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TEMA: 3D VIRTUAL TRAINING SYSTEM FOR A BIOREACTOR USING HARDWARE-IN-THE-LOOP

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Chapter 48
3D Virtual Training System for a Bioreactor Using *Hardware-in-the-Loop*

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Abstract This paper simulates a 3D virtual environment of a bioreactor based on the teaching-learning process in the engineering area. Using the Hardware-in-the-Loop simulation technique, the simulator was developed in the Unity 3D graphic engine, which is oriented to maintain in optimal conditions the variables involved in the process, such as: Biomass, recirculated biomass, dissolved oxygen, and chemical oxygen demand, the latter being the controlled variable. For the implemented simulator, traditional control techniques and modern control techniques are considered in order to evaluate the behavior of the variables. In order to give realism to the bioreactor, the hardware-in-the-Loop simulation technique is implemented in a low-cost hardware device, where the mathematical model of the process will be (On hardware-in-the-loop simulation. In 44th IEEE Conference on Decision and Control, and the European Control Conference, Seville, Spain), while the control algorithm is implemented in the mathematical software Matlab. Finally, the stability analysis is performed having the variables in their optimal operating points, as well as the good performance of the controllers in the presence of disturbances.

48.1 Introduction

The twenty-first century has faced different types of problems worldwide. From the depletion of non-renewable resources to facing climate change and pandemics.

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These problems have had an effect on the change of patterns of various processes such as the educational model or employment. Due to this, several professions have been disappearing to give way to new ones, as well as technologies have evolved accelerating technological development [1], so today we speak of industry 4.0 which provides continuous improvement in technological processes while allowing the emergence of new innovations in the field of automation, digitization, and the internet of things [2], within these fields virtual reality has had an important significance in the industry. This allows a state of immersion to the user experiencing contact between the real and virtual world, this connection is given by haptic devices that receive and send information [3].

The benefits of virtual reality to society are many: in the tourism field, it allows showing immersive spaces that provide tourists with unique experiences [4]. In the medical field, it can help in the treatment of Alzheimer's disease, to combat phobias, as well as help patients in the recovery process of injuries. In the industrial field, the development of manufacturing industry simulators prevents occupational hazards. In the architectural field, it allows the accurate evaluation of designs before they are built. In the educational field, it represents a teaching method that aids rapid learning capacity and promotes self-learning [5, 6]. In recent times, teaching in engineering has been accompanied by the use of virtual environments, due to the fact that such training is related to the concept of experiential learning. Virtual reality offers quite useful resources, which also leads to lower costs and risks both personal and equipment, there is no need to acquire physical equipment that is sometimes expensive [7, 8]. Thus, the use of 3D virtual environments allows simulating industrial work environments, in which operators or students can train and develop skills before interacting with the real industry [9, 10]. That is why in this situation a type of simulation that has gained great notoriety and applicability is the known Hardware-in-the-Loop (HIL) is one of the lowest cost alternatives that allows the user to simulate plants or control systems in real time, this is how the proposal to develop a HIL environment for monitoring and control of an activated sludge bioreactor in wastewater treatment arises. The HIL will consider the mathematical model of the bioreactor which is a central part of a bioprocess because it provides a link between the initial raw material and the product, bioreactors are vessels that provide a controlled environment that allows the efficient growth of cells and the formation of a product, they are traditionally used in the industrial fermentation process, manufacture of biological products such as food processing, in the biological treatment of waste [11].

This paper presents the development of a 3D virtual training system that allows to monitor and control the variables involved in the activated sludge bioreactor. Therefore, the mathematical model that represents the bioreactor behavior is considered, and the Hardware-in-the-Loop technique is implemented to evaluate control algorithms such as PID and fuzzy control, in order to analyze the behavior of the system.

48.2 System Structure

The development of the 3D virtual training system of a bioreactor is implemented so that the user, who is immersed in the virtual environment, interacts with a realistic industrial process, and at the same time is a training tool in the educational field that allows acquiring or strengthening the knowledge of the student or operator. Therefore, the virtual experiment is a sample of the physical experiment, ensuring an effective culmination of the handling of the process in future practical operations.

