HiL Virtual System for an Industrial Process, Control and Monitoring: Sulfuric Acid Production

Toaquiza Balderramo, Jaime Fernando y Tutasig Balarezo, Andrea Estefania

Departamento de Eléctrica y Electrónica

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Ing. Pruna Panchi, Edwin Patricio, DIR

Ing. Escobar Anchaguano, Ivon Patricia, CO

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HiL Virtual System for an Industrial Process, Control and Monitoring: *Sulfuric Acid Production*

Jaime F Toaquiza, Andrea E Tutasig, Edwin P Pruna and Ivon P Escobar
Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador
{jftoaquiza, aetutasig, eppruna, ipescobar}@espe.edu.ec

***Abstract*— Virtual environments allow the incorporation of new forms of study in process control. Thus, the Hardware in the Loop takes shape in training fields. In this article, a virtual environment of the sulfuric acid production process is developed. The three-dimensional model of the system is based on a natural system that is replicated in Blender software, and the virtual system is implemented in Unity 3D to simulate its behavior. This system is developed in the Hardware in The Loop approach, in which a process is simulated, and real devices perform the control. The interaction with the outside is a Human Machine Interface; this interface allows control and monitoring. In addition, the system provides support in the learning process of an operator in the process control area because interacting with a PLC in a physical way and applying tuning methods in real control loops without running risks brings the user closer to the work environment. The main result of this project is to obtain professional training tools in the field of process control.**

Keywords- Virtual Environment, Control and Monitoring, Hardware in The Loop.

I. INTRODUCTION

The basic concept behind "automation" is the operation of machinery and industrial processes with minimum involvement from human operators. As a result, to remain competitive, businesses in the industrial sector must employ flexible, economical, and efficient procedures. The process and manufacturing sectors require cutting-edge industrial automation and control systems more than ever to improve their operations in terms of speed, dependability, and product performance [1].

In this context the use of technologies that allow to experiment in a safe way, the different methods of tuning controllers are booming with it the term Hardware in the Loop (HiL), becomes more familiar in various fields.

There are many inconsistencies between the methodologies presented in the literature since the word HiL is defined differently and is not consistently applied. For instance, a number of publications define HiL as the testing of a control system using a real controller together with a simulated actual process. [2].

Contrarily, a HiL system can also be made up of a control system as software and a real system as hardware, according to El-Baz et al. [3]. The current testing concept can alternatively be referred to as software-in-the-loop (SiL), depending on the definition, where the control algorithm is run on a computer and therefore connected to the actual process. [2].

Sulfuric acid is the product of the basic chemical industry most widely used as an intermediate raw material in other processes, and is therefore the most manufactured chemical product in the world [4]. Thus, controlling and monitoring the production process of this input is of immense importance for professionals dedicated to process control, the access to this type of production plant is null, therefore virtualizing this type of environment through the mathematical modeling of its most important stages allows testing in a safe way without putting the user at risk.

Industry 4.0 requires professionals with a background in industrial environments. Therefore, it is necessary tools in which Professionals can perform tests safely. A booming solution is the HiL, which has several approaches; one developed in this project virtualizes the process of sulfuric acid production, consisting of different stages: level, temperature, pressure, and concentration.

The virtual environment did control by proportional–integral–derivative (PID) control loops. The control loops did implement on a programmable logic controller (PLC). For the interaction with the user and the virtual environment, there is a Human Machine Interface (HMI) in which the historical data, setpoints, and process values are presented, allowing interaction with the plant.

For the communication between the virtual environment and the PLC, industrial communication channels were implemented that allow the exchange of data in a fast and reliable way, using the Modbus TCP protocol.

II. SYSTEM STRUCTURE

This paper describes the development of an interactive virtual environment (HiL) for the implementation of control strategies in the sulfuric acid production process. The virtualization of this production process and implementation of control strategies for the different stages results in a safe environment free of occupational hazards. All this system was put into operation on a computer where the industrial plant resided and communicated through the TCP/IP protocol with the Siemens S7-1200 programmable logic controller. In addition, to interaction with the user, the system has an HMI that allows manipulation of the set points, visualizes the behavior of the process variables, and changes the operating mode of each control loop, thus acting as a means of interaction between the PLC and the user.

