

Implementation of the Quadruple Tank Process Using Computer Vision.

Mario E. Serrano*¹, Sebastian A. Godoy*², Mario M. Romera*³, Oscar A. Ortiz*⁴ and Gustavo J. E. Scaglia*⁵

*Institute of Chemical Engineering, National University of San Juan (UNSJ), CONICET
Av. Lib. San Martín Oeste 1109, San Juan J5400ARL, Argentine

¹serranoemanuel184@gmail.com

²sgodoy@unsj.edu.ar

³mromera@unsj.edu.ar

⁴rortiz@unsj.edu.ar

⁵gscaglia@unsj.edu.ar

Abstract—This paper presents an experimental tank system developed at the National University of San Juan for process control education. This plant is based on the quadruple tank, which is a multivariable laboratory plant of interconnected tanks that can be easily configured to exhibit the effect of non linear dynamics, saturation, constraints, etc. on the system behavior.

In the implementation, the original structure of the process has been modified to offer a wide variety of uses for both educational and research purposes. Different plants can be configured such as one single tank, two or three cascaded tanks. The dynamics parameters of each tank can be set up by tuning the cross-section of the outlet hole of the tank. Furthermore, the real plant has been implemented using computer vision and a PIC controller for the low level control. Supervision and control of the plant is carried out using Matlab.

Resumen—Este documento presenta un sistema experimental de tanques desarrollado en la Universidad Nacional de San Juan para utilizarlo en educación en control de procesos. Esta planta esta basada en el sistema de quadruple-tanque, el cual es una planta multivariable de laboratorio de tanques interconectados que pueden ser facilmente configurados para exhibir el efecto de dinamicas no lineales, saturacion, restricciones, etc. en el comportamiento del sistema.

En la implementacion, la estructura original del proceso a sido modificada para ofrecer una gran variedad de usos para propositos educacionales y de investigacion. Diferentes planta pueden ser configuradas tales como simple tanque, dos o tres tanques en cascada. Los parametros dinamicos de cada tanque pueden ser seteados modificando la seccion de paso en la salida de cada tanque. Ademas, la planta a sido implementada utilizando vision artificial y un controlador PIC para el control de bajo nivel. La supervision y control de la planta se lleva a cao utilizando MatLab.

of the difficulties encountered in control education consists of providing a theoretical foundation maintaining the practicality. To this aim, experimental labs provide a powerful tool to fill this gap. An experimental lab should be designed to show interesting and industrial relevant control problems which does not too skilled control solutions and real tools, such as instrumentation, control programs, etc.

The quadruple tank process is proved to be a very interesting system for control education in advanced control courses, as well, as in research courses [1]–[3]. The main property of this process its capacity to illustrate the impor-

Table I
SYSTEM PARAMETERS

State Variables	Unit	Concept
A_i	cm^2	Cross-section of tank i
a_i	cm^2	Cross-section of the outlet hole
h_i	m	Water level of the Tank i
q_a, q_b	m^3/h	Flow over the pumps
g	m/s^2	The acceleration of gravity
q_i	m^3/h	Flow over the each tank
γ		Parameters of the three-way valves

tance of multivariable zeros since these can be located at the right and the left half plane. Furthermore, there other interesting properties exist, such as the coupled nature of the plant, the measurable states, the nonlinear behavior.

To this aim, a laboratory plant based on the quadruple tank process has been designed and developed at National University of San Juan. This plant is used for both, educational and research purposes. The objective of this design was to provide flexibility to the plant. Thus, the plant can be easily configured to obtain different processes and the control was implemented by a computer MatLab®.

The proposed plant may be used to perform experimental tests that until now have only been studied by simulation in different works of literature [4], [5].

I. QUADRUPLE TANK PROCESS

This process is a laboratory plant proposed in [1] aimed to show the effect of non-minimum zeros of a multivariable system. The original plant consists of four interconnected tanks as shown in Fig 1. The inputs are the voltages of the two pumps and the outputs are the water levels in the lower four tanks.

