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| Abstract | This article offers the development of a realistic and intuitive virtual environment for training on pumping stations for drinking water supply systems. The environment has structures and equipment found in pumping stations that simplify the user interaction with the industrial process, instrumentation, monitoring and control of the station. The environment has been created using photogrammetry techniques, CAD tools and the UNITY 3D graphic engine that combined with MATLAB exchanges information in real time to execute the simulation of the process, achieving a high degree of realistic immersion. Experimental tests allow the operator to interact with the virtual environment and achieve maximum experience in the integrated station. Through experimental tests, the immersion of the training environment system is verified. |

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| Keywords (separated by '-') | Virtual environment - Pumping systems - Photogrammetry - Unity 3D |

# Virtual Training on Pumping Stations for Drinking Water Supply Systems

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**Abstract.** This article offers the development of a realistic and intuitive virtual environment for training on pumping stations for drinking water supply systems. The environment has structures and equipment found in pumping stations that simplify the user interaction with the industrial process, instrumentation, monitoring and control of the station. The environment has been created using photogrammetry techniques, CAD tools and the UNITY 3D graphic engine that combined with MATLAB exchanges information in real time to execute the simulation of the process, achieving a high degree of realistic immersion. Experimental tests allow the operator to interact with the virtual environment and achieve maximum experience in the integrated station. Through experimental tests, the immersion of the training environment system is verified. AQ1

**Keywords:** Virtual environment · Pumping systems · Photogrammetry · Unity 3D

## 1 Introduction

The training of professionals in the industry is a determining factor to maximize the efficiency of production processes and services offered by companies, estimating that the skills gained in the training sessions will be put into practice, not only in the operation of equipment but also in decision-making when facing adverse events [1]. The operational staff of an industry represents the starting point of its productivity. This is the reason why it is necessary that the company provides its employees with the appropriate knowledge and materials to ensure quality in the execution of procedures [1, 8–10]. For these reasons, the training in the operation of industrial plants must meet the needs of operators in terms of knowledge about the instrumentation and structure of the plant, as well as mitigation strategies for faults, thus minimizing losses due to human error [2, 3, 11].

Traditionally, one of the most used training methods is usually limited to user guides and verbal instructions, which do not significantly contribute for the future performance of operators. In other cases, personnel and logistical support are added to recreate scenarios in a specific space, which do not represent the workplace as it should be [2]. In addition, low occurrence situations can be rather difficult to simulate, as in the case of equipment failures or catastrophic events [2, 4, 10]. Then, when the training is simple and has a low impact on operators, the risk of human error increases and consequently the level of danger in the workplace.


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In this context, Information and Communication Technology <ICT> has revolutionized several fields of engineering and education [3, 12]. Virtual reality is one of the most used alternatives at present because of the potential it has demonstrated in these areas and the application fields for it grows according to the development and implementation of new technologies [5, 12, 15]. The realism and immersive capacity that virtual reality provides and makes it an ideal means for knowledge acquisition to be effective in the learning process or industrial training. It is also able to stimulate the user's senses to reproduce sensations that only could be experienced in real situations, which makes possible to evaluate these reactions and decision making to assess their abilities with a reliable degree of effectiveness [6, 7, 15]. Several virtual reality applications have been developed for training in fields such as medicine, manufacturing, construction, energy systems and a long et cetera [3, 13, 14]. In these cases, the user must achieve predetermined goals and follow working sequences to comply with certain tasks related to the training topic.

This work presents the development of a virtual reality system for training on pumping stations for drinking water supply systems of EP-EMAPA. The components of the pumping station are designed based on its P & ID diagram, using of photogrammetry techniques and Computer-Aided Design software. The characterization and animation of the objects is implemented in UNITY3D, in addition safety signs are added as well as sounds and lightness to achieve the desired realism and upgrade user experience. The dynamics and control of the plant are simulated using its transfer function in MATLAB, which works as a data manager for the emulation of process variables in the virtualized plant. Finally, methodical fault simulations are implemented in some zones so that the user can use their skills in emergency management. This makes possible to evaluate their speed of response when unfavorable situations occur. The system provides an adaptive learning process to be used according to the user's profile and the level of skills required. It also provides flexibility to be used at any time and the possibility of evaluating optimally the skills gained.

The present work describes the following stages: Sect. 2 describes the structure of the system; the virtualization of the environment using CAD software. The photogrammetry technique is detailed in Sect. 3; Sect. 4 describes the simulation and emulation of the process in UNITY3D and methods developed with MATLAB; Sect. 5 contains the results and Sect. 6 presents the conclusions and future applications of the system.

## 2 System Structure

This article describes the development of an interactive virtual environment for training in pumping systems for the distribution of drinking water through the virtualization of the plant and the emulation of the industrial process giving as a result a tool for training new operators in a safe environment and free of occupational hazard. In addition, it has the ability to detect potential danger caused by the inadequacy of the operator when controlling or manipulating the variable of interest of the industrial process. It even allows safety instruction in industrial plants through the interpretation of preventive and informative signals located in strategic locations of the pumping station.

The industrial processes control, hazard detection and safety education are developed through events that occur when the operator interacts with the pumping process, this allows the simulation of the behavior of the process and critical situations, which provide an interactive training environment for the user.

The events in the pumping process occur when the variable of interest exceeds its operating limits or when a control action is performed on the process. The training system uses both software and hardware tools which allow the virtualization of the training system the closer to reality. This virtualization of the environment is developed by means of photogrammetry techniques that generate the digitalization of the terrain, whereas the P&ID diagrams provide the necessary information that allows the virtualization of the pipes and instruments of the pumping station. The simulation of the process behavior is generated by the mathematical model developed through the analysis of components and variables acting in the process of the plant. The exchange of data with MATLAB together with the mathematical modeling produces a reliable behavior of the variables of the virtual environment. The realism and immersion of the system is granted by the virtual reality devices, facilitating the user the interaction with the process, instruments, monitoring, and control of the station and detection of hazards. The architecture of the virtual training system offered in this paper is shown in Fig. 1.

