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Decentralised control of a quadruple tank plant with a decoupled event-based strategy

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Abstract: In this work we focus on the development of a software tool, which allows users to perform experiments with event-based PI controllers in a multivariable system composed of four coupled tanks. The quadruple tank plant allows the student of control engineering to experiment and obtain an intuitive knowledge about multivariable systems (systems with more than one inputs and more than one outputs), to study the differences between the minimum phase and non-minimum phase behaviours and the difficulties in control that arise in the latter case, and all this with the motivation that the experiments can be done not only in simulation but with a real plant. The control system provides the possibility of using a decoupling net between the controllers and the actuators, which can have a direct or inverse scheme, and which can be used to reduce the effect of the interactions between inputs and outputs. Finally, we present a set of results illustrating the possibilities of the application to investigate the performance of the event-based controller together with a decoupling strategy.

Keywords: multivariable, PI, events, remote laboratory.

1. INTRODUCTION

When teaching engineering and in particular control theory, it becomes very important for a student to see in practice the theoretical results and get familiarized with the equipment and the instruments manipulation in real situations (Candelas and Sánchez (2005)). However, as studied in (Candelas et al. (2004)), not all colleges can afford the cost of the acquisition and constant maintenance of laboratory equipment, which can become excessive in many cases. In addition, the laboratories need the presence of instructors and also the timetable is frequently limited.

The use of remote laboratories is thus an alternative to be considered, to allow students to carry out experiences as if they were in the laboratory. It is common that this remote laboratories provide an interface to interact with the plant, and video streaming so that students can watch what actually happens, having a better sense of presence in the laboratory.

The quadruple tank introduced by (Johansson (1997, 2000)) has received a great attention because it presents interesting properties in both control education and research. The quadruple tank exhibits complex dynamics in an elegant and simple way. Such dynamic characteristics include interactions and a transmission zero location that are tunable in operation. With adequate tuning this system presents non-minimum phase behavior that arises due to the multivariable nature of the problem. For this reason the quadruple tank has been used to show the results of different control strategies and as an educational tool in teaching advanced multivariable control techniques.

However, remote laboratories imply the use of shared communication channels that can lead to delays or other problems that adversely affect the sytem stability. For these reasons we must optimize the delivery of data from different sensors, and a way to achieve this is through the use of sampling techniques and event-based control. For example, instead of sending data or control actions with a constant sampling period, the communications are done only when certain events are triggered.

In summary, event-based strategies are advantageous when the nature of the control problem impose restrictions over the number of control actions to be applied. This is due to the fact that, in periodic control systems, communications are done regardless of the state of the plant, and thus much of the information flow can be unnecessary. The benefits of event based sampling schemes have been proved for certain types of systems. In (Åstrom and Bernhardsson (1999)) periodic and event-based sampling for first order stochastic systems are compared. Different types of event-based PID control algorithms have been proposed in recent works, as in (Capponi et al. (2008); Vasyutynskyy and Kabitzsch (2006)) where a send-on-delta sampling is incorporated to the controller. In (Årzén (1999)) a state-feedback approach with a disturbance estimator is investigated. In (Sánchez et al. (2009); Chacón et al. (2010)) the set-point following task and the disturbance rejection are treated independently. From the implementation point of view, frequently the data acquisition hardware is designed to be used in periodic sampling systems. It is thus necessary in these cases to perform periodic sampling at high frequency and then to implement by software the event detection mechanism. Moreover, in many cases the energy efficiency is a key issue, as it occurs with wireless sensor networks (see Lunze and Lehmann (2010)), where the elements have autonomous power supply. In this cases the communication must be optimized to obtain the maximum life of the batteries.

If we combine the event-based concepts mentioned before with control strategies from multivariable systems, we could take advantage of the benefits from each field. Then, it would be very useful to have a remote laboratory both for teaching control theory concepts involving multivariable, non-minimum phase behavior, etc., but also for the research in event-based control of multivariable systems.

