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An Approach Based on an Adaptive Multi-rate Smith Predictor and Gain Scheduling for a Networked Control System: Implementation over Profibus-DP

Angel Cuenca, Julián Salt, Vicente Casanova, and Ricardo Pizá

Abstract: This paper presents a control strategy to face time-varying delays induced in a Networked Control System (NCS). The delay is divided into two parts: the largest one (an integer multiple of the bus cycle) is compensated by means of an adaptive multi-rate Smith predictor, and the smallest one (whose value is strictly smaller than the bus cycle) via a gain scheduling approach based on root locus contour and linearization techniques. The gains to be scheduled belong to a multi-rate PID controller. Control system stability is studied by means of Lyapunov theory. Simulation results and the implementation on a test-bed Profibus-DP environment illustrate that this control structure can maintain NCS performance and stability, despite the considered delays.

Keywords: Networked control system, network-induced delay, Smith predictor, PID controller tuning, Lyapunov theory.

1. INTRODUCTION

A Networked Control System (NCS) is a kind of control system where different devices exchange information among them through a shared communication medium. NCS can be found in applications as teleoperation, supervisory control, etc [1]. Sharing a bus can reduce wiring considerably and, consequently, system maintenance becomes easier and cheaper [2]. Thus, this kind of solutions can be advisable [3] and are becoming more and more common.

In a NCS the signal transmission is performed between a sender and a receiver (usually, sensor-to-controller and controller-to-actuator) through the shared medium. This feature can introduce delays, degrading the control performance. Thus, in this paper, in order to reduce the influence of these delays and maintain the control system behavior, an approach based on an adaptive Smith predictor and on gain scheduling (both in a multi-rate control scheme) is proposed.

Fig. 1 shows the NCS scenario considered in this work. The sensor device measures the interest variable at NT_1 period. The controller device uses this information to control the plant, implementing a multi-rate law with periods NT_2 and T_2. Due to the distance between sensor and controller, the information measured by the sensor is sent to the controller through a shared communication medium, and so, the control system becomes a NCS. The actuator device works at period T_2, and it is located close to the controller, with exclusive communication with the plant. Assuming this NCS structure, the controller-to-actuator delay does not exist and the sensor-to-controller one τ_{S-C} can be determined at the controller device by means of an initial synchronisation procedure or using time-stamping techniques. The communication task works with a NT_3 period. The frequency of the three clocks involved in the system can be the same, but it is difficult to guarantee a perfect synchronization among them. Then, skews Δ_2 (between sensor and controller clocks) and Δ_3 (between sensor and bus clocks) can be considered. The loop delay τ_{S-C} will depend on these time skews (and other factors to be commented in section 2). When the communication is performed in synchronous mode, the skew among the clocks is constant during each run of the control application, but the delay is different depending on how the skews are presented (see an

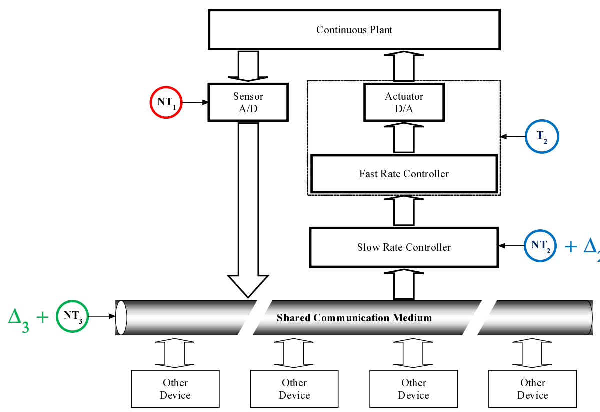

Fig. 1. Scheme for the considered NCS.

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Angel Cuenca, Julián Salt, Vicente Casanova, and Ricardo Pizá are with the Departamento de Ingeniería de Sistemas y Automática, Instituto Universitario de Automática e Informática Industrial, Universidad Politécnica de Valencia, Camino de Vera s/n 46022 Valencia, Spain (e-mails: {acuenca, julian, vcasanov, rpiza}@isa.upv.es).

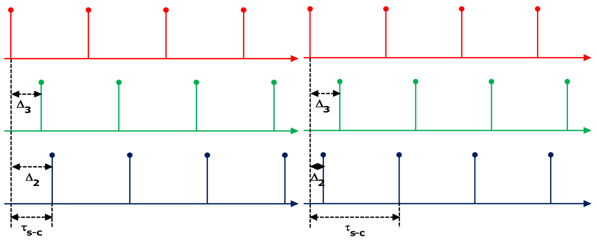

Fig. 2. Loop delay depending on the skew.

example in Fig. 2). If the fieldbus is operated in asynchronous mode, the delay can be variable. In works such as [4,5] other proposals are presented.

Next, the control problem treated in this paper is exposed. A main problem arises when designing the control system: the limitation imposed by the network configuration regarding the bus cycle rate. For example, if a large number of devices sharing the network were considered, this rate could not be fast enough to reach the desired specifications. In this context, the consideration of a multi-rate controller is justified, since it is directly connected to the actuator and can work N times faster than the bus cycle rate, improving the control system performance. So, as shown in Fig. 1, the controller can be decomposed into two sub-controllers: the slow rate one working at period NT (imposed by the bus cycle and/or the measurement period; then, it can be assumed that $NT_1=NT_2=NT_3=NT$) and the fast rate one working at period $T_2=T$ (the actuation period). But, another problem arises: the sensor-to-controller delay. This delay has influence on the application of the first control action (of the N to be considered), yielding a non-uniform actuation pattern. This fact causes some worsening of the control performance, since the control actions are designed to be uniformly applied [6]. The proposed solution lies on determining this network delay at the controller side and splitting it into two parts:

1) the largest one (an integer multiple of the bus period) will be compensated by means of an appropriate Smith predictor, which is able to work with different rate signals and adapt to time-varying delays. Thus, it is an adaptive multi-rate Smith predictor. In [7], other multi-rate Smith predictor approach can be found, but performing time-invariant delay compensation.