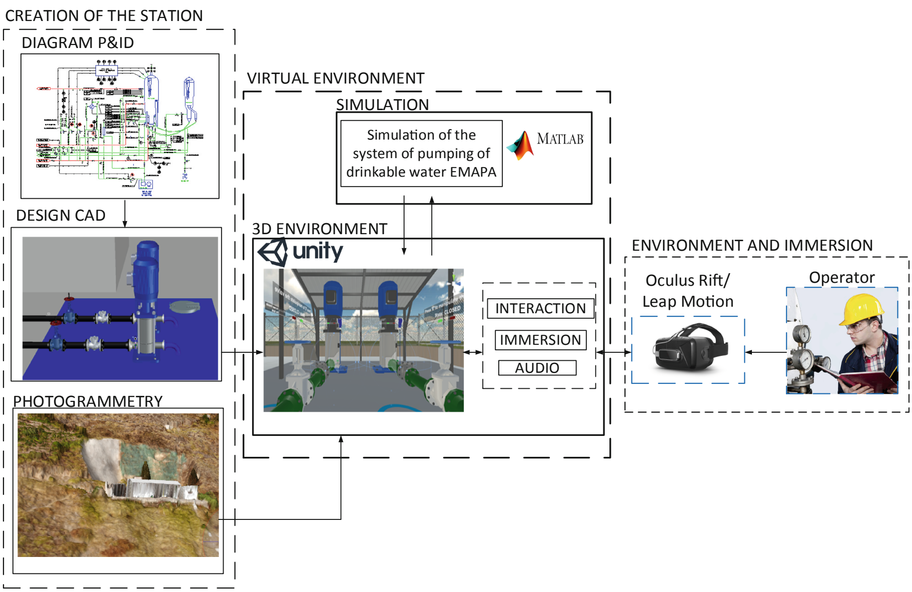



**Fig. 1.** Virtual training system architecture

This training system presents three main stages in its architecture: (i) *Creation of the station,* the virtual station is designed, from photos, P&ID diagrams and sounds found in the real station. In order to develop realistic 3D models of bombs, pipes, transmitters, valves and tanks in CAD software the three-dimensional survey of the area is achieved by using a UAV to capture several photos of the area, then they are classified and edited for reconstructing the area using photogrammetry techniques; (ii) *Virtual Environment,* the environment of the pumping station is implemented thanks to the UNITY3D graphics engine using different animations that allow interaction with the environment. MATLAB generates the simulation of the industrial process by means of the mathematical model obtained from the real behavior of the pumping station. Finally, (iii) *Interaction and Immersion*, it consists of virtual reality devices that allow the operator to interact with the virtual environment achieving the maximum possible experience of immersion and interaction in the integrated station.

## 3 Virtualization of the 3D Environment

This section describes the process used for the virtualization of the pumping plant through techniques of photogrammetry, CAD and UNITY 3D design, as well as avatar design, animations and sound effects that provide a high degree of immersion in the training environment.

### 3.1 Photogrammetry

This technique creates the 3D model of the structure of the pumping station from photographs taken with the UAV Mavic Air, which are processed in the Agisoft PhotoScan software to obtain a 3D reconstruction of the environment. The photogrammetry technique for the reconstruction of the 3D environment of the pumping station is described in Fig. 2.

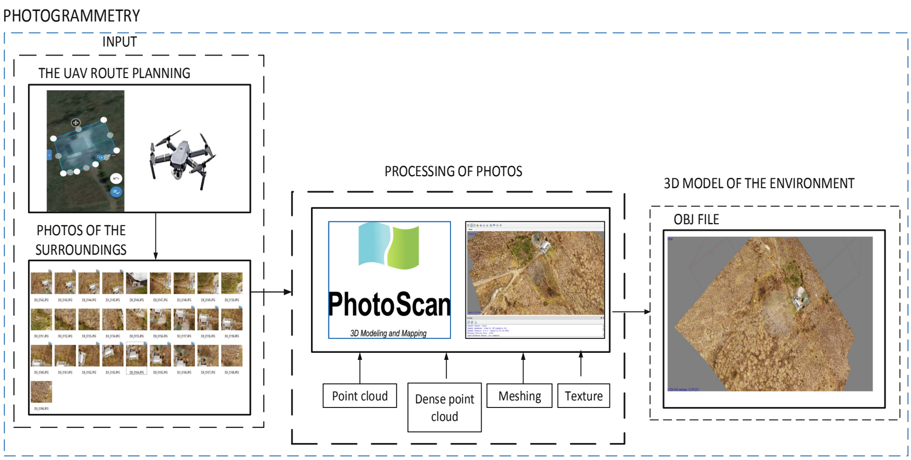



**Fig. 2.** Description of photogrammetry

In the input stage, the acquisition of photos is provided by the UAV Mavic Air, which first requires the route planning of the area of the pumping station to be rebuilt. Afterwards it captures the photos. This job is done by the Dronedeploy application, which obtains approximately 200 photos classified according to their capture distance in 3 groups that provides the appropriate information for the image processing stage.

The Agisoft PhotoScan software is used in the image processing stage; these processes requires the uploading of the photos in the software to perceive their quality and eliminate duplicate data, in order to generate a scattered points cloud that creates the base of the 3D model of the pumping station. The scattered points cloud allows the generation of a dense points cloud, which carries the largest amount of information from the pumping plant to generate a mesh and texture of the environment giving a more realistic visualization aspect. The output stage provides a 3D model in an .OBJ file with its respective textures that is used in the virtualization of the pumping station as the external part of the environment.

### 3.2 CAD Design

The CAD design allows virtualizing the internal structure of the pumping station, which consists of a system of pipes and industrial equipment.

The pumping process consists of 5 pumps, 2 of them are set up vertically and 3 horizontally and they are connected to the tanks, thanks to a pipelines system. The creation and three-dimensional interconnection of the piping systems and instruments in the pumping system is done by the AutoCAD Plant 3D software aimed to the design of industrial plants, see Fig. 3.

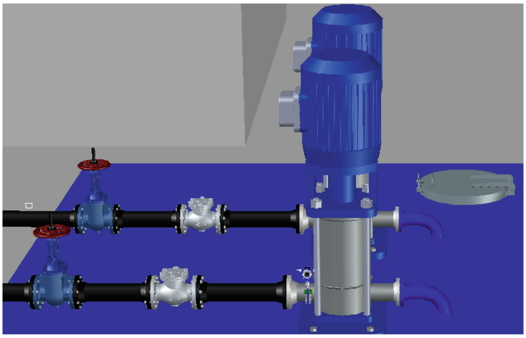


**Fig. 3.** Desing using AutoCAD plant 3D

The virtual environment of the pumping plant to perform training the closer to the reality requires a high level of detail in order to have high impact training. For this reason it is necessary to use other types of design software such as SolidWorks which allows the design of customized instruments, which gives even more realism to the pumping station and consequently to the training process. This is the reason why, additional components have been designed in SolidWorks, such as a control valve, see Fig. 4.