In this work we have addressed both issues by developing a remote laboratory with the quadruple tank and using it to obtain some interesting results. The organization of the paper is as follows. Section 2 defines the control problem. Section 4 describes the Remote Lab developed, and Section 5 presents the experimental results obtained with the system. Finally, the conclusions and some futures lines of work are commented in Section 6.

2. CONTROL PROBLEM DEFINITION

2.1 Physical Model

The quadruple tank plant (see Figure 1) can be seen as a system with two inputs, the voltages of the pumps, and two outputs, the water levels of the lower tanks. A mathematical model based on physical data together with its linearization around an operating point is derived in Johansson (2000). In the rest of the paper we will use the linearized model, which is described in the following paragraphs.

2.2 Linearized model

The mathematical model can be linearized around an operating point. Defining the variables $x_i = h_i - h_i^0$ and $u_i = u_i - u_i^0$, where h_i^0 and h_i^0 are respectively the steady state tank level and the input flow corresponding to the operating point, the linear system can be represented by the transfer functions matrix,

$$G(s) = \begin{pmatrix} \dfrac{\gamma_1 c_1}{1+sT_1} & \dfrac{(1-\gamma_2)c_1}{(1+sT_3)(1+sT_1)} \\ \dfrac{(1-\gamma_1)c_2}{(1+sT_4)(1+sT_2)} & \dfrac{\gamma_2 c_2}{1+sT_2} \end{pmatrix} \quad (1)$$

where $c_i = \frac{T_i K_i K_c}{A_i}$ and $T_i = \frac{A_i}{a_i}\sqrt{\frac{2h_i^0}{g}}$.

2.3 Minimum and non-minimum phase

One interesting property of the four tank system, from the academic point of view, is that the multivariable system can be of minimum or non-minimum phase depending on the configuration of the distribution valves. As explained in Johansson (2000), the zeros of the transfer matrix are the zeros of the numerator polynomial of the rational function

Fig. 1. Quadruple tank plant used in the remote laboratory. The plant is composed of two coupled tanks modules from Quanser (*www.quanser.com*).

$$detG(s) = \frac{c_1 c_2}{\gamma_1\gamma_2 \prod_{i=1}^{4}(1+sT_i)} \times \left[(1+sT_3)(1+T_4) - \frac{(1-\gamma_1)(1-\gamma_2)}{\gamma_1\gamma_2}\right] \quad (2)$$

This means that the matrix G has two finite zeros for $\gamma_1, \gamma_2 \in (0,1)$. One of them is always in the left half plane, but the location of the second can be either in the left or the right half plane. In particular, it can be showed that the system is non-minimum phase for

$$0 \leq \gamma_1 + \gamma_2 \leq 1, \quad (3)$$

and minimum phase for

$$1 < \gamma_1 + \gamma_2 \leq 2. \quad (4)$$

There exists a straightforward physical interpretation. If the system is minimum phase ($\gamma_1 + \gamma_2 > 1$), then the flow to the lower tanks is greater than the sum of the flows to the upper tanks, and the system is easier to be controlled. However, if the system is non-minimum phase ($\gamma_1 + \gamma_2 \leq 1$), the flow to the lower tanks is smaller than the sum of the flow to the upper tanks, and in this case the control of the plant is much more difficult.

The interaction is usually measured by the Relative Gain Array (RGA). The RGA is a matrix where each element λ_{ij} is associated to the input j and the output i, and it is calculated as the quotient of the open loop gain and the gain when the other loops are controlled. A value of λ_{ij} near to one is desirable, since the loop i-j is not affected by the other loops. A negative value is the worst case, because that means that there is a sign change in the loop

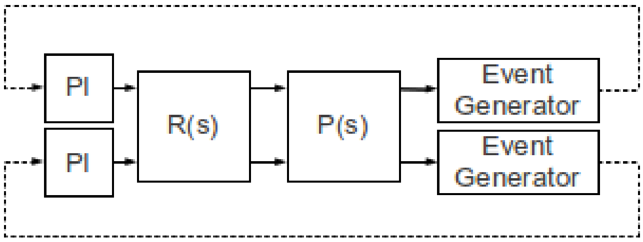


Fig. 2. Structure of the control system. The *Event Generator* blocks determine the instant when the measures of the plant are sent to the PI controllers. The decoupling network $R(s)$ allows the controllers to see the plant as two independent processes.

provoked by the control of th other loops. Since both the columns and the rows of the RGA matrix sum to one, for the 2×2 case the RGA is completely defined by giving the value of λ_{11}.

