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Virtual reality application of an enclosed tank as a teaching module for automatic control

Aplicación de realidad virtual de un tanque cerrado como un módulo de enseñanza para el control automático

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César Darío Cando Sangoquiza[1]
Alfa Soluciones – Ingeniería, Ecuador
cedario93@gmail.com
https://orcid.org/0009-0006-5765-1017

Willian David Morales Chicaiza[2]
Alfa Soluciones – Ingeniería, Ecuador
williansmorales00@gmail.com
https://orcid.org/0009-0009-2394-5297

Edison Guillermo Mullo Mullo[3]
Alfa Soluciones – Ingeniería, Ecuador
edisongmullom@gmail.com
https://orcid.org/0009-0000-9268-403X

Edison David Mañay Chochos[4]
Alfa Soluciones – Ingeniería, Ecuador
edmanay@outlook.com
https://orcid.org/0000-0002-3447-2511

ABSTRACT

In the field of engineering, Virtual Reality (VR) has emerged as a training option for students to generate practical skills in automatic process control. The article presents a VR application of a closed tank, which allows the introduction of control strategies for the pressure variable, using a microcontroller and a computer. The VR interface was implemented in Unity with the three-dimensional design of the plant shown to the user on the computer monitor, the mathematical model that characterizes the dynamic behavior of the process and the PID control strategy was established in the Arduino Uno module. Communication between the Arduino and the PC was established via RS-232 protocol. The VR environment consists of a panel for the selection and serial connection with the Arduino, also with inputs that allows to evaluate the control strategy as the SetPoint (SP) and the manual valve (a2), which is the actuator to introduce disturbance to the model. With the SP entered to the control system with perturbations of 20, 60 and 90%, the PID control performed well with minimal steady state errors. The dynamic behavior of the process is visualized in the VR environment with the movement of the control valve stem (a1), the process variable (PV) is displayed on the PIT 100-A transmitter and the trends of the variables (SP, PV and CV). The proposal can be replicated to other processes and different variables such as level, flow, etc.

KEYWORDS: virtual reality, unity 3d, arduino, pid control, pressure, closed tank

RESUMEN

En el campo de la ingeniería ha surgido la realidad virtual (VR) como una opción de capacitación para que los estudiantes generen habilidades prácticas en el control automático de procesos. El artículo expone una aplicación de VR de un tanque cerrado, que permite introducir estrategias de control de la variable presión, haciendo uso de un microcontrolador y un ordenador. Se logró implementar la interfaz de VR en Unity con el diseño tridimensional de la planta que se muestra al usuario en el monitor de la computadora, el modelo matemático que caracteriza el comportamiento dinámico del proceso y la estrategia de control PID se estableció en el módulo Arduino Uno. La comunicación entre el Arduino y la PC se estableció por medio del protocolo RS-232. El entorno VR consta de un panel para la selección y conexión serial con el Arduino, también con entradas que permite evaluar la estrategia de control como el SetPoint (SP) y la válvula manual (a2), que es el actuador para introducir perturbación al modelo. Con el SP ingresado al sistema de control con perturbaciones de 20, 60 y 90%, el control PID tuvo un buen rendimiento con errores en estado estacionario mínimos. El comportamiento dinámico del proceso se visualiza en el entorno VR con el movimiento del vástago de la válvula de control (a1), se visualiza la variable de proceso (PV) en el transmisor PIT 100-A y las tendencias de las variables (SP, PV y CV). La propuesta puede ser replicada a otros procesos y a variables diferentes como nivel, flujo, etc.

PALABRAS CLAVE: realidad virtual, Unity, Arduino, gestión industrial, tanque cerrado

Introduction

Industries must be competitive in the market, minimize production costs, reduce pollution, improve the quality and durability of their products. Achieving these objectives requires appropriate methods of production control, which are possible through the application of automatic control, therefore, in vocational training to achieve knowledge in control, automation and instrumentation is essential. Technological progress also has a direct and indirect impact on people's daily lives. Tipán (2022) proposed an application that allows people with a certain degree of disability to interact through computer vision, in particular the detection of movement with environments that simulate reality.

Education in various fields of engineering requires laboratories for students to receive high quality training and practical skills in the field of process control. The advancement of information technology has opened new horizons for learning and teaching worldwide. In addition to field practices, virtual simulations are becoming more and more common. A virtual environment can be a powerful tool in institutions where physical equipment is not available to put students in "hands-on" situations, allowing for greater equity in the teaching process (Charre-Ibarra et al., 2014).

Virtual Reality (VR) is acquiring great relevance in the educational field. It is necessary to promote the training of future professionals in the use of these emerging technologies that improve the teaching-learning processes (Cózar et al., 2019).

Sousa et al. (2021) proposed virtual reality as a tool for teaching and learning processes in the field of basic and professional education. For them, VR is analyzed as an alternative to ensure the quality of the educational process, especially in situations of physical distance due to the pandemic.

VR is a training tool for the industrial field, because it provides virtual experiences that are impossible in a real environment, in terms of safety in the operation of equipment and cost. The research conducted by Montalvo et al. (2020) presents an Augmented Reality system that allows users to train in the handling of HART instrumentation, using the Unity 3D platform and Meta 2 glasses.

