



Desarrollo de un entorno virtual 3D del proceso de refinación de azúcar, y control automático mediante un PLC utilizando la técnica Hardware in The Loop.

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Latacunga

3D virtual environment of the sugar refining process and automatic control using the hardware in the Loop technique.

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Abstract—This paper proposes the design of a 3D virtual environment of the sugar re-finishing process for the implementation of the Hardware in the Loop (HIL) technique and the design of PID controllers by means of a commercial programmable logic controller (PLC), developing operation and control tests in the plant. The 3D modeling of the virtual environment is developed from the P&ID diagram of the process, which indicates the arrangement of equipment and instruments with-in the virtual environment, the mathematical models of the process were developed from base equations, theorems and experimentation to determine the dynamics of operation of the sugar refining process, while the animations and realism were designed in the Unity 3D graphics engine. The interchange of information between the virtualized plant and the PLC, using the Modbus TCP/IP protocol, determined a fast and reliable communication. Finally, different control tests were developed, allowing to demonstrate that the HIL technique presents a complete control over the virtual plant as if it resembled reality.

Keywords- Sugar refining process, PID, PLC, Unity 3D, Modbus TCP/IP

I. INTRODUCTION

Industry 4.0 has required adapting to different environments, both in factories and laboratories, giving way to virtual environments as a tool for testing and design of controllers for automation systems, thus reducing the risks involved in real life [1]. An industrial process is made up of different operations to fulfil a specific objective, considering that dynamic variables such as: level, temperature, flow, pressure, among others, when properly controlled, increase the production, efficiency and quality of an industrial plant [2].

The sugar industry plays an important role in the commercial development of Ecuador with a total of 6 "sugar mills" distributed throughout Ecuador; sugar cane, abundant in the Ecuadorian coast and Amazon, is the main raw material used in the elaboration of the product [3]. The refining process in the sugar factories is composed of the following stages, as described in [4], i) sugar solution,

consists of mixing raw sugar with a little molasses and hot water to obtain a syrup that facilitates the execution of the following processes; ii) liquor cleaning, the dissolved sugar (syrup) is treated with phosphoric acid and lime to remove impurities from the clarifier through the formation of flocculants, and at the same time absorbing the dark color of the dissolved sugar.

Information on the operation of the sugar refining process is scarce due to factors such as: location, restricted access, private properties, etc., causing great problems among which are mentioned, loss of equipment, damage to machinery, personal accidents etc. The knowledge of the sugar refining process in conjunction with a control technique would solve different types of problems providing great benefits that are obtained by increasing the level of automatic control. [5]. With the advancement of technology, virtual reality is introduced into education, which allows the training in different environments that are not harmful to the practicing., facilitating the development of the cognitive and motor skills of future professionals [6]. The virtualization of the industrial process is designed to reduce the lack of experience in instrumentation and control operators in the industrial sector, with the following distribution: i) design a P&ID diagram, ii) 3D modeling of equipment and instrumentation, iii) application of animations and control variables in the plant [7].

The virtual environment is controlled by a physical PLC (Programmable Logic Controller) which is known as the Hardware in the Loop (HIL) technique, with the advantage of optimizing the tuning parameters (PID) to improve the robustness and reliability of the controller without the need to interrupt the real automated process, because the PLC does not differentiate between reality and simulation [8].

This work presents the development of a virtual environment of the sugar refining process and the automatic control by means of the HIL technique, which is divided into three substages: dissolving, preparation and mixing. All the equipment and components of each subprocess are designed from a P&ID diagram that is taken as a reference for the elaboration of the 3D plant using the Blender development soft-ware. The animation of the plant's objects is developed in the Unity 3D video game graphic engine. Within the virtual environment, is incorporated a control panel (HMI) that allows modified the control parameters (PID) and operation (PV, SP, CV) of each of the subprocesses, as well

as visualizing the evolution of each process variable. Communication was carried out through the use of an industrial protocol (ether-net) between Unity 3D and the PLC, where traditional control algorithms (PID) are implemented, which allow the evolution of the process to be controlled and visualized in real time. Providing a low-cost solution within the educational approach to expand the knowledge of students in the area of automatic process control.