For the quadruple tank process, this value only depends on the distribution of the pumps flow, and it can be expressed as $\lambda = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 - 1}$. In this particular case, the RGA takes positive values when the system is minimum phase and negative values when the system is non-minimum phase.

3. CONTROLLER

The structure of the control system is showed in Figure 2. It is a decentralized control where each input is paired with one output. To reduce the effect of the interactions, a decoupling network has been added to the output of the controllers. Ideally, with this component the quadruple tank plant can be seen as two non-interacting processes, and therefore the two control loops are independent. However, in practice the perfect decoupling cannot always be achieved.

The decoupling network is $R(s)$, a matrix of transfer functions such as when added to the plant, the aparent process $G(s) = R(s)P(s)$ is a diagonal matrix, i.e. $G(s)$ is a decoupled process.

The plant is represented as a 2×2 transfer function matrix $P(s)$. There are two *event generators* connected to the outputs. These blocks perform a fast sampling and send information to the controller only when the event triggering conditions are satisfied. Each event generator block is defined by two parameters, δ_p and δ_i. Two types of events are defined, proportional events and integral events. A proportional event is triggered when $|e(t) - e(t_{last})| > \delta_p$, where $e(t)$ is the current error and $e(t_{last})$ is the error at the previous event time. An integral event is triggered when $|IE(t) - IE(t_{last})| > \delta_i$, where $IE(t)$ is the current integrated error and $IE(t_{last})$ is the integrated error at the previous event time.

The two PI controllers together with the decoupling network $R(s)$ close both loops. The control signal in the PI controllers is updated only when a new sample is received from the sensors.

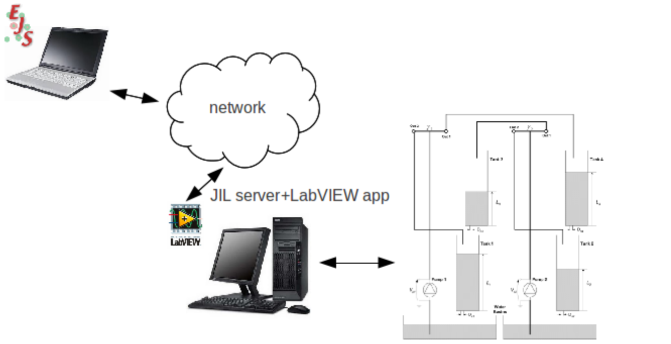


Fig. 3. Architecture of the Remote Lab. The server consist of a PC connected directly to the plant. The Graphical User Interface (GUI) can be ran in the same or in other PC with a network connection to the server. The communication is done over the network.

4. REMOTE LAB

4.1 Architecture

It is desired to give the system the possibilty to have phisically separated the control system and the user interface for configuration and/or monitoring. With this idea in mind, the system has been designed to have a three-tiered architecture. The server, which lies on the PC directly connected to the pumps and sensors, performs the communication with the plant via the data acquisition system and implements the control system. The client, which can be ran in the same or in another PC, consist of a user interface that allows the user to connect with the server. Finally, there is an intermediate application which simplifies the communication between the client and the server. Though the control algorithm is implemented in the server, the platform allows to send the control action from the client, and therefore it is easy to use a different control law. A simulation model is also provided, for the platform to be used even when the plant is not available.

This architecture is represented in Figure 3. It has been implemented with three software tools, namely,

EJS (*Easy Java Simulations*) is a free authoring tool written in Java that helps non-programmers to create interactive simulations in Java, mainly for teaching or learning purposes (*www.um.es/fem/EjsWiki*).

LabVIEW is a graphical programming environment used to develop sophisticated measurement, test, and control systems using intuitive icons and wires that resemble a flowchart.

