Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

A Hardware-in-the-Loop Prototype to design Benchmarks for Automation and Control Education ⋆

M. Castilla * **F. Rodríguez** * **J.D. Álvarez** * **J.G. Donaire** * **J. Ramos-Teodoro** *

* *Dpto. de Informática, Universidad de Almería, CIESOL-ceiA3, 04120, Almería, Spain (E-mail addresses: {mcastilla, frrodrig, jhervas, jugarcia, jeronimo.rt}@ual.es)*

Abstract: At present, most of the systems which can be found in an industrial environment present both sequential (discrete) or mixed (continuous and discrete) dynamics that must be controlled, monitored and supervised. For this reason, studying these systems and how they can be controlled is a crucial issue which should be covered in engineering education. This article presents a Hardware-in-the-Loop prototype which can be used for automation and control training. This prototype allows teachers to design, in an intuitive manner, different benchmarks to be solved by students in laboratory practice sessions. These benchmarks can be easily adapted to the level and the area of knowledge of students. An example of benchmark has been proposed and commented. Moreover, students' opinion regarding a preliminary version of the prototype has been included and discussed.

Keywords: Teaching curricula; Batch-processes control; Automation; Benchmarks.

1. INTRODUCTION

Practical or laboratory sessions in automatic control subjects in engineering degrees deal with the need to manage real plants, for educational purposes, with the aim to teach automatic and control concepts to the students. Usually, the number of plants in the laboratory is fewer than the students which causes a bottleneck when the students want to access to the plants in order to do their practical exercises. For students, both bachelors and masters ones, is important to manage real hardware and systems, and being familiar with all the concepts related with them. Concepts as electronic connections, communications, wiring diagrams, data acquisition and so on, must be covered by automatic and control education subjects in order to prepare students for when they are on the labour market and, by this way, they may apply their acquired knowledge.

In order to teach these concepts in laboratory sessions, there are many possibilities, such as, the use of real industrial plants specifically prepared for educational purposes or the development of benchmarks to be solved in simulation using models. In the first case, the main problem is the economic cost of acquiring new industrial plants or didactic equipment which, in some cases, is unaffordable for universities. On the contrary, in the second case, the principal disadvantage is that students only work in simulation, and thus, they lose the perception of reality, that is, using this solution there is a "decoupling" between students and hardware (the plant itself and the hardware used to control it).

One alternative to overcome this issue is to use Hardware-in-the-Loop (HIL) prototypes to support teaching and to avoid students have to wait for testing their designs in a real platform reducing, by this way, the wasted time (Tejado et al., 2016). In last years, is possible to find several works in literature that cover this topic. As examples, in (Carballo et al., 2018) a low-cost tracking system which emulates the behaviour of a heliostat field is built using open source hardware like a Raspberry Pi 3, a Pi Cam, a PWM electronic control and a relay module. This prototype can be used for educational purposes in subjects related to solar systems or renewable energies. On the other hand, in (Tejado et al., 2016) Arduino has been used to build a low-cost HIL for mobile robots. The simulation of the robot is built in Simscape, which is a toolbox for physical modelling developed in MATLAB/Simulink, this HIL can support learning in automatic control and robotics subjects in Electronics bachelor degrees. For teaching modern power systems in (Kotsampopoulos et al., 2016) a Power-HIL (PHIL) has been developed where inverters and a microgrid are used as hardware components of the PHIL experiments at the laboratory exercises. To monitor and control these laboratory components a Supervisory Control And Data Acquisition (SCADA) system has been developed. This PHIL can be useful to teach some modern power systems concepts in subjects of Electronics or Electrical Engineering grades. Finally, related to the previous work, in (Celeita et al., 2016) a real-time environment with HIL has been built to simulate the distribution system's behaviour of a smart grid and recreate selected signals.

⋆ This work has been funded by Teaching Innovation project named *"Desarrollo de un prototipo Hardware-in-the-Loop de bajo coste para la enseñanza de Automatización en estudios de Ingeniería"* belonging to the *Call for the creation of Teaching Innovation groups and Good Teaching Practices at the University of Almería* (Biennial 2019-20).

