A Miniaturized Industrial Plant for Educational Purpose in Industrial Control

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Abstract: This work presents a miniaturized industrial plant built to portray a hydraulic and thermal system. The system was developed in a low-cost open-source platform for studies in the fields of automation, dynamic systems, and control. In order to test its capacity, different techniques of classic and modern control, estimation, modeling, and identification were applied. It should be noted that the work provides the ability to reproduction and continuous development of the plant, and also examples of educational applications, reducing the demand for laboratory equipment acquisition for teaching and research in Universities.

Resumo: Este trabalho apresenta uma planta industrial miniaturizada construída para retratar um sistema hidráulico e térmico. O sistema foi desenvolvido em uma plataforma de baixo custo de código aberto para estudos nas áreas de automação, sistemas dinâmicos e controle. Para testar sua capacidade, foram aplicadas diferentes técnicas de controle clássico e moderno, estimação, modelagem e identificação. Deve-se notar que o trabalho fornece a capacidade de reprodução e desenvolvimento contínuo da planta, e também exemplos de aplicações educacionais, reduzindo a demanda por aquisição de equipamentos de laboratório para o ensino e pesquisa nas Universidades.

Keywords: Education; process control; industrial plant; embedded systems; Arduino.

Palavras-chaves: Educação; controle de processos; planta industrial; sistemas embarcados; Arduino.

1. INTRODUCTION

The engineering formation demands experimental and practical character (da Rocha Brito and Ciampi, 2007), in special in control and automation. According to Coelho et al. (2001), experiments by simulation are not enough and technical equipment are necessary to supply the demand for experience and applicability of theoretical content. In addition, with technological advances and needs coming from industry 4.0, new forms of teaching are needed to encompass these advances (Lasi et al., 2014), principally in control systems.

Following this trend, some commercial products are already used to promote this practical experience, like QUBE-Servo 2¹, Coupled Tanks¹, QDrone¹, QBot2¹, DC Motor Position Control System Using PID², Boiler control Demonstration² and Process Control Engineering Demonstration Plant³. They cover areas like classic, optimal, adaptive, neural and others control/estimation/identification methodologies practiced in chemical process, robotics, electronics, etc. These have been used not only for teaching, but for researching purpose too (Koutroulis et al., 2001).

However this kind of equipment requires high investment for acquisition (Rodriguez-Andina et al., 2010) and demands time and bureaucracy to be bought by Universi-

ties. Because of that, there is a trend of study for low-cost options based on embedded systems (D'Ausilio, 2012; Hercog and Jezernik, 2005). This type of system is already consolidated in industrial segment and could be easily applied for composing laboratory equipment capable of representing this segment, providing considerable cost reduction as education platforms (Malinowski and Yu, 2011).

As shown, low-cost educational prototypes have been developed for practical study in the fields of *automation, dynamic systems analysis and control* (Lu et al., 2007; Alvarado et al., 2006; Irigoyen et al., 2013; Soriano et al., 2014), with special attention to tank process (Saco et al., 2002; Pasamontes et al., 2012; Hlava et al., 2005; Johansson, 2000). It is proposed here the development of a system that constitutes a miniaturized industrial plant of a heated pump-fed tank, with controllable variables such as inlet flow, fluid level and temperature. Making this with a low-cost prototyping platform that communicates in real time with a computer.

The plant is constituted by a PVC pipe tank fed by a DC electric pump, with an AC heater inside, monitored by flow, level and temperature sensors. In addition there are some circuits: amplifiers, filters and a dimmer. All connected to an Arduino board, communicating via serial with software like *Scilab* and *Matlab*®.

Some methods were proposed to the system as didactical activities, like: transfer function response identification, proportional-integral controller (PI), regulator and state

¹ <https://www.quanser.com/products/>

² <https://www.aticoexport.com/product/>

³ <http://www.usdidactic.com/teaching-lab-equipment/>

observer, Kalman filter (FK) and model predictive control (MPC). Although the proposed tank has capacity of applications related to heating, this subsystem will not be addressed in this work. Only level-related applications will be exemplified.

This paper is organized as follows: Section 2 presents constructive and functional (hardware and software) aspects of the plant. Section 3 proposes and develops didactic activities like phenomenological modeling; identification; classic, modern and optimal control and estimation techniques. And the conclusions are presented in section 4.

2. MATERIALS AND METHODS

In this section it is presented the description of the constructive aspects of the plant, including materials and a piping and instrumentation diagram (PI&D), which could already be used as teaching activities.