JIL Server acts as an interface between EJS and LabVIEW. It provides an easy way to send and receive the values of variables directly without entering into low level programming details. JIL provides a Java API to link EJS variables to the controls and indicators of LabVIEW Virtual Instruments (VIs), and to control the load and the execution of these VIs (Vargas (2010)).

5. RESULTS

5.1 Simulation Results

In this section we present the results obtained in simulation. Two different configurations have been tested. For the first set of tests the plant has been configured to have minimum phase behaviour, and for the second set it has been configured as non-minimum phase system. The parameters of the linearized model used in the simulations have been obtained from the data sheet provided with the plant, and are those listed in Table 1. The values of δ_p, δ_i were tuned heuristicaly, increasing them progressively until the control performance decreased under acceptable levels.

Table 1. Simulation model parameters.

Parameter	Value	Description
A_i	15.517	Tank section (cm^2)
a_i	0.178	Outlet section (cm^2)
K	3.3	($cm^2/s/V$)

To compare cuantitatively the different controllers we have used as performance indexes,

- *Integrated Absolute Error*, which is defined as $IAE = \int_0^t |e(t)|dt$, and it is used to measure the control performance. The highest the IAE the more time to take the process to stabilize around the reference. The IAE has been calculated separately in two different contexts, during the set-point following task (IAE_{sp}) and during the disturbances rejection task (IAE_{dr}). The IAE has been calculated with a sampling period equal to that of the time based PI controller, $T_s = 0.1s$.
- *Reduction in control updates*, which is calculated as $\eta = 1 - \frac{N}{N_{ref}}$, where N is the number of events in the controller and N_{ref} is the number of updates in a time-based PI with the same nominal sampling period. The index η is a measure of the control effort.

5.2 Minimum phase configuration

Choosing $\gamma_1 = \gamma_2 = 0.6$, we have that $\gamma_1 + \gamma_2 = 1.2 \geq 1$ and therefore it is a minimum phase configuration. The operating point has been established in $h_1 = 15cm$ and $h_2 = 15cm$, which gives values for the inputs of the pumps of $v_1 = v_2 = 9.2583$.

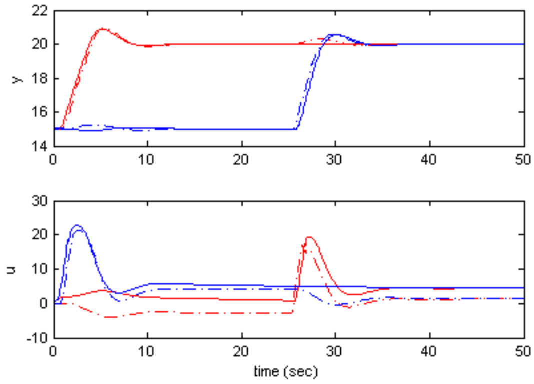
Substituting the values of Table 1 and the operating point in (1), the transfer function matrix for the linearized system is,

$$P(s) = \begin{pmatrix} \dfrac{1.944}{1+15.237s} & \dfrac{1.296}{(1+6.095s)(1+15.237s)} \\ \dfrac{1.296}{(1+6.095s)(1+15.237s)} & \dfrac{1.944}{1+15.237s} \end{pmatrix} \tag{5}$$

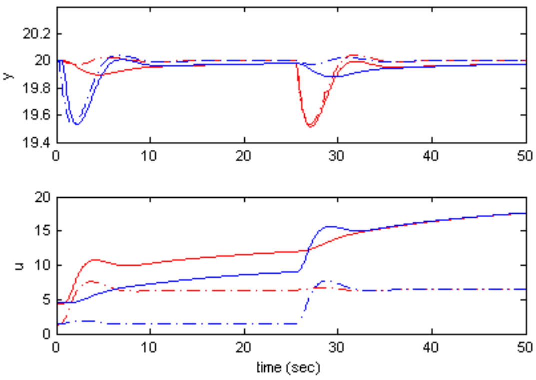
The PI controller parameters were tuned to have a phase margin of 60°, which yields values of $K_p = 4.1766$, $T_i = 2.1275$ for both loops.