The proposed virtualization of the activated sludge bioreactor is developed using CAD computer aided design techniques for piping design, as well as using SolidWorks software for the creation of certain process components such as centrifugal pumps, transmitters, all these designs should be exported with the extension. FBX extension because it is a Unity 3D compatible file. Also included are particular animations that are hosted in the Unity 3D software which allows the management of the movements, surround sound is also included in certain equipment of the process, in order to provide greater realism. All the above mentioned corresponds to the Unity 3D design of the virtual environment.

The programming codes that are housed in the scripts are the ones that allow the communication link between Matlab and Unity 3D and the shared memories are the ones that provide the data transfer of the variables that change in the virtual environment.

The Matlab software, which has high performance mathematical computation, is where the control algorithms that receive data in real time and are processed, for which the controlled variable (Chemical Oxygen Demand) is monitored from an HMI, generating control actions in case of disturbances or changes in set points, which allows maintaining the variables in their optimal points (Fig. 48.1).

48.3 Hardware-in-the-Loop Structure

The proposed HIL scheme consists of three main stages [12], see Fig. 48.2. (1) *Target hardware:* The control algorithms designed in the previous section are implemented. The proposed control algorithms will be implemented in Matlab software. (2) *Mathematical model:* Based on the dynamic equations that determine the behavior of the bioreactor it is possible to represent in a first order system with delay, resulting in the mathematical model of the bioreactor which will be implemented in a low-cost Raspberry Pi embedded card. (3) *Industrial virtual environment*: At this stage, the virtual environment is implemented, which is a water treatment plant and its purpose is that the user is immersed in the virtual environment allowing to interact with a realistic industrial process, and at the same time it is a tool that allows to acquire or strengthen the knowledge of the operator or student [13].

