EXPERIMENTAL DIDACTIC PLATFORM FOR TEACHING CONTROL SYSTEMS IN ENGINEERING

Caio Igor Gonçalves Chinelato[1]

DOI: 10.37702/REE2236-0158.v41p84-92.2022

ABSTRACT

The design and the analysis of control systems are fundamental topics in automation, electrical and electronics engineering courses. This work presents the proposal of an experimental didactic platform for teaching control systems in engineering to increase the efficiency of the students' learning. The didactic platform has several integrated modules with adjustable parameters, such as plants, controllers and reference signal generator, making possible the learning of fundamental concepts of control systems through practical experimentation. Initially, the main modules and the characteristics of the experimental didactic platform are presented. Posteriorly, experiments to be performed with the platform are proposed. These experiments deal with fundamental concepts of control systems, such as dynamic behavior of systems, open-loop and closed-loop systems and basic types of controllers. In these experiments, reference signals are applied in several control systems configurations and the output signals are analyzed with an oscilloscope. The results demonstrate that the experimental didactic platform is a precise and simple resource, and can be easily applied in control systems disciplines for engineering.

Keywords: Control systems; teaching engineering; didactic platforms; PID Control.

INTRODUCTION

The design and the analysis of control systems are fundamental topics in automation, electrical and electronics engineering courses and have developed a fundamental role in the advancement of engineering, science and modern industrial production process. In disciplines related to control systems, initially the students learn theoretically fundamental concepts, such as dynamical systems modeling, transient and steady-state response, systems analysis and controllers design. Posteriorly, the students perform computational simulations and practical experiments to assimilate these fundamental concepts and to integrate theory and practice. To increase the efficiency of the students' learning, it is crucial that the materials and the methodology applied in practical experiments be simple, precise and didactic.

Several works related to teaching control system in engineering are proposed in the literature. In Keles et al. (2017), it is described the application of a low-cost experimental didactic module for teaching basic concepts in the disciplines related to the modeling and control of dynamical systems in electrical and automation engineering. Carvalho, Ferreira and Gomes (2016) present an educational platform that performs the temperature control of two tanks aiming to assist the learning of fundamental concepts of control system in electrical engineering. The platform allows that the students apply project-based learning. In Cavazzana, Filho and Souza (2011), the control techniques gain scheduling and Proportional Integral Derivative (PID) are applied in a

[1] Professor at IFSP – Campus São Paulo; B. Sc. in Science and Technology (UFABC); B. Sc. in Instrumentation, Automation and Robotics Engineering (UFABC); M. Sc. Degree in Mechanical Engineering (UFABC); caio.chinelato@ifsp.edu.br

didactic prototype of an aerial stabilization platform. Soares et al. (2015) apply virtual and remote laboratory experiments to teach control and automation for engineering courses aiming to deal with the lack of didactic platforms in some situations.

Some works suggest the teaching of control systems applying low-cost hardware resources, such as Arduino and Raspberry Pi. Barber, Horra and Crespo (2013) and Candelas et al. (2015) propose laboratory experiments for teaching control systems using Arduino. Reck and Sreenivas (2016) elaborate a laboratory kit for control systems using Raspberry Pi. It is important to highlight that several companies provide didactic kits for teaching control systems, instrumentation, automation and robotics. These kits are widely used in several universities. In Garcia, Stein and Schaf (2012), a didactic plant is described and applied for teaching control and automation engineering.

OBJECTIVES

This work presents the proposal of an experimental didactic platform for teaching control system in engineering to increase the efficiency of the students' learning. The didactic platform has several integrated modules with adjustable parameters, such as plants, controllers and reference signal generator, making possible the learning of fundamental concepts of control systems through practical experimentation.

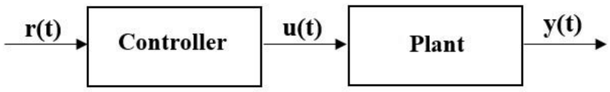
Initially, the main modules and the characteristics of the experimental didactic platform are presented. Posteriorly, experiments to be performed with the platform are proposed. These experiments deal with fundamental concepts of control systems, such as dynamical behavior of systems, open-loop and closed-loop systems and basic types of controllers).