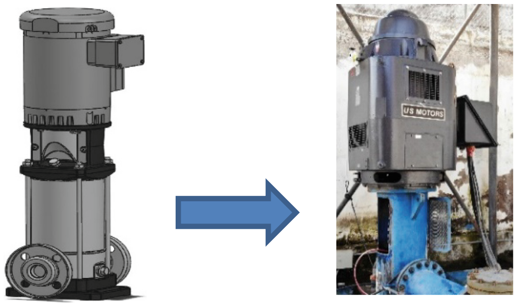



**Fig. 4.** Control valve designed in SolidWorks

### 3.3 Design in UNITY 3D

The design obtained in AutoCAD Plant 3D and the photogrammetry developed in Agisoft PhotoScan, are imported in FBX and OBJ format, respectively, Unity 3D, which are scaled and located inside the plant in their corresponding place. The design in format (* .fbx) must be characterized by the creation of materials, which will be assigned to each of the objects, unlike the photogrammetry that requires only the allocation of its texture. Photogrammetry, the design in AutoCAD Plant 3D, the creation of scripts and animations, the allocation of surround sound to existing equipment and the design of levels of ranks and privileges, make up the design in UNITY 3D, see Fig. 5. This provides a Training environment with greater realism for the user of the pumping plant.

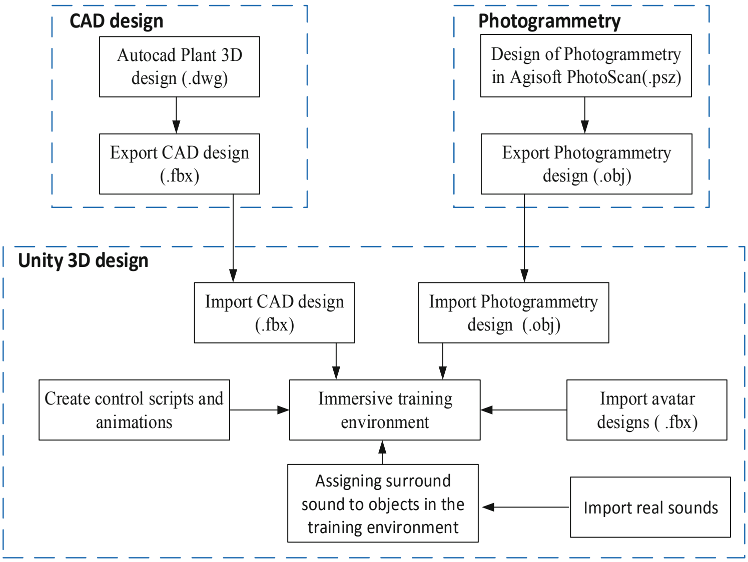



**Fig. 5.** Design process in unity 3D

### 3.4 Design of User Levels and Privileges

The training environment provides a menu that has the ability to select between 4 user levels and privileges determined in order to limit the activities it has and thus provide an specific learning method for each level of the pumping plant for distribution of drinking water, for this reason, avatars are created, which interact with the different processes of the pumping plant, these are created in Adobe Fuse (see Fig. 6), which is a program that allows to easily perform the Auto-Rigger when exporting them to the MIXAMO web page for the creation of the animations. The avatars have different types of clothing and accessories according to their different user levels and privileges within the plant. For this reason, a start scene was created in the training application (see Fig. 7) that allows selecting the different user levels and privileges with their respective avatars. The user levels and privileges that the training system offers are as follows: (i) *Supervisor, Engineer – High Level*, can manipulate manual valves, pump selectors and the HMI for the monitoring and control of the plant. In (ii) *Operator – Medium Level*, can manipulate manual valves and pump selectors. Finally, (iii) *Visitor - None*, sees the whole process, but cannot manipulate anything. This information is presented through an audio message and also in text boxes.

