PSO Algorithm-based Robust Design of PID Controller for Variable Time-delay Systems: AQM Application

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ABSTRACT
This paper formulates a robust control for variable time-delay system models. An automatic tuning method for PID-type controller is proposed. The adopted method integrates robust control design using Quantitative Feedback Theory (QFT) with Particle Swan Optimization heuristic algorithms (PSO) to systematize the loop-shaping stage. The objective of the design method is to reach a good compromise among robust stability, robust tracking and disturbance rejection with minimal control effort.
The resulting algorithm has attractive features, such as easy implementation, stable convergence characteristic and good computational efficiency. In particular, the results of the control design for active queue management (AQM) systems are presented. Simulations show improved congestion control and quality of service in TCP communication networks.

Keywords: Heuristic Optimization, PSO, Frequency Response, PID, Robust Control, QFT, AQM.

1. INTRODUCTION
Time delay systems arise in many practical engineering applications as inevitable consequence of information or material transmission. Some typical examples can be found in chemical processes, communication systems, power systems, and generally in any control system based on communication networks. Time-delay has a negative impact on system performance and may compromise stability [1],[2].
Their treatment is complex, especially when they vary over time or have uncertain values. In general, they are possible to be described by equivalent deterministic or statistical models which facilitate their study. Particularly for the deterministic case, robust control theory allows to represent them using the concept of uncertainty in the controller designs. Consequently, it ensures compliance with the performance criteria, independently of their value within the range of expected variation.
In this paper, a robust methodology to automatic or tuning of PID controllers for systems with uncertain varying time-delay is proposed. Quantitative Feedback Theory (QFT) [3] is combined with the Particle Swarm Optimization heuristic algorithm (PSO) [4] to determine the controller parameters so that the system achieves multiple optimal objectives in the conventional Pareto sense [5]. Robust stability, tracking properties, disturbance rejection and reduced sensitivity under varying operating conditions are specified.
Applying PSO to loop-shaping stage guarantees an automatic controller tuning procedure without overdesign. A more efficient controller is achieved; hence are obtained best results with simpler structures such as the PID. The characteristics and complexity of the problem does not allow the use of traditional optimization techniques, so smart search algorithms inspired by nature are presented as an effective alternative. Both QFT as PSO were selected following the criterion of maintaining clarity, simplicity and versatility of the procedures adopted and the good results that have been reported in various control applications [6] - [11]. The aim of QFT is the synthesis of a controller as simple as possible, with minimum bandwidth meeting the specifications at the lowest cost of feedback, taking into account model uncertainty.
PID controller is the most widely used control strategy in industry. Despite its simplicity, it can successfully solve a variety of complex problems [10]-[15].
The presented method is applied to design an alternative scheme of AQM to prevent congestion and to optimize the quality of service (QoS) in networks based on TCP. From the control theory based approach, the goal is to optimize the link utilization making the system less dependent on network load and reducing the effect of variable delay transmission. The robustness of the control is verified by simulations carried out using the dynamical model of the TCP behavior based on fluid-flow formulation [16]-[23]. This non-linear, non-stationary model proposed by Misra *et al.* [21], relates the key network variables. Variable operating conditions are contemplated with random parameter variations, such as number of active sessions, link capacity and round trip time (RTT).

QFT Overview

Quantitative Feedback Theory introduced by Horowitz [3] proposes a robust design methodology in the frequency domain based on standard feedback architecture of Fig. 1 (a). It allows the designer to meet specifications behavior over a specified region of uncertainty determined a priori in the modeling system. Regarding other methods of robust control, it presents greater transparency in the design process that relates to the complexity of the controller beforehand with feasibility of objectives. On the other hand, it quantitatively takes into account the cost of feedback regarding uncertainty.

From the transfer function of the process or system model, QFT takes into account that parameters, gain, poles and zeros may vary within known finite ranges. This leads to consider a region within the parameter space associated with uncertainty, Q, and a family of transfer functions, $\{P(j\omega,\boldsymbol{\theta}),\boldsymbol{\theta}\in\Theta\}$. One of them is adopted as the nominal plant model, $P_0(j\omega) = P(j\omega,\boldsymbol{\theta}_0)$, and used as the reference for the design. The uncertainty is included in the objectives to be achieved [6].

