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Development of an electro-pneumatic system for the practical training of pneumatic processes in the university environment

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Abstract. This article describes the implementation of an electro-pneumatic test bench, which allows the availability of a physical environment to promote learning. The aim of the paper is to create a tool that enables practical training and research of pneumatic processes for university students in the field of engineering. The control and automation system of the test bench is made up of wired logic panels, timers, and programmable logic controllers, which are integrated into a control board configured at 24 V (direct current) to guarantee safety. Additionally, ergonomic principles were considered for the construction of the electro-pneumatic bench, thus favoring the accessibility and safety of the users. Based on national and international regulations, working pressure of 9 bar and an approximate pressure drop of 0.07 bar were defined. The construction of the test bench is considered an educational strategy to facilitate and accelerate the learning process of the students. Additionally, the development of the electro-pneumatic bench allowed the dynamic characterization of double-acting actuators by integrating experimental data and numerical models. This allowed the detailed analysis of the displacement, velocity, and acceleration variables in this type of actuator, which contributes to the physical study of pneumatic systems.

1. Introduction
The process of learning through experimentation in any field of technology, science, engineering, medicine, and mathematics has proven to be an integral part of educational development [1,2]. To achieve this practical learning process, different methodologies have been chosen, among which are design projects, internships, service learning, job placements, and laboratory sections [3,4]. Experimental learning activities are included in different ways in the curricula of different engineering disciplines. Studies have shown that experimentation-based learning processes allow the student to observe the theoretical principles and concepts acquired [5-7]. Additionally, it provides the opportunity to acquire skills for measurement processes, data analysis, and laboratory work. In this way, professional competencies are sought, related to teamwork, independent learning, and mastery of research [8,9].

The type of project and experimentation in educational laboratories vary considerably between the different disciplines. The role that experimentation teams play influences the learning strategy. From the nature of the experiments, it is possible to define three types of classification: (1) learning activities where practical tasks are the main objective, (2) learning activities where practical tasks are a secondary objective, and (3) activities learning using simulations. The first classification involves developing experiments that allow the student to become familiar with the equipment and the practical environment. The above is to improve cognitive and psychomotor skills [10]. The second classification involves the use of equipment for the application of theoretical knowledge in a real environment. This category does not seek to develop the ability to operate specific equipment but rather to use it as a tool for data

collection and analysis. Finally, the third category involves the use of simulations as an alternative method for experimental analysis. In this category, those experiments that do not require the presence of physical equipment are studied. These experiments include a wide range of topics such as large and small scale fluid movement, design optimization processes, heat transfer processes, Computer-aided design (CAD) models, visualization of molecular mechanisms, among others [11-14].

The research described above demonstrates the importance of teaching labs as an essential component of engineering education. Due to the above, the present study aims to propose a methodology for constructing an electro-pneumatic laboratory focused on the teaching of pneumatic processes. In this way, it seeks to establish an environment of training and creativity for university students in engineering and physical sciences.

2. Methodology

Figure 1 describes the methodology used for the construction of the pneumatic network. As a first step in the construction of the pneumatic network, the type of material to be used was selected. For this, the normative code American Society of Mechanical Engineers (ASME) B31.1 [15] was taken into consideration, which provides a classification of the most convenient materials to be used depending on the transport fluid, environment, and nature of the process.