2) the smallest one (which is strictly less than a bus cycle) will be compensated via a gain scheduling approach, where the multi-rate PID controller gains will be modified in order to maintain the control performance obtained for the uniform actuation case. In [8] a scheduling approach is also proposed but considering a remote single-rate controller and without the possibility of adjusting independently the controller gains. Other similar development can be found in [9], where the sampling period and the control parameters are simultaneously scheduled to compensate the effect of Quality-of-Service (QoS) variation on NCS performance.

The present paper is divided in five parts: in Section 2 the study from a theoretical point of view is developed. Simulation results will show the expected improvements in Section 3. Section 4 presents a practical approach where the proposed control system is implemented over Profibus-DP. Real results validate the proposal. Finally, in section 5, the main conclusions are exposed.

2. THEORETICAL APPROACH

2.1. Signal basic

Two different Z-transforms can be expressed according to the considered sampling and updating periods over a continuous system. So, if the sampling or updating is carried out each T time units:

$$A^T(z) \triangleq Z_T\left[a(t)\right] = \sum_{k=0}^{\infty} a(kT)z^{-k}, \tag{1}$$

where A will be the sampled signal, and the variable z^{-1} represents the T-unit delay operator.

In the same way, if the sampling and updating period is $NT \quad (N \in \aleph^+)$:

$$A^{NT}(z_N) \triangleq Z_{NT}\left[a(t)\right] = \sum_{k=0}^{\infty} a(kNT)z_N^{-k}, \tag{2}$$

where it is easy to see the relationship $z_N = z^N$.

Moreover, two interesting operators are defined:

1) the skip operator, which is able to create a NT-sequence from a T-sequence, as follows:

$$\left[A^T(z)\right]^{NT} = A^{NT}(z_N) \triangleq \sum_{k=0}^{\infty} a(kNT)z^{-kN}. \tag{3}$$

2) the expand operator, which creates a T-sequence from a NT-sequence, yielding:

$$\left[A^{NT}(z_N)\right]^T = \hat{A}^T(z^N) \triangleq \sum_{k=0}^{\infty} \hat{a}(kT)z^{-kN} : \quad \begin{cases} \hat{a}(kT) = a(kT); \forall k = \lambda N \\ \hat{a}(kT) = 0; \qquad \forall k \neq \lambda N \end{cases}, \quad \lambda \in Z^+. \tag{4}$$

And finally, the Z-transform at period t (t is a basic period in such a way that $t \ll T$)) of a continuous process $G_p(s)$ plus a zero order hold device $H_t(s)$ will be used as:

$$Z_t\left[H_t(s)G_p(s)\right] \triangleq G_p^t(\overline{z}). \tag{5}$$

2.2. Problem scenario

Firstly, a continuous PID is designed according to classical methods in order to achieve certain specifications for the process to be controlled. This is the considered configuration for the continuous PID controller:

$$G_{PID}(s) = K_p\left(1 + \frac{1}{sT_i}\right)\left(1 + sT_d\right). \tag{6}$$

The second step is to convert the continuous PID into a multi-rate discrete one, $G_{PID}^{T,NT}(z, z_N)$. Some aspects of this conversion can be found in [10] and next are exposed:

1) slow rate part given by the PI sub-controller

$$G_{PI}^{NT}(z_N) = K_{PI}\frac{z_N - \left(1 - \frac{NT}{T_i}\right)}{z_N - 1}, \tag{7}$$

where usually K_{PI}=1.

2) fast rate part given by the PD sub-controller

$$G_{PD}^{T}(z) = K_{PD}\frac{z\left(1 + \frac{T_d}{T}\right) - \frac{T_d}{T}}{z}, \tag{8}$$

where usually K_{PD}=K_p.

3) interface between both sub-controllers, which is formed by two elements in this order: an expand operator and a zero order hold (because of using a step reference [11]).

Fig. 3 shows the overall behavior of the proposed NCS. The meaning of the encircled numbers is now detailed:

1) The sensor samples the process output at period *NT*. This device works in a time-driven operation mode.

2) The time between the instant in which the sensor sends the sample until it is received by the controller is named τ_{S-C}, which is assumed measurable. This time τ_{S-C} can include different kinds of delays such as processing and propagation delays, delays due to skewed clocks, etc. Anyway, this induced delay τ_{S-C} can be variable depending on different reasons (for example, network load or distances among devices). Depending on its magnitude, two different cases will be treated:

a) $\tau_{S-C} < NT$

b) $\tau_{S-C} \geq dNT,\, d \in \aleph^{+}$.

3) When the sample arrives at the controller, following an event-driven policy the controller generates *N* control actions. The first of them will be applied τ_{S-C} time units after the measurement was taken by the sensor. The others, as they are not influenced by the network delay, can be applied at period *T*, starting from the instant *T* of every period *NT*. This supposes a non-uniform actuation pattern.

