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Analysis of the Most Likely Regions of Stability of an NCS and Design of the Corresponding Event-driven Controller

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Abstract: In this paper, some issues related to design and analysis of real networked control systems (NCS) under the focus of the most likely region of stability are addressed. Such a system is cumbersome due to its inherent variable time delays, ranging from microseconds to hours. To show the influence of such huge variations in the control performance, a laboratory-scale luminosity system has been setup using the Internet as part of the control loop with dominant time constant in the order of milliseconds. Proportional and integral (PI) control strategies with and without explicit compensation for the time-delay variations were implemented using an event-driven controller. Using the well-known Monte Carlo method and subsequent analyses of time responses, it has been possible to identify the most likely region of stability. Some experimental results show the influence of the statistical parameters of the delays on the determination of the most likely regions of stability of the NCS and how these can be used in assessment and redesign of the control system. The experiments show that much larger delays than one sample period can be supported by real NCSs without becoming unstable.

Keywords: Networked control systems, real NCS, delay compensation, most likely regions of stability, delay statistics.

1 Introduction

Networked control system (NCS) is an emerging theme that has lately attracted much research interest as an effective control alternative. Some survey papers have been recently published in the literature[1, 2]. NCSs require the concurrence of proper tools for representation, analysis and synthesis of controlled feedback systems, aiming at reducing the existing gap between the theoretical achievement and practical applications[3–5] of NCS. This paper presents some experimental results. The authors believe that these experiments can provide: 1) a better understanding of the behavior of real NCSs with variable delays and 2) how far the control strategy can go to improve performance with the minimum risk of violating stability conditions.

In an NCS, the control loop is closed over data communication networks in real time. The control signals and feedback measurement (input and output signals of the plant) are transmitted over a network. As shown in Fig. 1, the NCS design should consider all delays in the loop, namely; τ_p (the plant itself); τ_s (the sensor data acquisition); τ_c (time spent in the execution of the control algorithm); τ_s (the actuation derive); τ_{sc} (time elapsed in the message transmissions between sensor and the controller) and τ_{cs} (time elapsed in the message transmissions between the controller and the actuator).

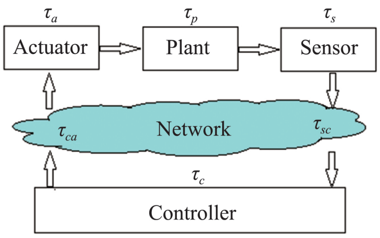

Fig. 1 NCS architecture

The control loop closed over a data network communication also has to cope with delay variations, sampling irregularities[6], noise in the communication channel, corrupted data, packet losses[7–13] connection losses and limited capacity of the network[14–16]. If the clocks of the local and remote stations are synchronized, by means of time stamps, e.g., it is always possible to determine the value of τ_{sc} at execution time of the control algorithm, the delay can be compensated by the controller[17].

However, the value of τ_{ca} is only known for sure after the control algorithm execution and this is obviously not available at the time that the controller generates the control signal. Therefore, more elaborate strategies for prediction and compensation of the delays are required in NCSs, depending on the way that delays occur and on the characteristics of the controlled process[6, 13, 18–28].

Research Article

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In the design of an NCS, there are some problems of great complexity that, in general, have been treated in an isolated way. Since the various factors affect one another, they should be integrally considered. This directly impacts the modeling, the analysis and the synthesis of the NCS. Concerning the variable delays, they cause irregularities in the sampling periods and a real NCS has to cope with fractional values of delays in relation to the sampling period. According to the literature, in general, the delays commonly observed in real NCSs can be grouped in two categories with the following characteristics: 1) They are variable and limited up to a single sampling period[24, 29, 30] or, in some cases, they are limited to two or three sampling periods[31] with bounded derivative[32] or unbounded derivative[29, 30]; 2) They are taken as deterministic[33] and considered fixed or limited to a maximum or medium value for analysis of specific operating conditions[23, 24]. There are few models that describe arbitrary variations of delays limited to a value greater than one sample period[35].

It is important to note that delay in NCSs should be treated differently from the one in traditional time-delay systems due to its particular characteristics. For example, when a long delay occurs in an NCS, the messages are queued and the controller, upon the reception of delayed signals, can processed them sequentially, almost instantly, in a very short time. Different from what happens in standard time delays systems, a great delay value can be recovered quickly if it is followed by small delays. That is, the delay increases with every sample and reduces almost instantly.

The effects of delays, found in real NCSs, usually, have been addressed either in isolation or in combination with certain constraints (in the majority of cases, limited to one sampling period) and other singularities, e.g., irregularsamplings[36],messagerejections[37],quantizationproblem[38], packet losses[39−42] and packet reordering[43]. This paper mainly focuses on the effect of the variable delays; the other listed singularities will be addressed using the proposed methodology in future works.

In this work, emphasis is given to the control design and analysis focusing on the most likely stability region of NCSs subject to variable delays, like those found in real systems. Under the current paradigm in the NCS area, the analysis and design are based on the maximum delay limit, by means of deterministic approaches. In this work, a probabilistic analysis approach is used, as an alternative to conventional design methods. It is expected that this study could emphasize the importance of the use of probabilistic methods for analysis and design of NCSs in a more realistic way, especially in practical applications[17, 44].

In a broader study of the authors, some real NCSs have been implemented, with time constants ranging from milliseconds to hours, including processes with constraints that require particular control solutions. Although different control strategies have been proposed, implemented and evaluated for each process, in this paper, it is decided to present the results obtained with the luminosity control loop of a laboratory-scale optical oven, since this loop has the smallest time constant. A system with small time constant is more difficult to establish the feedback control under a network since delays have more pronounced effects. Besides, faster systems require better accuracy in the synchronism between the local and remote stations and in the measured values of the varying delays. In [44], a methodology was proposed to make analyses of the most likely regions of stability in an NCS. It was evaluated in a simulated study using as a benchmark a first order system with time constant in order of seconds. In this work, this methodology has been applied to a real NCS using a system with time constant in order of milliseconds with varying delays in all links (τ_{sc}, τ_{ca} and τ_{sa}). Since these delays are effectively measured, a more accurate evaluation is feasible contributing to the implementation of adequate compensation techniques.

In [23], a time-driven proportional integral (PI) controller with explicit compensation for time-delay variations was proposed. Though based on [23], in this work, an event-driven PI controller has been proposed and implemented in a real system. Event-driven controllers are better suited to NCSs, since the varying delays found in real systems cause irregularities in the sampling times. An event triggered control was also used in [6, 13]. In this work, the event of messages arrival has been used to trigger the start of the control signal calculations.