The HIL approach includes a power amplifier, an electronic load and several inputs/outputs modules from National Instrumets (NI). The simulation software used to communicate with this HIL is DSSim-PC and LabVIEW, that is a software property of NI too, whereas the hardware used is NI Compact RIO. Using this HIL, the main concepts of smart grids can be learned by students of Electronics or Electrical Engineering bachelor degrees.

This paper presents an HIL prototype which can be used in automation and control subjects that belong to engineering grades to teach some concepts related to automatic and control. Therefore, the prototype presented in this paper tries to close the gap between university and industry by solving the main inconveniences derived from the alternatives previously mentioned through an HIL approach. This prototype allows teachers to design, in an easy and intuitive way, different benchmarks, that simulate industrial processes, to be solved by students in laboratory practice sessions. The prototype is formed by a Raspberry Pi, an Arduino DUE and other cheap hardware components, thus, is easy and cheap to build several prototypes for equipping a laboratory. Besides, in this paper an example of benchmark, that is implemented in the prototype, has been proposed and commented.

The rest of the paper is structured as follows: Section 2 describes the teaching framework in which the HIL will be used. Section 3 explains the materials and methods with which the HIL has been developed. The benchmark example is showed in Section 4 and, finally, the main conclusions that arise from this work are listed in Section 5.

2. TEACHING FRAMEWORK

From a teaching point of view, since Bachelor's and Master's degrees were implemented at the University of Almería (Spain) with the introduction of the European Higher Education Area in 2010, automation and control training has been given to more than 2000 students. In general, in these degrees the subjects related to automation and control are organised as follows: each subject is composed of didactic units formed by theoretical lessons and laboratory practice sessions. The main idea is to use laboratory practice sessions to reinforce theoretical concepts and learn how to apply them to solve real problems.

Within the University of Almería, the HIL prototype presented in this paper can be used to strengthen the theoretical concepts explained in the subjects gathered at Table 1. However, as can be inferred from that table, there are a large variety of subjects which belong to different degrees and levels. Hence, the development of laboratory practices focused on the needs of each group of students is an important part of the process. Additionally, it is necessary to illustrate the practical application of the theoretical concepts by proposing laboratory practices related to their area of expertise. For example, for a group of students enrolled at the subject *Automation and Process Control* of the *Bachelor's Degree in Agricultural Engineering*, a case study related to the control and automation of the crop irrigation process can be proposed.

Therefore, it would be ideal to have different educational plants adapted to the specific requisites and area of knowledge of each group of students. Nevertheless, there are two main inconveniences derived from this idea: i) universities cannot afford to have an educational plant for each area of knowledge due to economic constraints; and ii) students would make use of the same educational plants throughout their higher education. Hence, the HIL prototype presented in this paper is a tool which solves both problems, since it provides great flexibility to design benchmarks and to propose laboratory practices. More in detail, some of the objectives and concepts strengthen by means of the HIL prototype can be summarized as follows:

- To analyze the difference among continuous, sequential and batch processes and to identify the involved inputs, outputs and auxiliary variables.
- To perform physical connections among several devices and to study industrial communications like Industrial Ethernet.
- To develop appropriate models of a process depending on the type of system. To do that, several alternatives can be used as Petri Nets, flowcharts, classical identification techniques, etc.
- To explain the concept of automatic control and the development of appropriate controllers for continuous processes. For instance, this controllers can vary from basic techniques as PID controllers to more advanced controllers like Model Predictive Control (MPC) ones.
- To study the architecture of Programable Logic Controllers (PLCs), their operation principles and how they can be used to control batch processes.
- To introduce and apply the standard IEC1131-3 (IEC, 1993) which details the different programming languages admitted by PLCs.
- To develop SCADA systems for batch processes (Rodríguez et al., 2015).

As a result, to design benchmarks and to establish the activities proposed to students, it would be necessary to consider the requirements of each specific subject. Besides, it is also very important to analyze the prior knowledge of students acquired in other subjects.

3. MATERIALS AND METHODS

The basis of a HIL approach is to connect the real input/output signals of a controller to a system which simulates reality, so the controller acts as if it were assembled with the real system, see Fig. 1. Hence, using this approach allows to simulate a wide variety of scenarios (including disturbances or components' failure) in order to verify the behaviour of the controller and to improve its robustness and reliability. Additionally, this approach considerably reduces derived costs since it is not necessary to acquire new didactic equipments. However, taking into account the number of workstations in the laboratory, a low-cost solution, that can be portable and reused to pose different problems, in the area of engineering has to be found.