CONTROL SYSTEMS

A system is a combination of components that act together and perform a certain objective (OGATA, 2009). A control system aims to control the dynamical behavior of variables related to a plant or a process. The plant is basically the system to be controlled and can be considered part of an equipment or set of parts of an equipment that perform a specific operation. A process is an operation characterized by a series of steps to achieve an objective. Process control is usually related to the control of systems that involve variables such as flow, temperature and pressure (BEGA, 2011).

A block diagram describing the basic elements of a control system is presented in Figure 1. The system is constituted by a controller and a plant. A controller must be designed in order that the system output or the controlled variable *y(t)* tracks the system input or the reference variable *r(t)* with the best dynamic behavior possible. The controller applies a control signal or a control variable *u(t)* in the plant. The control system described in Figure 1 is an open-loop system, as there is no feedback of the system output *y(t)* for comparison with the system input *r(t)* (DORF; BISHOP, 2008).

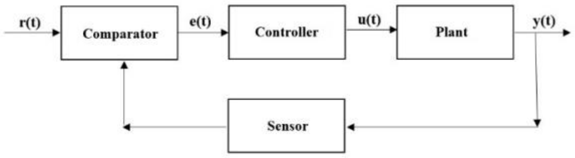
Figure 1 – Block diagram describing the basic elements of a control system



Source: elaborated by the author.

A block diagram describing a closed-loop control system is presented in Figure 2. In this case, there is a feedback of the system output *y(t)* for comparison with the system input *r(t).* The system output *y(t)* is measured by a sensor. The error signal *e(t) = r(t) – y(t)* is applied as the controller input. Closed-loop control systems make the output more precise and insensitive to disturbances. However, the feedback can generate instability and this must be observed in the design and implementation of the control system (OGATA, 2009).

Figure 2 – Block diagram describing a closed-loop control system



Source: elaborated by the author.

The mathematical model that describes the dynamical behavior of the plant must be obtained in order that the controller can be designed. This mathematical model is described through differential equations and is obtained using physical laws that determine the behavior of a particular system, such as Newton's laws for mechanical systems or Kirchhoff's laws for electrical systems. The system analysis is realized using Laplace transform for linear systems and state space for linear or nonlinear systems (DORF; BISHOP, 2008).

In this work, it is considered a second-order system given by the following transfer function (OGATA, 2009):

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \quad (1)$$

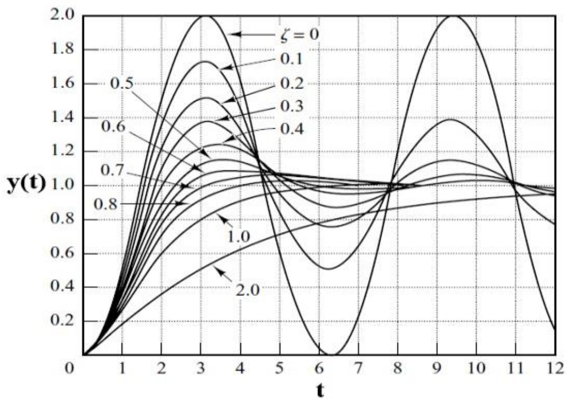
The dynamical behavior of the system is described in terms of the parameters damping ratio ζ, undamped natural frequency ω_n and time constant $T = 1/\zeta\omega_n$. Assuming that the closed-loop poles, i.e., the roots of the denominator in Eq. (1) are in the left-half *s* plane, it can be considered the following cases (OGATA, 2009):

- $0 < \zeta < 1$: the closed-loop poles are complex conjugates, the system is called underdamped and the response is oscillatory;
- $\zeta = 0$: the closed-loop poles are purely imaginary, the system becomes undamped and the response oscillates continuously;
- $\zeta = 1$: the closed-loop poles are real and equal, the system is called critically damped and the response is not oscillatory;
- $\zeta > 1$: the closed-loop poles are real and unequal, the system is called overdamped and the response is not oscillatory;

Closed-loop poles in the right-half *s* plane become the system unstable and must be avoided.