2.1 System description

The assembled system, Figure 1, is a miniaturized industrial plant with nonlinear characteristics, which is associated to liquid level, pump inlet flow rate and fluid temperature. Figure (a) shows the overall appearance of the kit. Figure (b), (c) and (d) show the pressure sensor for level measurement, the flow sensor and the pump, respectively.

Figura 1. Constructive details of the kit (a) and instruments: (b) pressure sensor, (c) flow sensor, (d) pump.

The PI&D, Figure 2, is formed by the main tank, another reservoir tank, a level metering system (LT), a centrifugal pump, an encoder flow meter (FE), a temperature sensor (TT), an electric heater, along with a digital signal acquisition system (FY and LY) and power amplification circuits (FC and TC). Finally, a mechanical valve to adjust the output flow. The elements are listed in Table 1 with their

approximate local prices, which demonstrates the low cost feature of the system.

Tabela 1. List of components

Code	Description	Price
LT	MPX5010DP pressure sensor	R\$100.00
FE	YF-S402C flow sensor	R\$35.00
TT	DS18B20 temp. sensor	R\$20.00
FY, LY	Signal conditioner (in Arduino)	R\$50.00
FC	PI controller (in Arduino)	-
TC	40A Dimmer circuit	R\$35.00
Heater	5500W shower resistance	R\$10.00
Pump	Windshield washer pump 12V DC	R\$45.00
Valve	1/2" water tap	R\$15.00
Power Supply	Output 12V DC 7A	R\$40.00
Main Tank	100mm PVC pipe (and cap)	R\$35.00
Reservoir	11L plastic container	R\$10.00
Total		R\$395.00

The (LT) is based in a differential pressure analog sensor with a tube immersed in the main tank as described in (Clifford, 2006). The fluid column in the tank applies a pressure at the pipe inlet proportional to the level $h(t)$. The proportional ratio is then manually calibrated according to the actual level.

Figura 2. PI&D of the plant.

2.2 Acquisition System and Software

The digital signal acquisition, control and communication system is formed by the educational open-source platform Arduino. Internally, there is a code that processes the serial communication⁴ and defines the acquisition of data⁵ and the application of signals to actuators. Connected to it there are some auxiliary circuits - sensors filters⁶, actuators signal amplifier and an AC dimmer. This interface was ideally treated as a system without associated dynamics.

⁴ <https://www.arduino.cc/reference/en/language/functions/communication/serial/>

⁵ <https://maker.pro/arduino/tutorial/how-to-interface-arduino-with-flow-rate-sensor-to-measure-liquid>

⁶ https://www.nxp.com/files-static/sensors/doc/data_sheet/MPX5010.pdf

With this it is possible to use some software like *Scilab* (free and open-source) or *Matlab®*. Using the toolbox *WG Serial Xcos IO Block*⁷ (XCOS environment) or *Serial Port Interface*⁸ (Matlab code environment) for serial communication. This allows the practical implementation of signal analysis, systems and control by block diagram and code.

3. DIDACTIC ACTIVITIES

Some techniques were proposed with the purpose of validating the plant in educational application. The mathematical model of the system, the numerical identification and representation of its dynamics, the design and application of classic, modern and optimal controls.

3.1 Level dynamics modeling

Fluid level dynamics $\dot{h}(t)$ (1) was determined by mass m conservation inside the tank and the relation between the inlet $w_{in}(t)$ and outlet $w_{out}(t)$ flows (Dorf and Bishop, 2009). Where A_1 is the area of the main tank base.

$$\dot{h}(t) = \frac{w_{in}(t) - w_{out}(t)}{A_1} \quad (1)$$

The outflow $w_{out}(t)$ is determined by the manual adjustment of the valve and responds to the laws of fluid dynamics. It can be obtained from the relation between the cross section area A_2 of the tap and the outlet velocity of the fluid by that area which, by Bernoulli's principle results in (2) (Dorf and Bishop, 2009). Where g is the gravity acceleration.

$$w_{out}(t) = A_2 \sqrt{2g} \sqrt{h(t)} \quad (2)$$

Substituting (2) in (1) results in level dynamics model

$$\dot{h}(t) = \frac{w_{in}(t) - A_2 \sqrt{2g} \sqrt{h(t)}}{A_1} \quad (3)$$

The pump, in the form of a centrifugal pump, has its structures represented by (4) to (6), which respectively means armature circuit, rotor mechanics and hydraulics (Isermann and Münchhof, 2010).

$$\dot{I}_b(t) = \frac{-R_b I_b(t) - \Psi \omega(t) + U_b(t)}{L_b} \quad (4)$$

$$\dot{\omega}(t) = \frac{\Psi I_b(t) - M_{f0} - \rho g h_{th} \omega(t) w_{in}(t)}{J_B} \quad (5)$$

$$\dot{w}_{in}(t) = \frac{(h_{nn} - h_{rr}) w_{in}^2(t)}{a_f} \quad (6)$$

Where L_b is the armature inductance, R_b armature resistance, $I_b(t)$ armature current, Ψ motor constant, $\omega(t)$ rotor angular velocity, $U_b(t)$ the voltage applied, J_B pump's moment of inertia, M_{f0} dry friction torque, ρ fluid density, h_{th} pump head coefficient, a_f tube characteristics, h_{nn} delivered head coefficient and h_{rr} flow friction in tube (Isermann and Münchhof, 2010).