This paper proposes a Virtual Reality application of a closed storage tank as a teaching module for automatic control, which facilitates the learning process in control engineering fields, so that the user does not need specialized equipment or expensive computer accessories. In this context, personal computers with Windows operating system are most commonly used in the educational sector. A computer generally consists of a display and input/output devices, which are used to interact with the VR system. When it comes to development software, there are two well-known options, Unity and Unreal, both of which offer easy-to-learn tools and large support communities for application development. When it is required to perform automation projects at the educational level electronic boards are widely used such as Microchip Technology and Arduino modules (Varela-Aldás et al., 2021). Based on these criteria, the components of the virtual reality system were determined.

1.1 Mathematical model of the closed storage tank

The model originates from a mathematical proposal of the dynamic characteristics of the process based on differential equations that describe the dynamic behavior of the process.

The flow through a valve is generally expressed by equation (1).

$$Q_v = K_v f(x)\sqrt{\frac{\Delta P}{\rho}} \tag{1}$$

Where Q_V is the flow through the valve, K_V constant, *f(x)* passage area, ΔP is differential pressure across the valve, ρ density of the liquid..

The final control element is considered to be a linear type valve, so $f(a_1)=a1$, (linear opening), therefore, the inlet valve is represented in equation (2).

$$q_i = k_1 a1 \tag{2}$$

The outlet valve $f(a_{\_2})=a_{\_2}$, $K_{\_v}=k2$, is given in equation (3).

$$q_o = k_2 a_2\sqrt{\frac{\Delta P}{\rho}} \tag{3}$$

The differential equation describing the pressure changes of a gas inside a tank, from which some leakage is allowed in subcritical regime, is given by equation (4) and (5).

$$\frac{dP}{dt} = -\frac{RTK_0A_0}{V}\sqrt{P_o(P-P_o)} + \frac{RT}{V}u \tag{4}$$

$$\frac{dP(t)}{dt} = \frac{V*T}{R}\left(a_1(t)\sqrt{P_i\big(P_i - P(t)\big)} - a_2(t)\sqrt{P(t)(P(t)-P_o)}\right) \tag{5}$$

Where u is the volume of gas per unit time, with which the tank is fed using a compressor. This value, it is assumed, does not depend on the pressure. The feeding is carried out in such a way that the pressure changes of the gas are sufficiently slow to be considered isothermal. V is the volume of the vessel, A_0 and K_0 are constants depending on the inlet valve and the gas under consideration. *R* is the universal gas constant and *T* is the temperature at which the process is carried out. P_0 is also a constant (Sira-Ramirez et al., 2018).

The objective of the article is to develop a VR instrument, which allows introducing the PID control strategy to the pressure process, making use of a microcontroller and a computer. The following sections describe the system design, the technologies and devices used for control and Virtual Reality. Also, the results of the implemented system are presented.

Methodology

To carry out the development of the Virtual Reality system of a closed tank for pressure control, it is based on the Work Breakdown Structure (WBS) methodology, which makes a project more manageable when it is broken down into individual parts, establishes the project boundaries and scope (Mañay et al., 2022).

Five work stages have been established for progress, which are shown in *Figure 1*.

Figure 1

Work Stages According to WBS Methodology

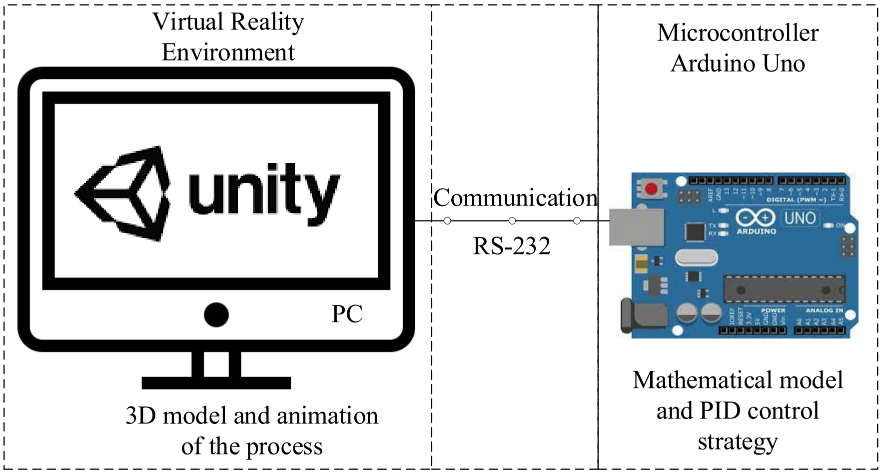
2.1 System architecture

The computer monitor displays the Virtual Reality interface to the user with the 3D model of the plant, while the mathematical function symbolizing the dynamic behavior of the process and the PID control strategy is located on the Arduino Uno module. The input elements (mouse and keyboard) allow interaction with the system. The game engine selected was Unity, which allows the development of an application with flexibility and cross-platform features. In addition, the proposal required a three-dimensional animated character or avatars, for which the Mixamo platform was used, which is a web application that allows downloading prefabricated characters and avatar animations. SolidWorks software was used to design the 3D components such as pipes, tanks, valves and transmitters.

