CONTROL TASKS IN A WATER FLOW MEASUREMENT SECTION OF A HYDRAULICS LABORATORY

Armando Cordeiro[1,3], João Palma[2], José Maia[1,3], Jorge Esteves[3,4,5]

[1]Escola Superior de Tecnologia de Setúbal, Instituto Politécnico de Setúbal
Estefanilha, 2914-508 Setúbal, Portugal. E-mail: acordeir@est.ips.pt
[2]Laboratório Nacional de Engenharia Civil, CIC
Av. do Brasil, 101, 1700-066 Lisboa, Portugal. E-mail: jpalma@lnec.pt

[3]Centro de Automática da Universidade Técnica de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[4]Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa
Av. Cons. Emídio Navarro,1949-014 Lisboa, Portugal

[5]Entidade Reguladora dos Serviços Energéticos

ABSTRACT

This paper presents the control solutions for a water flow measurement section of a hydraulics laboratory. After a brief description and analysis of the major automation requirements and constraints, the adopted solutions to provide flow control for flow-meters calibration are presented. The flow measurement section allows two calibration methods – gravity measurement method and reference flow-meter method – both requiring programmed constant flow control. The plant consists of a set of centrifugal pumps driven by three-phase induction motors with electronic variable speed drives, associated with motorised valves in order to provide a diversity of hydraulics configurations. The automated solution is based on closed-loop control with gain scheduling PID function embedded in a PLC program. The diverters, which play a commutator like function with the flow, are key organs in the process of gravity flow measurement. Induction motors controlled for minimum time motion drive the diverters. Deflection time is typically less than 150 milliseconds. A dedicated SCADA program was also developed.

KEYWORD: flow-meter calibration, gravity flow measurement, water flow control, hydraulics laboratory, laboratory automation.

1. LABORATORY PLANT DESCRIPTION

LEHid is a hydraulics laboratory recently set up in Lisbon, at Laboratório Nacional de Engenharia Civil (LNEC). The installation is devoted to hydraulics research, equipment testing and calibration. It consists of two major sections: one provided with facilities for pump testing and the other having a set of equipment for mass flow measurement.

In this paper, the focus is directed to the flow measurement section. This section consists of a hydromechanical arrangement with three pumps with mechanical output power between 115 kW (P1 and P2) and 220 kW (P3), two tanks equipped with load cells, rated to 30 tons and 3 tons, more than 30 motorised valves and 100 mm to 350 mm diameter pipes that allow a diversity of hydraulics configurations (see fig.1). At the top of each tank there is a flow diverter used to direct the water flow either to inside the tank or to a bypass pipe. Both diverters are actuated by three-phase induction motors (5.5 and 4 kW) and share a single electronic variable speed drive V5.

P1 to P3 are immersed rotor centrifugal pumps driven by three-phase induction motors with electronic variable speed drives (e.v.s.d.) V1 to V3. The water is pumped from and to an underground reservoir.

2. GLOBAL AUTOMATION OPTIONS

The major automation needs [1] for this laboratory were:

- closed-loop automatic control of flow-rate by using variable speed pumps, including safety precautions and and starting procedures;
- pressure regulation by needle valve adjustment;
- bi-directional motion symmetry of diverters with minimum deflection time and exact stop to provide the highest accuracy in gravity calibrations;
- automated configuration of admissible hydraulic circuits by valve actuation;
- automated test/calibration procedures, while keeping an adequate level of human assistance.

The definition of the global automation options and the choice of equipment were also constrained by:

- the need of integrating all essential equipment for accomplishing the above mentioned objectives;
- the diversity of available equipment and devices with different and even incompatible interfacing technologies.

