Implementation of an industrial control applied to a virtual reality scenario for real-time training

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***Abstract*—It has developed an innovative new concept hybrid system that relates the use of emerging technologies, such as virtual reality and industrial control, and PLC's. Currently, the causes of risk in the industry, such as safety, profitability, the training of specialized operators, are a vital and imperishable process at an industrial level. Currently, in industry 4.0, emerging technologies such as virtual reality used by cyber-physical systems and intelligent industrial automation and control system should be easily programmable, flexible, reliable, robust, and profitable. Therefore, applications focused on virtual reality interact with real-time industrial control. Consequently, this article presents the development of a virtual reality scenario of a plant that can remotely control the plant in real-time. These remote-control techniques are developed by digital signal processing, which is processed in PLC. The virtual scenario is built with a mathematical model with a response in a discrete-time of a dynamic system applied in the cyber-physical system, achieving the incorporation of the control of these systems through the PLC with physical signals in real-time.**

Keywords—virtual reality, operador training, industrial control.

I. INTRODUCTION

The impulse of industrial digitization is making use of a series of emerging technologies, such as the use of virtual reality (VR). Industry 4.0 and similar initiatives do not focus on "dark factories" without humans but have as allowing target people to work in tough smart factories s [1] with environments intelligent manufacturing results provide a first decisive and relevant indication influence the behavior of adoption by companies manufacture as [2]. Even though growing and intelligent automation is a vital part of these companies, humans continue to play an important role in manufacturing operations [3]. On the other hand, rapid technological progress in the more recent past has opened up a range of new potentials and business opportunities [4]. Trends and new slogans such as digitization, the Internet of Things (IoT), the Internet of Services (IoS) systems, and cyber-physical (CPS) are becoming more relevant time [5]. This allows researchers to work in hybrid systems relating RV to real-time industrial control such as the PLC. So the research is generalized into two basic paradigms that include: training of operators and saving time programming in the launch of a new industrial plant.

The role of operators is now more demanding and crucial than ever because of an apparent increase in the complexity of modern plants as e l increased automation, advanced control, and optimization online [6]. Modern industrial plant operators face additional challenges due to increased complexity, so the restructuring and adoption of training methods in the process industry have not yet kept pace with the pace of technological development [7]. As accident outcomes are closely related to process variables [8, 9], there is a quantitative risk assessment (QRA) methodology integrated with dynamic simulation linking process simulations with accident simulations [10]. Besides, the total cumulative value of the 100 largest losses that occurred between 1974 and 2013, based on the value of property damage in 2013, was estimated at more than US $ 34 billion, where the electricity generation areas (34%), refining (29%) and petrochemical (23%) sectors contributed the most, while the gas processing and distribution sectors shared a small fraction of 9 and 5%, respectively [11]. Consequently, researchers have been involved in the advancement of training methods for industrial operators [12], in order to improve their performance, reliability, and ability to handle normal, abnormal [13], and rare situations such as starts or stops [14]. Virtual reality is an important visualization technique that is increasingly being applied for security purposes in industrial plants [15]. Virtual reality and immersive environments [16] have been used in various applications related to training and education, mainly in engineering applications [17].

The RV [18] by itself is already used for training or training of operators in the plant, but as is known in any industrial plant, an easily programmable, flexible, reliable, robust, and profitable control is required, such as the PLC. PLCs are often a major part of automated systems in the industry [19]. They are very efficient and reliable in applications sequential control and process synchronization and auxiliary elements in industry manufacturing, chemistry, and processes [20]. Besides having the technological advantages of using PLC, it also reduces the prices in the complex and advanced level control system [21]. PLCs are designed to use a ladder diagram programming language that is already familiar to technicians and electricians.

Innovations and improvements in microprocessor technology [22] and software programming techniques have added more features and capabilities to the PLC [23]. These improvements allow the PLC to carry out more complex motion and process control [24] applications with higher speed [25]. Currently, more than a dozen manufacturers produce PLCs, Table 1 [26]. Most of these companies manufacture various models that vary in size, cost, and sophistication to meet specific application needs.

TABLE 1. LIST OF PLC MANUFACTURERS IN THE GLOBAL MARKET

No	Manufacturers	No	Manufacturers
1	Siemens	9	Panasonic
2	ABB	10	Idec
3	Schneider (Modicon)	11	Keyence
4	Rocwell (Allen-Bradley	12	Toshiba
5	Mitsubishi	13	Fuji
6	GE-Fanuc	14	Beckhoff
7	Omron	15	Bosch Rexroth
8	Koyo	16	Rockwell/Allen-Bradley