Figure 2 shows the components required for the implementation of the VR system.

Figure 2

VR System Architecture

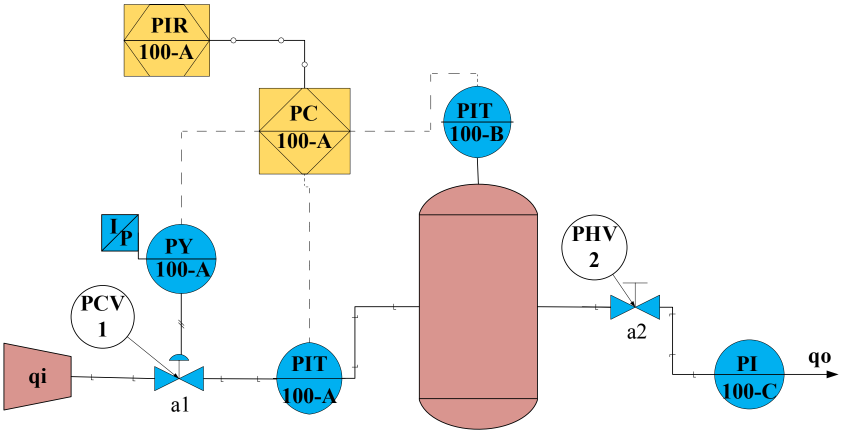


2.2 P&ID diagram of the process

The P&ID diagram of the pressurized storage tank process for pressure control can be seen in *Figure 3*.

Figure 3

P&ID Diagram of the Closed Storage Tank



The P&ID diagram shows the control loop (100) with the respective pressure indicating transmitter (PIT 100-A/B), pressure controller (PC), pressure indicating recorder (PIR), current to pressure converter (PY), pressure control valve (a1), manual pressure valve (a2) and pressure output indicator (PI 100-C).

The closed storage tank shown in Figure 3 has an inlet fluid ($q_{in}(t)$). These are piped to the vertical tank. The fluid pressure variable in the tank is controlled by the valve (a1) and the manual valve (a2), which are the actuators of the system.

2.3 3D virtual environment model

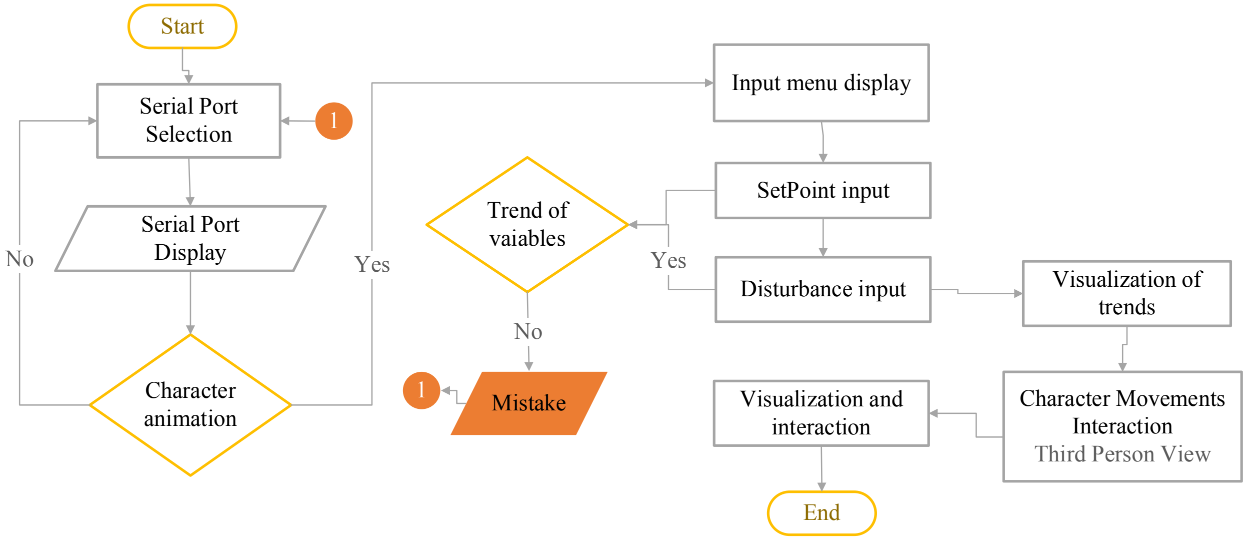
The 3D visualization environment, comprised of the three-dimensional model of objects in a real plant or laboratory, can replicate and study the dynamic behaviors of a process.

It is important to point out that there are no prescriptions for designing the Virtual Reality interface, since its structure and operation depend on the variable to be controlled. However, a methodological proposal is proposed to develop the virtual interface, which is done by designing the objects that make up the station in the Solidworks design software. The designed objects are sent to the virtualization environment in a 3D template to Unity to integrate text monitors, sounds, process animation, trend graphers and avatars that through the use of scripts and block code control the movements of the characters and third person interaction with the 3D objects, similar to a real industrial process.