Note two interesting consequences of this event-driven approach for the controller:

a) if $\tau_{S-C} - dNT \geq kT(k = 1,\dots,N-1; d \in \aleph)$, *k* of the *N* control actions will never be applied to the plant.

b) if the network delays of two consecutive samples, $\tau_{S-C}(k-1)$ and $\tau_{S-C}(k)$, accomplish the following condition:

$$\left.\begin{aligned} \tau_{S-C}(k-1) &= d(k-1)NT + \delta(k-1) \\ \tau_{S-C}(k) &= d(k)NT + \delta(k) \end{aligned}\right\} \\ : \delta(\cdot) < NT,\, \delta(\cdot) \in \Re \\ d(k-1) < d(k),\, d(\cdot) \in \aleph \tag{9}$$

that is, $d(\cdot)$ defines the largest part of each delay (the number of periods at *NT*), and $\delta(\cdot)$ represents the smallest part (strictly less than *NT*) of each delay, then there are $d(k) - d(k-1)$ *NT* periods between the reception of both samples where control actions are not generated. In this way, the last control action (generated when receiving the first of both samples) is held until a new control action will be generated as a consequence of collecting the second measurement. This fact can degrade the control system performance. The degradation can depend on the number of periods $d(k) - d(k-1)$ considered (the higher it is, the worse performance arises) and on the response time when the described situation is produced (the transient response is more influenced than the steady state).

So, in order to solve both problems, a deadline time can be established for the controller device in such a way that if this time is expired and the measurement did not arrive, the controller will trigger a special event in order to generate and apply the consequent control actions. This deadline time *dl* must accomplish that *dl*<*T*. So, none of the *N* control actions will be lost and the controller will be able to generate new control actions inside each *NT* period. But, since the current measurement is not available when the special event is triggered, an estimate value is required. To carry out this estimation, an appropriated Smith predictor will be considered.

Fig. 4 depicts the control structure of the described

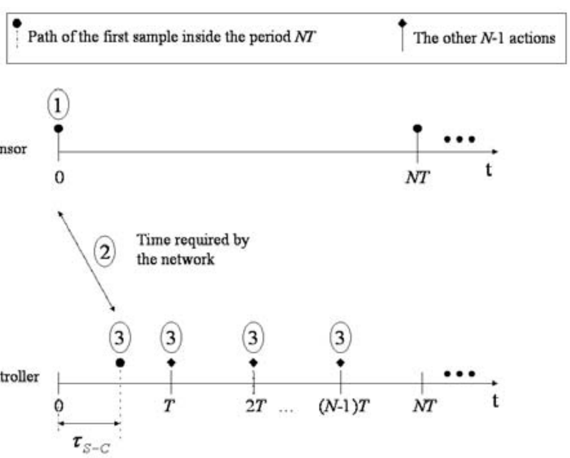

Fig. 3. Proposed NCS in the case $\tau_{S-C} < NT$.

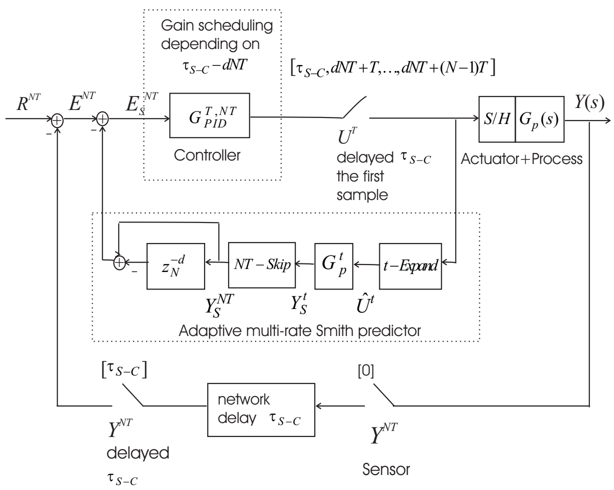

Fig. 4. Control structure of the described NCS.

NCS by means of a block diagram representation. The actuator is a Sample and Hold device (S/H), which carries out the D/A conversion following a non-uniform input pattern.

2.3. Adaptive multi-rate smith predictor

Its main goal is to compensate the largest part dNT of the network delay. The compensated error signal $E_S^{NT}(z_N)$ yields:

$$\begin{aligned} &E_S^{NT}(z_N) \\ &= E^{NT}(z_N) - (1 - z_N^{-d})[Z_t[H_t(s)G_p(s)] \cdot [U^T(z)]^t]^{NT} \\ &= E^{NT}(z_N) - (1 - z_N^{-d})[G_p^t(\overline{z}) \cdot \hat{U}^t(\overline{z})]^{NT} \\ &= E^{NT}(z_N) - (1 - z_N^{-d}) Y_S^{NT}(z_N), \end{aligned} \tag{10}$$

where $E^{NT}(z_N)$ is the system error signal at period NT and $Y_S^{NT}(z_N)$ is the measured output to be compensated. Once the variable delay τ_{S-C} is determined at the controller device, the Smith predictor must update its parameter d in order to compensate accurately the part dNT. The period t is defined small enough in order to collect the effect of the network delay part $\tau_{S-C} - dNT$ on the system response, and so, to achieve $Y_S^{NT}(z_N) \cong Y^{NT}(z_N)$. As a result, t must be defined as the greatest common divisor between $\tau_{S-C} - dNT$ and T, that is,

$$t = gcd(\tau_{S-C} - dNT, T). \tag{11}$$

2.4. Control system modelling via lifting

In order to reflect the non-uniform actuation, in this work the control system will be modeled via state-space representation adopting the so-called lifting methodology. In [12], the lifting representation for non-uniform sampling can be found. So, the state-space representation for the process takes this form:

$$\begin{aligned} x_p[(k+1)NT] &= A_p x_p(kNT) + B_p \begin{bmatrix} u(kNT + \tau_{S-C}) \\ u(kNT + T) \\ \vdots \\ u(kNT + (N-1)T) \end{bmatrix}, \\ y_p(kNT) &= C_p x_p(kNT) + D_p \begin{bmatrix} u(kNT + \tau_{S-C}) \\ u(kNT + T) \\ \vdots \\ u(kNT + (N-1)T) \end{bmatrix}, \end{aligned} \tag{12}$$

where N control signals (u array) will be applied for each period NT in the instants $[\tau_{S-C}, T, 2T, \ldots, (N\text{-}1)T]$ inside this period.

