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CAN-Based Networked Control Systems: A Co-Design of Time Delay Compensation and Message Scheduling

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ABSTRACT

The goal of this paper is to consider a co-design approach between time delay compensation and the message scheduling for CAN-Based Networked Control Systems (NCS). First we propose a hybrid priority scheme for the message scheduling in order to improve the Quality of Service (QoS). Second we present the way to calculate the closed-loop communication time delay and then compensate this time delay using the pole placement design method in order to improve the Quality of Control (QoC). The final objective is the implementation of a co-design which is the combination of the compensation for communication time delays and the message scheduling in order to have a more efficient NCS design..

Key Words : Co-design, Networked Control Systems, Message scheduling, QoS, QoC

Ⅰ. Introduction

The study and design of Networked Control Systems (NCS) based on CAN bus is a very important research area today because of its multidisciplinary aspect (Automatic Control, Computer Science, and Communication Network). Today the current design objective is to consider a co-design between the designs of Automatic Control (QoC) and Communication Network (QoS) in order to have efficient control systems[1] .

This paper presents a co-design between the QoC of the controller based on time delay compensations and the QoS of the communication network based on the scheduling of messages (Medium Access Control (MAC) protocol) for CAN-based control systems.

The MAC protocol of the CAN bus is the type of CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). Nodes which have frames to transmit listen to the medium, when the medium is free, they begin a medium access tournament by sending and comparing the ID (IDentifier) bits placed at the beginning of the frames. Each node has a unique ID which represents the priority of the frame sent by this node and which allows to do the medium access tournament. The tournament is done by a comparison bit by bit of the same rank among the IDs of the contending frames from the Most Significant Bit (MSB) to the Least Significant Bit (LSB). A bit 0 is a dominant bit and a bit 1 is a recessive bit. In a bit-by-bit comparison, a bit 0 overwrites a bit 1. Therefore the higher the priority is, the lower the ID value is. At the end of the tournament, the node which has the highest priority (*i.e.*, the lowest ID value) is the unique winner allowed to send its frame. The losers must wait until the end of the frame transmission of the winner and begin a new medium access tournament.

Some works[1,2] have considered both the time delay compensation and the message scheduling based on LEF (Large Error First) algorithm in which each message is assigned a priority level according

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to the error value. The higher the error is, the higher the priority is and vice versa. A limitation of this paper is that the error value encoding is not bounded.

In the paper[3], the proposed time delay compensation is designed according to the dominant pole method and the message scheduling is based on the control signal *u*. The authors proposed a message scheduling scheme based on hybrid priority for CAN network using the standard 11 bit ID field where the ID field is divided into 2 small levels. The level 1 (4 bits) represents a fixed priority and the level 2 (7 bit) represents a dynamic priority. A limitation of this study is to only use 4 bits for static priority, so they can determine a maximum number of 16 data flows (or nodes) which is not enough to address all nodes in a NCS.

The goal of this paper is to present a co-design to overcome the limitations analyzed above, which allows improving QoC and QoS simultaneously.

We use the tool TrueTime[4] for the simulation and the QoC evaluation. TrueTime is a toolbox based on Matlab/Simulink which allows simulating real-time network-based control systems.

This paper includes the following sections: the section II presents the context of the study; the section III presents the implementation of a hybrid priority scheme for message scheduling; the section IV presents the implementation of the compensation for communication time delays; the section V presents a co-design of time delay compensation and message scheduling; the conclusion is represented in the section VI.

Ⅱ. Context of the study

2.1 Process control application

The model of the considered process control application (using the Laplace transform) is given on Fig. 1.

The process to control is $G(s)=1000/s(2s+1)$. The *PD* (Proportional Derivative) controller is $PD=K(1+sT_d)$. The input reference is $R(s)=1/s$ (unity position step) and the output is $Y(s)$. The phase margin of $G(s)$ is 1.3° at the crossover frequency ω_c

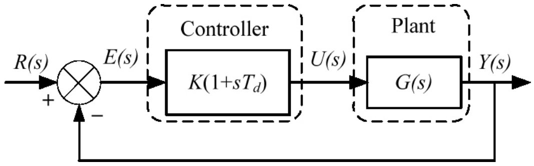


Fig. 1. Continuous control system.

= 22.4 rad/s (*i.e.*, the frequency such that $|G(j\omega_c)=1|$[5]. This phase margin is too small (the phase margin should be from 45° to 60°[6]). Here we consider that, initially, the *PD* controller must compensate a positive phase ϕ_c in order to have a system phase margin of 50°.

To do that, it must be:

$$\begin{cases} tg(\varphi_c)=T_d\omega_c \\ 20\left|\log(K(1+j\omega_c T_d))\right|=0 \end{cases} \tag{1}$$

We have K = 0.6598 and T_d = 0.0509 s. The closed-loop transfer function is:

$$F(s)=\frac{500K(1+T_d s)}{s^2+(0.5+500KT_d)s+500K} \tag{2}$$

$$F(s)=\frac{\omega_n^2(1+T_d s)}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{3}$$

Where ω_n is the natural pulsation (rad/s) and ζ is the damping coefficient.

We have ω_n^2=500K and $2\zeta\omega_n$ = 0.5+500KT_d which give ω_n = 18.16 rad/s and ζ = 0.48, the two poles $p_{1,2}$ are $p_{1,2}$= $-\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$

The settling time at 2% is t_s = 382 ms, the

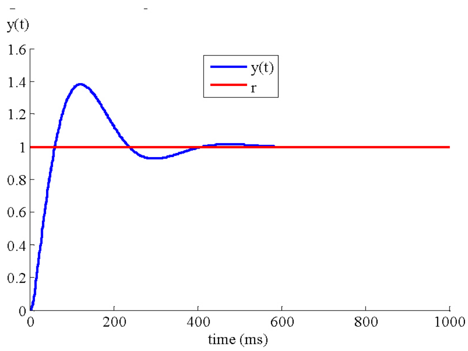


Fig. 2. Time response y(t).

Overshoot is O = 38.17 %. The time response $y(t)$ is represented in Fig. 2.

2.2 Implementation of a process control application on a CAN network

2.2.1 General model

The general model of the implementation of a process control application through a CAN network is shown on Fig. 3.

The sensor receives the sampled output y_k provided by the Analog Digital Converter (ADC) and sends it to the controller via the CAN bus. The controller receives y_k from the sensor, then calculates the control signal u_k and sends u_k to the actuator via the CAN bus. The actuator receives u_k, converts u_k into analog signal ($u(t)$) using the Digital Analog Converter (DAC) and then directly applies $u(t)$ to the Plant. The Zero Order Hold (ZOH) keeps the value $u(t)$ until the new sampling time.