3.1 Proposed Hardware-in-the-Loop prototype architecture

As it was previously mentioned, in this paper the design, development and implementation of a low-cost prototype based on a HIL approach is presented. Specifically, the

Table 1. List of subjects that will use the HIL prototype

Subject	Degree	Year
Industrial Automation	Bachelor's Degree in Industrial Engineering	2^o
Industrial Computing and Robotics	Bachelor's Degree in Computer Engineering	3^o
Industrial Computing	Bachelor's Degree in Industrial Electronics Engineering	3^o
Automation and Process Control	Bachelor's Degree in Agricultural Engineering	3^o
Industry 4.0	Master's Degree in Computer Science: Technology and Applications	1^o
Automation in Protected Crops	Master's Degree in Mediterranean Greenhouse Horticulture	1^o
Advanced Industrial Facilities	Master's Degree in Industrial Engineering	2^o

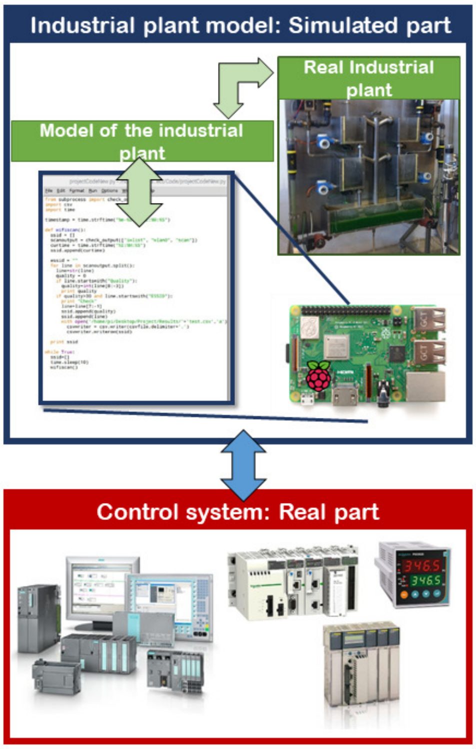

Fig. 1. Basis of a Hardware-in-the-Loop approach

proposed architecture for this prototype is divided into four different modules, as is shown in Fig. 2:

- *Process control module.* This prototype can be used to work with continuous, sequential or batch processes. In all cases, automatic control of the process will be performed by means of PLCs programmed according to the standard IEC1131-3 (IEC, 1993). To do that, the Schneider Unity Pro XL software is used. Sequential processes are well-known for being usually controlled through PLCs but, at present, it is also possible to control continuous processes since their programming language includes some basic controller blocks like PID controllers (Samin et al., 2011), or one can implement more advanced controllers, as MPC, using structured language (Krupa et al., 2018). Finally, it should be mentioned that for the development of appropriate controllers is necessary to have a model of the system. In our case, it has been decided that to model this type of processes students make use of Petri Nets, a paradigm widely used in automation.
- *Process supervision module.* Is is devoted to supervision and data acquisition of the main variables involved in the process, that is, the development of SCADA systems. To do that, the Schneider Citect SCADA software is used.
- *Communications module.* This module is responsible for the communication between the process control and process supervision modules. To do that, two different alternatives are proposed: i) using an Ole for Process Control (OPC) server, and ii) establishing a communication based on Industrial Ethernet.
- *Industrial plant emulation module.* The emulation of the plant is performed using a HIL approach. Concretely, the model of the industrial plant is implemented in Python and run using a Raspberry Pi 3 (Raspberry Pi, 2019). Nevertheless, as the Raspberry Pi 3 does not have appropriate hardware to be directly connected to the digital and analog boards of a PLC, a low-cost solution has been found. Raspberry Pi 3 device is connected to an Arduino DUE (Arduino, 2019) by means of an USB cable. Subsequently, as Arduino DUE device has several digital and analog outputs and inputs, they will be adapted by means of electronic circuits or voltage regulators to be connected to the digital and analog modules of the PLC.

