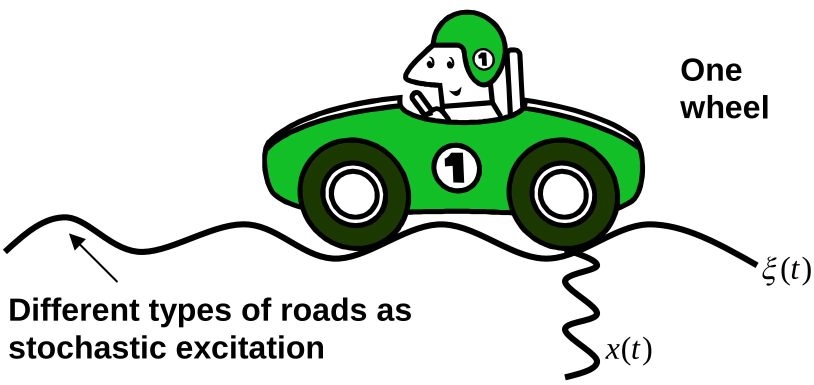
Quantum Computing based wise control design: example of benchmark simulation results

Quantum Fuzzy Inference

Control Object

Car's suspension control system design (<u>simplified illustrative example</u>)



Simplified version of car suspension system for one wheel may be considered as a *nonlinear oscillator with sizable nonlinear dissipative components* that can be described by the following equations:
of motion:

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

and

of entropy production rate:

$$\frac{dS}{dt} = \left[2\beta + a\dot{x}^2 + k_1 x^2 - 1\right]\dot{x} \cdot \dot{x},$$

where $\xi(t)$ is a given stochastic excitations with an appropriate probability density function, $u(t)$ is a control force and S is an entropy production of the given dynamic object.

Introduction

Main problem in intelligent control systems design is following: how to introduce *self-learning*, *self-adaptation* and *self-organizing capabilities* into the control process that enhanced robustness of developed advanced control system. Many learning schemes based on BP-algorithm or other have been proposed. But for more complicated unpredicted control situations (time delay and noise in sensor system, control object model parameters change, unpredicted stochastic noises etc.) learning and adaptation methods based on BP-algorithms doesn't supply robust control.

The complexity of problem is increased for the case of integrated control systems with the necessity to design the coordination control of many sub-systems as control objects with different optimization criteria (general problem of System of Engineering Systems).
Soft computing methodologies had expanded application areas of FC by adding *learning* and *adaptation* features. But still now it is difficult to design a “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:

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.
Now it is obvious that new sophisticated technologies must be considered and developed. Our quantum control algorithm of knowledge base self-organization is based on special form of *quantum fuzzy inference* based on quantum knowledge extraction from a few of Knowledge Bases designed by SC Optimizer tools.
Consider three chosen teaching conditions TS0, TS1, and TS2 (Fig. 1) for three Knowledge Bases (KB) design.
We choose the following spaces for PID gains schedule vector $K = [k_p k_d k_i]$ search: for k_p search: [0-50]; for k_d search: [0-20]; for k_i search: [0-20].
Remark. We call vector K as a control laws vector.

Teaching conditions

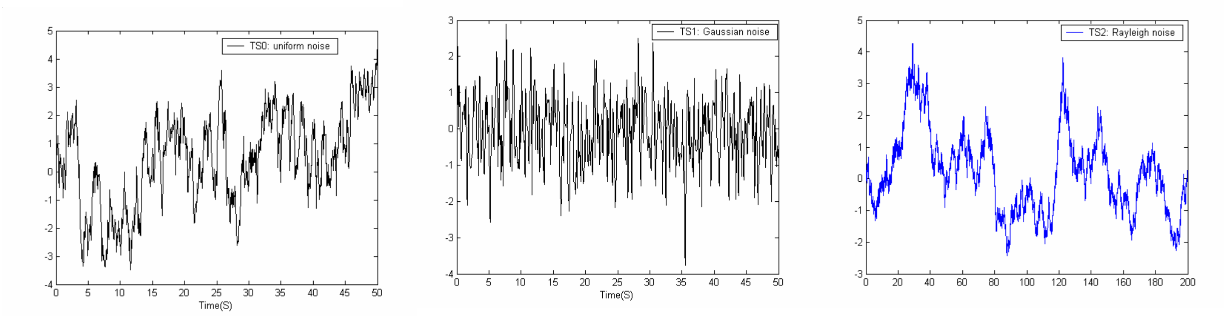
Model parameters: $\beta = 0.1; \alpha = 0.3; k_1 = 0.2; k = 5.$

Initial conditions: $[x_0][\dot{x}_0] = [2.5][0.1]$

Limited control force: $|u| \le 10\,(N)$

Sensor Delay Time = 0.001 sec;

Reference signal = 0



TS0: Uniform noise

TS1: Gaussian noise

TS2: Rayleigh noise

Figure 1. Nonlinear oscillator. Teaching conditions description

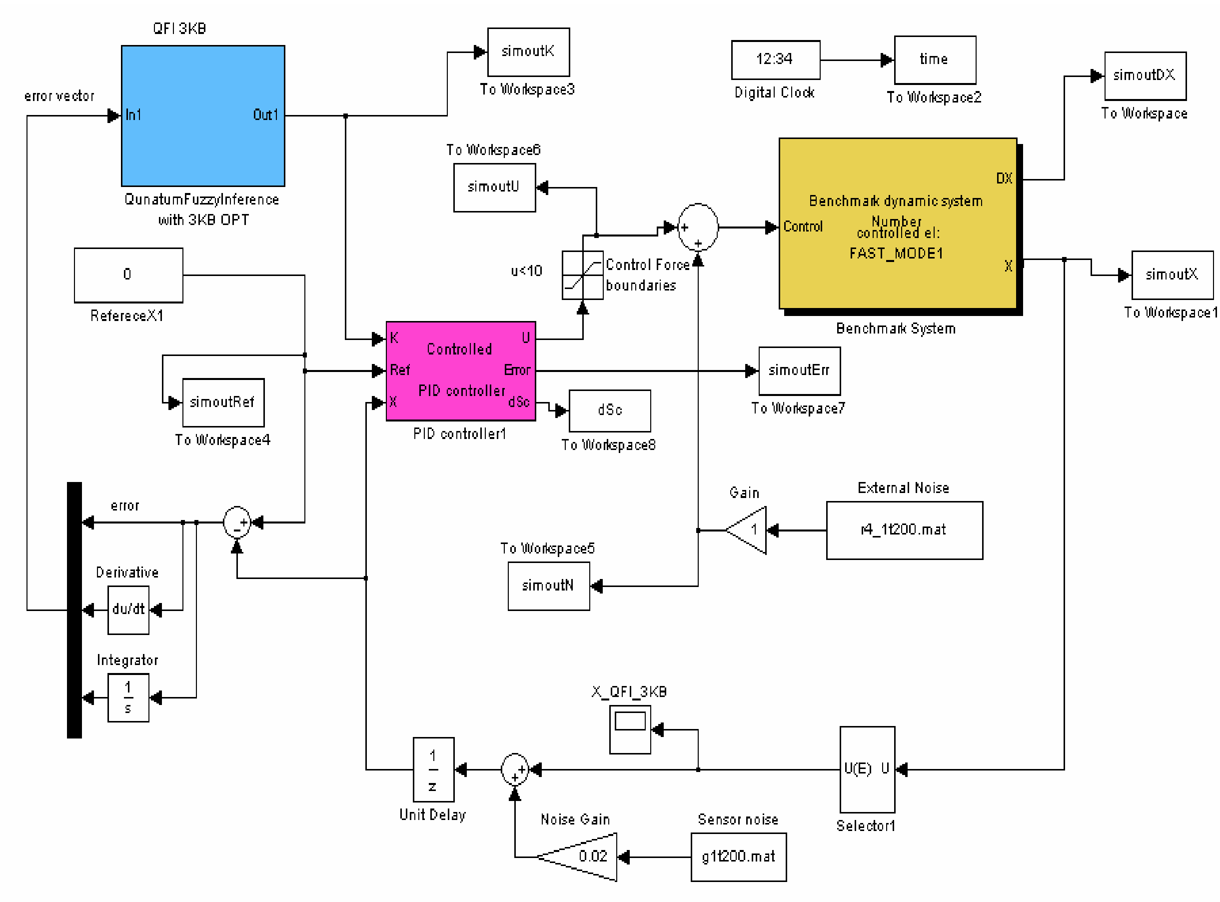


Figure 2. Nonlinear oscillator. Simulink model of control system based on QFI block.