The dynamical behavior of the system output *y(t)* for different values of ζ and considering the reference *r(t)* as a unit-step is described in Figure 3.

Figure 3 – Unit-step response of the system for different values of ζ.



Source: (OGATA, 2009).

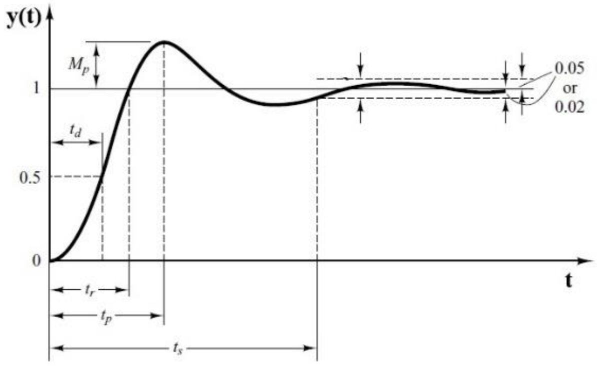
After obtaining the mathematical model of the system and the analysis of the dynamical behavior, a controller must be designed in order that the error signal *e(t)* tends to zero and the system output *y(t)* satisfies certain performance specifications in transient response, that corresponds to the behavior of the system from the initial state to the final state, and in steady-state, that corresponds to the behavior of the system when the time tends to infinity. These specifications are obtained through the unit-step response of the system and are (OGATA, 2009):

- Delay time t_d: time required for the response to reach half the final value the first time;
- Rise time t_r: time required for the response to rise from 0% to 100% of its final value;
- Peak time t_p: time required for the response to reach the first peak of the overshoot;
- Maximum (percent) overshoot *Mp*: maximum peak value of the response curve measured from unity;

- Settling time t_s: time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value (usually 2% or 5%);

These specifications are described graphically in Figure 4.

Figure 4 – Performance specifications considered for the controller design.



Source: (OGATA, 2009).

CONTROL TECHNIQUES

There are several control techniques. The techniques applied in the experiments proposed in this work are the two-position or on-off control and the PID control.

In the two-position control action, the controller has two fixed positions, typically on and off. This control technique is simple, inexpensive and widely used in both industrial and domestic control systems. This controller is mathematically described by the following expression (OGATA, 2009):

$$u(t) = U_1 \;\; for\; e(t) > 0$$
$$u(t) = U_2 \;\; for\; e(t) < 0 \qquad (2)$$

The control signal *u(t)* oscillates between two values U_1 and U_2, depending on the error signal *e(t)*.

The control technique PID is widely known and applied in industry and performs better than two-position control. The PID controller is mathematically described by the following expression (ASTROM; HAGGLUND, 1995):

$$u(t) = K_P(e(t) + T_I \int_0^t e(t)dt + T_D \frac{d}{dt} e(t)) \qquad (3)$$

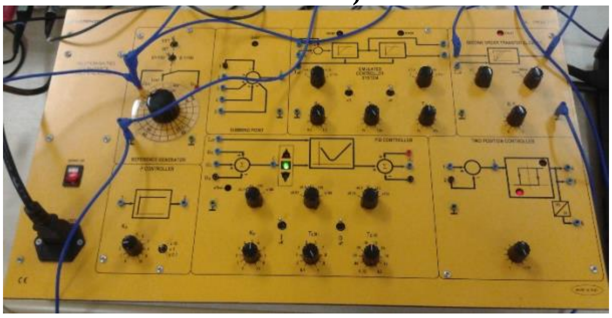
The control signal *u(t)* is constituted by three control actions. A proportional control action, where the error signal *e(t)* is multiplied by a gain K_P, an integral control action, where the integral of the error signal is multiplied by a gain $K_P T_I$ and a derivative control action, where the derivative of the error signal is multiplied by a gain $K_P T_D$. In some cases, the three control action are not applied simultaneously, such as PD controllers, where only proportional and derivative control actions are applied and PI controllers, where only proportional and integral control actions are applied. The design parameters of the PID controller are the gains K_P, T_I and T_D. The integral control action provides improvements on the steady-state response and the derivative control action provides improvements on the transient response.

