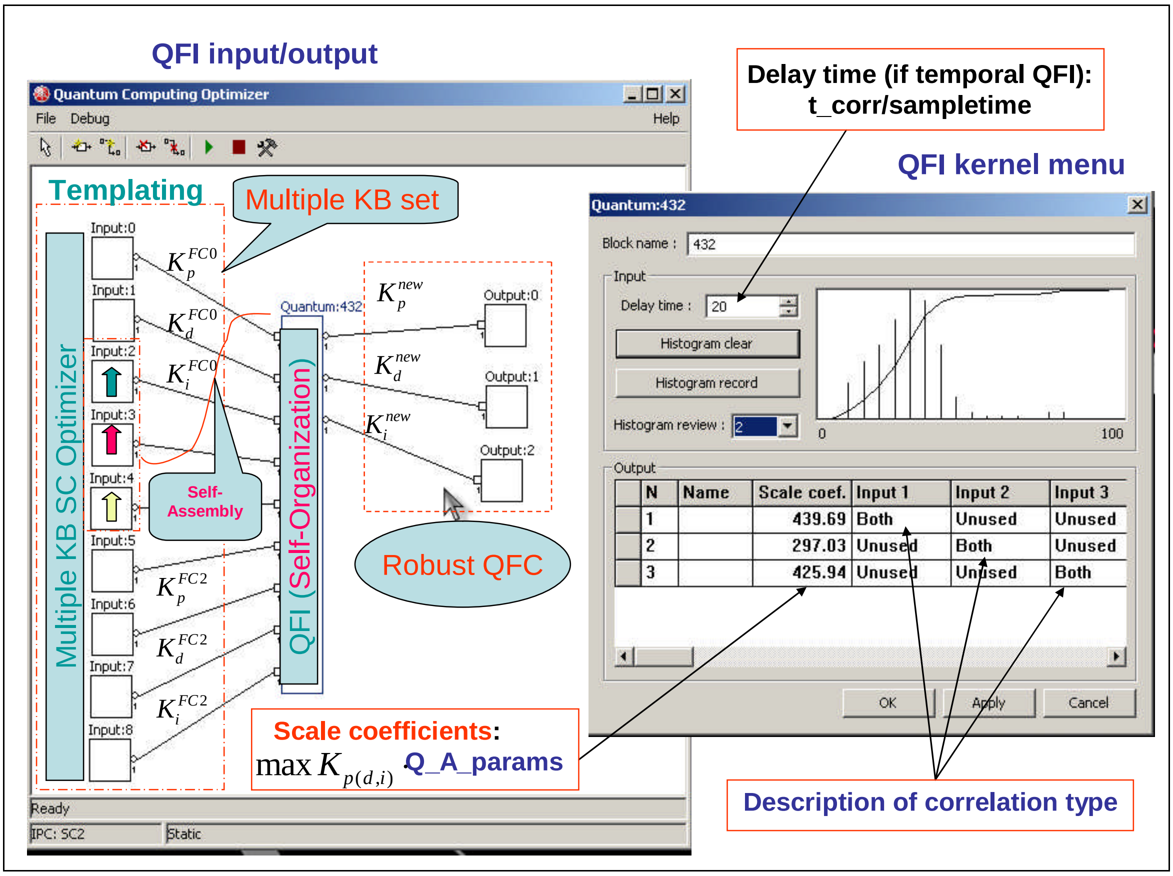


Figure 16: *QFI process by using QC Optimizer* (*QFI kernel*)

3. 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:

$$\ddot{\theta}=\frac{g\sin\theta+\cos\theta\left(\dfrac{+(u+\xi(t))+\{+a_1\dot{z}+a_2 z\}-ml\dot{\theta}^2\sin\theta}{M+m}\right)-k\dot{\theta}}{l\left(\dfrac{4}{3}-\dfrac{m\cos^2\theta}{M+m}\right)}, \tag{3.1a}$$

$$\ddot{z}=\frac{u+\xi(t)+\{-a_1\dot{z}-a_2 z\}+m\ell\left(\dot{\theta}^2\sin\theta-\ddot{\theta}\cos\theta\right)}{M+m}, \tag{3.1b}$$

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.

Figure 17 shows the geometrical model of "Cart-pole" system.