The VR environment consists of a panel with parameters for selection and serial connection to the Arduino Uno module (algorithm with the mathematical model of the plant and PID control). Also, the scene offers inputs that allow modifying process variables, such as the SetPoint (SP) value from 10 to 25 PSI and the a2 valve in the range of 20 to 90%, the a2 valve serves as a disturbance of the plant. The variables entered to the control system vary based on the mathematical model integrated in the microcontroller. In the VR environment, the dynamic behavior of the process is visualized with the movement of the control valve stem (a1) by means of the control variable (CV), the process variable (PV) is visualized in the PIT 100-A transmitter and the trends of the variables (SP, PV, CV). *Figure 4* represents the logical procedure to follow for the execution of the simulation of the plant, to avoid errors in the execution, since the Arduino module must be connected before running the simulation.

Figure 4

Virtual Reality Environment Execution Logic Diagram

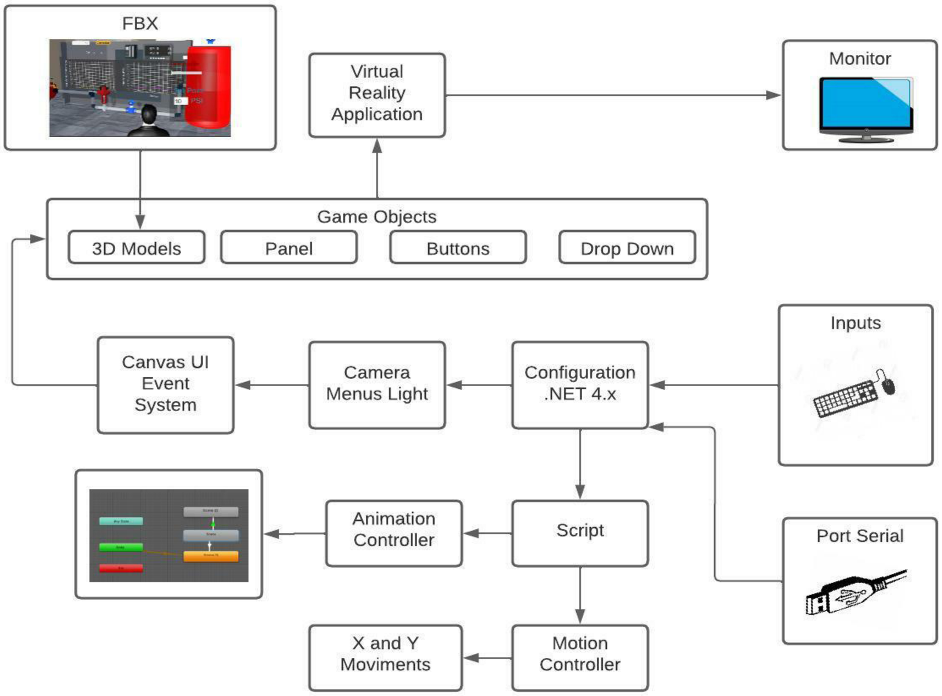


2.3 Development of the 3D virtual environment

Three-dimensional objects designed to import in FBX format to Unity and integrate with more structure components such as panels, buttons and selectors to generate the scene in the VR application, some objects can be modified using Canvas components. The control of the behavior of the objects is instantiated by the execution of the programs through scripts to create animations, vector images and two-dimensional time-dependent signals. *Figure 5* shows the methodology for creating the virtualization environment.

Figure 5

Methodology for Creating the Virtual Scenario



The set of components is coupled into a single object to form the process station, as shown in *Figure 6*.

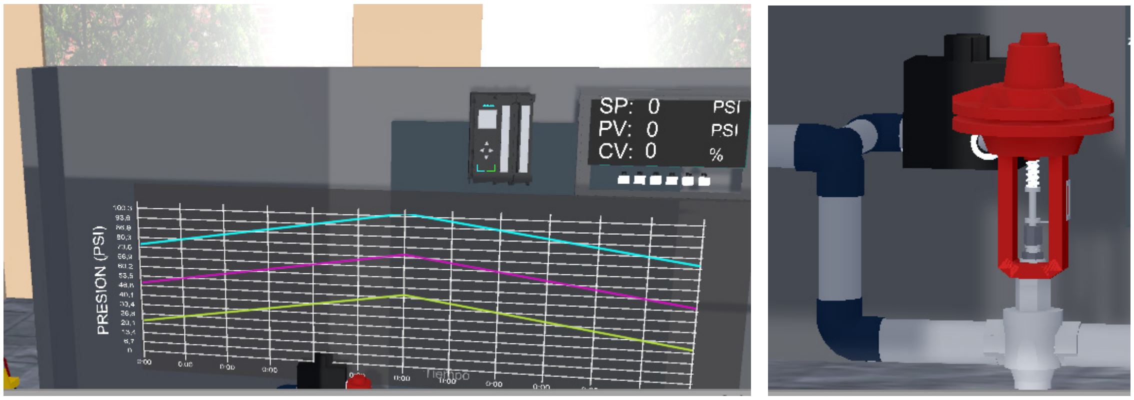
Figure 6

Virtualization of the Plant in a 3D Environment

The deployed scenario has control and visualization components, the graphical representation of the monitoring of the variables is shown in *Figure 7*(a), *Figure 7*(b) shows the proportional valve (a1) that allows pressure flow control.