METHODOLOGY

This work presents the proposal of an experimental didactic platform for teaching control systems in engineering so that the basic concepts described in the last section can be assimilated more efficiently by the students. For this purpose, it is applied the board for the study of the automatic control technology (DL 26ACTR) from *De Lorenzo*, which is an Italian company specialized in the design, development and production of training equipment for several technological areas, such as automation, electronics and instrumentation (DE LORENZO, 2021).

The didactic platform has several integrated modules with adjustable parameters, such as plants, controllers and reference signal generator. The modules are connected using connection cables and the parameters of each module are defined using adjustable switches and potentiometers for the implementation of the control systems. The example of an experimental setup with the didactic platform is shown in Figure 5, where it can be seen several modules integrated, connection cables, adjustable switches, potentiometers and indicator leds.

Figure 5 – Example of an experimental setup with the didactic platform (*De Lorenzo* board for the study of the automatic control technology DL 26ACTR)



Source: elaborated by the author.

The didactic platform has the following modules:

- Reference generator: generates a step signal as the system input or the reference variable *r(t)*. The signal amplitude is defined through an adjustable switch and a potentiometer. Besides that, an external reference input can be applied;
- Summing point: performs the addition or subtraction with the platform signals;
- Simulated controller system: consists of a first-order or a second-order generic plant with a PI controller. The plant parameters and the controller parameters K_P and T_I, described in Eq. (3), are defined through adjustable switches and potentiometers;
- Second order transfer element: consists of a second-order generic plant whose parameters ζ and $T = 1/\zeta\omega_n$, described in Eq. (1), can be defined through adjustable switches and a potentiometer;
- P controller: implements a proportional controller. The controller parameter K_P, described in Eq. (3), is defined through an adjustable switch and a potentiometer;
- PID controller: implements a PID controller. The controller parameters K_P, T_I and T_D, described in Eq. (3), are defined through adjustable switches and potentiometers;
- Two position controller: implements a two-position controller. The controller parameters U_1 and U_2, described in Eq. (2), are defined through a potentiometer;

A digital oscilloscope is applied to analyze the system signals as shown in Fig. 6. The oscilloscope channels are connected to the system output *y(t)* and the system input *r(t).*

Figure 6 – Digital oscilloscope applied to analyze the system signals

Source: elaborated by the author.

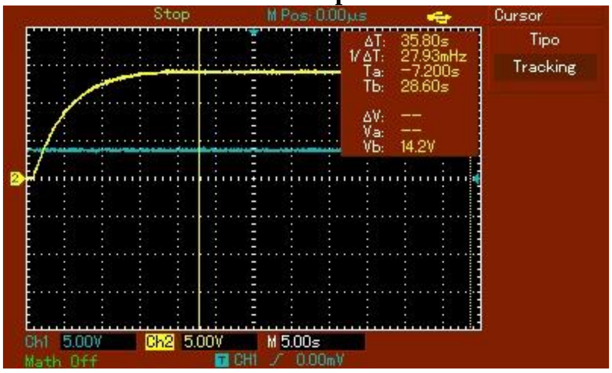
Some experiments are proposed with the platform in order to deal with fundamental concepts of control systems, such as dynamical behavior of systems, open-loop and closed-loop systems and basic types of controllers.

It is proposed an experiment with a system connected in open-loop without controller and four experiments with a system connected in closed-loop with controllers proportional, PI, PID and two-position; thus, the basic concepts described in the last sections can be analyzed experimentally.

RESULTS AND DISCUSSIONS

In the first experiment, the second-order generic plant, represented by the module second order transfer element, is connected in open-loop without controller. The plant parameters are $\zeta = 1.5$ and $T = 1\ s$. The reference input *r(t)*, generated by the module reference generator is a step with amplitude 4 V. The experimental setup is shown in Figure 5. The system output *y(t)* and the system input *r(t)* measured by the oscilloscope are presented in Figure 7.