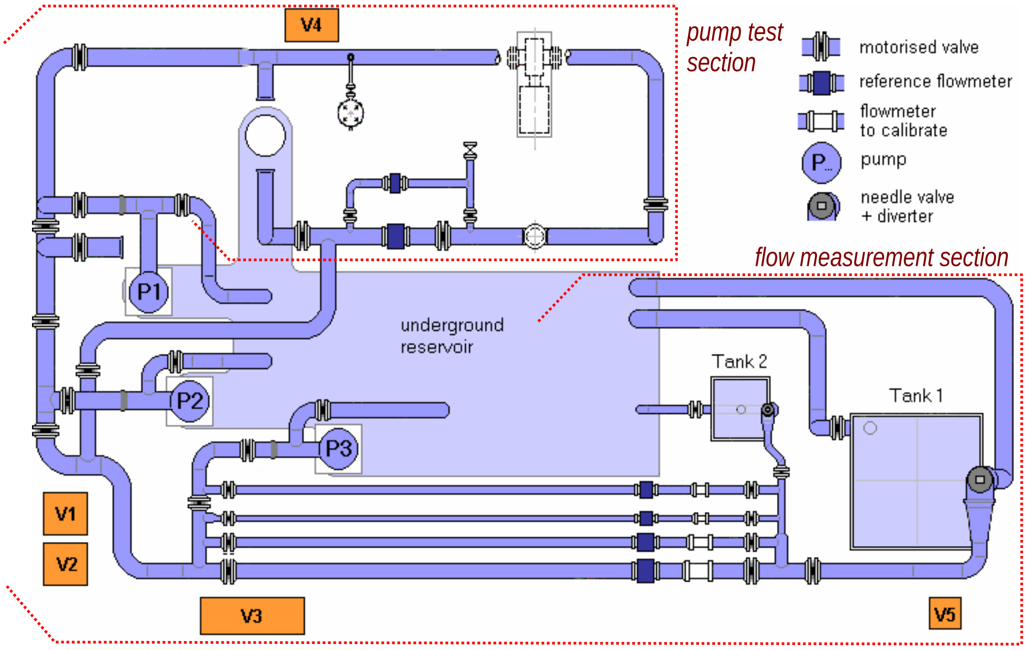

Fig. 1. Simplified plant view showing schematically the hydromechanical equipment of LEHid.

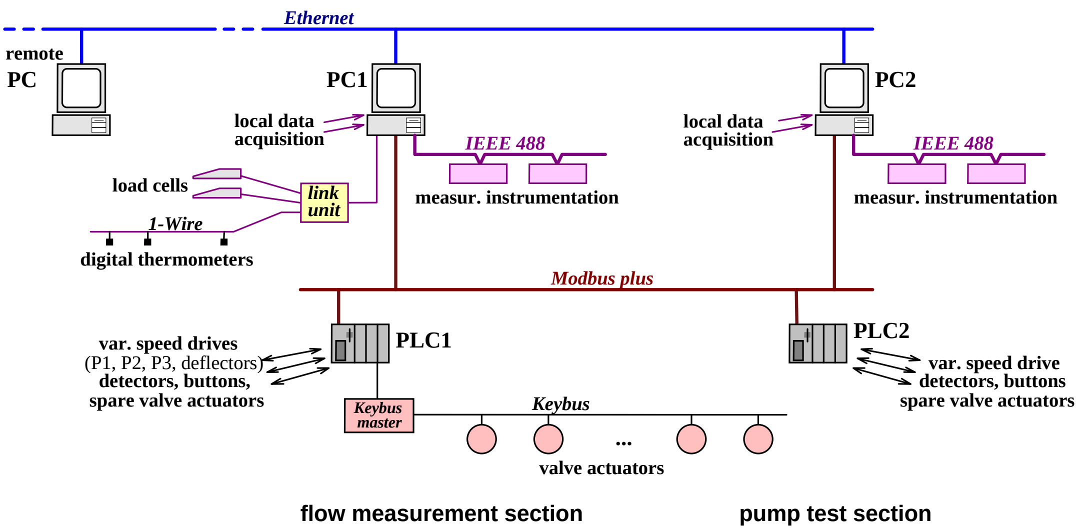

Fig. 2. Automation structure at LEHid.