The model of the system is derived from first principles as follows [1].

$$\begin{aligned}
 \frac{dh_1}{dt} &= -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_a}{A_1}q_a \\
 \frac{dh_2}{dt} &= -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_b}{A_2}q_b \\
 \frac{dh_3}{dt} &= -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{1-\gamma_b}{A_3}q_b \\
 \frac{dh_4}{dt} &= -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{1-\gamma_a}{A_4}q_a
 \end{aligned} \tag{1}$$

where the parameters of the plant are:

The plant possesses interesting features that make the plant appropriate to be used for both educational and research purposes. These ones are the following:

- All the states are measurable.
- The outputs are strongly coupled.
- The system is nonlinear.
- The states and inputs of the plant are constrained.
- The plant is handled harmlessly and easily.

Thus this plant can be used to show very interesting control problems. Among these problems, the following ones can be highlighted:

- Tracking control of multivariable systems
- Control of systems with RHPZ and limits of performance.
- Robust control.
- State estimation.
- Control under saturating actions.
- Control of systems subjected to constraints.

The design and implementation of the plant has been carried out in such a way that the potential educational interest is maximized. This is detailed in the following section.

II. SYSTEM DESCRIPTION

One of the main objectives in the implementation of the quadruple tank process has been to provide flexibility to the plant in the following aspects:

- Capability to set up different processes in the same plant.
- Capability to tune some parameters which allows us to configure the plant dynamics.
- Wide range of operating points.

Thus, the plant layout has been designed to meet these specifications (see Fig. 2). The designed plant differs from the quadruple tank process proposed in (Johansson, 2000) in the following items:

- The three-way valve has been replaced by two control valves controlling the flow of the pipes. This allows us to fix a desired flow ratio between the two pipes (that is, the parameter γ_i) and hence obtain an ideal three-way valve. Moreover, due to all the flows of the inlet pipes of the tanks are controlled, different processes can be configured.
- Extra pipes, manipulable valves and tank interconnections were added to set up the different processes. They will be shown in the following section.
- A manipulated valve with a position display has been placed in the outlets of the tanks in order to manipulate the cross-section of the outlet hole a_i . This allows us to configure the dynamics of each tank of the process.

Other relevant aspect of the plant the low cost measurement devices implementation and the highly accurate sensing provides a realistic framework to test controllers. Together with the low-level control system, these aspects will be shown later on.

A photograph of the implemented plant can be seen in figure 1. As it can be seen, this plant is larger than the typical scaled lab plants (Rusli et al., 2004; Johansson et al., 1999) (the total height is 2m and the tanks are 0.07m³ tall).



Figure 1. The implemented laboratory plant

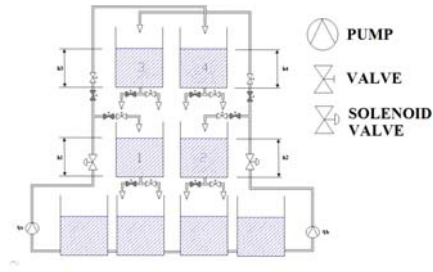


Figure 2. Laboratory plant layout

A. Setting up the plant

One of the main pros of the designed plant is the capability to configure different processes and dynamics. In Fig. 2, Fig. 3 and Fig. 4 some of the possible configurations are shown. They can be achieved by opening and closing some of the manipulable valves. It can be seen location of control valves in the tank inlets allows us to obtain a larger number of possible configurations.

The most immediate processes that can be configured are two and four cascaded tanks; it is also possible to configure a two cascaded tanks and two cascaded tanks, two inlets as can be seen in Figs. 3 and 4.

