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Executive Summary

The objective of this deliverable is to provide information about the benchmark cases. Four deliverables have been proposed and are described in this deliverable:

- **Four tank system**
- **Chemical benchmark case**
- **Electric power system**
- **Heat system**

The deliverable is organized in two documents, Part I (i.e., the current part) includes the description of the four tank system and part II describes the other three benchmark cases.

1 Description of the system

1.1 The Process

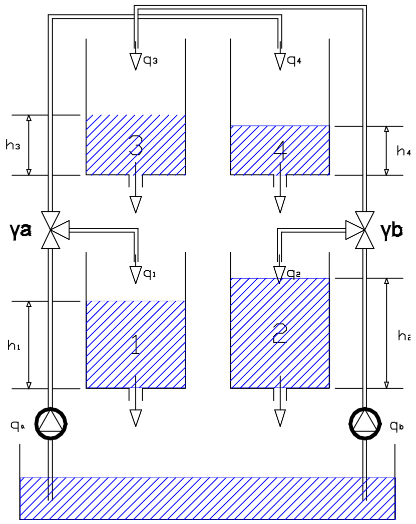
1.1.1 Give an overall view of the process: Functionality, operation targets, architecture:

The process is a hydraulic system of four tank interconnected. The four tank process is designed as an experimental benchmark for testing control techniques, either centralized, hierarchical or distributed controllers. The main property of this system is that it is highly configurable in a simple way. Thus, a great number of experiments can be thought and easily implemented. These facts make this process suitable as benchmark.

The overall target is to maintain the level of the tanks in a given range of admissible values. However, see that the operation target depends on the each proposed exercise and hence it not specified. In fact, the operation target can be decided together with the design of the exercise of the benchmark.

1.1.2 Physical description of the process (elements, dimensions, scales, ...)

The process is inspired in the educational system proposed by Johansson (IEEE trans. cont. syst, techn. 2000) to be used for proving control of multivariable systems with transmission zeros.



$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_a}{A_1}q_a$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_b}{A_2}q_b$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_b)}{A_3}q_b$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_a)}{A_4}q_a$$

Figure 1: The quadruple tank process

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_i		Parameters of the three-way valves

The four tank process to be used as benchmark retains the four tank structure: the four tanks in two levels. However, it has been modified enabling different configurations and interconnections of the tanks.

A schematic plot of the process is shown in the figure 2. It can be seen the four tanks (T1, T2, T3 and T4) which can be filled by several flows from a storage tank sited in the bottom of the plant. The tanks at top (T3 and T4) discharge in the tanks at bottom (T1 and T2 respectively).

The main valves regulate the flow of the main pipes of the plant. These are industrial control valves with an aperture controller which allows one use it as regulation valve or switching valve. The flow of each valve is continuously measured by a magnetic flow-meter, allowing a flow control loop manipulating the position of each valve.

The three-ways valve of the original quadruple-tank process has been emulated: according to the taken parameter γi and flow qi, the reference for each flow control loop is suitably calculated. Thus, the controllers are responsible to ensure the taken ratio and flow of each inlet.

It is worth noticing that the flows at the top can be configured to fill one (or both) of the tanks T3 and T4. This selection can be done by means of switching valves.

The tanks T1 and T2 are connected by a pipe at the bottom of the tank. This flow is manipulated by a switching valve.

The output flow of each tank can be adjusted by means of a tuning manual valve and regulated by means of a switching valve. The level of each tank is measured by a pressure sensor. Furthermore, there exists a high level switching sensor which is used as alarm to switch off the pumps.

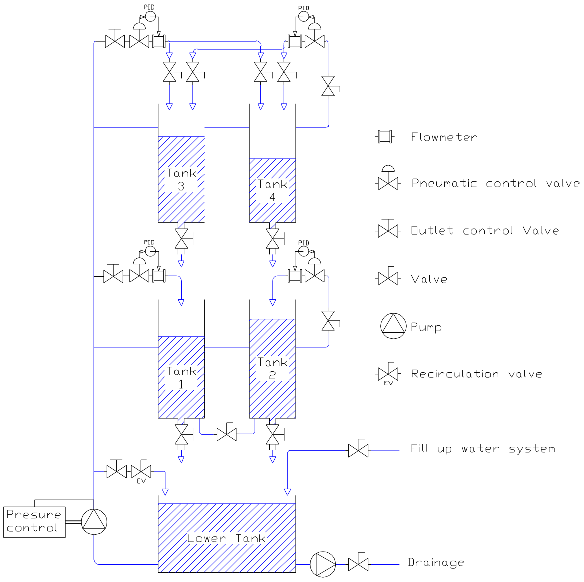


Figure 2: Diagram of the process

The sampling of each sensor as well as the command of each manipulated variable is carried out by a Siemens PLC. This device stores the data and allows one to develop low level controllers (PIDs), sequential controllers, plant supervisors. All the data is continuously available by means of an OPC server installed in a remote PC connected to the PLC (via RS-232).

The real dimensions of the plant can be found in the following table:

Variable	**Value**	**Unit**	**Description**
H1max	1.36	mts	Maximum level of Tank 1
H2max	1.36	mts	Maximum level of Tank 2
H3max	1.30	mts	Maximum level of Tank 3
H4max	1.30	mts	Maximum level of Tank 4
Hmin	0	mts	Minimum level of the tanks
Q1max	2.8	m3/h	Maximal inflow Tank 1
Q2max	2.45	m3/h	Maximal inflow Tank 2
Q3max	2.3	m3/h	Maximal inflow Tank 3
Q4max	2.4	m3/h	Maximal inflow Tank 4
Qmin	0	m3/h	Minimal inflow in all tanks
A	0.06	m2	Cross-section of all tanks

There are other parameters of the plant that can be manually adjusted by the user, although these are considered as fixed. The typical values of these parameters are the following:

Variable	**Value**	**Unit**	**Description**
a1	1.341e-4	m2	Discharge constant of tank 1
a2	1.533e-4	m2	Discharge constant of tank 2
a3	9.322e-5	m2	Discharge constant of tank 3
a4	9.061e-5	m2	Discharge constant of tank 4
γa	0.3		Parameter of the 3-way valve
γb	0.4		Parameter of the 3-way valve

The discharge constant of each can be tuned by manipulating the regulation valve of its outlet. This regulation valve allows up to 40 different apertures of the valve. Currently, these have been taken to provide the maximal range of levels for the available range of flows considering the values of the 3-ways valves the ones of the table. The real plant doesn't have 3-way valves nut the flows ratio are imposed in order to have the same behaviour.