We have two flows of frames: the Sensor-Controller flow which concerns the frames going from the sensor to the controller (noted f_{sc} flow and call "f_{sc} frame" a frame of this flow); the Controller-Actuator flow which concerns the frames going from the controller to the actuator (noted f_{ca} flow and call "f_{ca} frame" a frame of this flow). The sensor task is Time-Triggered while the controller and actuator tasks are Event-Triggered.

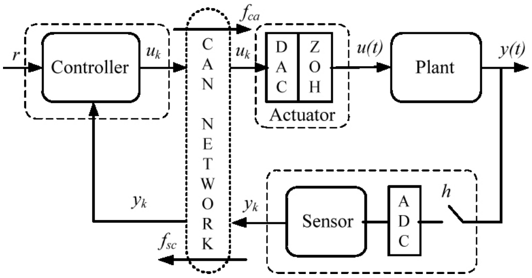


Fig. 3. Implementation of a process control application on a CAN network.

2.2.2 Sampling period

We call h the sampling period which is determined by considering the formula $\omega_n h \in [0.1;0.6]$[7]. Here we take h = 10 ms.

2.2.3 Communication time delays

Communication time delays in each sampling period consist of two components:

- The Sensor-Controller time delay concerns the transmission of f_{sc} frames (noted τ_{sc}) which is the duration between the sampling instant (t_k, k = 0, 1, 2⋯) and the reception instant of this frame by the controller. τ_{sc} includes the waiting time for medium access and the transmission time of a f_{sc} frame (noted D_{sc}).
- The Controller-Actuator time delay concerns the transmission of f_{ca} frames (noted τ_{ca}) elapsed from the ready-to-send instant of the f_{ca} frame till the reception instant of this frame by the actuator. τ_{ca} includes the waiting time for medium access and the transmission time of a f_{ca} frame (noted D_{ca}).

Note that the durations D_{sc} and D_{ca} can be easily calculated by knowing the frame length and transmission speed.

The communication time delay of a closed-loop control system is:

$$\tau = \tau_{sc} + \tau_{ca} \tag{4}$$

2.2.4 NCS model with time delays

The model of the implementation of a process control application on a network can be represented by the continuous model given on Fig. 4 where a time delay τ is represented as $e^{-\tau s}$

The transfer function $F(s)$ is now:

$$F(s) = \frac{K(1+sT_d)e^{-\tau_{ca}s}G(s)}{1+K(1+sT_d)e^{-\tau s}G(s)} \tag{5}$$

The exponential function can be replaced with the Padé first order approximation *i.e.*,

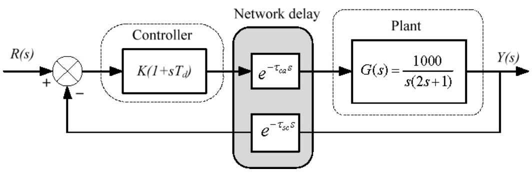


Fig. 4. Control system with time delays.

$$e^{-\tau s} \approx \frac{-s+\dfrac{2}{\tau}}{s+\dfrac{2}{\tau}} = \frac{-s+a}{s+a}, \quad e^{-\tau_{ca} s} \approx \frac{-s+\dfrac{2}{\tau_{ca}}}{s+\dfrac{2}{\tau_{ca}}} = \frac{-s+b}{s+b}$$

Where $a = \frac{2}{\tau}, b = \frac{2}{\tau_{ca}}$.

We get finally the transfer function in Equation (6). From Equation (6), we have 4 poles (3 poles p_1, p_2, p_3 of the polynomial $f_3(s)$, $p_4 = -2/\tau_{ca}$ and 3 zeros ($z_1 = -1/T_d$, $z_2 = -2/\tau$, $z_3 = 2/\tau_{ca}$).

2.3 Considered global control system

2.3.1 Control system setup

We implement 8 identical process control applications (noted P_1, P_2,⋯, P_8) through a CAN network. So we have 24 different nodes connected through a CAN network and 16 data flows (8 f_{sc} and 8 f_{ca} flows) sharing the network. We consider other parameters and conditions as followed: bit rate = 250 Kbit/s; data field length of a frame = 8 bytes, thus D_{sc} = D_{ca} = 150 bits ; the sensor tasks are synchronous and have the same sampling period.

2.3.2 Priority of messages

Generally, the priorities are static priorities, *i.e.*, each flow has a unique priority (specified *a priori* out of line) and all the frames of this flow have the same priority. In this work, we consider not only static priorities but also hybrid priorities (as we said in the introduction). The hybrid priority consists in structuring the field ID in two levels (Fig. 5) where the Level represents the uniqueness of the message (flow priority) which is a static priority and Level 2 represents the transmission urgency of the frame[9] . This concept has a great interest during the transient behavior of systems[10].

In the context of the competition based on these

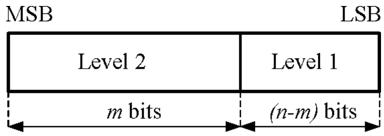


Fig. 5. Structure of the ID field.

hybrid priorities, the message scheduling is executed by comparing first the bits of the Level 2 (urgency predominance). If the urgencies are identical, the Level 1 (static priorities which have the uniqueness properties) resolves the competition.

2.2.3 Static priorities associated to the f_{sc} and f_{ca} flows

Here we consider the conclusion shown in : The priority of the f_{ca} flow should be higher than the priority of the f_{sc} flow in order to get the best results. Considering *n* process control applications (P_1, P_2,⋯, P_n), each process has one f_{sc} flow and one f_{ca} flow. We call $Prio\_f_{ca}\_i$ and $Prio\_f_{sc}\_i$ the priorities of the f_{sc} and f_{ca} flows of the process P_i (i = 1, 2,⋯, n), respectively. The priorities of 2n data flows are arranged in the following order: $Prio\_f_{ca}\_1 > Prio\_f_{ca}\_2 > \cdots > Prio\_f_{ca}\_n > Prio\_f_{sc}\_1 > Prio\_f_{sc}\_2 > \cdots > Prio\_f_{sc}\_n$.