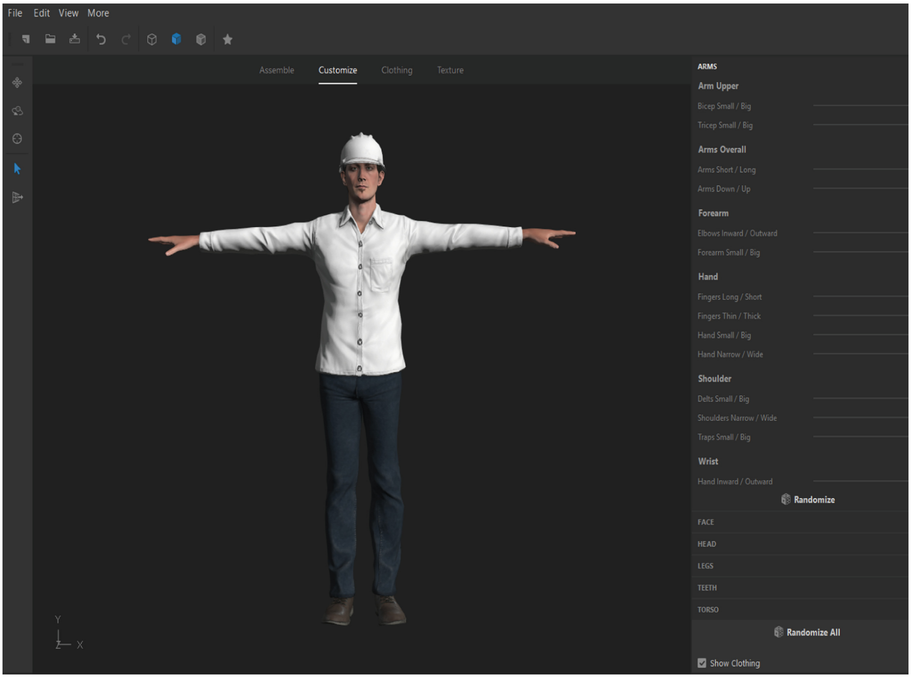



**Fig. 6.** Avatar created in Adobe Fuse

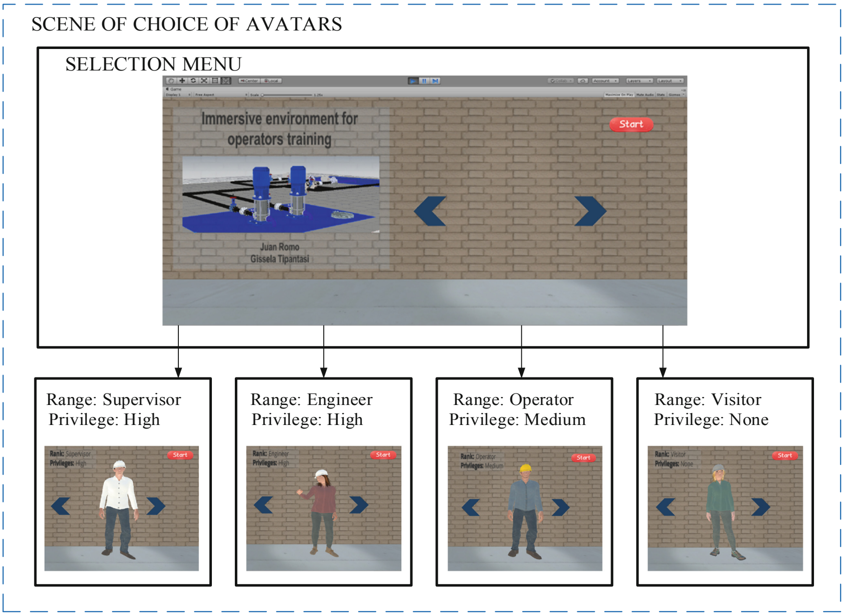



**Fig. 7.** Selection menu for avatar

## 3.5 Industrial Safety Signals and Immersive Ambient Sounds

**Industrial Safety Signals.** The interpretation and recognition of preventive and informative industrial safety signals provide the user with an environment conducive to training and assistance in accident management. For this reason, industrial safety signs are implemented in hazardous locations, to provide the user with the necessary information during the experience of an accident event that is generated in the training environment. In the Fig. 8, shows an industrial safety signal (informative), which indicates the existence of a fire extinguisher in a flammable environment, which allows the mitigation of a fire in a timely manner.

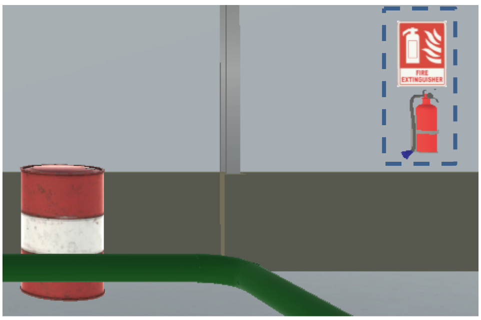



**Fig. 8.** Safety signals in a flammable environment

**Immersive Ambient Sounds.** Realism in the training environment is increased by providing characteristic sounds to industrial pumps, which are aggregated in the limited areas by the pumps and surround sound (see Fig. 9). With the purpose of obtaining a progressive sound attenuation effect as the user moves away or closer to the industrial equipment. The sounds assigned to the different elements of the immersive environment are obtained from real industrial processes with the purpose of improving the interaction with the equipment that the pumping plant possesses.

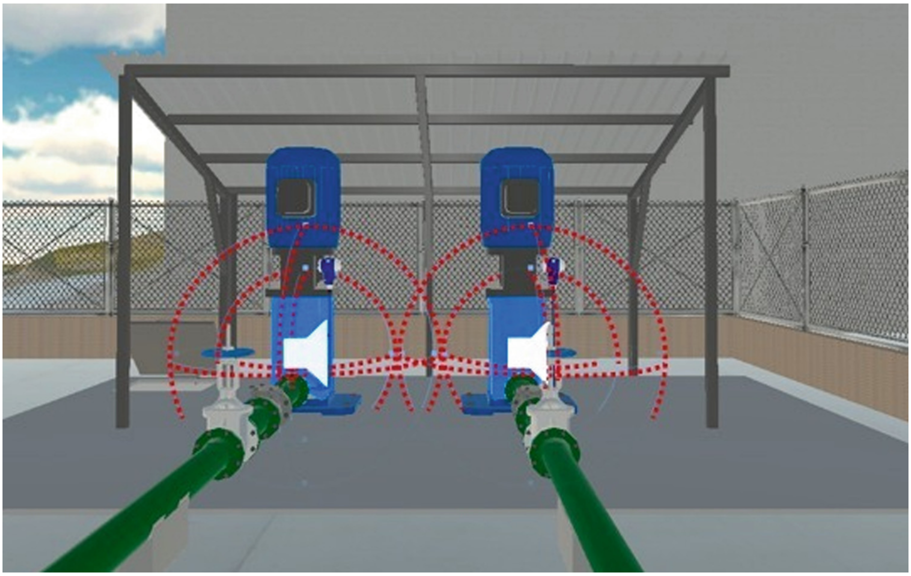


**Fig. 9.** Surround sound of pumping pumps

## 4 Process Simulation

This section presents the development of a mathematical modeling of the pumping station and the design of a controller that performs the simulation of the process through MATLAB.

### 4.1 Mathematical Model

Mathematical modeling is acquired through the schematic diagram of the process of pumping illustrated in Fig. 10, conformed by five pumps in parallel; which are divided into two groups: (i) S*kyrocket of chlorine*, formed by twin pumps 1 and 2 which are in charge of supplying enough chlorine to the water purification process; and finally (ii) *skyrocket of water*, formed by 3 and 4 identical bombs, as well as the auxiliary pump 5, which supplied water to the process. The inputs of the process are the voltages applied to the inverters of the pumps, while its output is the flow of chlorine and water.

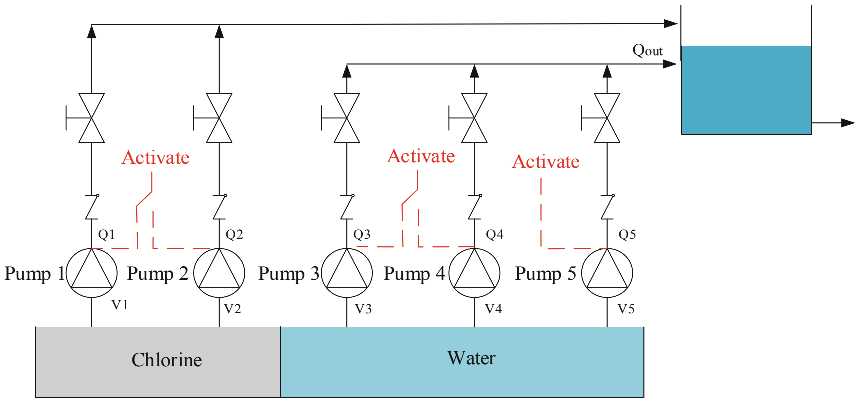



**Fig. 10.** Diagram of the pumping process

To know the relationship that exists between the variator input voltage measured in volt (V) that connects to the pump and the flow that this provides to the system measured in litres/second (l/s), it is necessary to do a trial with the data acquired from the pumping plant.