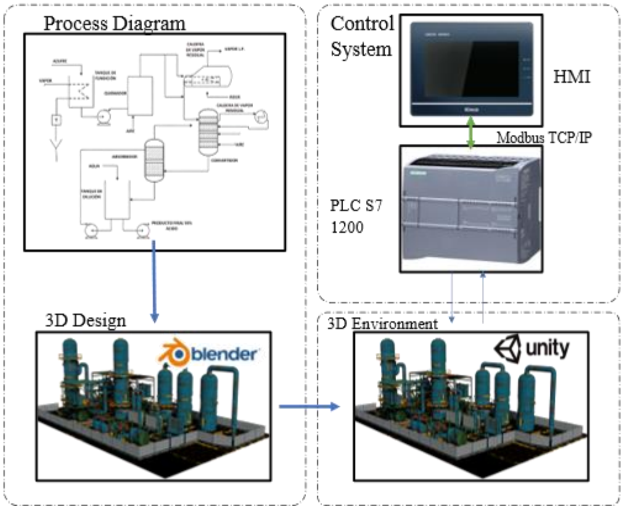

Figure 1. Virtual process architecture, control, and monitoring system

The behavior of the different stages did generate through mathematical models implemented by analyzing components of stages and variables that act in each stage.

The exchange of data between the virtual system and the programmable logic controller produces a reliable behavior close to reality due to its low latency in communication.

Creating the virtual environment begins with the study of the general diagram of the plant to understand each of the stages involved in the process; once the parts are defined, the 3D modeling process begins in Blender from photographs of an actual production plant. With the 3D model generated, it is imported into Unity 3D where each of the stages of the process are programmed.

As for the communication between the virtual environment and the PLC S7-1200, a bilateral connection is implemented through the Modbus TCP/IP protocol, accessing at tag level to the engineering variables.

The visualization of the variables that come from the controller and travel to the virtual plant is done using a Kinco HMI, which communicates within the industrial network connected to the PLC, this to facilitate access to the different controls of the stages.

III. Virtual Process Environment

This section describes the process implemented to create a HiL environment using Blender based on a P&ID diagram and Unity, allowing a close-to-reality environment, and prepare it for connection to the programmable logic controller (see Figure 2).

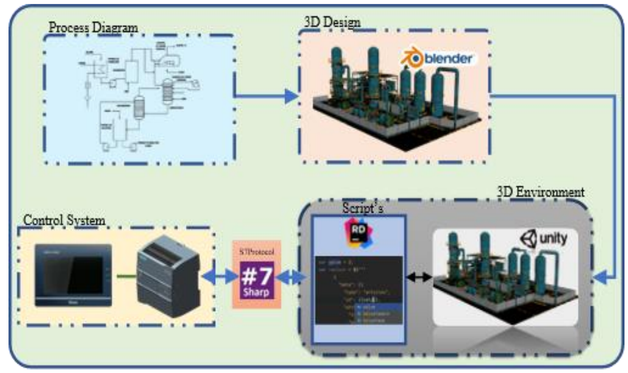

Figure 2. Virtual System Diagram for Sulfuric Acid Production Process

A. *P&ID Design*

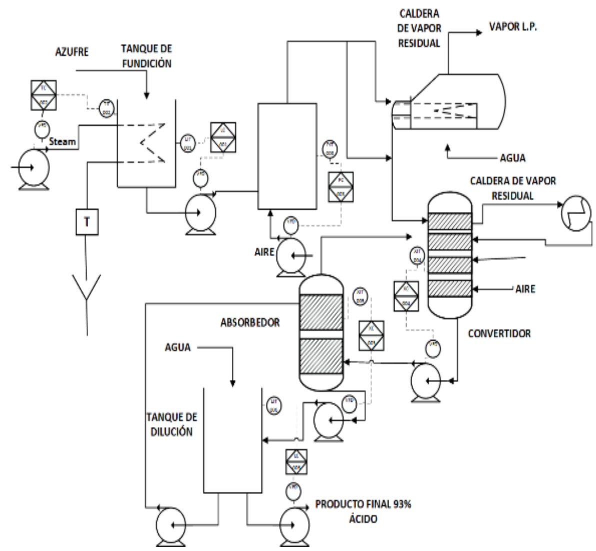

Figure 3. P&ID diagram of sulfuric acid production process

Based on the P&ID mentioned in [5], the idea was born to create a virtual environment focused on the production of sulfuric acid using this diagram as a basis and dividing the process into stages of level, temperature, pressure, and concentration.

