Virtual Training Module for the Extraction of Essential

Oils using a Distillation column

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Centro de Posgrados

Maestría en Electrónica y Automatización con mención en Redes Industriales

Artículo científico, previo a la obtención del título de Magíster en Electrónica y Automatización con mención en Redes Industriales

Ing. Andaluz Ortiz Víctor Hugo Ph.D

23 de enero del 2023

Virtual Training Module for the Extraction of Essential Oils Using a Distillation Column

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Abstract. The present project considers the development of a training system for a distillation column used for essential oil extraction processes based on the Hardware-in-the-Loop technique. The mathematical model is of the multivariable MIMO type obtained through the heuristic method considering the perturbations. According to the mathematical model obtained from the plant, it is implemented advanced nonlinear control algorithms that consider PID, FUZZY and MPC techniques. This allows the performance of the proposed controllers to be analyzed by means of the response time. With this information, the stability and robustness of the implemented algorithms are analyzed to evaluate the response of each process and possible errors. The system has an interactive and immersive virtual environment through a 3D graphic engine (Unity). The communication is bilateral in real time so that the process can be controlled and monitored. The implemented HMI interface is multifunctional as it can simulate the process in case the real plant is not available. The mathematical model resides in the virtual environment and the control is realized directly from MATLAB; with the real process, it would work as a graphical interface that allows showing the obtained results from the hardware.

Keywords: Training systems · Hardware-in-the-Loop · Distillation column · Control algorithm · HMI interface

1 Introduction

Industry 4.0 emerged in Germany in 2011, used to implement high-tech strategies that integrate advanced control systems with ICT to enable communication between the people, products and complex systems that make up an industry [1], considering the technologies that are integrated in the so-called CPS (Cyber Physical Systems), changes are generated in engineering systems and higher education [2], at the same time this allows the development of embedded systems, their connectivity and interaction of the physical world with the virtual world, providing integration of objects, information and people, which improves the production and use of goods and services, this being its main advantage; in addition, by associating various technologies, data can be stored in clouds, generating shared information, giving access to all authorized personnel in the industry [3]. The main technologies involved in Industry 4.0 are: *(i) Big data and data cloud:* manages opportunities for the improvement of future factories, manufacturing processes

M. Botto-Tobar et al. (Eds.): ICAT 2022, CCIS 1755, pp. 1–15, 2023.
https://doi.org/10.1007/978-3-031-24985-3_4

and enable the factory to provide new products and services [4]; (ii) *IoT or Internet of Things:* has applications to support industrial networks; it also performs intelligent monitoring and control through sensors, smart meters and smart mobile devices; (iii) *Smart manufacturing processes:* include dynamic, efficient processes, automated and real-time process communication for the management and control of a highly dynamic IoT-enabled environment; *(iv) Robotics:* they acquire innovative skills with capabilities to work without a human supervisor, including working to automate and coordinate a range of logistics processes and production tasks; *(v) Virtual Reality (VR):* Recreates spaces and situations in a virtual and interactive way, allows training industrial systems so that the user knows what he has to do in a real situation [5].

Virtual reality allows the virtualization of a process or scenario. Its objective is to provide the user comfort with a sense of immersion and interactivity to capture their attention [6]. It has diverse applications: support in design, industrial, education and commercial activities. The systems that use this digital tool have a very detailed perspective since it is possible to visualize structures and installations that are difficult to access, in addition to facilitating the design and appreciation of a realistic environment [7]. For industry and education, virtual systems can be effective and useful induction modules. Virtual environments seek to implement collaborative spaces that facilitate users to acquire skills and familiarize themselves with activities that will be carried out in real life [8]. In turn, these processes integrate actual parameters and units, which are of importance for new users of the facilities [9]. Virtual environments allow us to visualize the behavior of the control algorithms implemented in the simulations, which helps us to safely identify errors and monitor the functionality of the systems [10].