The major contributions of this paper are 1) the proposition of an event-driven controller based on a time driven-controller with explicit compensation and 2) to show, by means of some experimental results, that the statistical parameters of the delays have an impact on the determination of the most likely regions of an NCS stability. Therefore, they can be used in the assessment and redesign of the control system, so as to obtain better performance. It is worth emphasizing that the conventional methods commonly used for analysis and design of NCSs not so rarely result in extremely conservative systems with consequent significant loss of performance. Under these considerations, the proposed method can be seen as an alternative to implement an NCS with acceptable performance even in adverse conditions. It may be particularly advantageous when applied to systems prone to have delays of tens of sampling periods. Moreover, the statistical methods are useful to take into account the probability of occurrence of events with low probability but are also the ones that mostly reduce the stability margins. These unlikely events could be disregarded in closed loop design and, whenever necessary, included in an alarm status for eventual transfer to a more conservative control or even switched to manual mode.

2 System and platform descriptions

The experimental tests described in this work have been accomplished using a real test platform especially designed for monitoring and control purposes called NCS-CMUF[45]. In the NCS-CMUF platform, the networked control system can operate either in local mode (in which the control loop is closed only in the local network, controller area network (CAN)) or in remote mode (in which

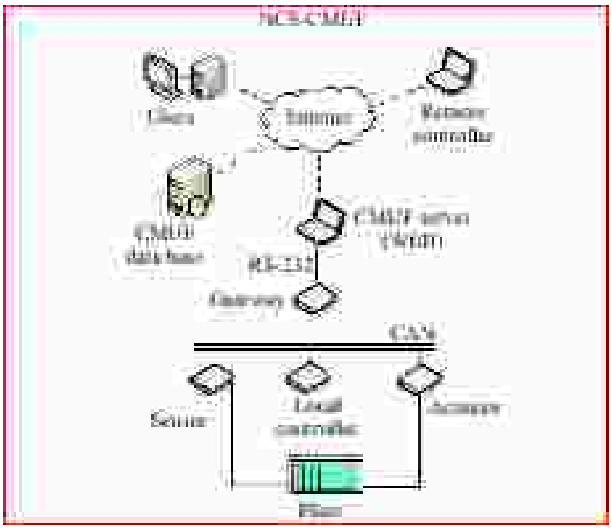

Fig. 2 NCS-CMUF architecture

the control loop is closed over a CAN, an RS-232 link and the Internet), as illustrated in Fig. 2.

In the results presented in this paper, the remote operation mode has been chosen, configured with the sensor and the actuator operating locally and the controller remotely. It was considered that the sensor is time-driven and the controller and the actuator are event-driven. That is, the sampling period is determined at the sensor level. At each sampling instant, the sensor sends a message with the most recent measurement of the plant output (feedback signal) over networks to the remote controller, which processes the feedback signal, generates the control signal and forwards it, via the networks, to the actuator. The actuator, in its turn, receives the control signal and sends an acknowledgement message back to the remote controller together with a time stamp. Since all messages have timestamps, it is possible to calculate the value of τ_{sc} and τ_{ca} delays. Even so, the value, of τ_{ca} delay is only available to the remote controller after the application of the control signal with the arrival of the acknowledgment message. Therefore, its effect can only be computed and eventually compensated in the following samplings. Every message generated by each one of the network elements has a specific serial number. The serial number is used to establish the communication handshaking and plays an important role in the networked control scheme. Upon receiving a message, the receiver station sends an acknowledgment message to the sender station with the same serial number of the original message. This structure allows the detection of possible packet loss or message repetition by means of the serial number checking. To minimize the occurrence of packet losses in the NCS-CMUF platform, the stations are provided with a mechanism for resending messages with a transmission buffer based on priority scheme and proper timeout settings.

In the NCS-CMUF platform, the synchronism between the local and remote stations (remote controller and CMUF server) is established by means of the network time protocol (NTP) service. The synchronism among the local stations is ensured by a remote reset of the clocks by means of messages. In the current setup, the software of the remote control station and the CMUF server (see Fig. 2) has been implemented in a computer with Linux kernel. The codes of the gateway, of the actuator, of the sensor and of the local controller stations (Fig. 2) have been implemented in PIC16F876A-based microcontrollers.

The plant used to develop the tests presented here consists of an optical oven equipped with an incandescent lamp and with temperature and luminosity sensors. The luminosity control loop has been chosen to be the controlled variable because it has a small time constant, in milliseconds (Since, from the point of view of networked controller, fast dynamics are more difficult to control than slow dynamics). The sensor measurement range is between 0 and 226 lux.

The actuation on the plant is performed by means of a circuit based on a thyristor that modulates the electric power delivered to the lamp. The actuation signal is sent to the plant by means of the pulse width modulation (PWM) output of the microcontroller station of the NCS-CMUF platform. Roughly speaking, this signal is inversely proportional to the root mean square (RMS) voltage applied to the lamp. The signal range is between 150 bits (corresponding to the maximum voltage of 108.4 V, i.e., 100% of the control signal) and 800 bits (corresponding to the minimum voltage of 27.7 V, i.e., 0% of control signal). The information in bits is given throughout the paper to highlight the nonlinear characteristic of the loop which the controller has to cope with.

3 Modeling and controller design

3.1 Modeling

A second-order model with time delay has been considered suitable to represent the dynamics of the luminosity loop. The traditional complementary response method is used to get the model parameters from actual step responses. The estimated transfer function is presented in (1) which has been used for design of controllers, with the dominant time constant equal to 201 ms and the gain equal to 0.63 (bit/bit) that corresponds to 2.6 lux/% of the control signal.

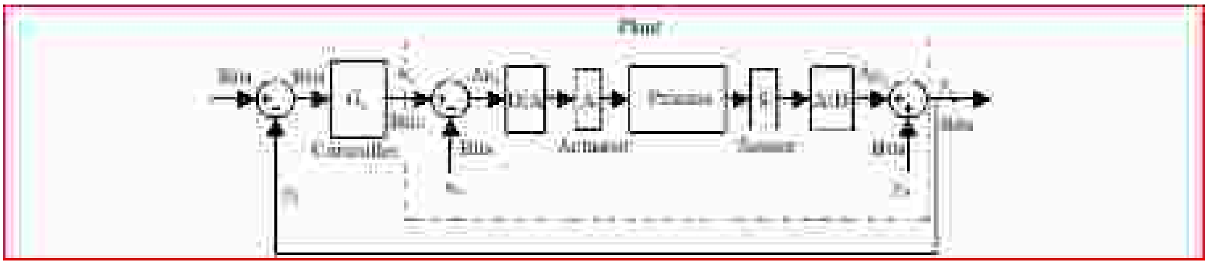

Fig. 3 Block diagram of the closed-loop system

$$G_L(s) = \frac{\Delta Y_L}{\Delta U_L} = \frac{0.63e^{-0.1s}}{(0.201s+1)(0.053s+1)}. \quad (1)$$

The discrete model has been obtained using the Z-transform with zero-order hold (ZOH) and a sampling time of the 100 milliseconds (this is the minimum value of the sampling time that is possible to implement on the NCS-CMUF platform). The discrete model output (in bits) is then given by (2):

$$\begin{aligned} \Delta y_{L(k)} &= -a_1 \Delta y_{L(k-1)} - a_2 \Delta y_{L(k-2)} + \\ & \quad b_1 \Delta u_{L(k-1-\theta_p)} + b_2 \Delta u_{L(k-2-\theta_p)} \\ y_{L(k)} &= \Delta y_{L(k)} + y_0 \\ u_{L(k)} &= \Delta u_{L(k)} + u_0 \end{aligned} \quad (2)$$

where y_L and u_L correspond, respectively, to the output and input of the plant, $a_1 = -0.759\,6$, $a_2 = 0.092\,2$, $b_1 = 0.143\,9$, $b_2 = 0.065\,6$, $y_0 = 126$ bits, $u_0 = 0$ bits and $\theta_p = 1$. Fig. 3 presents the block diagram of the closed-loop system.