At this point, emerging virtual reality technology for simulation and interaction of industrial control processes provides n an immersive experience in real situations without real risks [27]. Virtual reality (VR) offers a way to simulate reality [28]. Originally, it was used mainly for entertainment purposes, but nowadays the evolution of technologies, the appearance of multiple applications, and the reduction of costs have extended it to the manufacturing industry [29], for a safer human-machine interaction [30]. The innovation of the proposed approach is that it combines training, simulation, and control in a safe and inexpensive integrated application. Since many companies cannot afford to buy a robot [31] or specialized machinery specifically for training purposes, simulators are considered a cost-effective solution for the acquisition of basic technical skills [32, 33] and the design of the layout of the machine. Workplace [34]. And this leads to the possibility of recreating plants that are just going to be put into operation with virtual reality and connecting it to the PLC in real-time, to avoid wasting time in programming, according to the data obtained by Zäh and Wünsch (2005) time startup consume above the 15- 2 0 % of the time engineering design and construction of an automated system, and more than 70 % of this time is spent correcting errors control software that allows interaction between PLC and each of the system components [35]. To this day in most industries around the world, testing the actual functionality of an automated production system requires that the system be fully assembled. Therefore, the systematic deployment of cyber-physical systems avoids the aforementioned losses, leading to the transformation of the manufacturing industry with industry 4.0 [36].

II. MATERIALS AND METHOD

In the project developed the plant and its operation are displayed virtually and all its components son controlled by a PLC in time real. The methodology used is described below.

A. *Materials*

According to Figure 1, the architectured system cyber-physical comprises controllers' externals and motors cyber-physical. The interaction between these parts is carried out through a serial physical electronic interface.

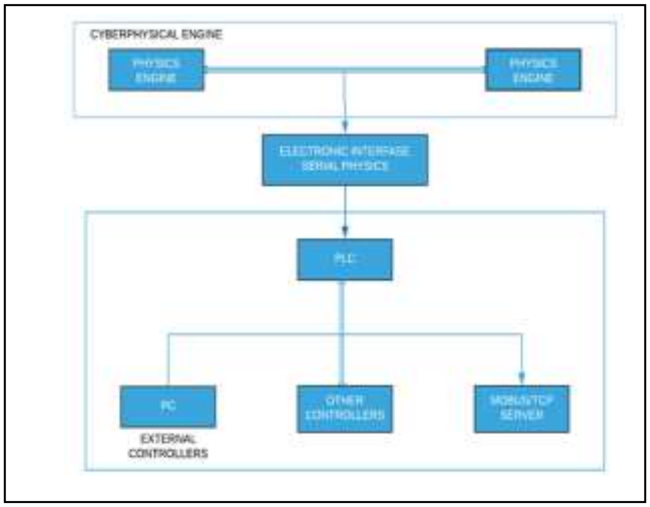


Fig. 1. System Architecture

In the part of the external drivers, a last-generation Nvidia GeForce GTX video card was used and for the cyber-physical engines [37], the Unity 3D software (version 2018.4.5f1) was used to develop the 3D environment of the dynamic system. The models of each of the components of the industrial plant were designed in full-scale CAD using SolidWorks® software. In addition, these models were exported in STL (Stereo Lithography) format to 3DS MAX, to reduce the polygons that form the meshing of each 3D model. The purpose of this treatment is to reduce the computational cost of the deployment graph fico in the virtual application.

Subsequently, each 3D model is sent in FBX (FilmBox) format to Unity 3D graphic.

The serial electronic interface is a model to interconnect the virtual reality scenario of the industrial plant and the industrial control PLC. The interface contains an “Arduino Mega”, 16 relays, and 16 optocouplers to manipulate the input signals and the digital output signals of the PLC. S and incorporates r or n RC filters and op-amps to work with analog input and output signals.

Industrial control that is implemented in the project was a PLC CompactLogix 5370 family of Allen Bradley shown in Figure 2.

Fig. 2. Compactlogic 5370 PLC

The Compactlogix 5370 PLC manages 12 digital outputs to control the solenoid valves, the conveyor belt motor, the fill injectors, among other actuators; 14 digital inputs to monitor the tank level, the bottle count, among others, and 1 analog output associated with the control signal in the time to be heated and 1 analog input that monitors the signal sent to the temperature sensor. E l PLC system is programmed into the software RSLogix 500 through a PC.

In addition, in the external controllers, a keypad module was connected to the PLC to directly operate the start-up and shutdown of the virtual industrial plant, said module is shown in Figure 3.

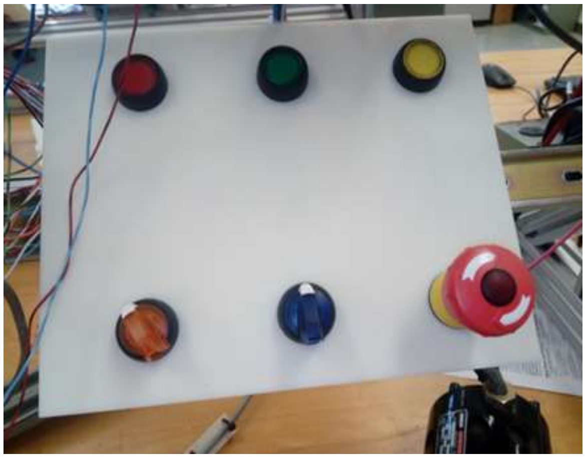


Fig. 3. Button panel module.