1.1.3 Objectives of the process and specific control aims

The four tanks plant is an educational plant appropriate to test control techniques on a real plant using industrial-type instrumentation and control system. Therefore the objective for this benchmark task is providing a highly configurable test-bed for centralized or distributed control. The structure of the plant, control inputs, controlled outputs and possible disturbances can be selected to obtain different test-beds.
The control aim of the process is to control the level of the tanks manipulating the inlet flows based on the available information of the plant at each sampling time.

1.1.4 Justify the complex or networked aspects of the process.

The main characteristics of the plant on this topic are the following:

- Nonlinear behaviour: derived from the discharge process of the tanks. This is even larger for lower levels of the tanks due to the eddy effect. Besides the nonlinearity of the dynamics can be raised by modifying the cross section of any tank.

- Coupling effect: the structure of the plant presents a high degree of coupling between the different subsystems through interconnections of the tanks. Manipulable parameters of the plant and the topology the selected test-bed plant allows to adjust the degree of coupling.

There also exist control objectives and constraints that induce couplings between the variables of the plant.

- Instruments dynamics: the flows of the plant are regulated by means of industrial control valves, the levels measured by industrial pressure sensors and the flows by industrial flow-meters. All these devices exhibit a dynamic behaviour as well as a non-linear characteristic. This effect is clear in the case of the control valves.

- Additional dynamics: The plant exhibits additional dynamic effects that could be considered in the model of the process. One of them is the dynamics of the inlet flows of the tanks. These are typically regulated by means of a flow control loop based on the measures of the flow-meters and manipulating the valves. The closed-loop dynamics is typically neglected in a simple model, and more exact models should be taken into account.

Another control structure that could be used is considering the aperture of each valve as manipulable variables, letting the flow without being regulated. The dynamics of the valve and the flow should be modelled in this case.

Another additional dynamic effect that could be modelled is the dynamics of the eddy effect that appears for lower levels (under 0.3 meters). This is a highly nonlinear effect which dynamics differs from the Bernouilli’s law based model. This effect is typically avoided forcing the level of each tank to be larger or equal to 0.3 meters.

1.1.5 Describe the interest of the process from different points of view: distributed control, hierarchical control, security issues, perturbations rejections, robustness issues, state estimation, identification…

The interest of the proposed benchmark can be summarized as follows:

- Distributed control: the proposed benchmark has been previously proposed as experimental plant to validate distributed MPC techniques in several papers [6] [7]. The main reason of this choice relies on the interconnected nature of the plant and the capability of adjust the degree of such interconnections.

- Hierarchical control: the proposed benchmark has been previously used as benchmark for hierarchical control techniques. The control structure of the plant is oriented to a hierarchical control with the lowest control loop to regulate the flows of each inlet, then an upper level to test the advanced control technique (such as GPC, MPC or nonlinear control techniques [1], [2], [3], [4], [5], [8] and [9]). Finally, the higher level checks the safety of the plant and decides the optimal operating point of the plant.

- Security issues: the plant has no security problem since the process consists in moving water from tanks to tanks. The only risk is flooding the laboratory, but this is avoided thanks to the level switches located at the top of each tank. If any of the level switches is activated, the plant is driven to an alarm state by the supervisory system and the propelling pump is switched off mitigating the flooding risk.

- Perturbation rejection: exogenous disturbances can be easily added to the plant. For instance, manual inlet valves can be partially opened to add an unexpected inlet flow. This can also be done with the interconnection manual valve, which adds a state-dependent disturbance. Finally, it can be transferred water from one tank to another one by means of a simple submersible pump, as proposed by [6].

- Robustness issues: a robust controller must cope with the unmodeled uncertainty as well as unmeasured disturbances. The nonlinear dynamics of the plant makes that any controller based on a linear model has some degree of robustness. In the model used is non linear, the obtained controller is potentially better yielding to larger domain of attractions. However robustness of the control law is still required due to the existing parametric uncertainty of the plant. In both cases, the controller must be robust to the unmeasured disturbances.

- State estimation: this plant is also suitable to test state estimation techniques. In a simple model the states of the plant are the levels and all of them are measurable. Then we can use a partial knowledge of the states to estimate the remaining. The estimated levels can be validated with the real measures of each level. Similar approaches can be used to estimate the flows of the inlet pipes or the position of the valves.

1.1.6 Enumerate and describe the Controlled variables (continuous or discrete, constraints, set-points, …)

Tank levels: continuous.

The physical limits of some of the variables are the following.

Variable	Value	Unit	Description
H1max	1.36	mts	Maximum level of Tank 1
H2max	1.36	mts	Maximum level of Tank 2
H3max	1.30	mts	Maximum level of Tank 3
H4max	1.30	mts	Maximum level of Tank 4

Furthermore, the storage tank has not got water enough to fill the 4 tanks. This induces a limit on the stored volume of water in the tanks, that can be expressed as follows:

$h1+h2+h3+h4 < 3.71$ m

Tighter constraints are typically considered in the control design in order to avoid the trigger of the alarm. Besides, the minimum values of the levels are typically forced to be larger than Hmin=0.3 m in order to avoid the zone where the effect of the eddies is significant.

1.1.7 Enumerate and describe the Manipulated variables (continuous or discrete, constraints, …)

The manipulated variables depend on the chosen control structure. If a cascaded control structure is chosen then the reference of each flow control loop are considered as inputs. These signals are continuous and the limits are given in the following chart.

Variable	Value	Unit	Description
Q1max	2.8	m3/h	Maximal inflow Tank 1
Q2max	2.45	m3/h	Maximal inflow Tank 2
Q3max	2.3	m3/h	Maximal inflow Tank 3
Q4max	2.4	m3/h	Maximal inflow Tank 4
Qmin	0	m3/h	Minimal inflow in all tanks

If a direct control structure is selected, then the manipulated variables are the aperture of each valve. These signals are continuous and must be limited between 0 and 1.

