Virtual Training System of a Horizontal Three-Phase Separator

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Abstract. This paper presents a virtual training system, developed in the Unity3D graphics engine, oriented to control a three-phase horizontal separator. The design of the virtual environment aims to provide users with the ability to implement different control strategies to test the evolution of the process against different desired values. Besides, it allows to visually verify the variation of the level within the separator. The option of user levels strengthens the concept of monitoring, control, and supervision in an industrial plant, and these advantages of the system will consolidate the learning process of engineering students. Finally, it was determined that the virtual training system is good because the percentage of SUS usability was 72.5%.

Keywords: MIMO, Three-phase separator, Virtual reality, Training, Law Controls

1 Introduction

According to the Association of the Hydrocarbons Industry of Ecuador (AIHE), oil represents 2.5% of the global GDP, while in Ecuador it represents 8.9% of the national economy as of 2019. For this reason, it has an impact on the economy of all nations, especially oil producing countries, thus becoming the most important energy resource worldwide. Furthermore, in the OPEC's Oil Market Report, it is mentioned that demand continues to increase. It is also said that South America holds 20% of the world's proven crude oil reserves, with Ecuador holding 2.5% [1] [2].

In fact, oil is not consumed directly, it is necessary to refine it first. Refining consists of a series of separation, transformation and purification processes to obtain its derivatives, e.g., gasoline, diesel, fuel oil, residues, jet fuel, LPG, asphalts, among others [3]. Thus, in the oil and gas industry, separators are commonly used to obtain water, crude oil and gas from the emulsified mixture extracted from the reservoirs. Horizontal separators are thus vessels whose essential purpose is to release water, oil and gas through independent pipelines using different separation methods [4]. However, the separation of the three phases is complicated by the fact that the control systems have difficulty adapting to internal changes in pressure and temperature, in addition to the formation of emulsion layers [5]. In this sense, the control of a horizontal three-phase separator, especially the interface level measurement, is considered a challenge for hydrocarbon processing, since the methods used in the oil industry are limited due to the demand for high reliability, variety of fluids, hostile environments and intrinsic safety issues [6]. In fact, in marketing and custody transfer, to accurately determine the net volume of oil, water and sediment content are measured [7]; therefore, a good separator performance is important.

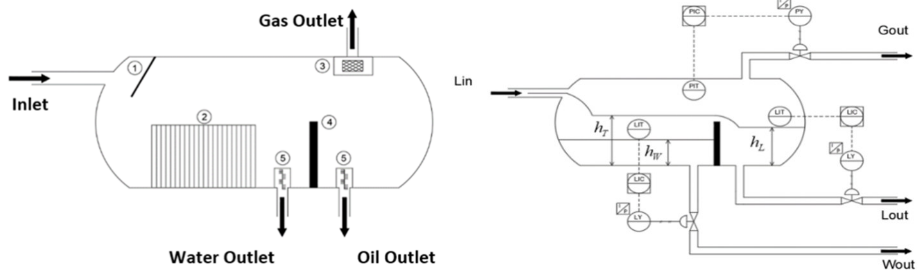
Due to the separation is a challenging process [8], controlling it implies knowing how the process works; selecting the necessary instrumentation to measure the variables to be controlled and monitored; understanding the control methods and techniques, among others. Thus, works have been found in the literature and can be grouped into three groups: *i) Modeling*, where the mathematical model is determined by applying the laws of conservation of mass, the phenomenon of thermodynamic equilibrium, the Eulerian multiphase model, in order to describe the dynamic behavior of the horizontal three-phase separator, predict the behavior and determine the efficiency of the separation [4][9][10]; *ii) Design of control algorithms*, one of the purposes of the control algorithms' is to modify the dynamics of the process to, e.g., maintain the water level inside the separator in a permitted range, smoothing the outlet flow of this phase, control the level and pressure inside the separator to improve the separation efficiency [11] [102]; and finally *iii) Simulation*, where to validate the mathematical models or the designed control actions, simulation is used because the physical form of the separator is not available. This validation strategy is generally carried out using numerical simulation or through mathematical software [13] [14] [15]. Nowadays and according to the advance of technology, Virtual Reality (VR) is an alternative to simulate an industrial process. VR is a dynamic three-dimensional simulation to recreate a real condition, using devices that stimulate the user's senses [16] [17] [18]. VR develops the ability to concentrate, because it allows the integration of three main components: immersion, interaction and imagination. As a result, virtual laboratories have been developed; applications, for smart devices, in augmented reality in order to e.g., train students in supervision, monitoring and control of industrial processes; in the use of LACT units, in the oil & gas industry; in the design of cooperative controls of mobile robots; among others [19] [20] [21]. In this way, learning is favored, complementing theoretical and practical knowledge in the area of engineering [22] [23].