This article is organized by the following stages: section 2 describes the system structure specifying the implementation of the virtual environment. The design and 3D modelling based on a P&ID diagram is described in section 3; section 4 describes the mathematical models used and the design of the PID controllers; section 5 describes the analysis of the experimental results; and finally, section 6 describes the conclusions obtained from the work.

II. SYSTEM STRUCTURE

This paper presents the development of an immersive virtual environment based on the HIL technique. The 3D design and modelling developed in Blender software is based on P&ID diagrams. The virtual environment of the process is based on three dynamic variables which are temperature, level and concentration (pH) whose mathematical models were obtained through design and experimentation; the virtual environment consists of three sub-processes (dissolving, preparation and mixing) and a control panel, where an HMI (Human Machine Interface) is displayed for visualization and control of the system variables. Communication between the S7-1200 PLC and the virtual environment uses the Modbus TCP/IP protocol together with the Uni-ty "SHARP7" library. See Fig 1.



Figure 1. System Structure.

III. DEVELOPMENT OF THE VIRTUAL ENVIROMENT

This section presents the methodology used to virtualize the industrial process corresponding to sugar refining, considering the P&ID diagram, the design of the components in the blender software, programming in Unity 3D, human-machine interface and communication between simulation and controller. See Fig 2.

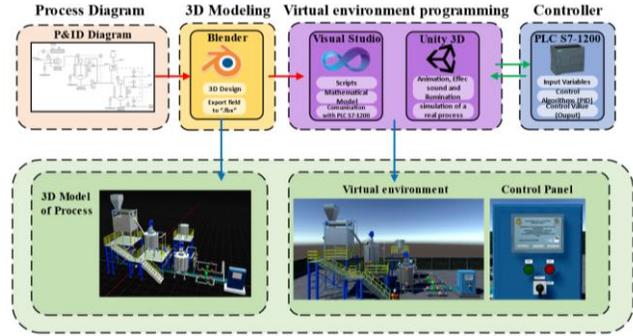


Figure 2. Process virtualization diagram.

A. P&ID diagram

The P&ID diagram is realized with ISA 5.1 and ISA 5.3 standards. The diagram consists of 3 sub-processes, the first one called "Dissolving tank", with a control valve (CV1) at the steam inlet, the product is conveyed by gravity to the next sub-process called "preparation tank", a control valve (CV2) is located at the steam inlet, it also has a centrifugal pump controlled by a variable frequency drive (VFD), with feedback to the same tank and sent to the next sub-process, between the second and third sub-process the acid is integrated with a concentration of 50% to enter the third sub-process, where has as actuators three control valves (CV3, CV4, CV5) corresponding to the variables temperature, level and concentration, respectively, the evolution of the variables is appreciated through the transmitters (TIT,LIT,CIT) that send 4 to 20 mA signals to the PLC, returning standard signals for the actuators (Control valves, VFD). See Fig 3.

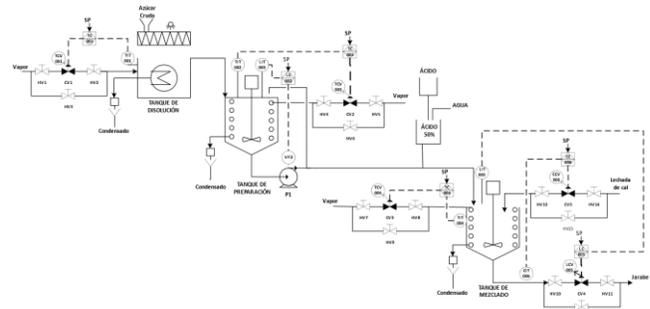


Figure 3. Process Instrumentation and Piping Diagram.

B. 3D desing in blender

Blender is part of the wide range of 3D development software, with the following advantages: it is cross-platform, has a varied list of useful tools, is composed of an OpenGL graphical user interface (GUI), has a large repertoire of information and an active community [9]. Taking advantage of the free access provided by the GNU license, the infrastructure, piping, equipment and devices mentioned in the P&ID diagram that contribute to the sugar refining process are modelled. See Fig 4.