In order to carry out the immersive virtual reality experience in an industrial plant, used the system of virtual reality Oculus Rift, one and touch controllers Oculus (Figure 4 and Figure 5). With the latter, supervision is performed by managing to hold the objects within the virtual scene.

Fig. 4. Oculus Rift and Oculus Sensor (oculus.com)

Fig. 5. Oculus Touch Controllers (oculus.com).

B. *Methodology*

The diagram of the implemented methodology is presented in Figure 6 [38].

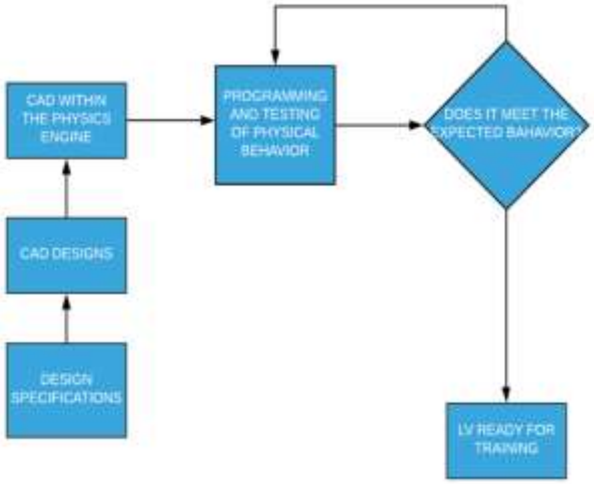


Fig. 6. Methodology

In the first instance, a series of specifications of the process to be virtualized is made. Once the physical characteristics are obtained from the process, the same as the dynamic behavior of each element (mechanisms, sensors, and actuators) proceed to the design CAD E l third step is to insert the CAD designs in physics engine to assign the dynamic behavior of each element. Finally, the performance of each element is tested to ensure that its behavior is as close to reality as possible. Each step of the methodology diagram is described in detail below.

1) *Design specs:* Virtual reality scenarios are built in two basic blocks of sensors and actuators which send and receive digital signals from the physical PLC. These signals are emulated from virtual devices such as motors, pistons, HMIs, among others. The behavior of these devices depends on the degree of sophistication of the model, which is compared with the behavior of real physical devices. Also, they are real electrical signals, since the input terminals and the output terminals on the PLC are physically connected. Said PLC is connected by a serial-USB port to the computer where the simulation is done in the laboratory virtual.

2) *CAD Designs:* The CAD design begins with the characterization of all the objects that will be visually available in the scene: keypads, tanks, filler, conveyor belts, bottles, among others. Subsequently, each of these components is designed according to the manufacturer's specifications or under null conditions. As for all the manipulated CAD models, they were developed at full scale in SolidWorks®, later they were converted into STL (Stereo Lithography) format, in this way it was possible to manipulate them in the 3 DS MAX software. In such software, it reduced the polygons that constitute the meshing of each 3D model. This treatment intends to reduce the computational cost of the graphic development of the virtual application. Finally, each 3D model is sent in FBX (FilmBox) format to Unity 3D.

3) *CAD* within the physics engine*:* The virtual stage acquires representation as the CAD models begin to be imported into Unity 3D. Each implanted component is known as " GameObject " and has incorporated a large number of properties, such as its position, its rotation, and its scale, which when transformed through programming code allow animating the " GameObject ". If you want the object to react to any physical property, such as gravity, one external torque, mass assignment, a given material, among others, is to be configured as a " Rigid Body ". Another substantial property to configure is that of " Collider ", which allows an object to interact with others in the scene. A " Collider " is an envelope region that defines the area of the approach of a body. So this area manages to take the shape of different geometric figures, such as spheres and cubes, or even take the right shape of the meshes of the object on which it operates. A body manages to interact with different bodies through the operation of one or more joints. These and other physical characteristics, such as lights, textures, sounds, among others, were configured in Unity 3D. For virtual commissioning shown in this work, the operator can freely navigate in the first person inside the entire scene and interact with things with his own hands. To make this interaction the system dealt " Oculus Rift", which is compatible with the systems cyber-physical as are the engines of Unity 3D

4) *Programming and testing of physical behavior:* The proposed methodology is designed to be implemented on virtual development platforms that include high-performance physics engines. This makes it possible to represent elementary physical conditions and characteristics to simulate the dynamics of rigid bodies. In this sense, the developers of this type of application must have a high degree of knowledge of the characteristics that their virtual platform allows them to implement or configure. Therefore, a platform is required that allows simulating the gravitational force, the detection of collisions, the inertial properties of the bodies, forces, torques, among others. The platform should also include the possibility of developing programming code that allows the mathematical representation of all the dynamic systems involved to be added to the virtual environment so that it can be controlled in real-time with the PLC. For the application object of this study, the modeling is carried out and the heat treatment is controlled by PLC with a PID control. The foregoing does not mean that the methodology is limited to the modeling of this type of actuators, sensors, or control algorithm, on the contrary, the methodology is open for what can be included within the laboratory any other type of system that is required to control and that can interact with the industrial plant [39]. This modeling stage is concluded until the expected physical behavior is obtained in all the physical systems embedded in the scenario.