The different parts of the controller can be expressed as a cascade-connected system (details omitted for brevity) yielding

$$x_C[(k+1)NT] = A_C x_C(kNT) + B_C e_s(kNT),$$

$$\begin{bmatrix} u(kNT + \tau_{S-C}) \\ u(kNT + T) \\ \vdots \\ u(kNT + (N-1)T) \end{bmatrix} = C_C x_C(kNT) + D_C e_s(kNT). \tag{13}$$

Assuming $D_p = 0$ for the sake of simplicity, the closed-loop system will be

$$\begin{aligned} x(kNT) &= \begin{bmatrix} x_C(kNT) \\ x_p(kNT) \end{bmatrix} \\ &= \begin{bmatrix} A_C & -B_C C_p \\ B_p C_C & A_p - B_p D_C C_p \end{bmatrix} x(kNT) \\ &= A_{cl} x(kNT). \end{aligned} \tag{14}$$

Thus, the closed-loop system evolution supposes $x[(k+1)NT] = A_{cl}^{k+1} x(0)$ when the delay τ_{S-C} is constant. This is the known and classic case [13]. But, in real scenarios, τ_{S-C} can be variable. This fact will suppose different state matrices in each period NT, that is

$$\begin{aligned} x(NT) &= A_{cl(\tau_{S-C}(1))} x(0), \\ x(2NT) &= A_{cl(\tau_{S-C}(2))} A_{cl(\tau_{S-C}(1))} x(0), \\ &\vdots \\ x\big[(k+1)NT\big] &= \prod_{i=1}^{k+1} A_{cl(\tau_{S-C}(i))} x(0). \end{aligned} \tag{15}$$

As shown, now the closed-loop system evolution takes the form of an infinite product of a finite number of matrices. Thus, it is important to study the stability of this particular control system.

2.5. Stability analysis

In [14] an adaptive single-rate approach is considered but a similar result like (15) is obtained. Then, following [14], these three Lyapunov conditions are enunciated in order to asses the closed-loop system stability:

1) A is asymptotically stable iff (16)
$\exists P > 0 : A^T_{cl(\tau_{S-C}(i))} \cdot P \cdot A_{cl(\tau_{S-C}(i))} - P < 0,$
$\forall A_{cl(\tau_{S-C}(i))} \in \mathrm{A}^k,\ k \geq 1$

2) If $\exists P > 0 : A^T_{cl(\tau_{S-C}(i))} \cdot P \cdot A_{cl(\tau_{S-C}(i))} - P < 0,$ (17)
$\forall A_{cl(\tau_{S-C}(i))} \in \mathrm{A}$ then A is asymptotically stable.

3) If $A^T_{cl(\tau_{S-C}(i))} \cdot A_{cl(\tau_{S-C}(i))} - I < 0,$ (18)

$\forall A_{cl(\tau_{S-C}(i))} \in \mathrm{A}$ then A is asymptotically stable, where $\mathrm{A} = \{A_{cl(\tau_{S-C}(i))} : \tau_{S-C}(i) \in \mathrm{T}\}$, T is a finite subset of $\aleph$, and $\tau_{S-C}(i) : \aleph \to \mathrm{T}$ is a map.

Considering inequalities in the sense of positive or negative definiteness, the first one is a necessary and sufficient stability condition. The others are sufficient although not necessary stability conditions, but they are easier to analyze.

Other NCS stability analysis can be found in related works. For example, in [15] a robust approach is considered, and in [16] linear matrix inequalities are used.

2.6. Multi-rate PID retuning methodology

The main goal of this section is to schedule the multi-rate PID controller gains in order to maintain the nominal (no-delay) control system performance, despite the variable, delayed application of the first control action. Since the PD sub-controller is the fastest rate control system device, retuning its gains suppose the most appreciable changes on the system performance. For this reason, the proposed approach is based on scheduling only the K_{PD} and T_d gains depending on the network delay. To perform this goal, from the lifting representation for the multi-rate control system (12)-(14), the consequent discrete zeros and poles map at NT period must be considered.

Then, considering the nominal controller gains as $K_{PD}^0 \equiv K_{PD}$, $T_d^0 \equiv T_d$, the resulting discrete closed-loop poles will be represented by $p_i^0, i=1..n$, being n the control system order. The control system dominant pole p^0 fulfills

$$p^0 : \left|p^0\right| = \max\left(\left|p_i^0\right|\right), i = 1..n \qquad (19)$$

that is, p^0 is the discrete pole with the maximum modulus for the nominal case.