In Fig.1, a typical two degrees of freedom control configuration is shown, where $P(s)$ represents the plant with uncertainty and $H(s)$ represents the sensor dynamics. Disturbances are modeled by W, D_1 and D_2 processes. The potential existence of noise is incorporated with N; R is the reference signal and Y is the control objective.

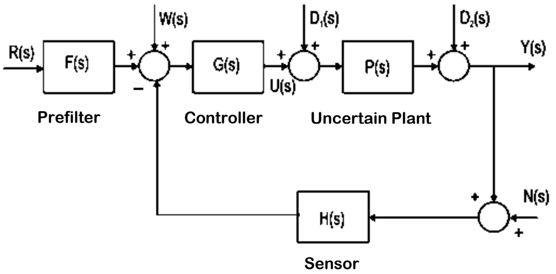

Fig. 1: Block diagram of the general control system.

In QFT, the inner loop controller $G(s)$ must compensate the uncertainty effect. The pre-filter F(s) can be included for a final settlement. For plant $P_0(s)$ its template is defined as the set of possible frequency responses associated with parametric uncertainty space. Quantitative specifications of stability, temporary behavior, and rejection or reduction of disturbances are expressed analytically in the frequency operation range, through restrictions on modules of transfer function families relating different loop variables, as shown in Fig. 1. Typical examples are listed in Table 1, where $L(j\omega,\boldsymbol{\theta}) = P(j\omega,\boldsymbol{\theta})\ G(j\omega)\ H(j\omega)$ denotes the family of open loop transfer functions. For the desired nominal open loop function $L_0(j\omega)e^{-j\omega\tau} = G(j\omega)\ P_0(j\omega)\ H_0(j\omega)\ e^{-j\omega\tau}$ these restrictions are represented as admissible regions in the module-phase complex plane known as Nichols chart. These regions are limited, for each frequency, by a set of curves called bounds.

The design consists in achieving the controller $G(j\omega)$ such as $L_0(j\omega)\ e^{-j\omega\tau}$ meets, as closely as possible, the constraint set defined by the bounds to avoid overdesign, while the high frequency gain and the bandwidth are minimized. If this goal is achieved for the nominal plant, it also holds for all loop transfer functions corresponding to the template.

From the point of view of optimum specifications fulfillment, the problem is of multiple targets with more than one possible solution Pareto efficient [5]. The bounds are invariable during the iterative optimization process, so that the calculations are reduced.

Table 1. Performance specifications in QFT design.

Specification	Constraints
Robust stability	$\left\lvert \frac{1}{1+L(j\omega,\boldsymbol{\theta})\, e^{j\omega(\tau+\Delta\tau)}} \right\rvert \le \delta_1(\omega),\ \omega\in\Omega_1$
Robust tracking	$\delta_m(\omega) \le \left\lvert \frac{P(j\omega,\boldsymbol{\theta})\, G(j\omega)}{1+L(j\omega,\boldsymbol{\theta})\, e^{j\omega(\tau+\Delta\tau)}} \right\rvert \le \delta_M(\omega)\ ,\ \omega\in\Omega_1$
Disturbance rejection	$\left\lvert \frac{P(j\omega,\boldsymbol{\theta})\, G(j\omega)}{1+L(j\omega,\boldsymbol{\theta})\, e^{j\omega(\tau+\Delta\tau)}} \right\rvert \le \delta_2(\omega),\ \omega\in\Omega_2$

Brief Review on Particle Swarm Optimization Algorithm

The robust control involves a complex formulation, highly nonlinear with a feasible non-convex space of solutions. Numerous heuristics methods of intelligent search have been proposed to obtain optimal results in this type of problems. These include algorithms that imitate natural phenomena based on populations. From a general point of view, it is considered a collection of individuals distributed within the feasible space of parameters. In the successive iterations, the individuals move trying to carry out space exploration effectively in search for the optimum. This is achieved in each iteration considering three (generally stochastic) steps: self-adaptation or improving their own performance, cooperation -where all members contribute to the transfer of information- and competition according the reached success.