5) *Impementation of the virtual laboratory:* The implementation consists of agreeing with all the stages mentioned above to obtain a virtual application that represents a laboratory of an industrial plant. The purpose is that the user can observe the real behavior of an industrial plant and can program an industrial PLC control in real-time, which allows him to see the interaction with the system and develop practical skills in the automation of industrial processes. In this scenario of the commissioning of an industrial plant, capacitive and inductive sensors, actuators such as DC motors, pistons were implemented. Also, sounds were added to all equipment representing the characteristics of the processes, to create a virtual environment adjusted to reality.

III. THEORY AND CALCULATION

Theories applied to control engineering are a major part of any process that wants to control in an industrial plant, E n this research was used the classical control theory that is analyzed control issues fed back single output and single entry. Also, the theory of dynamical systems, which is based on a mathematical model of a system, this being a replica of the real relationships between the input and the output of a system that are replaced by mathematical expressions and the theory of discrete-time signals, which are based on system analysis to transform into a discrete-time model with time lags.

A. Classical Control Theory

Most of the signals from the real world are analog. Sunlight, ambient temperature, wind speed, and the sound caused by the waves of the sea are clear examples of the magnitudes that must be handled when trying to measure, analyze or predict natural phenomena. The same happens in industrial processes in which the usual parameters are analog, such as the thickness of a sheet, the distance that separates a mobile robot from an obstacle or the pressure exerted by the plunger of a motor, the temperature in thermal systems, among others. The classical control theory dates back to the eighteenth century with the first relevant work in automatic control by James Watt who designed the centrifugal speed regulator to control the speed of the steam engine, giving way to the industrial revolution being crucial in times of history. In the initial stage of development of this theory Minorsky, Hazen and Nyquist contributed important works among many others, for example, Minosky in 1922 work on automatic controllers to guide vessels, showing that stability can be determined from the differential equations that describe the system, Nyquist in 1932 designed a relatively simple procedure to determine the stability of a system using closed-loop and Hazen in 1934 introduced the term servomechanism for position control systems, using relay servo mechanisms, capable of accurately following a changing input [40].

Therefore, for this project, the analysis of the transfer function was carried out according to the classical control theory. These transfer functions are obtained from different processes available at the industrial level, in our case the transfer function was obtained for the energy balance due to temperature changes in a tank containing a liquid, to control the dynamics or behavior of the temperature of said liquid, which can be observed through the sensors installed in an industry. In temporal terms, there are two possible forms of operation, dynamic and stationary, and this is graphically analyzed according to the variable of temperature concerning time In the differential equations representing industrial processes, these equations are preferably represented by derivative equations that depend on time, hence the name of dynamic behavior.

B. Dynamical Systems Theory

In order to understand the behavior of systems, it is necessary to obtain mathematical models that represent them. To analyze control systems, mathematical models of the elements used in said systems are needed. These models are equations that represent the relationship between the input and the output of the system. The response of a control system, or an element of the system, is made up of two parts: the steady-state response and the transient response. Differential equations are those that involve derivatives. These can be classified as the first order, second order, third order, among others, according to the derivative of the highest order in the equation. The methods used can be classified in essence, in which a satisfying solution is tested, and in which the equation is transformed into another form that can be handled by conventional algebra.

C. Discrete-time Signal Theory

Whenever a computer is used in measurement, signal processing, or control applications, the data, as viewed from the computer and the systems involved, is naturally discrete-time because a computer executes program code at discrete points of time. The discrete-time signal theory is useful in the design and analysis of control systems, signal filters, state estimators, and model estimation from process data system identification time series. This work develops the approximate discretization and digital design for control systems with delays of the industrial plant in virtual reality. To implement digital modeling, we use z transfer functions which is a useful type of discrete-time systems model, being analogous to the Laplace transform for continuous-time systems. The most important use of the z transform is to define transfer functions z that is used. The proposed method can be very close to the step response of the original continuous time-delayed control system by choosing various levels of energy loss. Digital computers have input and output signals that are not functions of continuous-time but rather a sequence of pulses. A practical way to think of these signals is as continuous weather signals that have been sampled at regular intervals; the samples, then, constitute a sequence in discrete time. One way to determine the behavior of systems subject to discrete-time signal inputs is by developing the Z transform. In a discrete-time signal processing system, there is a pulse sequence input and a pulse output.