The global automation scheme for the integration of equipment in the whole plant is presented in fig. 2 and is based on specific communication networks [2] for different categories of equipment. The automation structure is based on a set of two programmable logic controllers (PLC), an industrial type fieldbus (*Modbus plus*) [3] and a subordinate device level bus (*Keybus*) for valve control. Both controllers share related functions upon equipment in different places that have to operate in close connection. This structure provides the necessary safety for electromechanical equipment and associated automatic control subsystems, including validity checking on pump motor drives, valves and diverters.

Data acquisition, HMI (human-machine interface) and supervision tasks are less stringent relatively to safety and protection, and were centred around PC platforms, one at each major section.

High accuracy measurement instruments (for time, frequency, electrical and electromechanical quantities, strain, etc.) are networked through IEEE 488 buses. This option allows the instruments to be brought regularly to accredited laboratories according to specific calibration plans [1]. Flow-meters to calibrate generally have a pulsed signal output, as well as an analogue current and/or voltage output [4], which are read by the equipment integrated in the IEEE 488 bus.

Despite the attempt for full interoperability through digital data communication, a few devices had to be interfaced by conventional binary and analogue I/O ports with the Modicon PLCs or with two hardware units developed.

A special unit was built in order to integrate Meter Toledo load cell tank consoles having specific protocols, as well as a Dallas *1-Wire* network of digital thermometers, and connect them to a single RS-232C port in PC1 under *Modbus* RTU protocol (see fig. 3).

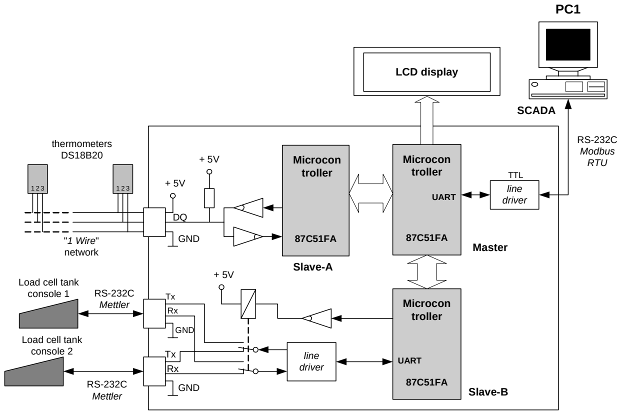

Fig. 3. Functional diagram of the hardware unit developed to integrate load cell tank consoles and a network of digital thermometers.

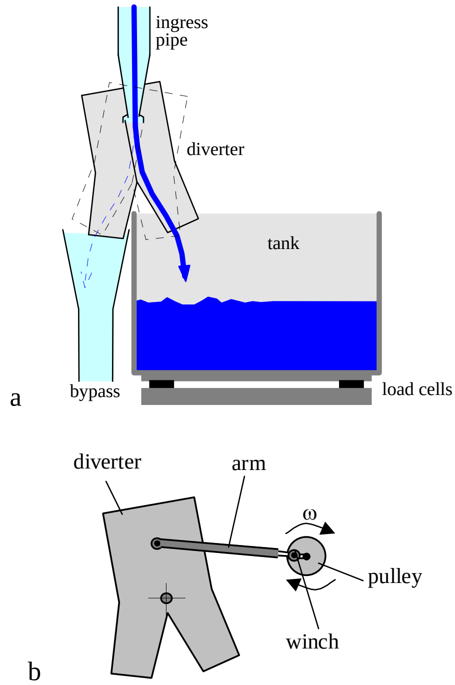

Fig. 4. Bi-directional motion of a diverter: a) tank filling process; b) pulley-arm transmission system.

The diverters are key organs in the process of gravity flow measurement. They are used to deflect the water to inside of the selected tank and back to a bypass pipe (see fig. 4) with bi-directional motion symmetry [5]. Diverters are controlled for minimum time motion in *bang-bang* mode. The angular deflection is the result of half a turn of the motor with a solenoid brake.