Figure 7

Virtual Scenario, (a) Rrend of Variables, (b) Control Valve (a1)

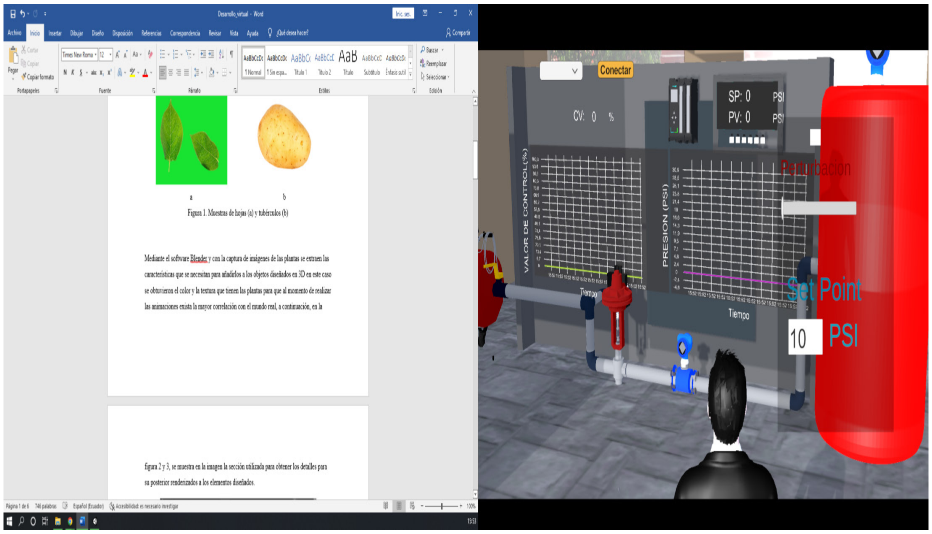


(a) (b)

The virtual interface allows to move the character by keyboard commands through the entire scenario composed by the objects designed and placed on the area with characteristics of a real environment as shown in *Figure 8*.

Figure 8

Avatar in the Virtual Work Environment



a b

Figura 1. Muestras de hojas (a) y tubérculos (b)

Mediante el software Blender y con la captura de imágenes de las plantas se extraen las características que se necesitan para añadirlos a los objetos diseñados en 3D en este caso se obtuvieron el color y la textura que tienen las plantas para que al momento de realizar las animaciones exista la mayor correlación con el mundo real, a continuación, en la figura 2 y 3, se muestra en la imagen la sección utilizada para obtener los detalles para su posterior renderizados a los elementos diseñados.

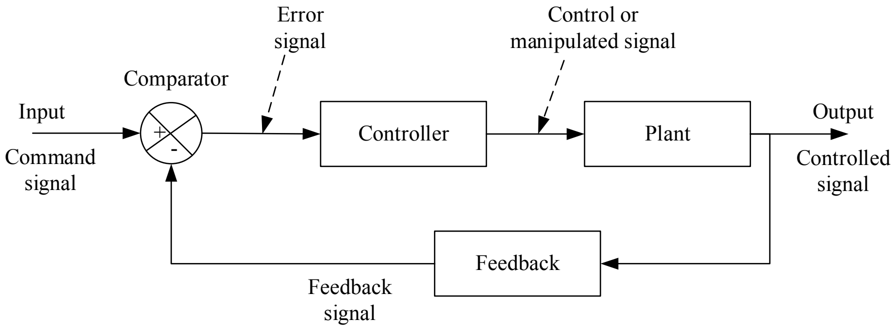
2.4 Control strategy design

Once the Virtual Reality environment of the pressurized storage tank is implemented, the PID control strategy for the pressure variable is designed and validated. The RS-232 protocol is used to achieve communication between the control algorithms and the scenario. The corresponding adjustments are made in each software and hardware, and then the communication is established and the data exchange is validated in real time.

In industrial processes, the measurement and control of the pressure variable is essential to achieve safe operating conditions. Any vessel or piping has a maximum working pressure and exceeding that pressure can cause equipment failures, mainly when exposed to flammable or corrosive liquids (Rodríguez et al., 2011). The study of control strategies is fundamental to manage variables in closed-loop processes, *Figure 9*. In control theory, a control strategy governs the dynamic behavior of a process by regulating a variable with reference to a SetPoint by means of an input variable (Flores-Bungacho et al., 2022). There is a classical strategy such as proportional integral derivative (PID) control, which is implemented in this article.

