Development of a Remote Laboratory for Control-engineering Education based on an Industrial Fluid Transport Platform

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Abstract: This paper presents the development of a remote laboratory based on an industrial fluid transport platform. The goal is to improve the control-engineering education using new technologies, saving equipment and personnel for the institution and time and money for the remote students. The pilot plant was initially developed for the study of fouling detection and adapted in this work for the development of a laboratory, in which students and researchers can, over the Internet, perform experiments without any limitation of time and location. The LabVIEW software was used to implement the Human-Machine Interface (HMI) through a didactic interaction and the developed remote laboratory has been tested to be used in different disciplines.

1 INTRODUCTION

A very common problem that occurs in industrial fluidic transport systems is the gradual accumulation of organic or inorganic substances along the inner surface of the tube in a process called fouling. It happens slowly and it is typical of the chemical, petroleum, food and pharmaceutical industries. This is a serious problem because the fouling reduces the internal diameter of the tube, as shown in Figure 1, increasing the internal pressure, even the rupture of the pipe (Rose, 1995).

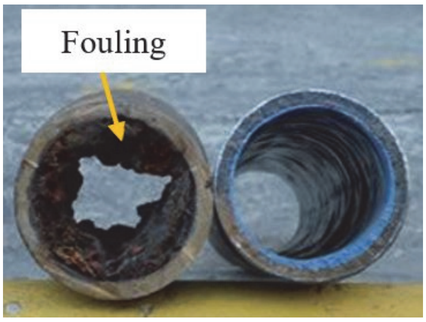

Figure 1: The comparison between tubes with (left) and without (right) fouling.

According to Mansoori (2002), pressure and flow variables are directly associated with this process. Consequently, these are the variables of interest for monitoring and control system, in order to avoid the fouling formation.

To promote the study of control systems and industrial automation, a remote laboratory was developed for an industrial fluid transport platform available at the Electronic Instrumentation and Control Laboratory (LIEC) in the Federal University of Campina Grande (UFCG), Brazil.

This paper is organized as follows. In section 2, a quick bibliographic review is made on industrial control systems. Section 3 presents the experimental platform under study with its all sensors and actuators. In section 4, the results obtained for an on-line experiment to test the laboratory are discussed. Finally, section 5 summarizes a conclusion about the remote laboratory developed and its applications for undergraduate students on Electrical Engineering and researchers on control systems.

2 CONTROL SYSTEMS

Control systems aim at a set of variables of a given process behaving in a specific way in the domain of time or frequency (Skogestad and Postlehwaite, 2005). Thus, the control system acts on manipulated variables with the interest of controlling the output variables of the process.

In general, a closed control loop is shown in Figure 2. The controller acts on the process to be

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controlled by a manipulated variable *u(t)*, calculated form the error *e(t)* between the desired set point *r(t)* and the measured value $y_m(t)$ of the output process variable (Ogata, 2009). The process may be subject to disturbances, which should be considered in the design of the control system.

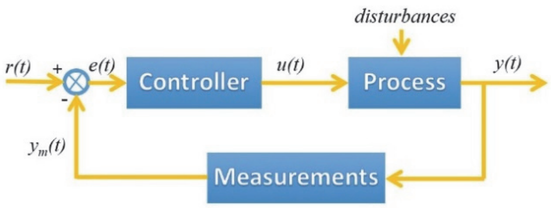


Figure 2: Control diagram in closed loop.

First of all, to design a control system, it is necessary to identify the models of plant under study through the modeling stage. Subsequently, the controller is tuned according to the models and the type of system.

2.1 Modeling

The identification of a mathematical model of the system, which allows the design of controllers for the plant, can usually be performed by two methods. In the first, it is necessary to know the equations that govern the physical phenomena associated to the system. However, the theoretical method can result in rather complex mathematical problems, so it is common in industry to use the experimental method (Ljung and Glad, 2016).

In the experimental method, the behavior of the variables of interest is observed through the application of known inputs that lead the outputs to have a behavior already determined mathematically. In practice, consecutive tests are performed on the system and the input and output data are stored and then processed in a specific software to adjust the experimental curves obtained to the known theoretical models.

2.2 PID Controller

The Proportional-Integral-Derivative (PID) action is the most used in the industry and has been used worldwide for industrial control systems. The popularity of PID controllers can be attributed in part to their robust performance over a wide range of operating conditions and in part to their functional simplicity, which allows engineers to operate them directly (National Instruments, 2011).