A second hardware unit (fig. 5) was built to control the motion of the diverters between two inductive detectors. The unit receives binary inputs from PLC1 and order the motion of the selected diverter through shared drive V5.

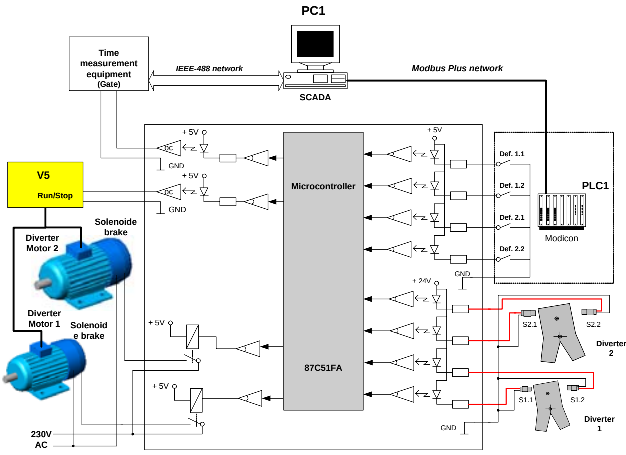

Fig. 5. Functional diagram of the hardware unit developed to control motion of the diverters.

Diverter travel time is in the order of 150 ms in the large tank and of 100 ms in the small tank. Such a short time and bi-directional motion symmetry, along with the high accuracy provided by time and weight measurement equipment, are essential for the intended metrological purposes.

3. CONTROL TASKS IN FLOW MEASUREMENT

The flow measurement section provides two calibration methods – gravity method and reference flow-meter method – both requiring programmed constant flow control. The gravity method is more complex but yields the highest accuracy. The reference flow-meter method uses a pre-calibrated flow-meter, e.g. by the gravity method or other method described in ISO 9104:1991(E), at least three times more accurate than the one to be calibrated [5], [6]. Photographs may be seen in fig. 6.

A flow-meter calibration procedure consists of a set of measurements made with a given hydraulic configuration; motorised valves are previously operated in order to select the pump group, the flow-meter pipe column and the load cell tank.

Pump operation is restricted to acceptable hydraulics configurations by coherence validation logic and the start and stop phases (including emergency stop) are smoothed in order to avoid critical hydraulic transients and protect the hydromechanical equipment. The acceleration and deceleration rates of the pump motor drives were selected to 15 seconds (0 to 50Hz).

Each measurement step is made at constant flow by using closed-loop control with a gain scheduling PID function embedded in PLC1 program. The actuator is the selected variable speed pump drive and the feedback signal (analogue output 4-20 mA) comes from a reference electromagnetic flow-meter placed ahead of the one to be calibrated. The V/f control mode was found acceptable for the v.s.p.d.

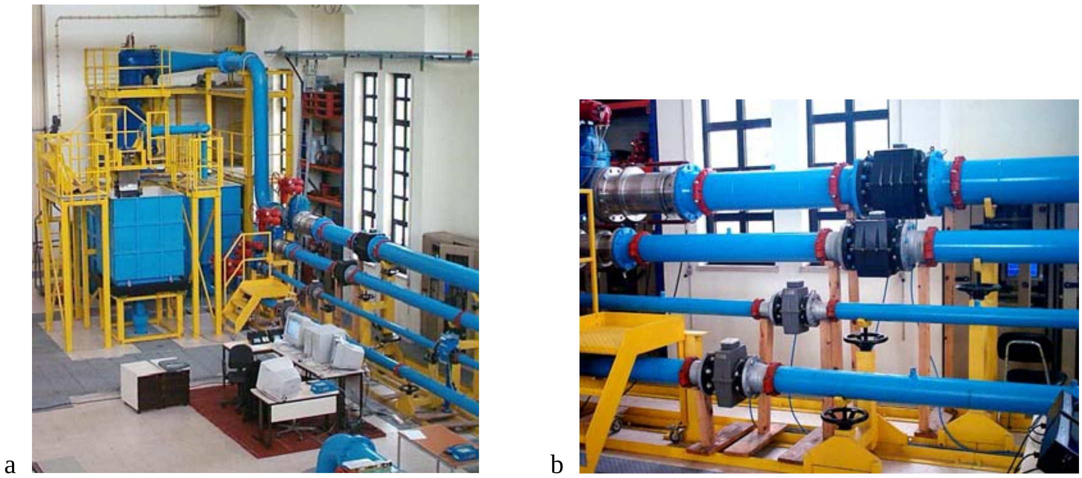

Fig. 6. a) Downstream view of flow measurement section; b) view of the set of reference electromagnetic flow-meters.

