Virtual Environment for Control Strategies Testing: A Hardware-in-the-Loop Approach

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Abstract. This work presents the development of a system based on the Hardware-In-the-Loop (HIL) simulation to carry out tests of controllers within a virtual environment consisting of a fully characterized industrial plant to emulate its real behavior. The virtual environment has been implemented using Blender and the Unity3D graphics engine, achieving a high level of realism in the models and their characteristics. In addition, a data acquisition method has been implemented through the generation and reading of electrical signals that allows the communication between the virtual plant and the controller that needs to be tested.

Keywords: Virtual environment · Hardware-in-the-Loop · Unity3D · Processes control

1 Introduction

The control strategies used in the process industry, such as manufacturing plants, nuclear plants, etc., are decisive for the optimal performance of each stage that make up a system. The control algorithms, designed to execute tasks autonomously, require a preliminary validation before commissioning the controller, for which they must be thoroughly tested in order to debug errors and guarantee their permanent and reliable execution [1]. However, the constant growth of modern control systems, in terms of size and complexity, hinders the logistics for verification based on testing the controllers within a physical plant that requires sensors, actuators and mechanical systems, which results in higher time consumption, high implementation costs and risk of equipment damage [2, 3].

In this context, is essential an efficient environment for the creation and validation of prototypes that groups all the user's requirements, capable of providing relevant data so that the system verification is effective and truthful. Therefore, it is required a much more complete simulation than the traditional, which can represent the characteristics of the system in terms of production, components workflow and machine efficiency together with the control algorithm. This need can be solved through the Hardware-In-The-Loop (HIL) technique, which is a real-time simulation of all the subsystems that make up a complex engineering system, which are modeled and coupled through numerical models for a complete representation. This simulation can be carried out in an embedded system or in a computer [4–7]. Thus, a control algorithm can be validated in a realistic way using the simulated sensors and actuators to verify the response of the

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system once the controller acts on them, this through a communication interface between the simulated system and the actual controller involved in the HIL architecture [5].

Nowadays, HIL simulation is widely used because of its low cost, details level, high effectiveness and safety that offers in various fields like electronics, robotics, automotive industry, energy industry and, recently, in education of processes control and automatisms [5–13]. Generally, these applications use a graphical interface that, in many cases, does not allow a realistic perception of the system or even dispenses with it. This is a problem when considering and evaluating different critical scenarios within the operation of the plant and, therefore, the ability of the controller to compensate disturbances. In addition, if these applications are used for educational purposes, the absence of an adequate graphical interface difficults the understanding of the system and therefore the learning process.

The alternative that some developers have used recently is the implementation of virtual environments, which allow the relevant data of the simulated system to be monitored and analyzed. Mainly, applications have been developed for testing vehicles and robotic platforms [14–18]. Using virtual environments for educational purposes is a teaching-learning method that has been studied and applied successfully at various levels due to the benefits it offers by providing experiences that cause a great impact on students. This strategy can take users to scenarios that are not easily accessible, all in a safe way and with the possibility of remaining in them for a long time, carrying out specific tasks that are useful to acquire knowledge [19–22]. In the case of engineering education, so-called “digital twins” are frequently used, which are virtual replicas of products or processes, including their physical and functional characteristics, to be used for different purposes such as analysis, simulation, control, improvement of processes, among others [23, 24].

Based on the fundamentals described in previous paragraphs, this article describes the development of a system based on Hardware-In-The-Loop simulation to test controllers using an interactive virtual environment that emulates the behavior of an industrial plant. The system will allow the user to manipulate the components of the plant to evaluate the response of the controller to critical scenarios and in a random manner. Communication between the virtual plant and the controller is implemented through the generation of electrical signals that represent the data from sensors and actuators. The virtual environment has been designed in Blender and the simulation, which includes the characterization of the plant components, has been fully implemented in Unity3D graphics engine. This article is organized into V sections, including the Introduction. Section 2 describes the structure of the system. Section 3 details the development of the system. In Sect. 4 the results are presented, including the performance analysis of a control algorithm after its testing through the system. Finally, the conclusions are presented in Sect. 5.

2 System Structure

The developed system, based on HIL simulation, uses specialized hardware and software tools that allow an optimal implementation and effective coupling between each of the stages. Figure 1 presents a diagram that describes the interaction between the devices and the programs used.

