



## Educational Foundation Fieldbus Pilot Plant

Vitor Viegas, J. M. Dias Pereira

**Abstract**—The paper presents a pilot plant built to demonstrate the principles of process control using the Foundation Fieldbus (FF) technology. Some theoretical background is given by explaining the logical layers of the technology, namely the physical layer, the communication stack and the user layer. Practical aspects, like the configuration of instruments, the design of a control strategy and the development of supervision software, are also covered by means of an application example. The example runs on the pilot plant making use of pressure, level and flow control loops, quantities widely found in the process industry. Experimental results are extracted and analyzed in order to evaluate the overall performance of the system.

**Index Terms**—Foundation Fieldbus, fieldbus control systems, process control, engineering education, pilot plant

### I. INTRODUCTION

THE Foundation Fieldbus (FF) [1-3] is a communication technology intended to connect instruments on the factory floor. It provides reliable real-time communications that allow the implementation of distributed control loops on physical processes.

As shown in figure 1, the FF technology distinguishes between low-speed communications (H1 level) and high-speed communications (H2 level). The H1 level acts as a digital replacement for 4-20 mA current loops widely used in industrial plants. The H2 level aggregates data from H1 segments and adds support for discrete control. Together, the H1 and H2 levels satisfy the automation needs of most

systems, whether they are continuous or discrete.

The FF technology is supervised by the Fieldbus Foundation [4], a non-profit consortium composed by end-users, manufacturers and research organizations. The foundation promotes and regulates the use of the technology while provides guidelines for the future. The regulation work includes rigorous certification programs that guarantee interoperability between equipment from different manufacturers. The goal is to give end-users the ability to choose the best hardware and software at any time without being stuck to a specific vendor.

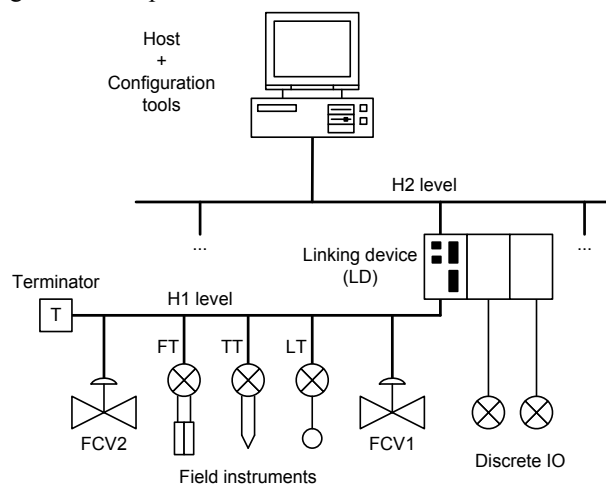


Fig. 1. FF overview.

#### A. H1 Level

The H1 level is a digital bus that implements a subset of the OSI (Open Systems Interconnection) model. The physical layer is fully implemented, while layers 2 to 7 are compressed in the so-called “communication stack”. The user layer (extra OSI) defines a library of functional blocks intended to build control applications. These three components (physical layer, communication stack and functional blocks) must all reside in

Vitor Viegas is with the LabIM/ DSI/ ESTSetúbal/ Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal, and with the Instituto de Telecomunicações, 1049-001 Lisboa, Portugal ([vitor.viegas@estsetubal.ips.pt](mailto:vitor.viegas@estsetubal.ips.pt)).

J. M. Dias Pereira is with the LabIM/ DSI/ ESTSetúbal/ Instituto Politécnico de Setúbal, 2910-761 Setúbal, Portugal, and with the Instituto de Telecomunicações, 1049-001 Lisboa, Portugal ([dias.pereira@estsetubal.ips.pt](mailto:dias.pereira@estsetubal.ips.pt)).

every FF instrument.

The physical layer conforms to the IEC 61158-2 standard [5] as follows: twisted pair, 31.25 kbit/s, power over bus (24 VDC), 32 devices per segment (maximum), 7600 m per segment (using up to 4 repeaters and depending on signal-to-noise ratio), free topology.