Manually switching valves. These are discrete signals and can be used to configure the plant for a given experiment, to control the plant or to reconfigure the process. They can also be used to simulate faults or disturbances on the plant.

1.1.8 Enumerate and describe Other Process Variables (e.g., measured disturbances, measured states, …)

The measured variables are the following:

- Levels of the tanks. Continuous
- Inlet flows. Continuous
- Position of the valves. Continuous
- Maximum allowable level. Discrete.

1.1.9 Possible non-measured disturbances (type, influence, …)

The plant has been designed to be highly configurable and this can be exploited to add unmeasured disturbances. Thus the unmeasured disturbances are the following:

- Inlet flows: the plant has a couple of manual valves downstream the regulation valves in the inlet of the upper tanks. These can be partially opened to add an unexpected inlet flow in the tanks.

- Interconnection between tanks 1 and 2: a valve located in the connection pipe can be manually open to allow a flow between both tanks. This disturbance is state-dependent.

- Water transfer: an additional disturbance can be easily added by means of a submersible pump transferring water from a tank to another.

- Section: Adding an object inside of one tank yields to a variation of the section of the tank that may depend on the level.

- Global disturbances: the uncertainty that the plant exhibits can be modelled as a global disturbance that should be taken into account in the control design to be rejected.

1.1.10 Characterize the dynamic of the process: type of dynamic, response time.

The dynamic of the process is nonlinear, stable and exhibits an over-damped step response. The time constant depends on the operating point (typically 30 min). It is worth to remark that the time constant of each tank can be manually adjusted thanks to valve located at its outlet pipe.

1.1.11 Is there available bibliography about the process?

- Internal Report. Application of the RMPCT to the 4 tank process.
- Internal Report. Designing of the 4tank process.
- 2006 ACE An educational plant based on the 4tank process
- 2008 MSC RMPCT applied to the 4tank process [4].

1.1.12 Are there available previous experimental results or bibliography about applying any type of control?

This plant has been used as test bed of several control techniques, as follows:

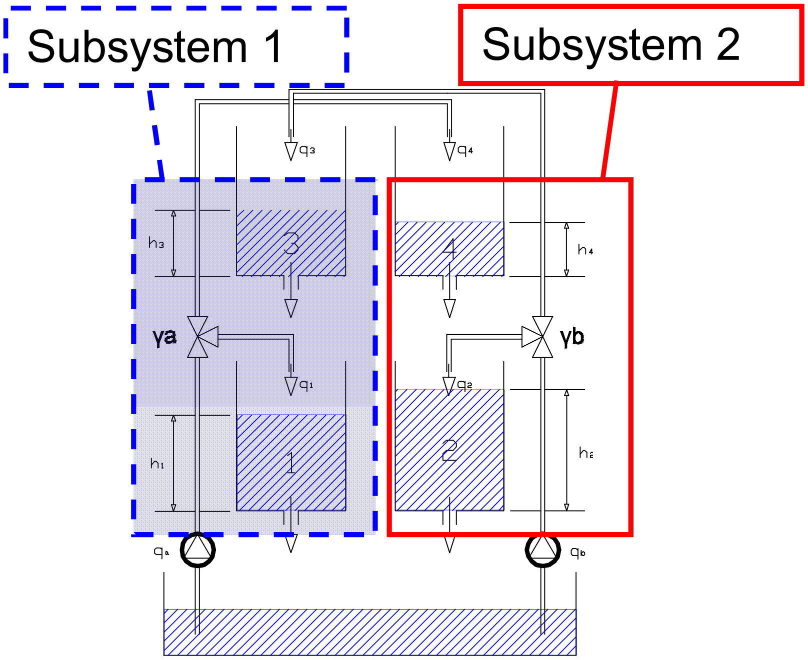
- Generalized Predictive Controller (GPC) [3].
- Robust tube-based MPC for tracking [4].
- Hybrid Control [1].
- Nonlinear MPC [8].
- Robust Control [9].
- Model Based Control [2].

1.2 Control System and Instrumentation

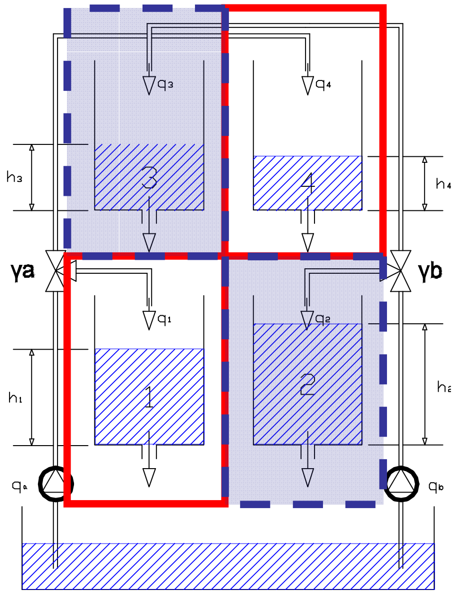
1.2.1 Is there a proposed partition of the system for distributed control?

Two different partitions are proposed:

- Partition 1: The 4 tanks system is divided in two subsystems, one with the two tanks on the left hand side and the other with the two tanks of the right hand side. The inputs will be chosen according to the chosen control strategy



- Partition 2: the system is divided in 2 subsystems: one consisting of the tanks 1 and 4 while the other consists of tanks 2 and 4. This is shown in the following figure:



The control objective is to regulate the levels h_1 and h_2 while keeping h_3 and h_4 inside of the constraints set by means of q_a and q_b that affect to both systems.

1.2.2 Is there a proposed distributed or hierarchical architecture? If yes, describe the architecture, communication issues,...

Partition 1 is based on the example proposed by Mercangöz et al (2007) to test a distributed MPC technique. In this partition, the subsystems are interconnected through the inputs. The overall control objective is to control the level of tanks 1 and 2 while fulfilling the constraints on the levels and on the inputs. Given that these two tanks are contained in different subsystems, the control objective must be satisfied by both local controllers simultaneously. Moreover, the presence of constraints on each level as well as on all the levels makes a distributed control of the plant necessary.