It is notable that a level controller is deficient in the control of the pump subsystem. So it is indicated the use of a

⁷ <https://atoms.scilab.org/toolboxes/wgserialxcosio/>

⁸ <https://www.mathworks.com/help/instrument/serial-port-interface.html>

control loop for the pump, preferably a closed-loop control with integral action. It could increase the robustness of the system to parametric variations, like replacement or its physical degradation (Nise and da Silva, 2002). A simple Proportional-Integral controller (PI) was adopted to ensure a closer approximation of a standardized, approximately linear and simplified dynamic. And for the following applications (4) to (6) will be replaced by the closed-loop linear equations of the PI-controlled pump with $w_{in(ref)}(t)$ as input and $w_{in}(t)$ as output. The controller design will be presented in Section 3.3.

Finally, we have as subsystem input the reference pump flow $w_{in(ref)}(t)$ and outputs the input flow $w_{in}(t)$ and height $h(t)$.

3.2 Identification

Based on Lyapunov's 1st method, it was applied, via *XCOS* in *Scilab* platform, a constant pump flow reference value $w_{in(ref)O}$, which results in a steady state flow w_{inO} , and waits until the level reaches the steady state h_O . The triplet $(w_{in(ref)O}, w_{inO}, h_O)$ is the operation point. With this data, it is possible to determine incremental linear models for the pump and tank level dynamics around an operating point, only valid for minor disturbances around it (Farid Golnaraghi, 2009), where $x_1(t) = h(t) - h_O$; $x_2(t) = w_{in}(t) - w_{inO}$ and $u(t) = w_{in(ref)}(t) - w_{in(ref)O}(t)$. The data was saved and applied to the *System Identification Toolbox*, configured in default mode, in *Matlab®* and a linear and operation point based model was obtained in continuous transfer function form. This procedure already uses the pump controlled by the proposed PI control, described in the next section.

In the operation point $h_O = 30$ cm and $w_{inO} = 20$ cm³/s, a step 5 cm³/s was applied. The input and output data was entered in the toolbox, resulting in two best-match continuous-time transfer function models, one 1st order for the tank dynamics (7) and another 2nd order for the controlled pump (8). This last one were not chosen as a 3rd order model as expected by (4) to (6) because the 2nd order one represented well the data, so the model order was reduced for simplicity.

$$\frac{H(s)}{W_{in}(s)} = \frac{0.01097}{s + 0.002579} \quad (7)$$

$$\frac{W_{in}(s)}{W_{in(ref)}(s)} = \frac{5.84}{s^2 + 1.616s + 5.84} \quad (8)$$

The level and pump model chosen is a 3rd order linear continuous-time model which is represented in state space and discretized with sample time $T = 0.3$ s (same sample time of the real system) resulting in (9).

$$\begin{cases} \mathbf{x}_{k+1} = \begin{bmatrix} 0.9992 & 0.0030 & 0.0004 \\ 0 & 0.7847 & 0.2176 \\ 0 & -1.2682 & 0.4331 \end{bmatrix} \mathbf{x}_k \\ \quad + \begin{bmatrix} 0.0003 \\ 0.2157 \\ 1.2706 \end{bmatrix} u_k \\ y_k = [1 \ 0 \ 0] \mathbf{x}_k \end{cases} \quad (9)$$

Where $\mathbf{x}_k = [x_{1k} x_{2k} x_{3k}]^T$, $x_3(t) = \dot{w}_{in}(t)$.

3.3 Control methods

The system is able to support several control techniques and some of them are described in the following. Project and application are based on linear system level model around an operation point previously obtained (9). Control methods were chosen to exemplify different educational applications.