$$Y[k] = y[k-1] + x[k] \qquad (1)$$

This equation is called the difference equation and it provides the relation between the output and the input for a system in discrete-time; it is comparable to the differential equation that is used with continuous-time systems to relate the output and the input. The input x, which is a particular discrete signal x[k], s added to the output y, with a delay of one unit of time, that is, y[k-1]. A feedback system, the discrete-time approximation to integration is given by the difference equation

$$Y[k] = y[k-1] + Tx[k] \qquad (2)$$

The Tustin z bilinear transformation method, according to is the most used to discretize continuous systems, of the following four methods “Zero Order Hold (ZOH) Method, Matched Pole-Zero Method, Backward difference Method, and Bilinear transformation” [41]. so to obtain the bilinear transformation method it is necessary to obtain a better approximation and this is achieved by considering a trapezoidal area. The area is T(x[k-1]+x[k])/2 and, in this way

$$Y[k] = y[k-1] + T(x[k-1] + x[k])/2 \qquad (3)$$

This is known as the Tustin approximation, which is considered that in conversion from analog control to digital control, $T(z+1)/2(z-1)$ o $2(1-z-1)/T(1+z-1)$ is substituted instead of S from the transfer equation obtained from the Laplace transform in order to perform approximate discretization and digital design for systems control by the signal delay of the plant. In the process of digitization or discretization two predominant factors serve to discretize the frequency and amplitude of the signal:

The frequency at which samples are captured. To obtain acceptable results, this frequency must at least double the maximum frequency contained in the analog signal (Shannon-Nyquist Theorem) [42]. This implies a strong restriction on the value of t.

The number of bits that make up the digital value of the samples. As it is easy to deduce, the more bits the converted sample has, the greater the precision in subsequent calculations and the errors generated will decrease.

These two characteristics, sampling frequency and the number of bits that the conversion produces are decisive for our process since they will set its working frequency and the size of the data bus through which the information circulates.

D. *Calculation Development*

The methodology that was applied for the development of the calculation to the technological equipment set in the virtual reality scenario. First, the classical control theory was considered, then the theory of first-order dynamical systems was considered, and finally, the discrete-time signal theory considering the Laplace transform where the bilinear method was applied to obtain the equation discretized.

Based on the classical control theory, of a feedback system, of an input and an output, where the most important part is the plant. The plant consisted of a tank where the product to be packaged is mixed and heated in an industrial process, where concepts such as the temperature of the fluid at the outlet of the tank (T(t)), the mass flow (F), the volume (V), The initial or inlet temperature (Te), he heat flux applied to the fluid inside the tank Q, the ambient temperature outside the tank (Ta(t)) he resistance of the adhered thermal material to the tank (R), the density of the fluid (p) and the specific heat (Cp).

Applying the theory of dynamic systems, considering that it is a thermal system, where the temperature value is variable in time until the expected temperature is achieved. The time and how the expected temperature is achieved depending on the physical characteristics of the elements involved in the system. In a general way, it is possible to express that this system is characterized by the heat transfer function in the tank, where the energy balance equation was analyzed. It is considered: the heat energy of the fluid that enters the tank is equal to the energy heat with which the fluid exits with the temperature difference plus the heat energy applied to the fluid inside the tank, minus the temperature difference between the fluid in the tank and the ambient temperature outside of the tank. For the last energy change it is considered as zero because the tank is well insulated, representing the system in equation 4:

$$VC_pp[dT/dt]=pC_pF[T_e-T(t)]+Q-(T(t)-T_a(t))/R \tag{4}$$

Therefore, the energy balance equation is represented by equation 5,

$$VC_pp(dT/dt)=pC_pF(T_e-T(t))+Q \tag{5}$$

To obtain the equation that represents the plant (tank), to facilitate the development of the equation, first, a change of constants is made as shown in equations 6, 7 and 8.

$$K_1= VC_pp \tag{6}$$

$$K_2 =pC_pF \tag{7}$$

$$\Delta T=T(t)-T_e \tag{8}$$

Considering the inlet temperature Te as a constant. Therefore, deriving equation 8 defines equation 9,

$$dT/dt=d\Delta T/dt \tag{9}$$

Therefore, the dynamic system of the plant's energy balance is represented by equation 10

$$K_1(d\Delta T/dt)=Q-K_2\Delta T \tag{10}$$

Applying the Laplace transform to equation 10, we obtain equation 11 and 12,

$$\pounds[K_1(d\Delta T/dt)=Q-K_2\Delta T] \tag{11}$$

$$K_1S\Delta T=Q-K_2\Delta T \tag{12}$$

From the previous equation, we isolate Q that represents the calorific power, obtaining the equation 13,

$$K_1S\Delta T+K_2\Delta T=Q \tag{13}$$

Factoring ΔT from equation 11 obtaining equation 14,

$$(K_1S+K_2)\Delta T=Q \tag{14}$$

Solving ΔT for equation 12 obtaining equation 15,

$$\Delta T=Q/(K_1S+K_2) \tag{15}$$

And according to classical control theory, the transfer equation of the plant (tank) is considered as the variable that represents the output between the variable that represents the input, so we obtain equation 16 that represents the transfer of the dynamical system in the Laplace domain,

$$\Delta T/Q=1/(K_1S+K_2) \quad (16)$$

The transfer function obtained previously is the response of the plant (tank) physically, so up to now the mathematical process that the system has undergone is to obtain an analog signal.