Advanced control algorithms allow to take control of a certain process, they can be implemented in embedded cards, computer software or with logic gates, the algorithms used are in open and closed loop with or without disturbances [11]. They can be simulated in free and commercial software, some of the control algorithms at industrial level are; *i) PID:* they are algorithms used with three variables: proportional, derivative and integral, hence their acronym [12], *ii) FUZZY:* for its implementation, lines of code are generated establishing rules or conditions to be fulfilled [13], *iii) MPC:* It is a predictive type controller in which a prediction horizon is generated, it is programmed by code or block diagram [14]. For the project, the three controllers are implemented in MATLAB software, then the behavior of each of them is analyzed according to the expected results. The training systems use this methodology to simulate industrial processes [15]. For the project, the three controllers are implemented in MATLAB software, then the behavior of each of them is analyzed according to the expected results. The training systems use these algorithms to simulate industrial processes in real time. The method used to evaluate them is the Hardware-in-the-Loop technique since the HIL implementation includes the use of the Unity 3D graphic engine used for the development of the virtual environment [16].

The COVID 19 pandemic caused the suspension of on-site classes, so that students of technical careers did not have access to laboratories for practice, so a didactic training system is built for a distillation column for essential oil extraction processes through the Hardware-in-the-Loop (HIL) technique. The present work consists of the construction of a didactic module that includes hardware and software through the HIL technique, which allows to emulate the dynamic behavior of the distillation column, for which a control unit (Raspberry Pi) is implemented in which the mathematical model SISO is located, which was obtained through the heuristic method and determines the characteristics and restrictions of the industrial process, in addition to considering the disturbances of the plant in closed loop, the model will be validated with data obtained in scientific bases. The control algorithms implemented in closed loop are: PID, FUZZY and MPC, the behavior of each process and errors will be evaluated. With the information obtained, the stability and robustness of the implemented algorithms will be analyzed to evaluate the behavior of each process and possible errors. For the HMI interface, an interactive and immersive virtual environment is considered through a 3D graphic engine (Unity), with real-time bilateral communication between Unity 3D and MATLAB to monitor and control the process. In addition, to facilitate connectivity, a switch is implemented to select whether the connection is via ethernet cable or wireless; the virtual environment will be executable on other Android devices so that all students can easily access it.

The following document consists of six sections. Section 1. Introduction to the topic to be covered, Sect. 2. Describes the essential oil extraction process, mathematical model and applications. Section3. Describes the development of the virtual environment in Unity 3D software according to the industrial process, Sect. 4. Implements and analyzes the implemented control algorithms PID, FUZZY and MPC, Sect. 5. Presents the results obtained from the simulation and an analysis. Finally, Sect. 6 contains the conclusions of the project.

2 Extraction of Essential Oils

This section describes the SISO mathematical model of the essential oil distillation column plant to be used, which is obtained using the heuristic method and taking into account the perturbations, to then virtualize its behavior in the Unity 3D graphic engine. The following characteristics were established for the selection of the plant, in order to obtain the equations that describe the process.

2.1 Process Description

It is an industrial-type process (see Fig. 1) in which water is heated in a boiler to produce superheated steam, which is transported through a pipeline to the vessel, the steam helps to release the essential oil molecules from the plant by increasing the temperature and pressure. The oil molecules released from the plant are then mixed with the steam. This mixture rises through the hydro distiller and reaches the condenser, which allows the mixture to cool and change to liquid phase. Finally, the liquid mixture reaches the Florentine, where the oil and water are separated. This water is known as hydrolat or hydrosol and is valuable in various industries.

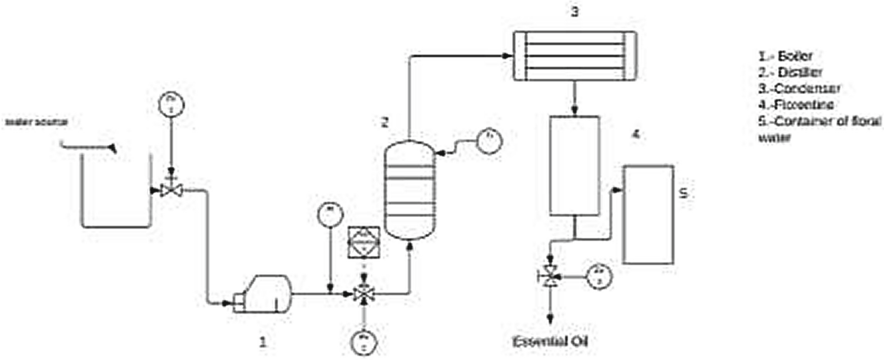

Fig. 1. P&ID diagram of the essential oil extraction process.