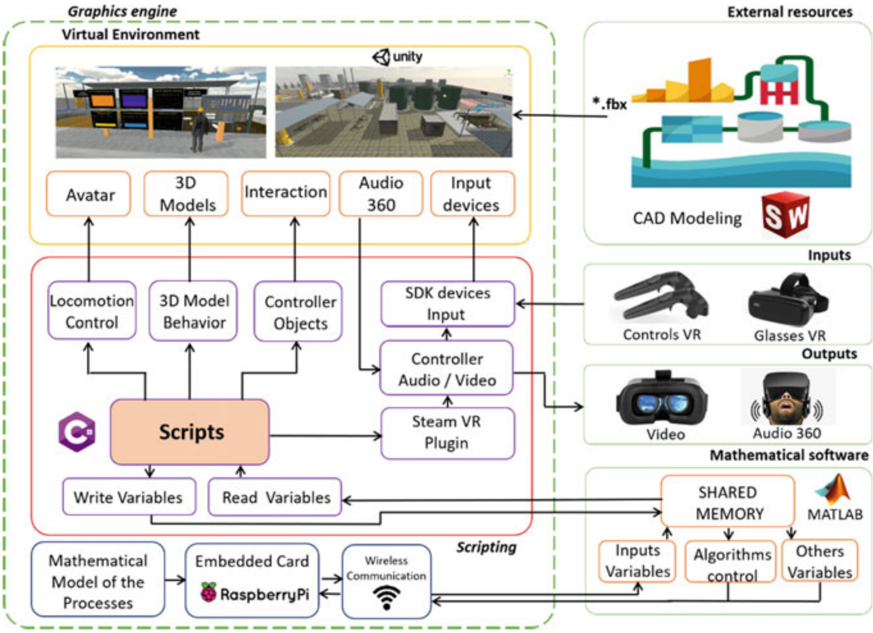

Fig. 48.1 System structure

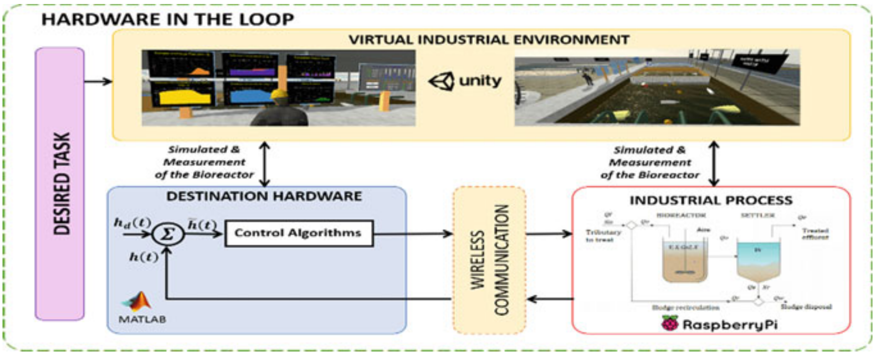

Fig. 48.2 Hardware-in-the-loop structure

48.4 Modeling and Control

48.4.1 Modeling

The realism of the virtual environment can be represented with the help of the mathematical model validated in [14], so that the dynamic behavior of the process can be represented in a first order system with delay. For which the sludge discharge flow is regulated by the valve position and the Chemical Oxygen Demand which is related to a transmitter. Therefore for the identification of parameters of the mathematical model is done by Smith's method, once a step signal is introduced in the manipulated variable of the process (valve position) to later verify the output signal of the transmitter, determining the values that is the time constant, the time delay, the gain of the system in steady state, when the output signal reached 28.3 and 63.2% of the final value [15].

$$\frac{Y(s)}{u(s)} = \frac{Ke^{-Ls}}{\tau s + 1} \tag{48.1}$$

Once the variables that make up the first order function with delay have been calculated, the transfer function is obtained. It is worth mentioning that the mathematical model obtained does not represent the dynamic behavior of a real bioreactor.

$$\frac{Y(s)}{u(s)} = \frac{0.4228106607e^{-1.157991924s}}{4.953257121s + 1} \tag{48.2}$$

The results obtained in the validation of the model are shown in Fig. 48.3, showing the tracking with an input signal different from the one obtained for parameter identification, where MV represents the validated model, MC represents the calculated model and MI is the model obtained by the optimization method.

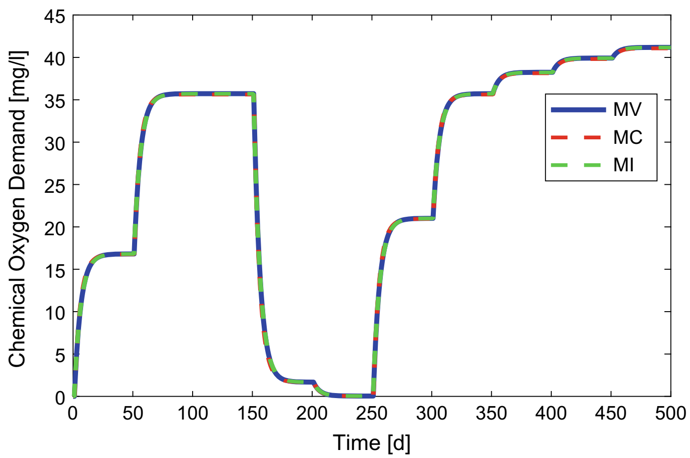

Fig. 48.3 System modeling and validation

48.4.2 Controller Design

In the design of the virtual environment, control algorithms are evaluated in order to consider the behavior of the process, therefore, it is important to mention that in this section two control strategies are considered: PID Control and Fuzzy Control.

PID Control

Immediately determined the transfer function that generates the behavior of the process, the constants involved in the PID controller are determined, in which the block diagram of the conventional PID controller is shown in Fig. 48.4 where is the sludge flow input, is the mathematical model of the process, and is the output flow, for the adjustment of the PID constants is developed by fine tuning methods, considering the following equations [16]. The equations for PID control are shown in their general equation and in their Rectangular Approximation form for implementation in Matlab software.

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t) + K_p T_d \frac{\mathrm{d}}{\mathrm{d}t} e(t) \tag{48.3}$$

$$u(n) = K_p e(n) + K_i T \sum_i e_i + K_d [e(n) - e(n-1)]/T \tag{48.4}$$

where the controller is composed of: is the proportional constant, is the integral constant, is the derivative constant and is the error signal of the flow process.

