3D Virtual System of a Distillation Tower, and Process Control Using the Hardware in the Loop Technique

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Abstract. This work presents the development of a 3D virtual environment of a binary distillation tower, and by means of the Hardware in the Loop (HIL) technique allows the training of users in process control. The virtual environment has instruments, equipment, animations and sounds of a high degree of quality existing in a binary distillation plant, the design is done using CAD tools and the Unity 3D graphics engine. The proposed system is a low-cost alternative developed with a high level of detail for the automatic control of a binary distillation tower, it also allows to develop several tests without risk of accidents with the comfort that the user requires for learning.

Keywords: Virtual reality · Distillation tower · Hardware in the loop · Process control

1 Introduction

Nowadays the industry focuses on many production areas, one of them is the chemical industry where the binary distillation tower is an important part [1, 7], its operation is based on separating compounds from a mixture by applying different degrees of temperature and pressure, and depending on the volatility of each element the distillate and sediment are obtained [2, 8].

The demands in current industrial processes require that an operator has the necessary experience in control of binary distillation towers from their academic training to their professional performance [1], in this context there are limitations that hinder such learning as the economic aspect, since didactic distillation systems cost high amounts of money, also access to these plants is very difficult for safety, integrity of people, environment and equipment [3, 10, 11].

Virtual reality in industry is capable of transmitting information that allows users to have systems similar to real industrial processes [2, 9, 11], using video animations or sounds in order to create applications that simulate training prior to interaction with different industrial plants [2].

The complementary technique for training with virtual reality is Hardware in the Loop, which allows interacting with physical variables within a virtual environment and reducing costs, unnecessary stoppages or breakdowns in industrial processes [5, 6, 10].

L. T. De Paolis et al. (Eds.): AVR 2021, LNCS 12980, pp. 621–638, 2021.
https://doi.org/10.1007/978-3-030-87595-4_45

Virtual reality complemented with the Hardware in the Loop technique provides good results applied in industrial processes, for example, a virtual laboratory with a Hardware in the Loop system for teaching industrial processes [3], another example is the “Amatrol T5552” application of the University of Cauca that is used for industrial processes and control practices within the institution [4].

The present research develops a 3D virtual environment of a binary distillation plant, composed of instruments, equipment and signage based on a real plant. The graphics, animations and sounds are of high quality, making the application pleasant to the user.

The virtual environment has a user-friendly human-machine interface (HMI) where the control menus and the trends of the industrial process variables are located, and the programmable logic controller used for the automatic control is used by means of the Hardware in the Loop technique.

2 Structure of the System

The development of an application in a 3D virtual environment is presented as a proposal for the training of operators of binary distillation tower plants, through the use of 3D animations and sounds controlled by the user from the keyboard. In addition, it allows learning advanced process control topics (Cascade Control), manipulating control constants through the use of an HMI screen, and observing trends.

The Virtual 3D system of a binary distillation tower uses Software and Hardware tools, which allow an interaction between physical variables produced by a DAQ system and animations within the virtual environment. The interaction between the devices and the programs used are shown in Fig. 1.

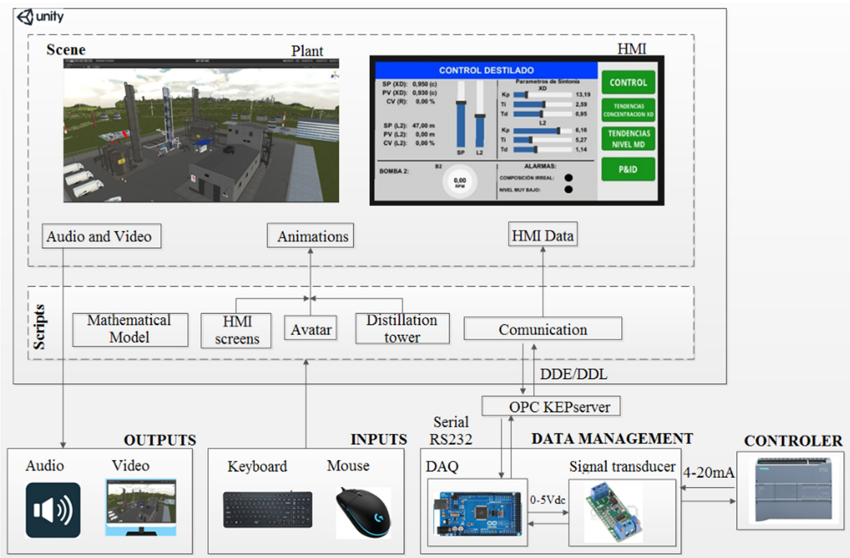


Fig. 1. Structure of the proposed system.

