



Desarrollo de un entorno virtual 3D del proceso de granulación de nitrato de amonio y control automático mediante la técnica de hardware in the loop e integración de la red industrial AS-Interface

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Carrera de Ingeniería en Electrónica e Instrumentación

Artículo académico, previo a la obtención del título de Ingeniero en Electrónica e Instrumentación

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6 de enero del 2023

Latacunga

Development of a 3d virtual environment of the ammonium nitrate granulation process and automatic control using the hardware in the loop technique and integration of the industrial network as-interface

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Abstract—This article presents the control and virtualization of an ammonium nitrate granulation process using the Hardware In the Loop (HIL) technique and the implementation of an industrial AS-Interface (AS-i) network. A virtual process with similar characteristics is implemented using CAD tools and the Unity 3D graphics engine, with the aim of simulating the behavior of an industrial process; which by using Arduino cards allows the generation and reception of standard electrical signals, which enable direct connection to an AS-i network. The result is an interactive and immersive virtual environment between the user and the industrial process, as well as successfully achieving the connection of the simulated process with an AS-i network and with a Programmable Logic Controller (PLC), until it ends in a supervision system. The dynamic modelling of a complete ammonium nitrate granulation process is incorporated into the virtual environment, as well as the virtualization of sensors and actuators typical of an industrial process, so that the virtualization is faithful to a real process.

Keywords-component; Granulation Process; Ammonium Nitrate; Hardware In the Loop; AS-interface.

I. INTRODUCTION

For its properties, ammonium nitrate is a compound that is widely used in various kinds of industries. Its main uses are in the manufacture of fertilizers and explosives. Ammonium nitrate is a salt composed of ammonium and nitrate ions, with a high nitrogen content. Its formula is NH_4NO_3 . The production of ammonium nitrate must be strictly controlled, because this compound can cause explosions, burns and other accidents. [1]

The production process in the fertilizer area starts from a storage and feed tank where a constant level is considered from which a weak solution of ammonium nitrate NH_4NO_3 is pumped to a single effect evaporator, evaporation is used to obtain products with high concentration with low energy impact, because only the first effect requires energy produced in a process outside the evaporator. Evaporators

with 1 to 8 effects are mainly used in industry, depending on the heat capacity of the substance, so the use of a single effect evaporator is analyzed, which is controlled by valves. [2-4]

The concentrated solution is pumped into a stirring-tank, in which a uniform mixture is assumed, then the concentrated solution is pumped to the top of a granulation tower, the concentrated NH_4NO_3 solution is blown from the top against an updraft of air. With the air, the droplets are cooled spherically and the moisture is partly re-moved from the compound, after which the residual moisture is removed by a rotary dryer. [4,5]

In this context, it is of utmost importance to control processes related to the manufacture of nitrogen-based fertilizers, since there is no production of this type of fertilizer in the country and training future professionals would lead to a new area of production that mainly favors the agricultural sector, which has a great weight in the total production of the country [6]. Therefore, acquiring knowledge about the ammonium nitrate granulation process becomes a complex task in the absence of a real plant or one that resembles the system mentioned before.

Based on this problem, the Hardware In the Loop (HIL) technique is presented as solution, which adapts to the established needs. HIL simulation is very much in demand nowadays, where some of the control loop components are physical and some are simulated. Usually, a process is simulated because it is not available or because performing experiments with a real process is too costly or time consuming [7]. In addition, the practice of HIL simulation aids the educational process at university and prepares students for professional commitments in industry [8].

This paper presents the control and virtualization of an ammonium nitrate granulation process using the Hardware In the Loop (HIL) technique and the implementation of an industrial AS-Interface (AS-i) network. In the HIL technique, only the ammonium nitrate process is simulated in a virtual environment, while the signal generation

(transmitters, actuators), the AS-i network and the controller are physical. A virtual process with similar characteristics is implemented using CAD tools and the Unity 3D graphic engine, with the aim of simulating the behavior of an industrial process; which by using Arduino cards allows the generation and reception of standard electrical signals (4-20mA), which enable direct connection to an AS-i network and therefore to the Programmable Logic Controller (PLC).