Diffuse Control

The fuzzy control is a modern controller, the block diagram of the fuzzy controller is shown in Fig. 48.5 where is the input sludge flow, is the mathematical model of the process, and is the output flow, for the fuzzy control has to go through three stages which are: the fuser is where the linguistic rules involved, fuzzy control performs an evaluation of the rules, and defusifier converts the linguistic rules into a numerical value to enter the process.

For the design of the controller, the Matlab software is used where Fig. 48.6 consists of 2 inputs, an error signal which is generated between the set point and the

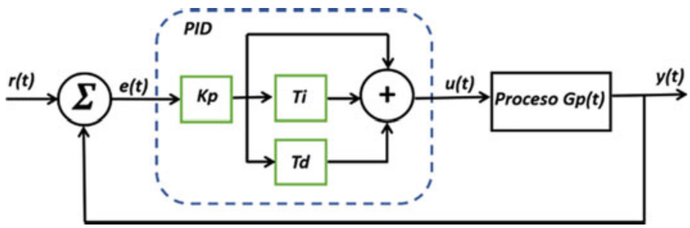

Fig. 48.4 PID control block diagram

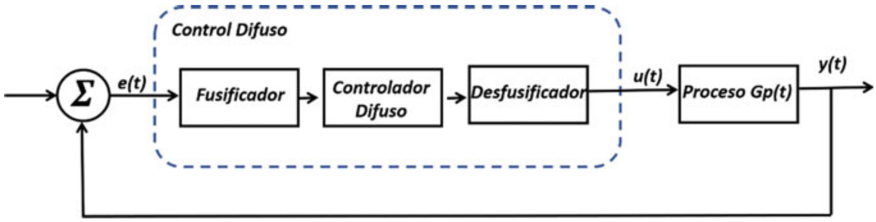

Fig. 48.5 Fuzzy control block diagram

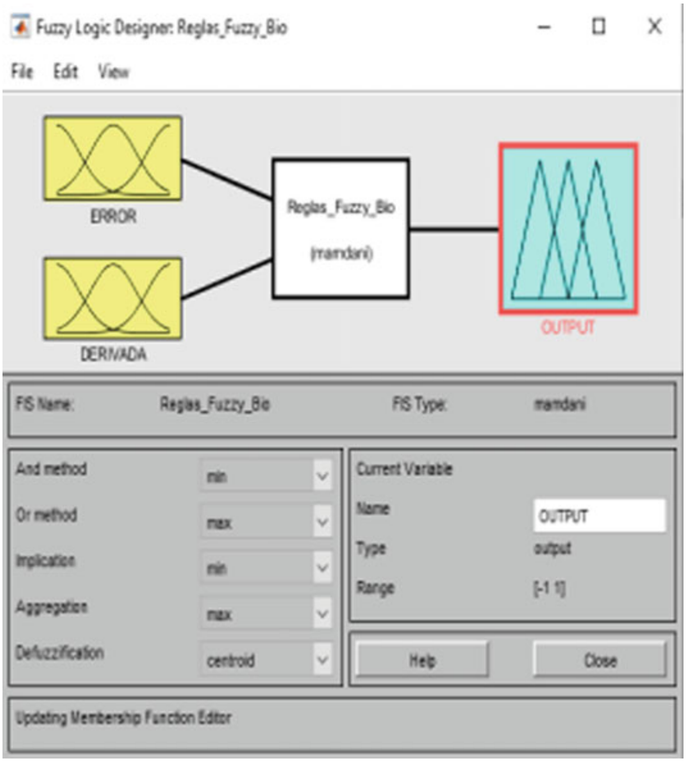

Fig. 48.6 General scheme of the fuzzy system

measurement of the controlled variable, another signal derived from the error, these inputs are transmitted to the controller rules obtaining an output signal that acts on the manipulated variable. The fuzzy controller is composed of 49 rules which are a product of the observation, the behavior of the plant, and above all are responsible for controlling the response of the controller with minimum errors [17].