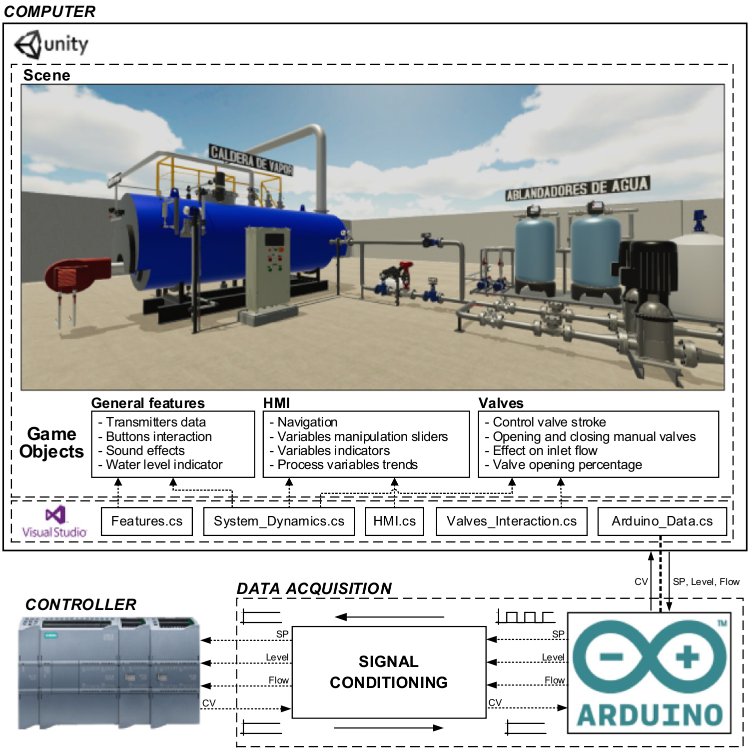

Fig. 1. System structure

The first stage consists of the simulation of an industrial plant, which is implemented in a computer, specifically in the Unity3D graphics engine. This plant is characterized based on a mathematical model which allows a simulation of its response in real time. This simulation includes all the inherent peculiarities of the real system, in this way it is possible to evaluate different critical scenarios interactively. To achieve this, it was implemented the ability to go through the entire environment, opening and closing valves, manipulate the setpoint, monitor plant parameters, etc.

Then, the data acquisition stage is implemented based on Arduino MEGA 2560 board, which serves to transform the simulation data into electrical signals to be used by the external devices that need to be tested. Also, this card allows the reading of voltage signals, which are converted into useful numerical data for the simulation. In addition, a signal conditioning stage is used to make them usable by any controller for its validation.

Finally, given the characteristics and approach of the proposed system, the use of industrial controllers is proposed for the verification of control algorithms.

3 Application Development

3.1 Virtual Environment

The virtual environment is designed from a steam generation system that uses a boiler. In general, steam generation is carried out by means of a boiler that evaporates the water inside, which has been previously treated in a previous stage. The control objective is the regulation of the water level in the boiler drum, for which a pneumatic control valve, level and flow transmitters are used. This system has been chosen for all the instrumentation it requires, which is beneficial to be used in engineering education, in addition, the variables involved in the process allow to test different control techniques to evaluate its performance in a comparative form. For this, the P&ID diagram of the system is taken as a basis, which is shown in Fig. 2.

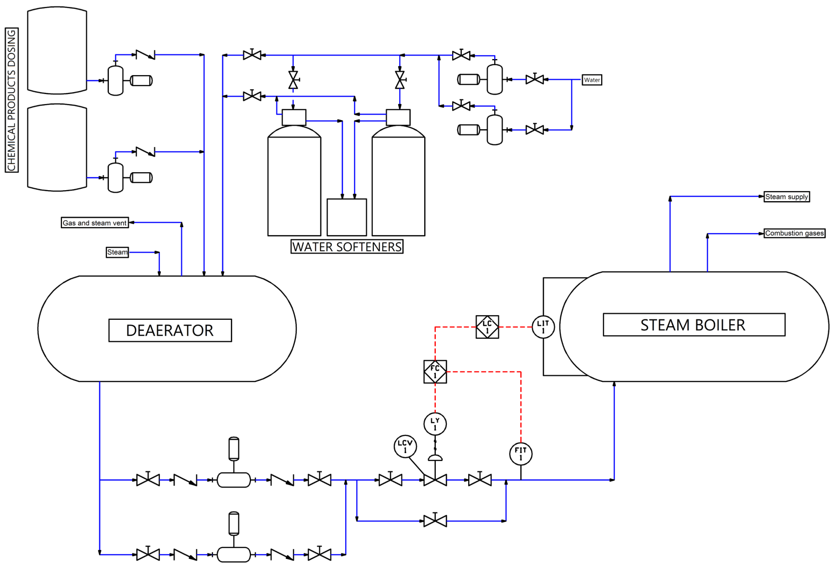

Fig. 2. Steam generation system P&ID diagram

The development of the virtual environment consists of several stages in which different specialized programs are used for the design of the plant and its subsequent characterization. The general workflow, used to create the environment, is described in Fig. 3.