The stages that comprise this work are composed as follows: Section 2 describes the System Structure, where the development and implementation of this work is detailed, in addition to obtaining the mathematical models of the process, which are fundamental for the complete operation of this project. Section 3 specifies the development of the 3D modelling with help of CAD tools for subsequent animation in a 3D simulator, and the generation of electrical signals for the emulation of inputs and outputs used in the AS-i industrial network. Section 4 corresponds to the control scheme, which defines the control strategies applied to each process variable, followed by the development of the HMI supervisory system design. Section 5 shows the analysis and results of the system operation, its implementation and correct communication between the virtual environment and the controller through the AS-i industrial network, the functionality of the transmitters and actuators, and the response curves of the process variables with their corresponding optimal controller. Finally, Section 6 describes the conclusions of this project.

II. SYSTEM STRUCTURE

This article is oriented to the use of the multiplatform game engine UNITY 3D in order to virtualize components (physical structures, transmitters and final control elements) that favor the understanding of the behavior of the plant starting from a P&ID diagram that is taken as a reference for the creation of the plant in 3D using computer aided design (CAD) software.

The virtualization of an ammonium nitrate granulation process in conjunction with standard electrical signals via serial communication to electrical input and output cards connected to an AS-i network, allows the implementation of control strategies; as result, we have the simulated environment plus the experience of implementing a physical network to a Programmable Logic Controller S7-1200 firmware V3, which through open OPC communication protocol allows manipulation of Set Points and display the Process Variables, and changing the operating mode between manual and automatic of each of the sub processes, allowing the interaction between the human and the machine.

Fig. 1 shows the implementation of the virtual environment proposed in this work, the architecture of the virtual system is comprised of three main stages: *i) Creation of the Virtual Environment* which, based on a P&ID diagram, facilitates the creation of the CAD design which is exported in ".fbx" format to the UNITY 3D graphic engine for the development of the virtual environment; *ii) Generation and Conditioning of Electrical Signals* is responsible, by serial communication, for sending and receiving interacting information between the conditioning stage and the virtual

stage; *iii) Industrial Network and Controller*, allows the decentralized communication of analogue inputs and outputs between the conditioning stage (slaves) and the programmable logic controller (master); *iv) Supervisory System*, allows the manipulation and control of process variables.

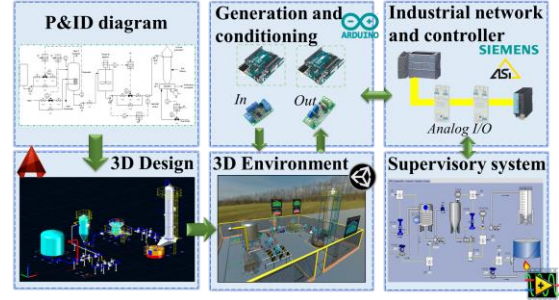


Figure 1. Virtual process architecture, electrical signal conditioning, industrial network, control and monitoring system.

A. Mathematical Process Models

Obtaining the mathematical models and their correct functioning are of great importance because all the behavior and evolution of the virtual environment depends on them.

The equations are presented below, where (1 and 2) represent the evaporator temperature and concentration, respectively; (3 and 4) represent the flow rate and mixer level, respectively; and (5) represent the dryer temperature.

$$\frac{dT_{ev}}{dt} = \frac{\rho_0 \cdot F_0}{V_1 \cdot \rho_1} (T_0 - T_{ev}) + \frac{Q_1}{V_1 \cdot \rho_1 \cdot Cp_1} \quad (1)$$

$$\frac{dC}{dt} = \frac{1}{V_1} (F_0 \cdot C_e - C) \quad (2)$$

$$\frac{df_{out}}{dt} = a_2 \cdot s_2 \cdot \sqrt{\frac{f_{in} - f_{out}}{g}} \quad (3)$$

$$\frac{dh_2}{dt} = \frac{1}{A_2} (F_1 - F_0) \quad (4)$$

$$\frac{dT_{dry}}{dt} = \frac{\rho_0 \cdot F_2}{V_2 \cdot \rho_1} (T_0 - T_{dry}) + \frac{Q_2}{V_2 \cdot \rho_1 \cdot Cp_1} \quad (5)$$