The communication stack implements a master-slave protocol that guarantees message delivery in real-time. The master is called “Link Active Scheduler” (LAS) because it distributes permissions to talk – also known as “tokens” – according a deterministic schedule. When a device receives the token, it publishes messages on the bus that are picked up and consumed by one or more subscribers. The LAS supports the following transactions:

- Programmed communications: Periodically, according a programmed control strategy, the LAS sends tokens of type CD (Compel Data). The device owning the CD token publishes data immediately without waiting for the subscriber(s) to confirm the reception. If data is lost, the system relies on the previous value until a new one is transmitted. This transaction is used to transfer variables and status information between functional blocks.
- Non-programmed communications: After executing the control strategy, the LAS reserves some time to send tokens of type PT (Pass Token). The device owning the PT token has a limited amount time to send messages by its own initiative. All messages have to be confirmed otherwise are repeated. This transaction is used to report events and to perform configuration tasks (such as setpoint adjustments, program downloading and remote diagnostics).
- Live list: The LAS scans for active devices by sending tokens of type PN (Probe Node) to all possible addresses (sequentially from 0 to 255). The target device responds by returning its unique IDentifier (ID) and tag. If a new device is found, it is added to the live list; if a device fails to respond three consecutive times, it is removed from the list.
- Time distribution: The LAS synchronizes the bus by broadcasting tokens of type TD (Time Distribution).

Each H1 bus has one primary master. Other devices can be configured as redundant masters provided they have LAS capabilities. The master with lowest address takes control automatically.

The programming interface of FF devices is based on functional blocks. Each device contains:

- One Resource Block (RB) that describes the general characteristics of the device (ID, tag, manufacturer, model, serial number, etc.).
- One or more Transducer Blocks (TB) that describe the characteristics of the attached transducers (transducer type, connection, compensation, calibration data, etc.).
- One or more Function Blocks (FB) that implement data processing algorithms. There are dozens of predefined FBs covering the most common functionalities (AI – Analog Input, AO – Analog Output, PID – Proportional Integral Derivative

controller, ARTH – ARiTHmetic, SG – Setpoint Generator, LLAG – Lead Lag, DENS – Density, LCF – Liquid Correction Factors, etc.).

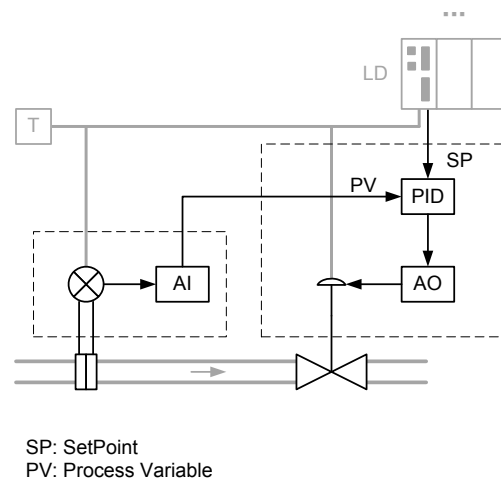


Fig. 2. Flow control loop (instruments and FB diagram).

The control strategy is defined by a FB diagram like the one shown in figure 2. The arrows establish data relations between FBs: if two interdependent FBs reside on the same device, data is transferred internally; if they reside in different devices, data is transferred across the bus. By dissecting the diagram it is possible to know who talks to whom and when; in other words, it is possible to schedule programmed communications.

The use of predefined FBs promotes interoperability because devices can be replaced while the program maintains the same structure.

### B. H2 Level

The H2 level aggregates data from the field, including H1 segments, Programmable Logic Controllers (PLC) and sensor buses. Over the last years there has been an effort to apply internet technologies at this level: Ethernet for data transmission, Internet Protocol (IP) for data routing, and Transport Control Protocol (TCP) and User Datagram Protocol (UDP) for data transport. This approach provides high baud rates (100 Mbit/s typical) and allows the use of inexpensive, off-the-shelf equipment. In return, it does not provide native support for real-time, power over bus or redundancy.

Each H1 segment is connected through a gateway called “Linking Device” (LD), which, most of the times, acts as the primary master and provides support for discrete control. When the host needs to access a particular H1 device, it sends TCP messages to the corresponding linking device which translates them into H1 communications. The reverse happens when the H1 device reports data to the host. UDP messages are used when the host needs to contact several linking devices simultaneously (to distribute time, for example). The process of translation is absolutely transparent so that configuration tools (residing on the host) can configure, diagnose and monitor H1 devices as if they were locally connected.