2.2.4 Criteria of the QoC evaluation

The QoC is evaluated through a cost function ITSE (Integral of Time-weighted Square Error):

$$J = \int_0^T t e^2(t) dt \tag{7}$$

with T > t_s in order to cover the transient regime duration. We consider T = 1000 ms and we get the value of J for the control system without network (section II-1) is J_0 = 0.001962 which is considered as the reference value. The QoC criteria is represented by the term:

$$\begin{aligned} F(s) &= \frac{500Ka(1+sT_d)(1+s/a)(1-s/b)}{\left[s^3+\left(0.5+a ?\ \ 00KT_d\right)s^2+\left(500KT_d+0.5a ?\ \ 00K\right)s+500Ka\right](1+s/b)} \\ &= \frac{500Ka(1+sT_d)(1+s/a)(1-s/b)}{\left[f_3(s)\right](1+s/b)} \end{aligned} \tag{6}$$

$$\frac{\Delta J}{J_0}\% = \frac{J - J_0}{J_0}\% \tag{8}$$

The smaller the value $\triangle J/J_0$ % is, the better the QoC is. We will also consider the time response for the QoC evaluation.

Ⅲ. The implementation of a hybrid priority scheme for message scheduling

3.1 Idea of hybrid priorities

The ID field into 2 small fields as represented in Fig. 5. Level 2 (*m* high significant bits) represents transmission urgency which is called dynamic priority part with its value *ID_dyn*. The *ID_dyn* can be changed during system operation and several data flows can share the same *ID_dyn*. Level 1 (*n-m* bits) which is called static priority part represents the uniqueness of data flows as its value *ID_sta* is fixed, unique and specified before system running. The uniqueness means that there are no two or more nodes having the same *ID_sta*. The term "hybrid priority" means the combination of dynamic priority and static priority. The idea of this ID field structure was first introduced in [10]. Then other studies[9,12] also used the similar ID field structure. The medium access tournament is done firstly by comparing Level 2. If there are several data flows having the same *ID_dyn*, Level 1 will determine the only winner allowed to access to the medium.

3.2 Specifying of the dynamic priority

Specifying dynamic priority part requires, firstly, to determine QoC parameter of the process control application which gives information on the transmission urgency, and secondly, to translate these urgencies into dynamic priorities (*i.e.*, computation of dynamic priorities).

Two main QoC parameters using for representing the transmission urgency are steady state error error e[2,12] and control signal u[3,9]. Some other works use the deadline[10,13]. With these parameters, the authors proposed different functions for computation of dynamic priorities. The principle is that the higher the values of *e, u* or deadline are, the higher the dynamic priorities are.

Concerning the works using the error *e*, they used an extended ID field of 29 bits (16 bits for *ID_dyn* and 10 bits for *ID_sta*). The value of *e* is encoded directly into the *ID_dyn* value. The first limitation is that, we have a wide range of error value and this is not bounded (for example when the system is unstable, the error is infinite). Mapping these error values in a definite number of priority bits is not an easy task. The second limitation is that, they assume the existence of a master node knowing the current states of all controller nodes. Maintaining a global state in the whole distributed control system can be problematic.

The works using the control signal *u* have overcome the unbounded value by a saturation value u_s (if u is higher than u_s, the dynamic priority is maximum). They used a standard ID filed of 11 bits (7 bits for *ID_dyn* and 4 bits for *ID_sta*). So, they can determine a maximum number of 16 data flows (or nodes) which is not enough to address all nodes in a NCS.

3.3 Proposal

3.3.1 A. ID field

We use an extended ID field of 29 bits with 11 bits for dynamic priority part, and 11 bits for static priority part. That overcomes the limitation concerning number of *ID_sta* bits.

3.3.2 Control parameters

Both the error *e* and the control signal *u* are used for making the dynamic priority.

3.3.3 Computation of dynamic priorities

The dynamic priority (noted *Prio_dyn*) is calculated by the controller using functions represented in Fig. 6 and Equations (9 & 10) where e_{max} and u_{max} are the maximum values of *e* and *u* respectively when we consider the initial continuous control system without the network.

$$f(e) = \begin{cases} Prio\_dyn_{\max}\dfrac{|e|}{|e|_{\max}}, & 0 \le |e| \le |e|_{\max} \\ Prio\_dyn_{\max}, & |e| > |e|_{\max} \end{cases} \tag{9}$$

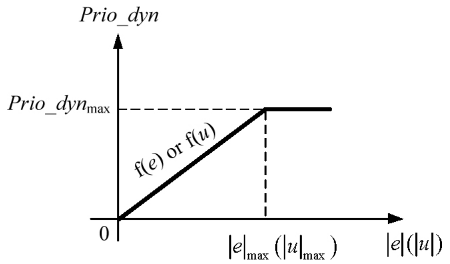


Fig. 6. Functions of e and u.

$$f(u)=\begin{cases} Prio\_dyn_{\max}\dfrac{|u|}{|u|_{\max}}, & 0\le |u|\le |u|_{\max} \\ Prio\_dyn_{\max}, & |u|>u_{\max} \end{cases} \quad (10)$$

3.3.4 Encoding priority into ID field

The dynamic priority part consists of 11 bits which is able to represent 2^{11} = 2048 priority levels from 0 to 2047. The minimum dynamic priority is $Prio\_dyn_{min}$ = 0 corresponding to the *ID_dyn* of 11 recessive bits (bit 1). The maximum dynamic priority is $Prio\_dyn_{max}$ = 2047 corresponding to the *ID_dyn* field of 11 dominant bits (bit 0). The relation between the *ID_dyn* and the *Prio_dyn* is as follows:

$$ID\_dyn = 2047 - Prio\_dyn \quad (11)$$

3.3.5 Implementation of the hybrid priority scheme

Before we present how the hybrid priority scheme works, we should consider the implementation of a process control application on the CAN network as represented on Fig. 7.

Now, we can see how the hybrid priority works. Firstly, concerning the static priority part, this priority of each node is specified before the system running. The subsection II-3C shows that we have to set static priority of the f_{ca} flow (noted $Prio\_sta_{fca}$) higher than that of the f_{sc} flow (noted $Prio\_sta_{fsc}$) in order to get the best results.

Here we will consider this conclusion. Secondly, concerning dynamic priority part, its implementation is as follows:

- At the instant t_k, the sensor samples the output (y_k) and gets dynamic priority ($Prio\_dyn_{k-1}$) sent from the controller in the previous period (*i.e.*, period starting at t_{k-1}). After that, the sensor uses this priority ($Prio\_dyn_{k-1}$) to send its frame (containing y_k) to the controller.
- After receiving the f_{sc} frame sent from the sensor, the controller computes the control signal u_k and the dynamic priority $Prio\_dyn_k$ (by equations (9 & 10) and sends its frame on the network. Then, the actuator will get u_k and apply it to the controlled plant, while the sensor will get $Prio\_dyn_k$ to use in the next sampling period (period starting at t_{k+1}).