Decoupling. For the linealized system around the operating point, the decoupling used in the experiments corresponds to the simplified case with $r_{11} = r_{22} = 1$, $r_{12} = -\frac{p_{12}}{p_{11}}$ and $r_{21} = -\frac{p_{21}}{p_{22}}$, which gives the following matrix,

$$R(s) = \begin{pmatrix} 1 & -\dfrac{0.1094}{s+0.1641} \\ -\dfrac{0.1094}{s+0.1641} & 1 \end{pmatrix} \tag{6}$$



(set-point following)



(disturbance rejection)

Fig. 4. Set-point steps (top) and disturbance rejection (bottom) for the plant with time-based PI without decoupling (dash-dotted line) and with decoupling (continuous line).

The PI parameters for the decoupled system were also tuned by using to have a phase margin of 60°, obtaining values of $K_{p_1} = 4.7646$ and $T_{i_1} = 1.4665$ for both loop.

Set-point step. With the purpose of illustrating the effect that the decoupling network produces in the system, the first tests we present are the responses to a set-point step change with a time based PI controller, both with the decoupling network activated and without it. These results are showed in Figure 4, and allow us to verify the performance of the decoupling net and to serve as a reference for the event-based controller. After an initial phase (not showed) where the output is still reaching the operating point, a set-point step change was applied to the first output. Then, when the process has moved to the new set-point, another step is introduced in the second loop.

It can be seen how the decoupling is very effective reducing the interaction between both loops. This will be an advantage for the event-based PI. As opposed to the previous case, where the set-point change increases the number of events for the two loops, the decoupling allows the controller of the loop that is not involved in the set-point change to remain independent at a certain level, i.e. the events do not increase significantly. For the event-based case, four different set of parameters have been tested, corresponding to $\delta_p = \delta_i = 0.01$, $\delta_p = \delta_i = 0.02$, $\delta_p = \delta_i = 0.05$ and $\delta_p = 0.01$, $\delta_i = 0.05$. It can be seen that, as it was expected, the performance of the controllers degrades when increasing the event thresholds. It can be observed that the events provoke oscillations around the set-point. Thus an excessive value of the thresholds can lead to an important decrease in performance. However, for reasonable values the performance is good and the updates in the control action are reduced significantly with respect to the periodic PI controller.

Disturbance rejection In the previous section we have seen that the decoupling provides the possibility of coping with the set-point following task in an independent way for the two outputs. However, one of the disadvantages of using decoupling strategies is that even with a good response to a set-point change, the disturbance rejection is not guaranteed. Thus it is also important to check whether the controller achieves good performance when disturbances are present in the system. The test performed is to introduce a disturbance when the system is in steady state and wait until the process recover its state previous to the disturbance (first in one input, then in the other one). The results can also be used as a reference to compare with the performance obtained by the event-based PI controllers. Finally, the comparison of the performance is showed in Table 2. It can be seen that the controller without decoupling obtains a better performance for the disturbance rejection task both in the IAE as in the reduction of events, while the controllers with decoupling obtain a better performance in the set-point following task.

Table 2. Performances of the controllers with the minimum phase plant (Simulation).

	δ_p	δ_i	IAE_{sp} (y_1/y_2)	IAE_{dr} (y_1/y_2)	η (PI_1/PI_2)
not dec.	0	0	12.86/10.32	1.58/1.59	0.0/0.0
	0.01	0.01	13.03/10.64	1.84/1.82	0.79/0.80
	0.02	0.02	13.02/11.18	2.04/1.95	0.80/0.83
	0.05	0.05	13.82/11.39	2.94/3.03	0.87/0.87
	0.01	0.05	12.95/10.47	2.04/2.05	0.83/0.84
dec.	0.0	0.0	11.83/10.44	3.10/3.15	0.0/0.0
	0.01	0.01	11.87/10.58	3.13/3.16	0.85/0.81
	0.02	0.02	11.98/10.48	3.09/3.15	0.87/0.85
	0.05	0.05	12.35/11.24	3.45/3.65	0.89/0.89
	0.01	0.05	11.69/10.42	3.07/3.16	0.85/0.85