When using the gravity measurement method, diverters are previously turned out to the bypass. The selected tank is emptied; its load cell is tared. After settling a flow-rate, the diverter at the selected tank is deflected to inside the tank. When this is almost full, as detected by an ultra-sonic level meter, the diverter is deflected back to the bypass pipe. The time elapsed between symmetrical diverter detection points is measured and the weight is read from the tank console. The tank emptying phase starts while the next flow step is initiated [4].

The mass flow during the filling time is obtained by:

$$q_m = \frac{m_1 - m_0}{\Delta t} \cdot (1+\varepsilon) \quad (1)$$

where:

- m_0 –mass of water before deflection (normally zero);
- m_1 –mass of water after deflection;
- Δt – filling time;
- ε – correction term introduced to take into account the difference in buoyancy exerted by the atmosphere on a given mass of water relatively to the volume of pattern weights used in the load cell calibration [5].

This operation is repeated for several flow-rates within flow-meter range. The mass flow and the measured values (as illustrated in fig. 7) from the flow-meter will be used to perform the calibration results.

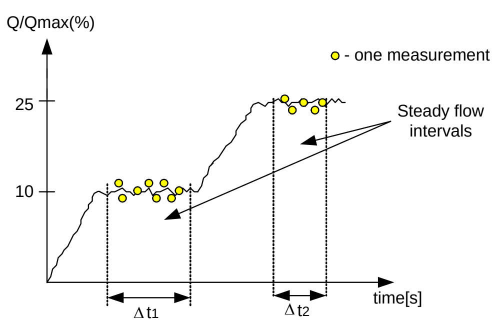

Fig. 7. Typical measurement steps at constant flow-rates.

The accuracy and the time response of the closed-loop flow-rate control system are not much demanding, the main objective being flow stabilisation [5], [6]. A closed-loop control with a gain scheduling PID function could easily guarantee the necessary flow stabilisation in successive steps.

A first difficulty in the flow-rate control of this hydraulic installation was creating a reliable model for the physical system. Some open-loop experimental results revealed different behaviour regarding pump speed variations and hydraulics configurations, as shown in fig. 8 and fig. 9.

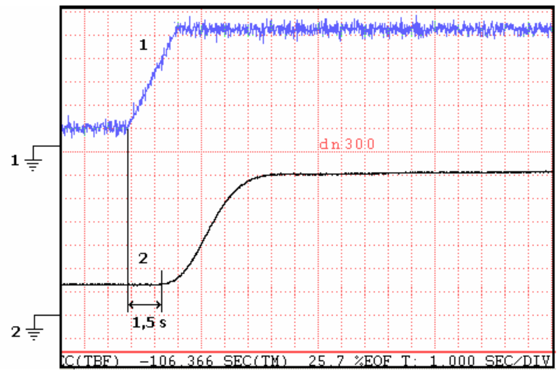

Fig. 8. Flow-rate response (2) to a ramp speed pump variation (1); Motor group 1 and 300 mm diameter pipe.