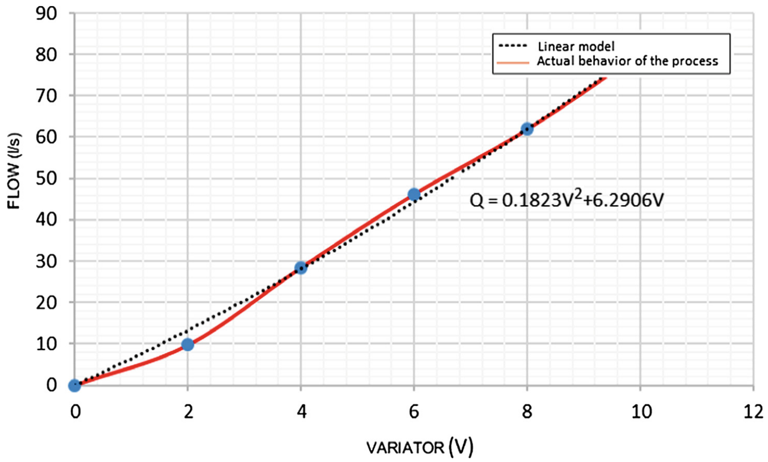



**Fig. 11.** Pump 1 voltage-flow ratio

Figure 11 shows the relationship between the tension applied to the frequency variator and the output flow, where the information is provided both of the actual behavior of the plant, as well as its linear model through the method of linear regression. So the approximate relationship that exists between tension (V) applied to the frequency converter and the flow rate (Q) is able to provide is:

$$Q = 0.1823V^2 + 6.2906V$$

Knowing the linearity between the tension and the flow is set two points of operation in order to obtain their respective earrings; obtaining a 70 flow equal to 52.96 (l/s) with a slope of 7,565 (l/s); while that with 80 flow is equal to 61.99 (l/s) with a slope of 7.748 (l/s), by which the average value of these earrings is therefore 7.656 (l/s).

Experimentally, the operation is described by the following equation [16]:

$$q_i = k_i V_i$$

where: qi is the flow of the pump outlet in ($cm^3/s$); Vi is the voltage applied to the frequency converter (V); ki is the slope of the curve linealizada around the point of operation having:

$$k_i = 7.656(l/s) = 7656\ cm^3/s$$

For dynamic behavior is a model test that a tension is introduced into the speed controller, is subjected to a voltage step pump and shows the behavior of the signal from the transmitter.

The dynamic of this system is typical of a first-order as the equation system:

$$G(s) = K/Ls + 1$$

So the model of each of the pumps pumping from the collected data system; and considering that pump 1 and 2 have the same characteristics as well as 3 and 4 twin pumps, you have the following equations:

$$G_{pump1}(s) = G_{pump2}(s) = 1.0614/1.544s + 1$$
$$G_{pump3}(s) = G_{pump4}(s) = 1.1723/1.746s + 1$$
$$G_{pump5}(s) = 0.964/1.04s + 1$$

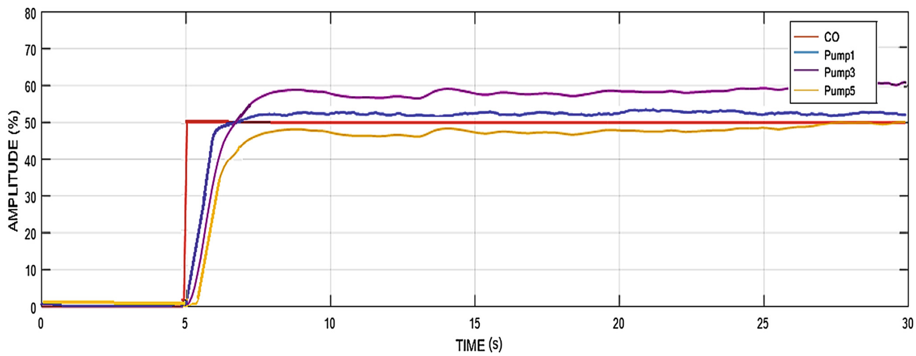



**Fig. 12.** Dynamic behavior on each flow response.

Figure 12 indicates the behavior of each of the flows, that by submitting to the pump at a given step of the response of flow input voltage follows a certain curve until it reaches its final value, from which the previous equations is valid.

Knowing the behavior dynamic of each one of the pumps of different groups, both the supply of chlorine and the water supply is obtained the following transfer functions:

$$G_{chlorine}(s) = 1.0614/1.544s + 1$$

$$G_{water}(s) = 2.902s + 2.136/1.816s^2 + 2.786s + 1$$

## 4.2 Ratio Control

This control algorithm allows to control the relationship between the chlorine flow variable and the water flow variable, in Fig. 13 it can be seen that there is only one control variable and two measurement variables, for this reason, this is a system of two inputs and one output, where a flow relation (FC) controller is placed.

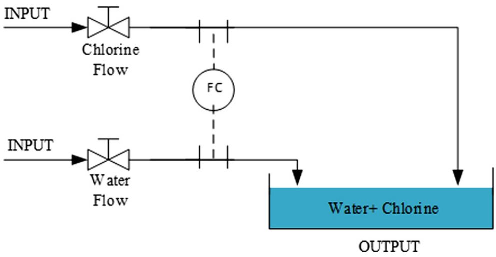



**Fig. 13.** System for the dosificatio of water

For controlling the dose of the flow of water and chlorine, the ratio control scheme is implemented see Fig. 14, where each variable of the process is regulated by the controllers C1 and C2, the result obtained from the first process (water flow) is multiplied by a ratio factor (a) and adopted as the set point to control the second process variable (chlorine flow), that is, $r2(t) = ay1(t)$ [17].

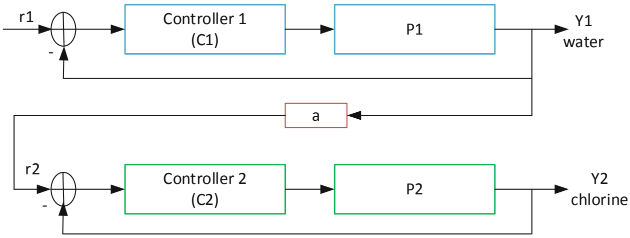



**Fig. 14.** Ratio control scheme

For the simulation and control of the process of drinking water purification, it is required the exchanging of significant process data between UNITY3D and MATLAB. For this task to be done it is necessary the design of an HMI and the respective programming (see Fig. 15), to subsequently implement an interconnection method through the TCP/IP communication protocol.