Among heuristic algorithms, PSO has been found useful in the design of controllers. Thanks to the clarity of its operation and the limited number of specific parameters, good regulation of convergence is achieved [24], [25]. The search procedure proposed by Kennedy and Eberhart [4] reproduces the social interaction between members of a group of the same species to accomplish an objective, as it occurs in flocks of birds or swarm of bees. Such social behavior is based on each individual's transmission of success to the rest of the group, resulting in a synergistic process enabling them to achieve a common goal in the best possible manner.

In PSO, each individual in a fixed population size is

associated with a position in the multidimensional search space that represents a possible value of the unknown parameter vector.
Initially, the positions are assigned randomly and go changing with a rate adjusted dynamically taking into account individual experience and the information shared by the rest of the group. In any case the best position reached by either the set or each member represents the set of parameters with which the lowest value of the objective function is obtained.
If $\boldsymbol{X}$ and $\boldsymbol{V}$ define the position and velocity vectors in n-dimensional parameter search space, N is the population size, $\boldsymbol{P}_{\text{best}}$ and $\boldsymbol{G}_{\text{best}}$ are the best positions achieved by each individual and by the group, respectively, the dynamic evolution or update of the positions and velocities in the k-th iteration are described by the following vector expressions:

$$\boldsymbol{V}^i_{k+1} = W_k \boldsymbol{V}^i_k + \Delta\boldsymbol{V}^i_k$$

$$\Delta\boldsymbol{V}^i_k = C_1 R_1 (\boldsymbol{P}^i_{best} - \boldsymbol{X}^i_k) + C_2 R_2 (\boldsymbol{G}^i_{best} - \boldsymbol{X}^i_k) \quad (1)$$

$$\boldsymbol{X}^i_{k+1} = \boldsymbol{X}^i_k + \boldsymbol{V}^i_{k+1} \quad (2)$$

$$W_{k+1} = W_{max} - (W_{max} - W_{min})\, k/k_{max} \quad (3)$$

where $1 \leq i \leq N$. The inertia W_k regulates the trade-off between the swarm global and local exploration abilities, and varies linearly between an initial maximum $W_{\max}$ and a minimum $W_{\min}$ on reaching the maximum allowed iterations, $k_{\max}$. The last two terms in the expression (1) represent the individual and collective intelligences, with C_1 and C_2 cognitive and social factors, and R_1 and R_2 random numbers uniformly distributed on [0,1].

Multi-objective Optimization in QFT Framework
The general PID controller structure is considered. It includes a proportional term, an integrative term and another derivative term to which a pole is incorporated to prevent high frequency noise amplification. Its transfer function is given by

$$G_{PID}(s) = K_p + \frac{K_i}{s} + \frac{K_d\, s}{\frac{K_d}{T}s + 1} \cdot \quad (4)$$

The dimension of the parameter space is $n = 4$ and the position is the vector of parameters $\boldsymbol{X} = [K_p\, K_i\, K_d\, T\,]^T$.
The objective function to be minimized includes robust stability, robust tracking, and disturbance rejection properties - through the distance between the open loop transfer function and the bounds - and the bandwidth constraint by the high frequency gain, according to

$$f(\mathbf{X}) = \gamma_1\, 20\log(K_{HF}) + \gamma_2 \sum_{k=1}^{n_f} f_{bdb}(\omega_k) + \gamma_3 \sum_{k=n_{lim}}^{n_f} f_{UHF}(\omega_k),$$

$$f_{bnd}(\omega_k) = d_k, \qquad k = 1,2,\cdots,n_f,$$

$$f_{UHF}(\omega_k) = d_{Lk}\,\delta, \quad k = n_{lim}, n_{lim}+1,\cdots,n_f, \quad (5)$$

where $\delta = \begin{cases} 0 & \text{if the condition is satisfied,} \\ 1 & \text{otherwise,} \end{cases}$