If a delay $\tau_{S-C} \neq 0$ is considered, closed-loop poles change its location at the zeros and poles map, resulting a new dominant pole $p^{\tau_{S-C}}$. As control performance now becomes worse, then $\left|p^{\tau_{S-C}}\right| > \left|p^0\right|$. Thus, the goal is to achieve that $p^{\tau_{S-C}} \cong p^0$ and so $\left|p^{\tau_{S-C}}\right| \cong \left|p^0\right|$. In order to do it, PD sub-controller gains will be modified, obtaining $K_{PD}^{\tau_{S-C}}$, $T_d^{\tau_{S-C}}$.

Thus, from (12)-(14) the discrete zeros and poles maps both for the nominal case and considering a delay $\tau_{S-C} \neq 0$ can be obtained and overlapped. Once $p^{\tau_{S-C}}, p^0$ are located, a grid which is able to bring them together is created. This grid is made varying K_{PD}^0, T_d^0 within certain ranges starting from the location of $p^{\tau_{S-C}}$. In this way, following different trajectories along the grid, $p^{\tau_{S-C}}$ will reach p^0, and so, the new $K_{PD}^{\tau_{S-C}}$, $T_d^{\tau_{S-C}}$ will be deduced.

If this study is carried out off-line for a few τ_{S-C} values, a summary table can be generated where, given a τ_{S-C}, its consequent $K_{PD}^{\tau_{S-C}}$, $T_d^{\tau_{S-C}}$ are found. Next, in order to extrapolate the general gain scheduling trend to the rest of τ_{S-C} values that can be considered inside a period NT, a solution based on the known least square estimate approach is proposed. The idea is to find a proportional law between τ_{S-C} and $K_{PD}^{\tau_{S-C}}$, $T_d^{\tau_{S-C}}$ by means of certain parameters x_{PD}, x_d (respectively) in such a way that a determined least square index J will be minimized. In this case

$$J(x,m) = \frac{1}{2}\sum_{i=1}^{m} e_i^2, \qquad (20)$$

where x will be x_{PD} or x_d (in each case), m is the number of τ_{S-C} values studied off-line, and e is the prediction error.

Once the least square problem is solved, two proportional laws will be obtained

$$\begin{aligned} K_{PD}^{\tau_{S-C}} &= x_{PD}\tau_{S-C} + K_{PD}^0, \\ T_d^{\tau_{S-C}} &= x_d\tau_{S-C} + T_d^0, \end{aligned} \qquad (21)$$

which are easily implemented in the PD sub-controller in order to schedule its gains depending on the network delay.

3. SIMULATION RESULTS

In this academic example, the process to be controlled is described by this transfer function:

$$G_p(s) = \frac{1}{0.25s^2 + 1.25s + 1}. \qquad (22)$$

In order to follow a step reference with null steady state error, a settling time around 2s and an overshoot around 20%, a continuous PID controller is designed, obtaining these parameters: $K_p = 6;\ T_d = 0.1;\ T_i = 0.67$.

Let us assume certain network limitation regarding to the bus cycle in such a way that a control/sampling period of at least 0.18s is required in order to fit the available bandwidth. In order to illustrate the proposed control strategy, the case where $T = 0.09\,s$, $NT = 0.18\,s$ (that is, N =2) is considered. First of all, the multi-rate controller must be defined according to (7)-(8). Next, the control system must be modelled via lifting according to (12)-(14) and depending on the considered delay τ_{S-C}. In order to simplify the explanation, only the case when a network delay τ_{S-C} =0.02s will be detailed.

Using Matltab-Simulink®, once the control system is modelled for both cases (nominal and with τ_{S-C} =0.02s), Fig. 5 overlaps their zeros and poles maps focusing only on the dominant closed-loop poles $p^{\tau_{S-C}}$, p^0. $p^{\tau_{S-C}}$ is marked with a diamond and p^0 with a square. The other points in the figure configure the grid. See also the dotted lines trajectories. Omitting details for brevity, following these trajectories the dominant poles are reached, and so, the control system can maintain the nominal control performance, despite applying the first control action with a delay of 0.02s.

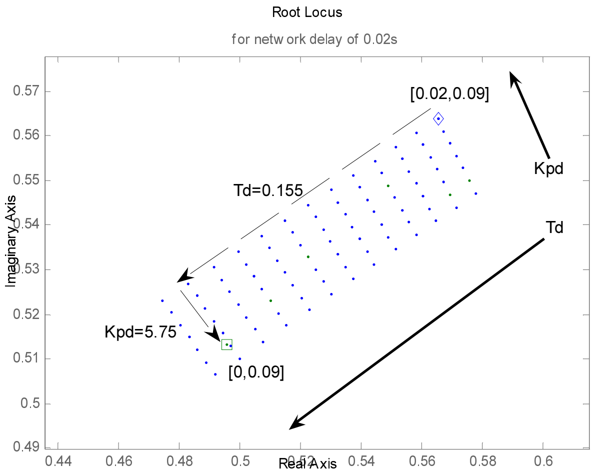

Fig. 5. Zeros and poles map for the delay τ_{S-C} =0.02s.

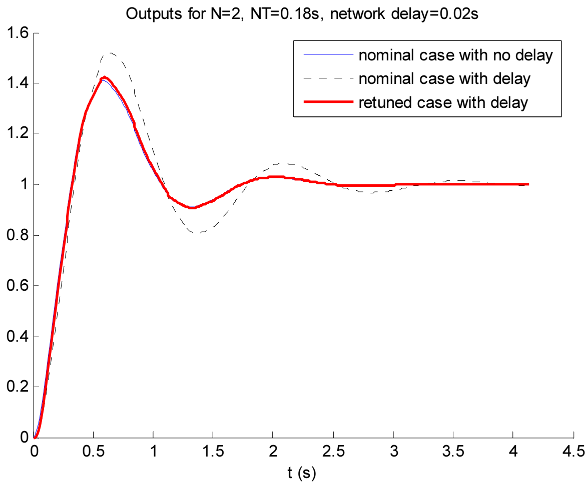

Fig. 6. Outputs for the network delay τ_{S-C} =0.02s.