Now we have three KBs designed for three teaching conditions:

- FC0 designed for teaching conditions TS0;
- FC1 designed for teaching conditions TS1;
- FC2 designed for teaching conditions TS2;

In the section “Technology”, Quantum control algorithm and Quantum Fuzzy Inference process (QFI) is described. Here we will only demonstrate simulation results and discuss them.

Self-organization capabilities of on-line QFI process

Our task: to show *self-organization capabilities of QFI process in on-line* with three chosen KB in the case of simulated unpredicted control situations.

On Fig. 2 Simulink structure of QFI based control is shown. On Fig.3 the structure of on-line QFI process with 3 KB is shown.
Remark. On Fig. 3, three K-vectors are shown: K0 is a control law vector that is the output from FC0- controller; K1 is a control law vector that is the output from FC1-controller; K2 is a control law vector that is the output from FC1-controller.

First of all we will investigate different types of quantum correlations and will choose a best type of quantum correlations for the given CO and chosen three KBs.

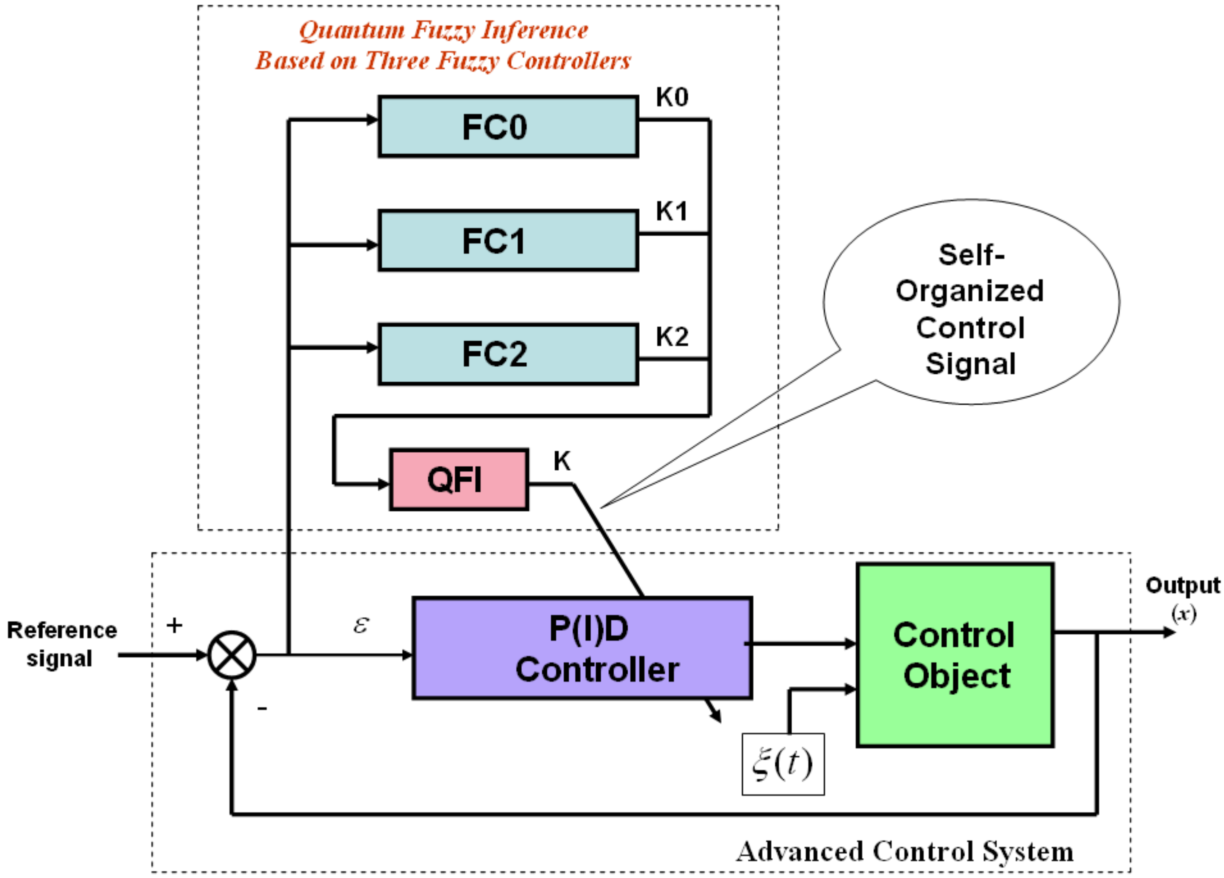


Figure 3. Nonlinear oscillator. Structure of QFI based control

Below three main types of quantum correlations used in QFI process are shown.

1. Temporal Quantum correlations (QFI tmp):

$$k_p^{1,2,3}(t)\ k_p^{1,2,3}(\Delta t) \to k_p^{new} \cdot gain_p;$$
$$k_d^{1,2,3}(t)\ k_d^{1,2,3}(\Delta t) \to k_d^{new} \cdot gain_d;$$
$$k_i^{1,2,3}(t)\ k_i^{1,2,3}(\Delta t) \to k_i^{new} \cdot gain_i$$

(Here 1,2,3 are indexes of KB and Δt **- correlation time = 0.05**)

2. Spatial Quantum correlations (QFI sp):

$$k_p^{1,2,3} k_d^{1,2,3} \to k_p^{new} \cdot gain_p;$$
$$k_d^{1,2,3} k_i^{1,2,3} \to k_d^{new} \cdot gain_d;$$
$$k_i^{1,2,3} k_p^{1,2,3} \to k_i^{new} \cdot gain_i$$

3. Spatio-temporal Quantum correlations (QFI sptmp):

$$k_p^1(t_i)k_d^1(t_i-\Delta t)k_p^2(t_i-\Delta t)k_d^2(t_i)k_p^3(t_i)k_d^3(t_i-\Delta t) \to k_p^{new}(t_i)\cdot gain_p;$$
$$k_d^1(t_i)k_i^1(t_i-\Delta t)k_d^2(t_i-\Delta t)k_i^2(t_i)k_d^3(t_i)k_i^3(t_i-\Delta t) \to k_d^{new}(t_i)\cdot gain_d;$$
$$k_i^1(t_i)k_p^1(t_i-\Delta t)k_i^2(t_i-\Delta t)k_p^2(t_i)k_i^3(t_i)k_p^3(t_i-\Delta t) \to k_i^{new}(t_i)\cdot gain_i.$$

Let us compare dynamic motion of our CO under three types of QFI based control: with temporal, spatio-temporal and spatial quantum correlations. We consider the comparison in chosen teaching conditions - TS1. On Fig.4, 5 and 6 the simulation results comparison is shown.