Concerning dynamic priority using to send the f_{ca} frame by the controller, there are two ways: the first one is that the controller use the $Prio\_dyn_k$ value which has just been computed[9]; and the second one is to use the $Prio\_dyn_{max}$[2,3]. It is evident that the second way ensures that f_{ca} frame will be sent immediately after the reception of f_{sc} frame (computational time delays in the controller is

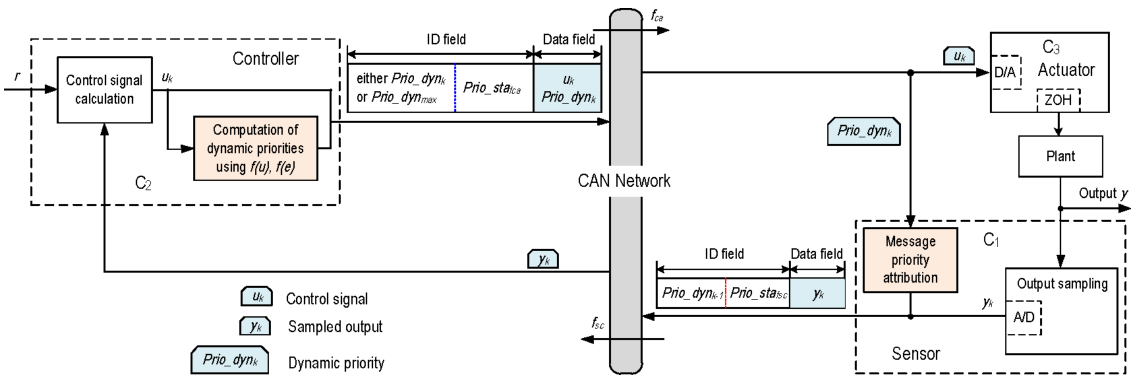


Fig. 7. Implementations of process control applications on a CAN network.

negligible). Therefore, comparing to the first way, the second way performs a shorter time delay of the closed loop.

In this paper, we consider the second one, *i.e.* the controller uses the $Prio\_dyn_{max}$ to send its frames.

Noting that, at the instant 0 (t_0 = 0), the sensor has no information about the dynamic priority from the controller. Therefore we consider that the sensor uses, at the first time, the $Prio\_dyn_{max}$.

3.4 Implementation of process control application on CAN network

3.4.1 Criteria of the QoS evaluation

In order to evaluate the QoS, we calculate first the communication time delay τ_i of the closed loop control system in each sampling period starting at t_i according to the Equation (4), then we compute the average value of theses time delays during the settling time t_s by the following formula:

$$\overline{\tau} = \frac{1}{n}\sum_{i=1}^{n}\tau_i \qquad (12)$$

Where n is the number of sampling period in the settling time. The smaller the value $\overline{\tau}$ is, the better the QoS is.

3.4.2 Criteria of the QoC evaluation

We use the criteria ITSE in the Equations (7 & 8).

3.4.3 Results

- Quality of Service (QoS)

We present the QoS in term of $\overline{\tau}$ of the 8 processes on Table 2 and the scheduling of frames in the first 10 sampling periods on Fig. 9a, 9b and 9c (in which f_{cai} and f_{sci} are the controller-actuator frame and sensor-controller frame of the process i).

For static priority scheme, the process with higher priority has smaller time delay (Table 2 and Fig. 9a). We see that P_1 has the highest priority so its delay is the smallest while P_8 has the lowest priority so its delay is the biggest. The frame exchanges are identical for all periods (Fig. 9a). The protocol based on static priority is called deterministic protocol.

For the hybrid priority scheme (with e and u), we obtain time delays more balanced than these with static priorities (Table 2). The frame exchanges are not identical in each sampling period (Fig. 9b, Fig. 9c) due to the predominant role of the parts "dynamic priority" which make the priority changed in each sampling period.

The QoS balance can be observed by the difference between the maximum delay and the minimum delay in each priority scheme in Table 2. We see that these differences are small with hybrid priorities (3.04 ms with e and 1.34 ms with u) while this value is very big with static priorities (8.4 ms).

- Quality of Control (QoC)

The QoC is represented on the Table 3 ($\Delta J/J_0$ %) and Fig. 8 (time responses $y(t)$). We see also the balances of QoC with hybrid priorities compared with static priorities. It is logical because balances of QoS induce balances of QoC. The conclusions of QoC for different priority schemes are similar to these of QoS.

Precisely, for the static priority scheme, the higher the priority is, the better the QoC is, and for the hybrid priority schemes, the QoCs are more balanced than these of the static priority scheme.

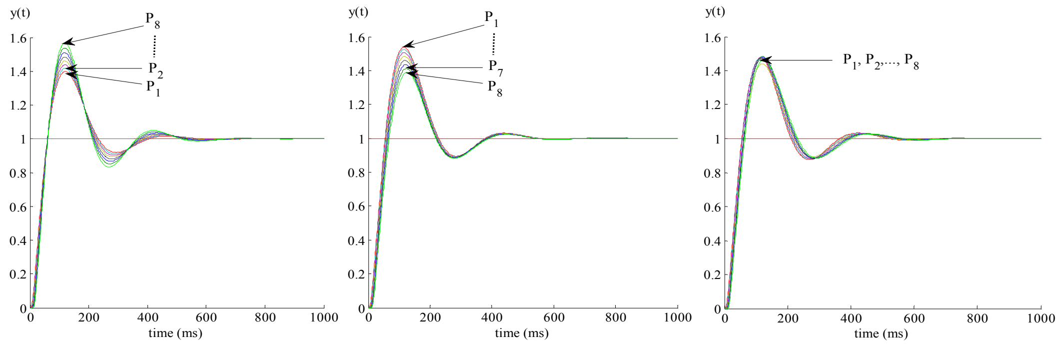
Note that the hybrid priority allows more balanced QoCs between processes than the static priority but the best QoC and the worst QoC belong to the static priority. The advantage of the hybrid priority is that if we have a QoC threshold which

Table 2. QoS ($\overline{\tau}$ms).

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	$\overline{\tau_{max}} - \overline{\tau_{min}}$
Static priority scheme	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6	8.4
Hybrid priority scheme with e	3.67	4.24	4.73	5.29	5.86	6.21	6.49	6.71	3.04
Hybrid priority scheme with u	4.73	4.87	5.01	5.58	5.65	5.51	5.79	6.07	1.34

Table 3. QoC ($\Delta J/J_0$ %).