Figure 9

Closed Loop Control Block Diagram



2.4.1 Design of the PID control algorithm

The PID control strategy is the most widely used in industrial applications; it is estimated that more than 90% of control loops use PID control, since it is a simple and effective strategy that does not require a great theoretical foundation for its use in everyday processes (Lozano-Valencia et al., 2012). The design of PID controllers can be achieved from different approaches, ranging from trial-and-error methods, as based on the dynamic model of the system. The PID algorithm can be described as shown in equation (6).

$$u(t) = \left(K_e(t) + \frac{K}{T_i} \int_0^t e(t)dt + KT_d \ \frac{d_e(t)}{dt} \ \right) \qquad (6)$$

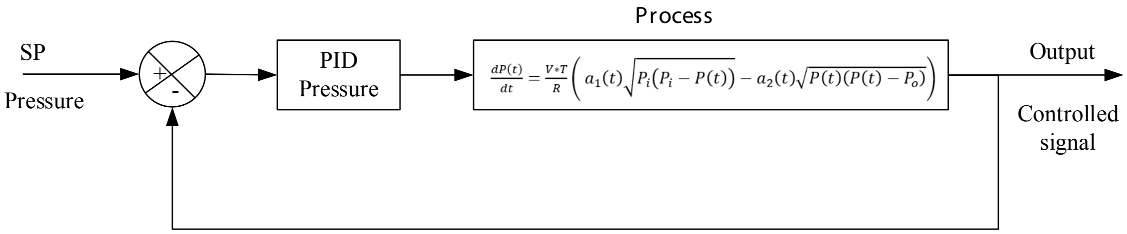
Where *u(t)* is the control signal, *e(t)* is the error, $\int_0^t e(t)dt$ is the integral of the error, and $(d_e\,(t))/dt$ is the derivative of the error. The control parameters are the proportional gain K_p, the integral gain

K_i=*K/Ti* where T_i is the integration time, and the derivative gain *K_d=KT_d* where T_d is the derivative time (Anitha et al., 2019; Burgasi et al., 2021).

In the pressurized tank station, the PID control loop is implemented for the pressure variable, as shown in the closed loop diagram in *Figure 10*.

Figure 10

Block Diagram of Implemented PID Control



The pressure control loop constants are tuned with the trial-and-error method, the values of each parameter are shown below: .

Results

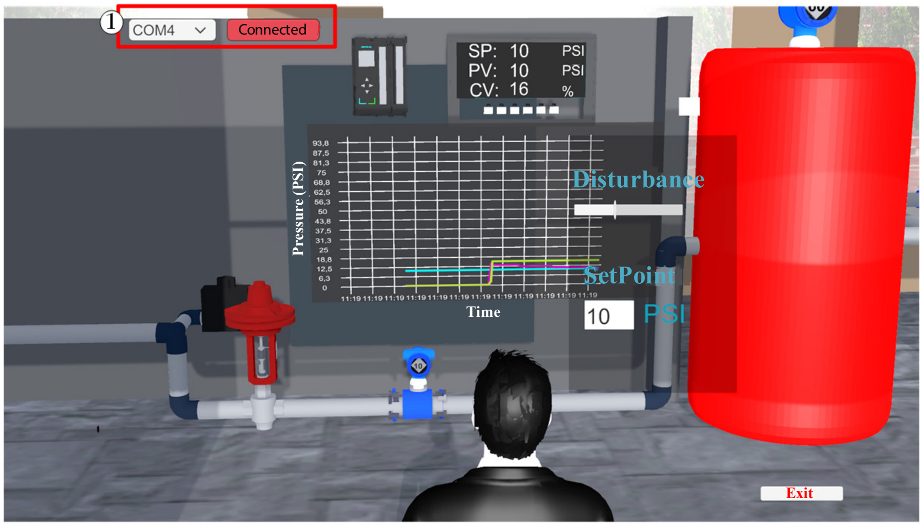
3.1 User immersion

The parameters used to describe the imprisonment process of a virtualized closed storage tank are as follows: *H=2m; D=1m; V=5; R=8.314472[J/(mol*K^0)]≈8500; T=273 K^0, P_i =30psi, P_o=10psi*.

When entering the virtualized system, the user can: i) visualize the pressure control process of the closed storage tank, by selecting the available serial port and pressing the “Connect” key (1), he/she can view the values and trends of the measured and controlled variables, see *Figure 11*.

Figure 11

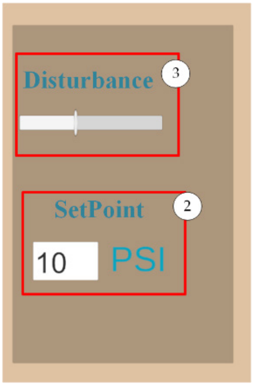
Process in the Immersive Environment



ii) change the desired values from the user interface, (2) the SetPoint in the range of 5 to 25 PSI and (3) the perturbation from 20 to 90%, see *Figure 12*.