B. *Blender Design*

The 3D design allows to appreciate the general structure of the sulfuric acid production process in its main stages, level, temperature, pressure, and concentration, which consists of a system of reactors, piping and industrial equipment modeled in such a way as to approximate reality. The final three-dimensional model made in Blender 3D is shown in Figure 4.

Figure 4. Parts of the production process of sulfuric acid in Blender 3D

C. *Unity 3D design*

From the 3D model obtained in Blender, they are implemented in the Unity 3D game engine, implementing the different industrial elements, such as transmitters and control elements. In this case, frequency converters and pumps for more realistic interaction sounds were implemented; an example of a temperature transmitter implemented in Unity 3D can be found in Figure 5.

Figure 5. Rosemount 3144p Temperature Transmitter

D. *Connection between PLC S7 1200 and Unity 3D*

For the connection between the virtual environment implemented in Unity 3D, The scripts have been implemented for directly accessing a database within the PLC; for this purpose, the S7Protocol has used a source code library under the GNU Library license [6]. Which is compatible with different Siemens controllers, among which is the S7 1200; the connection method between the controller and the virtual plant is done via Ethernet using the PLC's functions, such as PUT/GET, being necessary to enable this option.

IV. Dynamic System Model

Finding equations to describe the behavior of the system is key to 3D animation, since these equations can be used to describe the behavior of a process and find its state at any time instant. To this end, the sulfuric acid production process was divided into several stages to facilitate the handling of the differential equations that describe the process.

TABLE I. Mathematical Model Nomenclature

A: Area	V: Volume	p: Pressure
h: Height	T: Temperature	M: Molar mass
F_{in}: Inflow	F: Inflow	A_o: Output area
F_{out}: Output flow	T_i: Initial temperature	w_i: Air flow
g: Gravity	Q: Energy	C: Concentration
	ρ: Density	F: Mixing flow rate

A. *Mathematical Models*

- Level

$$A \cdot \frac{dh}{dt} = F_{in} - F_{out}\sqrt{2 \cdot g \cdot h(t)}$$

- Temperature

$$V \cdot \frac{dT}{dt} = F \cdot \left(T_i - T(t)\right) + \frac{Q(t)}{\rho \cdot C_p}$$

- Pressure

$$\frac{V \cdot M}{R_g \cdot \left(T + 273 \cdot K\right)} \cdot \frac{dp}{dt} = w_i(t) - \cdots$$

$$\cdots A_o \cdot \sqrt{\frac{2 \cdot M}{R_g \cdot \left(T + 273K\right)} \cdot p(t) \cdot \left(p(t) - p_o\right)}$$

- Concentration

$$\frac{dC}{dt} = \frac{1}{V}\left[F_1\left(C_1 - C\right) + F_2\left(C_2 - C\right) + F_3\left(C_3 - C\right)\right]$$

The mathematical models mentioned together are the main parts of the sulfuric acid production process, each fundamental to it. It is necessary to clarify that the process was simplified to obtain equations, and approximations have been taken so that the models behave adequately. This case is for the sub-process of temperature that, by nature, has a slow evolution. These models were obtained from the research carried out in the book on process control [7].

B. *Validation of mathematical models*

Figure 6 shows the behavior of the implemented mathematical models. Again, a step-type control signal is applied to verify the validity of each one, and as can be seen, each model responds adequately to the excitation.