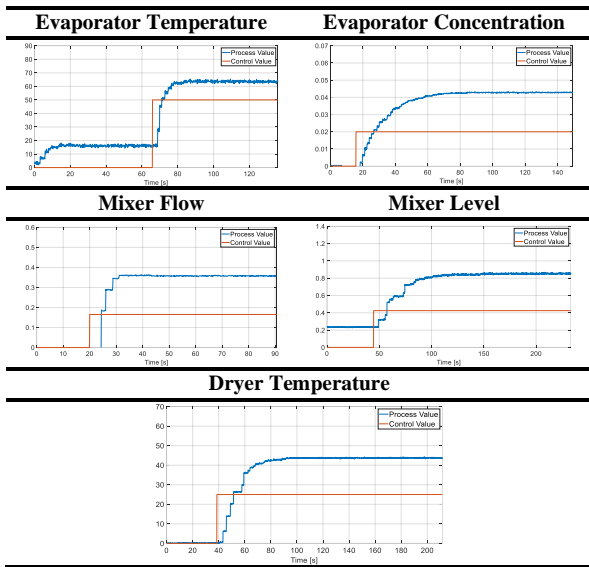
The nomenclature used is as follows; In the evaporator temperature equation: T_{ev} represents the evaporator temperature; ρ_0 and ρ_1 the input and output density of the evaporator; T_0 the ambient temperature; F_0 the evaporator input flow; V_1 the evaporator volume; Q_1 the heat transfer form; Cp_1 calorific capacity. The concentration equation: C represents the evaporator output concentration; C_e concentration entering the evaporator. In the mixer flow equation: f_{out} is the evaporator output flow rate; a_2 is the valve opening of the mixer discharge valve; s_2 is the cross-sectional area of the output pipeline; f_{in} the mixer input flow; g is gravity. In the mixer level equation: h_2 is the height of the mixer; A_2 the internal area of the mixer; F_1 and F_0 the input and output flow of the mixer, respectively. In the dryer temperature equation: T_{dry} is the temperature of the

dryer; F_2 the gas flow entering the dryer; V_2 the volume of the dryer. All functions evolve over time.

B. Mathematical Models Validation

The mathematical models are implemented in MatLab software to carry out open loop operation tests. Table I shows the evolution of the variables with respect to a step value change. Some variables are dependent on others, for example, the evaporator temperature depends on the evaporator concentration, and the mixer process depends on the evaporator process, so there is a correlation of variables that resembles reality.

TABLE I. OPEN-LOOP TESTING



III. SYSTEM DEVELOPMENT

This section describes the complete implementation process of this work corresponding to the creation of the virtual environment, scripts, electrical signal conditioning, the implementation of the industrial network and the controller and finally the super-vision system, the simplified diagram of the process is shown in Fig. 2.

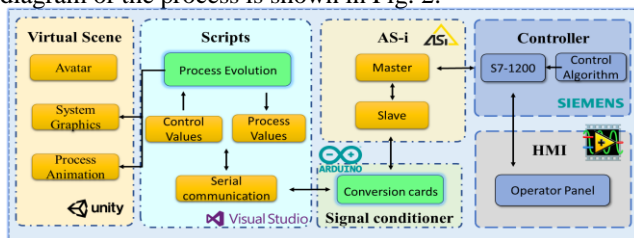


Figure 2. Design of an ammonium nitrate granulation plant.

The "Virtual Scene" stage simplifies the virtual environment developed in the Unity 3D graphic engine, which allows the user to interact with the simulated plant by visualizing the evolution of the process. This stage is subdivided as follows: *i) Avatar*, which navigates through the virtual environment visualizing the behavior of the process; *ii) System graphics*, shows the graphic curves

representing each process variable; *iii) Process Animation*, shows the respective process animations such as level variation, color change due to temperature, generation of nitrate granules.

The "Scripts" stage implements programming algorithms used in Visual Studio software. It consists of: *i) Process Evolution*, which includes the mathematical model that governs all process behavior; *ii) Control Values*, which varies the control action sent from the programmable logic controller; *iii) Process Values*, which sends the measured signals from the transmitters to the programmable logic controller; *iv) Serial Communication*, which is a set of algorithms that enable the serial port to send and receive data.

Continuing with the "Signal Conditioner" stage, it is composed only of: *i) Conversion Cards*, which are voltage to current and current to voltage converter cards connected to two Arduino UNO boards.

The "AS-i" stage consists of two devices: *i) Master*, which receives and continuously updates the data received from the slaves; *ii) Slave*, which is in charge of sending (Iout) and receiving (Iin) electrical signals.

The "Controller" stage contains the programmable logic controller (PLC S7-1200) CPU 1214 AC/DC/RLY which is connected directly to the master of the AS-i network, in this section there are only: *i) Control Algorithm*, contains the control strategies for the entire plant programmed in the Tia Portal V16 software.