γ_i are weighting factors; n_f is the number of frequencies considered within the working range; d_k and d_{Lk} denote the distances between the nominal open loop transfer function , L_0 ($j\omega_k$), and the corresponding bound, and the distance between the nominal open loop transfer function $\omega_k \geq \omega_{lim}$ ($k \geq k_{lim}$) and the so-called universal high frequency bound (UHB), respectively. This condition ensures good performance at high frequency. K_{HF} is the high frequency gain or feedback cost as defined in Eq. (6) where (m-r) denotes the difference between numbers of poles and zeros of L_0.

$$\lim_{\omega\to\infty} |L(j\omega)| = \lim_{\omega\to\infty} \frac{K_{HF}}{\omega^{m+2-r}} \quad (6)$$

A pair of restrictions, g_1 and g_2 in Eq. (7), are included to ensure both stability and fulfillment of the bounds during the process. The closed loop transfer function denominator is a quasi-polynomial. Then, to simplify the stability verification, the complex exponential is approximated by a zero on the right-half, $e^{s\tau} \approx (1 - s\tau)$. Thus, g_1 is defined taking into account that a linear and time invariant system is stable if the roots of its characteristic polynomial, p_i , are real and negative, or complexes with negative real part

$$g_1(\mathbf{X}) = \max_{1\leq i\leq m+2-r} \left(Re(p_i), 0\right) \leq 0,$$
$$g_2(\mathbf{X}) = \max_{1\leq i\leq n_f} \left(d_k, 0\right) \leq 0. \quad (7)$$

Restrictions and limits of search space treatment are performed by penalty method, and the criteria for convergence takes into account the invariance of the best found value of the objective function within the numerical tolerance considered acceptable during a number given iterations.

2. PID CONTROLLER DESIGN FOR AQM SUPPORTING TCP FLOWS

For queue management in TCP routers, various techniques have been proposed in order to avoid congestion without waiting for the remote information.

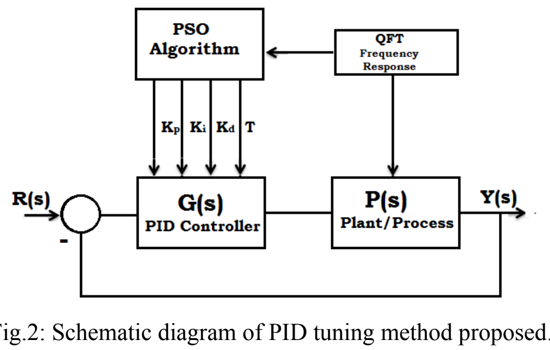

Fig.2: Schematic diagram of PID tuning method proposed.

The common problem is that each configuration is only suitable for certain traffic conditions. Hence, designing a PID control algorithm in the context of robust control theory is presented as a good alternative because it takes into account variable operating conditions through the uncertainty. Next, the design details based on this approach with the proposed QFT-PSO methodology are presented (Fig. 2).

Fluid-Flow Model of TCP Dynamics

A model based on the fluid-flux and represented by nonlinear stochastic differential equations was proposed by Misra *et al.*(2000).This model describes the dynamics of TCP during the congestion prevention mode. In this work, the simplified approach is used ignoring the slow start and time out mechanisms. Moreover, it has been assumed that the AQM scheme implemented marks packets using Explicit Congestion.

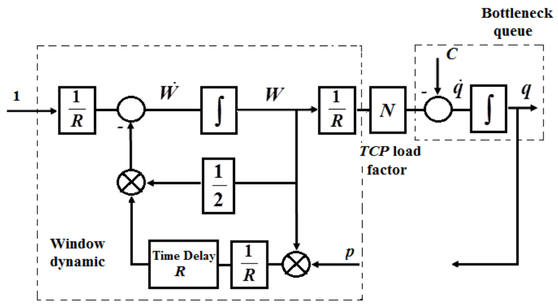

Fig. 3: Block diagram of TCP´s congestion-avoidance mode.