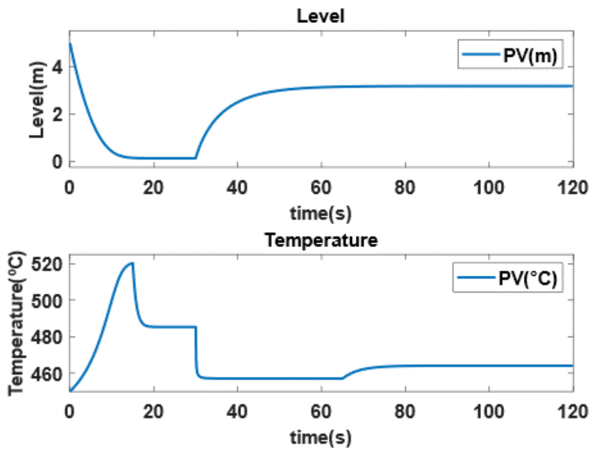

Figure 6. Validation of some open-loop mathematical models.

V. Development Of The Control And Supervision System

The structure of the control and supervision system are composed of a programmable logic controller on which are implemented different control loops, among which we can mention: PI, PID, which were tuned from different tuning methods.

The tuning method with greater presence at industrial level is the lambda tuning technique, which has two approaches, robust and aggressive. For the correct tuning of the control loops, it was necessary to obtain the mathematical model of the plant classically, i.e., to access the data acquired by the PLC through OPC, so with these data and the mathematical software MATLAB, an approximation of the transfer function of the process was obtained.

In the case of the different sub-processes implemented, the process is repeated to obtain mathematical models in the frequency domain. Table 2 shows the different mathematical models obtained by approximating a first order model with delay.

TABLE II. Mathematical models in the frequency domain.

Mathematical model	
Tank Level	$G(s)=\dfrac{1.0807\cdot e^{-1.9693s}}{1+28.601s}$
Temperature	$G(s)=\dfrac{0.9993\cdot e^{-0.3s}}{1+10.251s}$
Pressure	$G(s)=\dfrac{1.0011\cdot e^{-0.1471s}}{1+0.66227s}$
Concentration SO_3	$G(s)=\dfrac{1.3203\cdot e^{-0.03s}}{1+26.801s}$
Concentration H_2SO_4	$G(s)=\dfrac{1.3192\cdot e^{-0.1s}}{1+25.519s}$
Product Level	$G(s)=\dfrac{0.19394\cdot e^{-0.1s}}{1+176.73s}$

Depending on the mathematical models, PI to PID controllers with both direct and inverse action are implemented.

A. *Industrial network*

Communication between different devices regardless of the manufacturer is possible thanks to the different industrial communication protocols, an example of which is the Modbus protocol.

A member of the MODBUS family of straightforward, neutral communication protocols, MODBUS/TCP is designed for the monitoring and management of automation systems. It covers utilizing TCP/IP protocols and MODBUS messaging in an "Internet" or "Intranet" context. The protocols are now used most frequently for Ethernet connections between PLCs, I/O modules, and "gateways" to other straightforward fieldbus networks or I/O networks [8].

B. *Siemens S7 1200 Programmable Logic Controller*

The HiL approach in which a virtual system is controlled by a real device needs a controller as is the case of the Siemens S7 1200 PLC, which serves as a controller thanks to its control loops, for the sulfuric acid production plant in its simplified form needs 6 control loops, and thanks to its compatibility with Modbus TCP/IP networks allows interaction with devices from different manufacturers.

C. *Kinco HMI*

Human Machine Interfaces are necessary in the process industry since they are how the user interacts with the process in question, thus, using a Kinco HMI, a series of windows are implemented that allow modifying the variables of interest, as well as observing the evolution of the system without further complication. Figure 7 shows a sample of the windows implemented for user interaction.