	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
Static priority scheme	7.37	15.77	25.40	36.52	49.44	64.55	82.36	103.60
Hybrid priority scheme with *e*	72.76	66.21	57.34	47.55	38.04	29.52	22.30	16.58
Hybrid priority scheme with *u*	34.60	38.47	41.83	26.78	46.67	55.99	61.13	56.46



a) Static priority scheme
b) Hybrid priority scheme with e
c) Hybrid priority scheme with u

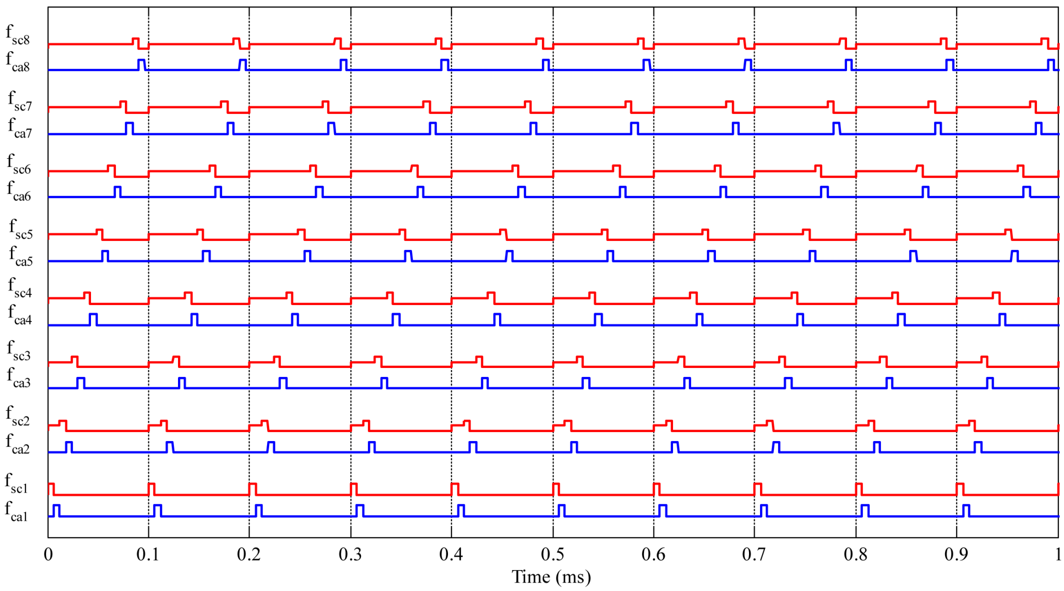
Fig. 8. Time responses.

can not to be exceeded, the hybrid priority scheme allows implementing more applications on the network than the static priority scheme. For example if the QoC threshold is 80%, we can implement all 8 processes with the hybrid priority but only 6 processes with the static priority (see Table 3).

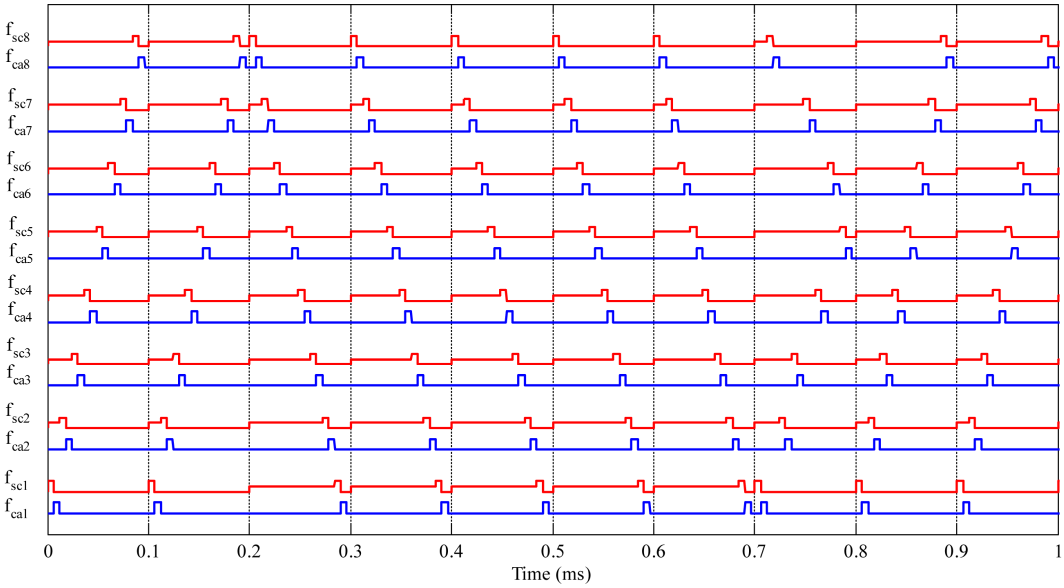
Ⅳ. The Implementation of the Compensation for Communication Time Delays

4.1 Ideas

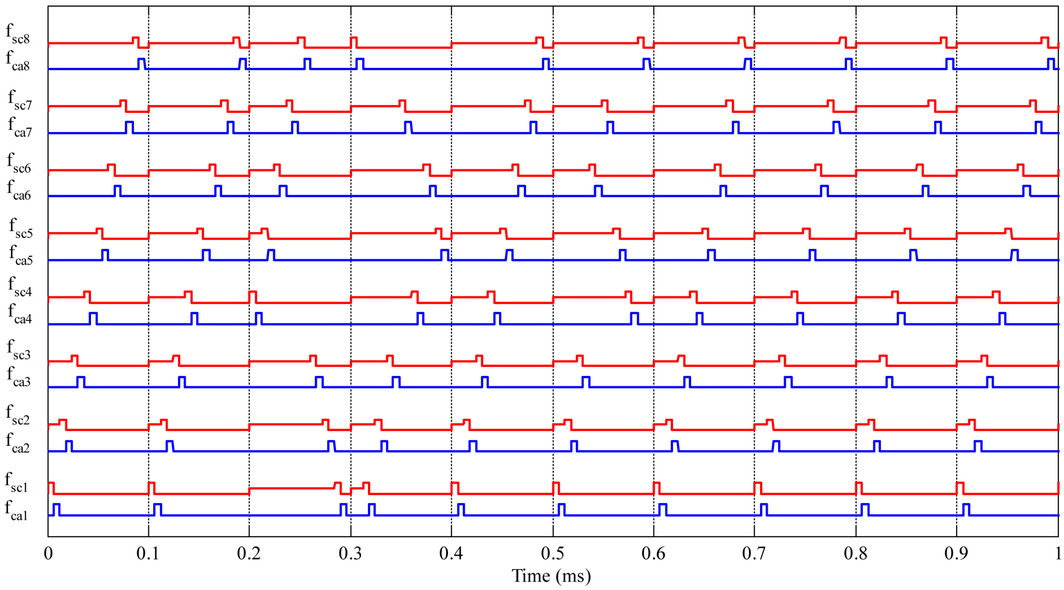
The QoS considered is the closed-loop



a) Static priority scheme: message exchanges in the first 10 sampling periods.



b) Hybrid priority scheme (parameter e): message exchanges in the first 10 sampling periods.



c) Hybrid priority scheme (parameter u): message exchanges in the first 10 sampling periods.