To observe this fact, Fig. 6 shows a simulation where three different outputs are depicted. The overshoot and settling time get worse (dotted line) when the delay appears and no retuning is carried out. If the controller gains are retuned (thick line), the performance is close to the nominal case (thin line).

This study can be repeated for different delays τ_{S-C}. In Table 1, results for other τ_{S-C} are summarized. Solving the consequent least square estimate problem, proportional laws which are able to extrapolate these results for every possible delay τ_{S-C} inside the period NT are obtained:

Table 1. Results summary.

τ_{S-C}	$K_{PD}^{\tau_{S-C}}$	$T_d^{\tau_{S-C}}$
0	6	0.1
0.01	5.90	0.125
0.02	5.75	0.155
…	…	…
0.05	5.40	0.345
…	…	…

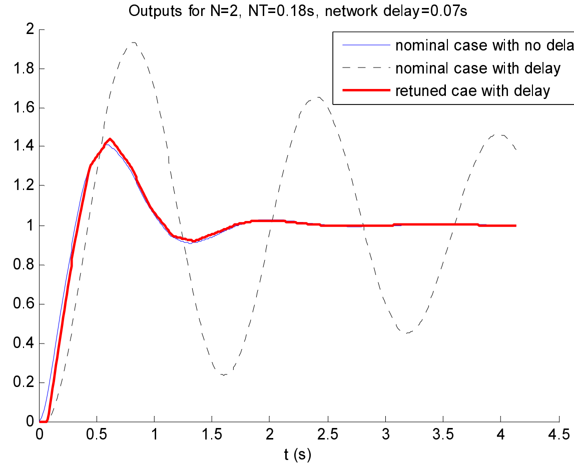

Fig. 7. Outputs for the network delay τ_{S-C} =0.07s.

$$\begin{aligned} K_{PD}^{\tau_{S-C}} &= -12\tau_{S-C} + K_{PD}^{0}, \\ T_d^{\tau_{S-C}} &= 4.5333\tau_{S-C} + T_d^{0}. \end{aligned} \tag{23}$$

If these laws are implemented in the PD sub-controller, it can schedule its gains depending on the delay, and so, generate the consequent control signal.

Following the previous laws, an interesting case is considered. This case assumes a delay of 0.07s. Fig. 7 shows that the nominal controller is on the verge of instability if this delay is considered, whereas the retuned one is able to reach the nominal behaviour despite the delay. From this delay value, the non-retuned control system response becomes unstable.

Once the gain scheduling strategy is treated, a simulation in order to check the behaviour of the proposed NCS is presented. It is based on considering a cyclic sequence of time-varying delays, which, in concrete time instants, can be longer than a bus cycle in order to simulate different network load conditions. From t_S=1.25s the cyclic sequence is incremented by a delay of 2NT. In the same way, in t_S=3.05 a new NT delay is added in such a way that the total delay considered from this moment is 3NT.

Firstly, Fig. 8 shows outputs according to the initial

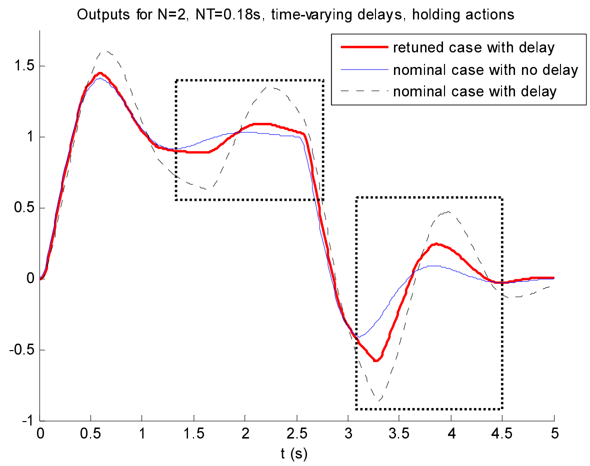

Fig. 8. Outputs (time-varying delays) by holding actions.

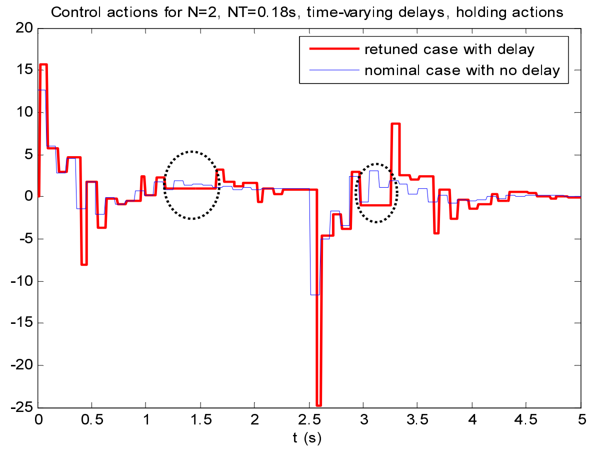

Fig. 9. Actions (time-varying delays) by holding actions.