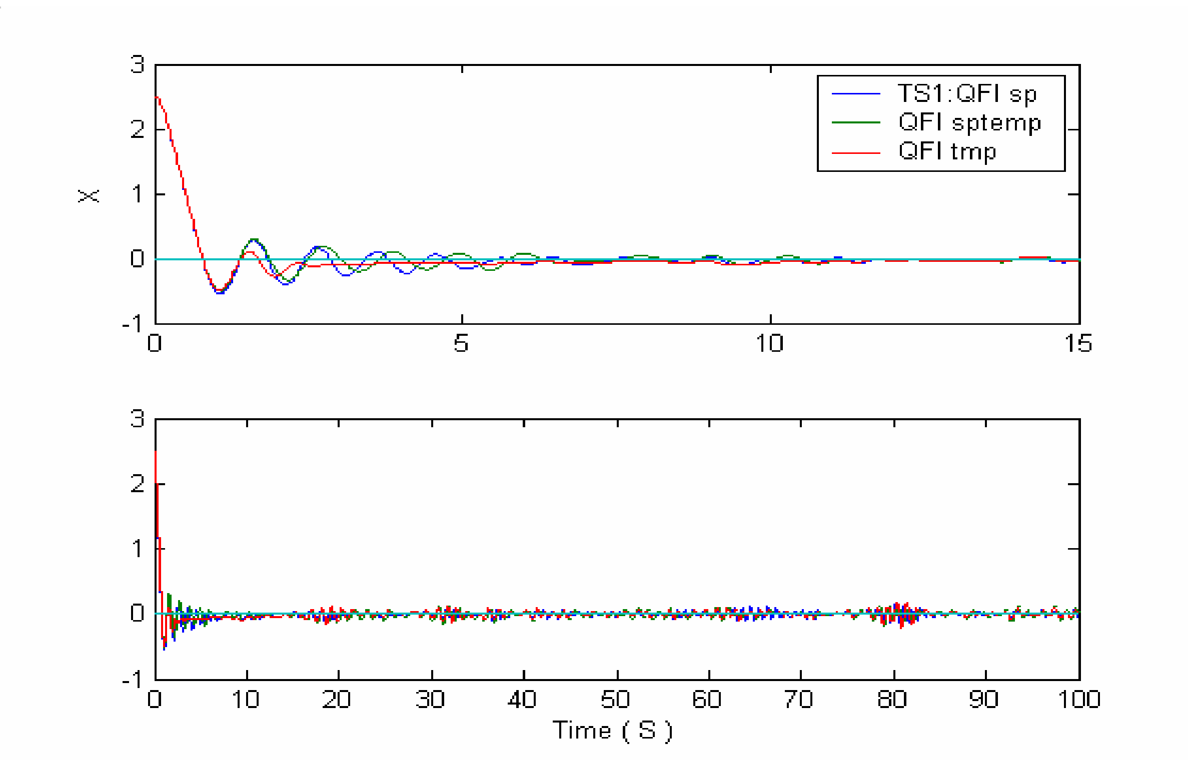


Figure 4. Nonlinear oscillator. TS1 situation. Dynamic motion comparison under three types of QFI based control

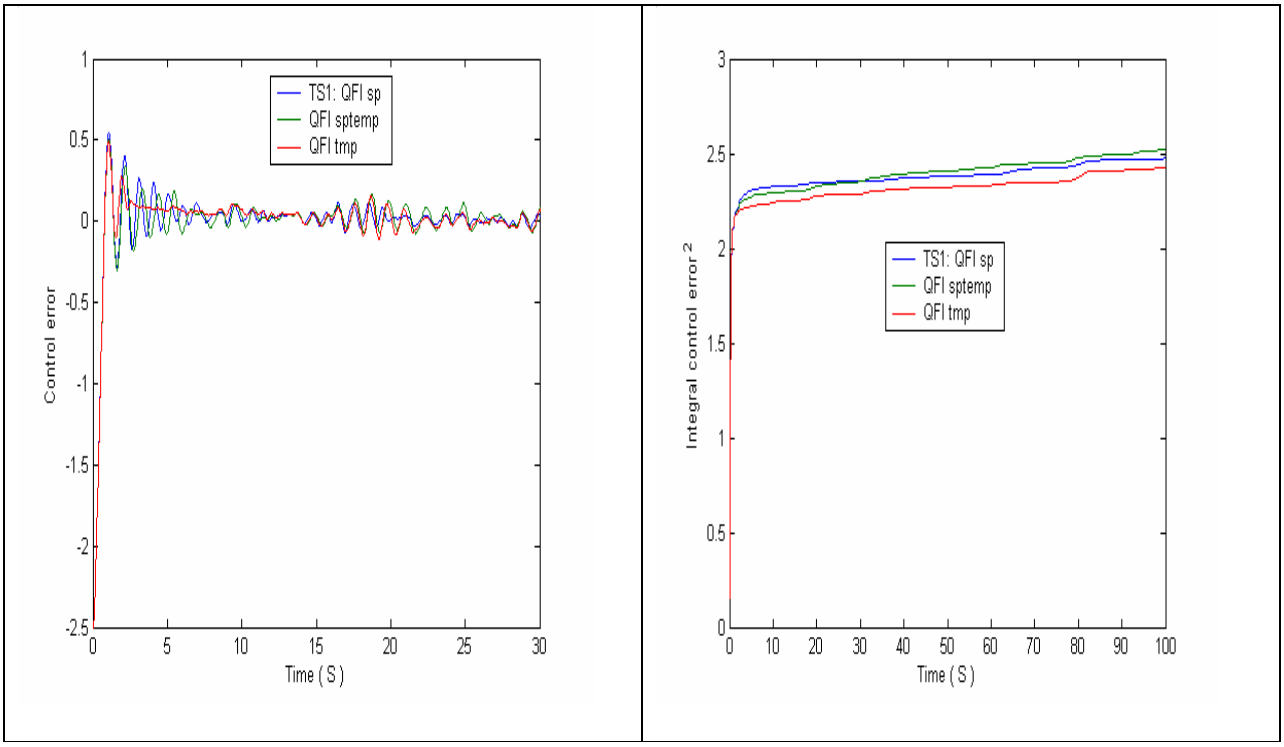


Figure 5. Nonlinear oscillator. TS1 situation. Dynamic motion comparison under three types of QFI based control. Control error comparison

From simulation results comparison we can make the following *conclusion*: in TS1 control situation, *temporal QFI with 3KB* gives better control than other types. For further comparisons we choose QFI process with temporal correlations.