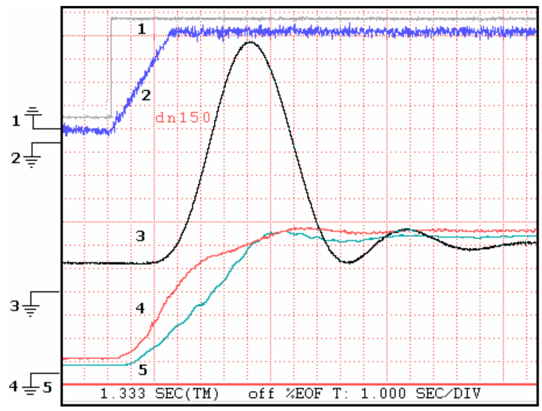

Fig. 9. Flow-rate response (3) to a ramp speed pump variation (2); Speed signal imposed to the variable speed pump drive (1); Pressure sensor in the centrifugal pump (4) and in the flow-meter pipe column (5); Motor group 2 and 150 mm diameter pipe.

Experimental results in other situations revealed oscillatory transient responses to speed pump variations (see fig. 9) caused by air accumulation; a specific procedure was created to expel all accumulated air during the starting phase.

Despite the non-linear behaviour an acceptable control solution was devised based on PI control with gain schedulling (see fig. 10). Parameter values result from simplified linear models for each hydraulic configuration around the desired flow-rate. Matlab/Simulink simulation and open-loop experimental results were used to create the simplified models.

The proportional and integral gain values were calculated using the binomial performance criterion [7]. These and other values (integral wind-up limits, alarm limits, etc.) were finally adjusted by experimental tests. Fig. 11 shows a record of three levels of flow regulation.

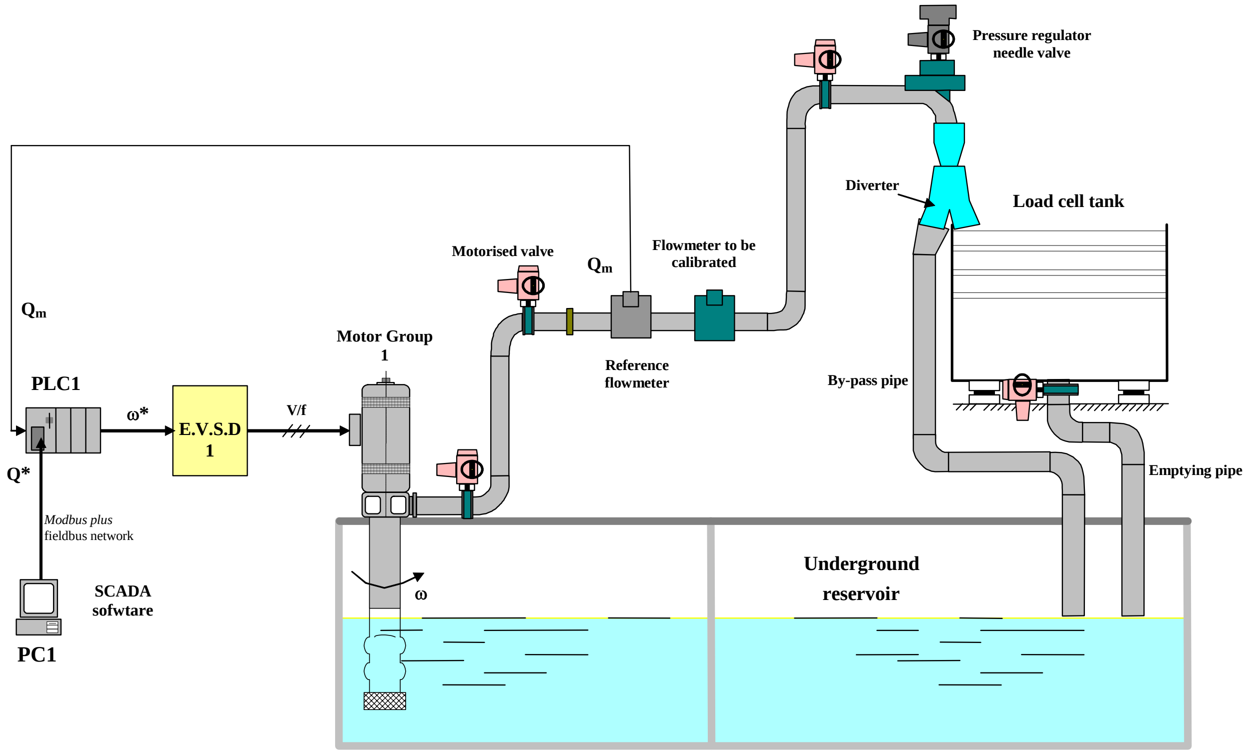

Fig. 10. Block diagram and synoptic description of closed-loop flow control devised for the flow-meter calibration section.