Classic Control: PID

The first experiment is a classic PI controller illustrating the possibility of applying a discrete-time controller through difference equation directly on Arduino. Control gains were initially tuned using Ziegler-Nichols method (Seborg et al., 2010) and further refined using experimental adjustment based on proportional and integral actions knowledge. The PI controller is then discretized resulting in $K_p = 0.585$ and $K_i = 2.04$. Remember that, besides the educational purpose, the PI controller as an inner loop promotes a more reliable dynamics to tank level identification and control. In Figure 3 it is shown the pump flow closed-loop dynamics and reference. A practical observation is that the pump saturates outside the range 0 to 30 cm^3/s .

Figure 3. Controlled pump dynamics.

Modern control: State observer and regulator

State regulators are designed to stabilize the state space origin of a linear system and define transitory characteristics. Observers allow the estimation of unknown or unmeasured state of the system (Ogata, 1995).

If a system described like (10) satisfies the conditions of controllability and observability, an observer (11) and a regulator (12) can be designed by pole placement technique, based on the chosen performance specifications (Nise and da Silva, 2002). After that, (11) and (12) could be directly written in the Arduino's code and executed in the system.

$$\begin{cases} \mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}u_k \\ y_k = \mathbf{C}\mathbf{x}_k \end{cases} \quad (10)$$

$$\hat{\mathbf{x}}_{k+1} = (\mathbf{A} - \mathbf{L}\mathbf{C})\hat{\mathbf{x}}_k + \mathbf{B}u_k + \mathbf{L}y_k \quad (11)$$

$$u_k = -\mathbf{K}\hat{\mathbf{x}}_k \quad (12)$$

Where $\mathbf{x}_k \in \mathbb{R}^3$ is the state vector, $u_k \in \mathbb{R}^1$ input vector, $y_k \in \mathbb{R}^1$ is output vector, $\mathbf{A} \in \mathbb{R}^{3 \times 3}$ state matrix, $\mathbf{B} \in$

$\mathbb{R}^{3 \times 1}$ input matrix, $\mathbf{C} \in \mathbb{R}^{1 \times 3}$ output matrix, $\mathbf{K} \in \mathbb{R}^{1 \times 3}$ control gain matrix, $\mathbf{L} \in \mathbb{R}^{3 \times 1}$ observer gain matrix.

Practical specification were chosen to the design (settling time $t_s = 9\text{s}$ and observer dynamics 5 times faster), resulting in $\mathbf{K} = [373.0155 \ 5.4968 \ 2.8666]$ and $\mathbf{L} = [1.7281 \ 197.7781 \ -56.0206]^T$. A perturbation of 200 cm^3 of water was direct applied to the main tank at t_d instant.

Figure 4. Classic observer and regulator dynamics for a 200 cm^3 volume disturb: (a) level h , (b) reference flow $w_{in(ref)}$.

As seen in Figure 4(a), the system was regulated, then the perturbation on system level increased it and the regulator actuated with output returning to reference of the linear system (h_o). Oscillatory behaviour was observed in the output and its amplitude could be reduced with better regulator and/or observer gains tuning.

By Figure 4(b), once $w_{in_k} \in [w_{in_{min}}, w_{in_{max}}] = [0, 30]$ cm^3/s because of the pump limits, it could be inferred that u_k is not achieved in practice. This interfered in control in control performance, as seen by the higher settling time.

In Figure 4(a) it is possible to see the observer worked relatively well, it approximated $\hat{h}_k$ to h_k . The other states had been estimated and used in the control law, but were not shown graphically, due to the inability to measure all of them.

Optimal control: Kalman filter and MPC

This example is used to show more capabilities of the proposed didactical plant. In this case a Kalman filter and a MPC are applied using a *Matlab®* code and Arduino is used for communication between computer and plant (note

that the pump PI controller still runs in Arduino). This methodology allows implementation of different modern control and estimation methods easily to the proposed plant and also using free and open source software like *Scilab*.

The MPC is a technique that uses the model of the plant to predict its future behavior and, with an optimization problem, the optimal input sequence is determined, here, to minimize the error between the reference r_k and state variable x_{1k} . Through the idea of receding horizon, the control sequence u_k is updated at every sampling moment and constraints can be informed to achieve better performance (Rossiter, 2003).