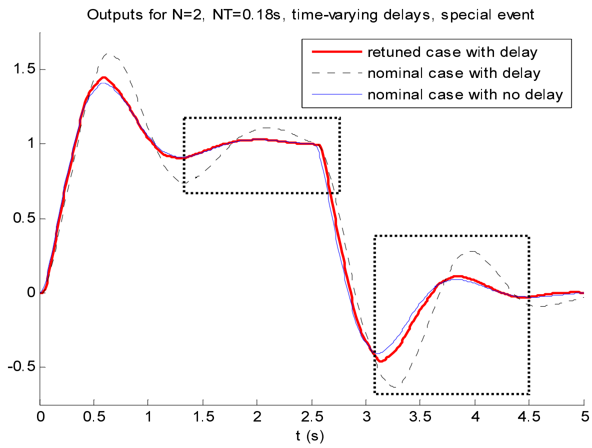

Fig. 10. Outputs (time-varying delays) via special event.

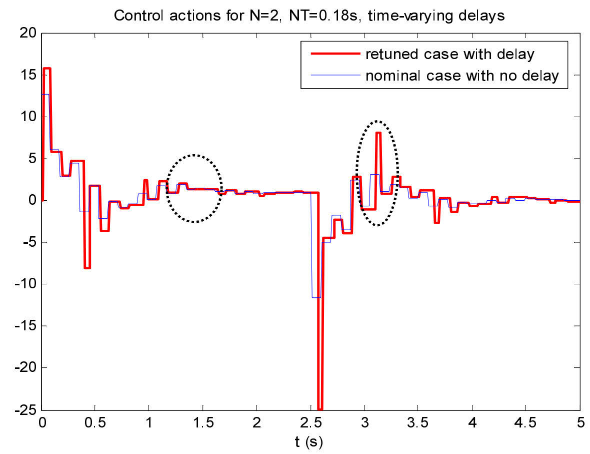

Fig. 11. Actions (time-varying delays) via special event.

approach for the controller device, that is, when the last control action is held if an event is not produced (see dotted circles in Fig. 9). The main conclusion is that, despite the considered delays, the proposed control approach tries to keep (thick line) the nominal control system performance (thin line), which is clearly degraded (dotted line) if delays appear and this control strategy is not implemented. However, the output obtained by the presented control strategy is not as accurate as desired because of not generating new control actions during $2NT$ periods from t_S=1.25s and during a NT period from t_S=3.05s.

In order to solve this problem, now the second approach is implemented for the controller device, that is, a special event is triggered to generate control actions in each period NT by using the predicted output. For the sake of simplicity, in this simulation the deadline time is defined variable and equal to the cyclic pattern. Fig. 10 shows results. The main conclusion is that now the proposed control approach can accurately keep (thick line) the nominal control system performance (thin line). Fig. 11 shows that now new control actions at t_S=1.25s and t_S=3.05s are generated (dotted circles), improving system output (dotted rectangles in Fig. 10).

4. PRACTICAL APPROACH: IMPLEMENTATION OVER PROFIBUS-DP

This section presents a particular case where the previously proposed control structure can be implemented. This application uses the X axis of a three dimensional laboratory model of an industrial crane and Profibus-DP as the shared communication medium. A conventional PC, running Matlab/Simulink Real Time Windows Target®, has been used to implement the control structure. AD and DA converters are used as interfaces to access the Profibus-DP network. With this implementation of a Profibus-based NCS (see Fig. 12) it is quite straightforward and easy to test any kind of control structures designed using Simulink as simulation tool.

By means of classical identification techniques, the transfer function of the DC motor for the X axis has been identified, yielding

$$G_X(s) = \frac{6.3}{s(s+17.7)}. \tag{24}$$

In addition, some non-linear behaviour has been identified, which will be taken into account in the real-time implementation. The control action saturates in ±1 and there is a dead zone of ±0.06. Both values are measured in control action units.

Each device (sensor and controller-actuator) and the fieldbus have independent and skewed clocks. Thus, as Profibus-DP is configured to operate in synchronous mode and the sampling and control periods are integer multiples, depending on the experiment the delay can vary and, consequently, a different case will be treated

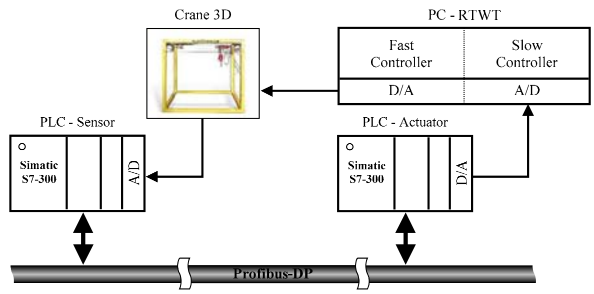

Fig. 12. Control structure implementation.

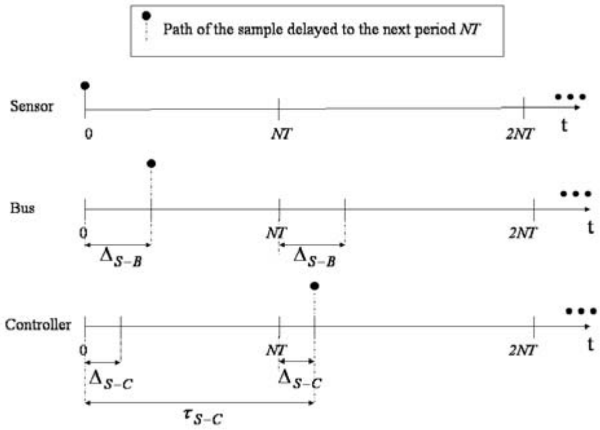

Fig. 13. Relation among clock skews for the experiment.