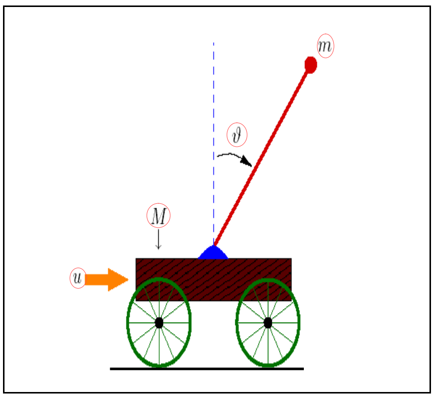


Figure 17: *"Cart-pole" system* [13]

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 (see, also Figure 17). 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. (3.1) shows that considered system has two degree of freedom but it is possible control this system with *one* FC that design optimal control force *u*. The "*cart-pole*" system has very complex dynamic.

In simple case equations of motion can be derived from first principles, where we assume that there is no friction. Furthermore, for qualitative analysis we can in first step ignore the cart and only consider the equations associated with the pendulum. We wish to understand how the optimal cost *V* depends on the initial conditions, that is, whether the so-called value function is continuous and what we can say about its smoothness. Writing $x_1 = \theta$ for the angle, and $x_2 = \dot{\theta}$ for the angular velocity, for the example of the balanced pendulum we can obtain a four-dimensional associated Hamiltonian system.

Since the (original) vector field is affine in the control u, we can explicitly write down $u^*(x, p)$ that minimizes the pre-Hamiltionian:

$$u^*\left(\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}\right) = -\frac{1}{r_1}\begin{bmatrix} 0 & \dfrac{\dfrac{m_r}{ml}\cos(x_1)}{\dfrac{4}{3} - m_r\cos^2(x_1)} \end{bmatrix}\begin{bmatrix} p_1 \\ p_2 \end{bmatrix}, \quad m_r = \frac{m}{m+M} \tag{3.2}$$

At this critical point $u = u^*$ we have the Hamiltonian

$$H(x, p) = K\left(x, p, u^*(x, p)\right) = q\left(x, u^*(x, p)\right) + p^{\mathrm{T}} f\left(x, u^*(x, p)\right) \tag{3.3}$$

that is related to the original problem and the associated Euler-Lagrange equation via a Legendre transformation.

Pontryagin's Minimum Principle says that if the pair $\left(x_0, u^*(\cdot)\right)$ is optimal, then the optimal trajectory pair $\left(x^*(\cdot), u^*(\cdot)\right)$ corresponds to a trajectory $\left(x^*(\cdot), p^*(\cdot)\right)$ via $u^*(t) = u^*\left(x^*(t), p^*(t)\right)$ along which $H(x, p)$ is constant. Hence, $\left(x^*(\cdot), p^*(\cdot)\right)$ is a solution to the following Hamiltonian system:

$$\begin{cases} \dot{x} = \dfrac{\partial}{\partial p} H(x, p) = f\left(x, u^*\right) \\ \dot{p} = -\dfrac{\partial}{\partial x} H(x, p) \end{cases} \tag{3.4}$$

For most choices, the associated optimal cost is only locally optimal and the associated solution is not the required globally minimal solution.

Furthermore, $\left(x^*(\cdot), p^*(\cdot)\right)$ lies on the stable manifold $W^S(0,0)$ of the origin, since $\left(x^*(t), p^*(t)\right) \to (0,0)$ as $t \to \infty$.

It is shown that the projection of $W^S(0,0)$ onto the x-space entirely covers the stabilizable domain for nonlinear control problems. This means that all initial conditions $x = x_0$ that can be driven to the origin have at least one associated value p_0 for p such that $\left(x_0, p_0\right) \in W^S(0,0)$.

The Hamiltonian for this case now follows immediately from Eq. (3.3).

Remark. Computing a two-dimensional global invariant manifold such as $W^S(0,0)$ is a serious challenge. In [13] is computed (a first part of) $W^S(0,0)$ with the corresponding algorithm. In these computations, focus solely on the dynamical system defined by the Hamiltonian (3.3), and ignore the associated optimal control problem, including the value of the cost involved in (locally) optimally controlling the system. The algorithm computes *geodesic level sets* of points that lie at the same geodesic distance to the origin. This means that the manifold is growing uniformly in all (geodesic) radial directions.

Projections of $W^S(0,0)$ are shown in Figure 18.