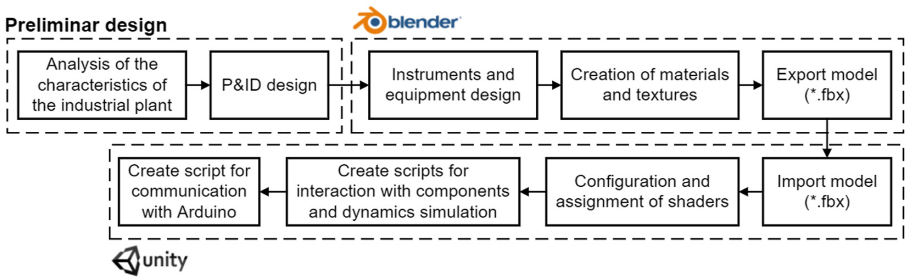

Fig. 3. Virtual environment design workflow

Design of the Industrial Plant

The 3D modeling of the industrial plant is completely implemented in Blender since the tools provided by this software allow a design with a high level of detail and realism. Then, based on the P&ID diagram of the plant, each instrument and equipment is designed, materials are created and assigned, and the models are optimized for later use within the graphic engine. In this design stage, the optimization of each model is very important, that is, it requires the elimination of duplicate vertices in the meshes, which greatly contributes to the performance of the application. In Fig. 4 the industrial plant modeled in Blender is shown.

Fig. 4. Industrial plant designed in Blender

The software used for 3D design allows modelling of objects with a high level of detail, which contributes to the realism of the application. In Fig. 5 the level and flow transmitters modeled in Blender are shown.

For each model, a pivot point was configured in a consistent location. This setting is important for creating animations and implementing user interaction with the objects.

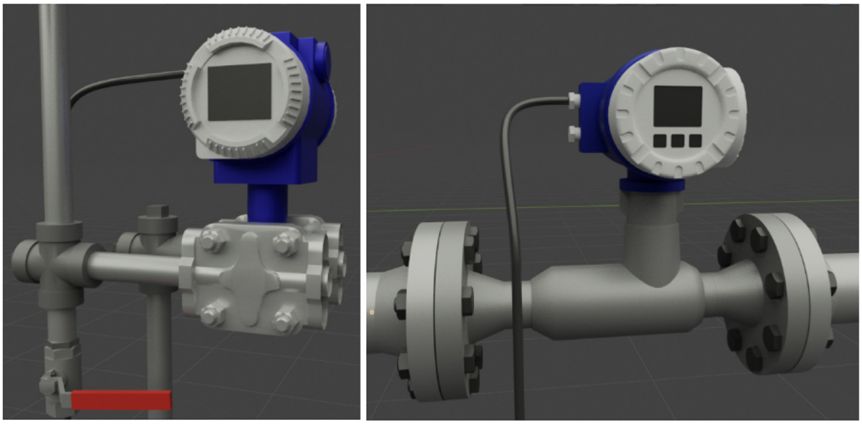

Fig. 5. Level transmitter (left) and flow transmitter (right) design

For example, in the actuator of a manual valve it is required that the pivot point be in the center of it to be able to execute its opening and closing in a correct and natural way, as shown in Fig. 6.

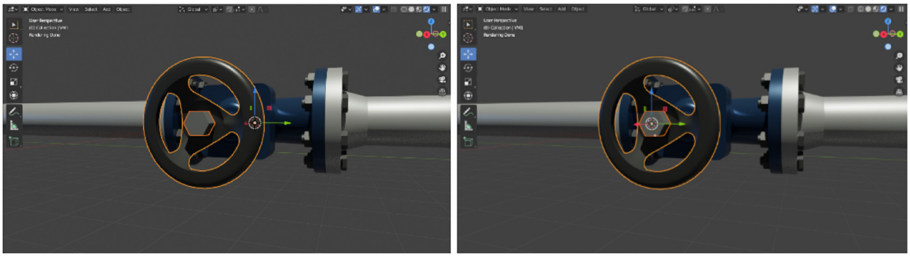

Fig. 6. Displaced pivot point (left) is corrected to rotate valve actuator on its axis (right)

The model of the industrial plant is exported in FBX format, which can be imported into Unity3D.