Dynamics of the plant can be set up by adjusting the cross-section of the outlets of the tanks. See that this parameter determines the constant time of the tanks and also the water level at a given operating point. Thus these parameters can be fixed with two objectives: change the time response of the system or change the variation range of the level. The dynamics can also be tuned by changing

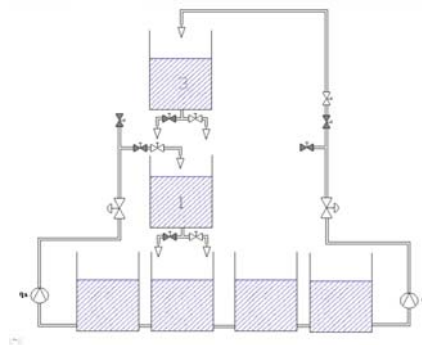


Figure 3. Two cascaded tanks, two inlets

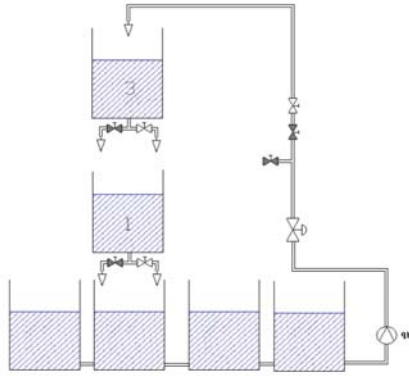


Figure 4. Two cascaded tanks

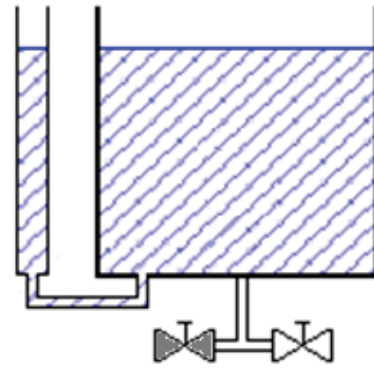


Figure 6. Connection of acrylic tube and the tank

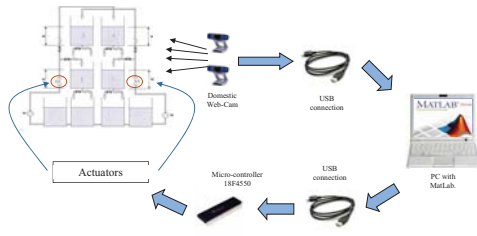


Figure 5. Two cascaded tanks

the cross section of the tank, putting an element to change the variation of the volume with the level. This allows us to enlarge the degree of nonlinearity of the plant or even obtain an hybrid system.

III. INSTRUMENTATION OF THE PLANT

The designed plant requires at least some devices to measure the water level in the tanks and control valves at each inlet of the tank. The layout of the instruments in the plant is show in Fig. 5.

The control system was developed fulfilling four objectives: low cost, precision, simplicity and user-friendly. This objectives are necessary when the plants is used in educational purposes and student placements.

A general idea of the connexion and interaction of the instruments is developed below.

The liquid level of the each tank is sensed using artificial vision. A web-cam is used to capture images and the Matlab software is the responsible of process and interprets those images. The toolbox *image processing* of Matlab is used to convert the images in a precise level value. Then the control actions are calculated through a control scheme defined by the user. Finally, this signals are sent using USB protocol to a control box formed by a PIC 18F4550 microcontroller. In the control box the control actions are transformed to manage the flow of the pumps.

Each subprocess will be detailed in the subsequent sections.

A. Level sensing

Getting the liquid level with high precision and low cost using un-contact sensors is a challenge task. Different

un-contact sensors exist in the market especially designed for measuring liquid level. Some examples are: infrared sensors, ultrasonic sensors, etc. but their prices are elevated. An alternative of low cost using artificial vision for the construction of a level sensor is developed in this work. A similar sensing system, to the proposed in this paper has been used in the literature, for measuring flow in a pipette [6]. Nowadays some concepts are used to determine the level in each tank. The presented sensor uses only two common domestic web-cams and Matlab toolboxes for accomplishing the objective. A camera is used to sense the liquid level in the tanks three and four, whilst the other one sense the tanks one and two (Fig. 1 and Fig. 5).

The domestic low-costed web-cam used is the FaceCam 320X, this camera has a 640x480 VGA resolution, manual focus and USB interface. A modification was performed in the four tanks, and in this way the camera can 'see' the liquid level. This modification includes a plastic transparent test tube added in an extreme of the tank. The Fig. 6 shows the modification.