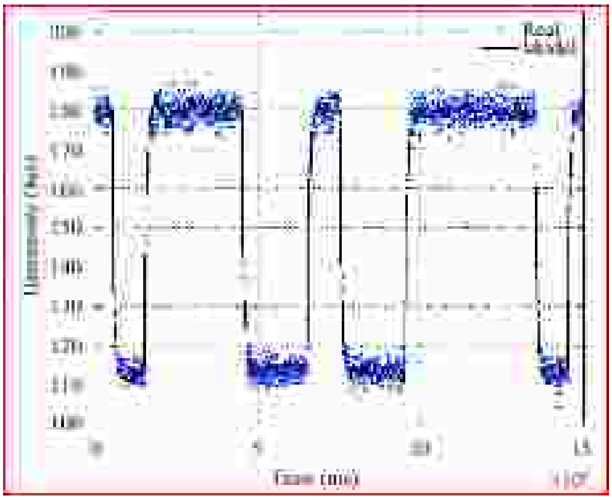

Fig. 4 Superposition of the simulated (solid line in black) and real (dot line in blue) responses of the plant output

Fig. 4 illustrates the plant output behavior (real and simulated by means of the model shown in (2) subject to a pseudo-random binary sequence (PRBS) input signal. This result confirms the model validation in real operation conditions.

3.2 Standard PI controller

In this work, a proportional plus-integral (PI) controller with anti-windup scheme has been designed. For the practical implementation of the controller, the discrete equations, obtained by bilinear transformation, have been used. The structure of the PI controller is shown in Fig. 5, where $K' = K_c(1 + h/(2T_i))$ and $\beta = (2T_i - h)/(2T_i + h)$, h is the sampling time, K_c is the proportional gain and T_i is the integral gain of the PI controller.

3.3 Event-driven controller: PI with explicit compensation for time-delay variations

The PI controller with explicit compensation for time-delay variations, proposed in [23], adapted for event-driven controller, has been implemented. In this control strategy, the time-delay variations are compensated by means of the explicit compensation of the control signal (Fig. 6). The main idea is the use of an extra feedback compensation aiming at reducing the deficiencies in the control signal (partially applied to the plant input in previous samples) as consequence of the τ_{ca} delay variations. Due to the large variability of τ_{ca} delays, the time at which the calculated control signal (at each sampling instant) is

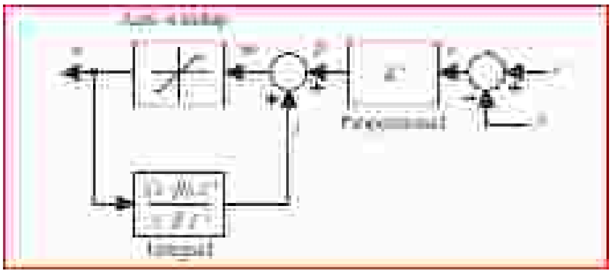

Fig. 5 Block diagram of the discrete PI controller with anti-windup

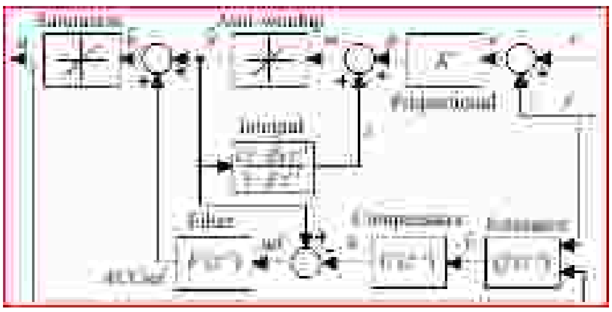

Fig. 6 Block diagram of the PI controller with explicit compensation of the control signal (PI+EC)

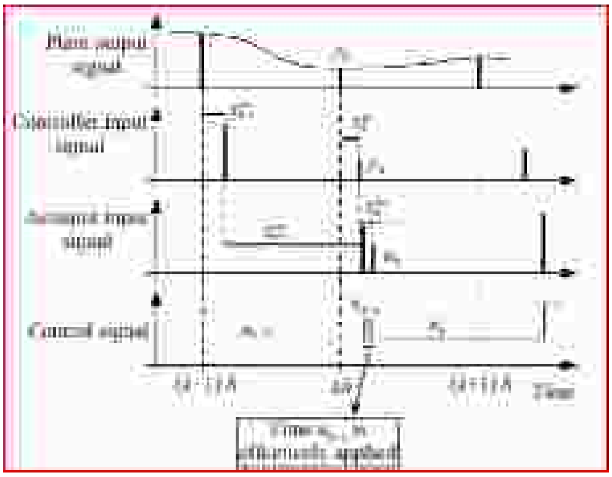

Fig. 7 Time profile of the signals in an NCS: effect of delays

effectively applied to the plant is also variable (and may be greater or smaller than one regular sampling period), as shown in Fig. 7. To illustrate this, in Fig. 7, the highligthed control signal, $u_{(k-1)}$, is effectively applied to the plant for less than one sampling period.

The control system (Fig. 6) makes use of an estimator to forecast the plant output values and, from them, to generate a compensation signal for the control action. Based on the model of the plant, the control signal (which is supposedly applied to the system at each sampling instant) is calculated and used to perform an extra compensation in the control signal[23].