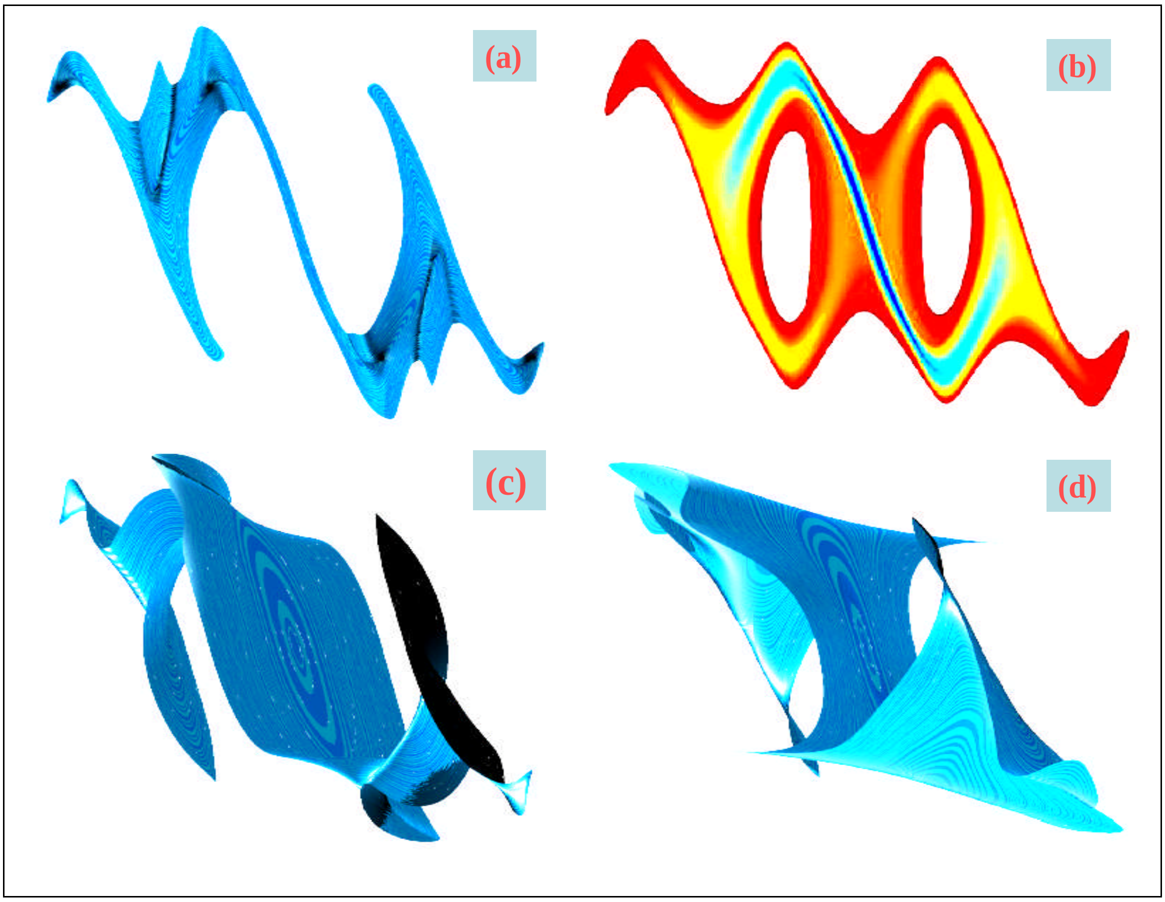


Figure 18: *The stable manifold* $W^S(0,0)$ *associated with the Hamiltonian (3.3) (panel a) is directly related to the value function V (panel b) as can be seen in the projection onto the* (x_1, x_2)*-plane*[13]

This manifold lives in a four-dimensional space and three-dimensional projections are shown as rotations in (x_1, x_2, p_1)-space (panel c) and (x_1, x_2, p_2)-space (panel d); see also the animation in the multimedia supplement (*Osinga* and *Hauser*, 2005 [13]).

The alternating dark and light blue bands indicate the location of the computed geodesic level sets. Animations of how the manifold is grown can be found in the multimedia supplement [13]. Figure 18(a) shows the vertical projection of $W^S(0,0)$ onto the (x_1, x_2)-plane.