For this partition two exercises can be proposed:

- Case 1.1: each subsystem is controlled by a pump according to a coupling analysis (such as the relative gain array). The pairing pump-subsystem is done to maximize the effect of the control action on the output.

- Case 1.2: similarly to the case 1.1, the coupling analysis is carried out but the pairing is done contrarily. This is unusual but the resulting decentralized system exhibit a more coupled behaviour between the subsystems.

In both cases, the information that is shared between the decentralized controller as well as the communication frequency can be chosen by the designer.

Partition 2 presents a coupling of different nature of the one of the partition 1. In this case, the coupling between the subsystems goes through the states. As well as for the partition 1, the control objectives and the presence of constraints requires a distributed control technique. Similarly to the partition 1, two different exercises can be considered:

- Case 2.1: each subsystem is controlled by the pump that controls the inlet flows of the tanks. In this case the coupling between both subsystems is through the states.

- Case 2.2: The pairing of subsystem-pump is the contrary of the case 2.1. This makes that the coupling is through the states and the inputs.

Regarding the communication issues, given that the states of each subsystem are measured, these are available to be shared between the subsystems. Then, the data to be shared could be selected by the user.

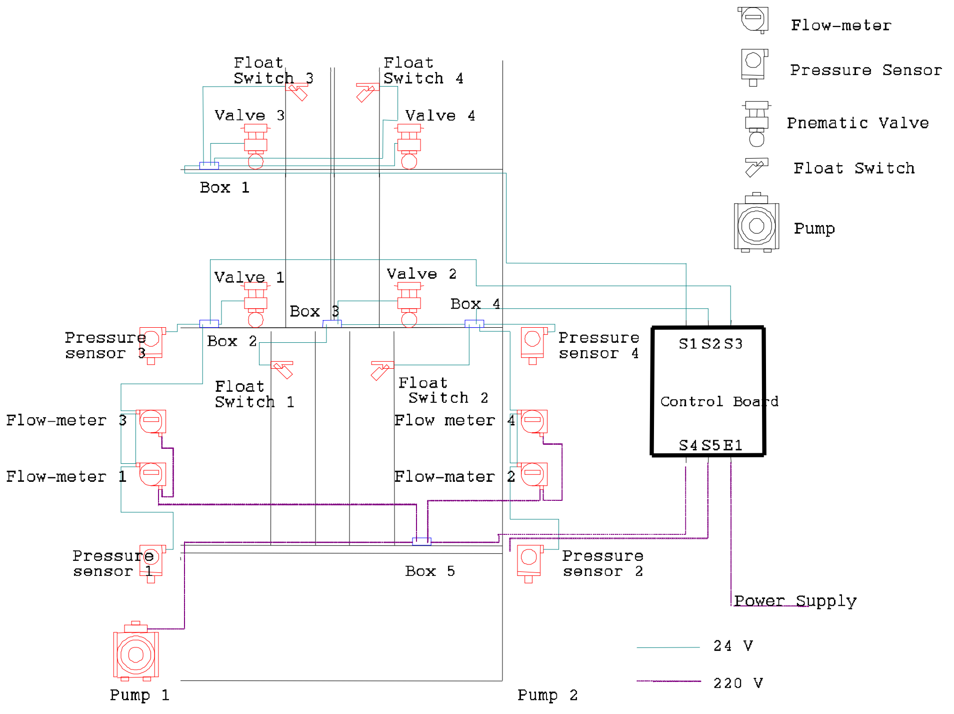
1.2.3 Describe the type and technical characteristics of the instrumentation: sensors, actuators. Enumerate and describe the measured / observed variables

The measurements provided by the sensors as well as the aperture of the valves are electrical signals (4-20 mA current loop). The wiring of these signals allows one to connect them to a Programmable Logic Controller (PLC) located in the control board or to connect them to an external device by means of plugs located in the panel of the control board.

The instruments of the plant are the following:

- Pressure sensors: Siemens Sitrans P 7MF4020 and 7MF4032. These are used to estimate the level of the tanks.
- Maximum Levels are detected by floats switches.
- Flowmeters: Electromagnetic flowmeters Siemens composed of Sitrans FM Flow sensor 711/S and Sitrans FM Transmitters Intermag/transmag.
- Pneumatic control valves: Siemens VC 101 with a positioner Sipart PS2 PA. The positioner also provides a measure of the real position of the valve.
- Pumping system: Pump SACI K41T 4HP plus DAB Active driver T/T5.5 pressure controller.
- The PLC: Siemens S7-200

A diagram of the instruments of the plant is shown in the following figure:



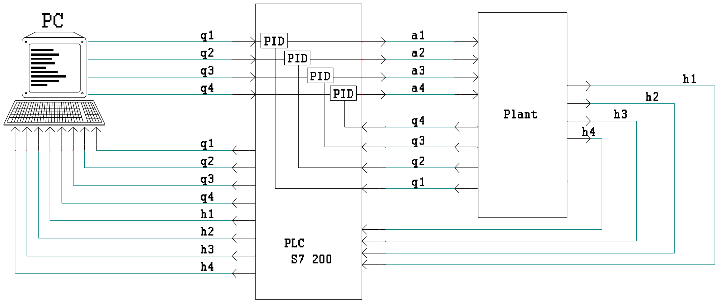
1.2.4 Describe the architecture of the basic control systems: PIDs, PLC, securities,……

The basic control system of the plant can be implemented according to the chosen control structure:

Cascaded Control: the control is divided in two levels: a lower level (inner loop) aimed to control the flow of each inlet and a higher level (outer loop) where the levels are controlled.
Direct Control: the levels are controlled manipulating directly the apertures of the valves.

On the other hand, the control law can be implemented in the PLC (which is the commonly used structure) or by means of an external device given that all the signals (measurements and control actions) are accessible in the control board using a 4-20 mA. transmission. The external control is interesting from an educational and practical point of view since this allows us to control the plant by means of standard low level controllers, such as industrial PIDs, or using different PLCs or data acquisition systems.

The PLC located in the control board can be used to implement (simple) control laws, such as the low level flow controllers or to be connected to a computer, allowing us to control the plant by means of an application running on the laptop. The following figure shows the diagram of the cascaded control structure where the low level PIDs are implemented in the PLC and the high level controller is implemented in the computer.



a: Opening Rate of the Valves.
q: Flows.
h: Levels.