Figure 7 – System output *y(t)* and system input *r(t)* for the first experiment



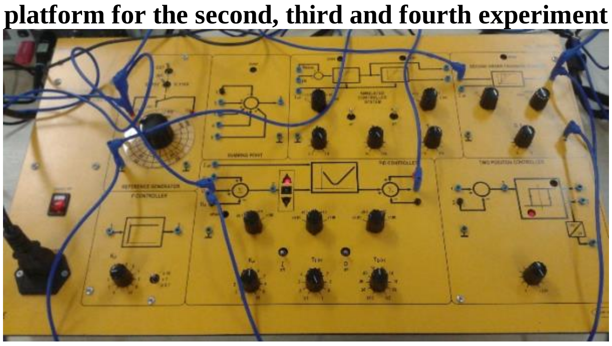
Source: elaborated by the author.

The result demonstrates a slow transient response and an imprecision in steady-state as expected for an open-loop system without controller.

In the second experiment, the plant parameters and the reference input are kept the same as in the first experiment, however a proportional controller is applied with the module PID controller and the system is connected in closed-loop. The controller parameters are $K_P = 0.5$, $T_I = 0$ and $T_D = 0$. The experimental setup is shown in Figure 8. The system output *y(t)* and the system input *r(t)* are presented in Figure 9.

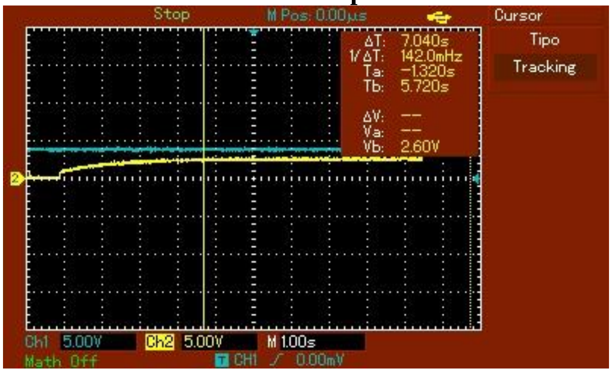
The result demonstrates a significant reduction in steady-state error. Thus, a system in closed-loop with a proportional controller makes the output more precise.

Figure 8 – Experimental setup with the didactic platform for the second, third and fourth experiment



Source: elaborated by the author.

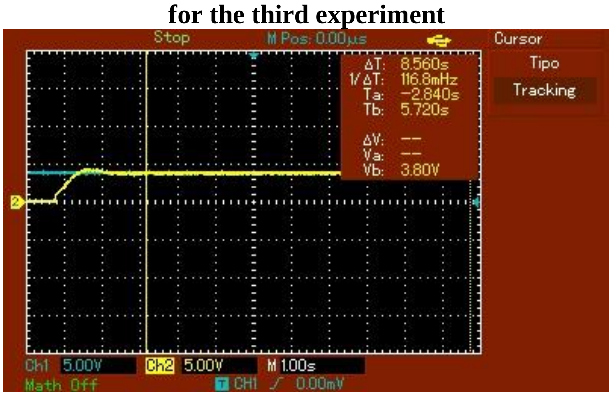
Figure 9 – System output *y(t)* and system input *r(t)* for the second experiment



Source: elaborated by the author.

In the third experiment, the plant parameters and the reference input are kept the same as in the first experiment, however a PID controller is applied with the system connected in closed-loop. The controller parameters are $K_P = 0.5$, $T_I = 1$ and $T_D = 10$. The experimental setup is the same as shown in Figure 8. The system output *y(t)* and the system input *r(t)* are presented in Figure 10.