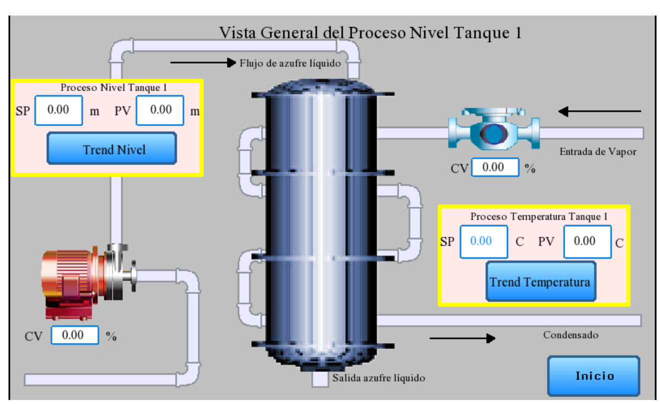

Figure 7. Level system control window

VI. ANALYSIS AND RESULTS

This section presents the behaviors of the level, temperature, pressure, and concentration sub-processes that are part of the sulfuric acid production, as well as each of their closed-loop behaviors. As almost all PID controllers are tuned on site, different tuning rules have been proposed in the literature that allow fine tuning of PID controllers on site [7].

In the case of the level and temperature process corresponding to sulfur smelting, in order to maintain the sulfur in a liquid state and convert it to a gaseous state, the temperature must be higher than 400ºC [9]. For this reason, a temperature of 480ºC was chosen as the initial set point for this process. In the process control analysis, the general level set points are kept at 50% of the maximum storage level, in order to maintain proper system operation without overflows and alarm activation [10], moreover, since it is a joint system of level and temperature, the change in level acts as a disturbance to the temperature process, as shown in Figure 8.

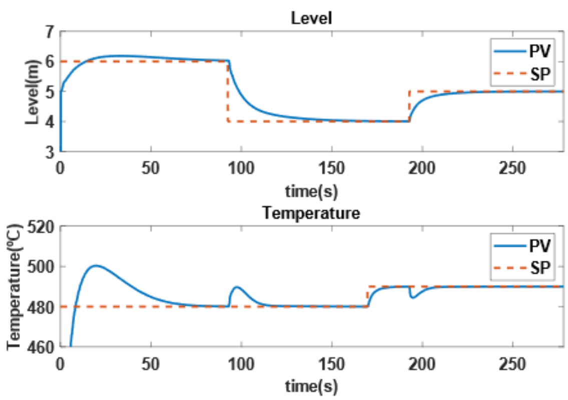

Figure 8. Level and temperature system behavior

Figure 8 shows how the controller can act at distinct set-point values, and the speed of its response to system disturbances. The controllers with the best performance on the level and temperature process are PID controllers with the Aggressive Lambda tuning method; the constants obtained for each case are shown in Table 3.

TABLE III. PID CONTROLLER CONSTANTS WITH LAMBDA TUNING

Process	Kp	Ti (s)	Td (s)
Level	0,925326177	29,58565	0,951879531
Temperature	1,00070049	10,401	0,147836746

The pressure process that is part of the burner in the sulfuric acid production has fast response characteristics, this behavior is expected according to the mathematical model obtained in Figure 9, this part of the system has a partly independent behavior, since it can be observed that the variations in pressure with changes in the other set points do not affect this stage to a great extent.

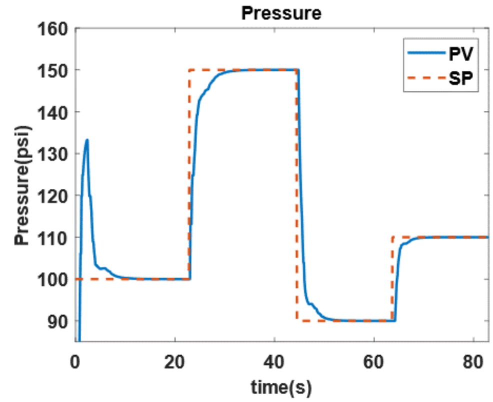

Figure 9. Behavior of the pressure system.

The implemented controller is a PI under the Robust Lambda tuning method, the constants obtained with this method are shown in Table 4.

TABLE IV. PI CONTROLLER CONSTANTS WITH ROBUST LAMBDA TUNING

Process	Kp	Ti(s)
Pressure	0,310014154	0,66227

The final stage of the sulfuric acid production process is based on having the concentrations of both sulfur dioxide and acid in such a way that it is a product consistent with the needs of the market, so that in Figure 10 is present the evolution of the concentrations that as can be seen it is a related system since the output of each stage becomes the input of the next, In particular, a sulfur trioxide concentration of at least 93% is required, and in the case of sulfuric acid, a concentration of at least 98% is necessary for commercialization, values that are taken as a reference for the operation of the system. As for the storage of the final product, it is a level system with inverse action.