In order to interpret the height in function of the number of pixels with the camera, a relationship between them is necessary to be established. To achieve this objective a grid background is placed and the distances, showed in Fig. 7, are measured. The grid background is used as measure patron. The distance a represents the height from the lens of the camera relative to the base, b represents the distance between the lens camera and the grid background, c the total vision of the camera, d the distance between the test tube and the grid background, f the distance from the lens to the test tube, x represents the height to be determined respect to the vision center, and at last, d_i represents the projection of x -projection on the grid background. The value of x is completely defined knowing the height of the pixel d_i with respect to the grid background. All distances are represented in centimeters. The values of the variables described are specified in Table II.

After the camera captures the RGB image, it is sent to the PC where the processing using MatLab is performed. The image is represented through a matrix array, where its size depends of the chosen resolution. The image is transformed into a gray-scale employing a brightness compensation adjustment and then into an edge-image through the function

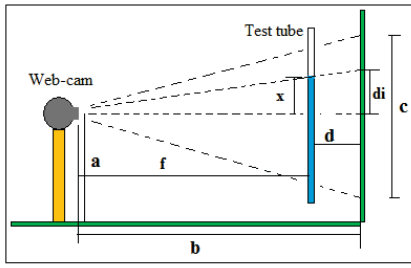


Figure 7. Camera position setting

Table II
PARAMETERS VALUES

Parameter	Unit	Value
a	cm	20
b	cm	21.5
c	cm	15
d	cm	3
f	cm	18.5

'edge', by last several filters are implemented with the objective to eliminate noise particles in the snapshot. These filters are included in the toolbox *image processing* facilitated by Matlab. The used filters are:

- Bwareaopen: removes from the edge-image all connected components that have fewer than N pixels, where N is a 1% of the image size.
- Imerode: erode the noise in the lines of the edge-image.
- Imopen: performs morphological opening on the edge-image allowing bind fragments of the same line.
- Imclose: performs morphological closing on the edge-image that defines the predominant lines.

Thereafter, the Hough transform is employed to detect the line that represents the liquid level of each tank. With this information and the relation between height and pixel described in Fig. 7 the liquid level for each tank is defined.

B. Controller design

Once the liquid level is obtained, the control action are calculated according the pre-defined scheme or a control scheme defined by the user.

The control objective of the plant depends on the chosen configuration although this is basically to regulate the levels of the tank. The plant is designed in such a way that allows one to choose different control structures to carry out the control task.

In order to use of the complete system easily, an user interface (GUI) was designed, where it is possible, among other options, choosing between two standard pre-defined controllers (Proportional and PID) or a programed scheme and included by the user. Other changeable option is choose the set-point that the tanks must be attain. In addition it is possible load a desired trajectory to be followed by the system for each tank. Besides is possible change the sampling time and observe the actual liquid level of each tank, the desired values and the actual control actions.

The pre-defined control schemes are Proportional (P) and Proportional?integral?derivative Controller (PID). These two configurations are pre-loaded with a default parameter, but

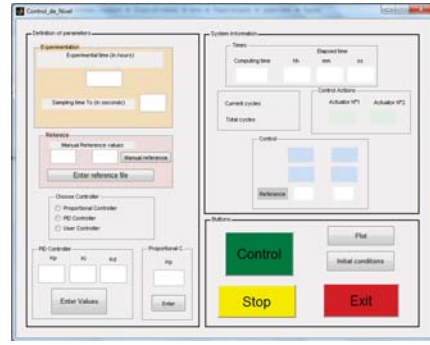


Figure 8. User interface

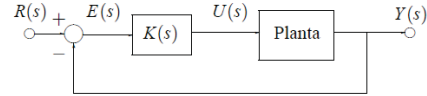


Figure 9. Proportional integrative derivative control scheme

it is possible change it by the user. Furthermore, as already mentioned, selecting the User controller, it is possible to add a custom scheme for the system. The Fig. (9) shows the PID control scheme implemented by default, where $Y(s)$ are the heights of the tanks, that represent the outputs of the system. $U(s)$ are the control actions that should be applied by that the outputs $Y(s)$ follows the reference signals $R(s)$. $E(s)$ are the error signals while $K(s)$ is the PID controller.