As described in the previous paragraphs, this paper presents a virtual training system, developed in the Unity3D graphics engine, oriented to control a three-phase horizontal separator. The design of the virtual environment aims to provide users with the ability to implement different control strategies in order to check the evolution of the process. The dynamics of the separation process is governed by a multivariable mathematical model, which means that, by changing the inputs, the system will react to satisfy the operation requirements, thus achieving greater realism in the virtual environment developed.

2 Oil Separation Process

Horizontal three-phase separators separate the gas phase from the liquid phase and also separate the water contained in the oil. For this reason, they are also known as free water separators (FWKO), used mainly when the fluids have a low gas-oil ratio [22].

The main parts of the separator can be defined as: *i) Inlet diverter,* the incoming fluid collides with the internal baffle, causing a change of direction and velocity (change of momentum) of the mixture, achieving a first separation, the liquid goes to the bottom and the gas to the top; *ii) Coalescing plates,* through the coalescing plates, most of the gas is separated from the liquid; *iii) Mist extractor,* installed at the gas outlet, it produces coalescence due to the collision between the particles and against the surface, causing the larger droplets to fall by gravity. The force of gravity also acts on the fluid, leaving the liquid in the vapor phase; *iv) Weir,* It divides the separator (vessel) into the separation chamber and the crude chamber. In the separation chamber, due to the difference in densities, the water is placed at the bottom and the oil at the top, which overflows (over the spillway) and crosses into the crude chamber; and finally; *v) Weir breaker,* They are placed at the outlet of the water and oil piping, to avoid the formation of eddies and prevent the gas from exiting through these pipes [25], see Fig. 1 (a). In the FWKO, the system inputs are considered to be the water, oil and gas valve openings, while the outputs are the water level in the separation chamber, the oil level in the crude oil chamber and the pressure inside the separator. There are three control loops for each of the controlled variables, in order to maintain their values at the desired values, see Fig. 1 (b).



(a) Parts of a horizontal three-phase separator (b) Variables controlled in separator

Fig. 1. Parts of a Horizontal Three-phase Separator.

Where L_{in} is the emulsified flow entering the separator; G_{in} is the gas flow contained in the emulsified flow; G_{out} is the gas exit flow; L_{out} is the oil exit flow; W_{out} is the water exit flow; h_T; is the total level in the separation chamber; h_W is the water level in the separation chamber; h_L represents the crude oil level in the crude oil chamber.

The dynamics of the separation process is governed by the multivariable mathematical model shown in (1), and is used to design the control law for the system [10].

$$\begin{bmatrix} h_W(s) \\ h_L(s) \\ h_p(s) \end{bmatrix} = \begin{bmatrix} -\frac{17}{206s+1} & 0 & \frac{2.4}{367s+1} \\ -\frac{126}{322s+1} & -\frac{169}{330s+1} & \frac{43}{508s+1} \\ 0 & 0 & -\frac{2.4}{2s+1} \end{bmatrix} \begin{bmatrix} X_W(s) \\ X_L(s) \\ X_G(s) \end{bmatrix} \tag{1}$$

where, h_p is the pressure inside the separator; X_W represents the water valve opening; X_L represents the oil valve opening; and X_G is the gas valve opening.

3 Virtual Environment

For the creation of the virtual environment, it is known that the location of the FWKO is in the facilities of the oil production operating companies located in the Amazon region, in this sense, an environment generated by the Standard Assets of Unity with Terrain, Trees, Grass, among others, is used.

The digitalization of the FWKO starts with the design of the P&ID's where the control loops are shown. The transformation of the 2D design to 3D is carried out in the 3D modeling software, Blender, to create the instruments, metallic structures, and equipment that do not have a 3D model available from the manufacturer. Then, the digitized model is imported into Unity 3D considering the proportion, scale, and use of materials for texturing. In the texturing process, the materials generated in the import, which correspond to each element that makes up the FWKO, are edited. The standard shader is also used due to the projected use of the application on a PC and with the premise of optimizing the use of resources, see Fig. 2.