In Fig. 6, $ACCud$ represents the accumulated control signal deficit. This deficit is calculated based on explicit compensation structure, that consists, essentially, of an estimator, $Q(z^{-1})$, a compensator, $C(z^{-1})$, and a filter, $F(z^{-1})$. The estimator makes use of an autoregressive model with exogenous input as in (3).

$$\begin{aligned}\Delta\hat{y}_{(k)} = &- a_1\Delta y_{(k-1)} - a_2\Delta y_{(k-2)} - \cdots - a_{na}\Delta y_{(k-na)} + \\ &b_1\Delta u_{(k-1)} + b_2\Delta u_{(k-2)} + \cdots + \\ &b_{nb}\Delta u_{(k-nb)}\hat{y}_{(k)} = \Delta\hat{y}_{(k)} + y_0\end{aligned} \tag{3}$$

where $a_1, \cdots, a_{na}$, $b_1, \cdots, b_{nb}$ and y_0 represent the plant model parameters, and y_0 and u_0 are the initial conditions. The control signal compensation is given by (4).

$$\begin{aligned}\Delta\overline{u}_{(k-1)} = &(\Delta\hat{y}_{(k)} + a_1\Delta\hat{y}_{(k-1)} + a_2\Delta\hat{y}_{(k-2)} + \\ &\cdots + a_{na}\Delta\hat{y}_{(k-na)} - b_2\Delta\overline{u}_{(k-2)} - \\ &\cdots - b_{nb}\Delta\overline{u}_{(k-nb)})/b_1 \\ \overline{u}_{(k-1)} = &\Delta\overline{u}_{(k-1)} + u_0.\end{aligned} \tag{4}$$

The control signal deficit (ud) is given by (5):

$$ud_{(k-1)} = \hat{u}_{(k-1)} - \overline{u}_{(k-1)} \tag{5}$$

where $\hat{u}$ is the control signal calculated without compen sation. The accumulated control signal deficit is then given by (6).

$$ACCud = \sum_{j=0}^{nm-1} \gamma ACCud + K_f(1-\gamma)ud_{(k-j-1)} \tag{6}$$

where K_f represents the filter gain, γ is the filter time constant and nm is the total number of measurements that come to the controller during the k-th sampling interval. In the results presented here, nm is considered 1, since the controller is event-driven and thus just one measurement arrives during the whole sampling period for the calculation of the control signal. In these tests, $K_f = 1$, and the filter time constant, γ, is either set equal to 0 (without filter) or $\gamma = 0.9$, and $\gamma = 0.95$ depending on the test performed.

The PI controller was designed using the well-known direct synthesis method. The application of this method is based on the process model and the desired closed-loop response. In this work, the desired closed-loop response was set to $\tau_d = \tau_1 + \tau_2 = 254$ ms, i.e., equal to the open loop time constant. Although the direct synthesis method applied to a process modeled as of second order results in a PID controller, in the design in question, the derivative term, T_d, was set to 0 (since the calculated T_d value does not satisfy a practical implementation restriction of the discrete controller). The values of the designed controller parameters are listed in Table 1.

Table 1 Controller parameter

Parameters	Values
K_c	1.14
K'	1.36
β	0.67
T_i	254 ms
h	100 ms

4 Analysis of the most likely region of stability

To analyze the most likely region of stability of the implemented NCS, the methodology proposed in [44] has been adopted. It is noteworthy that the most likely region of stability is directly related to the maximum delay limit (most likely statistically) that the NCS supports without becoming unstable.

The method proposed in [44] evaluates, in a systematic way, the possible behaviors of the system in closed-loop, subject to uncertainties, by means of the analysis of the time responses. The delays present in NCSs are treated as uncertain parameters. This method can be seen as a tool for the evaluation of the applicability of the various control techniques or settings to a given NCS. The methodology (based on the Monte Carlo experiments coupled with a sorting algorithm and a gradient search using the analysis of time responses) is intended to provide less conservative limits of stability, or equivalently, the most likely regions in which stability is likely to hold.

The accuracy of Monte Carlo algorithms depends on the representativeness of random samplings. The best results are achieved by increasing the number of samples. The results only ensure that all possible behaviors of the system were analyzed if the limit of the number of samples tends to infinity. However, it is possible to make a relatively fair analysis of the most likely behaviors of the system with a finite (relatively large) number of samples. Thus, the most likely stability regions can be probabilistically guaranteed. In [44], it has been shown that the method, compared to conventional approaches, gives a more realistic stability region for practical applications.

The method follows an algorithmic procedure whose steps are: 1) Randomly generate the uncertain parameters (in this case the delay) as commonly found in real NCSs using the Monte Carlo method; 2) For a given controller, simulate (during a time-window of n samples) the closed-loop system with the generated uncertain parameters; 3) Evaluate in this time-window (of n samples) if the behavior of the time response (step or impulse or null reference, with initial state condition different from zero) tends to destabilization or not; 4) Iteratively repeat steps 1) – 3) to find the most likely limit of uncertain parameters that provide a stable closed-loop system.

At each algorithm iteration, the set of uncertain parameters are generated and a data window with the plant output is evaluated. To achieve the most likely limit of the uncertain parameters, the algorithm has been implemented with a search and convergence criteria, as detailed in [44].

To analyze the luminosity control loop, some numerical simulations have been performed using the method proposed in [44]. To emulate the (variable) delay in a more realistic way, an oversampled discrete-time model (with the main sample period h=100 ms and the secondary sample h_2=h/200) has been used to generate the random delays at each k-th intersampling time instant ($t = kh_2$), $h_2 \ll h$ and the delays are considered as multiples of h_2. The oversampled discrete-time model, obtained using $h_2 = 0.5$ ms, is given by (2), where $a_1 = 1.988\,125\,9$, $a_2 = 0.988\,149\,3$, $b_1 = 0.736\,298\,1 \times 10^{-5}$, $b_2 = 0.733\,378\,0 \times 10^{-5}$, $y_0 = 126$ bits, $u_0 = 0$ bits and $\tau_p = 1h = 200h_2$; with the poles located at $p_1 = 0.997\,515\,5$ and $p_2 = 0.990\,610\,4$. At the plant output, y_L measurement noise has been added in the simulation to provide conditions as close as possible to the real conditions. The measurement noise added in the simulation has been generated based on the real noise measured at the plant. The distribution, mean and variance of the real measured noise have been determined from measured data and analyzed so that the generated noise can present similar characteristics in the simulation. The noise generated is Gaussian with mean equal to zero and variance around 7.5 lux^2 (that corresponds to the variance of the measured noise).

The simulations have been performed using the PI controller with setpoint equal to 179.5 lux (350 bits). The maximum (constant) delay determined from the phase margin (using (7)) with the PI controller is equal to 469 ms.

$$\tau_{\max} = \frac{P_m}{W_{cp}(180/\pi)} \tag{7}$$

where P_m is the phase margin and W_{cp} is the crossover frequency (at 0 dB). The phase margin has been determined considering the continuous plant coupled with a ZOH, $(1 - \mathrm{e}^{-sh})/h$, that is equivalent to the discrete system.