In particular, with the system, cyber-physical and controller industry, s and have time delays input and time delays output in a frame continuous - time or discrete time [43, 44] as shown in the following figure 7.

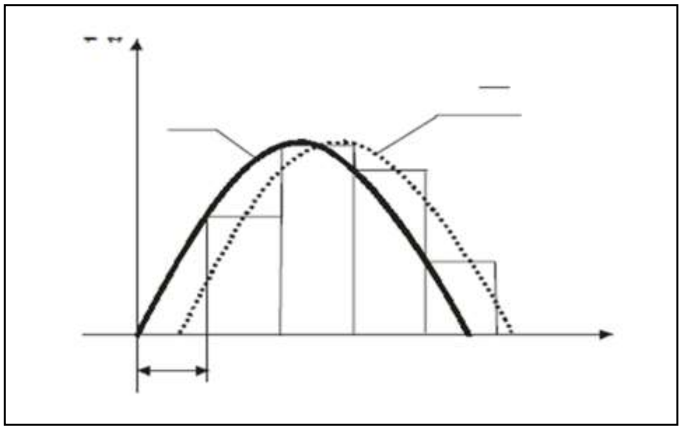


Fig. 7. Sampling and Hold Approach for Dead Time

In this research work, the interconnection of a virtual reality scenario at an industrial level that was controlled by an industrial controller in real-time was analyzed, applying the theory of discrete-time signals with the bilinear method in equation 16 where $S=2(1-z-1)/T(1+z-1)$ in addition, the Nyquist technique is considered, which considers systems that have delay times (periods) without the need to have approximations and therefore provides exact results of the absolute and relative stability of the system, so that T represents the sampling period that is considered less than 0.05, obtaining the equation 17.

$$T(Z)=Q(Z)/(K_1(2(1-Z^{-1})/T(1+Z^{-1}))+K_2) \quad (17)$$

Expanding the equation in the denominator gives equation 18.

$$T(Z)=Q(Z)/(((2K_1(1-Z^{-1})+TK_2(1+Z^{-1}))/T(1+Z^{-1})) \quad (18)$$

Multiplying the final denominator with the first numerator of the previous equation gives equation 19.

$$T(Z)=TQ(Z)(1+Z^{-1})/((2K_1(1-Z^{-1})+TK_2(1+Z^{-1})) \quad (19)$$

Developing the operations of multiplication and addition in the previous equation, equation 20 is obtained.

$$T(Z)=(TQ(Z)+TQ(Z)Z^{-1})/(2K_1-2K_1Z^{-1}+TK_2+TK_2Z^{-1}) \quad (20)$$

Factoring the denominator of the previous equation for Z gives equation 21.

$$T(Z)=(TQ(Z)+TQ(Z)Z^{-1})/((TK_2-2K_1)Z^{-1}+(TK_2+2K_1)) \quad (21)$$

Solving for the denominator of the previous equation, equation 22 is obtained.

$$T(Z)((TK_2-2K_1)Z^{-1}+(TK_2+2K_1))=TQ(Z)+TQ(Z)Z^{-1} \quad (22)$$

Developing the corresponding multiplications of the previous equation, equation 23 is obtained.

$$(TK_2-2K_1)T(Z)Z^{-1}+T(Z)(TK_2+2K_1)=TQ(Z)+TQ(Z)Z^{-1} \quad (23)$$

With the resolution of equation 2 1 where we apply the bilinear method, we obtain the discrete equation where the terms that are concerning Z we change it with the equivalence of K that the samples will represent, resulting in the following equation 24.

$$(TK_2-2K_1)T(K-1)+T(K)(TK_2+2K_1)=TQ(K)+TQ(K-1) \quad (24)$$

Solving for the first term of the previous equation that contains T(K-1) that represents a lagged sample of the temperature we have the equation 25.

$$T(K)(TK_2+2K_1)=TQ(K)+TQ(K-1)-(TK_2-2K_1)T(K-1) \quad (25)$$

Solving the previous equation for the constant terms we obtain equation 26.

$$T(K)=(TQ(K)+TQ(K-1)-(TK_2-2K_1)T(K-1))/(TK_2+2K_1) \quad (26)$$

Substituting the terms that makeup $\boldsymbol{K_1}$ and $\boldsymbol{K_2}$ in the previous equation, we obtain equation 27.