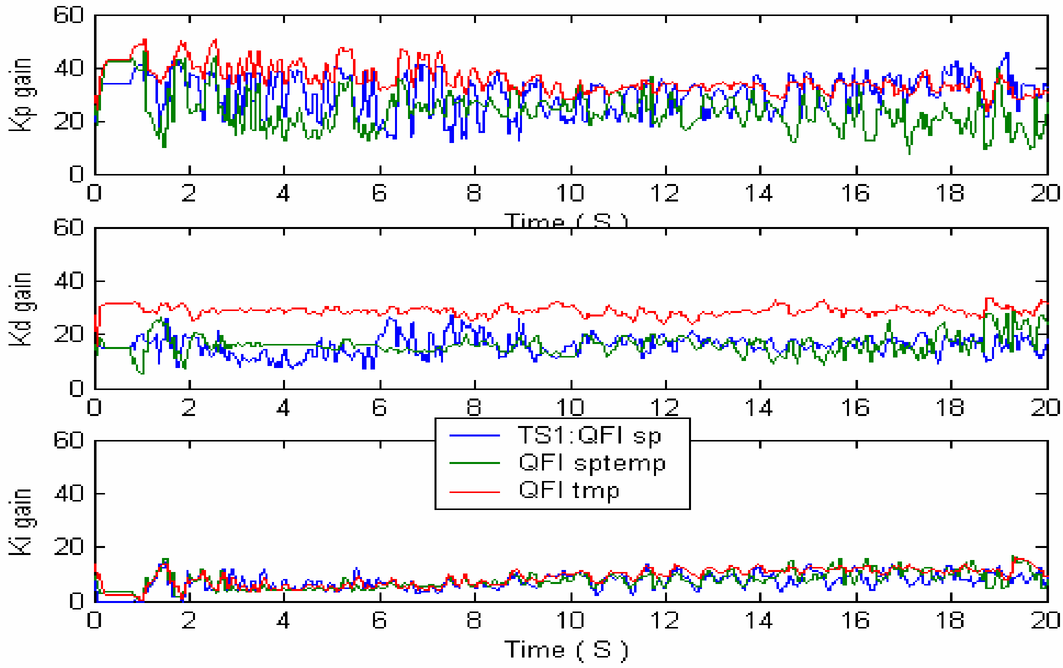


Figure 6. Nonlinear oscillator. TS1 situation. Dynamic motion comparison under three types of QFI based control. Control laws comparison

Now let us consider CO dynamic motion under the following types of control:

- FC0 designed for teaching conditions TS0;
- FC1 designed for teaching conditions TS1;
- FC2 designed for teaching conditions TS2;
- PID controller with the following constant PID gains: K = [30 15 5];
- QFI with temporal quantum correlations.

On Fig.7a,b, Fig.8a,b, Fig.9 and Fig.10 the simulation results comparison is shown in chosen TS1 control situation.

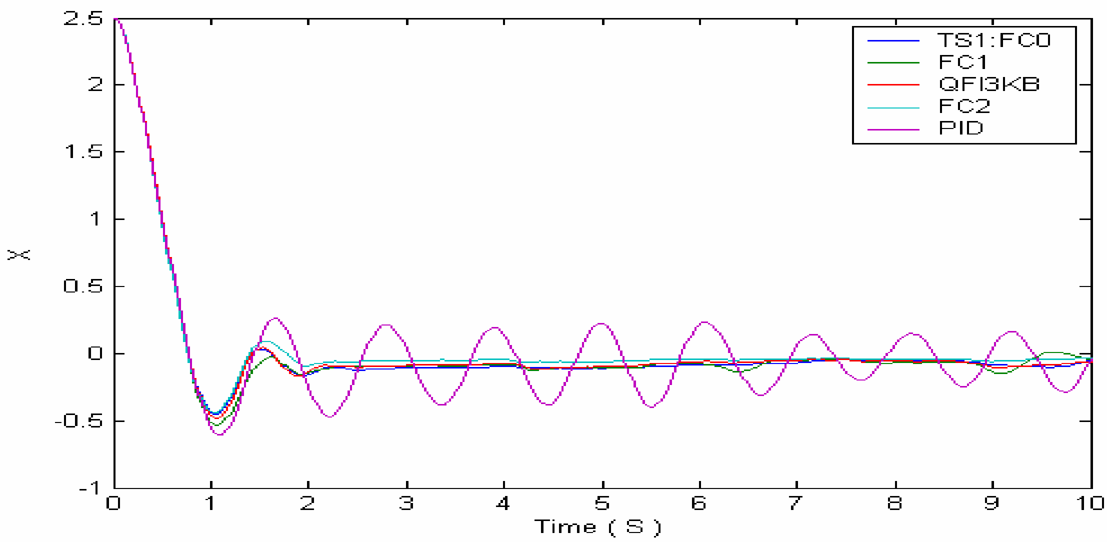


Figure 7a. Nonlinear oscillator. TS1 situation. Dynamic motion comparison. Time interval = [0-10] sec.

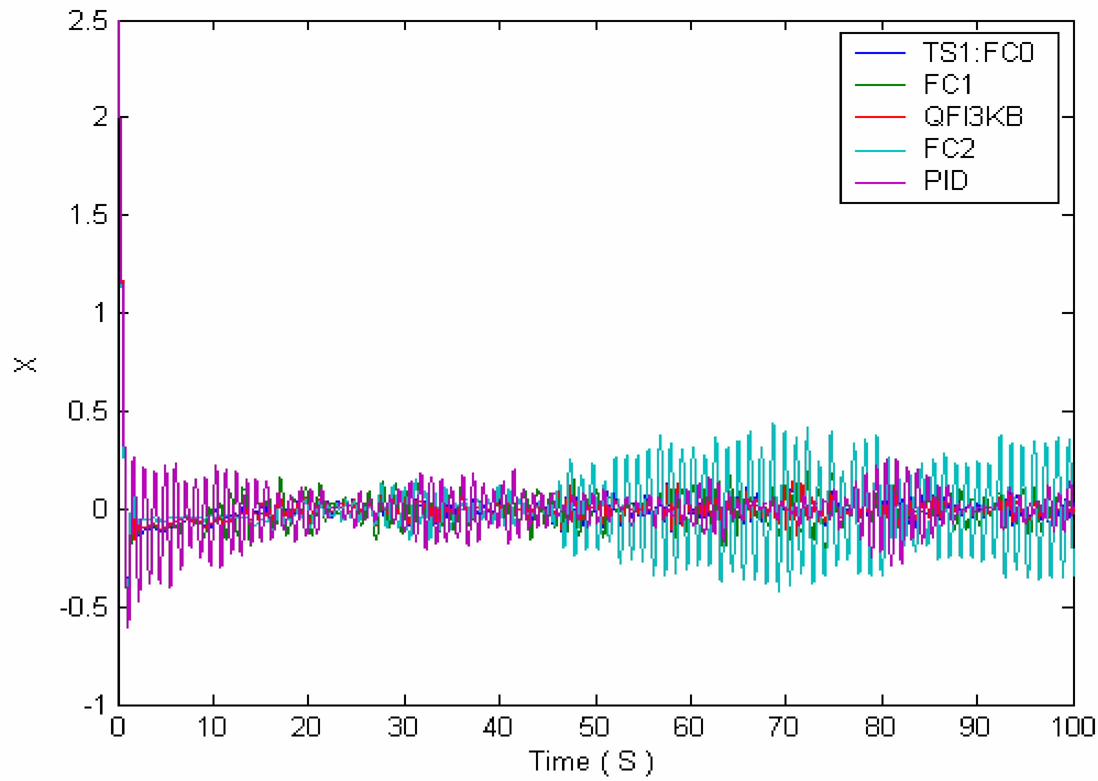


Figure 7b. Nonlinear oscillator. TS1 situation. Dynamic motion comparison. Time interval = [0-100] sec