As the name suggests, the PID controller is composed of three parameters: Kp [dimensionless], T_i [seconds] is the integral time constant and T_d [seconds] is the derivative time constant. Thus, the PID controller can be represented according to the Laplace Transform, as can be observed in the Equation (1).

$$C(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \qquad (1)$$

The parameters used to tune the PID controller can be calculated by several techniques. The most famous is the technique developed by Ziegler and Nichols (1942).

2.3 SISO Systems

Systems that have a single input and a single output variables are called SISO (Single Input Single Output) systems, as can be seen in Figure 3.

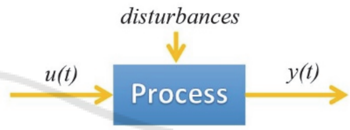


Figure 3: SISO system diagram.

As can be observed, in these systems the output variable *y(t)* can be directly controlled from the manipulated variable *u(t)*. Therefore, there will be only one control loop. The mathematical model that represents a process is called transfer function, and it is a mathematical function that transforms the input signal *u(t)* in the output *y(t)*.

2.4 MIMO Systems

It is quite common to find, in real industrial processes, control systems with more than one input and output. These systems are called MIMO (Multiple Input Multiple Output).

Figure 4 shows a MIMO system, in the frequency domain, with two inputs and two outputs, also known as the TITO (Two Inputs Two Outputs) system. It is observed that both manipulated variables interact directly with both outputs and therefore, there are now four control loops, defined by four transfer functions *Hij(s)*, each one representing the influence of input *j* on output *i*.

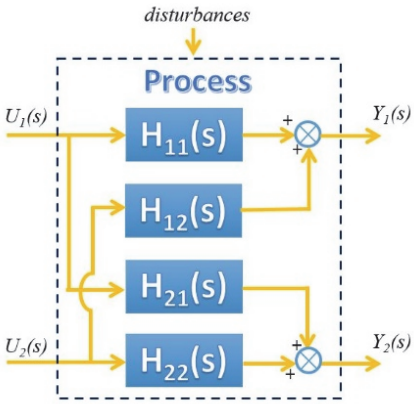


Figure 4: 2x2 MIMO system diagram.

MIMO control problems tend to be more complex than SISO, as there are interactions in the process between the output and manipulated variables. Generally, a change in a manipulated variable (U_1 or U_2) will affect all the others output variables (Y_1 and Y_2). Due to process interactions, the selection of the best loop parity can be difficult.

In order to identify the best parity of the loops for control (Y_1/U_1 and Y_2/U_2 or Y_1/U_2 and Y_2/U_1), several criteria were proposed like the Relative Gain Array (RGA), proposed by Bristol (1966), and the Relative Normalized Gain Array (RNGA) proposed by He et al. (2009). These methods propose an analysis of the force of interaction between the loops.

Once the control loops have been identified, it is possible to proceed with the design of the PID controllers, using a decentralized control structure. Thus, each controller is designed as if the MIMO system were a set of SISO systems.

2.4.1 Decoupling

When the interaction between the loops is not significant, a decentralized controller, as presented earlier, may be sufficient to ensure control of the system. However, if the interactions are more significant, a centralized controller using decoupling is more appropriate, as suggested by Garrido et al. (2011).

The decoupling is a matrix D of transfer functions, inserted between the control matrix and the processes matrix, as it can be observed in Figure 5. Its objective is to compensate the interaction between the process loops, so that the controller sees the Decoupling-Process set as independent SISO systems.

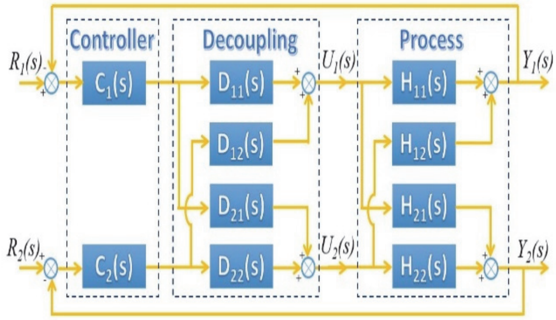


Figure 5: TITO system with decoupling diagram.

3 EXPERIMENTAL PLATFORM

The experimental platform, shown in Figure 6, is formed by galvanized steel tubes, being a 2” main tube and another two 1” and 1 1/2” tubes used to simulate disturbances on the system. The fluid used is water, which is stored in a 100 liter tank.