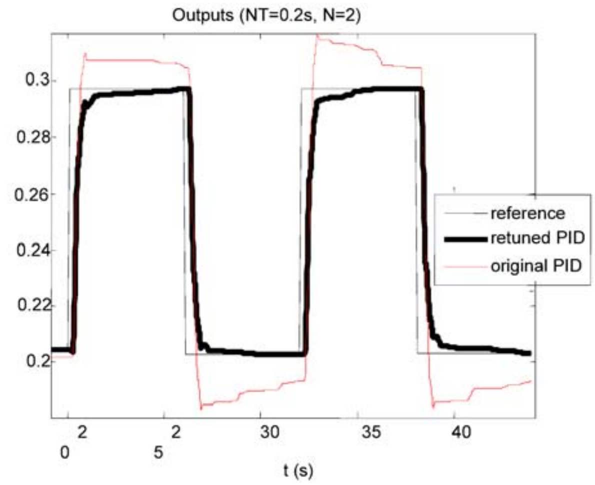

Fig. 14. Outputs for the experiment.

for the NCS (remember Fig. 2). This aspect can be detected by carrying out an initial synchronisation. In this practical approach τ_{S-C} depends more on the skew among clocks than on propagation delays (these ones are practically negligible due to the reduced wiring size).

Next, one of the developed experiments is presented. Fig. 13 shows the relation among clock skews in this experiment, being Δ_{S-B}, Δ_{S-C} the sensor-to-bus clock skew and the sensor-to-controller one, respectively. This relation implies a network delay $\tau_{S-C} = NT + \Delta_{S-C}$. The NT part of the delay will be compensated by the adaptive multi-rate Smith predictor and the other part, Δ_{S-C}, that is, $\tau_{S-C} - NT$, via the gain scheduling approach.

First of all, using the linear continuous model shown in (24), a classical PID controller has been designed to accomplish certain specifications (null steady-state error, settling time around 4s and overshoot around 5%). The obtained parameters are: $K_p = 12$, $T_d = 0.01$, $T_i = 3.5$. It is easy to prove that if this controller is digitally implemented at a period of 0.2s, the system response worsens drastically, becoming practically unstable. In fact, if the period is higher than 0.1s, the control specifications cannot be assured. But a lower period could not be achieved due to the bandwidth limitations when the controller is implemented on a loaded network. Thus, in order to not excessively load the network, let us define the sampling period as NT=0.2s and, in order to reach the specifications, the control period will be T=0.1s (i.e., N=2). Thus, a multi-rate controller following (7)-(8) will be implemented over the network.

Following a similar study than in the previous section, a proportional law for each PD sub-controller parameter can be performed:

$$\begin{aligned} K_{PD}^{\tau_{S-C}} &= -50\tau_{S-C} + K_{PD}^{0}, \\ T_d^{\tau_{S-C}} &= 0.5\tau_{S-C} + T_d^{0}. \end{aligned} \tag{25}$$

After implementing and executing on the work bench the proposed control structure, outputs are shown in Fig. 14. This figure shows the particular case where $\Delta_{S-C} = \tau_{S-C} - NT = 0.05$s. Results confirm a better control performance for the retuned multi-rate PID than for the original one (that is, the nominal multi-rate controller facing the network delay). The retuned case accomplishes the specifications (settling time around 4s and no overshoot due to the saturation), whereas the original one does not. Thus, the proposed control strategy is validated.

5. CONCLUSIONS

An approach to face time-varying delays on a NCS is introduced. This delay appears between sensor and controller-actuator and causes worse control performance. To solve this problem and maintain control specifications, a control strategy based on an adaptive Smith predictor and gain scheduling (both in a multi-rate control scheme) is proposed. In this way, delays larger than a bus cycle can be compensated, since the delay is split into two parts in such a way that the largest part (integer multiple of the bus cycle) is treated by the adaptive multi-rate Smith predictor, and the smallest one (which is strictly smaller than a bus cycle) by the multi-rate gain scheduling approach. This approach is based on the root locus contour technique and a least square estimate solution.

A multi-rate PID controller is utilized, since the network works at a slower rate (to reduce its load) and a faster control is needed in order to reach control specifications and improve transient response.

After observing the improvements of this control strategy by means of simulation, a real implementation based on the Profibus-DP network has been performed. Real results validate the proposed multi-rate control strategy.

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Ángel Cuenca received his M.Sc. degree in Computer Science in 1998 and his Ph.D. degree in Control Engineering in 2004, from the Technical University of Valencia. His research interests include multi-rate control systems, networked based control systems, and event-based control systems.

Julián Salt received his M.Sc. Degree in Industrial Engineering in 1986 and his Ph.D. degree in Control Engineering in 1992, from the Technical University of Valencia. He has been a Director of nine Ph.D. theses and coauthor of about 70 papers in journals and technical meetings. His research interests include non-conventionally sampled control and networked control systems.

Vicente Casanova received the M.Sc. degree in Computer Science in 1994, in Telecommunication Engineering in 2000 and his Ph.D. degree in Automatics and Industrial Informatics in 2005 from Technical University of Valencia. His research interests include networked control systems, multi-rate control, control with time-varying delays and analysis and modeling of Profibus-DP.

Ricardo Pizá received his B.Eng. degree in 1997, and his Ph.D. degree in Control Engineering in 2003 from Technical University of Valencia. His research interests include network based control systems, computer aided manufacturing, and robotics.