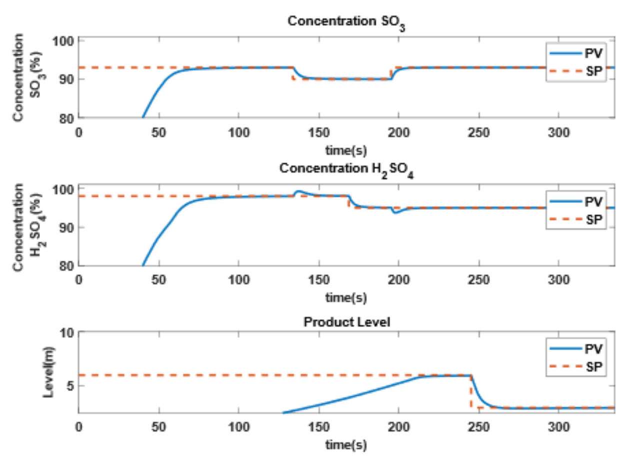

Figure 10. Concentration and product level system behavior

Figure 10 also shows the reliability of the implemented controllers, and how they compensate the disturbances of the previous stages, so that when the reference values change, the controller acts and the continuous control of the variables of interest is produced. The controllers chosen for the concentration stages are PID, and for the level stage a PI controller was implemented, the constants were obtained under the Lambda tuning method and are shown in Table 5.

TABLE V. CONTROLLER CONSTANTS FOR CONCENTRATIONS AND LEVEL

Process	Kp	Ti (s)	Td (s)
Concentration SO_3	0,75740362	26,816	0,014991609
Concentration H_2SO_4	0,758035173	25,569	0,049902225
Product Level	5,15331796	176,73	

The PLC programming was performed with the program using TIA Portal (Totally Integrated Automation Portal), using the KOP language, as well as from the communication with the virtual environment at the level of "tags" which were scaled, normalized among other operations, which are recurrently used, thus providing an experience identical to reality. Both the control actions and behavior of the plant are linked to the control loops, thus allowing full control of the plant, the blocks used to implement the loops have the characteristic of being customized so that there are loops in which the control action is direct and inverse action as appropriate.

The interaction with the user is through an HMI that allows the manipulation of the set points, the historical and operating modes; as an extra, different access levels are programmed, allowing an interaction according to the user's access level. For the communication of the Kinco HMI with the PLC, Modbus TCP/IP communication protocols were used, which were configured in the Kinco DTools V3.5.3 program.

The 3D models of the system were created in Blender based on photographs of a real plant, which is generated by three-dimensional geometric modeling, so once generated the system is exported to Unity 3D as shown in Figure. 11.

Figure 11. Virtual Environment Implemented

VII. CONCLUSIONS

The system is developed in the Hardware in The Loop approach in which a process is simulated, and the control is performed by a PLC, so the user has a real interaction with an industrial device. For the tuning of the control loops, the characteristic steps of a real process were followed, from acquiring the mathematical model to implementing the constants of the controllers, resulting in an efficient control at each stage of the process.

Through the implementation and tuning of control loops in a simulated plant, using a PLC allows a real programming experience of these controllers, without the risk of manipulating a real plant.

Basic and modified PID control methods have demonstrated their effectiveness in providing adequate control in the field of process control systems, while maybe in many particular instances they do not give optimal control. [7], as discussed in section 6.

Industrial networks and industrial communication protocols allow the interconnection between different equipment regardless of their manufacturer, being a clear example the possibility of interconnecting an HMI and PLC for control and monitoring of a virtual industrial process, having all the features and elements governing the HMI design standard such as ISA 101.

The limitations presented in this project were at the level of firmware in the PLCs because the communication features used are present in Siemens devices with firmware higher than 4.0. Also, to expand and avoid this limitation in future research, it is necessary to find new ways of connection; one of them may be using standardized electrical signals.

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