Fig. 9. Message exchanges in the first 10 sampling periods.

communication time delay during each sampling period. With the knowledge of τ, the controller can compensate this time delay by modifying the parameters K and T_d in such a way to maintain the same type of transient behavior for the process control application as before the implementation on the network. As the transfer function of the system implemented on the network, the modification of K and T_d, according to the pole placement design method, must keep the main role for the 2 poles $p_{1,2}$ which are called the dominant poles and integrate the conditions which give an insignificant role to the poles p_3, p_4 (called insignificant poles). Actually, the numerator of Equation (6) has now three zeros. Thus we have to evaluate the influence of these zeros on the overshoot.

4.2 Proposal

4.2.1 Computation of closed-loop communication time delays

The computation of closed-loop communication time delays is done by the controller in each sampling period.

Concerning the time delay τ_{sc}, as the controller has the knowledge of sampling instants t_k (k = 0, 1,⋯), it can easily deduce the value of τ_{sc} by the time difference between the reception instant of f_{sc} frames and t_k. Concerning the time delay τ_{ca}, it cannot be calculated because the f_{ca} frames have not been transmitted yet. However, due to the hypotheses in subsection II-3B (*i.e.*, the priority of the controller is higher than this of the sensor; there is no competition between the controllers; there is no data lost), the controller can immediately send its frame. *Therefore, τ_{ca} is equal to the duration of a frame transmission (D_{ca}).* The closed-loop time delay will be computed by the controller as followed:

$$\tau = \tau_{sc} + D_{ca} \tag{13}$$

4.2.2 Time delay compensation steps

The compensation for time delays done by the controller in each sampling period has the following steps:

- Step 1: Identifying expected poles including the dominant poles and the other poles which are selected equally to the real part of the dominant pole divided α, with $\alpha = 2 \div 10$[7].
- Step 2: Computing communication time delay τ.
- Step 3: Computing the controller parameters according to the time delay value in order to maintain the position or the value of the expected poles.
- Step 4: Computing the control signal based on the new control parameters calculated in the previous step.

4.3 The computations in the controller for the maintenance of the pole placement design method

Consider the polynomial $f_3(s)$ in the denominator of Equation (6), this polynomial concerns the poles p_1, p_2, p_3 and can be written as:

$$\begin{aligned}&(s-p_1)(s-p_2)(s-p_3) = \\ &= s^3-(2R+p_3)s^2+(2Rp_3+R^2+I^2)s-(R^2+I^2)p_3\end{aligned} \tag{14}$$

By identifying $f_3(s)$ with Equation (14), we get the relations which allow determining the values of p_3, K and T_d:

$$\begin{cases} p_3 = -\dfrac{a^3+(1+2R)a^2-(R^2+I^2)a}{a^2-2Ra+R^2+I^2} \\ K = -\dfrac{(R^2+I^2)p_3}{500a} \\ T_d = \dfrac{0.5+a+p_3+2R}{500K} \end{cases} \tag{15}$$

We replace the value of K in Equation (6) by this one found in Equation (15), we have now the transfer function $F(s)$:

$$F(s) = \frac{\omega_n^2(1+sT_d)(1+s/a)(1-s/b)}{(s^2+2\zeta\omega_n s+\omega_n^2)(1-s/p_3)(1+s/b)} \tag{16}$$

Note that p_3 and $p_4 = -2/\tau_{ca}$ are real poles.

4.4 Conditions for the insignificance of the poles p_3 and p_4

We take the conditions expressed by [5] *i.e.*, the real part is five times smaller than the real part of the dominant poles, then:

- $p_3 \leq 5R$ which need $\tau_{sc} + \tau_{ca} < 26.08$ ms.
- $p_4 \leq 5R$ which need $\tau_{ca} < 45.87$ ms.

These conditions are always satisfied as the sampling period h is 10 ms and $\tau_{sc} + \tau_{ca}$ is always smaller than h.

4.5 Effect of the zeros

"When a zero gets closer to the origin, the overshoot increases"[14,15]. For a negative zero (call z_0 the absolute value of this zero), in [14], the zero has a little effect and can be neglected if $|z_0|/\zeta\omega_n \geq 5 \Rightarrow |z_0| \geq 43.58$. For a positive zero (call z_0 the value of this zero), in [15], the overshoot is evaluated as follows:

$$O = e^{-\frac{\zeta(\Phi+\pi)}{\sqrt{1-\zeta^2}}}\sqrt{1+\frac{2\zeta\omega_n}{z_0}+\left(\frac{\omega_n}{z_0}\right)^2} \qquad (17)$$

Where $\Phi = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{z_0+\zeta\omega_n}$. We see that if $z_0/2\zeta\omega_n >> 1$ and $(z_0/\omega_n)^2 >> 1$, the overshoot can be re-written as $O = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}$ *i.e.*, we have the overshoot of the second order system without zero. We can thus consider that if $z_0/2\zeta\omega_n > 5$ and $(z_0/\omega_n)^2 > 5$ (these conditions induce that z_0 > 87.17 (with ω_n = 18.16, ζ = 0.48)).

We consider now the three zeros:

- The negative zero $z_2 = -2/\tau$: as $\tau = \tau_{sc} + \tau_{ca}$ is smaller than h, z_2 is smaller than −2/0.01 = −200. We see that $|z_2| > 43.58$. Thus the zero z_2 can be neglected.
- The positive zero $z_3 = 2/\tau_{ca}$: because of τ_{ca} is smaller than h, z_3 is bigger than 2/0.01 = 200, thus z_3 > 87.17. Hence the zero z_3 can be neglected.
- The negative zero $z_1 = -1/T_d$: note that this zero is based on a parameter of the controller (T_d). The effect of z_1 depends on the value of T_d; the higher the value of T_d is, the more closed the zero is to the origin, thus the zero has the stronger effect.

Remark about the transfer function after the compensation of the time delay: Considering the insignificance of the poles p_3, p_4 and the negligible effect of the zeros z_2 and z_3, the transfer function in Equation (16) can be written as Equation (18).

$$F(s) = \frac{\omega_n^2(1+sT_d)}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad (18)$$

We see that we have the same form as the transfer function of the system without delays in Equation (3), but the value of T_d is now changed.

4.6 Validation of the pole placement design method

Table 4 and Table 5 show the results obtained by considering different loop delays τ.

We see that the dominant poles are maintained which results from the action on K and T_d (decrease of K and increase of T_d).