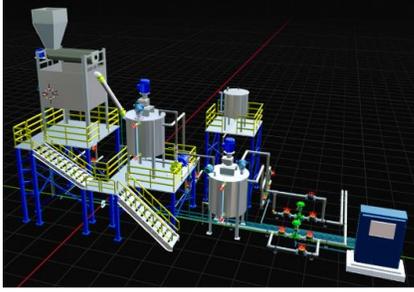


Figure 4. Industrial plant desinged in Blender.

C. Desing in Unity 3D

The Unity software allows the creation of 2D and 3D video games, applications on Windows, Mac, Android platforms, giving the user the ability to create virtual environments under a free personal license [10]. Considering the intuitive graphical inter-face for handling the animation, and characterization of the components and devices of the 3D model of the sugar refining process, this software is used to provide unique experiences to the user. See Fig 5.



Figure 5. Virtual enviroment developed in Unity 3D.

D. User Interface

A control panel is designed that incorporates an HMI that allows the user to interact and observe the evolution of the process variables in real time. The HMI contains three screens in each sub-process called operation, tuning and trends, as shown in Fig 6. It is also important to highlight that it has the possibility of directing the user to the transmitters located in the field, as well as instantiating the desired setpoint values (SP), the PID tuning parameters of each control loop and, in manual mode, modifying the control value (CV).

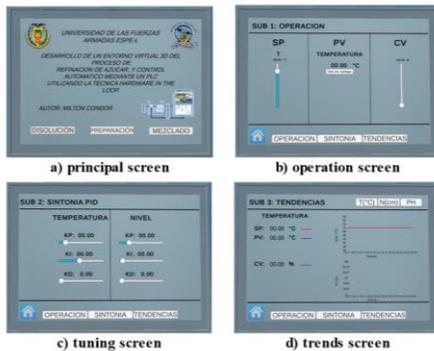


Figure 6. User Interface screens.

E. Communication with the virtual enviroment

The communication between the virtual environment of the sugar refining process and the S7-1200 PLC was implemented through the S7Protocol operating as a Snap7 Client port with the name "Sharp7", compatible with the Siemens S7-1200 device that is used in this work under the GNU Library license. [11], allowing unrestricted use of its resources.

The exchange of information by means of the S7Protocol consists of direct access to the variables located in the PLC. The PUT/GET function must be enabled in the programming software (Tia Portal) to establish the connection via Ethernet through a C# script that exchanges the information by means of addresses called "offset" located in the database created by the PLC.

IV. MODELLING AND CONTROL

Industrial processes due to their structure, conditions, and designs are represented by mathematical models that allow to approximate the real process dynamics to the simulated dynamics.

A. Mathematical modelling

The sugar refining process consists of the sub-processes of dissolving (SpD), preparation (SpP) and mixing (SpM), characterized by variables such as: Temperature, Level and Concentration are modeled from initial models, theorems, articles, etc. The temperature variable is present in the three sub-processes, starting with the base model extracted from [12], as well as the level model for the two final sub-processes, where modifications are necessary to obey the dynamics of each sub-process. The concentration variable is determined by means of a mass balance as proposed in [13], It should be noted that the constants and variables used by the heaters in this process are determined by experimentation and are obtained at [14], as well as the initial conditions.

TABLE I. NOMENCLATURA OF MATHEMATICAL MODELS

Temperature	Level	Concentration
T : variable temperature	h : height	C : concentration
F : variable flow	F : flow	F : flow
V : volume	A : area	V : volume
Q : heat input	fo : outward flow	
ρ : density	b : delay time	
Cp : calorific capacity	aK : valve constant	
a : delay time	g : gravity	

Table 1 contains the general nomenclature of the variables used in the mathematical models, however, some variables have suffixes such as: i, j, a, c, and s corresponding to initial, syrup, acid, lime slurry, and output, respectively.