Finally, the "HMI" stage, which incorporates tabs in the Labview software connected via OPC to the controller, allowing the supervision and control of the process.

A. Development of 3D Environment

For the design of the environment to be virtualized, the Autocad Plant 3D tool is used, which automatically sets design parameters such as types of materials depending on the previously configured international standards, this tool also calculates maximum and minimum tolerance values of angular connection between pipes, the design of industrial equipment such as tanks or agitators can use pre-established designs of the program, but they were replaced by assets that increase the realism of the process. This design can be exported in ".stl" format which is read in the next subsection. See Fig. 3.



Figure 3. Ammonium nitrate granulation plant design.

B. 3D Virtual Environment Simulation

For the development of the virtual environment, the ".stl" extension file generated in the previous section is imported.

The simulated system must behave like a real system, so the system is ruled by the mathematical model corresponding to each process.

The animation of each component of the simulation is programmed in Visual Studio with the help of scripts that allow serial communication between the simulation and the Arduino cards for reading and writing, in addition to allowing the visual animation of the various processes such as level variation inside the evaporator, movement of the mixer blades, positioning of control valves, visualization of measurements in indicator transmitters, interaction of an operator with the plant, among others. Fig. 4 shows the implementation of the 3D design in the Unity 3D development engine.



Figure 4. Simulation of an ammonium nitrate granulation plant.

C. Connection of Electrical Signal Inputs and Outputs

Two Arduino boards are used which, via serial port, communicate with the PC where the process simulation is located. By using two Arduino UNO boards, the sending and receiving of data does not collapse, which allows a full duplex connection between the simulation and the Arduino boards.

For the generation of current signals typical of industrial processes, voltage to current converters connected to the PWM outputs of the Arduino are used. Furthermore, the reception of current signals (4 - 20 mA) is done using current to voltage converters. Both cards allow the calibration of "Zero" and "Span". For each input and output variable a converter card is needed. See Fig. 5.

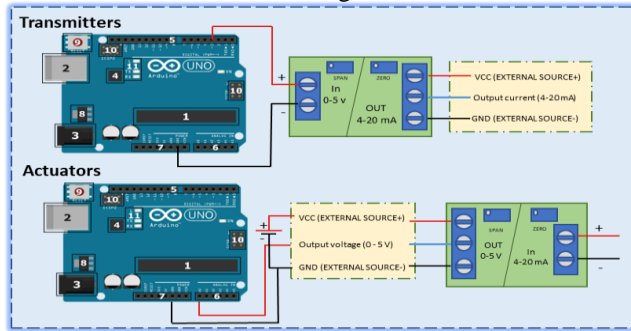


Figure 5. Connection of converter cards.

The current signals generated by the converters simulate the transmitter signals, which in turn are connected to the

AS-i input slaves. Similarly, the outputs of each AS-i slave generate the actuator signals, which are connected to the input of the current to voltage converters.

D. Connection and Configuration of AS-i Network

The AS-i network to be implemented depends on the number of process variables. There are a total of 5 variables to be controlled in the whole process, an input signal will be used to receive the values from the transmitters (4 - 20 mA) and at the same time an output signal will be used to send standard electrical signals (control action). In other words, the total number of slaves is 6 containing 2 channels per slave. See Fig. 7.

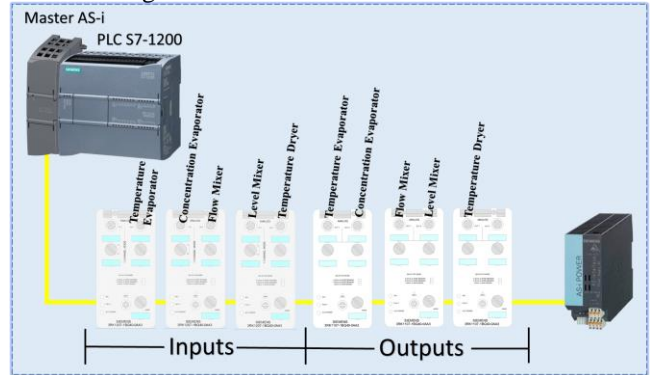


Figure 6. Connection diagram of the AS-i channels.