In the input stage, the computer keyboard and mouse are considered; by means of specific keys it will be possible to perform movements throughout the virtual environment as well as certain functionalities such as animations (molecules, control panel, etc.). In addition, the use of the mouse allows users to visualize the scenarios to understand the operation of the plant.

In the scripting stage, the communication between the HMI and the PLC is managed through OPC for automatic process control. The communication is bidirectional and occurs in real time thanks to the "communication" script.

The output stage contains sounds of the virtual plant elements including alarms, and all the animations and the environment are displayed on the screen and can be fully navigated.

3 Virtual Environment

For the development of the virtual environment is considered the diagram of a binary distillation tower, the process starts with the feeding in the middle part of the tower with a liquid called mixture. Inside the tower there are the trays in charge of transferring the energy, at the base of the tower the sediment is concentrated and passes through the reboiler so that the most volatile element ascends to the condenser, here the mixture changes its state to liquid and the distillate is obtained, if the condensed liquid does not

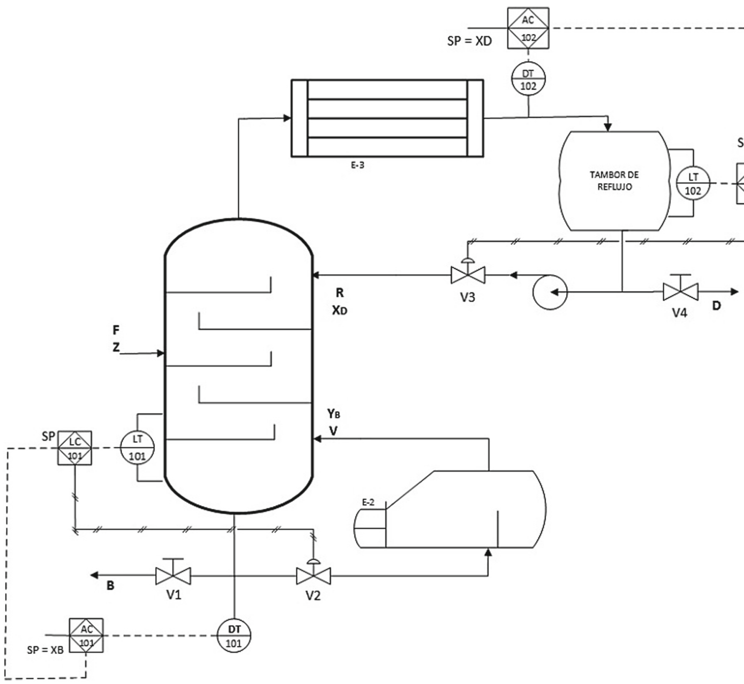


Fig. 2. P&ID diagram of the binary distillation tower.

have the adequate concentration, the reflux drum must resend the mixture to the upper plates of the tower so that the process is repeated as shown in Fig. 2.

Figure 3 shows the diagram describing the design and development process of the virtual environment.