TABLE I  
FIELD INSTRUMENTS

Tag	Manufacturer	Reference	Range	Signal	Brief description
FT1	Gebr. Muller	GEMU 830 + 1270 + 1275 (a)	5 to 50 l/min	4 to 20 mA	Variable area flowmeter.
LT1	Rosemount	D2A12A2S1B4	0 to 100% (b)	4 to 20 mA	Differential pressure transmitter.
FT2	Fischer Porter	F50DPF110-3	0 to 47.7 l/min	4 to 20 mA	Differential pressure transmitter coupled to a Venturi tube.
PT1	Smar	LD302	0 to 25400 mmH <sub>2</sub> O (c)	FF	Pressure transmitter.
IF1	Smar	IF302	4 to 20 mA	FF	Triple channel current/FF converter.
FCV1	Smar + Sart von Rohr	FY302 + MA821E63SP0 (d)	0 to 100%	FF	Fieldbus positioner coupled to a pneumatic valve.
FCV2	Smar + Sart von Rohr	FY302 + MA821E63SP0	0 to 100%	FF	Fieldbus positioner coupled to a pneumatic valve.

Notes:

- a) GEMU 830 refers to the variable area flowmeter, GEMU 1270 refers to the displacement/voltage converter, and GEMU 1275 refers to the voltage/current converter with local indicator.
- b) The range in meters depends on the dimensions of the tank.
- c) Gauge pressure.
- d) FY302 refers to positioner from Smar, and MA821E63SP0 refers to the pneumatic valve from Sart von Rohr.

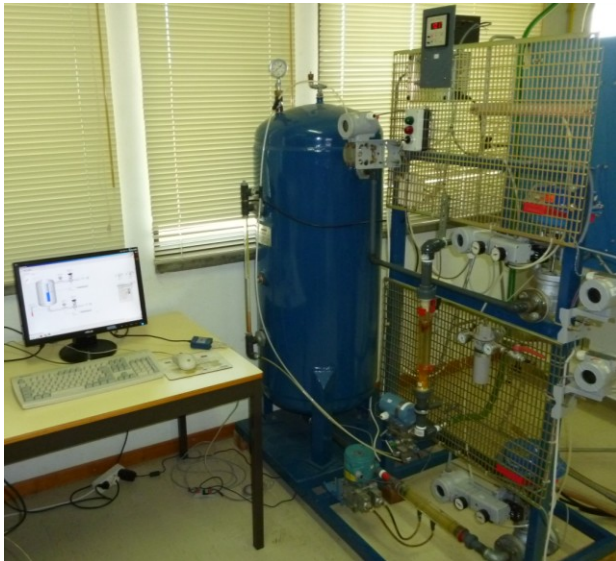


Fig. 3. Physical process (photo).

## II. PHYSICAL PROCESS

The physical process was built to train students in the principles of process control and FF instrumentation. The process contains all the equipment needed to run the following control loops (see figures 3 and 4):

- Level control loop: The water level inside the closed tank is measured by the transmitter LT1 and is controlled by operating the control valve FCV1. Information about water inflow and air pressure at the top of the tank is provided by transmitters FT1 and PT1, respectively. The tank is equipped with an exhaust valve to prevent pressures above 3 bar.
- Flow control loop: The flow of water leaving the tank is measured by the transmitter FT2 and is controlled by operating the control valve FCV2.

FF instruments were tied into a single H1 segment terminated by a 100 Ω resistor in series with a 100 nF capacitor. The H1 bus was connected directly to a computer (overcoming the H2 level) using an interface board that acts as linking device (model USB-8486 from National Instruments [6]). Finally, on the computer, it was installed the software needed to configure and supervise the pilot plant, namely NI-FBUS Configurator 4.0.1 [7], LabVIEW 2009 SP1 [8] and the Datalogging and Supervisory Control (DSC) module [9].

## III. CONFIGURATION OF FF INSTRUMENTS

The configuration of FF instruments is very challenging because it requires a deep understanding of the process, as well as expertise to deal with the multitude of options offered by functional blocks. The configuration was done online

BJICBhaving all FF instruments powered up and remotely visible. This requires patience (because the H1 bus is slow) but enables incremental error fixing. The work was done instrument by instrument walking through the following steps:

1. The instrument was reset to its factory defaults.
2. A unique address from 17 to 247 (in the range of permanent devices) was assigned to the instrument (address 16 is reserved by the interface board).
3. One or more FBs were instantiated to provide processing power for the instrument (according the needs of the control strategy).
4. Unique tags were assigned to the instrument and its