To determine the model of the essential oil extraction column, the following parameters are taken into account: The extraction system is isothermal and isobaric type, the number of leaves to be used in grams, the leaves should be similar in structure and preservation. The vapor phase inside the distillation vessel must have a perfect mixture, with a constant flow rate [17]. The accumulation of oil in the vapor phase is precise and thus facilitates the pure extraction of the oil. All the oil inside the trichomes is extracted during the process. The system consists of four phases: oil inside the trichome, condensed water, free oil outside the trichome and vapor phase. The essential oil is considered as a mixture of 1 or several components. The compound oil within the trichomes matches the distilled essential oil collected throughout the process. The composition is determined by GC/MS, gas chromatography (through) and mass spectrometry. Condensed water and essential oil are completely immiscible. The steam stream fed to the distillation vessel is free of impurities, that is to say that the oil is as pure as possible within the established times, for this process it is suggested between 0 to 30 min, since after that, burnt oil is obtained [18].

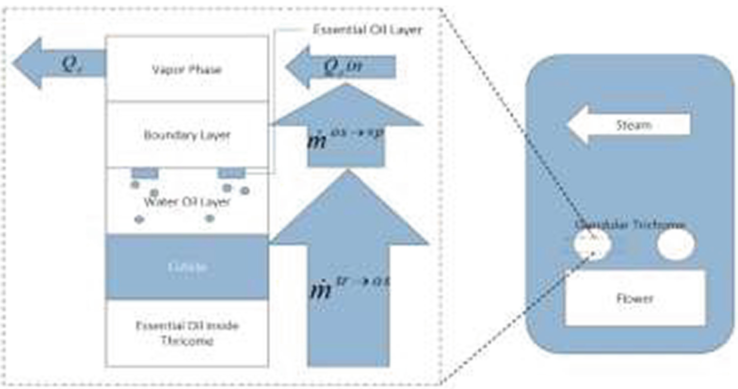

Fig. 2. Stages for the production of essential oils.

The mathematical model for the plant considers three stages (see Fig. 2) in the process of obtaining essential oils: *(i)* thermal oil whey obtained from the glandular trichomes, *(ii)* vapor-liquid equilibrium at the interface, taking into account the individual oil components, and *(iii)* oil mass transfer in the vapor phase [19].

Table 1 below shows the parameters under which each of the dynamic equations representing the mathematical model are evaluated.

Table 1. Initial plant conditions.

Acronym	Description	Used value
W	Leaf mass	2175 [gr]
K_{tr}	Kinetic constant of exudation	0.072 min^{-1}
C_1	Oil mass concentration equilibrium	0.001 [gr/cm^3]
h	Average thickness of oil spots	0,0115 [cm]
ρ_{eo}	Density of the essential oil liquid	1 [gr/cm^3]
$x_1(0)$	Initial oil mass fraction within trichomes	0.07[gr/gr]
$x_2(0)$	Initial mass of oil in the aqueous layer	0 gr
$x_3(0)$	Initial oil mass collected	0 gr

The following is a description of each of the stages for obtaining essential oils, taking into account the dynamics of the plant:

Stage 1. Thermal oil serum obtained from the glandular trichomes, to obtain it we use the following expression (1):

$$m^{tr \to os} = \frac{d(GW)}{dt} = K_{tr}GW \tag{1}$$

Stage 2. Equilibrium between vapor and liquid at the interface, taking into account the individual components of the oil, to determine this equilibrium we rely on the following expression (2):

$$\frac{dM^{os}}{dt} = K_{tr}GW - \frac{K_g M^{os}}{h\rho_{eo}}(C_1 - C) \tag{2}$$

Stage 3. Mass transfer of oil in vapor phase, as shown in (3).

$$\frac{dM^{sd}}{dt} = m^{os \to vp} = QC \tag{3}$$

These equations for the simulation of the different control algorithms implemented are represented in state spaces for which the variables change as follows: manipulated input ($x = u$), mass of oil inside the trichomes per mass of leaves $[gr/gr](x_1 = G)$ oil mass in the aqueous layer $[gr](x_2 = M^{os})$, oil mass collected $\left(x_3 = M^{sd}\right)$ [20].