The determination of the diameter of the pipe was carried out, taking into consideration the pressure values recommended by "Instituto de Normas Técnicas de Costa Rica (INTECO)", INTE/ISO 4414 [16]. It was decided to establish a pipe diameter of 3/4" in order to avoid significant changes in fluid temperature and avoid high-pressure drops. The design of the pneumatic network is indicated in Figure 2, which shows the different access points for the supply of air to the test equipment, which were considered in the hydraulic analysis. The equipment used for the construction of the electro-pneumatic bench is shown in Table 1.
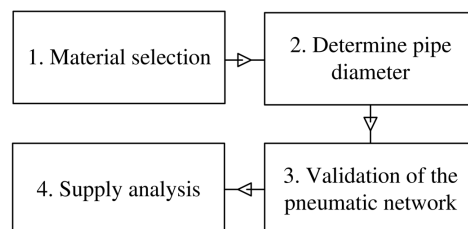
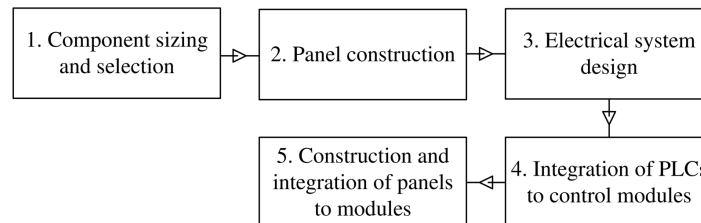**Figure 1.** Methodology for the construction of the pneumatic network.
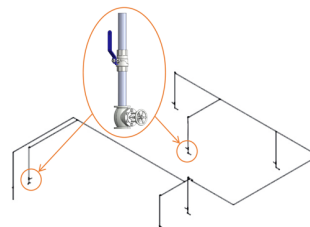
Figure 2. Design of the pneumatic network.

Table 1. Electropneumatic bench equipment.

Equipment	Selection criteria	Characteristic
Actuators	Influence that the variation of its dimensions has on the electro-pneumatic system, the space in the work panel, and functionality to guarantee the performance of the laboratory practices.	Piston diameter: 20 mm Shank diameter: 8 mm Stroke length: 100 mm Connection port diameter: 1/4 in
Valves	Guarantee versatility and functionality for conducting experimental practices.	5/3 CETOP 3 solenoid valves, with activation solenoids for both positions at 24 VDC (Volts of Direct Current). 5/2 CETOP 3 solenoid valves, with activation solenoids for both positions at 24 VDC (Volts of Direct Current).
Maintenance unit	Supply capacity of the pneumatic network.	Pressure regulator with working range from 0 to 12 bar. Membrane filter. Pressure regulator and shut-off valve with nominal flow rate of 750 L/min.

Electropneumatic test benches consist of an electrical control panel known as a control module, which commands the pneumatic power system, allowing the development of control and/or automation processes. Taking into account the above, a control module was designed in order to comply with the technical specifications necessary to carry out the laboratory experiments. The methodology used for the construction of the electrical control module is shown in Figure 3.

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┌──────────────────┐    ┌──────────────────┐    ┌──────────────────┐
│ 1. Component     │ ▷  │ 2. Panel         │ ▷  │ 3. Electrical    │
│ sizing and       │    │ construction     │    │ system design    │
│ selection        │    │                  │    │                  │
└──────────────────┘    └──────────────────┘    └──────────────────┘
                                                          │
                                                          ▽
┌──────────────────┐    ┌──────────────────┐
│ 5. Construction  │ ◁  │ 4. Integration   │
│ and integration  │    │ of PLCs to       │
│ of panels        │    │ control modules  │
│ to modules       │    │                  │
└──────────────────┘    └──────────────────┘
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Figure 3. Methodology for the design of the control system.

3. Results

To determine if the pneumatic network meets the required criteria, a series of simulations were performed using software SolidWorks and the flow simulation plug-in. Table 2 shows the conditions used for the simulation process.

**Table 2.** Pneumatic network simulation parameters.

Characteristics	Value
Nominal diameter	3/4 " Schedule 40
Initial volumetric flow	0.006135 m^3/s
Discharges at atmospheric pressure	101.3 KPa
Wall condition	Adiabatic
Rugosity	0.15 mm

The analysis of the pressure drop in the pneumatic network is shown in Figure 4. From the data obtained from the simulation, it can be observed that the lowest pressure in the network is approximately 8.93 bar, and the mean pressure of the network is 9.00 bar as shown in Figure 5, which implies a total pressure drop of the network of 0.07 bar. Taking into account the above, it is concluded that the new design of the pneumatic network does not increase the pressure drop above the recommended levels [17]. In this way, the increase in the costs of the power consumed by the compressor is avoided.