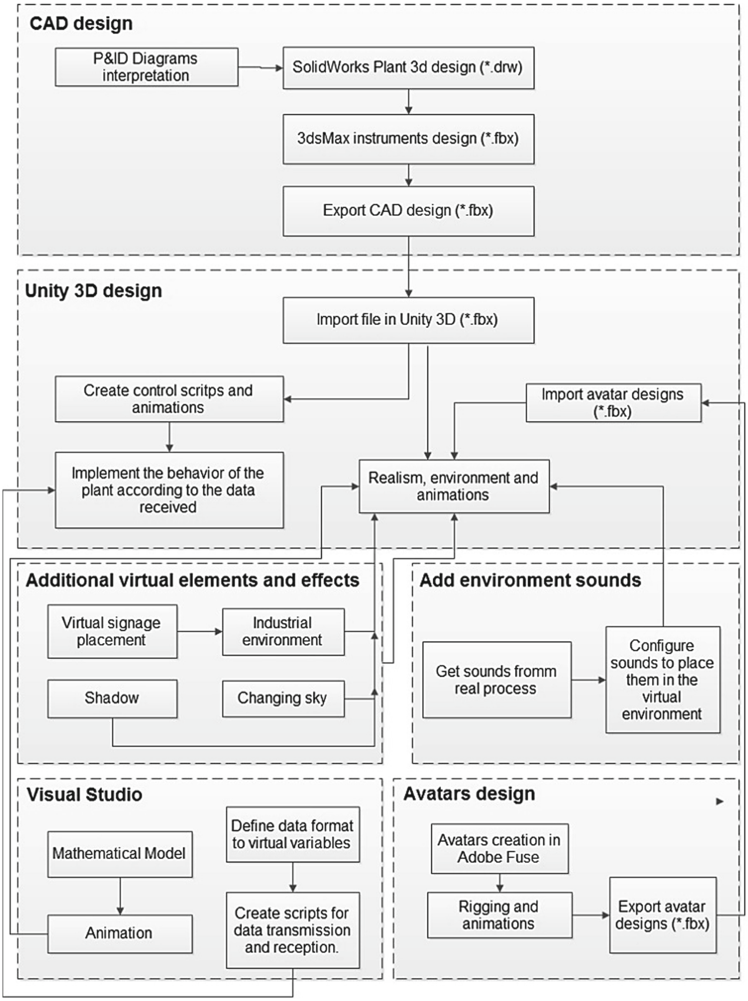


Fig. 3. Flowchart of the application development process.

3.1 Preliminary CAD Design

Considering that the system will allow training in the control of a distillation tower, it is necessary to have a level of detail and realism, to provide these attributes, specialized 3D design programs such as SolidWorks and 3DS Max are used, which have allowed to create and modify elements, equipment and industrial instruments that are part of the distillation plant, in order to improve the user experience, and give the details of each object to obtain a realistic environment, similar to a real plant. Figure 4 shows an instrument designed in the CAD software.

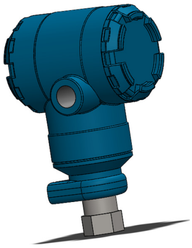


Fig. 4. CAD software design of a level transmitter.

3.2 Unity 3D Design

For the design in Unity 3D, we start in the scene window, where we place all the elements to be part of the plant, we use the 3DS MAX program for the conversion of files from ".drw" to ".fbx" as shown in Fig. 5.

Fig. 5. Unity 3D design of an actuator.

Once the elements with extension ".fbx" are obtained, they are selected from the folder where they are saved and dragged to the UNITY Project window, which are added and displayed in the scene window where they are placed according to the plant design, as shown in Fig. 6.

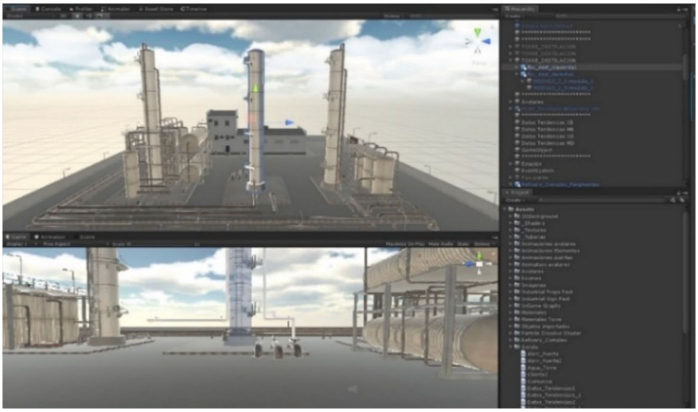


Fig. 6. 3D design of the distillation tower environment in Unity.

The plant has 3 distillation towers with similar characteristics, the central tower has a cross section throughout its body, so that the distillation process can be observed in greater detail, making it more didactic for the user, as shown in Fig. 7.

Fig. 7. 3D design of the distillation tower in Unity.

Based on the P&ID diagram, the other elements of the plant that make up a binary distillation tower are located, which are the condenser, reflux drum, valves, piping, transmitters, etc. The following result is obtained Fig. 8

Fig. 8. Binary distillation tower design based on the P&ID diagram.

3.3 HMI Design

The operation of the HMI of the Virtual 3D system of a binary distillation tower is focused on being intuitive and easy to use, located in the central part of the distillation tower, it allows the user to make the necessary changes for the automatic control of the process, Fig. 9 shows the structure of the HMI.