The state vector (x) and the manipulated input (u) are defined as follows (4):

$$x = [x_1, x_2, x_3]^T = \left[G, M^{os}, M^{sd}\right]^T, u = Q \tag{4}$$

The following expressions (5), (6) and (7) represent the dynamics of the three stages of the oil extraction process in state spaces, for which the following change of variables is used $Q = u$ the same that represents the volumetric flow of the steam [cm^3/min]

System input is represented by u and the output is $x_3 = \sum_{i=0}^{n} x_{i3}$

$$\dot{x}_1 = -K_{tr} W x_1 \tag{5}$$

$$\dot{x}_2 = K_{tr} W x_1 - \frac{K_g C_1 x_2}{h\rho_{eo}}\left[1 - \left(\frac{K_g x_2}{\mu h \rho_{eo} + K_g x_2}\right)\right] \tag{6}$$

$$\dot{x}_3 = \frac{K_g \mu C_1 x_2}{(\mu h \rho_{eo} + K_g x_2)} \tag{7}$$

From the equations described above all are constant parameters except for K_g which is the mass transfer coefficient, which varies as a function of the vapor volumetric flow rate Q. According to the close relationship between these two variables and the experimental data obtained, the following expression is approximated, taking into account that the relationship is valid for flow rates that have as maximum and minimum values $21100 < Q < 100000\left[cm^3/\min\right]$, a constant steam flow is assumed $Q = u\left[cm^3/\min\right]$ [21]

$$K_g = 470.000(Q - 74400) + 31.4 \tag{8}$$

Once the equations of the mathematical model and each one of the parameters are established, each one of them is entered into the MATLAB software to validate the selected model. The graph below (see Fig. 3) shows the results obtained from the mathematical model implemented where (a) mass of leaves; (b) aqueous phase; (c) oil collected; (d) yield in percentage.

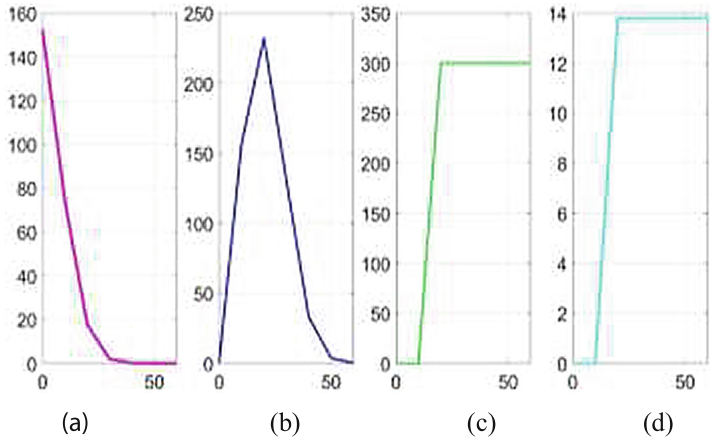

Fig. 3. Behavior of the mathematical model (a) mass of leaves; (b) aqueous phase; (c) oil collected; (d) yield in percentage.

3 Virtual Environment

For the teaching-learning process, virtual environments are oriented to simulate processes or scenes as in real life, to allow the person to interact with the simulation as if he/she were in the real environment. The objective of the training systems is to improve the implemented techniques and methods of the simulated processes, for their application in work or educational activities [22]. The implemented training system consists of a virtual environment designed in Unity 3D software in which the graphs obtained from each of the implemented control techniques (PID, FUZZY and MPC) will be shown. In addition, the environment allows the user to visualize the stages of the process as if they were in the industrial plant [23]. The virtual environment will additionally be executable on Android devices.

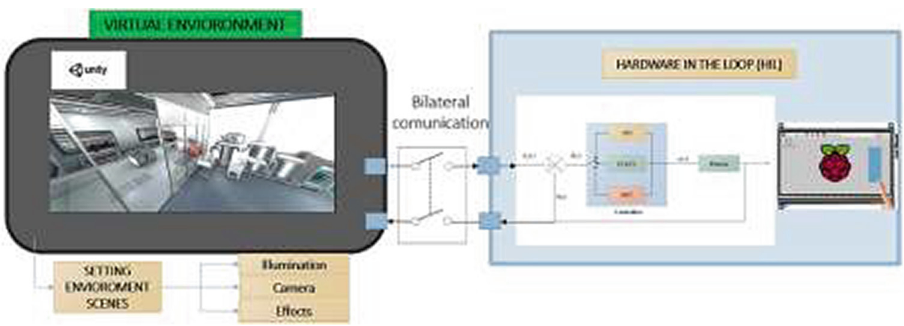

Fig. 4. Virtualization of the process.