All the process variables are periodically sampled and stored in the PLC RAM in a real time data base. These variables can be accessed from the computer thanks to the existing connection with the computer via the standard serial RS-232. The protocol is the Siemens PPI which is fast enough for the control of the plant.

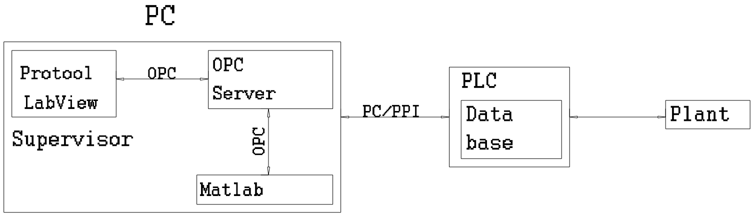
Upper-level controllers are typically executed in the computer and these vary the manipulated variables by accessing to the corresponding variables of the real-time data base. The details of this issue are given in the following section.

1.2.5 Description of the basic control system (software and hardware) including Operating system, SCADA,…

In order to enhance the connectivity of the process, the real-time data base is accessible by means of an open and free protocol that can be easily found in control suites and SCADAs: the OPC (OLE for Process Control) protocol.

To this aim, an OPC server developed by Kepware Inc. has been installed. This software reads the variables from the data base of the PLC using the PPI protocol. Then, the program builds a real time data base in the PC. These variables can be used (read and/or write) by other applications by means of the OPC protocol in a server-client architecture.
Thus, no SCADA is used in the plant, but any external program can access to the plant by means of the OPC client. Currently, a Man-Machine Interface application has been developed in Labview and Matlab has been used to develop and test the different control laws.

This is illustrated in the following figure:



Notice that an industrial SCADA (for instance SIMATICit) that implements an OPC client could be connected to the plant. Furthermore, based on the OPC protocol, connectivity of the plant from the World-Wide-Web is also possible

1.2.6 Manual/auto, remote operation

The control structure of the plant does not implement a manual/auto or a remote operation of the plant.

1.2.7 Alarm system. What are the alarm messages available?, what are the possibilities of reconfiguration?, what are the degraded modes and the critical modes?

In order to avoid overflows of the tanks, a float is installed at the top of each tank and the on/off signal is wired to the control board where an emergency stop of the plant is carried out closing the valves and stopping the pumps.

Another critical state appears if the storage tank is emptied. In this case, the pressure control of the pump avoids a malfunction of the pump and this is switched off.

The control objectives have been chosen to avoid all this critical situations by means of suitable constraints on the levels.

1.2.8 Man machine Interfaces

In the control structure currently implemented, the Man-Machine Interface of the plant has been implemented in Labview VI, and Matlab is only devoted to execute the control law.

The MMI is composed of 5 screens:

Main Screen: it is devoted to show all the variables of the plant (left part):

- Valve’s apertures.
- Levels.
- Flows.
- References of the PIDs.
- Parameters of the PIDs.
- Discrete variables like:
  - Level switches.
  - Pump On/Off.
  - Manual/Automatic.
  - Recirculation On/Off.
  - Recirculation protection of the pump On/Off.
  - PIDs On/Off
  - Compensation on the nonlinearities of the aperture-flow characteristic (for the PIDs).

The right part is devoted to manipulate the values of the variables that can be manipulated.

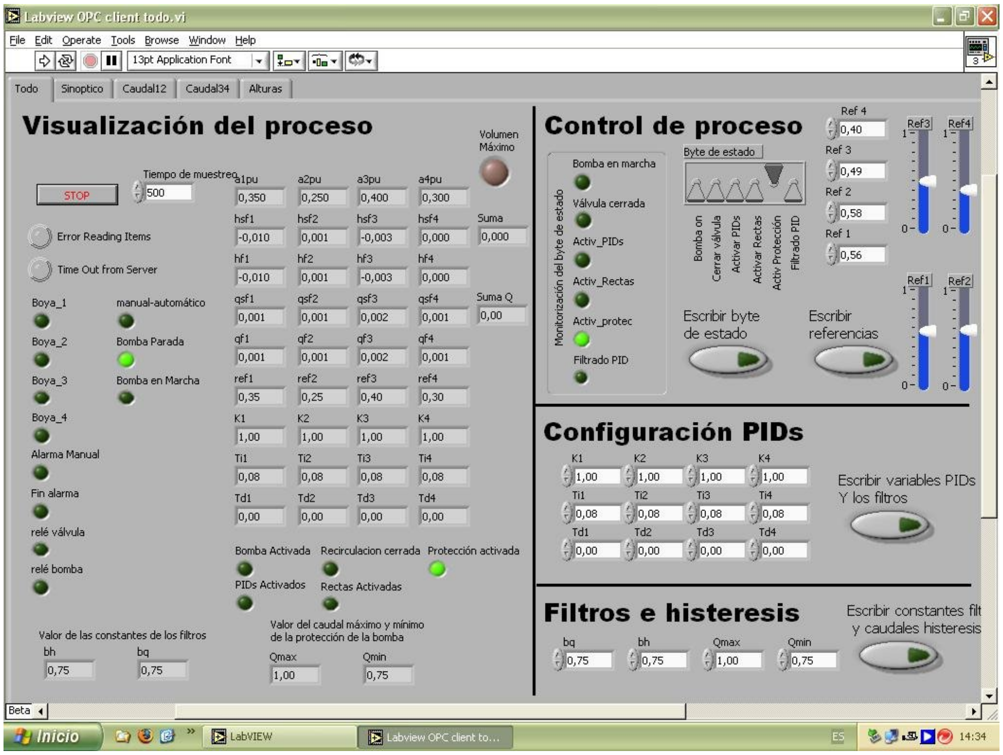
- Apertures. If the PIDs are deactivated the reference values are written directly to the apertures.
- The reference of the flows for the PIDs (PIDS on)
- The parameters of the PIDs.
- Parameters of the hysteresis of the recirculation protection of the pump.
- All the discrete variables can be written.

Synoptic of the plant Screen: an animated schematic picture of the plant is shown together with the values of the main variables.

