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Construction and operation of a modular didactic unit for Proportional-Integral-Derivative (PID) level control in tank

Construção e operação de uma unidade didática modular para controle de nível Proporcional-Integral-Derivativo (PID) em tanque

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Resumo

Foi realizada a construção e operação de uma unidade didática modular para controle de nível PID, com a função de capacitar o aluno quanto ao uso dos instrumentos envolvidos. O algoritmo desenvolvido operou em arduino juntamente com um suplemento, elaborando visuais gráficos em tempo real de execução. Espera-se que a utilização desta unidade possibilite a qualificação técnica, aplicada à resolução de problemas e implementação de soluções, de acordo com os ensinos ministrados nas aulas.

Palavras-chave: Ferramentas Computacionais. Tecnologia Educacional. Controle de Processo. Simulação de Processo.

Abstract

The construction and operation of a modular didactic unit for PID level control was carried out with the function of qualifying the student regarding the use of the instruments involved. The developed algorithm operated in Arduino together with a supplement, elaborating graphic visuals in real-time execution. It is expected that the use of this unit will enable the technical qualification, applied to problem resolution and implementation of solutions, according to teachings in class.

Keywords: Computational Tools. Educational Technology. Process Control. Process Simulation.

Nomenclature

A	Amps
ADC	Analog-to-Digital Converter
AD	Analog Digital
DC	Direct Current
GND	Graduated Neutral Density
KB	Kilobyte

KΩ	Kiloohm
mA	Milliamps
PID	Proportional-Integral-Derivative
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation
USB	Universal Serial Port
V	Volts
V D-C	Volts in Direct Current

1. Introduction

The study of chemical engineering involves the use of certain tools to develop technical and experimental skills, primarily to aid the understanding of theoretical concepts and how they can be applied in industrial processes. Laboratories are the spaces dedicated to apply this knowledge. However, they are largely poorly equipped or possess outdated/failing equipment, reducing the quality and range of the knowledge produced (Shibayama, 2019).

In an industrial plant, the process steps can be physically modelled using didactic units, to qualify the user and train them on how to use the instruments involved. Didactic units are usually constructed with one objective alone and the training involves steps to be followed, according to a pre-established result. This type of approach prevents creating too many different solutions to solve problems (Felder *et al.*, 2011).

Alternatively, there is another teaching approach that is based on learning via problem solving and developing projects (Felder *et al.*, 2011). Instead of using pre-made didactic units, students can project and construct their own units, on which they can carry out optimization analyses and evaluate possible changes. Through this process, they are able to develop the necessary technical and experimental skills.

Since their introduction some decades ago, PID controllers have been effectively employed in fields controlled by industrial processes, including metallurgy, chemistry and energy (Ogata, 2009; Shamsuzzoha, 2018; Plaza-Glinga *et al.*, 2017; Fan *et al.*, 2019; Saad *et al.*, 2012). Two of the main factors for the continual application of PID controllers are their easy of analysis and design, as well as being easily implemented. A PID controller uses feedback to establish a control loop, making it simple to understand and adaptable to a wide range of control systems (Mourtas *et al.*, 2023). In addition, various adjustment rules can provide the PIC control method with the greater ability to guarantee acceptable control results (Somefun *et al.*, 2021; Ziegler and Nichols, 1993; Sung *et al.*, 1998; Lim *et al.*, 2023). Thus, it is imperative that the chemical engineering student has the knowledge and authority to execute the PID controller and its instrumentation.

The objective of the present study was therefore to construct and operate a low-cost modular didactic unit for a PID level control tank that can be easily reproduced, using an Arduino microcontroller.

2. Research Design

2.1 *Description of the didactic unit*

While the didactic unit is in operation (Figure 1), pump 1 sent water to the upper part of the control tank. When it left the tank, there was a bifurcation that took two different routes, of 111 cm and 215 cm, respectively. The user in turn chose the route through which the fluid could pass by activating two solenoid valves to simulate the dead time.