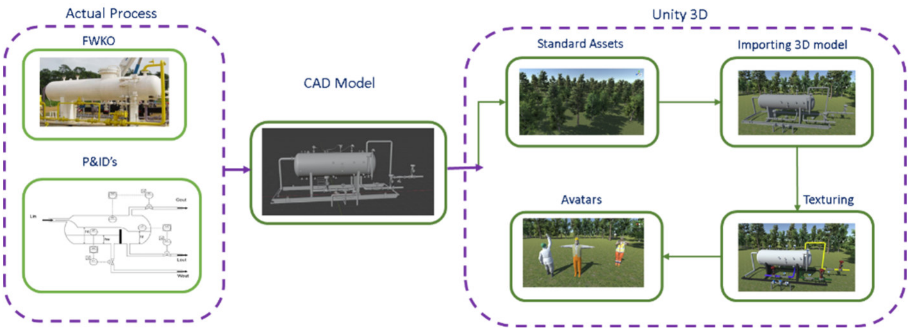


Fig. 2. Development of the virtual environment

The programming of the virtual environment is done in separate scripts so that the elements have an independent behavior, but at the same time, the developed code allows communication between them when required. A liquid filling effect is programmed in the separation chamber and the crude chamber so that the level evolves according to the value of the process output variables received from the simulation of the mathematical model in Matlab. This effect is achieved by using a 3D model for each chamber, so that the liquid takes the shape of the separator, in this case, a cylinder.

The system will use two semi-cylinders modified in their extension and height dimensions, which will show the space occupied by the liquid inside the cylinder, see Fig. 3.

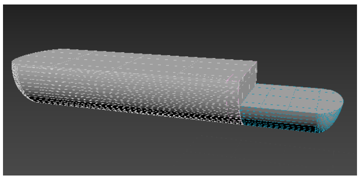


Fig. 3. Semi-cylinders for the filling effect.

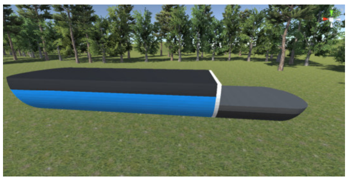


Fig. 4. Shader programming.

In this sense, in the Unity 3D editor, a shader is prepared which, employing a control slider, allows the desired value of the levels of pressure to be set. The new shader fulfills the function of distributing two color variables in the texture applied to the 3D model, one color variable and the other a Base (RGB) trans (A). Using a Fade Map, the orientation and level of change between the two variables are defined, generally, a gradient is used between the colors black and white. Finally, the control is obtained by applying the Alpha cutoff to the shader, which resizes the entire surface of the 3D model to a value between 0 and 1, see Fig. 4.

Also, the application must have real-time graphs to visualize the behavior of the input variables, output variables, errors, and control actions that show the performance of the control system developed in MATLAB. These graphs are displayed on the user interface and as dynamic information on the screens located in the control room. To this end, a class structure is created that allows the information mirroring to be executed in several instances. Since there are 3 variables in the process, a system of classes is used to reuse code and at the same time consume and send data between Unity and Matlab. On the other hand, bilateral real-time communication between the Unity 3D graphics engine and the mathematical software is carried out using shared memories, see Fig. 5.

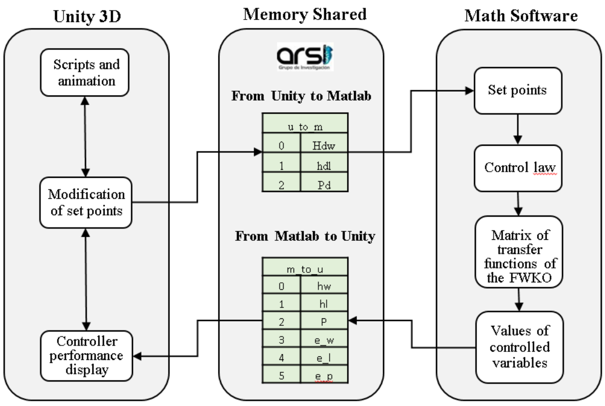


Fig. 5. Bilateral communication.

Finally, avatars are generated that represent the privileges according to user level: operator, engineer, and supervisor. These are compatible with the Unity Rig to apply locomotion animations and specific tasks to be performed in the virtual environment

4 Controller Structure

This section presents the control scheme implemented in the Virtual Training System for the horizontal three-phase separator, see Fig. 6.