Once the pneumatic network was installed, a supply study was carried out to determine that the pressure managed by the network meets the supply requirements. For this, pressure monitoring was carried out at the feeding points of the laboratory benches. The study consisted of measuring the pressure by means of a manometer coupled to the regulator of the filter regulator lubricator (FRL) unit in all the banks for 15 days; at the end of each day, the mean pressure of the network was calculated.
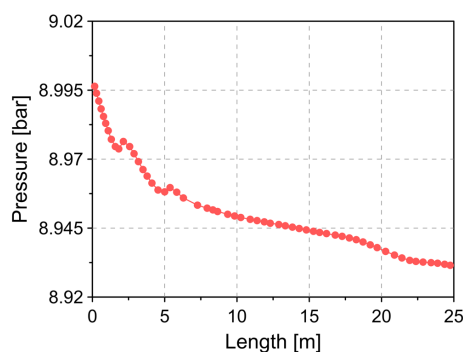
Figure 4. Pressure drops as a function of pipe length.
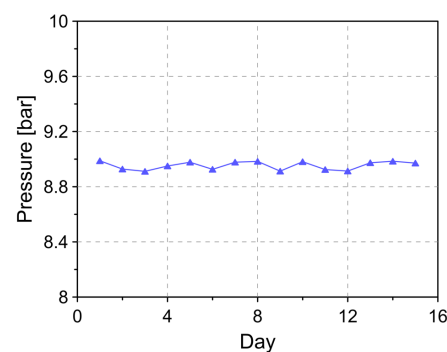
**Figure 5.** Average pressure of the pneumatic network.

Electropneumatic benches require the structure of a control module. The design of the control module corresponds to a horizontal metal box with vents on its sides. The structure is constructed of 12-gauge galvanized steel with dimensions of 26 cm high × 104.4 cm wide × 30 cm deep. The structure of the control modules is shown in Figure 6(a). To guarantee the rigidity and stability of the structure, a simulation was carried out using SolidWorks software, considering a static load of 1000 N. To evaluate the design, the Von Mises stress criterion was established, which is based Von Mises Hencky's theory. The Von Mises stress was determined from Equation (1).

$$\sigma_{\text{Von Mises}} = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2}{2}}, \tag{1}$$

where σ_1, σ_2 and σ_3 are the Von Mises principal stresses. The factor of safety (FOS) from the Von Mises stress is calculated using Equation (2).

$$\text{FOS} = \frac{\sigma_{\text{lim}}}{\sigma_{\text{Von Mises}}}, \tag{2}$$

where σ_{lim} is the elastic limit stress of the material; the results obtained from the simulation are shown in Figure 6(b) and Figure 6(c); from the results, it was guaranteed that the stress distribution in the galvanized steel structure due to the load does not exceed the elastic limit of the material (204 MPa), the maximum value for the Von Mises stress being 1.21 MPa and the minimum safety factor of 168. In this way, it is concluded that the chosen material provides the design with high resistance and durability.
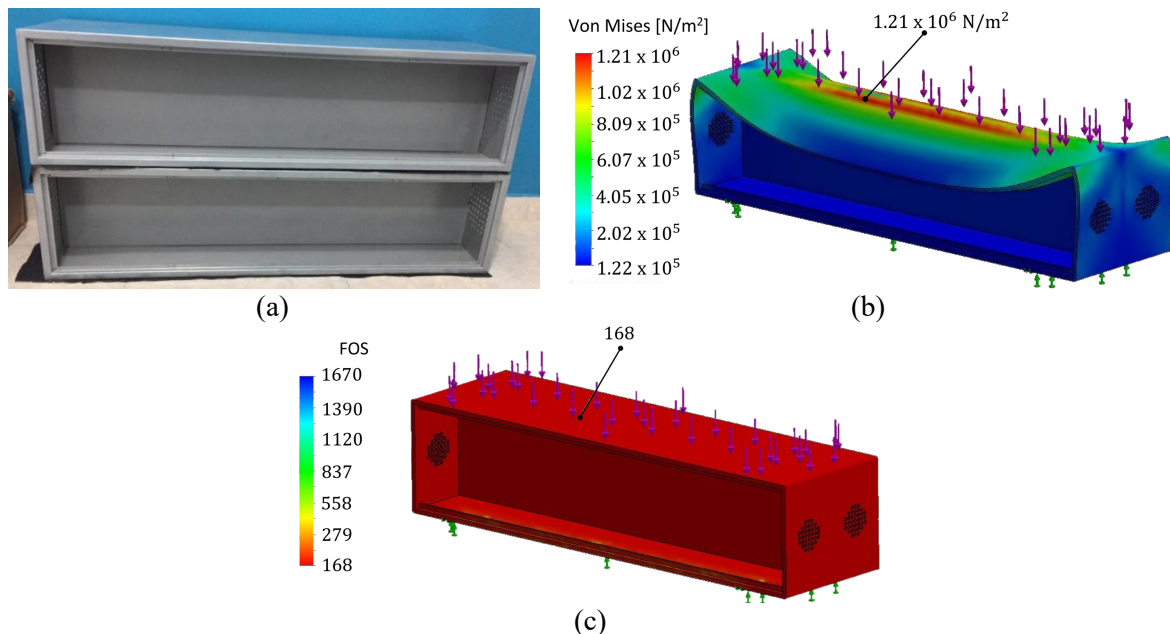
Figure 6. (a) structure of the control module of the electro-pneumatic bench; (b) Von Mises stress distribution of the structure;(c) factor of safety of the structure.