3.1 PLC

A Programmable Logic Controller (PLC) can be defined as an industrial computer that contains hardware and software used to perform the control functions. The PLC used in the platform is Siemens S7-200, and includes a module with CPU 226, a microcomputer, programming software STEP 7-Micro/WIN SP9 version 4.0, whose programming is done in Ladder language, and a PC/PPI communication cable. In addition, there are a set of EM231, EM232 and EM235 modules for reading and triggering the analog inputs and outputs and the ASI CP243-2 communication module.

3.2 Sensors

Each tube of the platform has its respective pressure and flow sensors. The flow sensors are turbine flowmeters and utilize the mechanical energy of the fluid to rotate a rotor according to the flow. Then the flow is measured from the rotational speed of this rotor by means of an externally installed Hall Effect sensor, Figure 7(a). This Signet Model 8550-1 sensor also features a measurement transmitter and display panel, Figure 7(b), powered by a 24V DC source, and it provides flow ratings from 3 to 38 LPM (liters per minute).

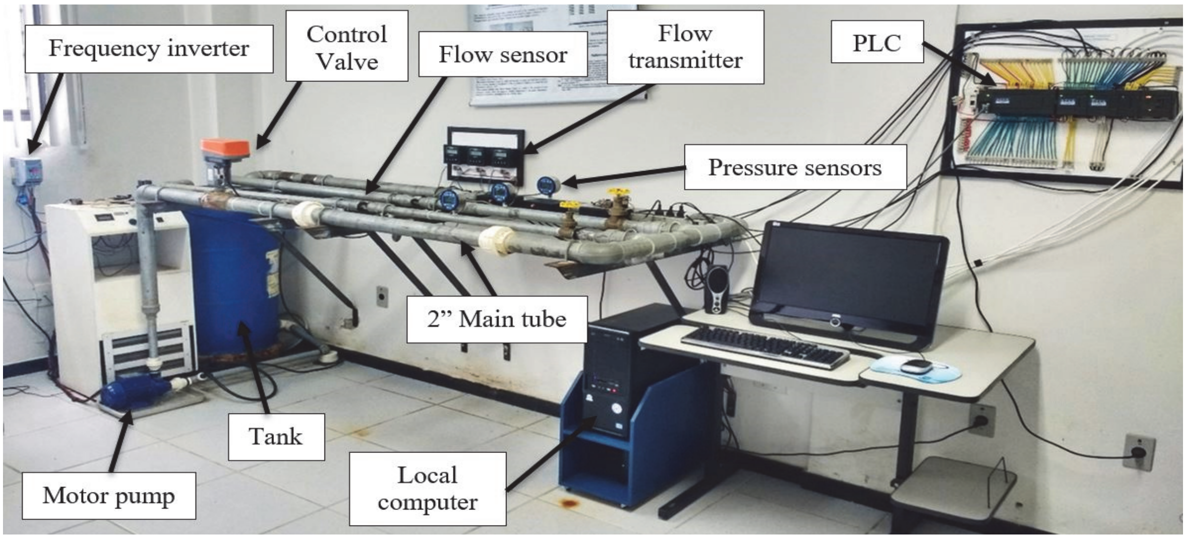


Figure 6: Photograph of the experimental platform.

(a) (b)

Figure 7: (a) Flow sensor; (b) Flow transmitter.

The pressure sensors, as shown in Figure 8, are of the strain gauge type and are based on the principle of varying the resistance of a wire. Through the interconnection of four strips in a Wheatstone bridge circuit, adjusted and balanced to the initial condition, it is possible to measure the pressure by means of the unbalance proportional to the variation of the resistance of each strip. This instrument, model 2274-XAO from Ashcroft, offers digital display in 9 units: psi, mmHg, Pol, Hg, ft, Mpa, KPa, kgf/cm^2 and mBar.

Figure 8: Pressure sensor with an integrated transmitter.

There is also a temperature sensor LM35, Figure 9, of TO-92 encapsulation submerged within the tank. This is a precision sensor, manufactured by National Semiconductor, which has a linear voltage output relative to the temperature when powered by a single (4-20V DC) or symmetrical voltage source. This sensor does not require any external calibration to provide its measurements, having temperature values ranging from ¼°C or even ¾°C, operating within a temperature range of -55°C to 150°C.