Therefore, the materials used to develop the architecture proposed in this work can be summarized as follows: a PC, a Schneider Modicon M340 PLC (Schneider Electric M340 PLC, 2019) with digital and analog boards, a Raspberry Pi 3, an Arduino DUE, a protoboard, some Dupont wires, and voltage regulators. The PLC available at the University of Almería is composed of a four slots rack, a CPS 2000 power source, a BMX P34 2020 CPU, an AMM 0600 board consisting of four analog inputs and two analog outputs, and a DDM 16022 board with eight digital inputs and eight digital outputs. An overview of the complete prototype is shown in Fig. 3.

3.2 Preliminary evaluation of the proposed architecture

Throughout the academic year 2018/19, the upper part of the proposed architecture (process supervision, communication, and process control modules) has been tested and evaluated by students enrolled in the subject *Industrial Computing*. This subject belongs to 3^{rd} year of the Bachelor's Degree in Industrial Electronics Engineering. To do that, the dynamics of the batch process had been implemented into the PLC by means of structured language. In order to evaluate the students' satisfaction with this first phase, they carried out a voluntary and anonymous survey composed of 10 questions. The most significant conclusions obtained from this survey can be summarized as follows:

- The upper part of the proposed architecture obtained a mean score equal to 8.14.

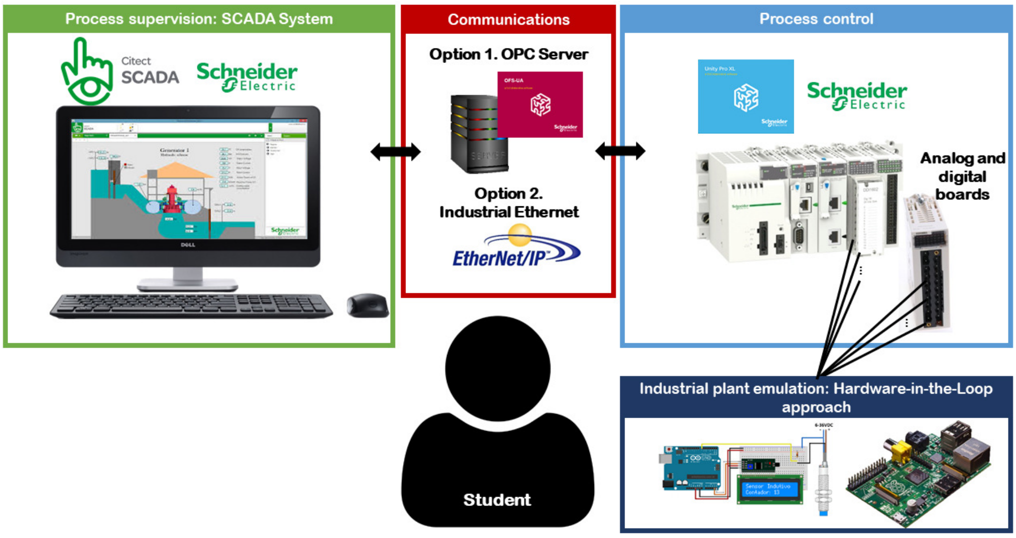

Fig. 2. Proposed Hardware-in-the-loop architecture

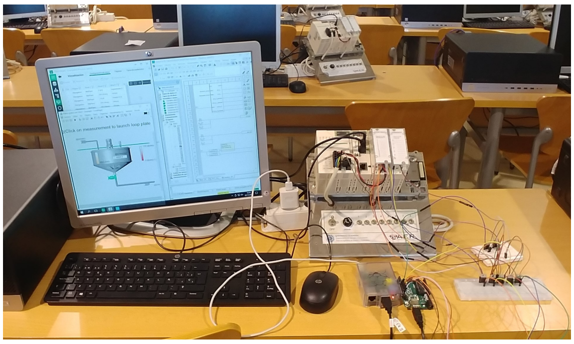

Fig. 3. Overview of the HIL prototype developed at the University of Almería

- 77% of students believe that the proposed architecture has helped them to understand the real interconnection between controllers and SCADA systems.
- 63.8% of students think that this tool is useful to learn how to design SCADA systems.
- 69.7% of students believe that extending the prototype to include the HIL module would increase their motivation. They justified that with only the upper part of the architecture they lose the perception of reality since they do not perform a real connection between the controller and the *"real"* plant.