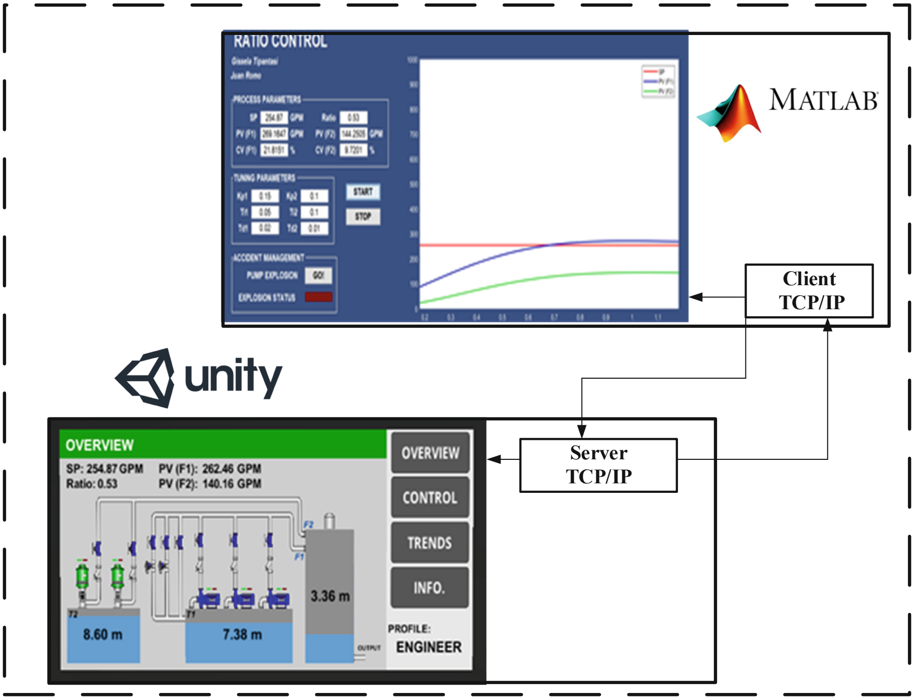



**Fig. 15.** Data exchanging between applications diagram

## 5 Analyses and Results

The training environment developed is oriented towards the correct behavior of the control algorithm that governs the water purification process and in the generation of emergency events that may occur in the drinking water distribution system. In this way, the user will have an integrated and effective training to control the different equipment and emergencies that occur in the pumping plant.

The Fig. 16 presents a menu that allows the selection of the different privileges and ranges that the application possesses, in order to choose the type of preparation that is required to receive.

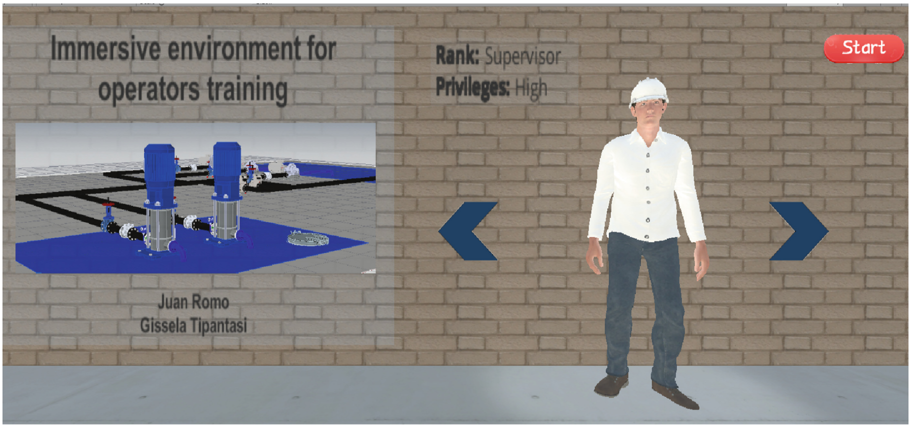



**Fig. 16.** Privilege selection menu

The virtual environment offers a visual and auditory explanation of the activities that are allowed to be performed within the plant, depending on the privilege and range selected, see Fig. 17.

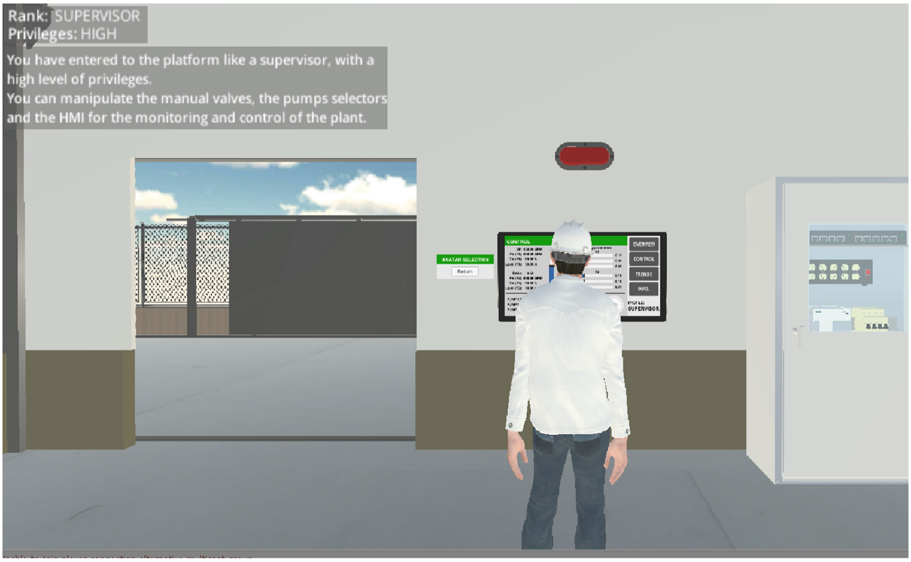
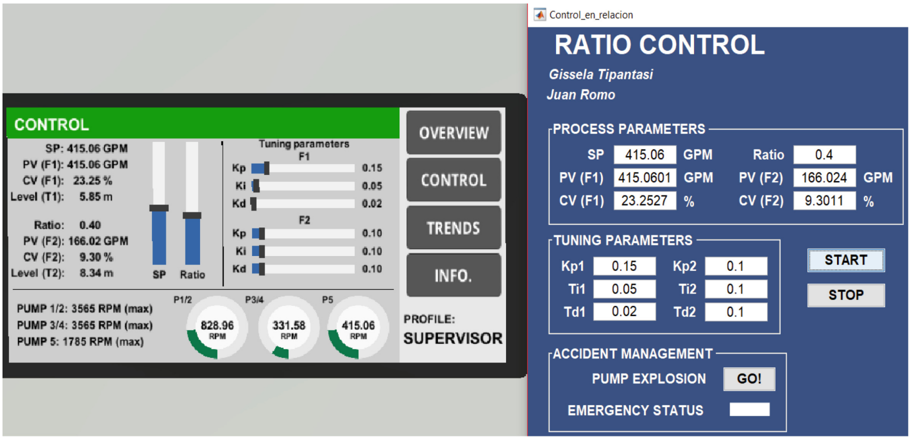