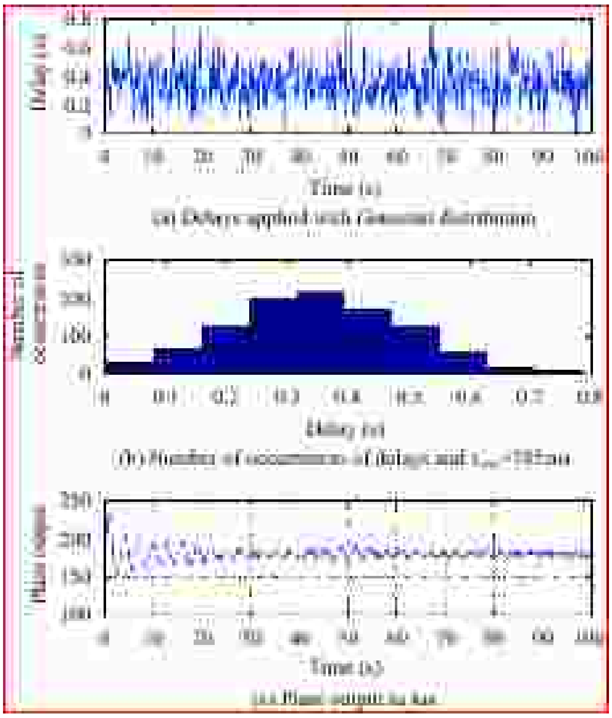

Fig. 8 Stability threshold for NCS of the luminosity loop

The variable delays have been simulated with uniform, Gaussian and exponential distributions. Fig. 8 illustrates simulation results of the NCS with the luminosity loop and the delays with Gaussian distribution. The maximum obtained delay was equal to $\tau_{\max} = 785$ ms, i.e., greater than 7 samples (as $h = 100$ ms). Fig. 8 (a) depicts the delays applied with Gaussian distribution, Fig. 8 (b) the number of occurrence of delays and Fig. 8 (c) shows the plant output.

Table 2 summarizes the values of maximum delay, average delay, delay variance and the algorithm runtime (obtained using a computer with Intel i3 2.4 GHz processor and 2 GB RAM). The proposed algorithm is sequentially executed 10 times (#1 to #10) with 1 000 samples and random delays with Gaussian distribution.

The same procedure has been repeated with uniform distribution and the results are listed in Table 3.

Comparing the data listed in Table 2 with the ones in Table 3, it can be seen that the maximum values obtained for the delays with uniform and Gaussian distributions were very similar (The average of 10 tests was equal to 763 ms for a Gaussian distribution and 767 ms for a uniform distribution). Reflecting that for this loop, the effect of the distribution (uniform or Gaussian) was not so pronounced, under the simulated conditions. As for the exponential distribution, whose results are shown in Fig. 9 and in Table 4, the maximum obtained delay was $\tau_{\max} = 5.985$ s, i.e., greater than the delays obtained for the Gaussian and uniform distributions.

Table 2 Simulation results: delays with Gaussian distribution

Test #	Run time (s)	Average delay (s)	Variance	$\tau_{\max}$ (s)
1	56.61	0.352	0.020	0.785
2	39.42	0.314	0.016	0.690
3	36.03	0.349	0.019	0.745
4	27.38	0.352	0.020	0.840
5	39.29	0.338	0.018	0.815
6	53.75	0.355	0.019	0.800
7	23.70	0.326	0.016	0.750
8	33.15	0.277	0.013	0.615
9	23.82	0.340	0.018	0.830
10	25.37	0.359	0.018	0.760
Average	35.85	0.336	0.018	0.763

Table 3 Simulation results: delays with uniform distribution

Test #	Run time (s)	Average delay (s)	Variance	$\tau_{\max}$ (s)
1	49.45	0.398	0.051	0.795
2	35.64	0.337	0.039	0.675
3	43.08	0.283	0.029	0.575
4	27.31	0.424	0.061	0.845
5	28.05	0.406	0.055	0.825
6	37.44	0.432	0.058	0.855
7	41.46	0.402	0.054	0.810
8	57.15	0.398	0.051	0.795
9	26.09	0.386	0.048	0.775
10	22.31	0.348	0.041	0.720
Average	36.80	0.381	0.049	0.767

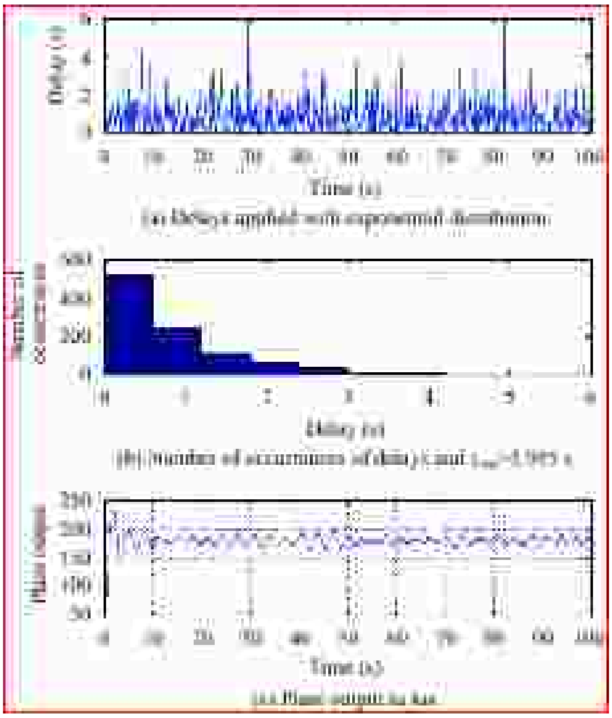

Fig. 9 Stability threshold for NCS of the luminosity loop

Table 4 Simulation results: delays with exponential distribution

Test #	Run time (s)	Average delay (s)	Variance	$\tau_{\max}$ (s)
1	39.53	0.819	0.647	5.985
2	23.34	0.491	0.238	2.875
3	29.47	0.598	0.372	3.820
4	36.86	0.511	0.264	3.440
5	27.57	0.517	0.276	3.280
6	45.80	0.530	0.243	3.085
7	10.39	0.783	0.574	4.980
8	25.70	0.483	0.235	3.545
9	50.99	0.560	0.302	3.205
10	34.67	0.505	0.252	3.770
Average	32.43	0.580	0.340	3.799

5 Experimental results

The results presented here upon were obtained in a real NCS applied to the luminosity loop (see Section 2). In the tests accomplished in the real plant, the stations of the remote controller and CMUF server (see Fig. 2) were physically located in a laboratory at a university campus and they were configured with fixed IP in the same subnetwork. Firstly, some tests have been performed considering only the natural delays of the network.

Since the natural delays did not present larger variations, some experimental tests have been subsequently conducted with artificially increased delays (with the aid of a buffer placed in the feedback loop). The use of this buffer turned possible a more detailed analysis of the effects of larger delays and with reproducible characteristics to evaluate different types of controllers.

5.1 Experiments with the natural delays of the network

The behavior of an NCS, in closed-loop, subject to natural delays of a real network, is evaluated in the experiments considered in this subsection. Thus, the tests have been performed with PI and PI with explicit compensation (PI+EC) controllers. The loop behavior in each test, together with the profile of delay variations are presented below.