The virtual environment for its development is based on the scheme presented in Fig. 4, which has the following phases: *(i) External resources:* includes all the components that are immersed in the virtual environment, which can be organized into two groups: (a) The simulation of the user who is represented by an Avatar and uses the simulator as a person would in real life; (b) the virtualized industrial oil extraction plant in which the different advanced control algorithms are implemented so that the behavior of the mathematical model can be controlled and verified. *(ii)* For the development process of the *virtual environment* in Unity 3D is organized in two groups: (a) Virtualized plant: this scenario has each of the processes followed to extract the essential oil, a control room where the graphs obtained from each controller (PID, FUZZY and MPC) are displayed, and an operator (Avatar) that simulates the user. It is worth mentioning that the communication between MATLAB and Unity 3D; (b) programming scripts are used to develop virtual environments, so for plant virtualization several scripts are used to simulate plant characteristics considering plant disturbances. The virtual input libraries are managed through scripts making communication and interaction in the system possible. Other scripts are used for virtual scenery, lighting and user interface. All scripts together make the simulated virtual environment interactive and immersive. *(iii) the controller* which allows the implementation of advanced control algorithms to evaluate and monitor plant behavior. The scheme implemented is based on a cascade system, using wireless communication to link the controller and the MATLAB software, as well as bilateral communication between the didactic module and the virtual environment, taking into account disturbances. Finally, we have *(iv) the human operator* whose function is to modify the simulation parameters and provide the disturbance data by means of the valve placed in the virtual environment and the module.

4 Control Algorithms

This section presents the proposed control algorithms for the essential oil extraction process, which are of nonlinear type. PID, FUZZY and MPC techniques have been considered to be implemented, this scheme (See Fig. 5) shows the design in two main stages according to the requirements of the system to be implemented: *(i)* In this stage MATLAB software is used to simulate the controllers based on the mathematical model of the plant; *(ii)* The second stage refers to virtual reality, for which the Unity 3D simulator is used in which the mathematical models that simulate the behavior of the industrial plant are placed. This system is designed so that the user can change the controller to be used and enter the value of the perturbation, also the process can be visualized on an Android device, which provides convenience to users and has a bidirectional communication [24].

Where: $x3_d$ are desired values (grams of essential oil harvested), $x3$ are actual process values, $\tilde{h}$ are errors entering the controllers, and finally u are the control actions.

4.1 PID Control

A classic control is the PID whose control algorithm consists of three basic methods, proportional (P), integral (I) and derivative (D), the most used are the basic algorithms P, PI or PID [18].

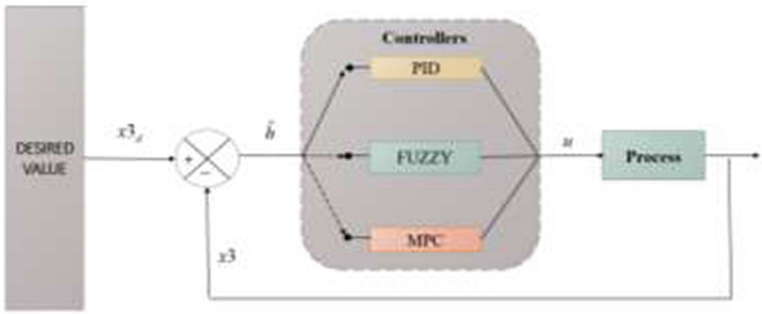

Fig. 5. General scheme of proposed controllers.

For the mathematical representation of a PID controller in discrete time, three control actions described in Eq. (9) are taken into account:

$$u(t) = k_c e(t) + \frac{k_c}{\tau_i}\int_0^1 e(t)dt + k_c\tau_d\frac{de(t)}{dt} \tag{9}$$

The error of the PID controller is defined by the difference of the Set Point, ($x3d$), and the process variable ($x3$), as shown in expression (10) in discrete time.

$$e(k) = x3_d - x3 \tag{10}$$

4.2 Fuzzy Control

Fuzzy logic aims to identify whether something or someone is part of a given set [23]. The steam entrainment essential oil distillation column has an input x = u which represents the volumetric flow; and an output which represents the collected essential oil x3, for the development of the Output Membership Functions (FMS) at the ends are placed trapezoids and in the center triangles, the operating range of the optimal oil output is [0–30] minutes which is the time taken by the extraction process and is constituted by the following sets: HM (high mass), MM (medium), LM (low). For the Inlet Membership Function (IMF) in a similar way as for the volumetric flow rate as for the volumetric flow whose range is 21100<u<10000 [cm^3/min], trapezoids are placed at the ends and central triangles, the operating range for the volumetric flow and is constituted by the following sets VS (very slow), M (medium), VF (very fast). For the development of this controller, a total of seven rules were established taking into account the inputs and outputs of the process.