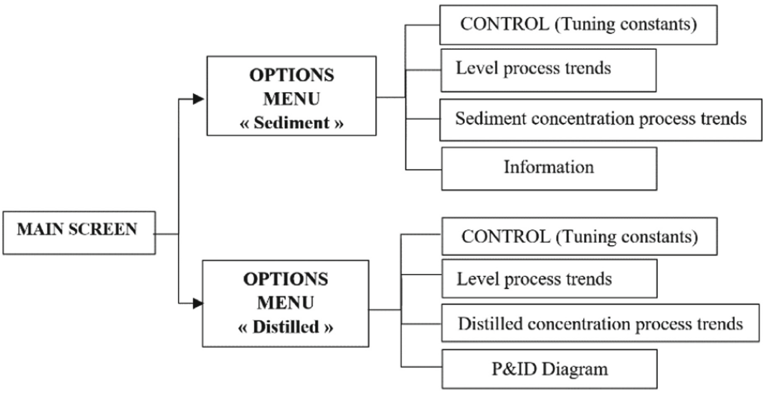


Fig. 9. Distillation tower HMI design flowchart.

Figure 10 shows the two processes (sediment and distillate), the controller tuning parameters for each process, as well as the control variables and essential information for the control of the binary distillation tower process.

Fig. 10. Main screen of the developed HMI.

The control panel provides information about the P&ID diagram of the binary distillation tower for the user to locate the different areas of the industrial process (distillation tower), as shown in Fig. 11.

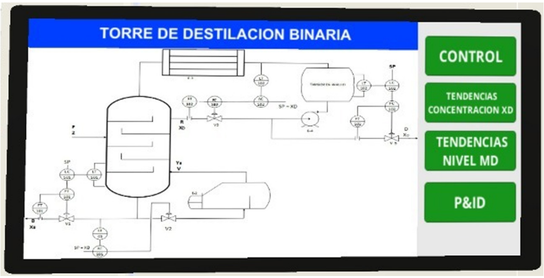


Fig. 11. Distillation tower P&ID diagram information.

3.4 Design of the Virtual Environment, Elements and Effects

In this stage, all the details of an industrial plant are added, including a control panel which contains the final control elements, the programmable automaton and the signaling system Fig. 12.

To give more realism to the environment, an industrial environment and details that allow the user to have a better experience were included. Scenarios were developed

Fig. 12. Implementation of elements to improve the detail to the virtual environment.

outside the plant, a parking lot and a landscape with a forest and industries. In addition to implementing effects, shadows and a variant sky, as shown in Fig. 13.

Fig. 13. Implementing effects, shadows, environmental movements to the virtual environment.

3.5 Creation of Environmental Sounds

The environmental sounds of several industrial equipment are created in order to increase the realism of the virtual environment, corresponding to the pumps, condenser and reboiler which are part of the distillation tower. In case the user moves away from the plant, this sound will be diminished.

3.6 Avatar Design

The avatar is obtained from Adobe Fuse, where predefined designs are available, which can be modified in terms of appearance and clothing, to make it more realistic according to the needs or the environment to be used, in this case being an industry, protective clothing is considered: gloves, helmet, boots, etc. as shown in Fig. 14.

Fig. 14. Final design of the avatar.

The animations of the avatar's movements are made in the MIXAMO software, these animations are walking, turning left or right, walking in any direction, these movements are focused on defined points of the avatar's body Fig. 15.

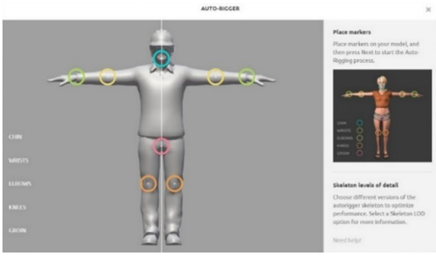


Fig. 15. Movements and animations assigned to the Avatar using MIXAMO software.

For each movement a preview of the movement is obtained to determine if it is in accordance with the needs of the animation, as seen in the movement "walking" presented in Fig. 16.

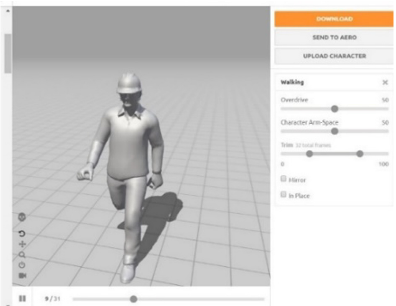


Fig. 16. Preview of the movement "walk".