Note that $W^S(0,0)$ is an unbounded manifold, even though it seems to be bounded in some of the x_1- and x_2-directions in a neighborhood of the origin. In this neighborhood, the manifold stretches mainly in the p_1- and p_2-directions.

A better impression of the manifold is given in Figures 18(c)-(d), where the manifold is projected onto a three-dimensional space. Figure 18(c) shows the projection $\{p_2 = 0\}$ and Figure 18(d) the projection $\{p_1 = 0\}$. In each figure the manifold is only rotated away slightly from its position in Figure 18(a). A sense of depth is also given by considering the rings near the origin, which are almost perfect circles in $\mathbb{R}^4$ because the manifold is very flat initially. The distortion of these circles in Figures 18(c)-(d) is due to the viewpoint of the projections. The animations in the multimedia supplement [13] give a better idea of what $W^S(0,0)$ looks like in four-dimensional space. Thus 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 19 shows the advanced control system structure with resource of unpredicted control situations.

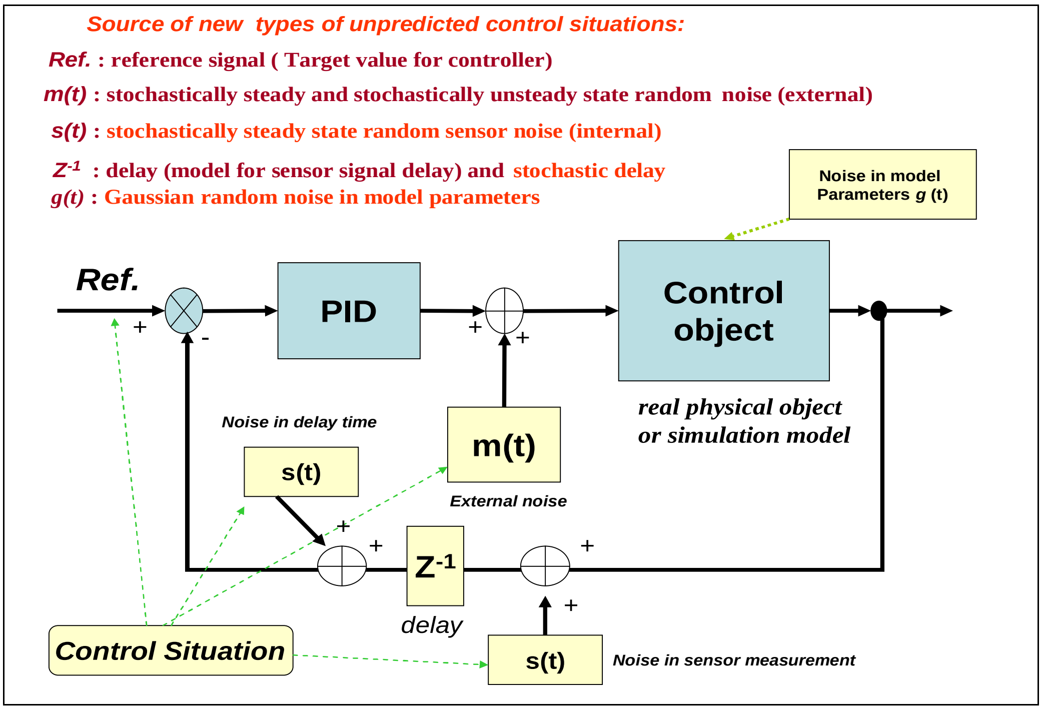


Figure 19: *Advanced control system with resource of unpredicted control situations*

Figure 20 shows MatLab Smulink model simulation of unpredicted situations for "*cart-pole*" system (3.1).