The control tank was built with a 10 cm wide, 78 cm high PVC pipe. The tank was open at the top, and closed at the base with a cap and had a total capacity of 6.1 liters. At the front of the control tank, a level gauge with half inch connections and a transparent, flexible hose was installed. The fluid was supplied at the top of the tank, so that the input flow was not affected by the pressure from reservoir 1 as well as to prevent air bubbles and turbulence. It was placed close to the control tank's wall, in order to reduce any interference when measuring the level and consequently in the execution of the control.

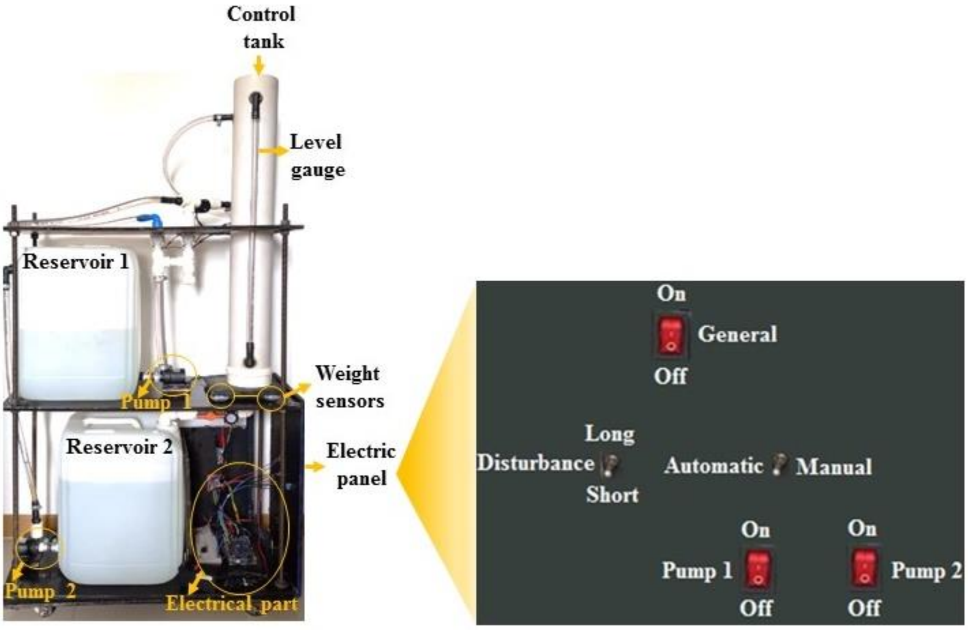

Figure 1 - Components of the modular didactic unit.

The outflow of fluid towards reservoir 2 took place by the force of gravity via an opening in the cap. It is worth highlighting that the role of reservoirs 1 and 2 was to store the fluid utilized in the control when the system was paused or switched off. Both reservoirs are of the same model type, were made from polythene and had a capacity to hold 20 liters.

Point zero of the control tank was 1.0 cm above the base and the control tank was installed on top of a square, wooden support, where four weight sensors were installed. The electric panel was composed of a microcontroller, a motor driver, a protoboard, a DC-DC converter and button cables. The components of the didactic unit were also fixed onto 1 cm thick plywood boards, together with 1m in long and half inch wide iron threaded rods.

2.2 Hardware project

The Arduino MEGA 2560 microcontroller was chosen due to its flash memory capacity of 256KB, and 54 digital and 16 analog ports. The centrifugal pumps chosen were of no specific brand. According to the manufacturer, they are able to pump non-corrosive liquids at temperatures above 80ºC and can operate with a continual current of 12V DC. In addition, the pump's motors do not have brushes, are capable of elevating the fluid to 5m in height and work at a maximum outflow of 800 L/h.

The microcontroller used was unable to withstand currents above 40mA per entry, making the direct connection between the pumps in the Arduino impossible. It was therefore necessary to implement a motor driver module. The L298N H-bridge module was chosen, which is capable of controlling up to two DC motors at up to 2A each one. In order to create a stable and level balance with the didactic unit's structural plan, four load cells were used in the Wheatstone bridge, together with the plank of wood to support the control tank. The communication between the bridge and the Arduino took place via a HX711 analog-to-digital converter (ADC) and with the aid of a balance calibration algorithm. The maximum error was 1.25% and the average 0.88%.