Figure 10 – System output *y(t)* and system input *r(t)* for the third experiment



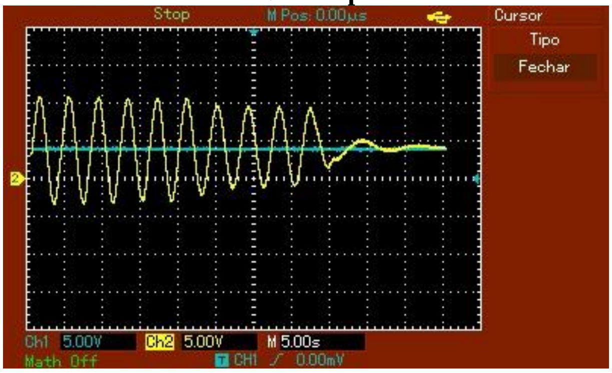
Source: elaborated by the author.

The result demonstrates a response more precise. The transient response is faster due to the derivative control action and the steady-state error is almost zero due to the integral control action.

The fourth experiment is proposed with the objective to show the influence of the derivative control action in the transient response. The plant parameters and the reference input are kept the same as in the first experiment, however a PI controller is applied with the system connected in closed-loop. The controller parameters are $K_P = 0.5$ and $T_I = 0.1$. The experimental setup is the same as shown in

Figure 8. The system output *y(t)* and the system input *r(t)* are presented in Figure 11. Initially, the response exhibits an oscillatory behavior. After a time interval, a derivative control action with gain $T_D = 10$ is applied together with the action proportional and integral. It can be seen that after the application of the derivative control action, the oscillations vanish and the system tracks the reference input precisely.

Figure 11 – System output *y(t)* and system input *r(t)* for the fourth experiment

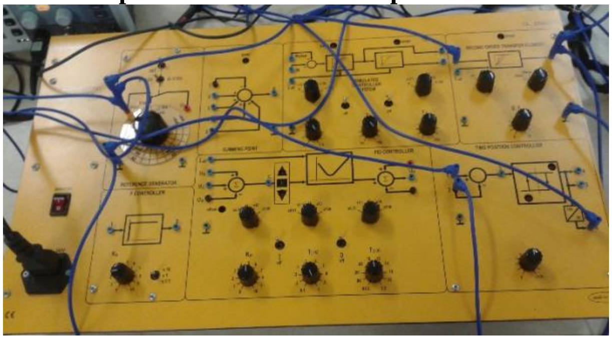


Source: elaborated by the author.

In the fifth experiment, the plant parameters and the reference input are kept the same as in the first experiment, however a two-position controller is applied with the module two position controller and the system is connected in closed-loop. The controller parameters are $U_1 = +1,25$ *V* and $U_2 = -1,25$ *V*. The experimental setup is shown in Figure 12. The system output *y(t)* and the system input *r(t)* are presented in Figure 13.

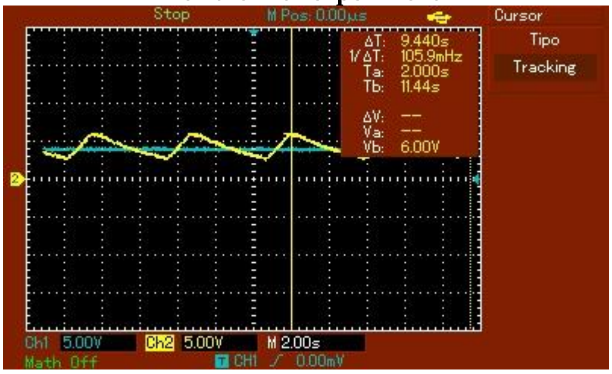
The result demonstrates that the system output oscillates between two values depending on the error signal *e(t)*. As expected theoretically, PID controller performs better than two-position controller.

Figure 12 – Experimental setup with the didactic platform for the fifth experiment



Source: elaborated by the author.

Figure 13 – System output *y(t)* and system input *r(t)* for the fifth experiment



Source: elaborated by the author.

CONCLUSIONS

This work presents the proposal of an experimental didactic platform for teaching control systems in engineering to increase the efficiency of the students' learning. The application of didactic resources like this is very important to promote better assimilation and comprehension of fundamental concepts related to control systems and integration between theory and practice.

The results demonstrates that the experimental didactic platform is a simple resource, because connection cables and an oscilloscope are enough to perform several experiments with control systems. The platform also presents precision in the results with the modules related to the reference inputs, plants and controllers.