We also see the increase of the overshoot (mainly due to the increase of the zero $z_1 = -1/T_d$; the role of the zeros z_2, z_3 and of the poles p_3, p_4 is negligible)

4.7 Considering the implementation of the 8 process control applications

We want to show here the interest of the pole placement design method (which is based on an adaptive controller *i.e.* the parameters of the controller are modified according to the closed-loop

Table 4. Validation of the pole placement design method, τ_{sc} = 1 ms.

τ_{ca} (ms)	τ (ms)	K	T_d (s)	$p_{1,2}$	p_3	p_4	O (%)	z_1	z_2	z_3
1	2	0.6372	0.0533	-8.72 ± j15.93	-966	-2000	**32.15**	-18.7	-1000	2000
2	3	0.6260	0.0544	-8.72 ± j15.93	-633	-1000	**33.73**	-18.4	-667	1000
3	4	0.6148	0.0554	-8.72 ± j15.93	-466	-667	**35.46**	-18.1	-500	667

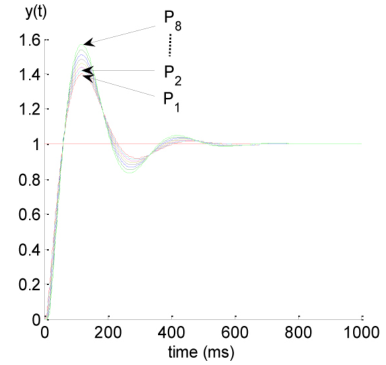
Table 5. Validation of the pole placement design method, τ_{ca} = 1 ms.

τ_{sc} (ms)	τ (ms)	K	T_d (s)	$p_{1,2}$	p_3	p_4	O (%)	z_1	z_2	z_3
1	2	0.6372	0.0533	-8.72 ± j15.93	-966	-2000	**32.15**	-18.7	-1000	2000
2	3	0.6260	0.0544	-8.72 ± j15.93	-633	-2000	**32.74**	-18.4	-667	2000
3	4	0.6148	0.0554	-8.72 ± j15.93	-466	-2000	**33.35**	-18.1	-500	2000

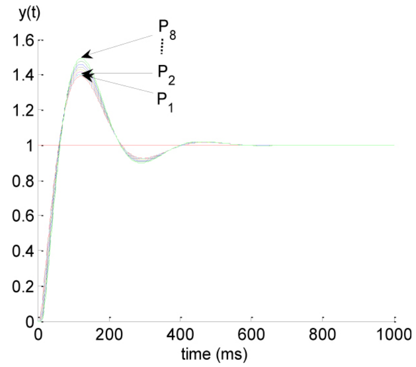
communication time delays) in comparison with the case where we do not use this method (*i.e.*, we have a fixed controller). The comparison between the case adaptive controller (*i.e.*, compensation) and the case fixed controller (*i.e.*, non-compensation) is presented on and on Fig. 10 (time responses *y(t)*).

From the results of the case non-compensation: the performances follow the order of the priorities which is normal (lower is the priority, then higher is the time delay and less good is the performance).

From the results of the case compensation for communication time delay: it improves the results (what was waited for!) which are less dispersed (the influence of the priorities is reduced); however we cannot have identical performances for all the process control applications because of the effect of the zero $-1/T_d$ (as the applications which have less priority have higher delays, the compensation requires higher values of T_d which induces that the zero $-1/T_d$ moves closer to the origin).



a) Non-Compensation



b) Compensation for Communication time delay

Fig. 10. Time responses of the 8 applications.

We note also the effect of the zero $-1/T_d$ by the increase of O (Fig. 10 (b)) compared with the O (secction II-1) of the control system without network.

V. A Co-Design of Time Delay Compensation and Message Scheduling

5.1 Ideas

The idea is to combine the frame scheduling scheme based on the hybrid priority and the method of compensation for communication time delay in order to have a more efficient NCSs. However, concerning the close-loop time delay compensation, in the sampling period k, we cannot consider here that the controller can use the value of the close-loop communication time delay of the sampling period $(k-1)$ because now, taking into account for the dynamic priority used by the sensor task, the time delay (τ_{sc} + τ_{ca}) changes every period. Then the controller must make the delay compensation in the sampling period k by knowing the close-loop communication time delay of this sampling period k. We explain now this implementation.

5.2 Principle of the implementation of the co-design

This principle, relatively to the sampling period starting at t_k, is represented on Fig. 11 where we indicate the content of the f_{sc} and f_{ca} frames and the computations done by the controller.

The process of co-design implementation in each cycle starting at t_k as follows: Sensor sampling state variables x and receive priority value sent from the controller in the previous period (period starting at t_{k-1}), then use the sensor priority this ($Prio\_dyn_{k-1}$) to send a message containing x_k to the controller.

The controller after receiving the signal from the sensor x_k, will perform the following steps:

- The computations of dynamic priority $Prio\_dyn_k$ based on the function *f(u)* and *f(e)* (by Equations (9 & 10).
- Calculations of close-loop communication time delay τ and the parameters of the controller

according to the communication time delay τ, *i.e.*, implementation of the compensation for close-loop communication time delay.

- Calculations of the control signal u_k.
- Send messages including control signal u_k and dynamic priority $Prio\_dyn_k$ on the network.
- Then the actuator will receive the value u_k and apply to control plant, while the sensor will get $Prio\_dyn_k$ to use for the next period (period starting at t_{k+1}).

5.3 Performance evaluation and summary of obtained results

We still consider the implementation of 8 applications (P_1, $P_2 \cdots$ P_8) studied in the previous sections. The results ($\Delta J/J_0$ %) of the implementation of the co-design are represented graphically on Fig. 12, obviously show the balanced performances provided by the hybrid priority compared with the static priority and by the co-design compared with the static priority scheme (compensation). From these results, we can say that, if we have a constraint of performance which cannot be exceeded (not too small), the hybrid priority allows implementing more applications than the static one and, extensionally, the bidirectional relation co-design allows implementing more applications than the static priority scheme (compensation).

The visualizations of the time responses provided by the different relations are represented on Fig. 13.