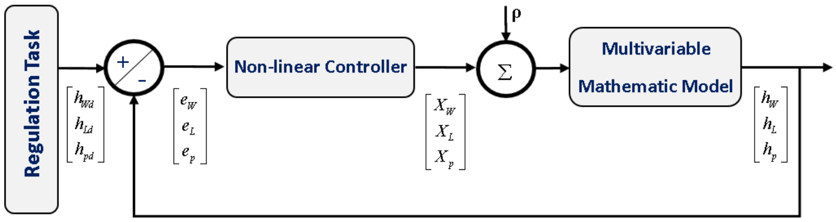


Fig. 6. Control Structure.

In the Fig. 6 h_{Wd} is the desired value for the water level; h_{Ld} is the desired value for the oil level; h_{pd} is the desired value for the pressure inside the separator; e_W is the error of the water level variable; e_L is the error of the oil level variable; e_p is the error of the pressure variable.

The proposed controller considers the saturation of the commands $\mathbf{x}_{\min} < \mathbf{x}_{\mathbf{ref}}(t) < \mathbf{x}_{\max}$; and receives as input signals $\mathbf{h}_{\mathbf{d}}(t)\big| t \in [t_0, t_f]$, which describe the desired values of the three-phase separator, in order to execute a regulation control of the water level, crude oil level and pressure variables. The control problem is to find the control actions $\mathbf{x}(t)\big| t \in [t_0, t_f]$ to achieve the desired values at the output of the three-phase separator. Therefore, the control error is defined as $\mathbf{e}(t) = \mathbf{h}_{\mathbf{d}}(t) - \mathbf{x}(t)$, and as a consequence the control error is expressed as,

$$\lim_{t\to\infty} \mathbf{e}(t) = \mathbf{0} \in R^3 .$$

The proposed controller considers the mathematical model in the time domain of the horizontal three-phase separator represented by (2)

$$\begin{bmatrix} \dot{h}_W \\ \dot{h}_L \\ \dot{h}_p \end{bmatrix} = \begin{bmatrix} -\frac{17}{206} e^{-\frac{T}{206}} & 0 & \frac{12}{1835} e^{-\frac{T}{367}} \\ -\frac{9}{23} e^{-\frac{T}{322}} & -\frac{169}{330} e^{-\frac{T}{330}} & \frac{43}{508} e^{-\frac{T}{508}} \\ 0 & 0 & -\frac{6}{5} e^{-\frac{T}{2}} \end{bmatrix} \begin{bmatrix} X_W \\ X_L \\ X_p \end{bmatrix}$$

$$\dot{\mathbf{h}}(t) = \mathbf{J}(t)\mathbf{x}(t) \qquad (2)$$

Now, $\mathbf{x}(t)$ can be represented in terms of $\dot{\mathbf{h}}(t)$ through the inverse matrix of $\mathbf{J}(t) \in R^{3\times3}$,

$$\mathbf{x}(t) = \mathbf{J}^{-1}(t)\dot{\mathbf{h}}(t) \tag{3}$$

where $\mathbf{J}^{-1}(t) = Adj(\mathbf{J})^T / |\mathbf{J}|$; therefore, the following control law is proposed for a regulatory control of the water and oil variables

$$\mathbf{x_{ref}}(t) = \mathbf{J}^{-1}(t)\mathbf{K}\tanh(\mathbf{e}(t)) \tag{4}$$

From equation (4) the control error is defined as $\mathbf{e}(t) = \begin{bmatrix} e_W & e_L & e_p \end{bmatrix}$; $\mathbf{K} \in R^{3\times3}$ is a positive definite matrix that weighs the control errors. The function $\tanh(.)$ is included to limit control errors $\mathbf{e}(t)$.

The control error behavior is analyzed through the Lyapunov theory. Substituting (4) in (2), the closed loop equation is obtained

$$\dot{\mathbf{h}}(t) = \mathbf{J}(t)\mathbf{J}^{-1}(t)\mathbf{K}\tanh(\mathbf{e}(t)) \tag{5}$$