To constantly measure the behavior of and variations in fluid flow at the entrance and exit of the control tank, YF-S201 water flow sensors were installed. These were made of a plastic structure with half inch threaded connections, an impeller shaft connected to a rotor, a magnet in one of the blades and a hall sensor, able to detect variations in the magnetic field. After calibration, the constant obtained for the flow sensor at the entrance of the control tank was 7.0 pulses/s.L.min with a maximum error of 2%, and at the exit of the tank, 7.5 pulses/s.L/min with a maximum error of 4%.

To avoid accidents when using the didactic unit, an audible signal device was implemented in the event of reservoir 2 approaching overflow. To this end, a level sensor was developed, consisting of two needles 4 cm in length, separated by 1 mm, and attached to the side of reservoir 2, 30 cm from the base and with a capacity of 20.5 liters. Thus, together with the microcontroller, a signal was sent to the active buzzer that produced a sound effect.

Within this context, with the aid of the free online software EasyEDA, it was possible to develop an electric circuit used in the didactic unit. To better understand the unit, it was divided into four parts, namely the microcontroller circuit, the balance circuit, the external circuit of pump 2 and the external circuit of the solenoid valves. The microcontroller circuit involved various components vital to the unit's operation, such as the microcontroller, motor driver, flow sensors, level sensor, active buzzer and navigation buttons. The first was supplied with a voltage of 12V DC and the second with 16V DC from a 19V DC source using a Step-Down module to regulate the output voltage. The others operate at 5V DC. A protoboard was used as a busbar to facilitate the +5V DC and GND connections. From the microcontroller three digital inputs were used for the buttons, two digital inputs for the A/D converter, an external interrupt pin for each flow sensor, a digital input for the probe and a digital output for the active buzzer. Regarding communication with the motor driver, two digital outputs were used to control the motor's direction and brake, in addition to a

Pulse-Width Modulation (PWM) signal. For each pin input, a 10KΩ pull-up resistor was used inside the Arduino, to prevent the input value fluctuating when the pin was disconnected. In addition, for the supply of pumps and solenoid valves, IN4007 diodes were installed to protect the parallel circuit against the reverse currents.

The balanced circuit relied on an A/D converter and the load cells. Thus, the HX711 module was supplied by the microcontroller at 5V DC. The functioning of the module was dependent on a digital input and a digital output, which made the connection with the cells. Finally, the unit's other two circuits operated externally to the control system, so that they did not interfere in the unit's operation. Pump 2's external circuit had a 12V DC source in which the GND was connected directly to pump 2 and the +12V DC was connected to a switch with two poles, which, when pressed, permitted the positive route to the pump. The external circuit of the solenoid valves had a 12V DC source in which the GND was shared and connected directly in the two valves and the +12V DC was connected to the central pole of a 3-pole switch. Therefore, any position of switches A or B would always guarantee that one valve was shut and the other open.

2.3 Software Project

The electrical panel featured five buttons on its side, the first group of which, with four buttons, represented the system's control. The purpose of the first button was to switch the algorithm functions on or off, as well as being used as an emergency shutdown. The second button, called Automatic/Manual, enabled the user to choose whether the pumps were operated in the PID automatic mode, when the switch was to the left, or in the manual mode, when the switch was to the right. Buttons 3 and 4 were derived from the manual mode, in which the user chose to switch pump 1 and pump 2 on or off, respectively. The second group featured one button, which when pointing up (the switch), the liquid flowed in a direction with a greater loss of power, and when pointing down, it flowed in a direction with a lower loss in power.