Once the movements are defined, each of them is downloaded in ".fbx" format, they are added to the avatar script in UNITY and assigned to the necessary keys through programming using Visual Studio.

3.7 Programming in Visual Studio

The programming is done in Visual Studio, within Unity scripts are created which contain the commands for animation, communication and mathematical model of the plant, also an additional program is created for communication between UNITY and the OPC, which is responsible for sending and receiving data to and from the PLC respectively, in Fig. 17 explains the structure of the programming done through scripts in Visual Studio.

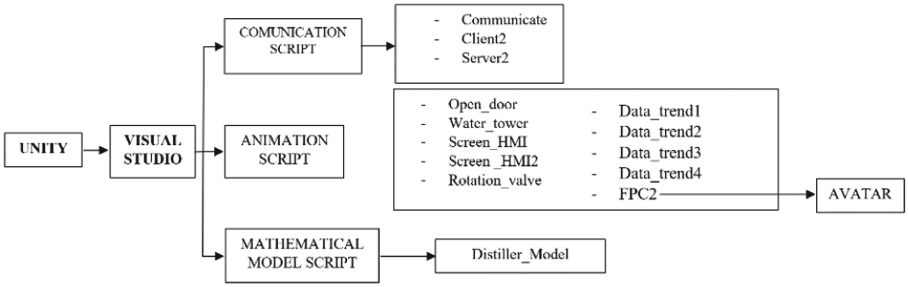


Fig. 17. Flowchart of the scripts developed in unity.

Animation Scripts. In this script there are all the programming commands corresponding to the animation of the binary distillation tower, as well as the avatar, besides containing the commands that control from the keyboard the actions to be performed by the avatar.

Communication Scripts. In these scripts the communication of all the programming done in Visual Studio with the 3D virtual environment in UNITY is established and in the same way for it to communicate with the OPC through the DLL and DDE. The functionality of the communication scripts is explained in Fig. 18:

Fig. 18. Communication flowchart between unity and the OPC.

3.8 Signal Acquisition and Conditioning

An Arduino MEGA 2560 is used as DAQ to send signals to the PLC and vice versa, these signals have noise and must be conditioned to decrease the load effect that is produced between the Arduino and the PLC, the signal conditioning presented in Fig. 19 is applied.

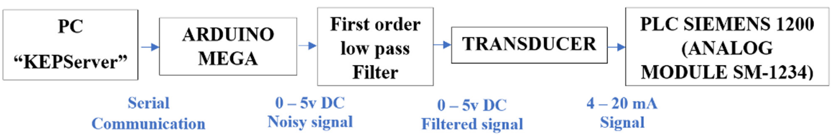


Fig. 19. Signal conditioning flowchart.

3.9 Design and Construction of the Hardware in the Loop Case

The design and construction of the case for the HIL allows the connections to be adequate for each stage when the user wants to perform tests, the correct distribution of the case will allow the identification of the elements for the use of the didactic system, as shown in Fig. 20.

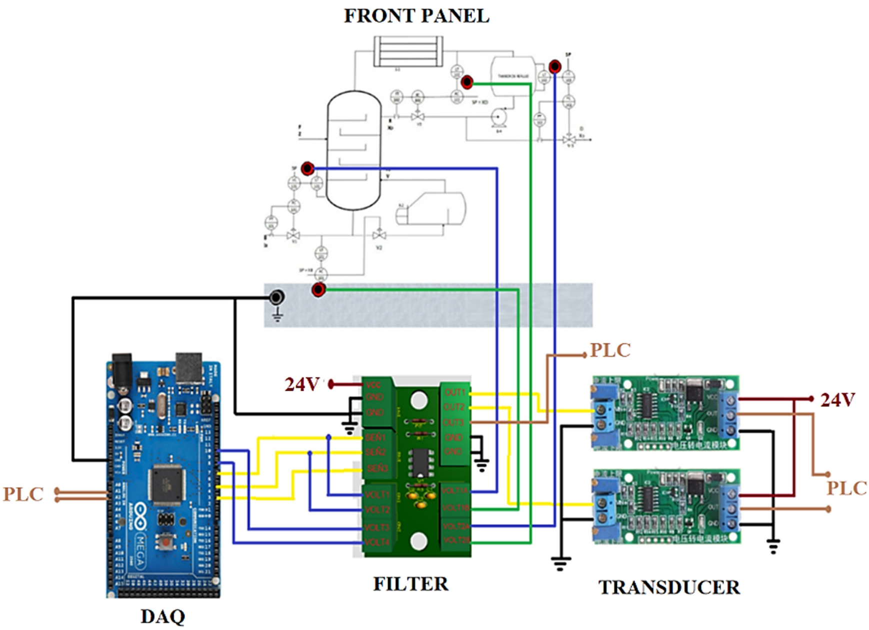


Fig. 20. Case design for the HIL system.