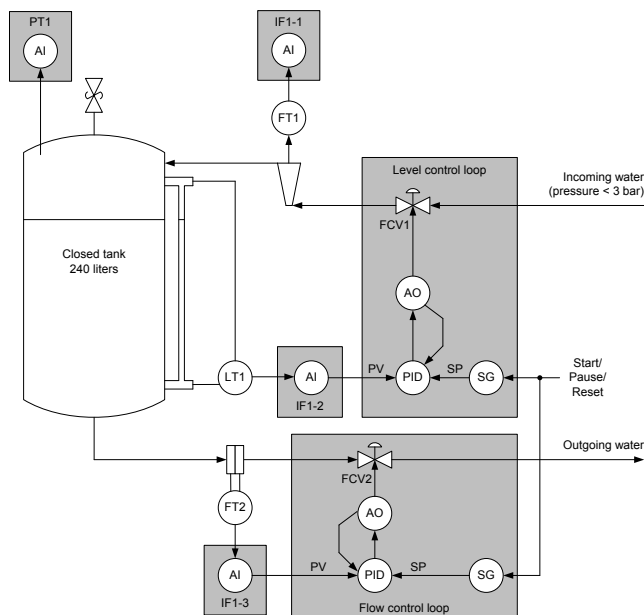


Fig. 4. Physical process (P&I diagram).

functional blocks.

5. Each functional block was configured as described in table 2. For this purpose it was important to study each parameter in detail [10], as well as the operation manuals of the instruments [11-13].

The interface board was configured as the primary master by resetting all its parameters to the default values. No other (redundant) masters were implemented.

Having configured the H1 bus, it was time to build a control application for the plant. The application, shown in figure 5, is composed by two main sections:

1. The top section implements the level control loop. This loop is closed by a PID controller that receives the process variable from the level transmitter LT1 (via channel 2 of the converter IF1), and writes the output variable to the positioner of the control valve FCV1. The AO, PID and SG function blocks are cascaded to increase loop consistency: if a function block breaks the loop (by passing to Manual mode, for example), the upstream blocks freeze their operation; if the loop is restored, the upstream blocks resume automatically.
2. The bottom section is similar to the top one, with the difference that it applies to the flow control loop. The process variable comes from the flow transmitter FT2 (via channel 3 of converter IF1), and the output variable goes to the positioner of the control valve FCV2.
3. Two function generators supply the setpoints of the control loops. The waveforms are pre-defined but the operator has the chance to start/pause/reset both generators synchronously.

Figure 6 shows the schedule associated to the control application. The configurator gives time for instruments to do internal processing (blue bars), as well as to exchange data across the H1 bus (red bars). The control loops run with a sampling period of 800 ms.

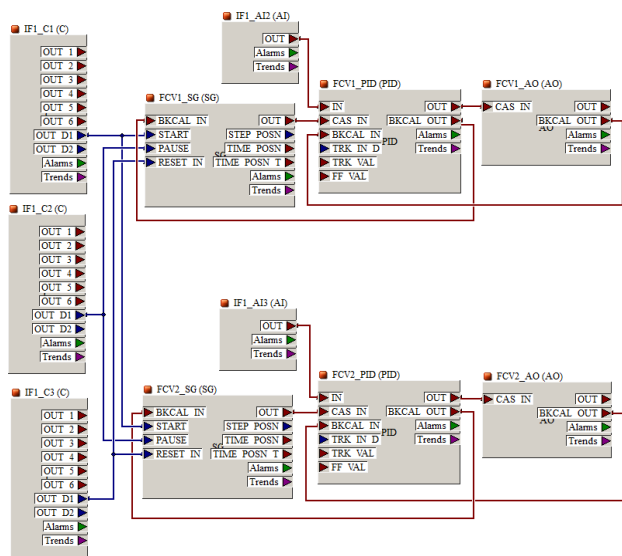


Fig. 5. Control application.

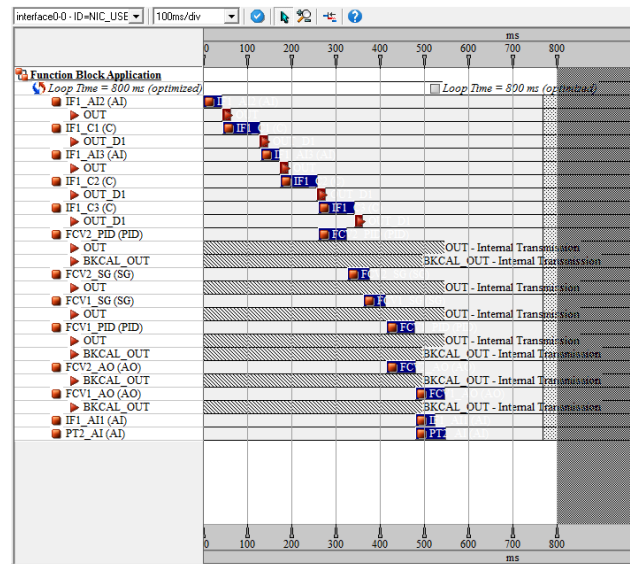


Fig. 6. Schedule of the control application.