Part of the operation of the didactic unit took place through a computer and the free software TelemetryViewer v0.7. The "User inputs" section was the only one to be manipulated in the algorithm. To do so it was possible to change the proportional gain (K), the total time (T_i) and the derivative time (T_d), that received numbers with up to one decimal point; the setpoint can also be altered, following the same rule. It was necessary to connect the program with the USB port (UART:COM) that was connected to the microcontroller and to determine the transmission speed. The software then detected how many values were separated by a comma and asked the user to provide their name and measurement unit. It was possible to alter the subdivision of the workspace and choose between the determined types of graphs available.

The project's algorithm was structured in a loop sequence which was executed again once it was finalized. The integrated development environment, available for free on the Arduino website, was used to develop the source code, which was divided into large blocks to guarantee linear reading and interpreting. The first part was the only one that had global variables that could be altered by the user. In the second part, all global variables were defined, and the pins that would be used and the objects created were determined. The third part was responsible for starting the serial communication and interruptions, indicating the type of pins (input or output), guaranteeing that pump 1 remained stopped, calibrating the balance, starting the PID in manual mode (turned off) and imposing limits on its output range. The Arduino model selected had a PWM excursion of 8 bits (28 = 256), guaranteeing a variation of 12V DC/256 = 0.046875 V DC/unit.

3. Results and Discussion

3.1 Dynamic balance and model elaboration

Considering the hypothesis that no chemical reaction took place, that there was only water and no temperature variations between the output and input points of the control tank, the system's balance of mass was given by Equation 1, in which M is the mass of fluid in the tank, t is the time, F_{in} is the input flow and F_{out} is the output flow.

$$\frac{dM}{dt} = F_{in} - F_{out} \tag{1}$$

The output flow depended on the height (h) of the fluid in the control tank and to understand the nature of this relationship the graph was plotted between these variables, using the output valve at 60% open (Figure 2).

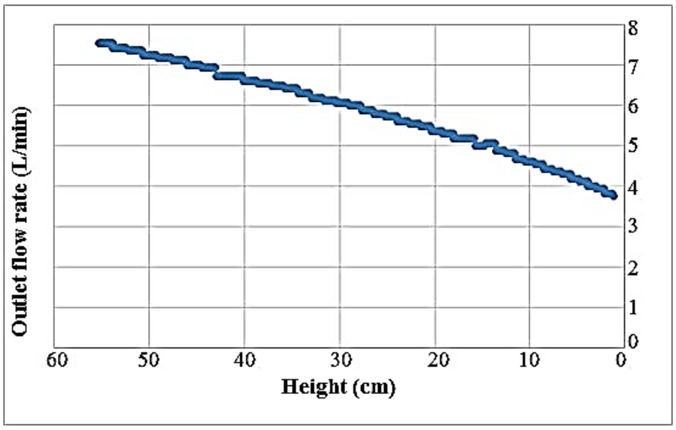

Figure 2 - Height of the fluid in the tank by the output flow with the valve at 60% open.

Based on the 483 points obtained, a regression was carried out to identify a function to represent these data (Equation 2).

$$F_{out} = 0.8719\,h + 3.9231 \qquad (r^2 = 0.9916) \tag{2}$$

By analyzing the regression, it was possible to deduce that the output flow presented a sufficiently linear relationship with the height of the fluid in the tank. In addition, variable h

presented in Equation 2 was the result of substituting Equation 3 in 4, in which V is the volume, A the area and ρ the density.

$$V = A\,h \tag{3}$$

$$M = V\,\rho \tag{4}$$

Thus, the final theoretical model of the control tank (Equation 5) was generated to substitute Equations 2, 3 and 4 in Equation 1, considering the direct conversion by the density of 1 kg/L and that the control tank had fixed dimensions, with the area of its cross-section at approximately 78.5cm^2.

$$\frac{d_h}{d_t} = \frac{F_{in} - (0.8719\,h + 3.9231)}{78.5} \tag{5}$$

Finally, when applying the Laplace transform in Equation 5 and considering its initial condition of zero (y(0)=0), the theoretical transfer function of the control tank was obtained (G_{tc}).

$$G_{tc}\,(s) = \frac{0.0127}{s + 0.0112} \tag{6}$$

3.2 PID controller tuning

The PWM value was initially 200, which represented an output voltage on the motor driver pin of 9.4V DC. For this configuration, the level at the steady state was stabilized at 31.1cm. The PWM speed chosen was 55 and when activated, the level in the control tank changed, reaching a new stability of 37.7 cm, after 389 seconds (Figure 3).