Characterization, Animation and Simulation

The plant model is imported in FBX format in Unity3D, where all the components are characterized. For this, materials or shaders are created and configured for each of the models since those created in Blender are not compatible with the graphics engine. Then, the lighting sources, shadows, etc. are configured. These details are necessary to achieve the desired realism, see Fig. 7.

Fig. 7. Virtual environment developed in Unity3D

An HMI (Human-Machine Interface) has been designed for the monitoring and control of the virtual plant. In this way the user is able to manipulate the set-point and monitor the response of the system. The windows that make up the HMI have been created using UI (User Interface) tools such as buttons, sliders and texts, see Fig. 8.

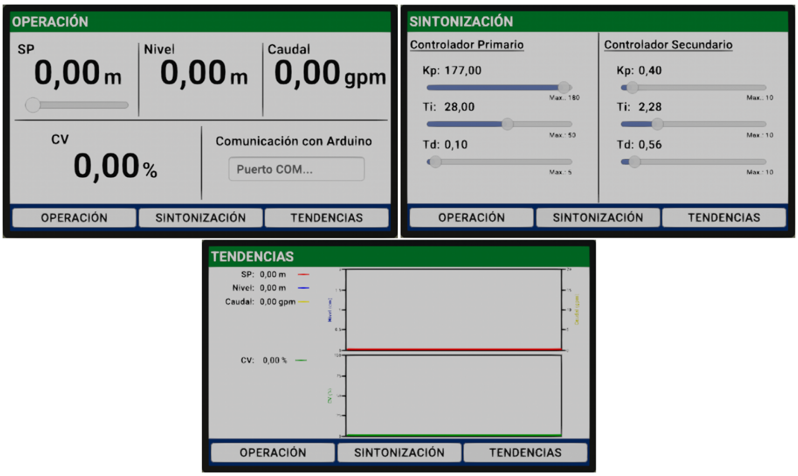

Fig. 8. HMI windows

The data of the flow and level transmitters are presented using UI tools as in the case of the HMI, see Fig. 9.

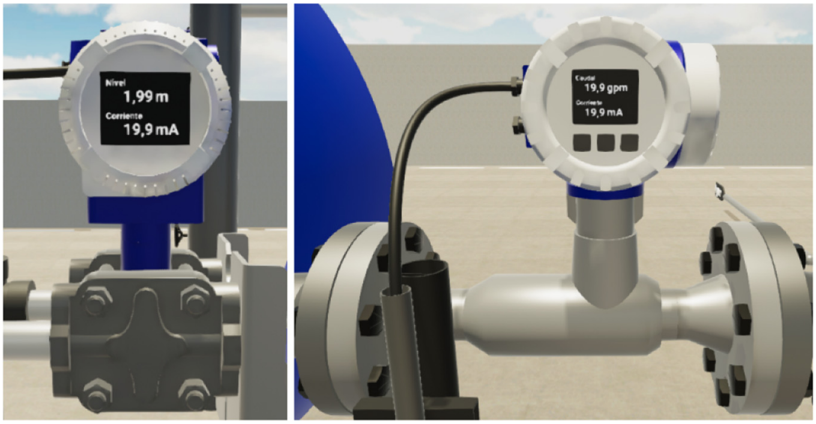

Fig. 9. Level transmitter (left) and flow transmitter (right) data

The control valve has been animated through a script that controls its stroke from an input data in a range from 0 to 100%. Thus, the movement of the actuator and the deflection of the pressure gauge that indicates the pressure supplied to the valve have been implemented, as shown in Fig. 10.