$$T(K)=(TQ(K)+TQ(K-1)-(TpC_pF-2VC_pp)T(K-1))/(TpC_pF+2VC_pp) \quad (27)$$

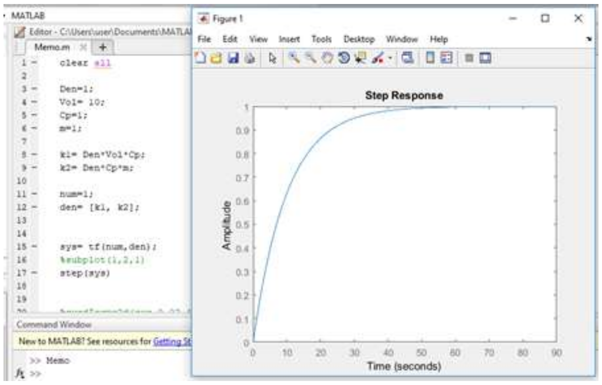
Therefore, equation 27 represents our plant in approximate discretization, this equation is inserted into the cyber-physical system of virtual reality.

IV. RESULT

The results achieved in the project research are related to the discrete-time response of the plant operation. First, the mathematical analysis is carried out to demonstrate the feasibility of the transmission of signals between the real industrial control PLC and the virtual stage of the project, so that the plant is controlled in real-time using the MATLAB R2015 software. In this analysis, the answer was primarily obtained in continuous time with the transfer function obtained from the plant, subsequently, the response in discrete-time was achieved by applying the Tustin function Finally, the discretized response was obtained by exporting the data to Excel, to check the operation of the commissioning of the automated industrial plant connecting the PLC physically, with virtual reality for training.

A. *Analysis of the dynamic system in its analog response in matlab R2015 and Excel software*

After having obtained the equations in the previous section, the response in continuous time was first obtained from the transfer function of the energy balance, which would be the behavior of the plant physically operating, considering water as liquid, taking its density, specific weight, mass flow, and specific heat. So the simulation of the response is shown in Figure 8.



```
clear all

Den=1;
Vol= 10;
Cp=1;
m=1;

k1= Den*Vol*Cp;
k2= Den*Cp*m;

num=1;
den= [k1, k2];


sys= tf(num,den);
%subplot(1,2,1)
step(sys)
```

New to MATLAB? See resources for Getting St

```
>> Memo
fx >>
```

Fig. 8. The continuous-time response of the plant

Likewise, the simulation was performed again in MATLAB R2015 response in continuous time of the plant, but applying the method of Tustin with a sampling of 0.02 to discretize the signal and obtain results to compare with the response in discrete time, the following figure 9 represents the function in continuous time, but with its discretized signal. As can be seen in the figure, samples were taken at 20%, 63%, 90%, and 100% to make the corresponding comparisons with the discrete-time simulation.

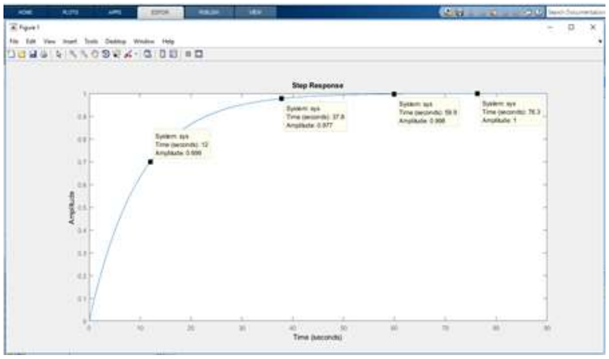


Fig. 9. Discretized continuous-time response signal.

As mentioned above, when obtaining the sampled equation with the Z transform under the Tustin method, it was applied directly to the cyber-physical system using Unity 3D software, from this software more than three thousand five hundred samples were directly exported to Excel applying a period of T = 0.02, taking samples in the simulation development at 20%, 63%, 90% and 100% as shown in figure 10, to demonstrate that the difference between the discretized analog signal in continuous time and the sampled digital signal in discrete time the trend of the relative error is towards zero that the difference between the discretized analog signal in continuous time and the sampled digital signal in discrete time the trend of the relative error is towards zero.

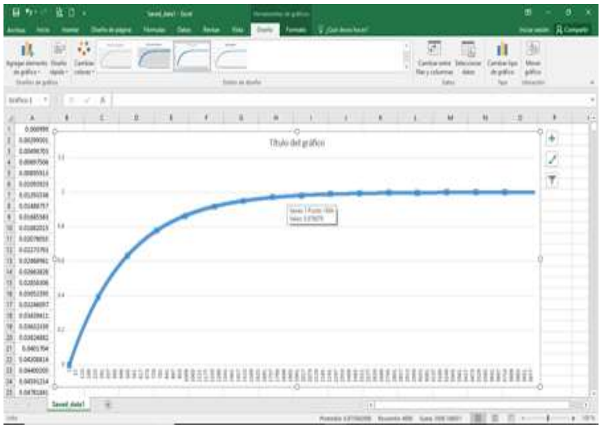


Fig. 10. Discretized signal exported to Excel from Unity 3D

After obtaining samples of signals both sustained periods of time and discrete-time apply equation 27 to determine whether our system is able to interrelate with the scenario of virtual reality so that it can be operated or controlled by the PLC in real-time.