Notification to inform the TCP sources of impending congestion. This model relates the mean value of the main network variables and is described by a system of two coupled nonlinear time-variant differential equations. It is recommended to consult [21] for model details and to see Fig. 3 for a block diagram.

A block diagram representation is shown in Fig. 3, where W is the average TCP window size (packages), q is the average queue length (packets), R is the round-trip time (sec), C is the link capacity (packets/sec), T_p is the propagation delay (sec), N is the load factor (number of TCP sessions) and p is the probability of packet mark ($p \in (0,1)$).

The first step for the model small-signal linearization around an operating point is the derivation of the time invariant equations under the following hypothesis: the temporal delays are assumed to be constant and equal to R_0; the operation point satisfies the nonlinear time variant equations; the number of TCP sessions and the link capacity are constant; $N(t) \equiv N$: constant and $C(t) \equiv C$: constant. [22],[23].

In the steady state operation point (W_0, q_0, p_0), $\dot{W} = 0$ and $\dot{q} = 0$ so, the following equations are obtained $W_0^2\, p_0 = 2, \quad R_0 = \frac{q_0}{C} + T_p, \quad W_0 = \frac{R_0 C}{N}.$

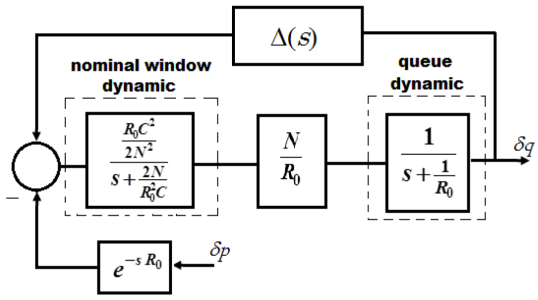

Fig. 4: Block diagram of the linearized model with high frequency uncertainty

The schematics for the resulting linear model is shown in Fig. 4 where perturbed state variables about the operation point are

$$\delta W(t) = W(t) - W_0, \qquad \delta q(t) = q(t) - q_0,$$

and the corresponding perturbed control action is

$$\delta p(t) = p(t) - p_0.$$

The linear model may be considered composed by a nominal part (low frequency) and a high frequency residual. The former is taken as the plant model for the TCP behavior and contains the delay and the dynamics both of the queue and the window. The latter is accounted as parasitic uncertainty following Eq. (8), and is to be included in the process design as an input disturbance [22], [26] as shown in Fig. 4 and 5,

$$P(s)e^{-Rs} = \frac{\frac{RC^2}{2N}}{\left(s + \frac{2N}{CR^2}\right)\left(s + \frac{1}{R}\right)} e^{-Rs}$$

$$\Delta(s) = \frac{2N^2 s}{R^2 C^3}(1 - e^{-Rs}) \ . \qquad (8)$$

The parametric uncertainty is established by the family of plants with different gain and poles according to the operating conditions of the network $100 \le N \le 150$, $3650 \le C \le 3850$, $0.150 \le R \le 0.246$.

The specifications imposed in this work according to table 1 with $H_0(j\omega) = 1$ and considering that $\left| e^{-j\omega\tau} \right| = 1$ are shown in

$\delta_2 = 1.2$, $\Omega_1 = \{\omega: 0.01 \le \omega \le 35\}$, $\Omega_2 = \{\omega \in \Omega_1: \omega \ge \omega_{lim} = 15\}$

$$\delta_m(\omega) = \left| \frac{2}{(s+0.5)(s+1)(s+4)} \right| \qquad \delta_M(\omega) = \left| \frac{0.7\,(s+1)}{s^2 + 1.306\,s + 0.7} \right|$$

$$\delta_1 = \alpha \left| \Delta(j\omega) \right|^{-1} < \alpha \left| \frac{C^3 R^3}{4N^2} \frac{(s+10)}{s} \right| . \qquad (9)$$

The parameters used for the PSO are: size of the population N= 60, C_1 =1.2, C_2 = 0.5, $0.4 \le W \le 0.9$.