Flow plot screens: two screens show the plot of the evolution of the inlet flow of each tank together with their references.

Level plot screen: the evolution plot of the levels is plotted

A screen-shot of the main screen and the synoptic screen of the MMI are respectively shown in the following figures:



Tiempo de muestreo 500

a1pu	a2pu	a3pu	a4pu	
0,350	0,250	0,400	0,300	
hsf1	hsf2	hsf3	hsf4	Suma
-0,010	0,001	-0,003	0,000	0,000
hf1	hf2	hf3	hf4	
-0,010	0,001	-0,003	0,000	
qsf1	qsf2	qsf3	qsf4	Suma Q
0,001	0,001	0,002	0,001	0,00
qf1	qf2	qf3	qf4	
0,001	0,001	0,002	0,001	
ref1	ref2	ref3	ref4	
0,35	0,25	0,40	0,30	
K1	K2	K3	K4	
1,00	1,00	1,00	1,00	
Ti1	Ti2	Ti3	Ti4	
0,08	0,08	0,08	0,08	
Td1	Td2	Td3	Td4	
0,00	0,00	0,00	0,00	

Valor de las constantes de los filtros

bh 0,75
bq 0,75

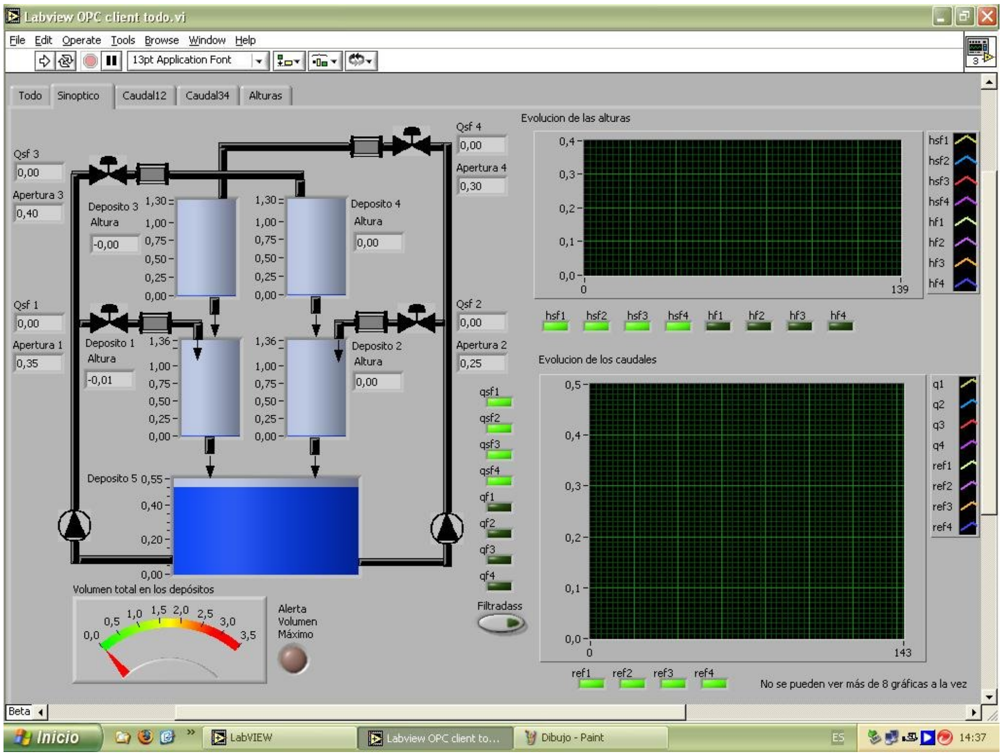
Valor del caudal máximo y mínimo de la protección de la bomba

Qmax 1,00
Qmin 0,75

Ref 4 0,40
Ref 3 0,49
Ref 2 0,58
Ref 1 0,56

K1	K2	K3	K4
1,00	1,00	1,00	1,00
Ti1	Ti2	Ti3	Ti4
0,08	0,08	0,08	0,08
Td1	Td2	Td3	Td4
0,00	0,00	0,00	0,00

bq 0,75
bh 0,75
Qmax 1,00
Qmin 0,75



Qsf 3: 0,00

Apertura 3: 0,40

Qsf 4: 0,00

Apertura 4: 0,30

Deposito 3 Altura: -0,00

Deposito 4 Altura: 0,00

Qsf 1: 0,00

Apertura 1: 0,35

Qsf 2: 0,00

Apertura 2: 0,25

Deposito 1 Altura: -0,01

Deposito 2 Altura: 0,00

No se pueden ver más de 8 gráficas a la vez

1.2.9 Data storage

The control structure allows that any OPC-client application connected to the server is capable to storage the read data. Currently, Matlab stores the sampled variables while the control law is executed. Once the test is finished, the data is stored as variables of the workspace that can be saved to a file using the ad-hoc Matlab functions.

1.2.10 Can be configured? Is it possible to inject faults?, Is it possible to command reconfigurations? Is it possible to inject artificial perturbations?

As it was aforementioned the plant allows many different configurations. Only the valves located at the output of the tanks have to change manually.

As it was commented in section 1.1.9, the possible perturbations are the following:

- Inlet flows: the plant has a couple of manual valves downstream the regulation valves in the inlet of the upper tanks. These can be partially opened to add an unexpected inlet flow in the tanks.

- Interconnection between tanks 1 and 2: a valve located in the connection pipe can be manually open to allow a flow between both tanks. This disturbance is state-dependent.

- Water transfer: an additional disturbance can be easily added by means of a submersible pump transferring water from a tank to another.

- Section: Adding an object inside of one tank yields to a variation of the section of the tank that may depend on the level.

1.2.11 External connectivity: OPC, web,….

An application can connect to the plant by means of the OPC protocol, which requires a built-in OPC client.

1.2.12 Range of admissible sampling periods

The sampling time depends on the plant dynamics, which is configurable. The typical sample period for the outer-loop controller is 5 seg and for the inner flow control loop is 0.5 seg.

1.2.13 Do there exist saturations (in amplitude, in speed…) in the actuators or in the sensors?

Depending on the chosen structure, the manipulated variables may be the aperture of the valves or the set-point of the flows of the inlet stream of the tanks. In both cases, there exist limits on control signal. These are derived from the limited aperture of the control valve as well as the dynamics of the pneumatic actuator. Limits on the aperture lead to limits to the flows.