#### IV. SUPERVISION APPLICATION

The supervision application allows the pilot plant to be operated by people without expertise on the FF technology. It provides a graphical environment where the operator can monitor the system without worrying about configuration details and low level communications.

The supervision application was written in LabVIEW using the facilities provided by the DSC module. The application interacts with the FF infrastructure using the OPC-DA (Open Process Control Data Access) [14-15] server that comes with the NI-FBUS Configurator. The development went through the following stages:

1. An OPC client was created and connected to the OPC-DA server. The server exposes data items representing the parameters of functional blocks.
2. The data items of interest (those related with setpoints, process variables and output variables) were bound to shared variables created expressly for that purpose.
3. Each shared variable was configured in terms of data type, access type (read only or read & write), alarming (HiHi, Hi, Lo and LoLo), data logging and security (remote access permissions).
4. A virtual instrument was built to provide a rich graphical interface for the operator (see figure 7). The controls and indicators were bound to the shared variables in order to synchronize the front panel with the system. The operator can monitor the system (by reading process variables and output variables) and send commands to the setpoint generators (start/pause/resume).



TABLE II  
CONFIGURATION OF FF INSTRUMENTS

Current to FF converter IF1, address = 23 (a)				
Block	Category	Parameter	Value	Comment
IF1_RB (Resource block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_TB1 (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_TB2 (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_TB3 (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_AI1 (Analog Input FB)	Scaling	XD_SCALE.EU_100	20	Transducer's input range (4 to 20 mA).
		XD_SCALE.EU_0	4	
		XD_SCALE.UNITS_INDEX	mA	
		OUT_SCALE.EU_100	50	Output range (0 to 50 l/min). This range applies to the incoming water flow.
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	L/min		
	L_TYPE	Indirect	The input range is linearly converted to the output range.	
Process	CHANNEL	1	Links to the transducer block IF1_TB1.	
	MODE_BLK.TARGET	Auto	Activates the block.	
IF1_AI2 (Analog Input FB)	Scaling	XD_SCALE.EU_100	20	Transducer's input range (4 to 20 mA).
		XD_SCALE.EU_0	4	
		XD_SCALE.UNITS_INDEX	mA	
		OUT_SCALE.EU_100	100	Output range (0 to 100%). This range applies to the water level inside the tank.
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	%		
	L_TYPE	Indirect	The input range is linearly converted to the output range.	
Process	CHANNEL	2	Links to the transducer block IF1_TB2.	
	MODE_BLK.TARGET	Auto	Activates the block.	
IF1_AI3 (Analog Input FB)	Scaling	XD_SCALE.EU_100	20	Transducer's input range (4 to 20 mA).
		XD_SCALE.EU_0	4	
		XD_SCALE.UNITS_INDEX	mA	
		OUT_SCALE.EU_100	47.7	Output range (0 to 47.7 l/min). This range applies to the outgoing water flow.
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	L/min		
	L_TYPE	Indirect Sq Root	The input range is converted to the output range by applying the square root operation. Useful for flow meters based on differential pressure.	
Process	CHANNEL	3	Links to the transducer block IF1_TB3.	
	MODE_BLK.TARGET	Auto	Activates the block.	
IF1_C1 (Constant FB)	Others	CT_VAL_D1	0 or 1	Value of the discrete output D1. This constant starts the setpoint generators on a rising edge.
	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_C2 (Constant FB)	Others	CT_VAL_D1	0 or 1	Pauses the setpoint generators (value = 1) or not (value = 0).
	Process	MODE_BLK.TARGET	Auto	Activates the block.
IF1_C3 (Constant FB)	Others	CT_VAL_D1	0 or 1	Resets the setpoint generators on a rising edge.
	Process	MODE_BLK.TARGET	Auto	Activates the block.