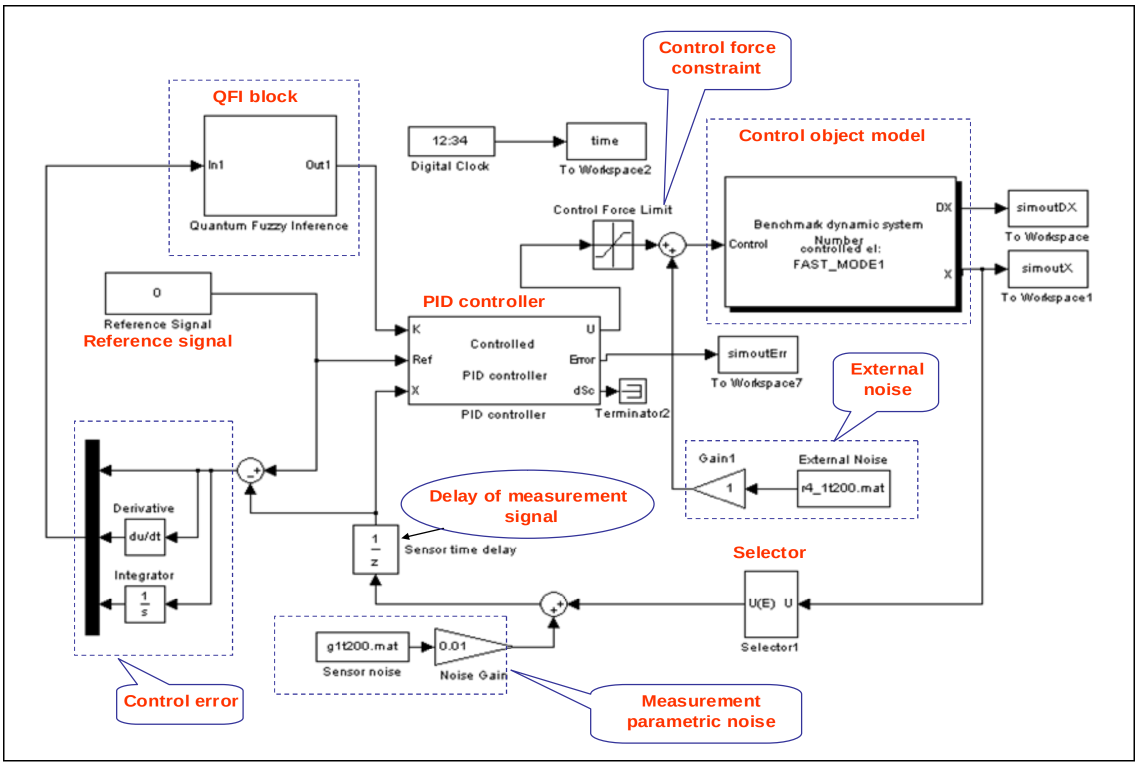


Figure 20: *MatLab Simulink model for simulation of intelligent control for system* (3.1) *in unpredicted control situations*

Example 1: *Inverted pendulum*. Figure 21 shows control laws obtained as result of QFI in Figure 19 with scaling gains = [1 1 1] for pendulum control model without consideration cart position.