Once the industrial network has been implemented, it is necessary to address each of the slaves with the help of the AS-i addressing device (3RK1904-2AB01), which in turn matches the respective address assigned in the PLC programming (Tia Portal). Once the AS-i industrial network has been implemented and there is no error on the part of any component, the electrical signals highlighted in Section 3.3 can be connected to the network slaves with the help of M12 connectors.

IV. AUTOMATIC PROCESS CONTROL

Some control techniques are proposed and the one that best suits the conditions of each process is implemented.

Since the mathematical models are implemented within the Unity virtual environment, an approximation of the response curve with respect to a real process is obtained. From this point, control techniques can be implemented.

First, the virtual environment has to be treated as if it were a real process, i.e., its mathematical model is not known, so data collection is continued with the system in open loop and the system is excited by means of a step, in order to observe its evolution with respect to time. Once the data collection of all the variables has been completed, with the help of the mathematical software MatLab and its "ident" tool, the transfer function of each variable is obtained and, based on this, the calculation of the controllers is carried out.

A. Control Strategies

In the first instance, in order to obtain the controllers, open loop experiments are carried out with the different variables to verify the behavior of the plant and to find out

the limitations of the mathematical models. With these considerations, with the help of the mathematical software MatLab, response curves are obtained for the calculation of the variables that correspond to the control tuning methods to be implemented, such as: Cohen Coon, Aggressive Lambda, Robust Lambda and Haalman.

Under the limitations of communication with low-cost elements, such as the Arduino and its cards, there is a considerable delay in sending and receiving, so, through tests with different control techniques, we opted for the implementation of the Robust Lambda control technique in all the variables of the system, because its response covers the communication needs. Table II shows the constants obtained by calculation.

TABLE II. ROBUST LAMBDA CONTROLLER CONSTANTS.

Variable	Kp	Ti [s]	Td [s]
Evaporator Temperature	0.7604	2.7337	0
Evaporator Concentration	0.3338	15.8725	1.02251
Mixer Flow	0.2951	4.8188	0.78359
Mixer Level	1.1261	14.3098	3.02855
Dryer Temperature	0.5124	10.0309	2.44565

B. Supervisory System Design

Once all the communication between the virtual environment and the controller (PLC) has been implemented through the AS-i industrial network, the variables are displayed on a screen so that the operator can obtain the necessary information for supervision, so an HMI is designed in the LabView software. This application shows the animation of the process in real time that goes hand in hand with the virtual environment, showing process values and control values. See Fig. 8.

The HMI is divided into tabs. (1) Main Screen: shows the main components of the plant, such as transmitters and actuators with their respective control loops. (2) P&ID Diagram: as its name indicates, it shows the piping and instrumentation diagram. The 3 subsequent tabs (3-5) show the control of each divided process: Evaporator, Mixer and Dryer, respectively. Each tab shows the type of control with which the user can interact (manual and automatic), an animation with respect to its variable and, finally, its response curves, showing: Set Point (SP), Process Value (PV) and Control Value (CV). See Fig. 9.

The values are sent and received via OPC communication between the PLC and the HMI.



Figure 7. HMI Developed in LabView.

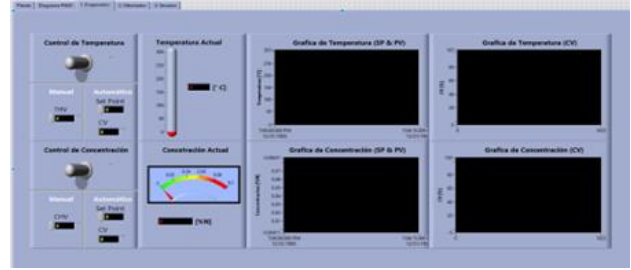


Figure 8. Evaporator Tab.

V. ANALYSIS AND RESULTS

In the virtual environment, the animations of the processes that make up the plant can be visualized. Like any real plant, it needs to be controlled, so a transmitter is needed to obtain the variable to be controlled and a control action to bring the process to the desired setpoint. Data is sent and received through the serial ports to the Arduino cards in conjunction with the conditioning stage, to work with standard current signals (4 - 20 mA), which are received and sent by the AS-i network slaves, which in turn have a connection to the controller (see Fig. 11).