Figure 48.7 shows the evolution of the different control algorithms applied to the water treatment plant, SP monitoring tests are performed in different ranges of

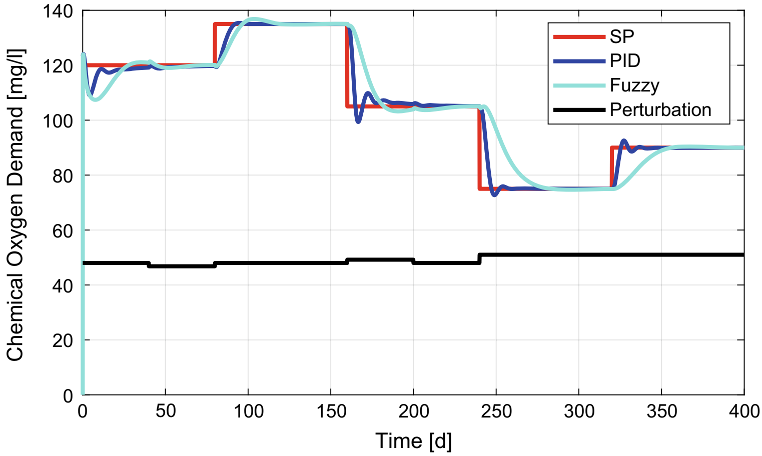

Fig. 48.7 Behavior of the PID controller and fuzzy control in the presence of reference changes

operation that the plant works in order to analyze the responses of each controller, and responses to disturbances such as temperature, where we conclude that the PID controller is more efficient than the Fuzzy controller.

The errors obtained in the implemented control algorithms are shown in Fig. 48.7, the error response of the PID control at certain values is very large thus affecting the control and unlike the fuzzy control the control response is minimal giving a non-aggressive control response and having a more efficient control.

48.5 Results

In Fig. 48.8 the implementation of the Hardware-in-the-Loop technique is presented, for which a Core I7 main computer is considered where the control algorithms are located, while the mathematical model of the bioreactor is implemented in a 4 Gb Raspberry Pi card. Finally, an Xbee card is used for bidirectional communication between the equipment.

The following are the results of the virtualization of a bioreactor, the 3D virtual environment will be a virtual training system in the engineering area. Allowing the user to be immersed in the process through the different stages that correspond to the bioreactor where the behavior of the different variables will be visualized, as well as the evolution of the proposed control algorithms. Figure 48.9 shows an overview of the development of the interface in the Unity 3D graphic engine, the different stages are explained below.

The first stage, called pretreatment of the water, is the place where the influent to be treated is stored in a pool containing a grid, which prevents the passage of

Fig. 48.8 Implementation of the hardware-in-the-loop technique

Fig. 48.9 Schematic of the bioreactor virtual environment

the different heavy wastes that come along with the influent, this is done with the objective of preventing future clogging in later stages, see Fig. 48.10.

The grease trap stage is a process that separates the grease and oils contained in the influent to be treated, because the density of the grease is lower than that of the water, the surface of the pool will maintain the grease content allowing the flow to the bioreactor of only the water to be treated, see Fig. 48.11.

In this stage, also known as aeration tank, fine bubble diffusers blow air into the water so that the organic matter degrades the pollutant feedstock, allowing it to be converted into Dissolved Oxygen Concentrations, Biomass, and Substrate. see Fig. 48.12.