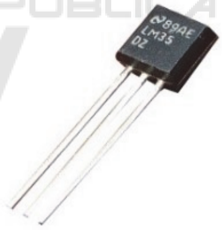


Figure 9: Temperature sensor.

3.3 Actuators

Regarding the actuators, the main tube has a control valve, model G250 from manufacturer Belimo. It is a two-way globe valve with a single seat and a nominal diameter of 2". This is a valve with linear motion, as it has a plug attached to a rod that moves linearly to the seat, varying the area of passage of the fluid.

The control of the valve is done by an electric actuator, model NVF24-MTF-E-US of the same manufacturer. This actuator converts the electrical power provided by the controller into mechanical power, changing the relative position between the plug and the seat. In a fault condition, the valve is fully closed in order to guarantee the safety of the process. It is powered by a 24V DC power supply with 5.5W power. The valve and the actuator are shown in Figure 10.

Figure 10: Control valve and its electrical actuator.

As for the other actuator present on the platform, there is a frequency inverter, model CFW 080026 S2024 PSZ from the manufacturer WEG, Figure 11(a), which acts on the speed control of a motor pump, based on frequency variation. The inverter has a single-phase power supply 200-240V AC, 0.5CV power, 4 poles with 220V three-phase output. It also has four digital inputs and one analog input for communication with the PLC and a resolution of 0.01Hz for frequencies up to 100Hz.

The motor pump, Figure 11(b), is a centrifugal pump, model P500T hydro bloc from manufacturer KSB. It has power of 0.5CV in 3500RPM, 2 poles and three-phase power supply 220 V.

(a) (b)

Figure 11: (a) Frequency inverter; (b) Motor pump.

4 RESULTS

The experience in Engineering teaching has shown that a complementary approach combining theoretical and practical activities is vital for effective and efficient learning (Callaghan et al., 2005). In this sense, engineering education has incorporated advances in technologies to promote expected outcomes and a successful understanding.

4.1 HMI

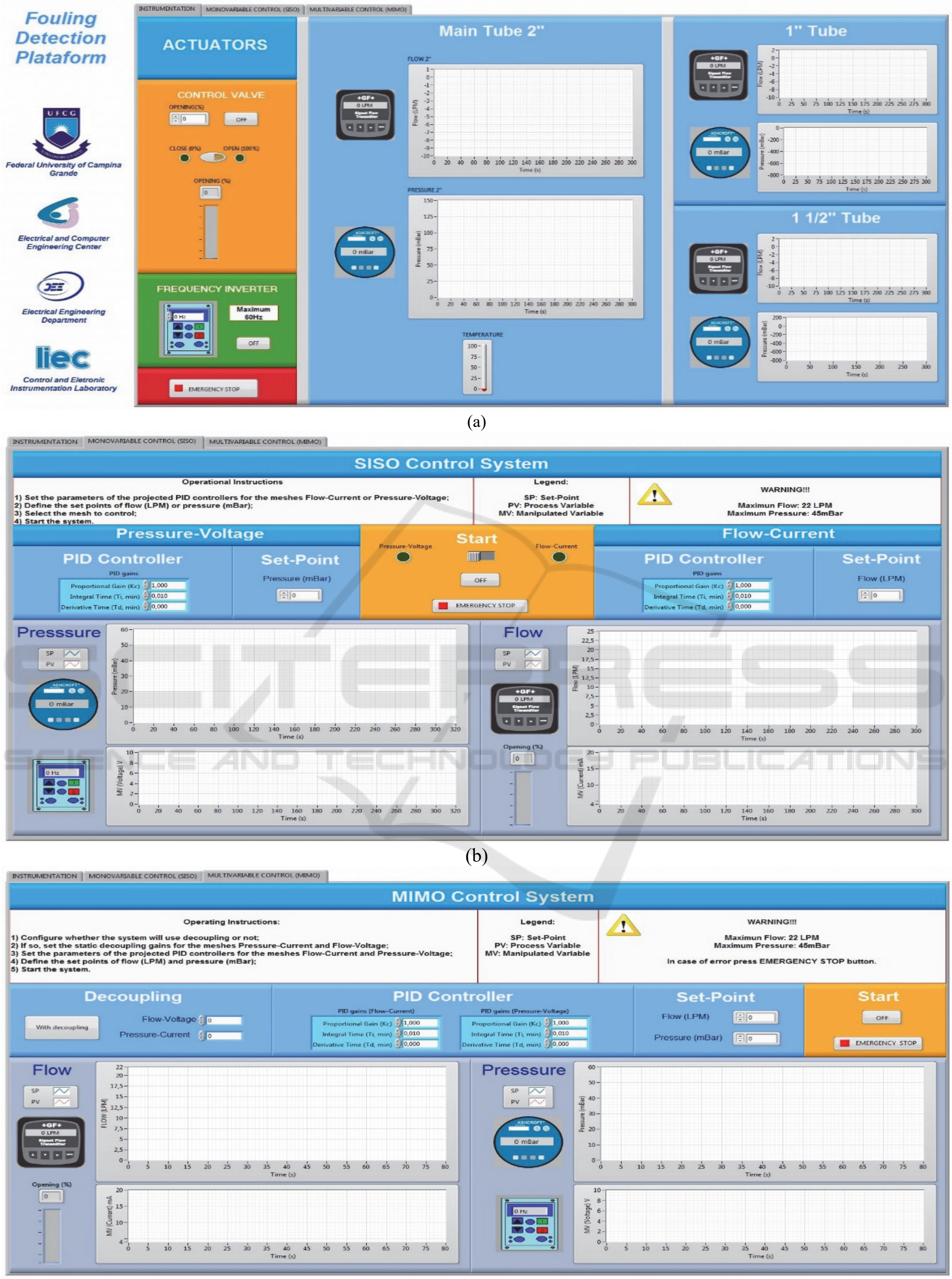
In this section, the HMI is presented, which allows on-line interaction between students and the platform, as well as the results of an experiment performed through remote access.