Mathematical model of temperature present in SpD, SpP, and SpM

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \frac{Q(t-a)}{pVCp} \quad (1)$$

$$\frac{dT}{dt} = \frac{1}{V} [F_j(T_j - T) + F_a(T_a - T) + F_c(T_c - T)] + \frac{Q(t-a)}{pVCp} \quad (2)$$

Mathematical model of level present in SpP, and SpM

$$\frac{dh}{dt} = \frac{1}{A\rho_s} [\rho_j F_j + 0.2(f_o(t-b)) - 1.2f_o(t)] \quad (3)$$

$$\frac{dh}{dt} = \frac{1}{A} [F_j + F_a + F_c - aK\sqrt{2gh}] \quad (4)$$

Mathematical concentration model present in SpM

$$\frac{dC}{dt} = \frac{1}{V} [F_j(C_j - C) + F_a(C_a - C) + F_c(C_c - C)] \quad (5)$$

Equations 1 and 2 represent the temperature variable of the dissolution and mixing subprocess respectively, highlighting that equation 1 is repeated in the preparation process; equations 3 and 4 symbolize the level variable of the preparation and mixing subprocess respectively, finally, the concentration variable present only in the mixing subprocess represented by equation 5, resulting in a total of 5 equations, de-fined in C# scripts with a sampling time of 0.1 sec.

B. Validation of mathematical models

To determine the open-loop response of the different processes, the process input must be excited to analyze the evolution of the output variable, using the mathematical software MATLAB, the response of the level, concentration and temperature models of the mixing subprocess to a step input is shown. See Fig 7.

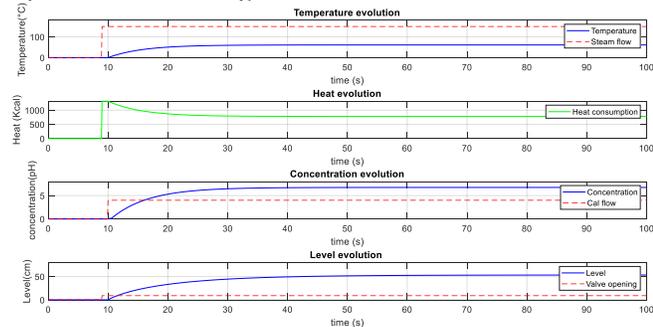


Figure 7. Responses to a step input from the mixing aubprocess.

Figure 7 represents the correlation between the mathematical models of the sugar refining process in the SpM. The temperature in the tank evolves by means of heat exchange from the incoming steam, which reduces the initial heat due to heat transfer; this phenomenon occurs in the three sub-processes. For the implementation of the system it was considered to interact the outputs of the previous process

with the next one, producing internal perturbations of the system that will be reflected in the results section

C. Controller desing

The traditional PI, PID tuning methods are widely used in the industry, the Lambda method stands out for having equations that determine a robust or aggressive response, to determine the gains of the PID controller it is necessary to approximate the mathematical model in the time domain to a model in the frequency domain of first order with delay [15].

The method of obtaining data consists of extracting the information from the PLC tags through OPC communication, allowing to save the information of the inputs and outputs of the mathematical models of the virtual environment, to be processed in the Ident tool of Matlab, thus obtaining a first order model with delay in the frequency domain. See table 2.

TABLE II. DELAYED FIRST-ORDER MODELS OF THE SUGAR REFINING PROCESS STAGES

Variables	Dissolution subprocess	Preparation subprocess	Mixing subprocess
Temperatur e	$\frac{1.1516}{1+3.0975s} e^{-0.1s}$	$\frac{0.9842}{1+2.3816s} e^{-0.1326s}$	$\frac{1.1062}{1+1.6965s} e^{-0.1s}$
Level		$\frac{0.77}{1+4.522s} e^{-0.1s}$	$\frac{0.6045}{1+5.1958s} e^{-0.0945s}$
Concentrati on			$\frac{0.903}{1+3.3115s} e^{-0.3273s}$

The lambda tuning method works with the model parameters in the frequency domain, such as: gain, settling time and dead time, therefore, it is considered to use the robust and aggressive controllers for the control of the variables within the sugar refining process. See Table 3.