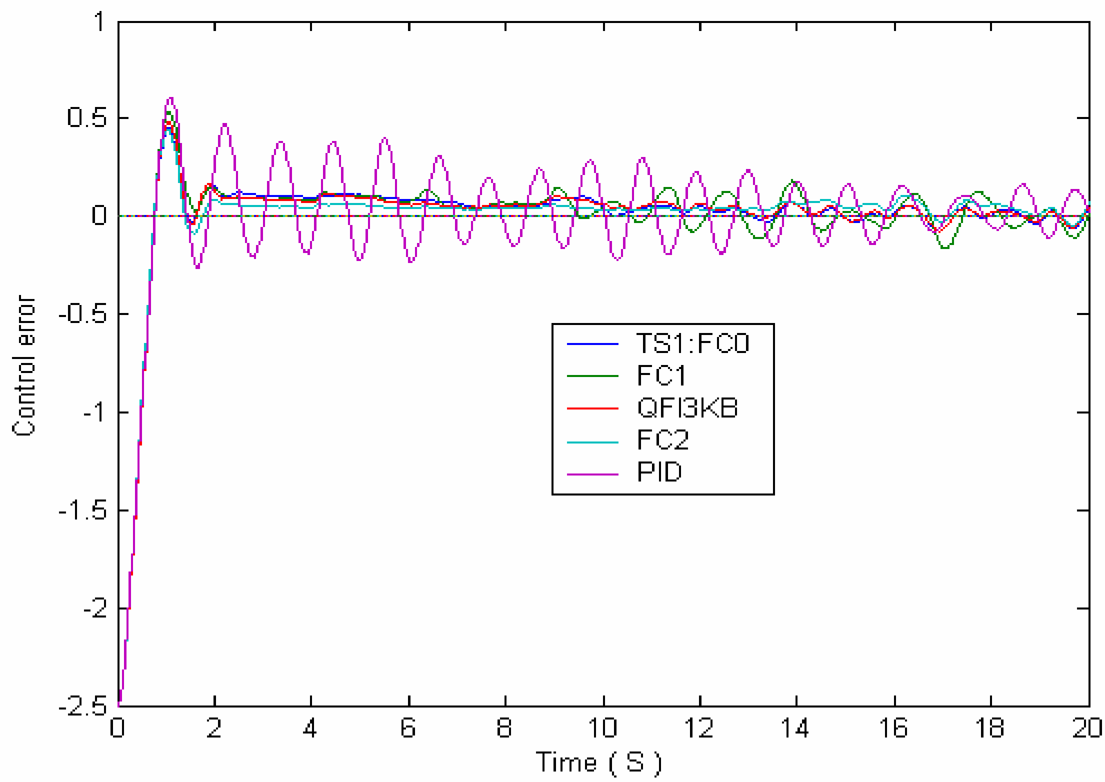


Figure 8a. Nonlinear oscillator. TS1 situation. Control error comparison.

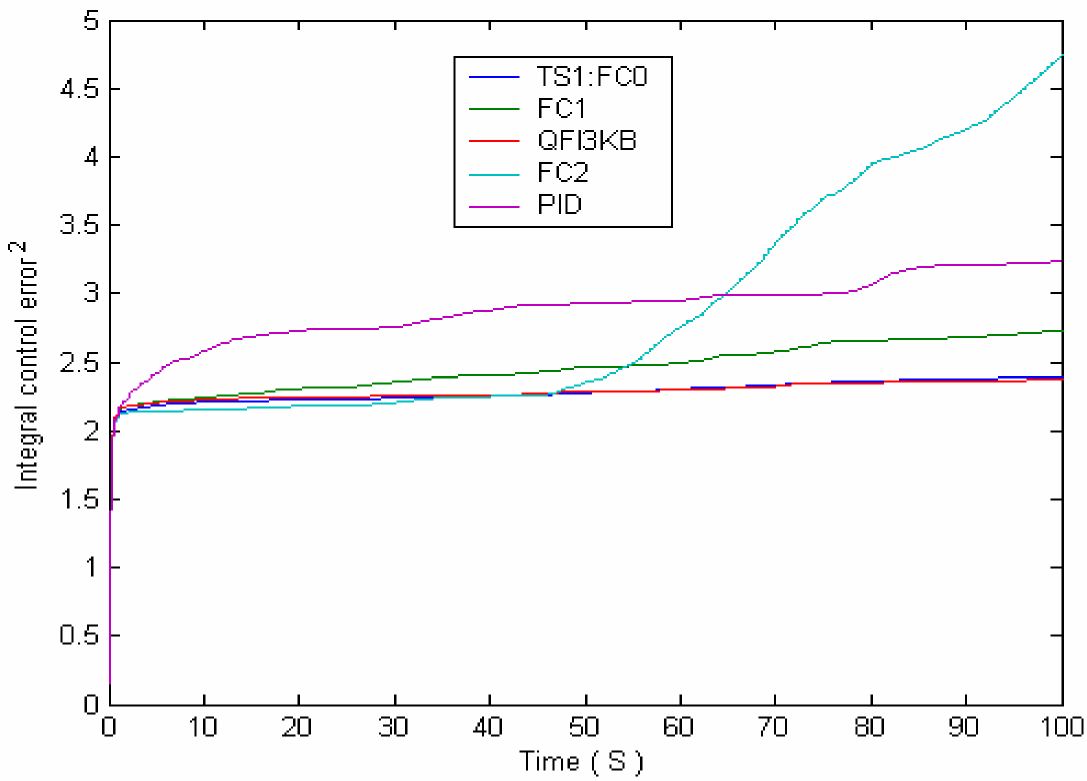


Figure 8b. Nonlinear oscillator. TS1 situation. Integral control error comparison.

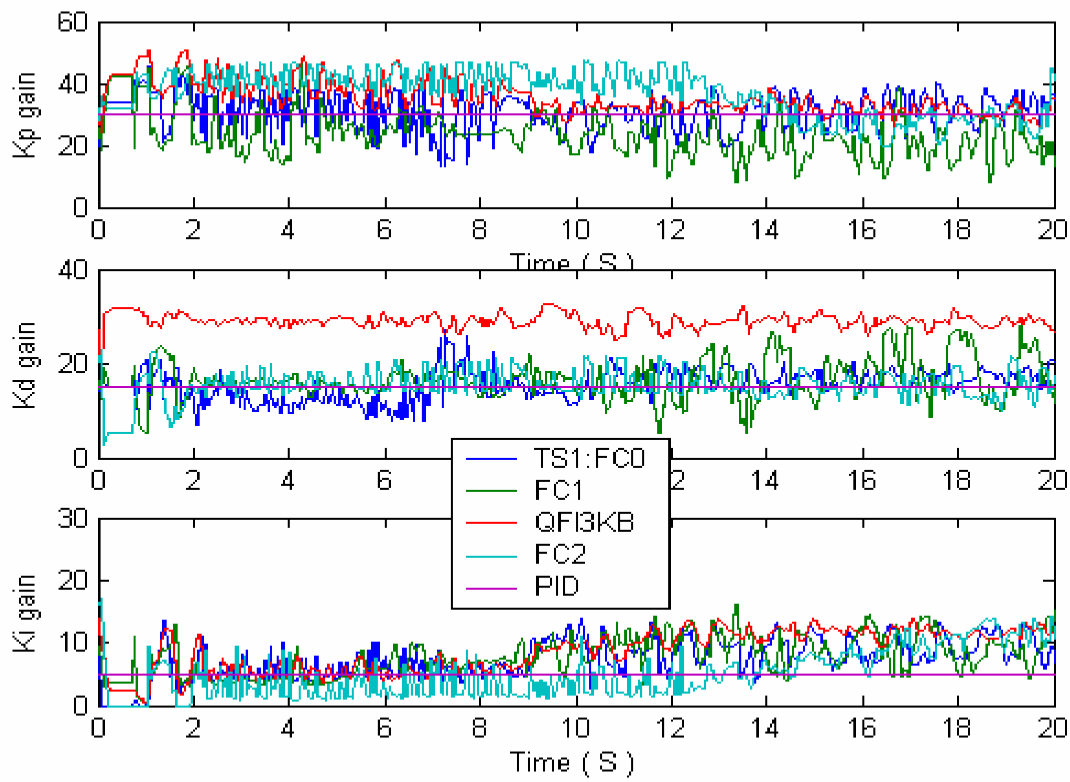


Figure 9. Nonlinear oscillator. TS1 situation. Control laws comparison.