In order to implement the remote access to the study platform, a HMI was developed, allowing a didactic interaction between the students and the platform. The tool used was LabVIEW (Laboratory Virtual Engineering Workbench) software, which is a development environment for a graphical programming language developed by National Instruments.

Programs in LabVIEW are called Virtual Instruments (VI). Each VI has three components: a block diagram, a front panel and a connection panel. The software also has the Remote Panels tool that converts the application into a remote laboratory, where the HMI created for the purpose of controlling and monitoring industrial plant is fully accessible by the remote user.

The developed interface is divided in three tabs and in all of them the user can download the collected data. The first is the Instrumentation tab, Figure 12(a), in which the user has direct access to all sensors and actuators present on the platform. From this tab, the user can perform tests to the industrial process modeling, to deal with data in a specific software, to identify the mathematical models and then design the PID controllers and the decoupling.

The SISO tab, Figure 12(b), allows the user to perform the SISO control of the experimental platform loops, while the Multivariable Control tab, Figure 12(c), allows the user to perform the MIMO control of the system. Thus, in both tabs the user enters the parameters of the controllers and decoupling, defines a set point for the variables of interest and monitors, in real time, the behavior of the control system implemented.



(a)

(b)

(c)

Figure 12: (a) Instrumentation tab; (b) SISO tab; (c) MIMO tab.

4.2 Experimental Results

Step response tests were performed in the four loops of the system: Flow-Voltage, Flow-Current, Pressure-Voltage and Pressure-Current. The manipulated variables voltage and current correspond to the voltage applied to the frequency inverter and the current applied to the actuator of the control valve, respectively. The collected data were processed in the Matlab software and the four identified FOPDT (First Order Plus Dead Time) models are presented in Table 1.

Table 1: Identified Models.

Loop	Transfer Function Model
Flow-Voltage	$G_{11}(s) = \frac{0.86}{9.97s + 1} e^{-8.25s}$
Flow-Current	$G_{21}(s) = \frac{1.18}{18.79s + 1} e^{-6.08s}$
Pressure-Voltage	$G_{12}(s) = \frac{0.05}{5.20s + 1} e^{-10.01s}$
Pressure-Current	$G_{22}(s) = \frac{0.04}{10.82s + 1} e^{-6.08s}$

From the models presented, the analysis of the interaction between the loops of the system was performed according to the RGA and RNGA criteria, presented previously. Both methods indicate that the best parity for control is obtained using the Current-Flow and Pressure-Voltage loops.

Once the mathematical models of the system were know and the loops for control were defined, the PID controllers were designed. The tuning method used was the one proposed by Ziegler and Nichols, previously mentioned. The parameters obtained for the controllers are presented in Table 2.

Table 2: PID Controllers.