3.10 Control Algorithms Implemented

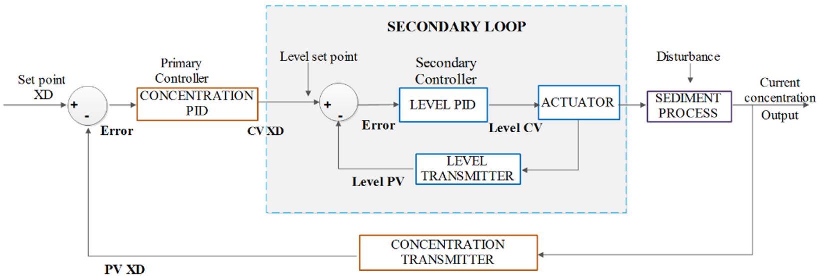


Fig. 21. Block diagram of the cascade control of the base - reboiler assembly.

The cascade control is implemented in two sections of the distillation column called “Reflux drum assembly” where the distillate is obtained and “Base - reboiler assembly” from which the sediment is extracted, as shown in Fig. 21 and Fig. 22 respectively.

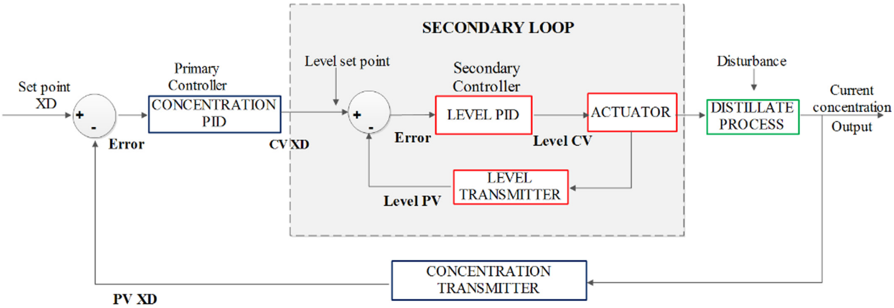


Fig. 22. Block diagram of the cascade control of the reflux drum assembly.

Figure 23 shows the tuning methods implemented in the “base - reboiler assembly” and in the “reflux drum assembly”, which allow optimal control at this stage.

“REBOILER BASE” ASSEMBLY

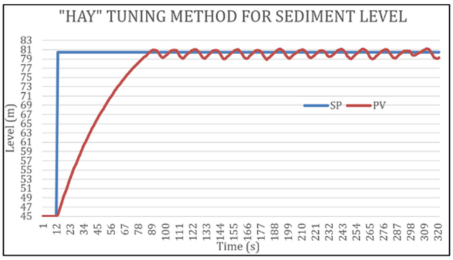
TUNING CONSTANTS FOR TESTS ON THE SECONDARY LOOP

Methods \ Parameters	Kp	Ti (s)	Td (s)
FORD	46,65237675	2,06	0,3811
HAY	12,60875047	3,296	0,824
ASTROM	29,63056361	2,06	0,515

TUNING CONSTANTS FOR TESTS ON THE PRIMARY LOOP

Methods \ Parameters	Kp	Ti (s)	Td (s)
CHIEN	29,65506477	0,000238	0,000042
MOROS	37,45902919	0,0002	0,000042
ZIEGLER NICHOLS	62,43171531	0,0002	0,00005