With the proposed experiments, the students are able to verify some concepts of instrumentation and practical characteristics of control systems, such as dynamical response of open-loop and closed-loop systems and behavior of different types of controllers.

Experiments like these are fundamental in the assimilation of basic concepts related to control systems, which are initially studied theoretically and verified through computational simulations.

The results also demonstrates experimentally the advantage of a closed-loop system in comparison with an open-loop system, the differences of behavior between a two-position controller and a PID controller, and the influence of the proportional, integral and derivative control actions in the controlled system.

Obviously, other experiences can be proposed, such as plants and controllers with distinct parameters and configurations, or modifications in the reference inputs. Besides that, it would be interesting that the dynamical responses were initially calculated analytically, posteriorly verified numerically through computational simulations and finally validated experimentally through the proposed didactic platform.

Therefore, the experimental didactic platform is a resource efficient to be applied for teaching control systems in several engineering courses, such as automation, electrical and electronics.

REFERENCES

ASTROM, K. J.; HAGGLUND, T. **PID controllers**: theory, design and tuning. ISA: The Instrumentation, Systems and Automation Society, 1995.

BARBER, R.; HORRA, M.; CRESPO, J. Control practices using Simulink with Arduino as low cost hardware. **Proceedings…** IFAC symposium advances in control education, Sheffield, UK, 2013.

BEGA, E. A. **Instrumentação industrial**. Interciências, 2011.

CANDELAS, F. A. et al. Experiences on using Arduino for laboratory experiments of automatic control and robotics. **IFAC-PapersOnLine**, v. 48, n. 29, 2015.

CARVALHO, D.; FERREIRA, D. A.; GOMES, F. J. Desenvolvimento de uma plataforma educacional baseada em PJBL para ensino de controle. **Proceedings...** Congresso Brasileiro de Educação em Engenharia (COBENGE), Natal, Brazil, 2016.

CAVAZZANA, E.; FILHO, J. D.; SOUZA, E. M. R. Construção de uma plataforma didática para estudo da técnica de controle gain scheduling utilizando um escalonador mecânico de ganhos. **Proceedings...** Congresso Brasileiro de Educação em Engenharia (COBENGE), Blumenau, Brazil, 2011.

DE LORENZO. **Automatic control technology**. Available at: < https://www.delorenzoglobal.com/automation/control-technology/>. Access in: 19 apr. 2021.

DORF, R. C.; BISHOP, R. H. **Modern control systems**. New Jersey, Pearson, 2008.

GARCIA, T. R.; STEIN, G. M.; SCHAF, F. M. Criando cenários práticos alternativos para o Ensino de Engenharia de controle e automação: interface remota para planta didática multiprocessos. **Proceedings...** Congresso Brasileiro de Educação em Engenharia (COBENGE), Belém, Brazil, 2012.

KELES, N. A. et al. Módulos didáticos para o ensino de análise e controle de sistemas dinâmicos. **Proceedings...** Simpósio Brasileiro de Automação Inteligente (SBAI), Porto Alegre, Brazil, 2017.

OGATA, K. **Modern control engineering**. New York, Prentice Hall, 2009.

RECK, R. M.; SREENIVAS, R. S. Developing an affordable and portable control systems laboratory kit with a Raspberry Pi. **Electronics**, v. 5, n. 3, 2016.

SOARES, F. et al. Experiences in automation and control in engineering education with real-world based educational kits. **Sensors and Transducers**, v. 193, n. 10, 2015.

AUTHOR'S BIOGRAPHICAL DATA

Caio Igor Gonçalves Chinelato – Received his B. Sc. in Science and Technology, B. Sc. in Instrumentation, Automation and Robotics Engineering and M. Sc. degree in Mechanical Engineering from the Universidade Federal do ABC (UFABC), Santo André, Brazil, in 2009, 2011 and 2014, respectively. Since 2014, he has been a professor at Instituto Federal de São Paulo (IFSP) – Campus São Paulo. His research interests include control systems, mechatronics, robotics and teaching engineering.