Fig. 48.10 Pretreatment pool

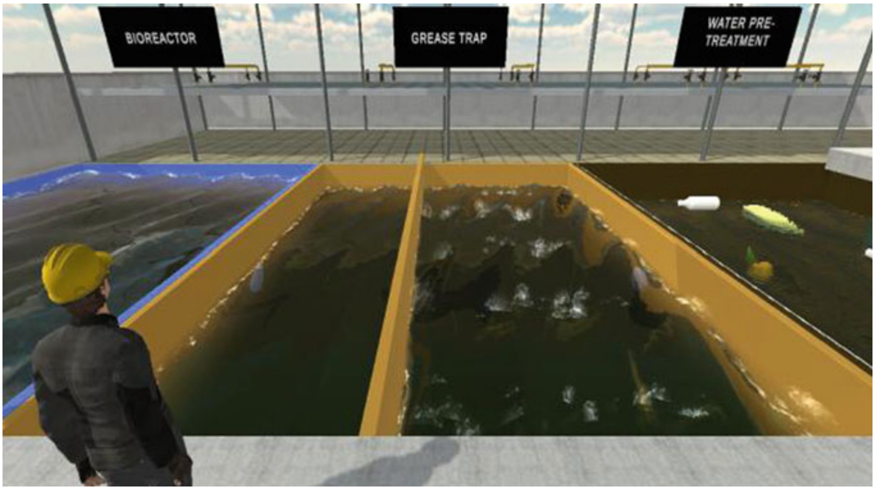

Fig. 48.11 Grease trap pool

In this process, the clarifier has the objective of separating the water and the sludge by sedimentation. Due to the effect of gravity, the sludge will be located in the lower part of the pool and will also be recirculated to the aeration tank, while the water is located in the upper part. See Fig. 48.13.

As a final stage of the wastewater treatment process, each of the pools that give final products to the treated water and the pool where the sludge waste will be stored is shown. See Fig. 48.14.

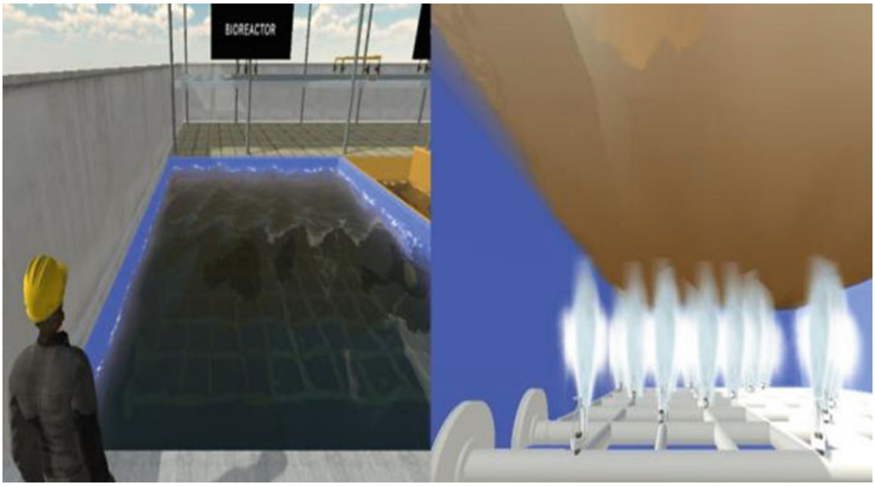

Fig. 48.12 Aeration process

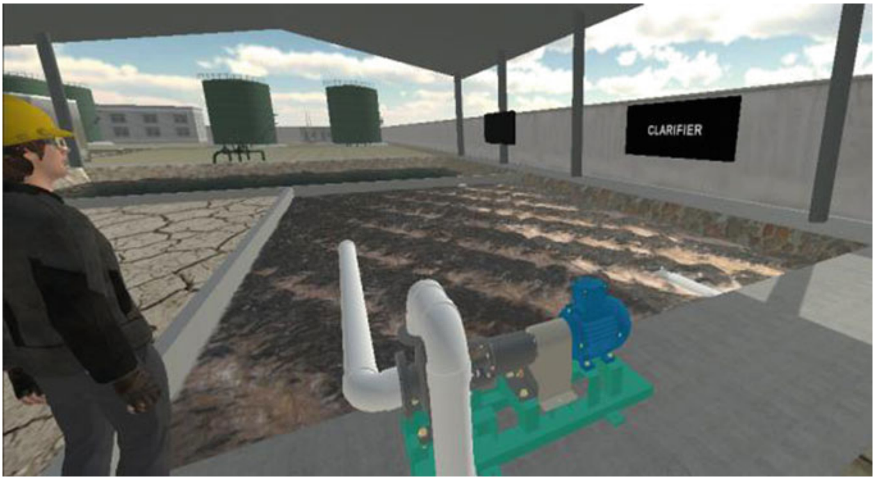

Fig. 48.13 Clarification process

There is also an HMI panel where the different graphs of the variables involved in the process are shown, the HMI allows the reference change of the Chemical Oxygen Demand allowing to observe how it evolves over time, the behavior of the implemented control algorithms, it is also possible to enter disturbances to the process thus providing greater realism to the virtual environment. Figure 48.15 shows the behavior of the PID control algorithm presenting a rapid response in the reference change in the graph that presents the substrate concentration, also in the presence of a sudden change in the position of the valve generating deterioration in the element.