4.3 MPC Control

The MPC controller applied to a SISO steam entrainment essential oil extraction system seeks to minimize the volumetric flow error. Therefore, it can be said that it seeks to minimize the abrupt control actions of the volumetric flow that affect the concentration of floral water and essential oil during steam entrainment, so the control of the process variable Q is performed to determine the control actions as shown in the following equation

$$J(k) = \sum_{i=N_w}^{N_p} \delta(k) \left\| \hat{h}(k+i|K) - h_d(k+i|k) \right\|_D^2 + \sum_{i=0}^{N_{C-1}} \lambda(k) \| \Delta u(k+i-1) \|_D^2 \quad (11)$$

Governed by the following boundaries

$$\Delta u_{\min} \le \Delta u \le \Delta u_{\max} \quad (12)$$

$$h_{\min} \le h \le h_{\max} \quad (13)$$

There are control action constraints such as volumetric steam flow as Δ_u. The same is true for the maximum and minimum limits of the process outputs represented by h. The constants and correspond to the weight of the error and the weight of the control action variations, respectively.

Where N_w, N_p and N_c are the start of the prediction horizon, the number of samples of the prediction horizon and the control horizon respectively; the control horizon must always be shorter than the prediction horizon; $\hat{h}$ are the predicted outputs of the collected oil mass. In addition, $\delta(k)$ and $\lambda(k)$ are constant values and thus $J(k)$ can be expressed as a function that depends only on future control actions. To implement the predictive control model, MPC, it is necessary to represent the equations in state spaces as shown in the expressions (5), (6) and (7).

5 Analysis and Results

This section presents the training system developed in each of its stages: the control algorithms implemented in the Raspberry Pi and in the MATLAB software. The virtual environment that shows the processes to obtain the essential oil, the valve that will allow us to enter the perturbations. In addition, the results obtained can be displayed on a screen in the didactic module and at the same time in the virtual environment in the control room.

5.1 Implemented Module

In Fig. 6 shows the electrical schematic implemented in the didactic module, which consists of the following components: *(i) Control unit:* a Raspberry pi 4 model b is used, for the power supply the power is transformed from 120/220 V to 5V in direct current; *(ii) Input:* the control unit has inputs for peripherals (keyboard, mouse, among others) and analog inputs; in our case we use this input to simulate disturbances in the plant. *(iii) Output Peripherals:* for the implemented module we have a 7" screen compatible with Raspberry pi and a monitor. The communication is bilateral between the module components, also the embedded card is the one that stores the advanced controllers for the simulation.

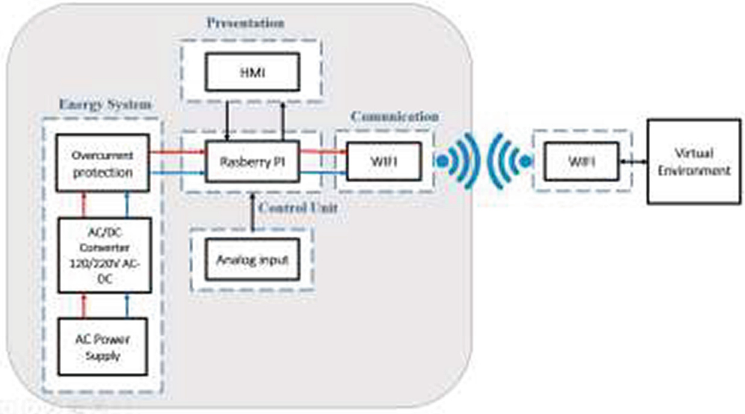

Fig. 6. Electrical block diagram

Fig. 7. Training module operation

5.2 Virtual Environment

The designed interface is developed in Unity 3D software (See Fig. 7a), for its development several scripts were taken as a basis for the simulation environment to be interactive and immersive. The design consists of a control station in which six screens can be displayed, two of them present the graphs of the variables of the mathematical model and the reaction of the traditional PID controller (See Fig. 7b), for the FUZZY and MPC control algorithm the same visualization method is used (model and control algorithm). The avatar shown in the environment can move around the plant simulating being the operator of the system, it is also responsible for interacting with the interface to give the appearance of entering the values required by the plant to operate and the values of the disturbances. It is also possible to visualize within the simulation each of the stages that must be followed to extract the essential oil.