TABLE III. PI, PID CONTROLLER PARAMETERS: LAMBDA

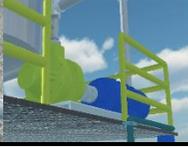
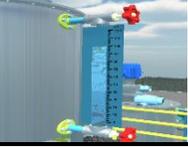
	Kp	Ti (seg)	Td (seg)
SpD Temperature (Robust)	0.2863	3.0975	0
SpP Temperature (Robust)	0.3448	2.4479	0.0400
SpP level (Aggressive)	1.2694	4.5219	0
SpM Temperature (Robust)	0.3071	1.7475	0.0291
SpM level (Aggressive)	1.6246	5.1958	0
SpM Concentration (Aggressive)	1.1066	3.4751	0.1559

V. EXPERIMENT RESULTS

This section presents the implementation of the HIL technique in the control of the sugar refining process. The virtual environment includes equipment, instruments and accessories shown in Table 4. The executable application of the virtual environment containing the mathematical models that govern the behavior of the plant is installed on a computer with Windows 10 operating system, sixth generation Intel Core I5 processor. The control algorithms

are programmed in a programmable logic controller (PLC.1200 CPU 1214 AC/DC/RLY), while the communication between the virtual process and the controller is developed through Ethernet with the Modbus TCP/IP protocol and the Sharp7 library.

TABLE IV. INDUSTRIAL INSTRUMENTS AND DEVICES

Temperature transmitter (TIT)	Level transmitter (LIT)	Concentration transmitter (CIT)
		
Control valve	Centrifugal pump	Level indicator
		
Control panel	Mixing tank	Virtual plant
		

The physical variables that make up the sugar refining process are determined by the dynamic models implemented in the virtual environment. For the calculation of the PID parameters, the first order mathematical models with delay are needed, which are obtained with the MATLAB tool "ident", which have an approximation of more than 96%. See Fig 8.

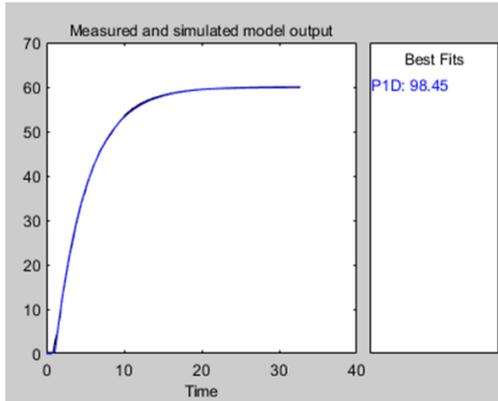


Figure 8. Percentage of approximation of the SpP level model.

The temperature, level and concentration variables of each sugar refining sub-process is controlled by the robust and aggressive lambda method (PI, PID), the gains obtained and implemented are shown in Table 3. The behavior of the variables in front of the control algorithm is characterized by

slight oscillations and over impulses generated by the control signal. See Fig 9.

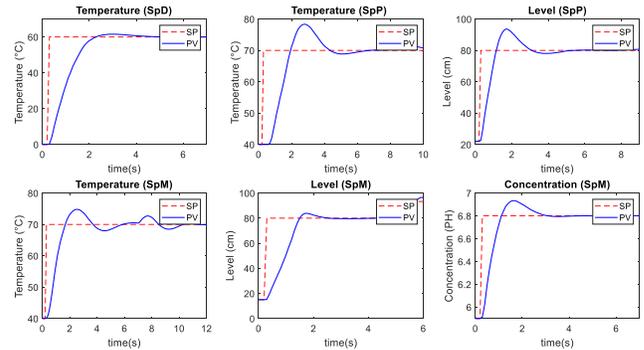


Figure 9. Behavior of the variables of the industrial sugar refining process.

For an industry it is essential to maintain the process variables at a desired value, therefore, in the sugar refining process the desired set points for the temperature variable in SpD start with a value of 60°C, allowing the raw sugar to be converted into syrup to be transported by piping to the following sub-processes (SpP, SpM), where it is maintained at temperatures above 65°C [16]. The system tends to correlate the sub-processes due to its physical structure, when there is a set point change in the temperature of the SpD or SpP it causes successive disturbances in the inlets of the preparation and mixing tanks respectively. see Fig 10. In addition, in the SpM the tank temperature is disturbed by changes in concentration due to the inlet of the lime slurry, which has a certain temperature.