Conclusion: from simulation results you can see that in teaching conditions TS1, two controllers (FC0 and QFI) are winners from the "min control error" criterion.

Robustness investigation

Let us consider CO dynamic behavior under four types of control in the case of ***extra-ordinary control situation.***

For example, take the following control conditions names as **R1**:

- external noise - Rayleigh noise as in TS2 teaching conditions;
- new sensor's delay time = 0.0125;
- new sensor's noise gain = 0.02 ;
- new model parameter Beta = - 0.1;
- TS initial conditions and simulation time t = 200 sec.

On Figures 11-14 the simulation results comparison is shown in R1 control situation.

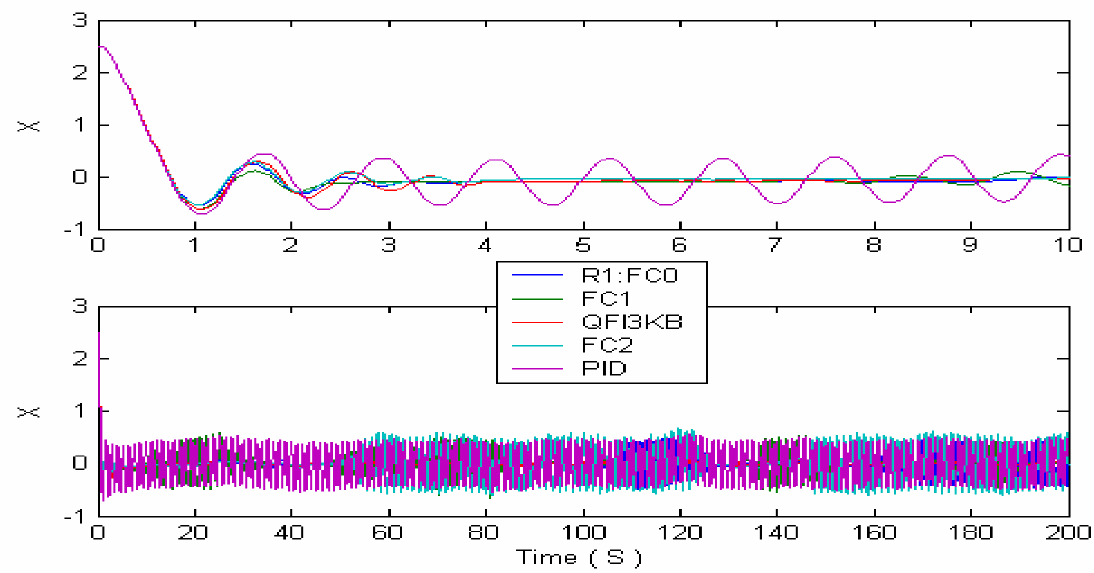


Figure 11a. Nonlinear oscillator. R1 situation. Dynamic motion comparison.
(time intervals are [0-10] sec and [0-200] sec)

On Fig. 11a you can see that four controllers (FC0,FC1, FC2 and PID) are failed in the new extra-ordinary control situation. But QFI-based controller with self-organization capability is successful. On the following below figure 11b we show CO dynamic motion without PID control.

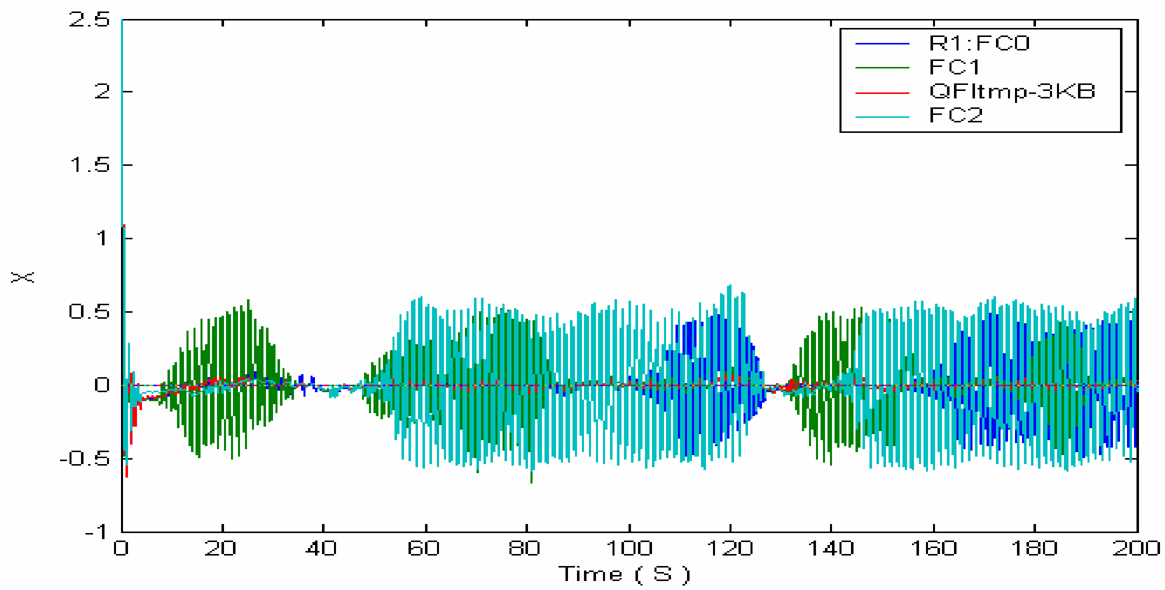


Figure 11b. Nonlinear oscillator. R1 situation. Dynamic motion comparison *without PID control.*

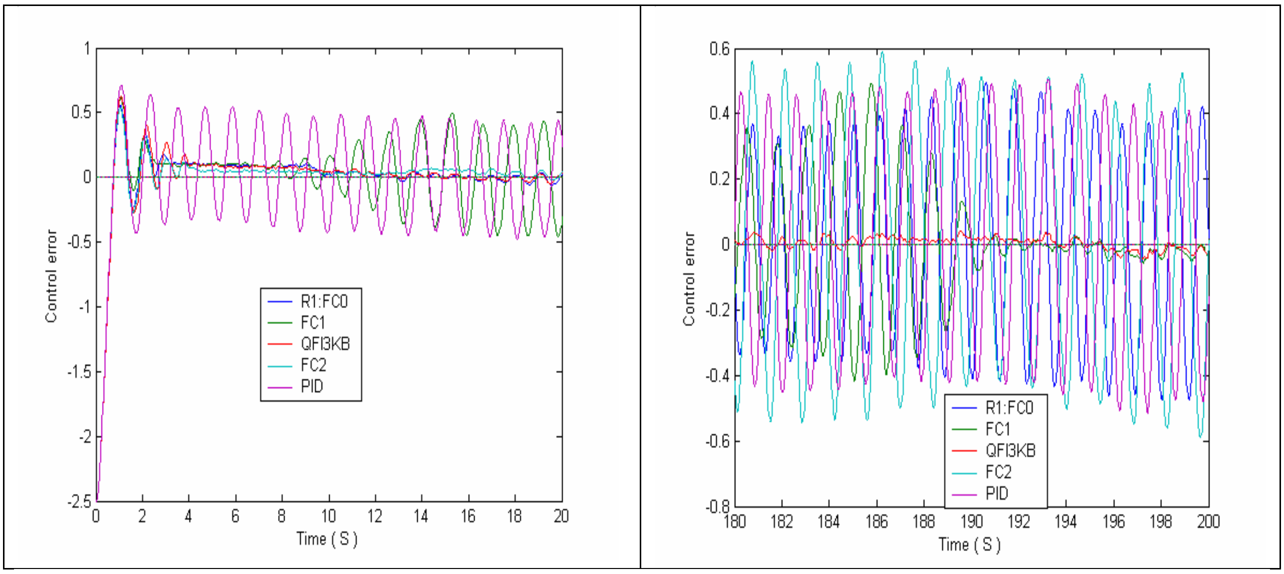


Figure 12. Nonlinear oscillator. R1 situation. Control error comparison.
(time intervals are [0-20] sec and [180-200] sec)