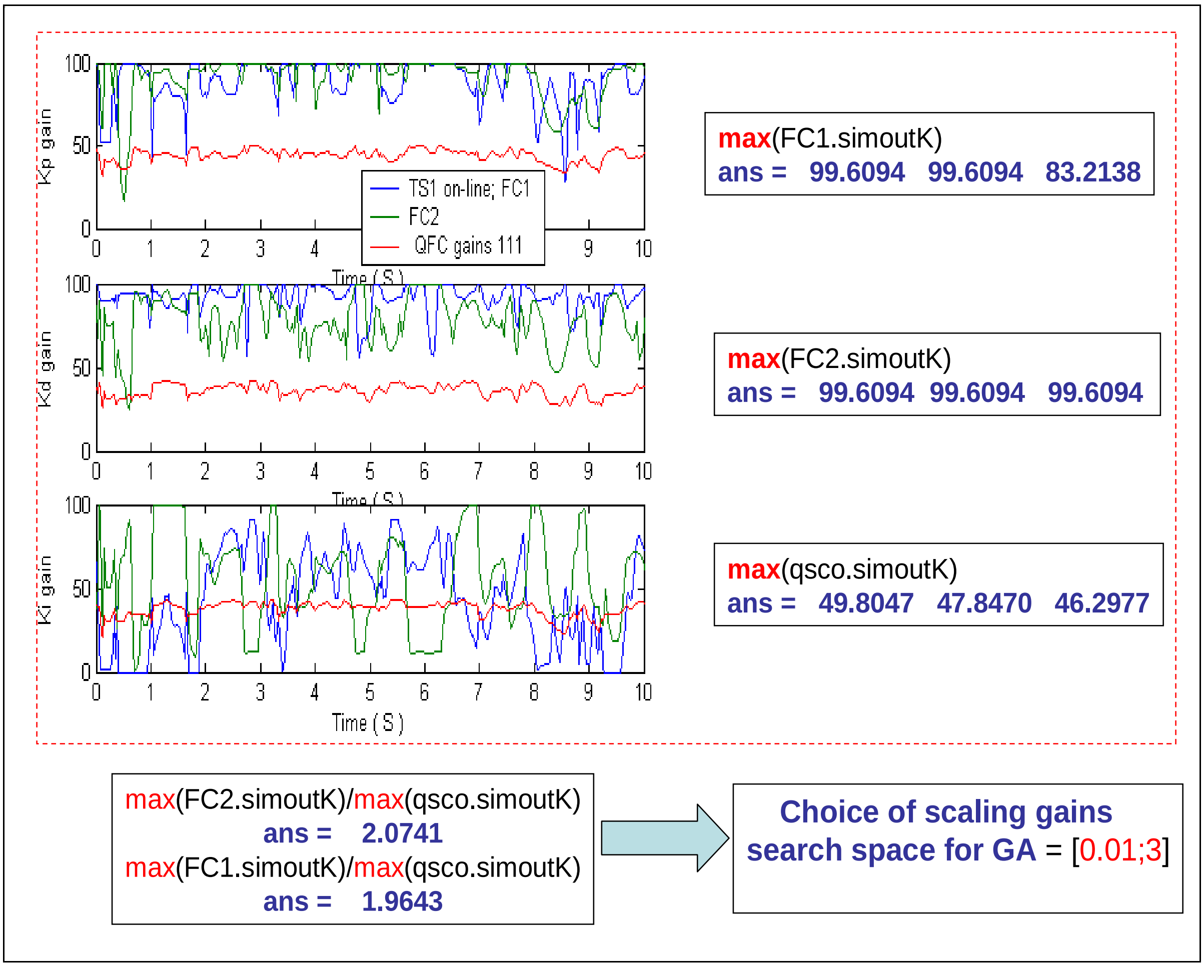


Figure 21: *Simulation results of control laws of FC and QFC*

Remark: File (**qsco**.simoutK) represents results of QFI.

Let us consider now the problem of robust intelligent control design for system (3.1) in unpredicted situations according to structures on Figures 18 and 19 (see, Table 1).

Example 2: *Robust Intelligent control of* "*Cart-pole*" *system in unpredicted control situations*.

Table 1 shows different types of unpredicted control situations for the system (3.1).

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

We will consider situation New 2 from Table 1 as example of a new unpredicted control situation. With SCO was designed four KB for different types of noises $\xi(t)$ (see, Figure 22).