BEST RESPONSE CURVE OBTAINED. USING THE HAY METHOD PARAMETERS



BEST RESPONSE CURVE OBTAINED. USING THE PARAMETERS OF THE ZIEGLER NICHOLS METHOD

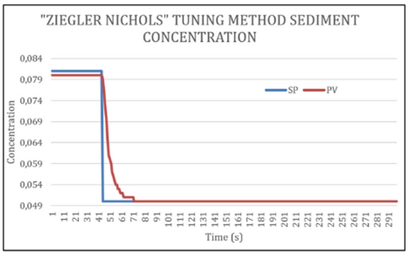
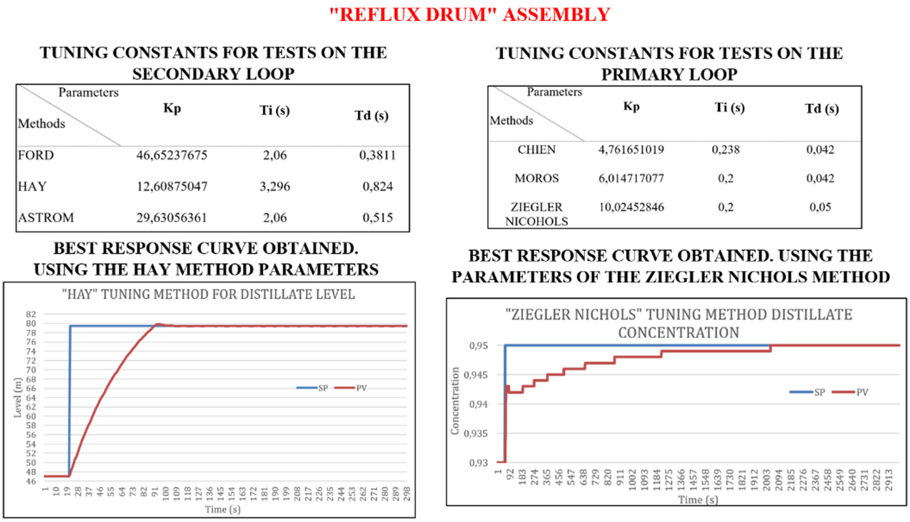


Fig. 23. Implemented tuning methods, and response curves of the controllers in the “base - reboiler assembly”.

For the “Reflux Drum Assembly” 3 different tuning methods were implemented in each of its loops corresponding to the level and concentration of the distillate as shown in Fig. 24.



Methods \ Parameters	Kp	Ti (s)	Td (s)
FORD	46,65237675	2,06	0,3811
HAY	12,60875047	3,296	0,824
ASTROM	29,63056361	2,06	0,515

Methods \ Parameters	Kp	Ti (s)	Td (s)
CHIEN	4,761651019	0,238	0,042
MOROS	6,014717077	0,2	0,042
ZIEGLER NICOHOLS	10,02452846	0,2	0,05

Fig. 24. Implemented tuning methods and response curves of the controllers in the "Reflux drum assembly".

4 Results

The 3D virtual system offers the user a training in the automatic control of a binary distillation tower, the implemented system is presented in Fig. 25.

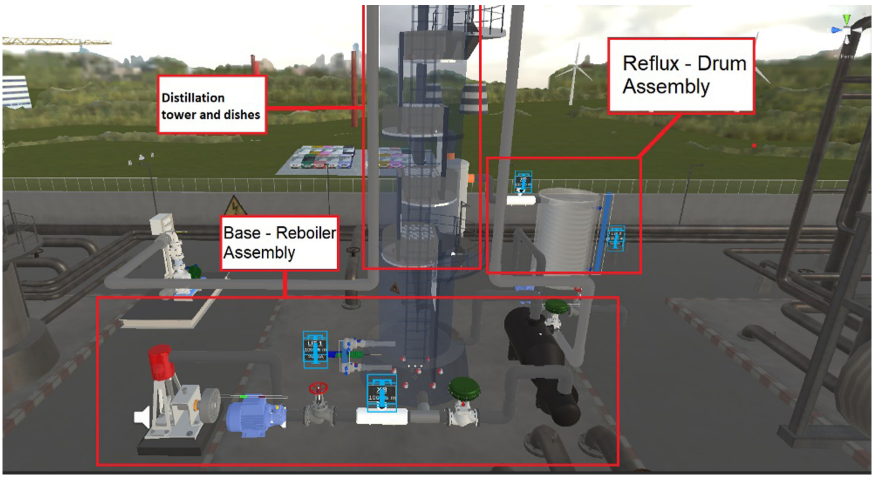


Fig. 25. Final result of the binary distillation tower implemented in Unity 3D.