5.3 Non-minimum phase configuration

Choosing $\gamma_1 = \gamma_2 = 0.4$, we have that $\gamma_1 + \gamma_2 = 0.8 \leq 1$ and therefore it is a non-minimum phase configuration. Substituting the parameters values in (1) the transfer function matrix for the linearized system is

$$P(s) = \begin{pmatrix} \dfrac{1.06}{1+12,44s} & \dfrac{1.59}{(1+7.47s)(1+12.44s)} \\ \dfrac{1.59}{(1+7.47s)(1+12.44s)} & \dfrac{1.06}{1+12.44s} \end{pmatrix} \quad (7)$$

For the linealized system around the operating point, the decoupling used in the experiments corresponds to the simplified case with $r_{11} = r_{22} = 1$, $r_{12} = -\frac{p_{12}}{p_{11}}$ and $r_{21} = -\frac{p_{21}}{p_{22}}$, which gives the following matrix

$$R(s) = \begin{pmatrix} 1 & \dfrac{-0.0072s + 0.0109}{s^2 + 0.2296s + 0.0108} \\ \dfrac{-0.0072s + 0.0109}{s^2 + 0.2296s + 0.0108} & 1 \end{pmatrix}. \quad (8)$$

Three different set of parameters have been tested, corresponding to $\delta_p = \delta_i = 0.01$, $\delta_p = \delta_i = 0.02$ and $\delta_p = \delta_i = 0.05$. As the configuration has non-minimum phase behaviour, the system is much more difficult to control, and the time scale is longer than in the previous case. The values of the performance indexes are showed in Table 3. The better result was obtained by the event-based PI controller with $\delta_p = 0.05$, $\delta_i = 0.15$, which achieved a control performance comparable to the time-based PI, with a number of control action significantly reduced.

Table 3. Performances of the controllers with the non minimum-phase plant.

	δ_p	δ_i	IAE_{sp} (y_1/y_2)	IAE_{dr} (y_1/y_2)	η (y_1/y_2)
dec.	0.0	0.0	113.20/100.81	107.69/106.49	0
	0.01	0.05	116.48/104.67	110.55/108.93	0.38/0.40
	0.05	0.05	118.04/109.92	120.65/121.69	0.68/0.68
	0.05	0.15	110.36/105.93	121.56/122.83	0.84/0.84

5.4 Experimental Results

We have identified a process model using the experimental data obtained from the quadruple tank plant. The transfer functions obtained are,

$$P(s) = \begin{pmatrix} \dfrac{15.049}{23.379s+1} & \dfrac{11.49}{(29.679s+1)(31.489s+1)} \\ \dfrac{13.457}{(91.197s+1)(21.695s+1)} & \dfrac{15.662}{22.26s+1} \end{pmatrix}. \quad (9)$$

From this matrix, the decoupling network have been obtained as,

$$R(s) = \begin{pmatrix} 1 & \dfrac{-0.01911(s+0.04279)}{s^2+0.0655s+0.0011} \\ \dfrac{-0.0097(s+0.04489)}{(s+0.0463)(s+0.0108)} & 1 \end{pmatrix}. \quad (10)$$

The PI controllers have been tuned to obtain a phase margin of 60°, which yields the parameters values of $K_p = 0.54$, $T_i = 3.26$ for the first loop and $K_p = 0.52$, $T_i = 3.11$ for the second loop. The procedure is the same as in the simulation examples, i.e. a set-point change is introduced in the first loop, then in the second loop. After that a disturbance is introduced in one loop, and then in the other loop. The same experiment is repeated varying the values of the event triggering thresholds. The results obtained in the experiments are qualitatively similar to the simulations, i.e. the benefits of using the decoupling network together with the event-based strategy are more remarkable for the set-point following task. Figure 5 shows the results of the set-point change applied to the controller with the decoupling network and event thresholds $\delta_p = 0.01$ and $\delta_i = 0.10$. The performance indexes of the controllers tested can be seen in Table 4.