Control valve FCV1, address = 25 (a)				
Block	Category	Parameter	Value	Comment
FCV1_RB (Resource Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV1_TB (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV1_SG (Setpoint Generator FB)	Others	START_VAL	{30, 30, 60, 60, 60, 60, 30, 30, 30, 0}	Arrays that define the value and duration of each segment of the setpoint profile.
		DURATION	{60, 2, 150, 2, 150, 2, 150, 2, 60, 0}	
		TIME_UNITS	Seconds	Timer units.
		AUTO_CYCLE	Auto cycle	Automatically resets the timer and restarts the profile.
	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV1_PID (PID FB)	Scaling	PV_SCALE.EU_100	100	Range of the Process Variable (PV) (0 to 100%). In the present case, the PV is the water level inside the tank.
		PV_SCALE.EU_0	0	
		PV_SCALE.UNITS_INDEX	%	
		OUT_SCALE.EU_100	100	Range of the Output Variable (OV) (0 to 100%). In the present case, the OV is the valve opening.
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	%		
	Tuning	GAIN	6	Proportional gain (Kp) of the PID controller.
		RESET	4 Sec	Reset time (Ti) of the PID controller.
		RATE	8 Sec	Derivative time (Td) of the PID controller.
	Options	STATUS_OPTS	IFS if bad IN	If the block input goes bad (due to a communications failure, for example), initiate fault state in the cascaded block.
SP.VALUE		xxx	Level setpoint.	
Process	MODE_BLK.TARGET	Cascade	The controller follows the setpoint given by the setpoint generator (block FCV1_SG).	

Control valve FCV1, address = 25 (a)				
Block	Category	Parameter	Value	Comment
FCV1_AO (Analog Output FB)	Scaling	PV_SCALE.EU_100	100	Input range (0 to 100%).
		PV_SCALE.EU_0	0	
		PV_SCALE.UNITS_INDEX	%	
		XD_SCALE.EU_100	100	Actuator's output range (0 to 100%). The input range is linearly converted to the output range.
		XD_SCALE.EU_0	0	
	XD_SCALE.UNITS_INDEX	%		
	Options	IO_OPTS	Fault state to value	The fault state is activated if the block input has a status of BAD for more than two seconds. If this happens, the valve is closed (value = 0) to guarantee safety.
		FSTATE_TIME	2 Sec	
		FSTATE_VAL	0	
	Process	CHANNEL	1	Links to the transducer block FCV1_TB.
MODE_BLK.TARGET		Cascade	The block follows the output given by the controller (block FCV1_PID). Meanwhile, it applies scaling and checks the fault state condition.	

Control valve FCV2, address = 26 (a)				
Block	Category	Parameter	Value	Comment
FCV2_RB (Resource Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV2_TB (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV2_SG (Setpoint Generator FB)	Others	START_VAL	{5, 5, 5, 5, 10, 10, 10, 10, 5, 5, 0}	Arrays that define the value and duration of each segment of the setpoint profile.
		DURATION	{60, 2, 150, 2, 150, 2, 150, 2, 60, 0}	
		TIME_UNITS	Seconds	Timer units.
		AUTO_CYCLE	Auto cycle	Automatically resets the timer and restarts the profile.
	Process	MODE_BLK.TARGET	Auto	Activates the block.
FCV2_PID (PID FB)	Scaling	PV_SCALE.EU_100	47.7	Range of the Process Variable (PV) (0 to 47.7 l/min). In the present case, the PV is the outgoing water flow.
		PV_SCALE.EU_0	0	
		PV_SCALE.UNITS_INDEX	L/min	
		OUT_SCALE.EU_100	100	Range of the Output Variable (OV) (0 to 100%). In the present case, the OV is the valve opening.
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	%		
	Tuning	GAIN	0.5	Proportional gain (Kp) of the PID controller.
		RESET	4 Sec	Reset time (Ti) of the PID controller.
		RATE	1 Sec	Derivative time (Td) of the PID controller.
Options	STATUS_OPTS	IFS if bad IN	If the block input goes bad (due to a communications failure, for example), initiate fault state in the cascaded block.	
Process	SP.VALUE	xxx	Flow setpoint.	
	MODE_BLK.TARGET	Cascade	The controller follows the setpoint given by the setpoint generator (block FCV2_SG).	
FCV2_AO (Analog Output FB)	Scaling	PV_SCALE.EU_100	100	Input range (0 to 100%).
		PV_SCALE.EU_0	0	
		PV_SCALE.UNITS_INDEX	%	
		XD_SCALE.EU_100	100	Actuator's output range (0 to 100%). The input range is linearly converted to the output range.
		XD_SCALE.EU_0	0	
	XD_SCALE.UNITS_INDEX	%		
	Options	IO_OPTS	Fault state to value	The fault state is activated if the block input has a status of BAD for more than two seconds. If this happens, the valve is closed (value = 0) to guarantee safety.
		FSTATE_TIME	2 Sec	
		FSTATE_VAL	0	
	Process	CHANNEL	1	Links to the transducer block FCV2_TB.
MODE_BLK.TARGET		Cascade	The block follows the output given by the controller (block FCV2_PID). Meanwhile, it applies scaling and checks the fault state condition.	