The profiles of the plant output, of the control signal and of the characteristics of delays obtained with PI controller are illustrated in Fig. 10 for a typical operating condition. Fig. 10 (a) presents an excerpt of the controlled plant output during an experimental test of over an hour long (or 38 000 samples) and the setpoint (PRBS signal) with detail of the last 6 000 samples. In Fig. 10 (b), the corresponding control signal is shown. Fig. 10 (c) shows the variation profile of delays τ_{sc}, τ_{ca} and τ_{sa}. Note that, at the beginning of the test, there is a loss of synchronism, reflected by the increment in τ_{ca} and decrement in τ_{sc}. This synchronism error is mitigated during the test by the use of a dynamic synchronization strategy

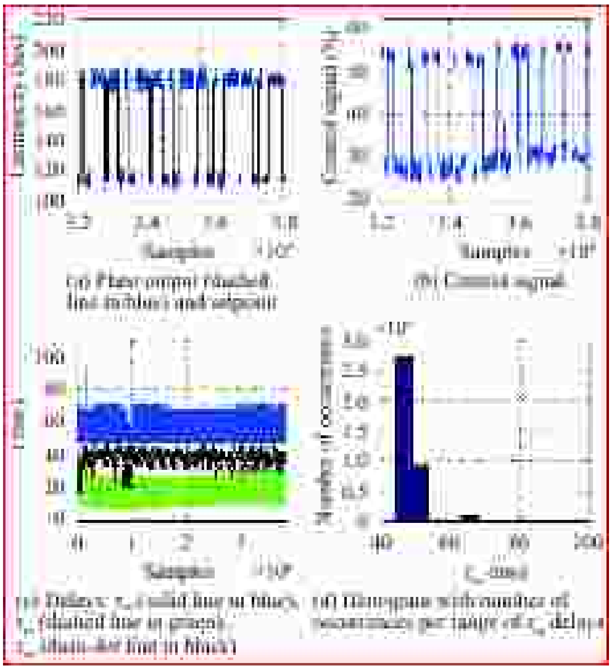

Fig. 10 Test 1, PI controller and PRBS reference

that has been implemented in the NCS-CMUF platform, which uses the standard NTP service. However, it is noteworthy that this offset between the clocks (less than 10 ms) that has been detected can be also occur during the tests, since this offset value is in the range normally provided by the NTP service (most likely between 0.1 ms and 10 ms, but can exceed a hundred milliseconds with low probability of occurrence)[46]. Synchronism assurance is one of the major challenges in a implementation of real NCSs.

Fig. 10 (d) shows the histogram with the number of occurrences per range of τ_{sa} delays. The analysis of Figs. 10 (a) and 10 (c) shows no correlation between the maximum delay values and higher amplitudes of oscillations in the plant output. Note that the plant output was little affected by variation of the delays in this test, since the ratio $\tau_{\max}/h$ was less than 1. This result confirms

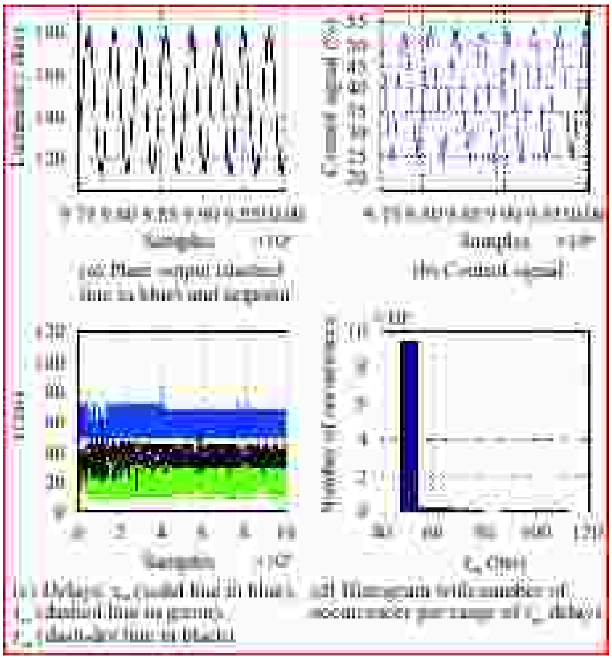

Fig. 11 Test 2, PI controller and sinusoidal reference

that delays smaller than one sampling period do not affect significantly the response of this loop. Under this condition of natural delays measured on the network, where the ratio $\tau_{\max}/h$ was less than 1, the PI controller is able to keep controlling the loop, following closely a PRBS reference. To verify if the performance (surprisingly good) obtained with PI controller, in real network, is not due to the PRBS reference features (that only has 2 levels), other tests were performed in closed loop with PI using a sinusoidal reference (Fig. 11).

The plant output, the control signal and delay characteristics measured in the NCS controlled by a longer period of time (100 000 samples) with sinusoidal reference can be seen in Fig. 11. Fig. 11 (a) shows only the final part of the test to allow better viewing of the response. Note that the system also followed the reference with more slow variations such as the sinusoidal signal.

In order to find possible improvements that a more elaborate control system could introduce, compensation strategies have been implemented, such as the PI controller with explicit compensation strategy (PI+EC), described in Section 3. This strategy uses a structure with a first-order filter for filtering the accumulated control signal deficit. Three values for the time constant of the filter (γ), $\gamma = 0$, $\gamma = 0.9$ and $\gamma = 0.95$ have been considered in the tests presented in the paper. Figs. 12 and 13 illustrate the plant output and the characteristics of the