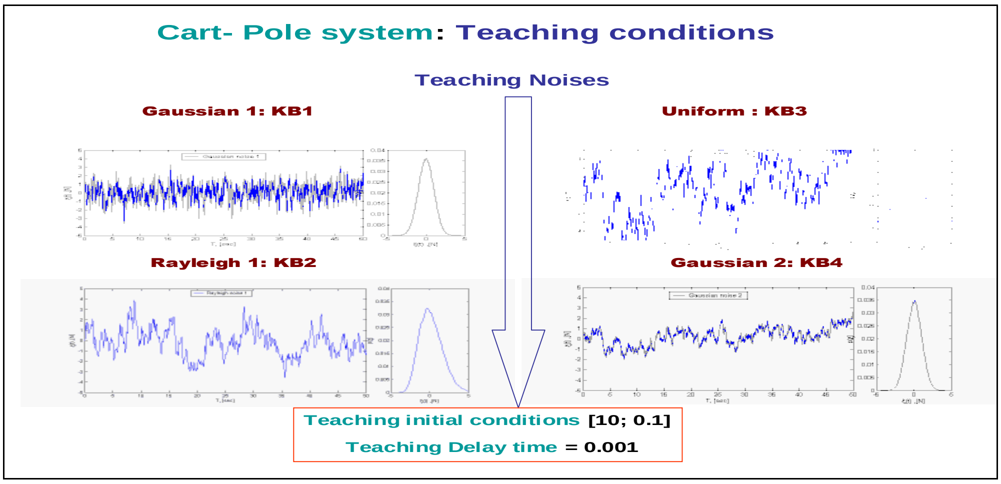


Figure 22: *Teaching conditions*

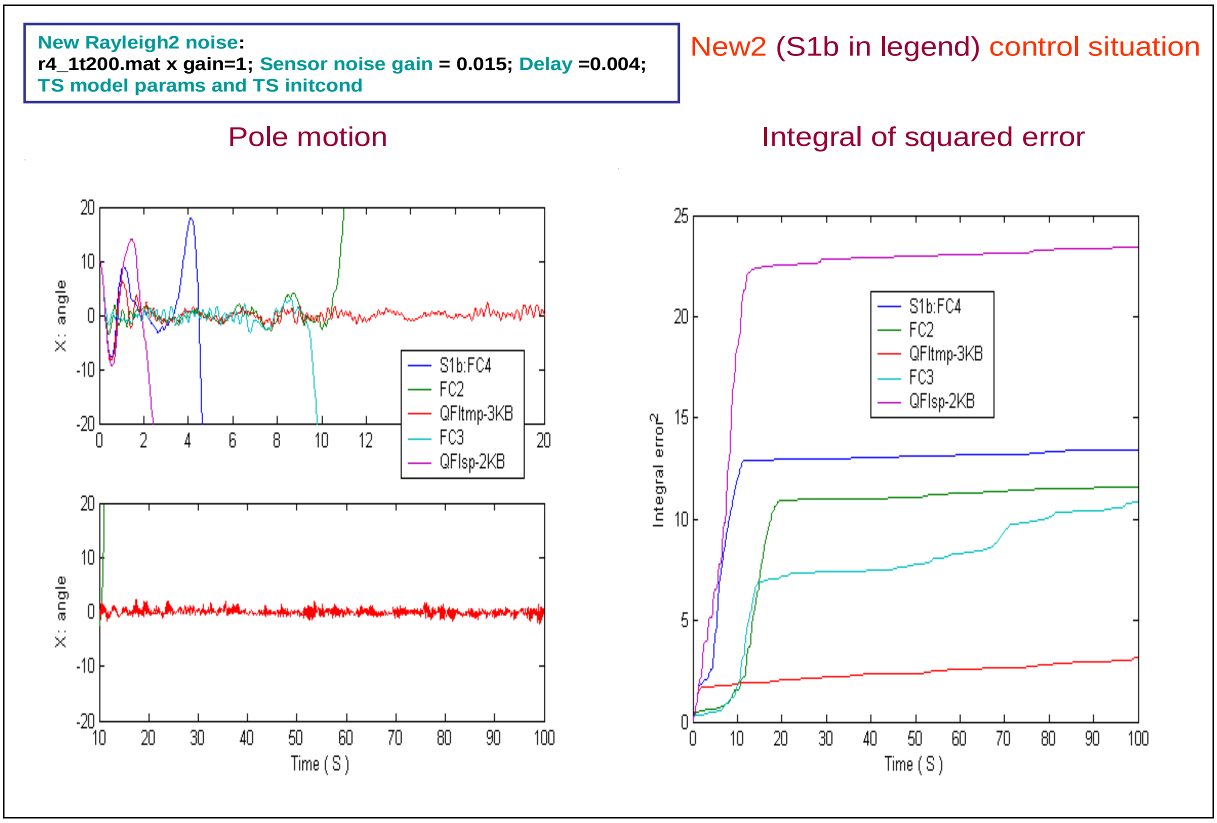


Figure 23: *Comparison of dynamic behavior of system* (3.1) *in new unpredicted control situation* (**New 2**) *for cases with two and three KB in QFI*

Figure 23 shows dynamic behavior of considered control system in new unpredicted control situation for cases with two and three KB in QFI.

Figure 24 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). 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* [10] between stability, controllability and robustness in self-organization process (from viewpoint of physical background of global robustness in intelligent control systems).