Pressure transmitter PT1, address = 21 (a)				
Block	Category	Parameter	Value	Comment
PT1_RB (Resource Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
PT1_TB (Transducer Block)	Process	MODE_BLK.TARGET	Auto	Activates the block.
PT1_AI (Analog Input FB)	Scaling	XD_SCALE.EU_100	25400	Transducer's input range (between 0 and 25400 mmH2O).
		XD_SCALE.EU_0	0	
		XD_SCALE.UNITS_INDEX	mmH2O (68°F)	
		OUT_SCALE.EU_100	36.1263	Output range (between 0 and 36.1263 psig).
		OUT_SCALE.EU_0	0	
	OUT_SCALE.UNITS_INDEX	psig		
		L_TYPE	Indirect	The input range is linearly converted to the output range (in psig).
	Process	CHANNEL	1	Links to the transducer block PT1_TB.
MODE_BLK.TARGET		Auto	Activates the block.	

Notes:  
a) For sake of simplicity, the configuration of the display transducer block was omitted.

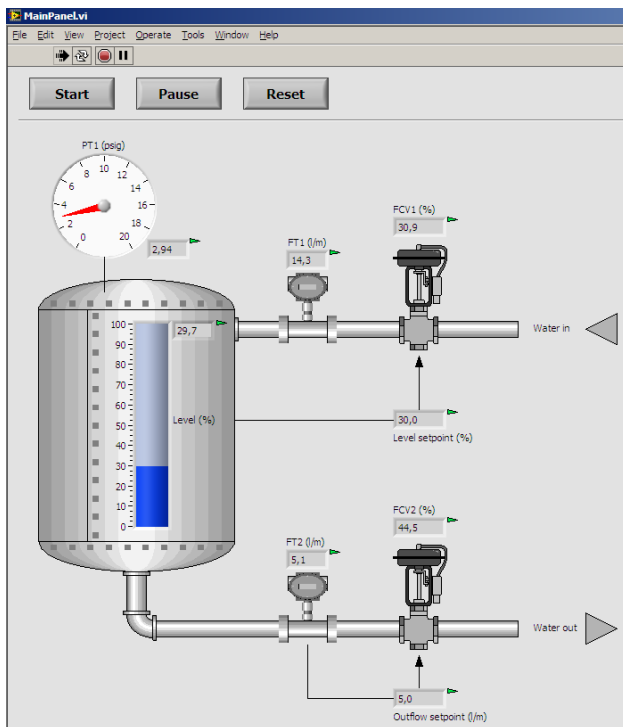


Fig. 7. Supervision application.

## V. EXPERIMENTAL RESULTS

Both control loops were tested over their dynamic ranges. For each controller, the setpoint, the process variable and the output variable were remotely monitored and recorded. The experiments were carried out according the following methodology:

1. The PID controllers were tuned in advance using the trial and error method. The level controller was configured with proportional gain  $K_p = 6$ , reset time  $T_i = 4$  s and derivative time  $T_d = 8$  s. The flow controller was configured with  $K_p = 0.5$ ,  $T_i = 4$  s and  $T_d = 1$  s.
2. The system was started with level and flow setpoints of 30% and 5 l/min, respectively. Time was given for all variables to stabilize.
3. Data recording was started at  $t = 0$  min.
4. At  $t = 1$  min the level setpoint was changed to 60%.
5. At  $t = 3.5$  min the flow setpoint was changed to 10 l/min.
6. At  $t = 6$  min the level setpoint returned to 30%.
7. At  $t = 8.5$  min the flow setpoint returned to 5 l/min.
8. Data recording was stopped soon after  $t = 10$  min.