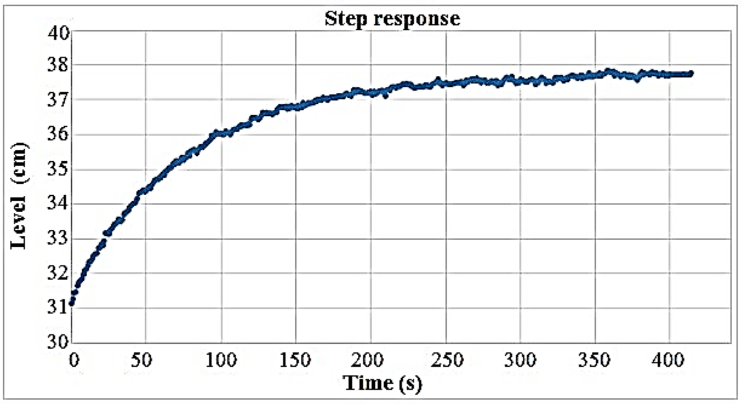

Figure 3 - Response curve for the disturbance in the open-loop system.

The values obtained were 213.6 for K, 1 for T_i and 0.25 for T_d, according to the calculation proposed by the Ziegler-Nichols method (Mo, 2023).

Since Equation 6 only reflected the control tank, the pump had to be included, and considered a constant, given that its dynamic behavior was faster than the system as a whole. The pump therefore received the voltage signal v(s) and converted it into output F(s), while the control tank converted the output according to the fluid level. Thus, the transfer function of the system (*G*(s)) had to relate volts with centimeters. The mathematical representation, applying the multiplication property, is shown in Equation 7.

$$G(s) = K_{pump} \,.\, G_{tc}(s) = \frac{0.0127\, K_{pump}}{s + 0.0112} = \frac{K_{system}}{s + 0.0112} \tag{7}$$

In order to establish the system's static gain, it was necessary to identify the steady state when the unit was operating at the limit below the PID. In other words, the pump was operated with PWM 107 (5V DC) and the level established registered. Thus, Equation 8 was determined.

$$K_{system} = \frac{h_{max} - h_{min}}{v_{max} - v_{min}} = \frac{37.7 - 1.5}{12 - 1.5} = 5.17\frac{cm}{V} \tag{8}$$

Finally, the system's transfer function can be given according to Equation 9.

$$G(s) = \frac{5.17}{s + 0.0112} \tag{9}$$

3.3 PID controller behavior

The test on the parameters K, T_i e T_d that were obtained previously, was then carried out. To do so, a new experiment was performed based on a step disturbance; as a result, the setpoint went from the initial value of 1.5cm to 10cm. The first steady state was reached when establishing the PWM at 107 in manual mode, while the second steady state was configured in the automatic mode, thus the change to the setpoint took place when activating the button on the electric panel to operate the system in the automatic mode (Figure 4).

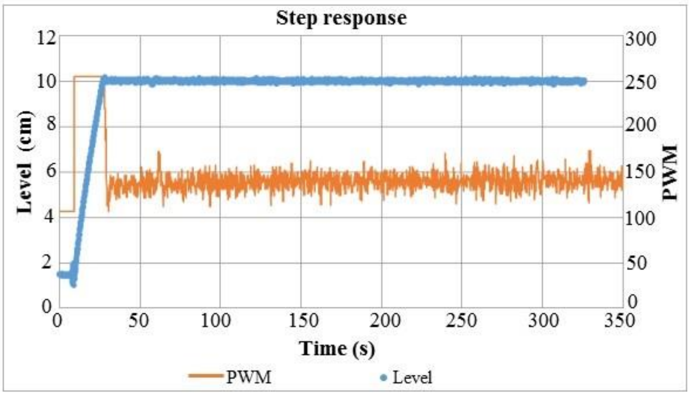

Figure 4 - Response curve for the disturbance in the closed-loop system.