Figure 12

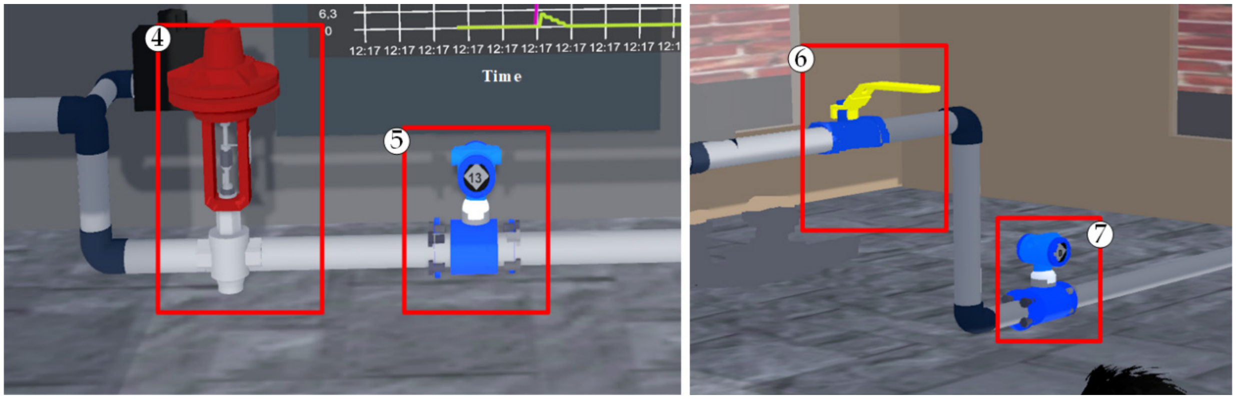
SetPoint Change and Disturbance



iii) The control of the implemented system makes the respective indicators and actuators dynamic: (4) the control valve (a1) has an animation in which the stem moves depending on the control signal, (5) the PIT-100A shows the process variable, (6) the manual valve (a2) is the actuator that inputs disturbance to the system and (7) the PI shows the output pressure, see *Figure 13*.

Figure 13

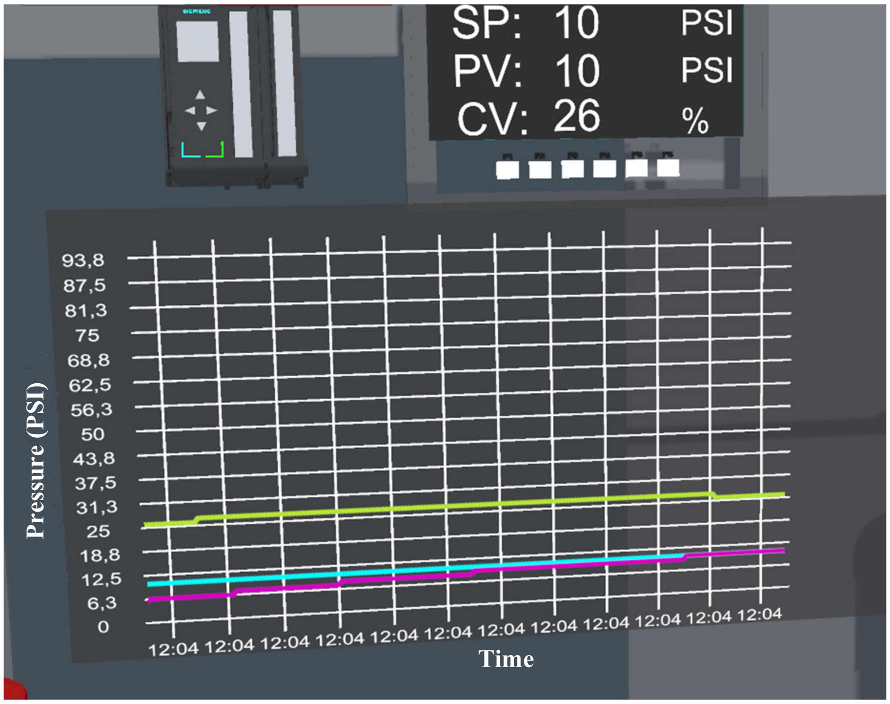
Actuators and Process Indicators



iv) the behavior of the controlled variables, control errors and pressure actions can be visualized in the trend graph, see *Figure 14*.