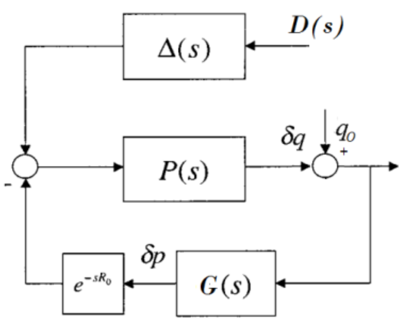

Fig. 5: AQM in the QFT framework.

The Fig. 6 shows the templates describing the dispersion in the frequency response due to the uncertainty and Fig. 7 shows the resulting design for the open loop frequency response with PID controller and the composite bounds on de Nichols chart.

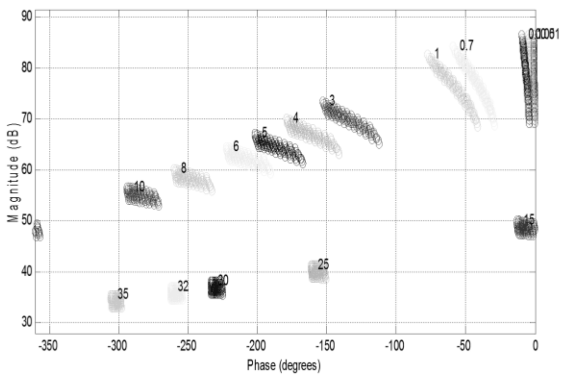

Fig. 6: QFT model Templates

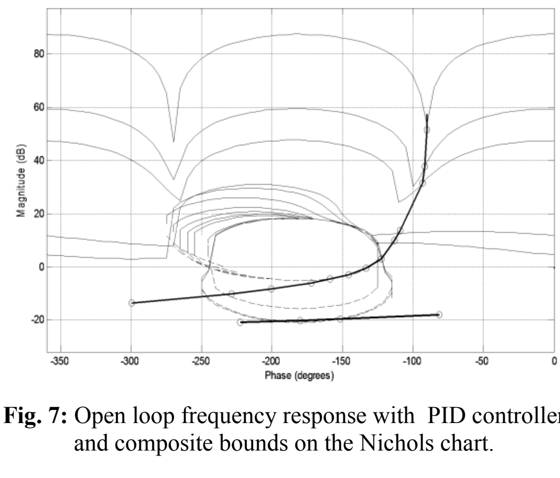

Fig. 7: Open loop frequency response with PID controller and composite bounds on the Nichols chart.

The achieved controller parameters are:
$[K_p\ K_i\ K_d\ T\,]^T = [1.8999\ 10^{-4}\ 1.7\ 10^{-4}\ 4.2472\ 10^{-5}\ 1000]^T$.
Robustness is guaranteed since the shaped frequency response, at each design frequency, lies above the bounds, neither enters the U-contours nor intersects the critical point (-180°, 0 dB).
The phase and the gain margins along with the crossover frequency, MF = 50.8°, MG= 6.7 dB, ω_0 = 2.8 *rad/sec*. The settling time and overshoot t_s = 5.7 sec, M_p=11%.

Robustness analysis
Robustness can be checked by simulation using the non-stationary, non-lineal model implemented with Simulink®.
In order to comparison a typical benchmark network has been selected. Following [26] and [27] random variation of the parameters that describe the stochastic nature of the network dynamics are considered and illustrated in Fig. 8.
The buffer is considered to be large enough to avoid overflow and the average packet size is 500 bytes. The results are compared with those presented in [27] using a PI control.
With the control proposed in this paper, the response is faster, the queue average value and the RTT present less variations around the setup point and the queuing delay result smaller (Fig. 9,10,11).
Efficient queue utilization, regulated queuing delay and robustness are obtained.