$$E_r = ((\text{period in continuous time} - \text{discrete time sample})/\text{period in continuous time})*100 \qquad (27)$$

Applying equation 27 to samples obtained the following results:

$$E_{r20\%} = ((0.699-0.6989003)/0.699)*100 = 0.014263$$

$$E_{r63\%} = ((0.977-0.976879)/0.977)*100 = 0.0123$$

$$E_{r90\%} = ((0.998-0.99770378)/0.998)*100 = 0.02968$$

$$E_{r100\%} = ((1-0.999507)/1)*100 = 0.0493$$

According to Rosengaus (1998) laboratories working with signal processing allows a maximum relative error of 0.25% [42]. Therefore, according to the data obtained, it is shown that the virtual system adapts to reality, therefore, the industrial PLC controller can operate in real-time to control all the machinery that is in the virtual reality scenarios.

B. *Validation of the implementation of industrial control to a virtuaI reality scenario in real-time*

Figure 11 shows the individual programming in the PC to the PLC with the Rockwell Automation RS Logix 500. The task software user is to program the PLC ladder language, programming with the methodology of state machines, to test control routines in the industrial plant found within virtual reality scenarios.

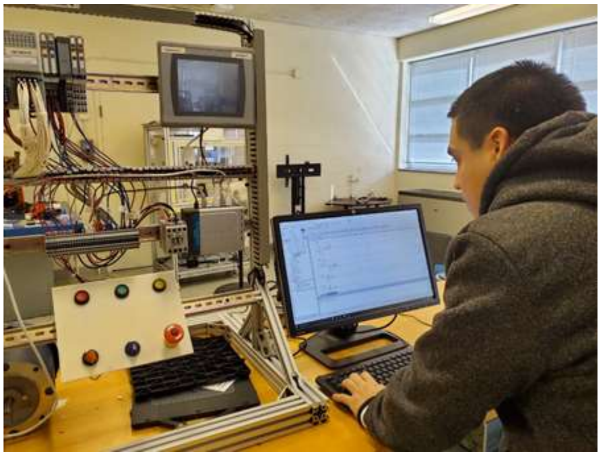


Fig. 11. User programming the PLC.

To program the Allen Bradley family's Compactlogic PLC, the sequence of filling the tank (plant) was taken, the operation of the conveyor belt that carries the empty bottles, valves that feed double-acting cylinders for the extraction of the liquid was addressed, as well as pneumatic cylinders that are on the conveyor belt that hold the empty bottles for filling, in figure 12 a part of the programming is shown operating in real-time.

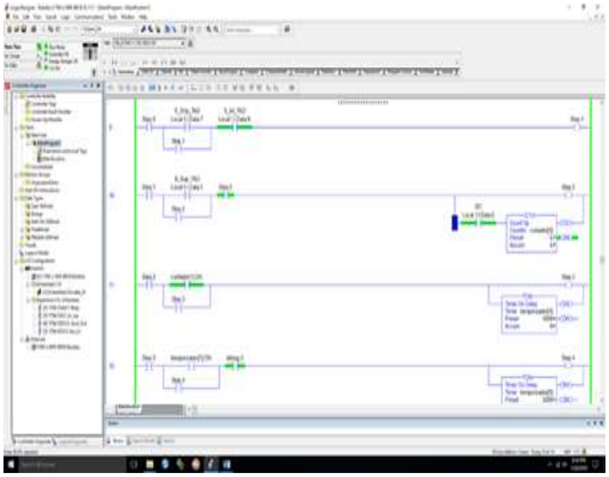


Fig. 12. program operating in real-time

Having performed the tests programming the PLC programming industrial control is validated in the virtual reality scenarios as shown in Figure 13, where the user interacts with the plant using a virtual reality helmet (Oculus Rift) and controls to be able to grasp the objects that appear in the scene like the one to review the bottles.

Fig. 13. A user inside the scene

C. *Conclusions*

This paper presents the implementation of the industrial real-time control applied to virtual reality scenarios in an immersive framework of training safe, secure, and low cost in an environment of efficient and innovative work, of course always depending on the frontiers of mathematics, this gave the guideline to demonstrate that hybrid systems can be interconnected.

In the fourth industrial revolution, industries tend to improve competitiveness, so training quickly and repeatedly necessary to have experienced staff to handle the automated industrial processes and prevent disasters or loss both economic and human. Recalling that now all companies tend to industrial automation, and where required a robust control that supports moisture, dust, high temperature, noise, etc., which do not affect the processing of the signals of each industrial process, Therefore, in this research the PLC was considered since it is currently the most recommended in the industries.

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