According to the data registered, the change to the setpoint took place at 8.7 seconds, and shortly after, at 9.2, the PID changed the PWM value. In this case the overshoot was 1.3% and the settling time lasted 18.9 seconds. During the 584 seconds that the unit was operating at the new setpoint, a maximum error of 1.7% was registered.

Also according to Figure 4, in the first seconds there was an abnormal variation in the reading of the level variable. This can be explained by the physical activation of the button on the electric panel, generating noise interference on the weight sensors.

The initial intention was to carry out manual tuning, in the form of a synchronization map, however, as the initial parameters of the controller were seen to be effective, this tuning was not necessary. Instead, a new approach was proposed to test the behavior of the PID by adding 0.5L of water to the control tank. This took place in two forms, as a pulse disturbance, at the shortest time interval possible, and as a ramp disturbance, over 15 seconds (Figure 5 a-b).

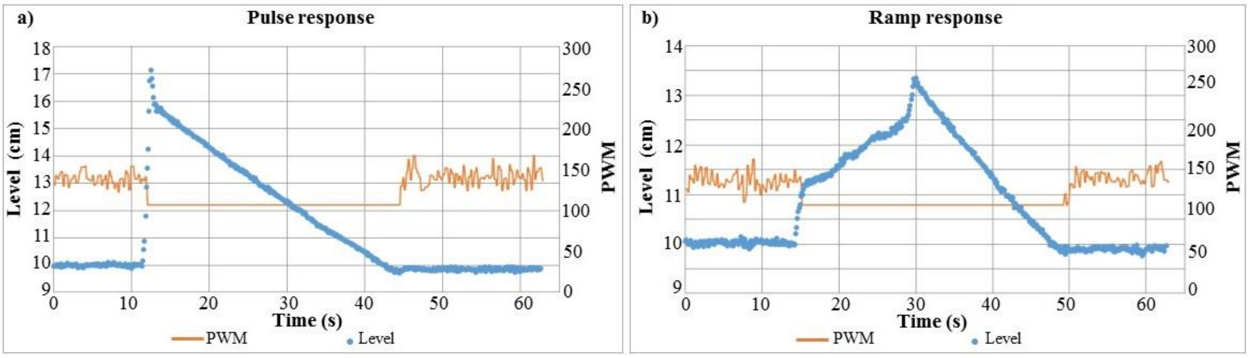

Figure 5 - Response curve of the system for a) the pulse disturbance and b) for the ramp disturbance.

Thus, the dead time, the overshoot, the settling time and the system error in the permanent regime were compared to evaluate the behavior of the system in relation to the disturbances tested (Table 1).

Table 1 - Comparison of the results generated for different disturbances

Disturbance	Dead time (s)	Overshoot (%)	Settling time (s)	Error (%)	Samples
Change in setpoint	0.50	1.27	18.87	1.70	2820
Pulse	0.12	2.90	31.48	2.77	551
Ramp (15s)	0.23	2.04	33.70	2.34	551

Thus, when maintaining the change in the setpoint as a reference disturbance, the parameters obtained resulted in a PID capable of working in different situations with extremely low overshoot and errors (< 3%). Despite the interference and noise when activating the system automatically, it did not prevent the dead time from going above 10^1 seconds.

4 Concluding Remarks

The didactic unit for PID level control represented the consolidation of the theoretical knowledge applied in practice. This is because this project, whether during the development phase or when the unit is being operated, involves considerable practical study that covers subjects such as Algorithms and Computer Programming, Industrial Chemical Processes, Transport Phenomenon, Unit Operations and Control of Chemical Processes, that constitute the curriculum of the majority of Chemical Engineering courses. In addition, considering the use of the didactic unit itself, it was possible to obtain excellent control and develop an intuitive and modular system, which was able to take on new functionalities.

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