Slew rate limitations are taken into account considering the dynamic model of the valve. The levels of the tanks are also limited to the height of the tanks. The limits of the variables of the process are described in a previous section.

1.2.14 Can actuators and sensors be added?

No.

1.2.15 Can additional control loops be added, if necessary (e.g. anti-windup schemes)?

Yes. The inner loops could be implemented in the PLC while new outer loop can be implemented in Matlab, for instance.

1.3 Security

1.3.1 Describe the emergency procedures: emergency shut-downs, fast shut-downs. Are they automated or is it possible to control them (monitoring and supervisory functions)?

In case of emergency, an emergency red button is located in the control board. This must be manually switched from the lab. The same effect can be obtained by switching off the pump, which can be done from the MMI.

The electric wiring of the plant as well as the instruments and operators are suitably protected by a residual current device and circuit breakers located in the control board. The electricity supply can be switched off by the main switch located in the control board.

1.3.2 Define the limits of operation. How is the controller notified when the operation constraints are no longer verified? Do you know sufficient conditions on the inputs (bounds, maximal speed, algebraic conditions…) so that these limits are guaranteed?

The plant can be operated in the whole admissible range of operation. In the case that the constraints are not verified, the flow switches send a signal to the PLC and the alarm state is triggered, switching off the pump.

1.3.3 What are the security requirements? What are the properties which have to be verified during the system operation? What are the critical states that the system must never reach?

The quadruple-tank process is a very safe process to be operated; the critical issue to take into account is the levels of the tank. If one of them reaches the maximum level a security external circuit will stop the pump avoiding the possible overflow. This alarm state can be read from the real-time data base, but the plant must be re-operated manually by switching off an alarm button.

Another critical issue (related with the levels) is the empty the storage tank. If the level of the storage tank is below a certain value, the pump could take air leading to a malfunction of the pump. The DAB Active driver T/T5.5 pressure controller of the pump could switch off the pump to avoid a fault of the pump. This state can not be read by the PLC and then, it is not noticed in the MMI or in the real-time data base.

1.4 Process Models

1.4.1 Is there any available model of the process? If yes,

A simple model of the plant is available by the users and can be found in the virtual portal of the project. This model is simple enough to be easily simulated while it is sufficiently accurate.

More complex models may include the actuator dynamics and the eddy effect in the tank empty process.

1.4.2 Specify the objective of the model/s (control, simulation, reliability analysis, security analysis, formal verification …)

The available model has been derived to be used to design model-based controllers. The parameters of the model have been estimated from experimental data. The obtained model has been experimentally validated.

It is worth remarking that from our experience on the plant, the model is a very reliable tool to design and test controllers for the plant.

1.4.3 Are multiple models of the plant with different degrees of complexity available (e.g. ranging from approximated linear models with few variables to nonlinear detailed models accounting for all the dynamics)?

Besides the model aforementioned, linear models have been also successfully used. These have been derived by linearizing the non-linear model.

1.4.4 Describe the model/s: type, simplification assumptions, part of the process modelled,…

The simplifications assumed in the model are the following:

- The dynamics of the flow control loop is faster than the dynamics of the tanks and it can be neglected.
- There is no noise on the measures.
- The discharge constant of the tanks are constant for all the operation range.

1.4.5 How are specified modelling errors?

These have not been specified

1.4.6 What is the language/tool used to implement the model?

Currently, Matlab/Simulink has been used, but any application capable to connect with the PLC using the OPC protocol could also be used.

1.4.7 Has it been validated? How?

Yes, the model has been experimentally validated by comparing the experimental results with the expected results according to the model.

1.4.8 Is it available any documentation?

Yes, related documents can be found in the virtual portal of the project.

1.4.9 What kind of experiments can be performed in order to obtain or calibrate new models? Which part of the model can be easily recalibrated?

In order to model the dynamics of the flow control loop, standard test to obtain experimental data to identify the model can be easily implemented.

The other source of uncertainty is the dynamics of the empty process of the tank. This basically requires obtaining the outlet flow as a function of the level. This means to determine how is the function and identify its parameters. For instance, if the Bernoulli's law is used, the discharge constant would be the parameter to identify.

An easy experimental test to be performed is to fill the tank and measure the evolution of the level of the tank.

1.4.10 Is there any available data for identification?

Stored data of previous tests is available for identification. Nevertheless, specialized tests on the plant could be easily executed if necessary.

2 Experiments

2.1 General operating conditions

2.1.1 Specify the plant availability (24 hours/day, only at night, …)

Standard working hours.

2.1.2 Is it necessary a human supervisor at the site? Why?

The plant is quite safe to be operated, but it would be recommendable a human supervisor in the labs if an alarm is triggered or to start-up the plant.

2.1.3 If yes, could this supervisor experiments any control strategy or does he need an expert of this control strategy participating to the experiments? Does this expert need some special formation for the operating conditions?

The operation of the plant can be easily learned by the user. On the other hand, the control structure available for the benchmark test requires a Matlab function embedded in a Simulink block. This facilitates the execution of the test by the supervisor. Then, this does not need to be an expertise in the control strategy to be tested.

2.1.4 Describe the Start/Stop procedures

The start process it is as follows:

- Switch on the energy supply to the plant (by a switcher located in the control law
- Switch on the pump
- Start the remote PC where the OPC server is installed
- Start the OPC Server
- Start the MMI application (Labview)
- Start Matlab and open the Simulink file.

The close procedure is just the inverse of the start.

2.1.5 Manual/automatic switching

The control valves can be manually actuated from the MMI.

2.1.6 Auxiliary equipment needed

None

2.1.7 Is there an experiment data base?

The data of the test of the different controllers applied on the plant have been stored, but there not exists a data-base for that. This could be developed for the project in order to make the results available in the virtual portal.

2.2 Experiments description

2.2.1 Specify the objectives of the experiment, control objectives

The control objective is control the levels of the tanks1 and 2 while the levels of the tanks 3 and 4 verifies the constraints in minimum time. A performance criterion can be to minimize the mean square root error.