Considering that $\mathbf{J}(t)\mathbf{J}^{-1}(t) = \mathbf{I}_{3\times3}$ y $\dot{\mathbf{e}}(t) = -\dot{\mathbf{x}}(t)$, then (5) can be represented by

$$\dot{\mathbf{e}}(t) = -\mathbf{K}\tanh(\mathbf{e}(t)) \tag{6}$$

For the stability analysis it is considered, for the moment $\boldsymbol{\rho} = 0$ and based on Lyapunov's Theory the candidate function is considered $V(\mathbf{e}(t)) = \frac{1}{2}\mathbf{e}^{\mathrm{T}}\mathbf{e}$. The derivative with respect to time and considering (6), it is possible to define that $\dot{V}(\mathbf{e}(t)) = -\mathbf{e}^{\mathrm{T}}\mathbf{K}\tanh(\mathbf{e}(t)) < 0$. Therefore, it is concluded that the errors with control $\mathbf{e}(t) = \mathbf{0} \in R^3$ with $t \to \infty$, that is, an asymptotic stability. Considering a perturbation $\boldsymbol{\rho}(t) \neq 0$ at the process input the closed loop equation considering (4) and (2) is,

$$\dot{\mathbf{e}}(t) = -\mathbf{K}\tanh(\mathbf{e}(t)) + \mathbf{J}\boldsymbol{\rho} \tag{7}$$

Now considering the Lyapunov candidate function similar to the previous case, the first derivative with respect to time and considering (7), it is defined as

$$\dot{V}(\mathbf{e}(t)) = -\mathbf{e}^{\mathrm{T}}\mathbf{K}\tanh(\mathbf{e}) + \mathbf{e}^{\mathrm{T}}\mathbf{J}\boldsymbol{\rho} \tag{8}$$

A sufficient condition for it to be negative is,

$$\left|\mathbf{e}^{\mathrm{T}}\mathbf{K}\tanh(\mathbf{e})\right| > \left|\mathbf{e}^{\mathrm{T}}\mathbf{J}\boldsymbol{\rho}\right| \tag{9}$$

therefore, it is possible to conclude that the control errors are finally bounded, with bound

$$\|\mathbf{e}(t)\| < \frac{\|\mathbf{J}\boldsymbol{\rho}(t)\|}{\lambda_{\min}(\mathbf{K})\tanh(\mathbf{e}(t))}. \tag{10}$$

It is important to mention that $\|\boldsymbol{\rho}(t)\| < \kappa_p$ where κ_p is a positive constant. In conclusion, if the perturbation $\boldsymbol{\rho}(t)$ is bounded, therefore, the control error $\mathbf{e}(t)$ is stable with bounding defined in (10).

5 Analysis and Results

This section shows the results obtained from the virtual training system of the three-phase horizontal separator and they are shown in three stages: *i) Virtual Environment,* where the user's interaction with the virtual environment developed in the Unity 3D graphics engine is presented.; *ii) Process Control*, where the performance of the control algorithms developed in Section 4 is shown; and finally, *iii) System Usability,* where the usability results of the virtual training system are shown.

For the implementation of the virtual system developed, an Inspirion 5593 computer with an Intel Core i7-1065g7 CPU @ 1.3-1.5GHz processor, 16GB RAM and NVIDIA GeForce MX23 video card was used, see Fig. 7.

Fig. 7. Virtual training system developed.

5.1 Virtual Environment

User interaction in the virtual system depends on the privileges obtained after logging into the system, see Fig. 8 (a). Three levels have been established. The user as supervisor has full privileges within the system. The user as an engineer has a medium privilege level. The user as an operator has a low level of privileges. The avatar’s clothing defines the user’s level such as show in the Fig. 8 (b)(c)(d).

(a) Registration in the system

(b) Supervisor Level

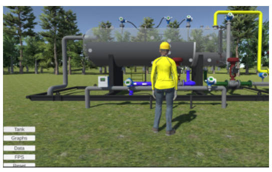
(c) Engineer Level

(d) Operator Level

Fig. 8. Log in to the system.

The virtual system developed considers the implementation of the mathematical model of the horizontal three-phase separator in order to simulate its real behavior; while the control scheme proposed in Section 4, allows visualizing the performance of the controller. In this way, when the user moves within the training system he/she will be able to visualize the following: *i) Tank Filling Effect*, visualize the effect of filling or emptying of liquid in the separator by pressing the "Tank" key as well as the values of the measured variables on the displays of the field transmitters, see Fig. 9; *ii) Control Variable Modification,* the desired values of the controlled variables can be changed from the user interface, privileges permitting, see Fig. 10; *iii) Controller Behavior,* the increase or decrease of the values of the controlled variables, the control errors and the control actions are visualized in the graphs presented, in this way, it is possible to evaluate if the designed controller is adequate, see Fig. 11; *iv) Measuring Principles of Transmitters,* It is well known that to control a physical variable it is necessary to measure it, but it is also important to install the transmitters with the correct measurement principles to get an accurate value, so in the training system, the measurement principles of the installed transmitters are displayed when the user approaches them, see Fig. 12.