Regarding the level control loop (see figure 8), the collected data can be analyzed as follows:

- At  $t = 1$  min the controller opens valve FCV1 to increase the level. The response has some overshoot and stabilizes after 2 min (approximately).
- At  $t = 6$  min the controller closes valve FCV1 to decrease the level. The response has negligible overshoot and stabilizes almost immediately.
- The level controller is insensitive to flow variations mainly due to the large capacity of the tank.
- The level controller is characterized by good tracking

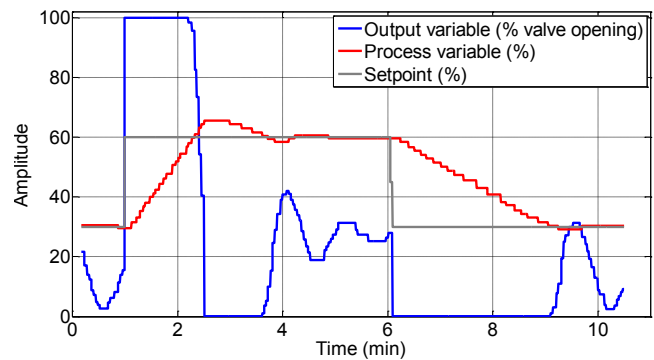


Fig. 8. Level control loop.

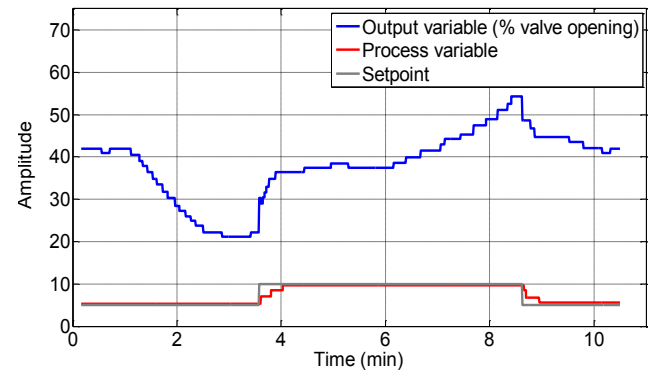


Fig. 9. Flow control loop.

capability, small overshoot, short settling time and good immunity to external disturbances (in particular those related with flow variations).

With respect to the flow control loop (see figure 9), the comments are similar:

- From  $t = 1$  min to  $t = 3.5$  min the controller gradually closes valve FCV2 to compensate the increase of level.
- From  $t = 6$  min to  $t = 8.5$  min the controller gradually opens valve FCV2 to compensate the decrease of level.
- At  $t = 3.5$  min the controller opens valve FCV2 to increase the flow. The response has no overshoot and stabilizes after half a minute (approximately).
- At  $t = 8.5$  min the controller closes valve FCV2 to decrease the flow. The response has no overshoot and stabilizes after half a minute (approximately).
- The flow controller is characterized by good tracking capability, no overshoot, short settling time and good immunity to external disturbances (in particular those related with level variations).

The supervision software has always worked as expected during the experiments.

## VI. CONCLUSION

The main topics of the FF technology were covered, both theoretically and practically. The implementation of a pilot plant was explained, including the conception of the physical process, the configuration of field instruments, the design of the control strategy and the development of the supervision software. The plant was tested in order to evaluate the behavior of each control loop, including mutual interferences

caused by setpoint changes. The plant worked as expected and showed good performance even when large changes in setpoints occurred.

Computer Science from IST. His main research interests are included in the Instrumentation and Measurement areas.

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**Vítor Viegas** was born in Portugal in 1976. He received his degree in Electrical and Computer Engineering from the Instituto Superior Técnico (IST) of the Universidade Técnica de Lisboa (UTL) in 1999. He received the MSc and PhD degrees from the same school in 2003 and 2012, respectively. He works as

Assistant Professor at the Instituto Politécnico de Setúbal (IPS). His main research activities concern smart transducers and industrial informatics.



**J. M. Dias Pereira (M’00 - SM’04)** was born in Portugal in 1959. He received his degree in Electrical Engineering from the Instituto Superior Técnico (IST) of the Universidade Técnica de Lisboa (UTL) in 1982. During almost eight years he worked for Portugal Telecom in digital switching and transmission systems. In

1992, he returned to teaching as Assistant Professor at the Instituto Politécnico de Setúbal (IPS), where he is, at present, as Coordinator Professor. In 1995 he received the MSc degree and in 1999 the PhD degree in Electrical Engineering and