3.3 How to design a Benchmark

In this section, the methodology followed to design a benchmark for the proposed prototype is shown. It is worthy to mention that it represents a guideline which should be adapted to the level of the students and the theoretical concepts to be reinforced. More in detail, the steps which compose this procedure are:

(1) To analyse the competences of the subject, as well as, the previous knowledge of the students enrolled in it.
(2) To select an industrial plant which can be modelled as a batch process. For instance, the operation of a beer or soap manufacturing plants. The selection of this plant should be related to the area of expertise of the students.
(3) To identify and decide the inputs and outputs of the selected process. To do that, one should take into consideration the constraints imposed by the PLCs, that is, the number of inputs and outputs available (both digital and analog ones).
(4) To develop a model of the selected process which will be considered as the real industrial process. This model, implemented in Python, should be run by the Raspberry Pi 3. Special emphasis should be placed on the continuous part of the process.
(5) To connect and interface the Raspberry Pi 3 (Raspberry Pi, 2019) and the Arduino (Arduino, 2019) through the USB cable. For that, firstly, you should install Arduino on Raspbian (operating system included in Raspberry Pi). Afterwards, the communication can be established using the *serial communication* library in Python.
(6) To perform the pin mapping, that is, to associate each input and output variable with its corresponding pin of the Arduino device.
(7) To connect the Arduino device with the digital and analog modules of the PLC. To do that, it is required to consider the input and output voltages of both the Arduino and the digital and analog modules of the PLC. Moreover, appropriate circuits or voltage regulators should be designed and built to perform this connection correctly.
(8) Finally, the batch process, its main variables and the physical connections between all hardware should be clearly described to the students.

3.4 Evaluation metrics to compare the performance of proposed controllers

Designing a benchmark is almost as important as the metrics that will be used to evaluate the performance of the solutions provided by students. As the proposed benchmark is prepared to work with batch processes, in this section performance metrics related to both continuous and sequential processes are proposed:

Evaluation metrics for continuous processes. To evaluate the performance of the controllers developed for the continuous part of the process, a quantitative analysis is performed. Set-point tracking analysis is based on the Integral Absolute Error (IAE) and the Integral Time-weighted Absolute Error (ITAE). Besides, the control effort is also evaluated by means of the Integral Absolute Variation of control signal (IAVU) index (Bejarano et al., 2018).

Evaluation metrics for sequential processes. On the contrary, the goodness of the sequential part of the process has also to be evaluated. Despite Petri Nets models developed by students can be graphically compared with a standard solution, it might be appropriate to establish some quantitative metrics. To do that, it is possible to use some toolboxes as the one presented by Matcovschi et al. (2003) which will estimate some statistics related to transitions and places as utilization, distance between arrivals, queue length, etc. The meaning of these metrics will vary as a function of the batch process selected. For instance, in Renganathan and Bhaskar (2012) the metric *Arrival distance* refers to the time taken for filling some tanks and the metric *Service distance* defines the time taken for draining the liquid from the tanks through valves.

4. EXAMPLE OF BENCHMARK: BEER MANUFACTURING PROCESS

To illustrate the capabilities provided by the presented prototype, in this section an example of benchmark is expounded. More in detail, the proposed example focuses on a beer manufacturing batch process, covering from fermentation process to packing, see Fig. 4. On the one hand, the fermentation process has continuous dynamics, as temperature and pressure should be controlled during it. On the other hand, to obtain a finished bottle of beer several steps have to be carried out in the same order (e.g. fermenting, conditioning, filtering, packaging), so the case detailed below consist of both continuous and sequential processes. A detailed description of the beer manufacturing process and the proposed activities is included. The standard solution of this benchmark has not been included in this paper due to the lack of space.

4.1 Problem description provided to students

Supposing that barley grains have been prepared in an appropriate way to begin the fermentation process, the fermentation tank receives the appropriate amount of wort and yeast. Inside fermentation tank it is necessary to control indoor temperature and pressure, which can be considered a continuous process. To do that, a valve that regulates the amount of water which flows through the cooling jacket (V_{water}) and a valve used to extract CO_2 originated by the fermentation process (V_{CO_2}) are used. The relations among indoor temperature and pressure in the fermentation tank as a function of these valves can be observed in Fig. 5. Hence, the control system has to maintain the temperature and pressure inside the fermentation tank equal to 13°C and 1.4 atm respectively. Besides, the temperature of the wort affects the indoor temperature, an thus, it can be considered as a disturbance.