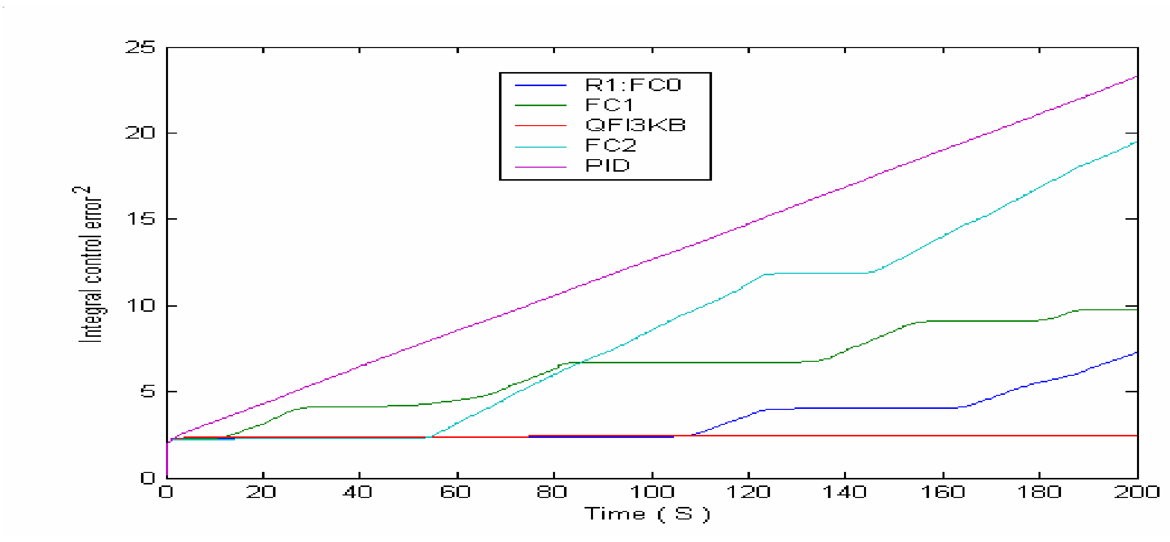


Figure 13. Nonlinear oscillator. R1 situation. Integral control error comparison.

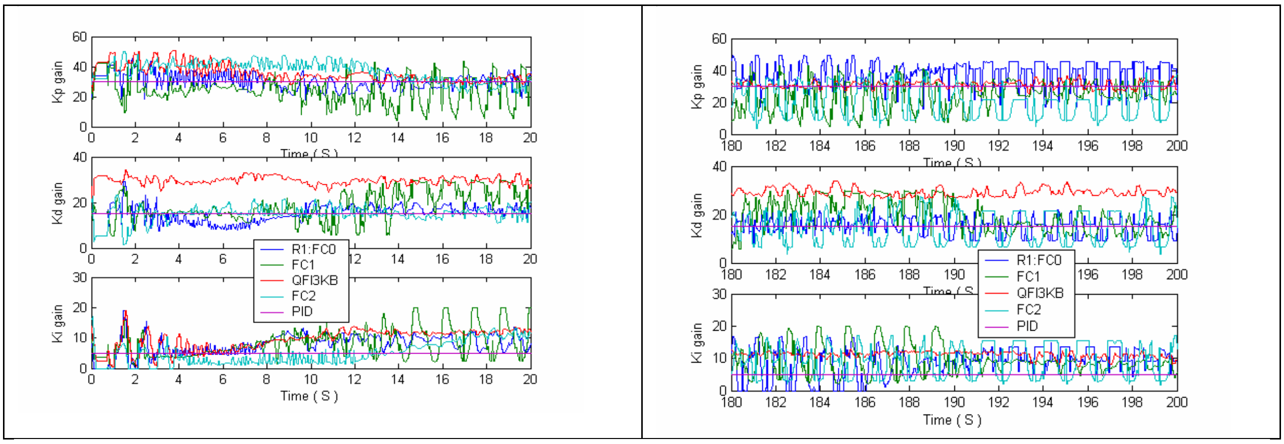


Figure 14. Nonlinear oscillator. R1 situation. Control laws comparison.
(time intervals are [0-20] sec and [180-200] sec)

Extend now the extra-ordinary range of unpredicted situations as shown in Fig.15.

R1 situation
External noise: TS2 noise;
New sensor's delay time = 0.0125;
New model parameter: Beta = - 0.1;
TS initial conditions;
t = 200 sec.

R1a situation
External noise: TS2 noise;
Sensor's delay time = 0.0125;
Bigger sensor's noise (gain = 0.035);
Model parameter: Beta = - 0.1;
TS initial conditions;
t = 200 sec.

R1b situation
External noise: TS2 noise;
Sensor's delay time = 0.0125;
New model parameter: Beta = - 0.2;
TS initial conditions;
t = 200 sec.

Figure 15. New unpredicted control situations

On Fig. 16 and Fig. 17 the simulation results comparison is shown in R1a and R1b control situation.