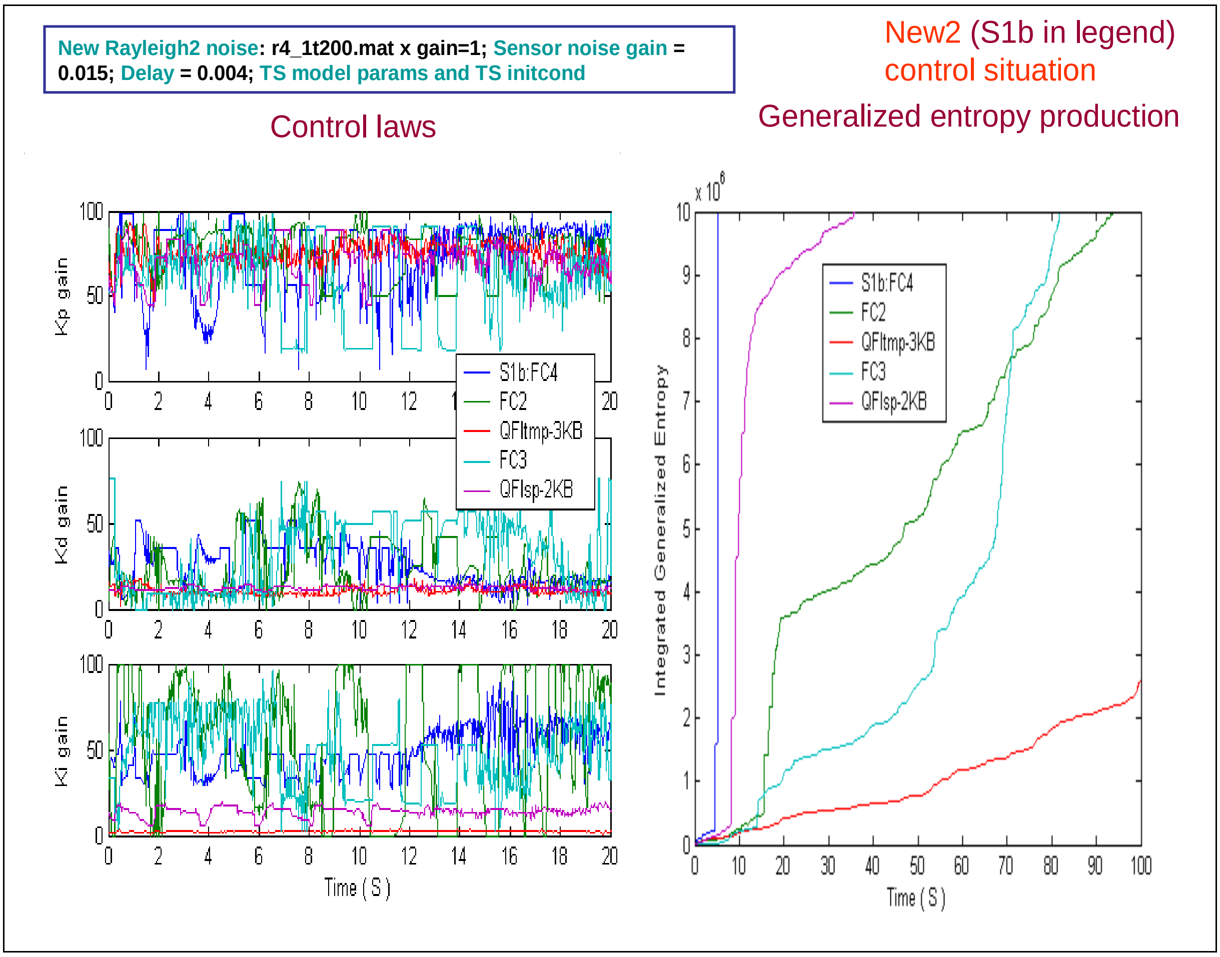


Figure 24: *Results of simulation of control laws for coefficient gain schedule and loss of resource in considered intelligent control system* (*increasing of generalized entropy production*)

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 [6, 9, 12] in design of intelligent control systems.

Conclusions

1. QFI model supports the self-organization process in design technology of robust KB with optimal *thermodynamic trade-off* [10] between *stability*, *controllability* and *robustness* in intelligent control processes of unpredicted control situations.
2. Structure of SW-support as QFI toolkit is developed.
3. Effectiveness of QMS is demonstrated with Benchmark simulation results.
4. 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 [16].
5. Quantum fuzzy controller (QFC) based on QFI is demonstrated the increasing robustness in complex unpredicted control situations.
6. For global unstable control object *robust* QFC is designed from three fuzzy controllers that are *non-robust* in unpredicted control situation.
7. New design effect (the new *Parrondo*'s game effect [14, 15]) in advanced control theory and design technology of intelligent control system is showed.
8. Effectiveness of quantum control application with new design principle "*Simple wise controller for complex control objects*" [6, 12] in classical control systems is demonstrated.

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