One of the main advantages of having an electro-pneumatic system is the ability to carry out experimental studies focused on the dynamics of different types of pneumatic actuators. These devices are essential in robotic and industrial automation applications due to their low cost, ease of assembly, and high strength. Therefore, the analysis of the movement of the actuators is indispensable for precise control of the processes. Next, a methodology is proposed for the kinematic characterization of double-acting pneumatic actuators, which is based on the joint use of mathematical models and data obtained experimentally.

The mathematical model used to describe the dynamics of the double-acting pneumatic actuator is based on the considerations proposed by Richer and Hurmuzlu [18], as shown in Equation (3).

$$P_1 \cdot A_1 - P_2 \cdot A_2 - P_a \cdot A_r - \beta \cdot \dot{y} - F_c - F_l = (m_l + m_r) \cdot \ddot{y}, \qquad (3)$$

where y is the rod position, m_l and m_r are the load mass and rod mass, β is the viscous friction of the cylinder, F_c and F_l are the Coulomb friction force and the external force, P_a is the atmospheric pressure, P_1 and P_2 are the pressure in cylinder chambers 1 and 2, A_1 and A_2 are the piston area in chamber 1 and chamber 2, and A_r is the rod transverse area. The volume of each actuator chamber is determined by Equation (4).

$$V_i = V_{0.i} + A_i \cdot \left(\frac{L}{2} + y\right), \qquad (4)$$

where $i = 1, 2$ represents the cylinder chamber. L represent the piston stroke. The behavior of the solenoid valve that controls the actuator is defined by Equation (5) [18].

$$2k_s x_s + c_s \dot{x}_s + M_s \cdot \ddot{x}_s = K_f \cdot i_c, \qquad (5)$$

where x_s is the spool displacement, k_s is the spool spring constant, c_s is the viscous friction force, M_s is the coil and spool assembly mass, i_c is the coil current and K_c is the coil force coefficient. The double-acting actuator experimental test bench diagram is shown in Figure 7.
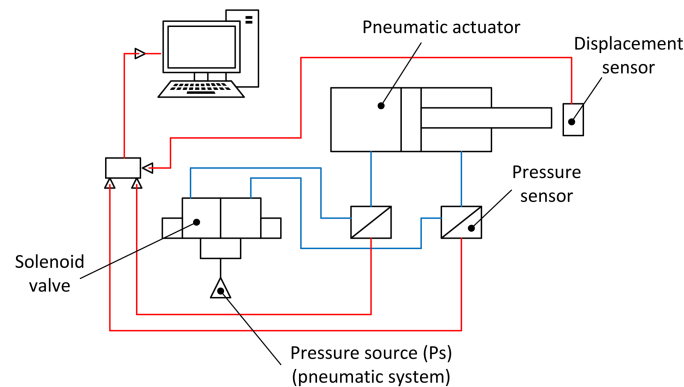

Figure 7. Double acting actuator experimental bench.