The designed interface facilitates the use of the complete system for the students, where they will experience different conditions and different controllers for the tracking trajectory and regulation of the tanks level.

C. Communication and actuators

Once the control actions were obtained, the Matlab software sends these values to a control box. The control box is composed by a PIC microcontroller 18F4550 and two decoupled power outputs. The microcontroller receive the value of control actions calculated in the previous section and a timebase through the USB protocol. The PC recognizes the micro-controller how a plug and play Human Interface Device (HID), therefore it is not necessary to configure each time, which it is connected. The PIC transforms the received control actions by the PC in two PWM signals with a period equals the received timebase. Then the PWM signals which were generated are sent to the decoupled power outputs. These outputs actuate in two electro-valves that control the flow q_a y q_b from the two pumps. The Fig. 10 shows the schematic circuit implemented.

IV. EXPERIMENTAL RESULTS

In this section the developed system performance is shown by experimental tests. A picture of the real system is shown in Fig. 1. Several tests were performed in the plant, in this paper some results are shown in the following subsections .

The controllers operation with different reference signals was tested. First the system performance was evaluated considering different values of set points. The proportional controller and the PID controller were implemented with

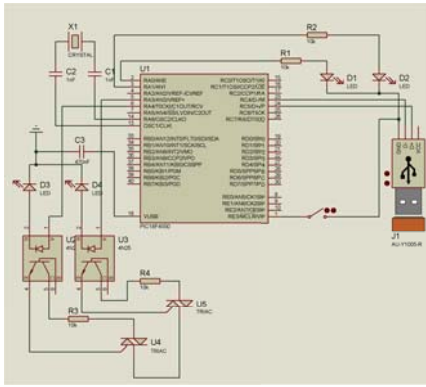


Figure 10. Schematic circuit control board

these reference signals. Then, the performance of PID controller performance with a sine reference signal is evaluated.

A. Proportional controller

First the system performance is evaluated using the proportional controller. Different levels of set points were set in each tank. Various empirical tests were conducted to determine the value of the gain K_p . It was adopted in the first 10 minutes $K_p = 3$, $K_p = 5$ over the next 5 minutes and the rest of the test was experimented with $K_p = 10$. The latter value was programmed in the user interface as default. The idea of changing the constant of proportionality is to evaluate the system behavior the system under such variation. The initial conditions of the system were $[h_1 \ h_2] = [0.03\text{m} \ 0.04\text{m}]$ and the chosen sampling period was $T_s = 10\text{s}$.

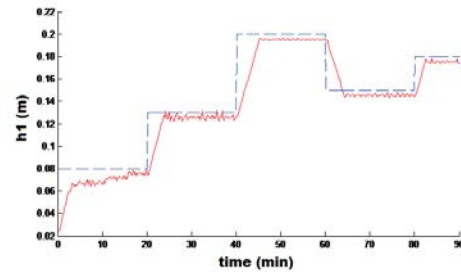
Figure 11 shows the results of experimentation. As it can be seen, the system reaches and follows the values of the reference set point. In addition, the direct effect of the variation of the proportional gain (K_p) in the response speed of the control system is observed. It is noted a $K_p = 10$ has faster response and a steady-state error of 5 mm, which is an acceptable value when is compared with the reference signal.

B. PID controller

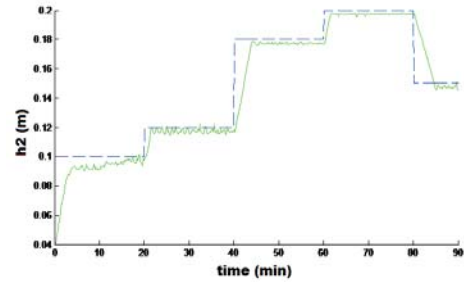
Now the results obtained with the PID controller are shown. The heuristic method was used to tune the controller, which consists in to varying the controller's parameters, through the system response analysis. The obtained controller parameters are $K_p = 10$, $K_i = 0.005$ and $K_d = 10$ (these parameters are configured in the user interface in the default values). The sampling time chosen was $T_s = 10\text{s}$. The initial conditions were chosen $[h_1 \ h_2] = [0.05\text{m} \ 0.06\text{m}]$.