Table 4. Performances of the controllers with the minimum-phase real plant (Real plant).

	δ_p	δ_i	IAE_{sp} (y_1/y_2)	IAE_{dr} (y_1/y_2)	η (y_1/y_2)
dec.	0.0	0.0	8.04/10.17	2.06/2.19	0
	0.01	0.1	9.89/12.21	2.31/2.40	0.66/0.42
not dec.	0.0	0.0	8.59/9.77	1.44/1.52	0
	0.01	0.1	10.01/10.64	2.74/2.81	0.68/0.51

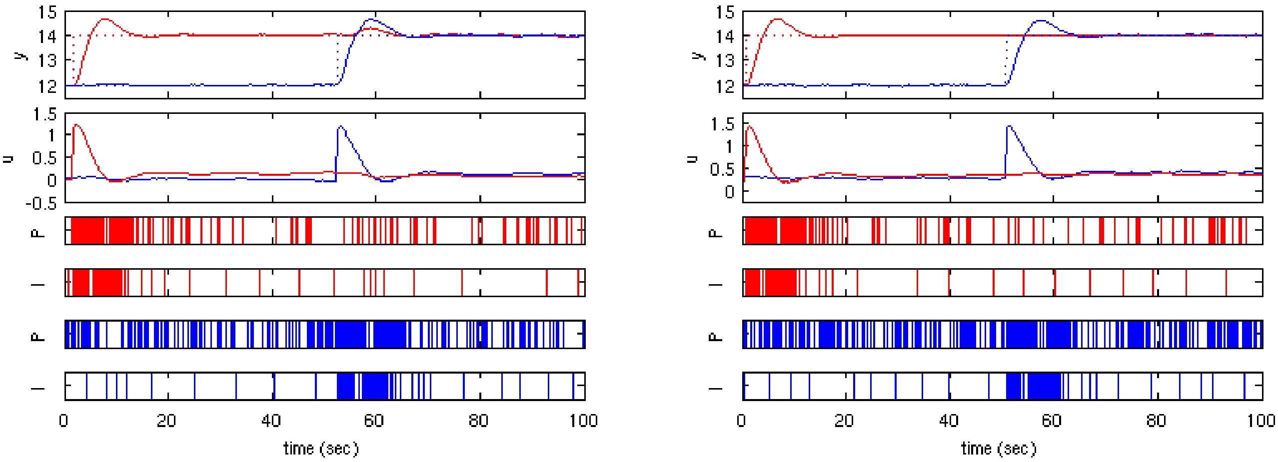


Fig. 5. Set-point step responses of the non-minimum phase plant with event thresholds $\delta_p = 0.01$, $\delta_i = 0.1$ with decoupling (left) and without decoupling (right). The plots show (from top to bottom) the water levels, the control signal, and the proportional and integral event times.

6. CONCLUSIONS

The main results of this work have been the success in the development of the experimental framework for testing new control methods based on events and the good performance achieved by the control system. We have obtained good results with the algorithm based on the combination of event-driven control and decoupling strategies. The use of a decentralized control scheme with event-based PI controllers and the decoupling network obtained a good performance and led to a reduction in the number of communications compared to the time-based controller. However, due to the interaction presented in the system, a disturbance or set-point change introduced in one loop provokes the increasing in the number of events of all controllers. With the decoupling network a set-point change in one control loop can be managed by its associate controller without affecting the other loop, and thus leading to a reduction in the number of events of this second loop. It must be noted however that the results were not as good in all the circumstances. One of the disadvantages of decoupling is that though when the set-point following task achieves a good performance the disturbance rejection task is not guaranteed. In particular, for the non-minimum phase system this was a problem that in the worst case led to unstabilities. This problem can be aggravated with the introduction of event-based mechanisms. As future lines of works, though the results presented for the event-based PI controller together with the decoupling strategy are promising, still much work has to be done. More tests have to be done with non-minimal phase configurations to verify experimentally the stability of the controllers, and the benefits of the different types of decoupling networks implemented, i.e. direct decoupling and inverse decoupling.

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