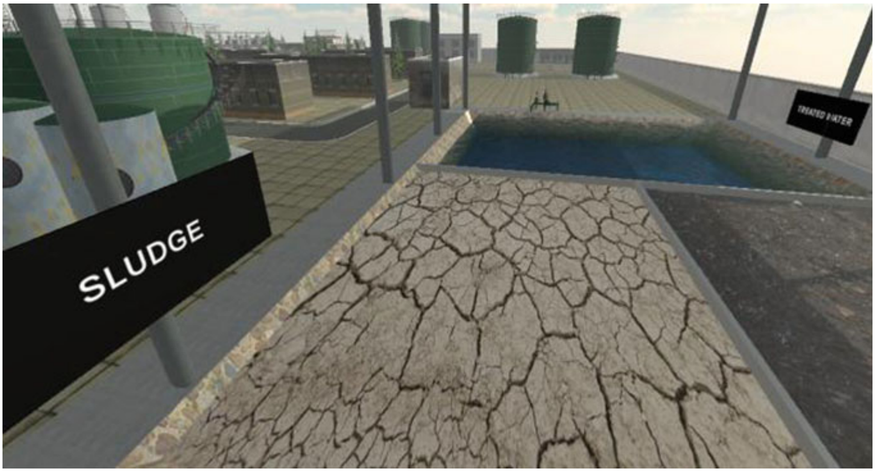

Fig. 48.14 Sludge and treated water pool

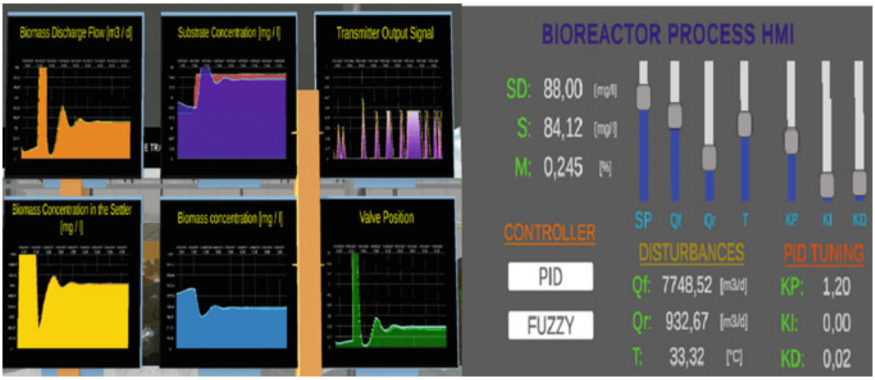

Fig. 48.15 HMI and panel of the system variables graphs

While when using the Fuzzy algorithm it presents a slow response but does not present abrupt changes in the valve position.

48.6 Conclusions

The virtual environment of the bioreactor fulfills its function as a tool for the teaching and learning process in the engineering area, which provides useful features to the operator or student immersed in the environment with the possibility of performing a virtual tour through the different stages of the process. The dynamic behavior of the bioreactor that was represented in an equation is reflected in the realism of the process, in addition in the implementation of the control techniques it was possible to verify that they have an optimal performance before changes of reference or disturbances that are generated in the execution of the process, allowing in this way to maintain in the optimal points the variables and to observe how they evolve in the time.

In the virtual training system, it can be highlighted that there are several advantages such as, the familiarization of the process stages, the creation of safe situations in critical processes in order to help in several aspects that are important, for example: industrial safety, a high increase in the productivity of the process, operator training, etc.

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