The developed application starts with a front view of the HMI, which allows the user to enter the tuning constants of the controller and also to observe the response curves of the process, as presented in Fig. 26.

Fig. 26. User's initial position in front of the HMI.

By means of the avatar the user can go to any point of the environment, and with the help of the mouse redirect the view to all the places, to observe the details of the animation of the stages of the process Fig. 27.

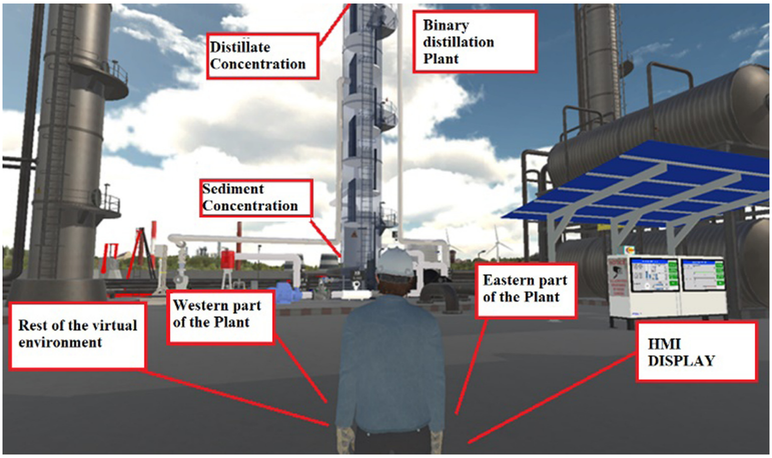


Fig. 27. General parts of the distillation plant.

The details of the animation correspond to the operation of a real distillation tower, so that the user becomes familiar with the plant and knows its stages, as presented in Fig. 28.

Due to the complexity of the system and so that the user can understand the distillation process, an animation is created inside the transparent tower.

The animation starts with the mixture entering the middle of the tower and filling the lower plates, when it reaches the base and depending on the concentration of the sediment, the mixture passes through the reboiler and re-enters the tower as steam.

Fig. 28. Details implemented in the virtual environment.

The vapor rises and passes to the condenser, if the distillate does not have the required concentration the liquid re-enters the tower through the reflux drum, which will fill the upper plates in a descending way to repeat the process. See Fig. 29.

Fig. 29. Sequence of operation of the distillation tower.

In order to demonstrate the performance of the application, the industrial instruments in operation (transmitters and valves, etc.) are presented.

In each image of the industrial elements, the precision and detail can be observed, as well as their performance with respect to the measured and controlled variable. Figure 30.

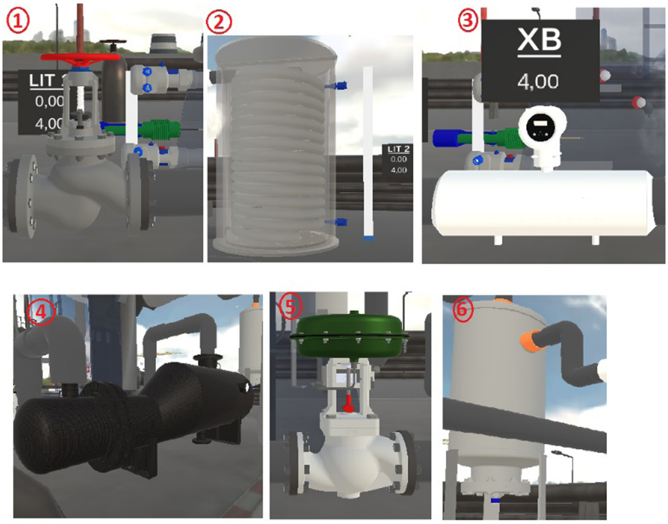


Fig. 30. Operation of the industrial instruments in the virtual environment of the distillation tower.

5 Conclusions

The system implemented by means of the Hardware in the Loop simulation technique, allows the virtualization of a binary distillation tower and the control of the process with the use of a real PLC, which will help the training in automatic control of industrial processes.

The implemented system allows to know the operation of a distillation tower, the behaviour of the transmitters and actuators in a virtual way; for this purpose, the instruments and industrial equipment used in the virtual environment are designed with similar characteristics to real equipment (appearance and physical behaviour).

The operation of the system was validated through the design of PID controllers in the PLC, obtaining a stable control in each stage of the distillation tower (virtual environment).

Acknowledgements. 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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