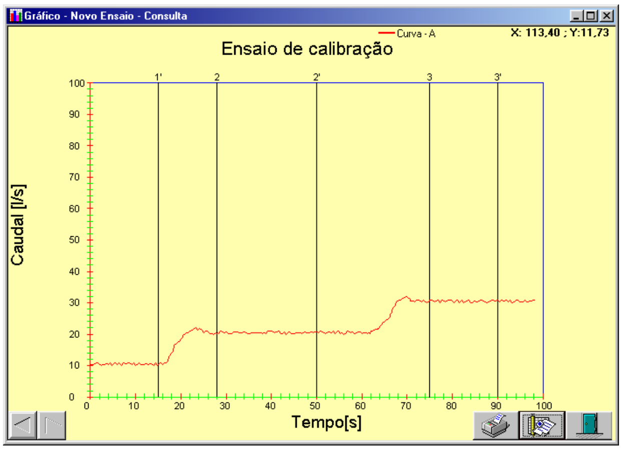

Fig. 11. Sample diagram of the flow-rate transient response in closed-loop control (steps of a calibration procedure).

The pressure regulation is made by adjusting the needle valve at the top of the tank. After constant flow stabilization provided by PLC1, the SCADA (Supervisory Control and Data Acquisition) software operates the motorized needle valve slowly to achieve the desired pressure. Although the mutual influence of pressure and flow-rate, it is possible to control separately both due to the inherently slow pressure variations. The embedded PLC1 program guarantee safety limits of pressure in the case of failure in SCADA software or PC.

4. SCADA ENVIRONMENT

On account of the complexity of the hydraulics circuits, admissible configurations, fault operations and human capabilities to manage all the required information, it was considered as essential the creation of a SCADA program.

Human intervention in this laboratory is required both at the *decision level* (as to define hydraulics configurations, test profiles, system parameterisation) and at an *assistance level* in an external control loop for fault/alarm management, perception of further details of operation and emergency actions.

HMI is needed for this purpose, as well as data management and documentation resources, provided by any SCADA (Supervisory Control and Data Acquisition) environment [9]. Calibration reports are the essential output documents to be produced.

The SCADA software for the flowmetry section is based on an open architecture, running on a personnel computer (PC1) with *Windows 2000, developed with Microsoft Visual Basic 6.0*.
This SCADA program is also responsible for high hierarchy level control tasks, namely:

. monitoring permissible ranges of process variables and hydraulics configurations (with alarm generation and safety sequencing);
. automated guidance of the PLC based flow control loop and pressure settling during calibration tests.

HMI screens of the automated installation include text and shape placement resources, control objects, diagrams and trend charts of the automated process [9, 10]. Fig. 12 illustrates a synoptic general screen with detached command windows.

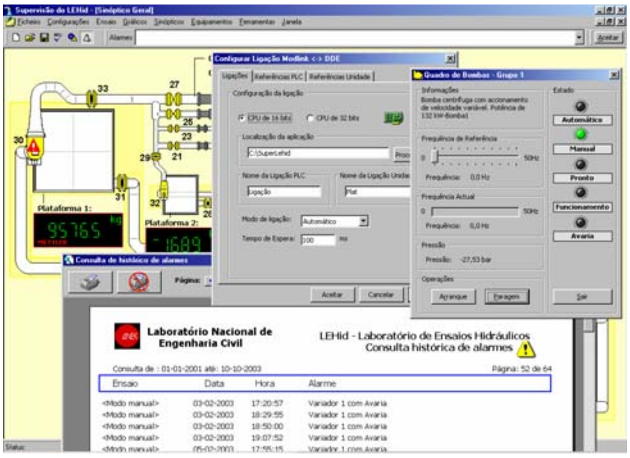

Fig. 12. Sample screen of the supervisory program.