Figure 14

Process Variables and Trends

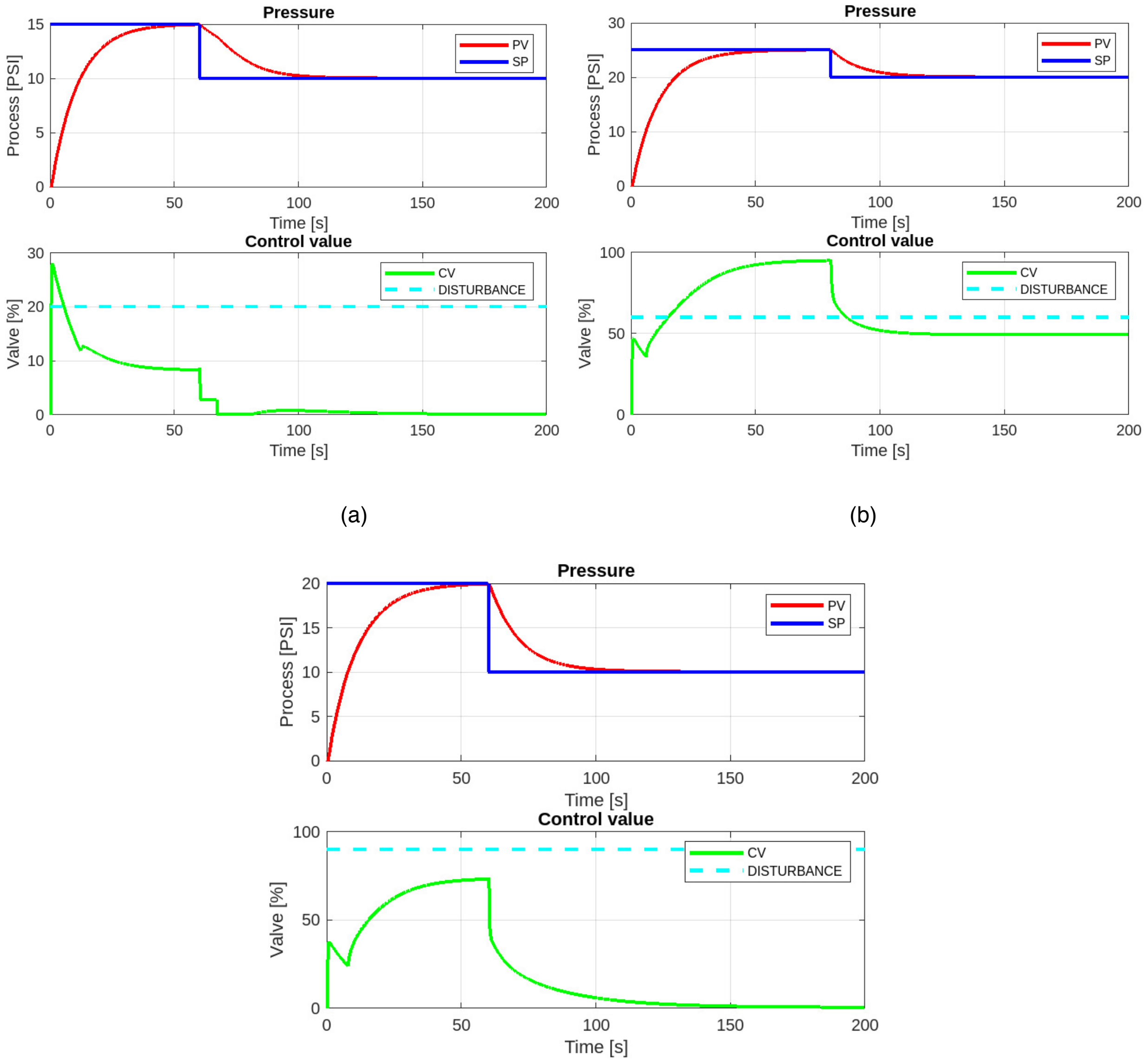


3.2 Process Control

The performance graph of the designed PID control law shows that the control errors tend to zero asymptotically over time. To evaluate the control, the manual valve (a2) is kept open at 20%, 60% and 90%, the results are shown in *Figure 15*.

Figure 15

Performance of Process Variables, Manual Valve (a2): (a) 20%, (b) 60% and (c) 90%



(a)

(b)

(c)

3.3 System usability

A 10-question questionnaire is established to test the usability of the virtual reality system (SUS); it is shown in *Table 1*. The questionnaire applied to the users is weighted from 1 to 5; where 1 total disagreement to 5 total agreements. The evaluation of the answers is based on subtracting 1 from the result in the odd questions; while in the even questions the result obtained is subtracted from 5. To obtain the SUS value, the data obtained are added and multiplied by 2.5 to obtain 100% (Chiliquinga et al., 2021; Proaño & Andaluz, 2021). The SUS test indicates that percentages of up to 70% will consider the system to be good (Andaluz et al., 2018).

Table 1

Usability Questionnaire

Nº	Questions	Results	Operations
1	Is the information displayed on the screen what is needed to understand what the site is about?	**5**	**5-1=4**
2	Do I understand and comprehend the screen elements presented on the system?	4	**5-4=1**
3	Is the application easy to use?	**5**	**5-1=4**
4	Do I need previous knowledge to use the system?	1	5-1=4
5	Does the system provide me with the information I need to understand the process?	4	**4-1=3**
6	Do the icons provide explanatory information?	**2**	**5-2=3**
7	Do the interface colors resemble those of the real world?	5	5-1=4
8	How often would you use the application?	4	**5-4=1**
9	Can anyone use the system?	**5**	**5-1=4**
10	Does the application offer intuitive interface control?	4	5-4=1
Total	**72.5**		

Table 1 shows the evaluation of the virtual environment (SUS) of the process to determine the percentage of usability of the project, obtained a score of 72.5%, being considered a good system, however, the project needs to implement improvements to obtain greater results and maximize the user experience in immersive environments.

Conclusion

The objective of creating a Virtual Reality tool for the teaching-learning process was achieved, the project allowed to introduce variations to the PID controller through the virtual environment and also to visualize the dynamic behavior of the pressure process in the VR environment with the movement of the control valve stem (a1), the value of the pressure variable in the transmitter in PIT-100A and to vary the manual valve (a2) to enter disturbances to the process. An Arduino Uno microcontroller and a laptop computer were used. The VR system had an investment of 910 USD: the Arduino microcontroller cost 12 USD and the computer used has the following characteristics (Intel(R) Core (TM) i7-8650U CPU @ 1.90GHz 2.11 GHz) with a cost of 900USD, this type of computer is generally available to university students, generating a minimum investment for the implementation of this type of project.

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