Figure 9 shows how the system reaches and follows the reference values quickly. In addition, it can be seen that better track the desired values is obtained regarding the proportional controller. In each set point change can be seen a small overshoot, due to the integral action of the controller. The figure 9 shows that once the desired value levels are reached, a steady state error of about 4 millimeters are maintained.

Finally, a test is performed with a variable reference signal. The chosen reference signal is a sine wave of amplitude

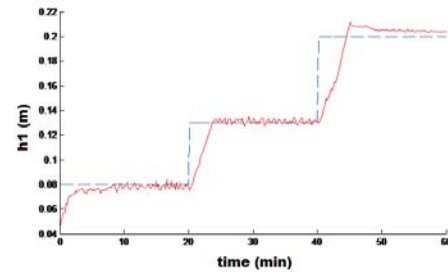


(a) Level of tank 1

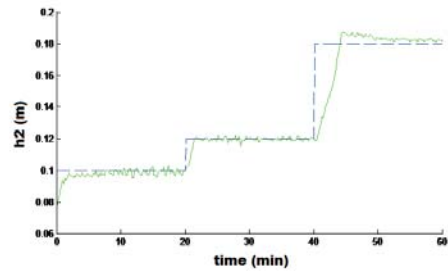


(b) Level of tank 2

Figure 11. Experimental results with proportional controller



(a) Level of tank 1



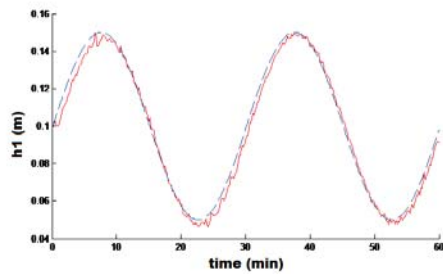
(b) Level of tank 2

Figure 12. Experimental results with PID controller

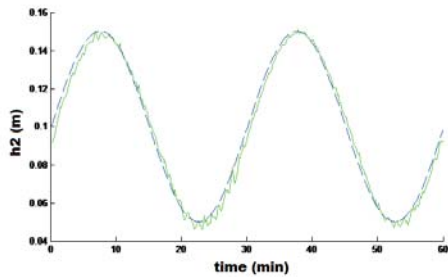
0.05m and 30 minute period. The controller parameters are the default (the same used in the above test). The initial conditions of the system are $[h_1 \ h_2] = [0.101\text{m} \ 0.09\text{m}]$. The sine reference signal starts in 0.1m in each tank.

Figure 13 shows the levels of the tanks and the reference signals, a good response of the system is observed. It can be seen that the errors obtained in the experience are low compared to the fluid level in each tank. The system has an acceptable tracking of the reference signal without unwanted oscillations.

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(a) Level of tank 1



(b) Level of tank 2

Figure 13. Experimental results with PID controller and sinusoidal trajectory

V. CONCLUSION

This paper presents the design and implementation of a laboratory plant based on the quadruple tank process. The main objective of the design of the plant is its flexibility. Thus, the plant can be configured to obtain different processes. Moreover the control structure is also flexible, two predefined drivers are available (Proportional controller and PID controller). It also gives the user the possibility to write your own control law. In this case, MatLab environment can be used. The connectivity of the plant results to be very interesting for the objectives of the plant: education and research. For instance for basic control courses Simulink and MatLab platform are the most used.

In addition, it is interesting to highlight that the plant has been built with commercial instrumentation, making it easy to reproduce. Finally it is worth to remark that this plant has been successfully used for practical works of students in basic control courses as well as our research group.

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