The developed software also includes digital communication with interface boards and *IEEE-488* buses; the *Modbus Plus* and *Modbus RTU* interfaces are accessed via dynamic data exchange (DDE), as provided by the proprietary *Modicon* application named *Modlink* [11]. Fig. 13 shows the *Modlink* based architecture.

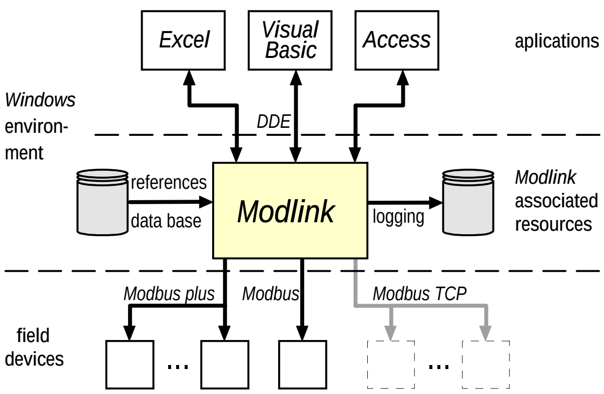

Fig. 13. Modlink software connections.

5. CONCLUSION

A structured set of automation and control resources was developed for a water flow measurement section of a Hydraulics Laboratory. The automation solution was created for satisfying given requirements defined for this installation. PLCs were adopted as main control units at the level of power actuation and system protection (i.e. within a kernel of higher reliability). SCADA functions are less critical and could be placed in PC platforms.

The adopted solution for flow control, based in gain scheduled closed-loop control with PID function embedded in PLC1 could guarantee the required accuracy in flow stabilisation. For metrological purposes, minimum time motion and bi-directional symmetry were considered in the design of drive solutions for diverters.

These control activities remain behind the HMI synoptic environment but are essential tools for obtaining the desired laboratory performace. The costless SCADA software developed succeded in simplifying the operator's work (not replacing him/her).

Experimental results reveal a satisfactory behaviour of the control tasks for the overall high-grade accuracy envisaged for this plant.

Acknowledgement

The authors fully acknowledge the Head of LEHid, José Duarte Henriques, for his special support and encouragement.

REFERENCES

[1] Palma, J., Cordeiro, A., "Integrated Solution for the Automation of a Hydraulics Laboratory", *Proc. of the 4th International Conference on Industrial Automation*, Montréal, June 2003.

[2] Jordan, J., *Serial Networked Field Instrumentation*, Wiley, 1995.

[3] Modicon - AEG, *Modbus Plus Network Planning and Installation Guide*, GM-MBPL-001, 1990.

[4] Spitzer, D. W. (ed.), *Flow Measurement: Practical Guide for Measurement and Control*, Instrument Society of America, 1991.

[5] ISO 4185-1980(E), "Measurement of liquid flow in closed circuits - Weighing method".

[6] ISO 9104:1991(E), "Measurement of fluid flow in close circuits – Methods of evaluation the performance of electromagnetic flow-meters for liquids".

[7] D'Azzo, Houpis; *Linear Control System Analysis and Design*, Chap. 15, McGraw-Hill, 1981;

[8] Richard, G., *Visual Basic Programmer's Guide to Serial Communications*, Mabry, ISBN 0-273-02820-0.

[9] Mital, A.; Pennathur, A., "Perspectives on Designing Human Interfaces for Automated Systems", in Shell and Hall (ed.) *Handbook of Industrial Automation*, Marcel Dekker, 2000.

[10] Johnson, D., "Getting the message across", *Control Engineering*, September 1997.

[11] Modicon - Schneider Electric, *Modlink User Guide*, 890 USE 129 00, 1997.