Loop	Kp	T_i	T_d
Flow-Current	3.71	12.17	3.04
Pressure-Voltage	0.62	20.02	5.01

A set of static decoupling, presented in Table 3, were also calculated for the MIMO control system, according to Garrido et al. (2011).

Table 3: Static Decoupling.

Decoupling	Static Value
D_{11}=D_{22}	1.0000
D_{12}	-0.7276
D_{21}	-0.9020

Using the remote access to the platform, experiments were performed to study the MIMO control system using static decoupling. In Figures 13 and 14, it is possible to observe the behavior, in real time, of the system implemented for the Flow-Current and Pressure-Voltage loops, respectively.

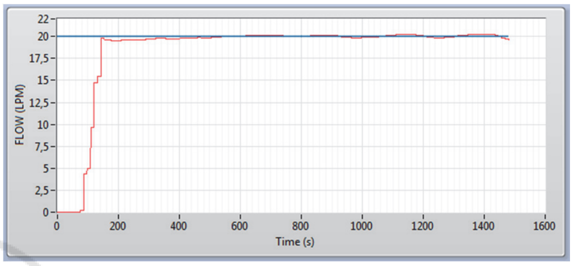


Figure 13: Flow-Current control response.

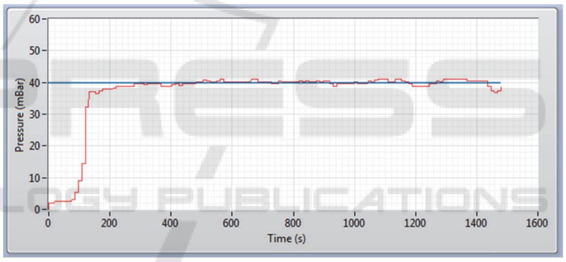


Figure 14: Pressure-Voltage control response.

This whole experiment was executed via remote access. It can be noticed that from the initial data collected it was possible to analyze the process and design a control system. When implemented, the control system ensured that the platform operated within flow and pressure values defined by the user.

4.3 Remote Laboratory

According to National Instruments (2002), a remote laboratory can be defined as a computer controlled laboratory, which can be accessed and controlled externally trough different communication methods. Thus, a remote lab can be an experiment or process executed locally on the LabVIEW platform, but with the ability to be monitored and controlled over the Internet using the developed HMI.

During the remote access, data acquisition continues on the local computer, but the remote user has full control over the platform. Other users may try to access the interface monitor of the application in progress, but only one client can control the application at a time. At any time during this process, the local machine operator can take control over the application.

The web page of the developed remote laboratory is shown in Figure 15, is better explained in Melo et al. (2012).

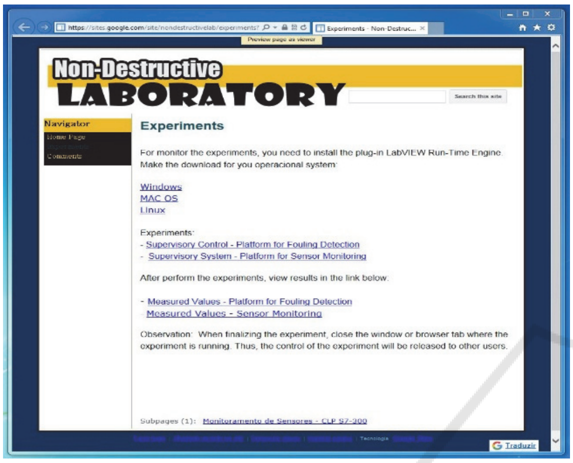


Figure 15: Non-Destructive Laboratory web page.

5 CONCLUSIONS

In this paper it was presented the implementation of a remote laboratory for the study of control systems and industrial automation. One of the great advantages of the experimental platform used is that different control strategies can be implemented for both SISO and MIMO systems in a single environment.

The incorporation of new technologies applied to teaching, especially to distance education, gives to students the opportunity to interact at any time with a real laboratory. Thus, the laboratory not only illustrates the concepts acquired in theory, but it also allows students to see how unexpected events and natural phenomena affect real-world measurements and control algorithms.

The developed laboratory was tested, as presented in the subsection 4.2, with an experiment on the control of the multivariable system with PID controllers and decoupling devices. However, the present experiment is only one of many others that can be performed by students of the disciplines of Analog Control, Electronic Instrumentation and Industrial Automation Systems modules in order to complement the theory seen in the classroom.

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