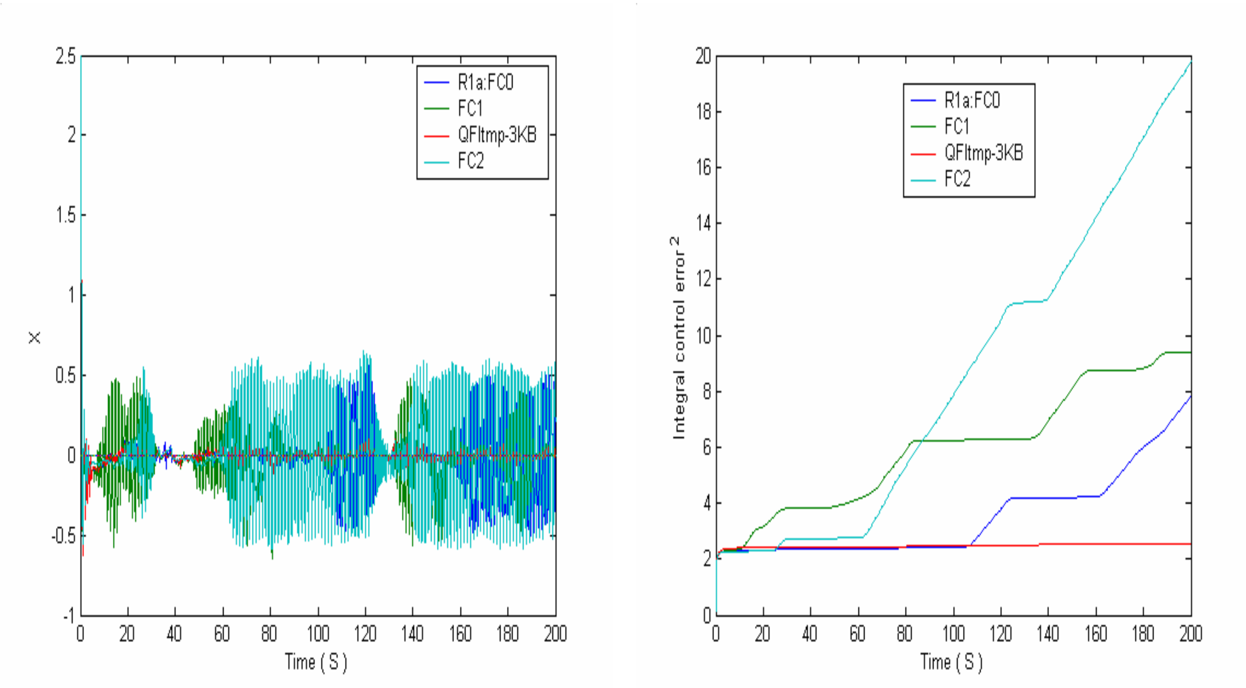


Figure 16. Nonlinear oscillator. R1a situation. Dynamic motion comparison (*without PID control*).

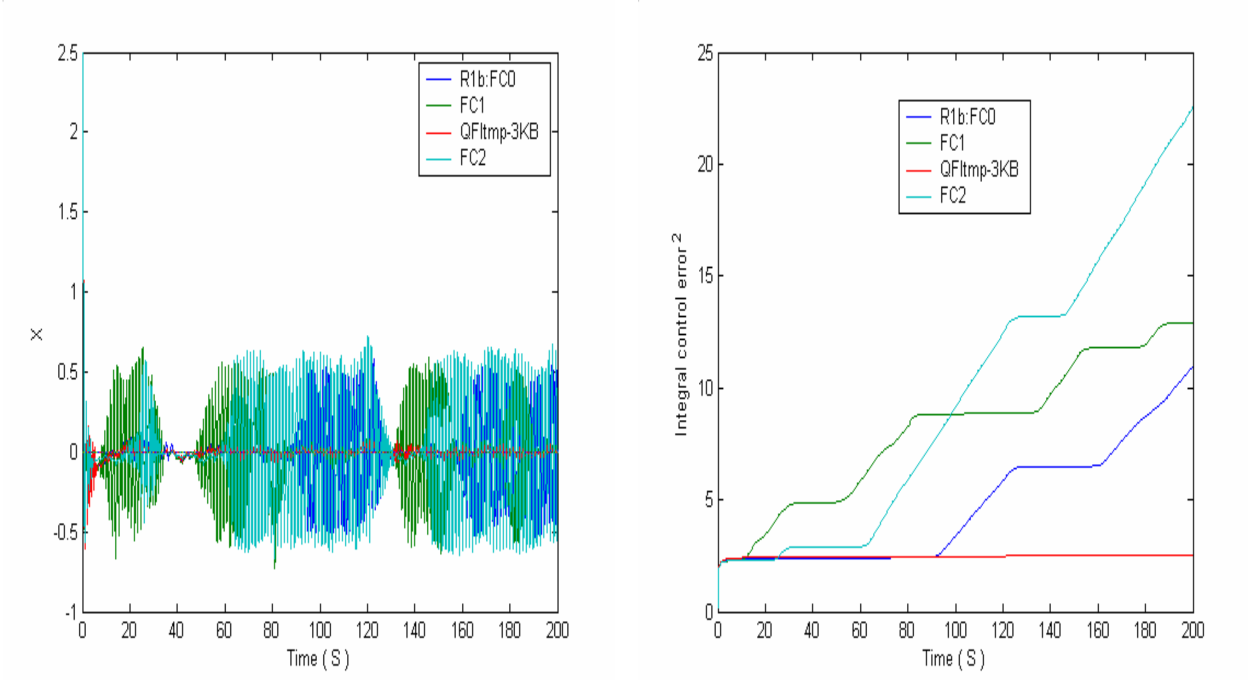


Figure 17. Nonlinear oscillator. R1b situation. Dynamic motion comparison (*without PID control*)

Comparison of temporal QFI with 2KB and temporal QFI with3KB

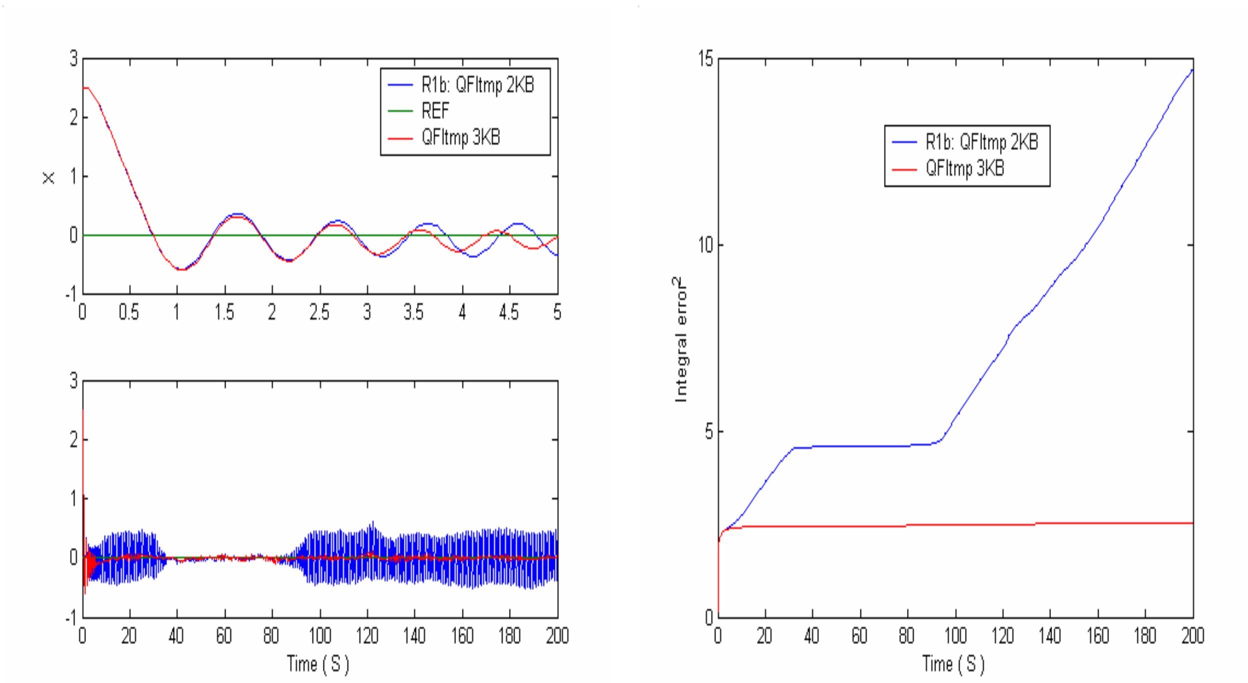


Figure 18. Nonlinear oscillator. R1b situation. Dynamic motion comparison

Main conclusions

- **QFI based controllers are essentially increase robustness properties of FC based on soft computing;**
- **With respect to QFI with 2 KB QFI with 3KB increases robustness of quantum controllers.**