The results of the kinematic characteristics of the double-acting actuator are shown in Figure 8. This figure shows the kinematic behavior of the actuator as a function of time for a supply pressure (P_s) of 2 bar, 4 bar and 6 bar. The curves describe the movement of the horizontally oriented piston rod. Displacement analysis (see Figure 8(a)) shows that the latency time for a P_s of 2 bars, 4 bar, and 6 bar was 0.350 s, 0.303 s, and 0.253 s, respectively. During the active phase of the piston, a displacement time of 0.795 s, 0.793 s, and 0.708 s was obtained for a P_s of 2 bars, 4 bar, and 6 bar, respectively.

The analysis of the velocity curves (see Figure 8(b)) shows the presence of an underdamped behavior during the final stage of the movement, which tends to be amplified when the supply pressure is reduced. This is a consequence of the reduction in the magnitude of the force that tries to resist the piston recoil. From the results described in Figure 8(c), it was observed that the acceleration peaks were 1785 cm/s², 1502 cm/s², and 1021 cm/s² for a P_s of 2 bars, 4 bar, and 6 bar.
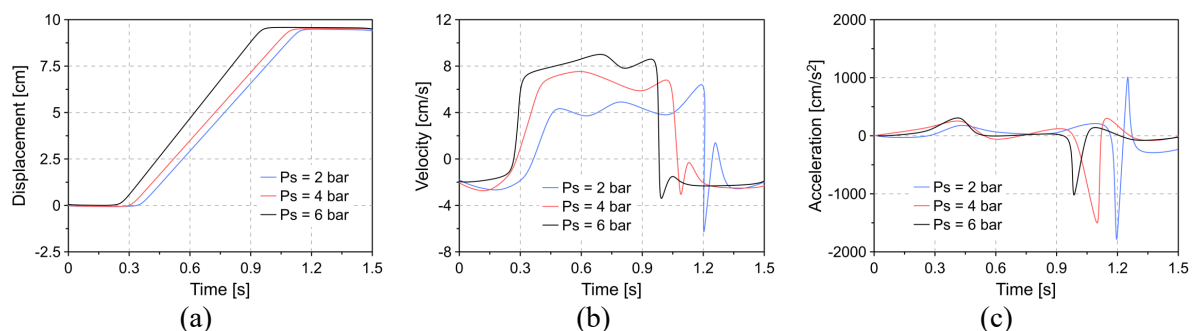
Figure 8. Kinematic characteristics of the double acting actuator; (a) displacement; (b) velocity; (c) acceleration.

4. Conclusions

In the present work, a methodology for the construction of a bench focused on the teaching of pneumatic systems is described. In this way, it seeks to help students understand the operation of pneumatic processes in a practical environment applied to the field of engineering.

The design of the pneumatic network and the distribution of the different test benches within the laboratory make possible future modifications or repairs of said network. In turn, this enabled new workspaces to be enabled with all the work panels of the banks. Additional, construction and commissioning of an automation system for electro-pneumatic test benches, which works with 24 V direct current connection ports, providing security when handling. Said system allows the development of practices by means of wired logic, as well as the possibility of carrying out experiences with the use of a programmable logic controllers, that provides a practical approach to the student with the automation of pneumatic power systems.

The development of the laboratory contributes to the generation of spaces for the creation of research projects that have a favorable impact on industrial development and the study of the physical variables that influence pneumatic systems. To demonstrate this point, a methodology was developed for the dynamic characterization of double-acting actuators by integrating experimental data and numerical models. This allowed the detailed analysis of the variables of displacement, velocity, and acceleration in this type of actuator. The study carried out shows that the 50% increase in the supply pressure allows a reduction of 14% and 6% in the latency time and the displacement time. Additionally, a 24% decrease in the maximum acceleration peaks is demonstrated because of the decrease in the supply pressure.

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