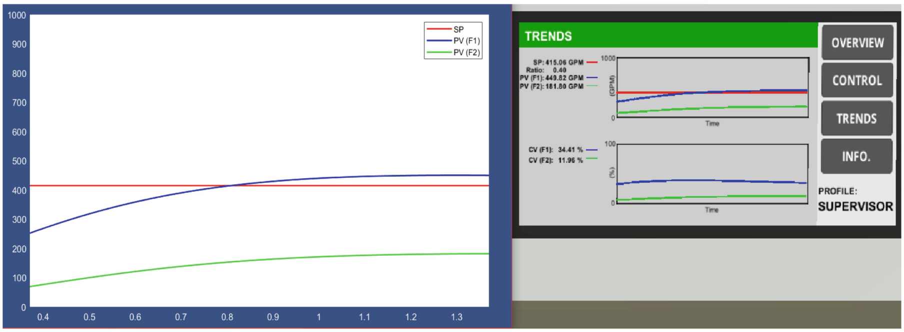

**Fig. 17.** Activities allowed for the avatar

The training system for personnel consists of events, both in the control algorithm and in emergencies present in water purification.

**Control Algorithm for Water Purification.** In order to demonstrate the correct functioning of the control algorithm applied to water purification, the following experiment is presented, which consists in establishing a ratio of 0, 4, to dose chlorine to 40% and water to 60%, in addition to placing a set point 504.07 gallons per minute (GPM), in order to corroborate the process data that validate the correct tuning and operation of the control algorithm. In Fig. 18 the data of the control variable (CV) and the process variable (PV) are counteracted, both in the water flow (F1) and in the chlorine flow (F2) presented in the Matlab software and in the virtual environment HMI. (a) Validates the operation of the control algorithm to counteract Matlab software data and virtual environment HMI. (b) Validates the correct tuning of the control algorithm to compare the Matlab software trends and the virtual environment HMI.



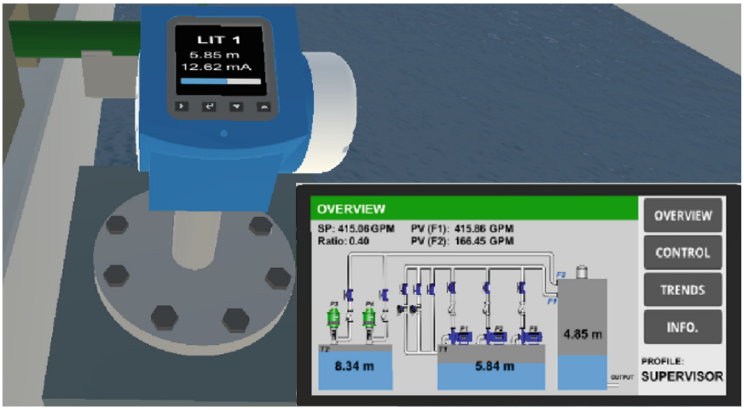

(a) Data from the Matlab software and the virtual environment HMI.



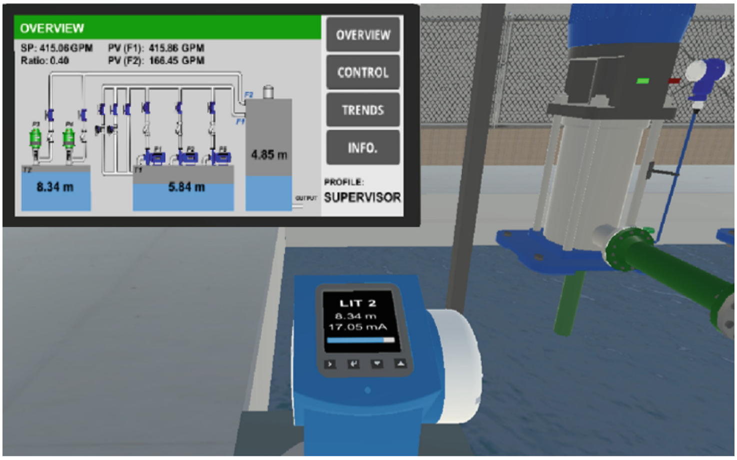

(b) Trends in Matlab software and virtual environment HMI.

**Fig. 18.** Control algorithm data contrast

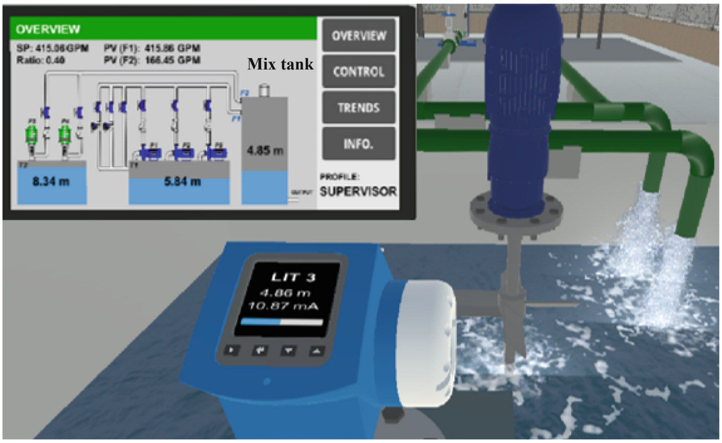
The F1 and F2 provide changes of levels in the water tank (T1), chlorine tank (T2) and in the tank containing the mixture, all this can be seen both in the virtual environment HMI and in the indicator transmitters level (LIT) that each tank has, see Fig. 19.




(a) Check level T1 in both LIT1 and Overview.




(b) Check level T2 in both LIT2 and Overview.




(c) Check the level of the mix tank in both the LIT3 and the Overview.

**Fig. 19.** Level contrast between LIT and overview

**Emergency Management in the Process.** This event focuses on generating an industrial emergency and the measures that the user must take to mitigate the emergency. The accident that occurs is the explosion of a pump, causing a training situation for the user against emergencies, see Fig. 20.