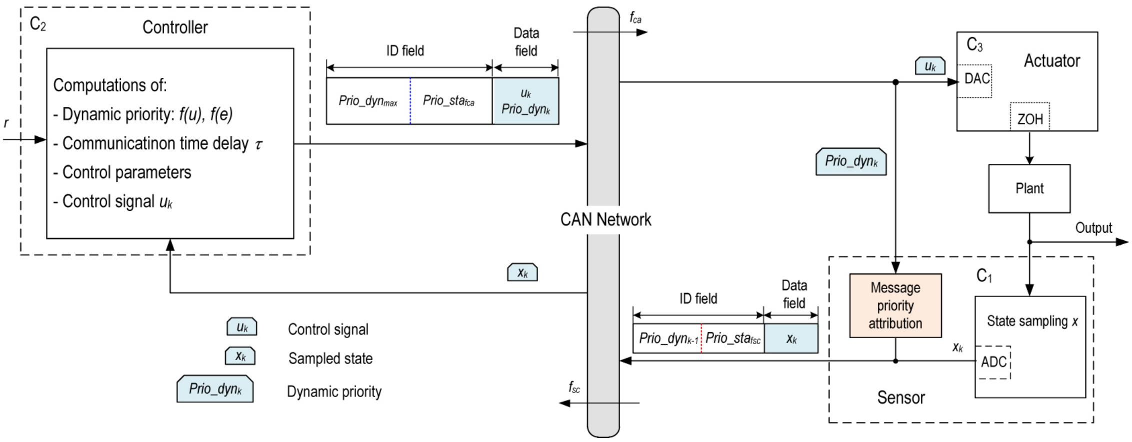


Fig. 11. Principle of the implementation of the co-design.

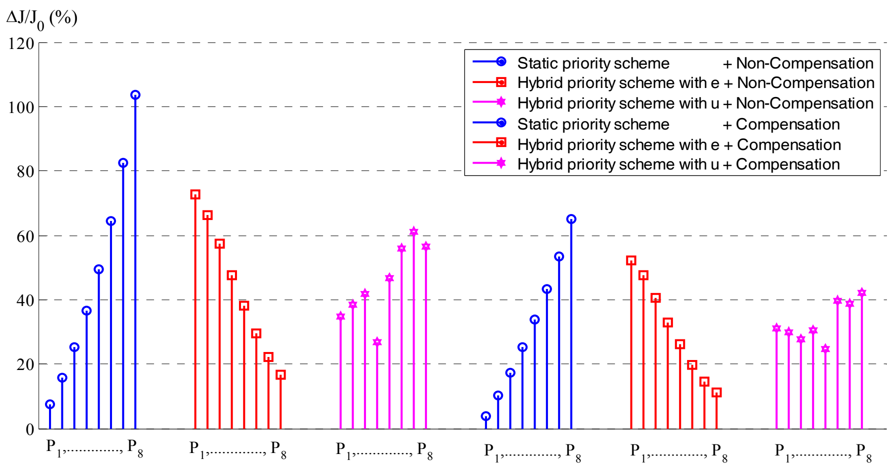


Fig. 12. Graphic representation of the QoC ($\Delta J/J_0$ %) of the 8 applications.

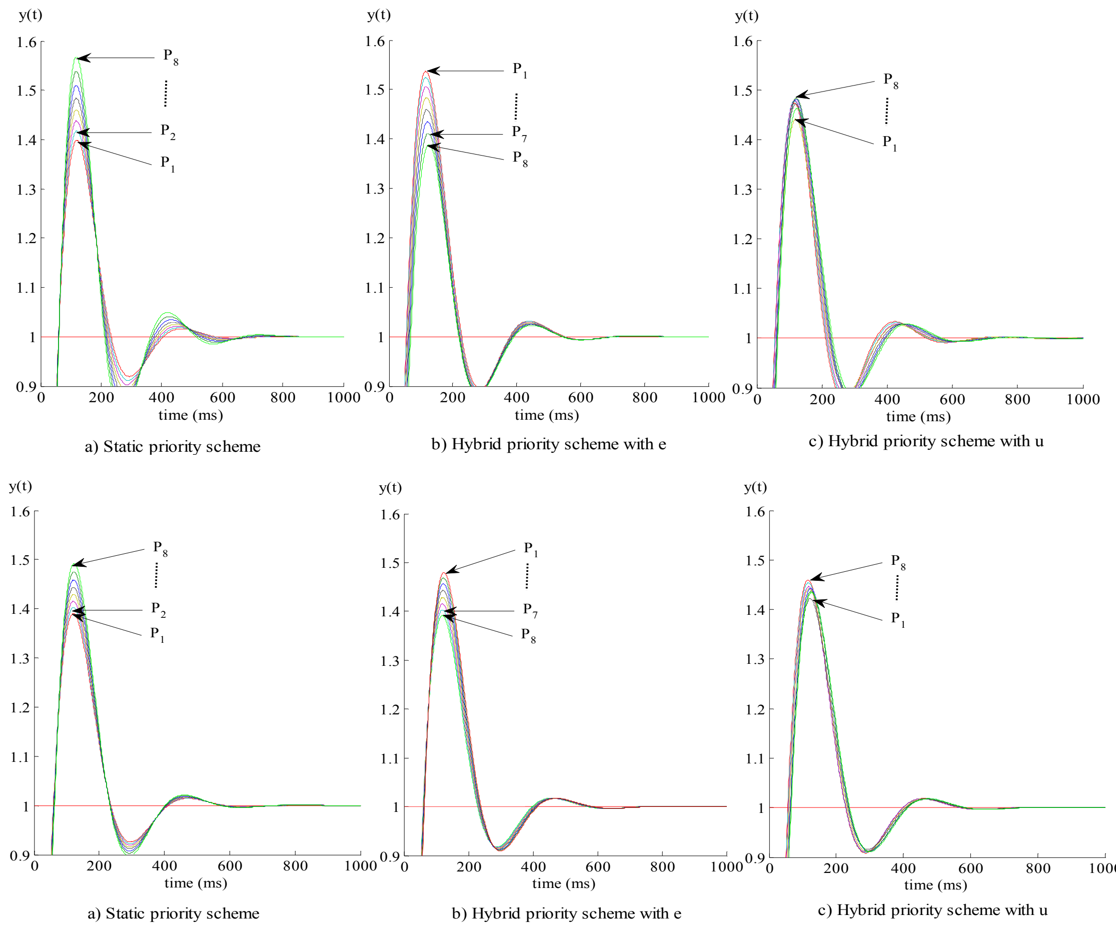


Fig. 13. Zoom time responses (top: without co-design (zoom of Fig. 8); bottom: co-design).

Ⅵ. Conclusions

In this paper, we have presented a co-design between the time delay compensation and the message scheduling which have the following advantages. First, this co-design overcomes the limitations of related works discussed in Section I (bounded error value, limited number of network nodes). And second, this co-design allows improving simultaneously the QoC and the QoS of CAN-based NCSs. More precisely, by the hybrid priority, we have balance aspect compared with the static priority and by the delay compensation, we maintain the balanced aspect while improving the QoC. The results obtained also allow considering the possibility to implement more applications than with the static priority.

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