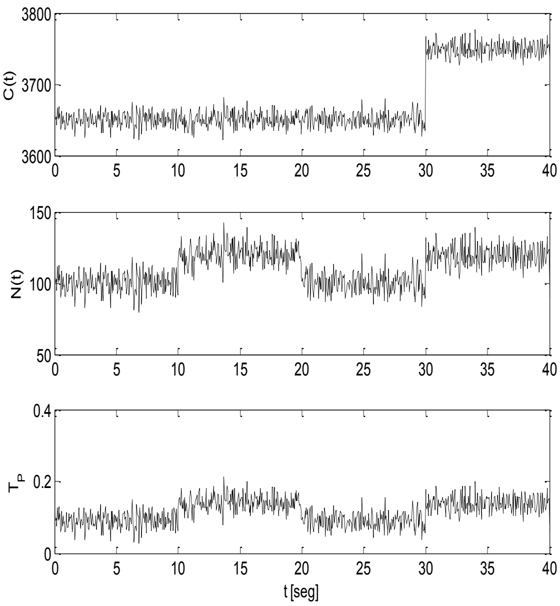

Fig. 8: Random variations in the network parameters *C, N* and T_p

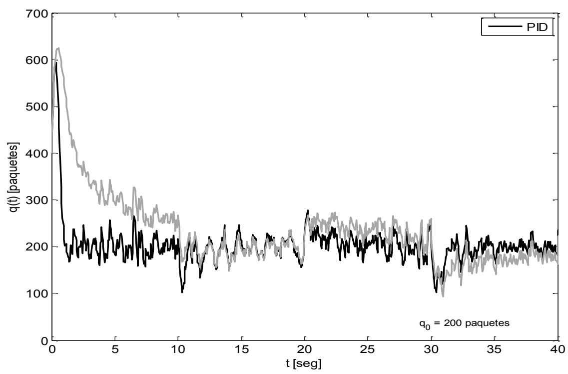

Fig.9: Instantaneous queue length with controller, q_0= 200.

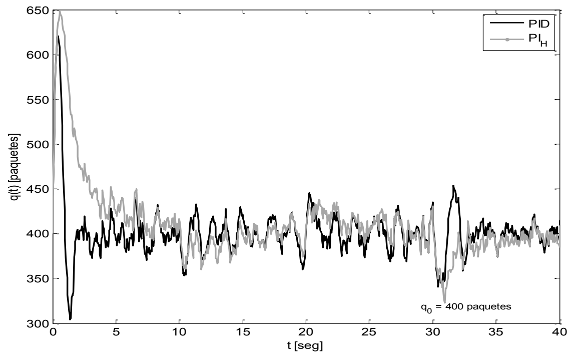

Fig.10: Instantaneous queue length with controller, q_0= 400.

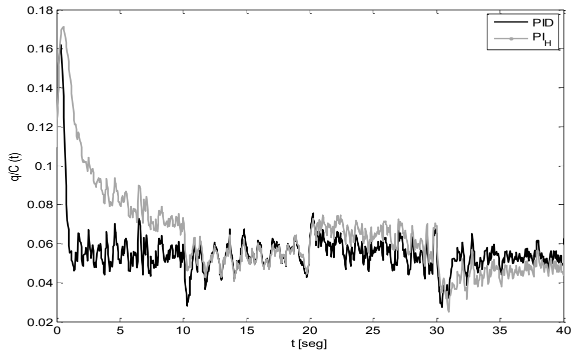

Fig 11: Instantaneous RTT with the controller for q_0=200.

3. CONCLUSIONS AND FUTURE WORK

In this paper a robust methodology for the design of PID controllers for systems with bounded time variable delay using QFT and PSO algorithm is proposed. This combination delivers the best controller performance fulfilling the design specifications even in the worst cases as imposed by the uncertainty. The PSO algorithm converges to one of the possible optimal solutions with low dispersion as measured by the variance of the parameter vector converge value. Good results are obtained in an application for an actual control scheme queue in networks with changing operating conditions. Performance criteria of the control theory and the network analysis are both taken into account. Comparisons with published results are made and reinforce the methodology effectiveness. Simulations results using the non-linear model implemented with Simulink validate the design. The stochastic nature of the process was included by using random parameters in the network description. Good results are also expected with the use of a net simulator such as the *ns*2. A non trivial extension of this work would be to consider a network topology with multiple links.

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