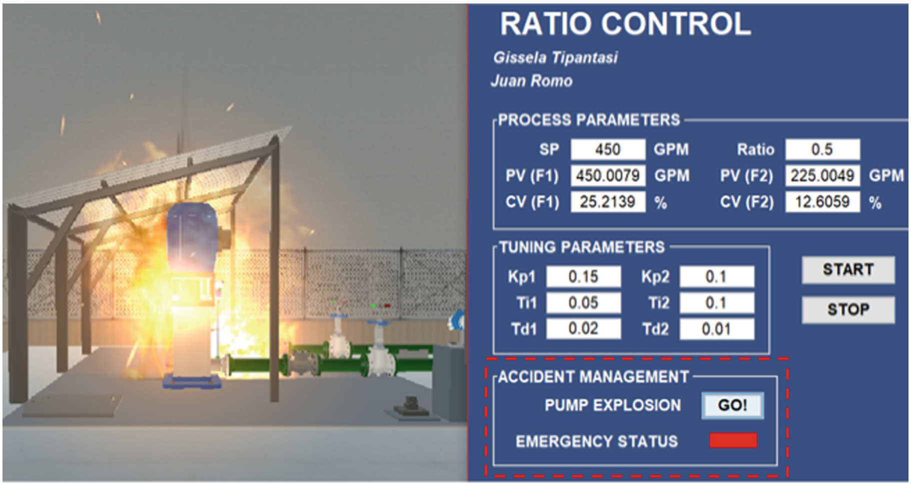



**Fig. 20.** Explosion of the bomb 3

To end the accident that is evidenced in the emergency status located in the accident manager, immediate corrective actions are performed described through informative tables that must be executed by the user, see Fig. 21.

The results presented below indicate the validity of the usability of virtual training environments, to carry out an adequate recognition and management of pumping stations for drinking water supply systems. For this purpose, the SUS summarized evaluation method is used [19]. Generally providing the style scale that generates a single number, represented by an average composed of the usability of the application for virtual training environments as shown in Table 1.

The total number, obtained from the sum of the operation in each question, results in 36.53; based on this result, the SUS score is expressed by a multiplication of 2.5, which means a percentage of 91.33%, representing a high usability for the recognition and proper management of pumping stations for potable water supply systems.

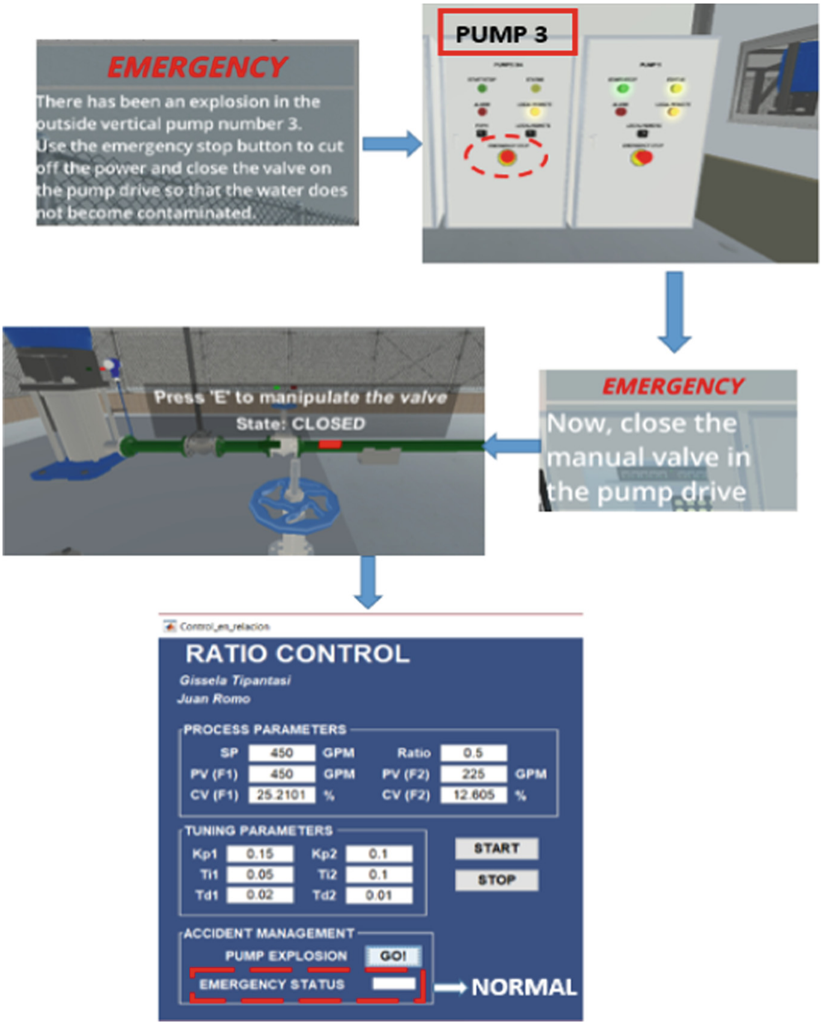



**Fig. 21.** Actions to mitigate the explosion

**Table 1.** Results of the questionnaire.

| Questions | Punctuation | | | | | Operation |
|---|---|---|---|---|---|---|
| Would you like to use this virtual training environment frequently? | | | | 3 | 12 | 3.80 |
| Did you find that the virtual training environment is unnecessary and complex? | 13 | 2 | | | | 3.87 |
| Was it easy to use the virtual training environment? | | | | 3 | 12 | 3.80 |
| Did you need a technician to be able to use this application? | 10 | 3 | 2 | | | 3.53 |
| Is the controller in relation used for the dosing of water and chlorine efficient for drinking water purification? | | 1 | 2 | | 12 | 3.53 |
| Is the virtual training environment adequate to become familiar with the equipment that the pumping station has? | 12 | 1 | 2 | | | 3.67 |
| Did the training environment provide some perception into the purification process of drinking water carried out in the pumping station? | | | 1 | 2 | 12 | 3.73 |
| Found the application difficult to use? | 13 | | 1 | 1 | | 3.67 |
| Was it easy to manipulate the avatars within the application? | | | 2 | 2 | 11 | 3.60 |
| Did you need to learn many things before using the application? | 8 | 4 | 3 | | | 3.33 |
| Total | | | | | | 36.53 |

## 6 Conclusion

The use of the virtual environment provides adequate training to staff in case of emergencies and in the implementation of control techniques that allow simulating the response of the process, which together with the virtual keyboard created generates a large amount of information on the most relevant variables of the process.

The virtual environment provided by the application provides realism in the structure of the 3D reconstruction of the pumping plant; as well as in the design of the 3D objects implemented for the realistic and continuous training of the pumping station for the distribution of drinking water. Finally, the virtual environment application provides useful knowledge to field operators in both industrial safety and process control, which in turn reduces risks.

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