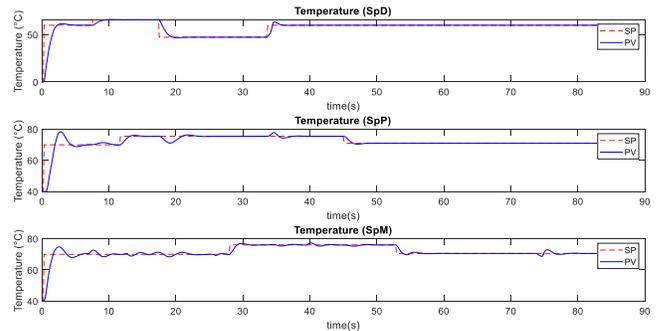


Figure 10. Correlation of temperature at SpD, SpP and SpM.

The final stage of sugar refining consists of maintaining the SpM process variables at the desired value, sugar is a commercial product that must meet certain quality and protection parameters, therefore, the concentration of hydrogen ions (pH) must be maintained in the range of 6.5 to 7.2 by adding lime slurry. The concentration process has disturbances due to the level variable SpP and in turn the concentration generates disturbances in the level variable SpM, where the reliability and robustness of the control algorithms previously designed with the lambda method is tested. See Fig 11.

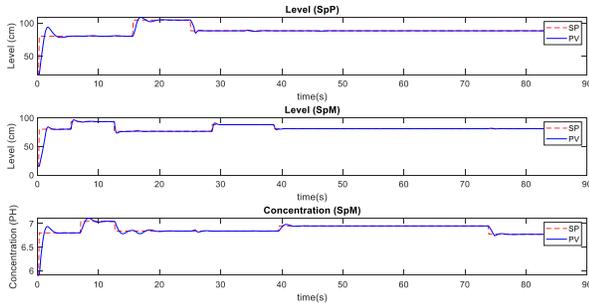


Figure 11. Evolution and effects of concentration.

The information exchange between the virtual environment and the PLC has a response time of 0.1 second. Figure 12 shows the graphic interface that simulates an HMI where the temperature evolution of the dissolution subprocess is displayed, demonstrating the robustness of the control signal and the compensation produced by the internal disturbances.

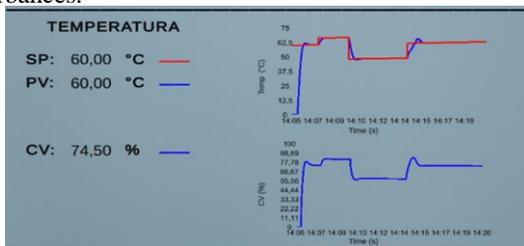


Figure 12. temperature trend displayed on the HMI.

VI. CONCLUSIONS

The implementation of the Hardware in the Loop technique for the sugar refining process present in the sugar industries of Ecuador proved the HIL paradigm that consists of deceiving the physical controller into thinking that it is connected to an industrial process when in reality it is a virtual environment simulated on the PC. Therefore, the use of the virtual environment designed facilitated the understanding of the operation of the sub-processes (dissolution, preparation and mixing) that make up the sugar refining process. In addition to the contribution it has in the training of professionals by the great similarity with reality achieved by designing the virtual environment, giving the user the experience of becoming familiar with the transmitters of the brand rosemount with the following series: 3144p (TIT), 5408 (LIT), and 5081p (CIT) widely used in the industry.

The use of the commercial controller S7-1200 CPU 1214 AC/DC/RLY allowed acquiring the necessary experience for the design of controllers through the handling of blocks of the TIA PORTAL programming software and the PID Lambda tuning method, resulting in a robust controller against disturbances and setpoint changes possible with the communication through the Modbus TCP/IP protocol that demonstrated its reliability and speed in the transmission and reception of information as a bilateral communication channel between the controller and the virtual environment, increasing the performance of the PID control algorithms.

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