A linear MPC algorithm with integral action was applied to the system (9) represented by (10), that was rewritten in the form (13) as described by Ruscio (2013). This new system (13) was associated to the performance index (14) and constraints (15). (13-15) is solved rewriting them as a Quadratic Programming (QP) form.

$$\begin{cases} \begin{bmatrix} \hat{x}_{k+1} \\ \Delta x_{k+1} \\ y_k \end{bmatrix} = \begin{bmatrix} \hat{A} & 0 \\ C & I \end{bmatrix} \begin{bmatrix} \hat{x}_k \\ \Delta x_k \end{bmatrix} + \begin{bmatrix} \hat{B} \\ 0 \end{bmatrix} \Delta u_k \\ y_k = \begin{bmatrix} C & I \end{bmatrix} \begin{bmatrix} \hat{x}_k \\ \Delta x_k \end{bmatrix} \end{cases} \quad (13)$$

$$J_k = \frac{1}{2} \sum_{i=1}^{L_y} [(y_{k+i} - r_{k+i})^T Q^{mpc} (y_{k+i} - r_{k+i}) + \sum_{i=1}^{L_y} \Delta u_{k+i-1}^T R^{mpc} \Delta u_{k+i-1}] \quad (14)$$

$$\mathcal{A} \Delta u_k |_{L_u} \leq b_k \quad (15)$$

Where Δu_k is the control increment, Q^{mpc} and R^{mpc} are weights, $\mathcal{A}$ is a matrix with ones and zeros and b_k incorporates the limits Δu_{min} , Δu_{max} , u_{min} and u_{max} (Ruscio, 2013).

Solving QP, an updated vector Δu with L_u (control horizon) size is computed based on the predicted output vector with L_y (predicted horizon) size and, normally, only the first one is applied $u_k = \Delta u_k^* + u_{k-1}$ where * means optimal. All this happening at every sampling moment.

A linear Kalman Filter (FK) was also applied. An optimal observer capable to estimate the system state based on its model and white noise corrupted measurements (Grewal and Andrews, 2001).

First it is predicted the pre-state $\hat{x}_k^-$ (16) and the error covariance P_k^- (17), then the Kalman gain K_k^{fk} (18). Corrections are made after, resulting in $\hat{x}_k$ (19) and P_k (20). In practical situation, there are noises added to (10), in x_{k+1} , the process noise w_k , and in y_k , the measurement noise v_k , $w_k \sim \mathcal{N}(0, Q^{fk})$ and $v_k \sim \mathcal{N}(0, R^{fk})$. Where Q^{fk} is the process noise covariance and R^{fk} the measurement noise covariance, both acting like adjustable weights for the estimation/filtering process (Welch et al., 1995).

$$\hat{x}_k^- = A\hat{x}_{k-1}^- + Bu_{k-1} \quad (16)$$

$$P_k^- = AP_{k-1}A^T + Q^{fk} \quad (17)$$

$$K_k^{fk} = P_k^- C^T (C P_k^- C^T + R^{fk})^{-1} \quad (18)$$

$$\hat{x}_k = \hat{x}_k^- + K_k^{fk} (y_k - C\hat{x}_k^-) \quad (19)$$

$$P_k = (I - K_k^{fk} C) P_k^- \quad (20)$$

The controller was configured with: $L_u = 10$, $L_y = 15$, $Q^{mpc} = 100 \cdot I^{(L_y \times L_y)}$, $R^{mpc} = I^{(L_u \times L_u)}$, $\Delta u_{min,max} = 20/4.6$, $u_{min} = -20$ and $u_{max} = 10$. And the FK: $Q^{fk} = 10000 \cdot I^{(3 \times 3)}$, $R^{fk} = 10$. The reference $r = 40$ cm.

Figure 5. MPC and Kalman Filter dynamics for 40 cm level reference: (a) level h , (b) reference flow $w_{in(ref)}$.

From the Figure 5(a) it can be seen that the MPC was able to take the system to the desired reference and keep stable after that and the FK was able to estimate $x_1(t)$. From the Figure 5(b) the control effort remained in the restriction as defined in the specified constraints.

The MPC application showed here can be considered more complex than others techniques. This may confirm the capacity of the plant for more than practical study, but to research purpose.

4. CONCLUSION

The construction of low-cost MIMO practical tank process was presented. Focusing in the hydraulic subsystem (SISO), didactic activities were proposed and applied. A PI&D were used to represent the system. A phenomenological nonlinear and an identified linear models were obtained with the knowledge of practical restrictions of the system, such as pump saturation. A classical control

method - PI, and modern control - state observer and regulator were implemented directly in Arduino. A optimal control - KF and MPC were implemented by a computer communicating via serial with the plant.

It was possible to use a low cost embedded system for the construction of an educational plant. This system allowed the direct implementation of estimation and control techniques in its interior, besides being able to act as an acquisition board for computer control application. Favouring several other applications and techniques, including the development of other similar educational equipment.

Results presented here were able to exemplify the capabilities of the low-cost platform proposed in control/modeling/identification/estimation areas for educational and research purposes.

Therefore, this work can be continued, adding more functionalities and implementing countless others techniques, like exploring the thermal subsystem, proving more educational and validation of research results.

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