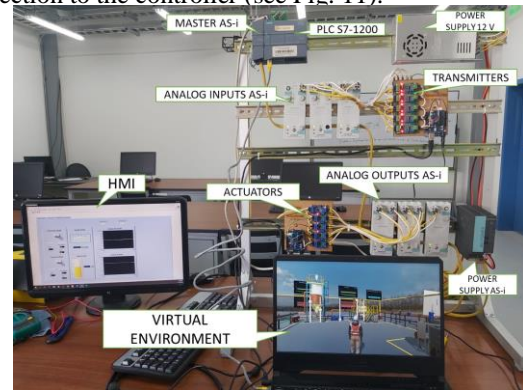





Figure 9. Implementation and Operation of the Project.

Table 3 shows the current generated in the virtual environment and the current measured with the help of the Fluke 707 precision instrument, plus the percentage error to show the percentage deviation of the generated value from the measured value.

TABLE III. OPEN-LOOP TESTING

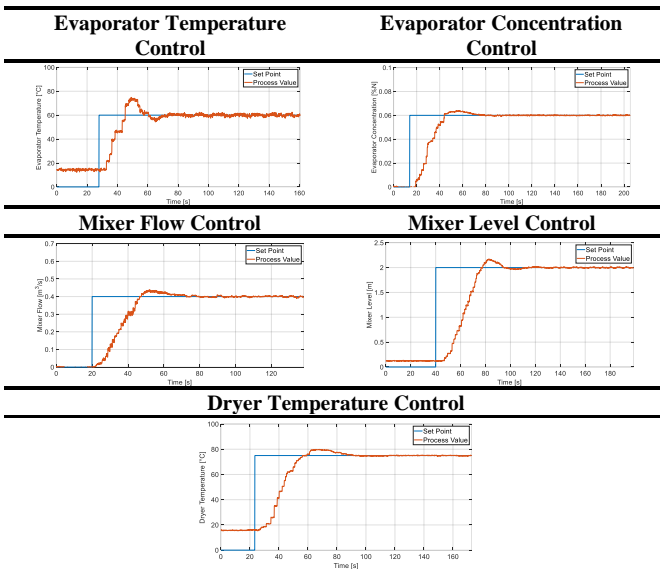
Instrument	Image	Generated (mA)	Measured (mA)	Error (%)
TIT		7.21	7.299	1.234
LIT		18.25	18.433	1.002

FIT		13.65	13.624	0.218
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Measuring error between simulated and measured values. The errors calculated in the table above show that the deviations are less than 1.5%. Considering that it was implemented on low-cost cards, it is determined that the voltage-current and current-voltage converters fulfil the purpose of sending and receiving signals that were generated from the virtual environment.

Afterwards, open-loop tests were carried out for the respective controller calculation and eventually the PID controller was implemented for all variables with the Robust Lambda tuning method, due to the communication limitation. In the implementation of the controllers, the response curve to the assignment of the respective operating setpoint has been obtained. See Table 4.

TABLE IV. CURVES OF THE CONTROLLED VARIABLES.



It can be noted that each variable is controlled with its respective control strategy implemented, despite the noise generated by the low-cost modules, the control law manages to position its variable at the desired value with a small percentage of over impulse.

VI. CONCLUSIONS

This work has achieved a correct connection between a 3D virtual environment with a physical AS-i network plus a programmable logic controller (PLC), in addition to achieving a correct tuning of the diverse PID controllers that govern each sub process. The connection of a supervisory system via OPC communication to another computer has also been achieved.

The mathematical models governing the behavior of each process, be it temperature, concentration, level and flow simulated and tested in the mathematical software (MatLab),

are faithful to the behavior of a real system, being co-dependent on each other.

By generating and reading standard electrical signals, a physical connection to an AS-i network has been achieved, where, despite communication delays, successful two-way communication has been achieved.

For the design of the controllers, the software (Tia Portal V16) was required, where, using control techniques, tuning constants have been introduced to the respective PID blocks in compliance with the control actions.

With the implementation of the 3D industrial environment, it was possible to introduce the operator in an inverse and interactive environment, since it is possible to visualize the animations of the processes, similar to how a real process would be, in addition to observing the final control elements that respond to the control law that act in each process.

To demonstrate the correct operation of the network and consequently of the controllers, tuning tests were carried out to determine the best tuning method for each process, using graphs to analyze settling times, over impulse and dead time.

ACKNOWLEDGMENT

The authors would like to thank the Universidad de las Fuerzas Armadas ESPE for the support for the development of this work, especially the project 2020-PIC-017-CTE “Simulación de proceso industriales, mediante la técnica Hardware in the Loop, para el desarrollo de prácticas en Automatización Industrial”.

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