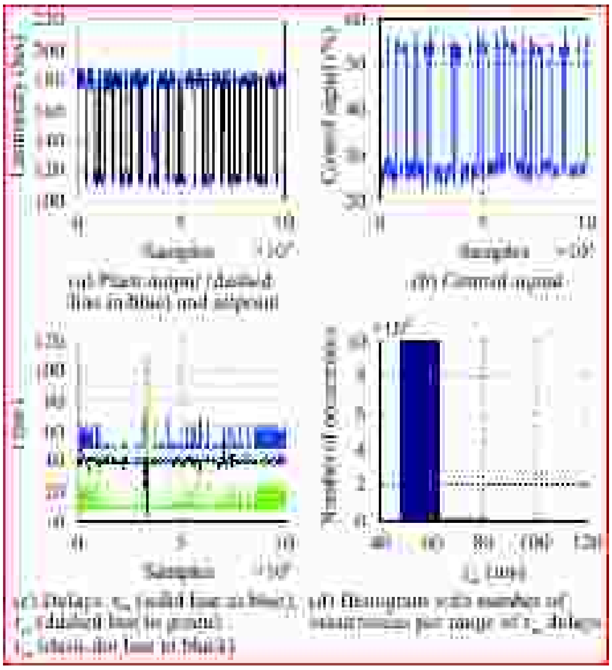

Fig. 12 Test 3, PI+EC controller and γ=0.9

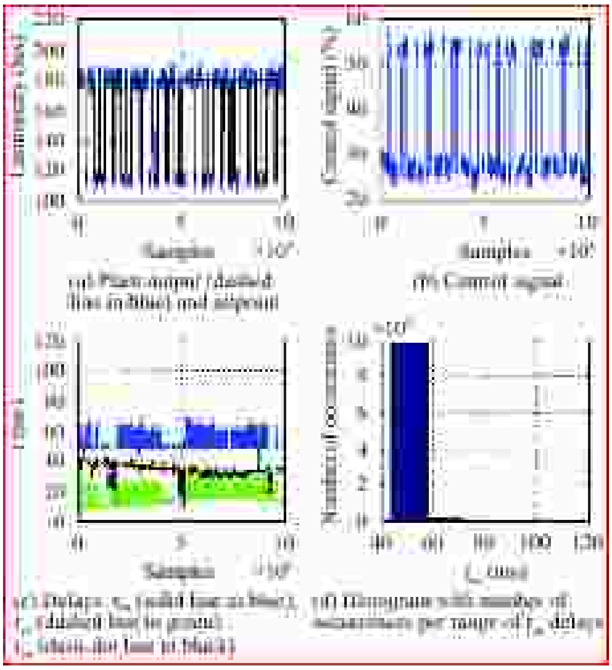

Fig. 13 Test 4, PI+EC controller and γ=0.95

delays measured in the tests with $\gamma = 0.9$ and $\gamma = 0.95$, respectively.

The ratio $\tau_{\max}/h$ was also small (slightly larger than 1, since the maximum delay is less than 110 ms and the sampling time is equal to 100 ms) in tests (Figs. 12 and 13), thus, it was not possible to see a significant improvement with the use of the explicit compensation strategy in these cases, a fact that can be evaluated by visual inspection and by error variance, for which the values are shown in Table 5.

Table 5 Comparison of the controllers: with natural delays

Control	Number of samples	Error variance (lux^2)	Control signal variance (%^{2})	Average τ_{sa} (ms)	Variance τ_{sa} (ms^2)
PI	38 084	61.80	162.6	49.71	14.76
PI+EC (γ=0)	10 000	62.79	179.5	48.63	8.302
PI+EC (γ=0.9)	10 000	58.87	170.8	48.31	4.101
PI+EC (γ=0.95)	10 000	62.14	168.3	48.51	4.872

Table 5 presents a comparison of results obtained in tests performed using different types of controllers, with PRBS signals as reference. Table 5 shows the type of controller, the number of samples in each test, the error variance (in units of lux^2), the control signal variance (in units of %^{2}[47]), the average of τ_{sa}(in units of ms) and the variance of τ_{sa} (in units of ms^2) (the values shown in Table 5 were calculated between the samples 1 000 and 10 000). Note that the average values of τ_{sa} in the tests are similar to each other and less than half of the sampling time, with a small variance.

Comparing the error variances obtained with PI+EC controller with different γ values, it is noticed that there is a reduction in the error variance for $\gamma = 0.9$, indicating that the choice of the time constant of the filter is a relevant factor in the design. The explicit compensation strategy is an interesting alternative for applications on platforms where the messages do not have time stamps. However, the influence of the adopted filter warrants further investigations. Experimental tests have been performed with two types of controllers in NCSs subject to natural delays of the network. The time constant of the plant is the order of milliseconds, even with a plant with dynamics so fast, the controllers showed good results tracking the reference (PRBS and sinusoidal). In the practical implementation, it is very difficult to establish the synchronization between the clocks of the local and remote stations, especially for NCSs in plants with fast dynamics such as luminosity loop, in which the time constant is in the order of milliseconds. It is noteworthy that plants with faster dynamics require a more precision in synchronism, which is more difficult to ensure. Note, in Fig. 13 (c), that the offset between the clocks of the local and remote stations varied over the test. This increases the difficulty to keep the synchronism with the precision of a few milliseconds.

As the ratio $\tau_{\max}/h$ has been small (less than 1) in the tests performed with the natural delays of the network, the effects of delays have not been very pronounced. Consequently, the effects of compensation made by the controllers have not been significant in these tests. For a better evaluation of the possible improvements that control strategies can provide, in the following sections, some res-

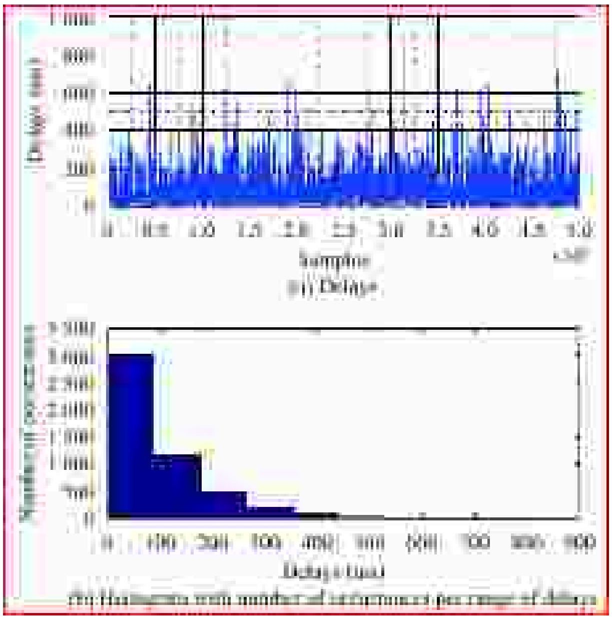

Fig. 14 Profile of the artificially increased delays

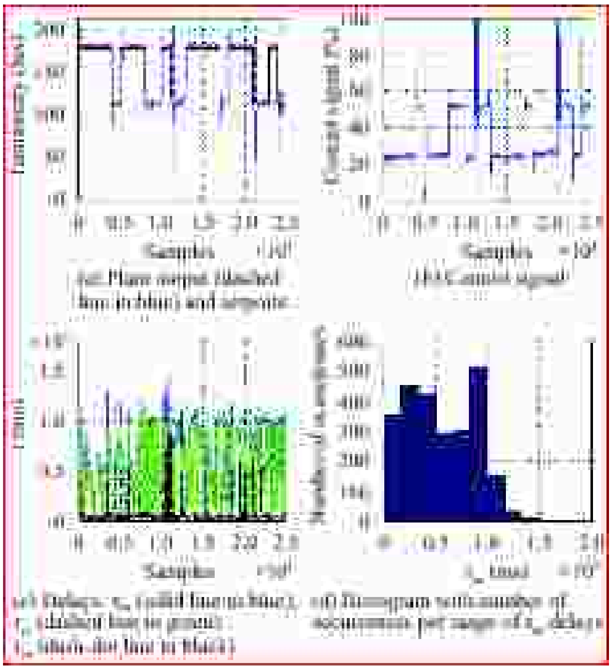

Fig. 15 Test 5, PI controller with artificially increased delays

ults will be presented obtained in tests using the artificially increased delays.