Fig. 8. (a) Process control room, (b) SCADA monitoring and virtualized plant.

5.3 Implemented Control Schemes

The PID, Fuzzy and MPC control algorithms were implemented for the distillation column, which, when the process variables evolve in a given time, reach the desired value, therefore the control error value in the implemented controllers approaches zero. The implemented controllers have a correct operation since when the process variables evolve they reach the desired value in a certain course of time, due to this the control errors approach the value of zero in each of the variations made. In (Fig. 9) the implemented PID, FUZZY and MPC controls represent the response obtained from the plant as a function of the *(i) error*: the one that tends to zero asymptotically in the three controllers. *(ii) Control value*: in this graph it can be seen that when there is an overshoot, the controllers

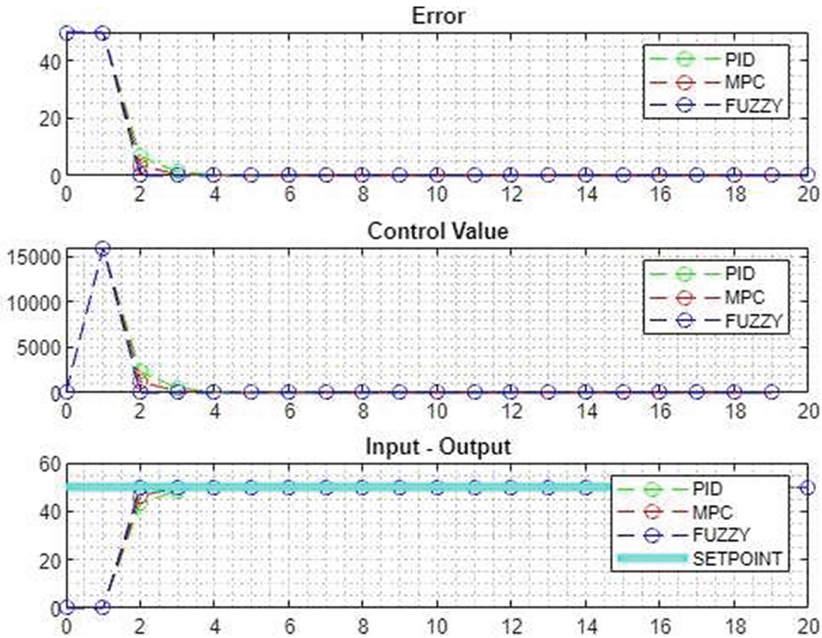

Fig. 9. Evolution of the system in the virtual environment.

perform an optimal process control since their performance is similar, the controller from which the best response is obtained is the FUZZY. *(iii) Inputs and outputs:* the three implemented controllers reach the desired values in the Set Point, being the PID control the slowest for the implemented process. It should be noted that our process is slow, so a range of 0 to 20 min is taken. Finally, after analyzing each of the responses obtained from the controllers, it can be said that the FUZZY controller is the optimal one for our process.

6 Conclusions

The design and construction of the virtual training module through the Hardware-in-the-Loop technique allows students to access the industrial practices in a realistic and friendly virtual environment, as it can simulate the process in case of not having the real plant as is the case of the process of extraction of essential oils by steam entrainment; the mathematical model runs in MATLAB online and communicates with the Unity platform, the Raspberry Pi card that acts as a control unit is responsible for running the MATLAB file online; Through this file it is possible to run and evaluate the response of each PID controller, FUZZY and MPC with respect to the plant allowing the user to act through the built-in HMI allowing the display of 2d screens with the responses of the algorithms applied in this project; having a Raspberry card can be connected to other attachments such as two potentiometers that act as analog elements and through them you can enter setpoint values and disturbances locally.

Acknowledgment. This article shows the results of the Degree Project of the Master's Programme in "Maestría en Electrónica y Automatización con Mención en Redes Industriales" of the Postgraduate Centre of the Universidad de las Fuerzas Armadas ESPE.

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