Afterwards, the product resulting from the fermentation process is discharged into the maturation tank. To do that, it is required to open the valve V_{ferm} and to turn on the pump named as $Pump2$. The process of filling this tank ends when sector M_{HL} is activated. Once the maturation tank is full, the product should remain in the tank 40 s. Then, the product is translated to the carbonation tank by opening the valve V_{mat} and turning on the pump $Pump3$. The process of filling the carbonation tank finishes when sensors M_{LL} or C_{HL} are activated. The carbonation process lasts for 60 s. Subsequently, pump $Pump4$ is turned on to move the beer from the carbonation tank to the storage one until sensor Alm_{HL} is activated.

Finally, the bottles are filled using the beer stored in the storage tank. To do this, the motor of the conveyor belt must be switched on until a new empty bottle is detected (activation of sensor d). To fill the bottle, it is necessary to open the V_{ALM} valve for 5 s. Each storage tank allows to fill 24 bottles. Besides, at the end of the conveyor belt there is a robot responsible for picking the bottles up from the conveyor belt and placing them inside a box. When this box is completely full the same robot moves the box from the conveyor belt to a pallet located next to it.

4.2 Proposed activities

Once that the benchmark has been defined, it is necessary to define the activities to be performed by students. It is worthy to mention that the prototype has been thought to be used during the whole subject, and thus, these activities should be proposed based on the theoretical concepts included in this course. In this paper, these activities are proposed for the subject Industry 4.0 within the Master's Degree in Computer Science: Technologies and Applications program. More in detail, the laboratory practices proposed can be summarized as follows:

- To make an analysis of the beer manufacturing process identifying inputs, outputs, and auxiliary variables needed to its control.
- To develop a model of the proposed process by means of Petri Nets. Moreover, students should obtain models related to the continuous dynamics of the process, that is, the fermentation tank, by means of classical identification techniques.
- To design a controller for the complete process using PLCs. To do that, students should realize the following steps: i) to perform the physical connection between the HIL prototype and the PLC and, additionally, to establish the memory mapping inside the PLC based on how they have connected the HIL prototype and the PLC; ii) to implement in structured language a controller of the continuous part by means of simple control loops, like feedback or feedback+feedforward approaches; and iii) to implement using ladder-diagram or instruction-list languages the control of the complete process.
- To establish a connection between the PLC and a computer or a tablet through the use of industrial communication networks as Industrial Ethernet.
- To develop a SCADA system of the process.

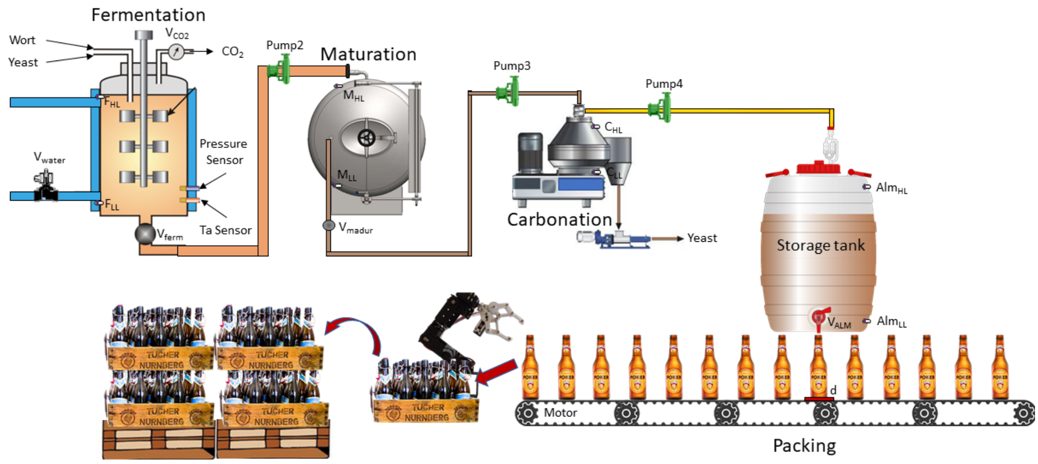

Fig. 4. Scheme of the proposed benchmark: Beer manufacturing process

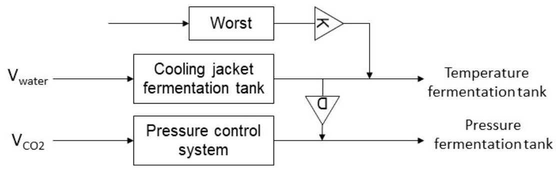

Fig. 5. Existing relations in the fermentation tank

Finally, students should test the goodness of their controller using the performance metrics shown in Section 3.4.