5.2 Experiments with additional delays

Additional delays (beyond the nature of the network) with exponential distribution were inserted into the sensor-controller link. Fig. 14 illustrates the additional delays profile and the histogram with the number of occurrences.

Fig. 15 presents some test results performed with a PI controller with additional delays. Although large amplitude oscillations can be detected in this test, the system remained controlled and stable. Fig. 15 (c) shows the occurrence of a τ_{sa} delay equal to 1 652 ms (at sample 1 068), i.e. greater than 16 sampling periods. Between the samples 1 074 and 1 080, the τ_{sa} delay remained in a value greater than 1 300 ms. After a setpoint change (which occurs in the sample 1 100), oscillations between 3 and 207 lux have been detected (this range corresponds to 180%

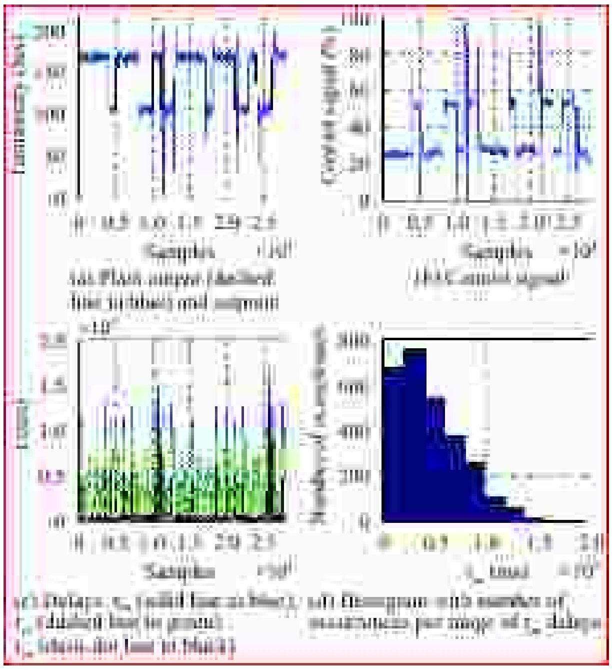

Fig. 16 Test 6, PI+EC controller, $\gamma = 0.9$, with artificially increased delays

of the reference value set at 113 lux or 97% undershoot and 83% overshoot). These large amplitude oscillations are momentary due to the time varying characteristics of the delays. It is seen that the oscillations disappear after sample 1 170. Fig. 15 (d) shows the histogram with the number of occurrences within the range of τ_{sa} delays. 99% of the delays are less than 1 200 ms and average delay equals to 603 ms, i.e. greater than 6 sample periods. The system remained stable, even with the average delay greater than the limit obtained for constant delay (equal to 469 ms, as seen in Section 4).

Fig. 16 presents the results obtained with PI controller with explicit compensation, $\gamma = 0.9$ and additional delays.

Although the biggest delay registered in this test is equal to 1 936 ms, with only one occurrence at sample 1 241, this delay was not the one that resulted in the worst oscillations of the test. In the period between the samples 1 115 and 1 160, there have been detected higher and longer oscillations (between 2 and 214 lux). This fact corroborates the argument that the effect of the delay depends on the way in which they occur and not only on its maxim-

Table 6 Comparison between the controllers: Additional delays

Control	Number of samples	Error variance (lux^2)	Control signal variance ($\%^2$)	Average τ_{sa} (ms)	Variance τ_{sa} (ms^2)
PI	2 500	394.6	282.1	603.4	1.036×10^5
PI+EC (γ=0.9)	2 800	468.5	302.2	443.7	8.605×10^4

um value. So, a single delay of higher value and less frequent (i.e., with low probability of occurrence), can be supported by real NCSs without becoming unstable or even deteriorating their performance. Therefore, if it is considered only the maximum delay as limit to the design of controllers, conservative results can be unnecessarily obtained, emphasizing the importance and advantage of considering the effects of delays in a probabilistic way and not deterministic.

Table 6 shows a comparison between the two tests performed with additional delays. The delay profiles were quite different as illustrated by the histogram (Fig. 15 (d) and Fig. 16 (d)) and can also be confirmed by the average delays indicated in Table 6.

The tests with additional delays confirm that maxim-

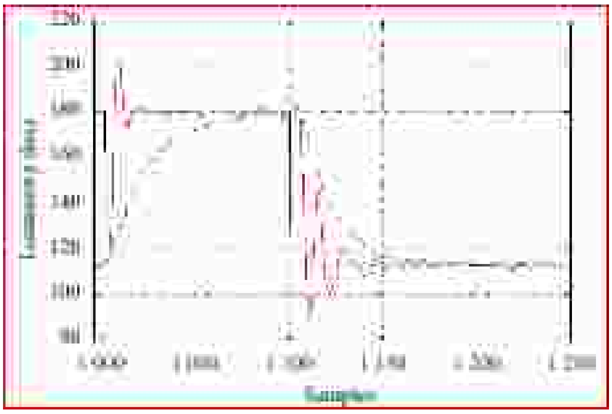

Fig. 17 Simulation, PI+EC controller, γ =0.9: setpoint (solid line in black), plant output simulated with K_c=1.14 (solid line in red) and plant output simulated with K_c=0.18 (dash-dot line in blue)

um delays greater than 19 samples and average delays greater than the limit obtained for constant delays can be supported by this NCS without becoming unstable. If only constant (deterministic) delays are considered, the design of controllers will be limited by the maximum possible delay, resulting in conservative results and unnecessarily degraded performance. In the case study presented here, if it is considered the delay of 19 sample periods in the design of the PI controller, the proportional gain K_c should be reduced from 1.14 to 0.18, i.e., around 6 times. This reduction can result in a significant performance loss, as shown in the simulation responses of Fig. 17. It can be seen that the system response becomes much slower with the reduction of the controller gain.

6 Conclusions

The authors expect that the results presented in the paper could contribute to a more realistic evaluation of the behavior of real NCSs. Several experimental results performed in the luminosity loop confirm the importance of using proper tools for analysis and design of controllers closed over networked loops. In particular, it is shown the necessity of considering the delay statistics for NCSs analysis and design. If only the maximum delay limit is used in the design of the controllers, conservative results can be obtained, with unnecessary loss of performance.

The presented results show the effectiveness of control strategies in practical cases. The results show that delays much higher than one sampling period can be supported by real NCSs, even when designed for much smaller delays. Successful experimental running with ratio $\tau_{\max}/h$ greater than 19 sampling periods were presented with the system remaining stable. This fact demonstrates that limiting the maximum delay to one sampling time may be too restrictive.

The use of more elaborate strategies to cope for greater delay variations depends heavily on the possibility of determining with higher accuracy, in real time, the actual delays present in the NCS loop. Some possibilities have been considered in the paper but this matter, for its importance, warrants further investigations.

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