(a) Normal View



(b) Transparent View

Fig. 9. Horizontal Three-Phase Separator.

Fig. 10. System dynamics

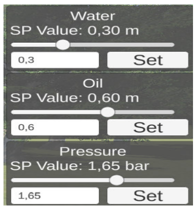


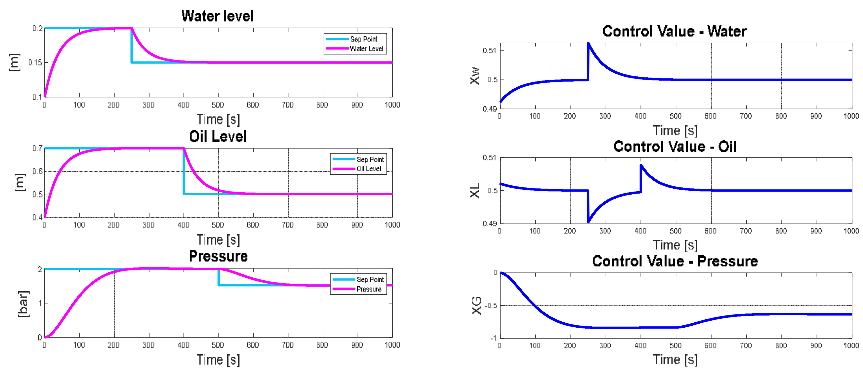
Fig. 11. Change of set points.

Fig. 12. Field instrumentation.

5.2 Process Control

The implementation of the control scheme proposed in Section 4, considers the control algorithms for the variables of water level in the separation chamber, oil level in the oil chamber and pressure inside the separator.

The Fig. 13 (a), presents the variation of water level, oil level and pressure against set point changes occurring at different times and it is observed that the error tends to zero asymptotically when time tends to infinity. This means that the system is stable. The Fig. 13 (b), shows the evolution of the water valve opening X_W ; the evolution of the oil valve opening X_L ; and the evolution of the gas valve opening X_G . The variation of the valve openings occurs to maintain the value of the controlled variable at the desired value



(a) Controlled Variables

(b) Value opening

Fig. 13. Performance of process variables.

5.3 System Usability

Finally, to determine the usability of the system, a 10-question SUS questionnaire was applied. The answers have a range from 1 to 5, where 1=I completely disagree and 5=I agree. The method for evaluating the responses is to subtract 1 from the results of the odd-numbered questions. The results of the even-numbered questions are subtracted from the result of 5. The final result must be multiplied by 2.5 to get a value of 100%. The SUS test indicates that percentages up to 70% will consider the system to be good [26].

Table 1. Usability Questionnaire

Item	Questions	Results	Operation
1	I am familiar with VR training systems.	3	3-1
2	I think I would like to use the training system often	2	5-2
3	I thought the system was user-friendly	5	5-1
4	I think I would need the help of a technician to use this training system.	1	5-1
5	I think the training system is intuitive.	4	4-1
6	I thought there were many inconsistencies in the training system.	3	5-3
7	I think users would quickly learn to use this system.	4	4-1
8	I think I should be trained before using the training system.	2	5-2
9	I think that after using the training system, I already know how the FWKO works.	3	3-1
10	I consider it cumbersome to use a training system for an industrial process.	2	5-2
			29

La Table 1 shows the application of the process to determine the usability percentage for the virtual training system of a three-phase horizontal separator, and the usability percentage was determined to be 72.5%.

6 Conclusions

VR allows the development of virtual environments to simulate industrial processes, to which students do not have access, especially in the Oil&Gas industry where the exploitation, production, and refining activities that are executed are restricted and it can be said that it would be impossible to implement, by training, some control algorithms in the FWKO. In this sense, the implemented training system will contribute to the teaching-learning process to strengthen the theoretical concepts of control algorithm design. Furthermore, the student will be able to repeat the training as many times as necessary until the control law produces a stable and robust system without any risk to the student's safety or the safety of the process. Besides, knowledge of the principles of measurement and of the instruments that must be installed to measure the variables to be controlled or monitored according to the operating characteristics of the process is consolidated. Also, the implementation of a multi-user system strengthens the concept of monitoring, control and supervision in users. Finally, it is determined that the virtual training system to control a horizontal three-phase separator is good because the SUS percentage was 72.5%.

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