2.2.2 Describe the experiments: steps to be performed, input signals, scenario

Not defined yet.

2.2.3 Can the user suggest a new implementation, new closed-loops, new sensors and actuators to manage some difficulties?

New control loops or implementations could be proposed by the users. However the addition of new sensors and actuators is not possible.

2.2.4 Is it possible to define new experiments by the user? Describe the procedure

The experiment will be defined by the benchmark. In order to define new experiments, two different cases must be considered:

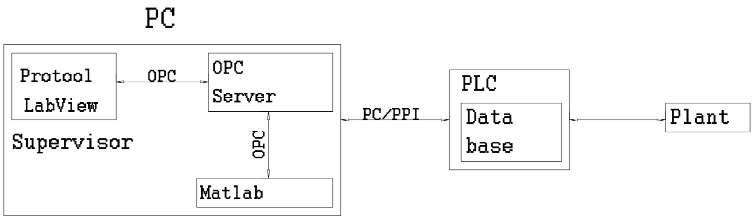
The topology and parameters of the plant are not varied. In this case, the definition is easy since all the measured data of the plant is available to the user, and the experiment would only require a new definition of the control function.

The topology and parameters of the plant are varied. In this case, the definition of the new experiment requires the expertise of the supervisor, since this would require, for instance, switching manual valves, re-tuning the inner loop controllers, adjusting the operation range and adjust other plant parameters to avoid a narrow operation range or a too slow dynamics of the plant.

2.3 Experiment implementation

2.3.1 Describe the actual control architecture and software in use from the user point of view (labview, matlab, DCS, C code, PLC code…)

The control architecture proposed for the benchmark is the aforementioned and it is shown in the following figure:



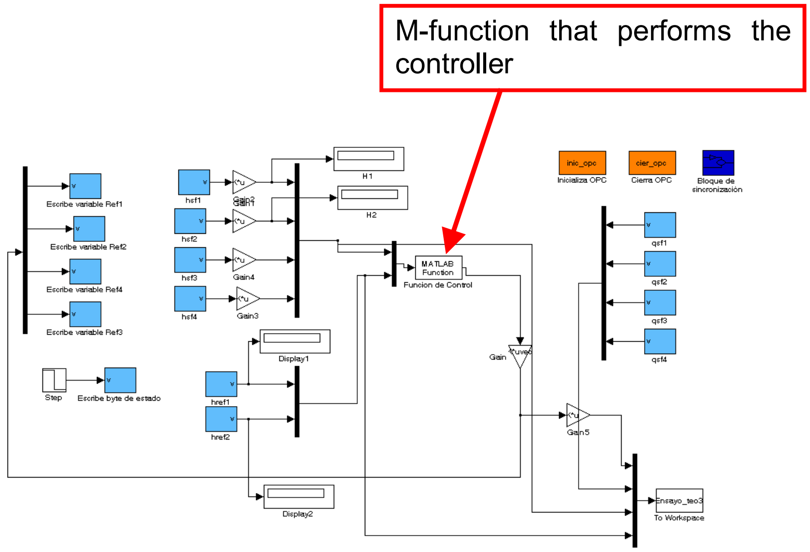
The control law is implemented in Matlab and the sampling time is 5 seconds. The supervision is carried out by the MMI executed in Labview. Other implementation of the control law would be possible if it has an OPC client embedded.

2.3.2 Describe the control algorithm implementation format, i.e., what must be done for adding/modifying new control structures.

To perform the controller, only a Matlab m-function is required. The inputs of this function are the measured levels of the tanks at the current sampling time, the references of the tanks 1 and 2 and possibly, the rest of the measured variables of the plant. The function must provide the manipulated variables, that are, the desired flow of each ideal pump if the cascaded structure is chosen, or the apertures of the four valves, in the cases that direct control is used.

Manipulated_Variables= Controller (Measured_Levels, References,…
Other_measured_variables)

This function is embedded in a Simulink block and executed.


M-function that performs the controller

2.4 Performance measures

2.4.1 Define the indexes to measure the performance of the experiments in relation to the control aims, robustness of the control system, facility of use and operation, economic issues....

CRITERIA	**TYPE**	**INDICATOR**
Control objectives	Qualitative	Value from 1 to 10 1: Standard control objective 10: Very ambitious control objective
Designing of the Controller		
Design time	Quantitative	Number of hours to get the controller designed
Documentation	Qualitative	Value from 1 to 10 1: Poor 10: Complete
Knowledge required	Qualitative	Value from 1 to 10 1: Very little knowledge required 10: High knowledge required.
Modelling requirement	Qualitative	Value from 1 to 10 1: No model or a simple model required 10: A very sophisticated and precise model required
Tests required on the system	Quantitative	Number of hours of tests required.
Controller requirement		
Computation time needed	Quantitative	Minimum sampling time
Memory needed	Quantitative	Number of Kbytes
Auxiliary Software needed	Qualitative	Value from 1 to 10 1: Complex and or expensive auxiliary software required 10: No auxiliary software required
Results of the test		
Perturbation response	Quantitative	Maximum error
Set point change response	Quantitative	Settling time
Variance	Quantitative	Variance
Basin of attraction	Quantitative	Volume of attraction basin
Robustness	Qualitative	Value form 1 to 10 1: Very fragile 10: Very robust
Accumulated error	Quantitative	Accumulated error
Cost of the control strategy in terms of energy	Quantitative	Integral area of manipulated variable
Constraint violations	Quantitative	Integral area error of constraint violations
Adaptation capability	Quantitative	Integral area error when process parameters are changed
Safety	Qualitative	Value from 1 to 10 1: Major safety issues. 10: An intrinsically safe controller

2.4.2 Is it possible to estimate cost of the control strategy in terms of energy, necessity and difficulty of the calibrations, optimality?

The main cost of the operation is the cost to pump the water. Since the pressure of the pump is regulated, the cost will depend on the total flow pumped that it inferred from the measured inlet flow of each tank.

2.4.3 Can the goals be reformulated?

Yes.

2.4.4 Define the threshold of the indexes

Not defined yet.

2.4.5 Is there an experimental result database and statistical tools to compare with previous experiment results?

Not in the context of distributed control. This will be done for the project.

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