5. CONCLUSIONS

Most part of existing industrial processes have mixed dynamics, that is, continuous and sequential ones. Hence, it is necessary to find new alternatives which allow to reinforce theoretical lessons with laboratory practices which prepare students to job market. This paper presents a Hardware-in-the-Loop prototype which allows the use of mixed dynamic processes into laboratory practice sessions by means of benchmarks. It can be used for both automation and control training. Moreover, performance metrics for the evaluation of those benchmarks have been proposed.

As future works, in the next academic course the complete prototype is going to be used with students of bachelor degrees. Besides, they will be asked to fill in an anonymous survey to express their opinion about the HIL prototype and how this experience can be improved before extending its use to other subjects.

REFERENCES

Arduino (2019). Official website: https://www.arduino.cc/ (Last accessed on 6th November 2019).

Bejarano, G., Alfaya, J., Rodríguez, D., Morilla, F., and Ortega, M.G. (2018). Benchmark for PID control of refrigeration systems based on vapour compression. *IFAC-PapersOnLine*, 51(4), 497–502.

Carballo, J.A., Bonilla, J., Roca, L., and Berenguel, M. (2018). New low-cost solar tracking system based on open source hardware for educational purposes. *Solar Energy*, 174, 826–836.

Celeita, D., Hernandez, M., Ramos, G., Penafiel, N., Rangel, M., and Bernal, J.D. (2016). Implementation of an educational real-time platform for relaying automation on smart grids. *Electric Power Systems Research*, 130, 156–166.

IEC (1993). International standard IEC 1131-3. *Standardized format for programming programmable controllers.*

Kotsampopoulos, P.C., Kleftakis, V.A., and Hatziargyriou, N.D. (2016). Laboratory education of modern power systems using phil simulation. *IEEE Transactions on Power Systems*, 32(5), 3992–4001.

Krupa, P., Limon, D., and Alamo, T. (2018). Implementation of Model Predictive Controllers in Programmable Logic Controllers using IEC 61131-3 standard. In *European Control Conference (ECC)*, 1–6. doi: 10.23919/ECC.2018.8550126.

Matcovschi, M.H., Mahulea, C., and Pastravanu, O. (2003). Petri Net Toolbox for MATLAB. In *11th Mediterranean Conference on Control and Automation*, 1–6.

Raspberry Pi (2019). Official website: https://www.raspberrypi.org/ (Last accessed on 6th November 2019).

Renganathan, K. and Bhaskar, V. (2012). Performance evaluation and model checking in systems modeled as Hybrid Petri nets. *Applied Mathematical Modelling*, 36, 3941–3947.

Rodríguez, F., Castilla, M., Sánchez, J., and Pawlowski, A. (2015). Semi-virtual Plant for the Modelling, Control and Supervision of batch-processes. An example of a greenhouse irrigation system. *IFAC Papers Online*, 48-29, 123–128.

Samin, R.E., Jie, L.M., and Zawawi, M.A. (2011). PID implementation of heating tank in mini automation plant using Programmable Logic Controller (PLC). In *International Conference on Electrical, Control and Computer Engineering 2011 (InECCE)*, 515–519. doi: 10.1109/INECCE.2011.5953937.

Schneider Electric M340 PLC (2019). Official website: https://www.se.com/es/es/product-range-presentation/1468-modicon-m340/ (Last accessed on 6th November 2019).

Tejado, I., Serrano, J., Pérez, E., Torres, D., and Vinagre, B.M. (2016). Low-cost hardware-in-the-loop testbed of a mobile robot to support learning in automatic control and robotics. *IFAC-PapersOnLine*, 49(6), 242–247.