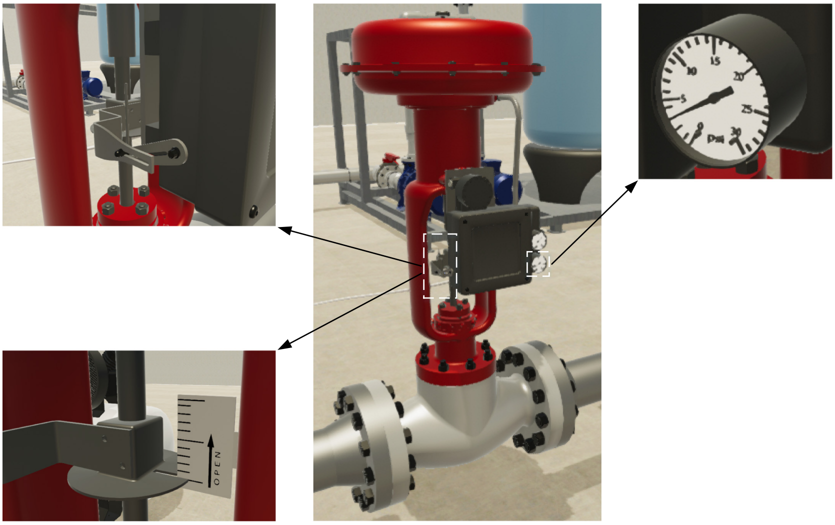

Fig. 10. Control valve animation

Manual valves are interactive, so they can be opened and closed proportionally as required by the user. To achieve this, a collider must be assigned to the valve actuator and the respective script that will allow interaction with the object, as shown in Fig. 11.

Characteristic sounds for industrial equipment are added to enhance user experience and application realism. These sounds are obtained from real equipment and are placed on

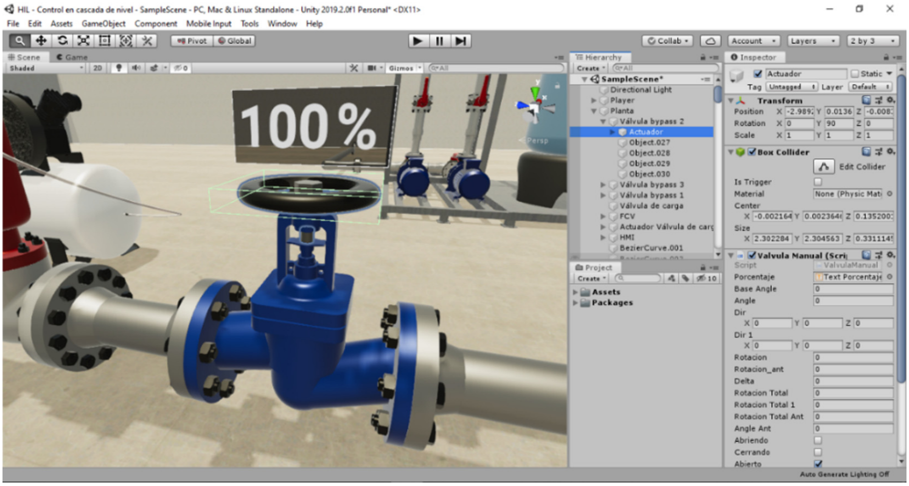

Fig. 11. Interactable manual valve

the corresponding models within the application. In this way, through the tools provided by Unity3D, it is possible that the audio clips are reproduced repetitively and propagate in a realistic way through the environment. Sounds have been added to buttons, switches, pumps, alarms, among others. In Fig. 12 an audio component is shown that is used to reproduce the sounds required for that area.

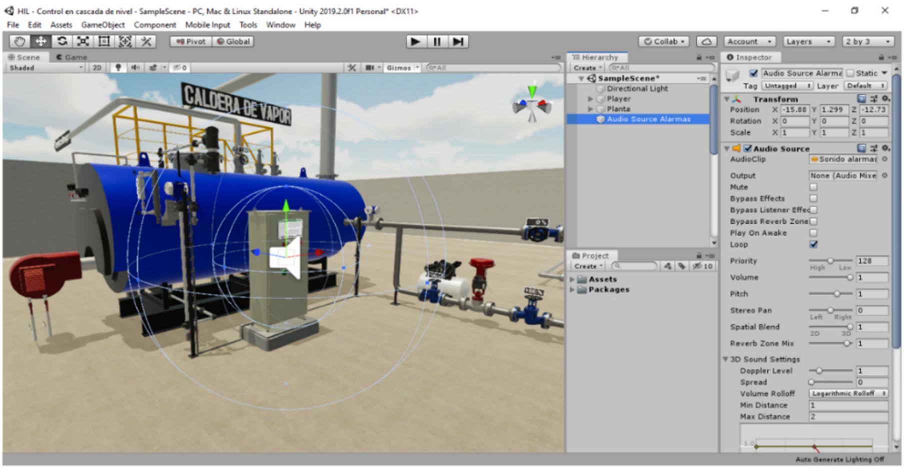

Fig. 12. Sound component in the cabinet area

Once the interactive characteristics of the environment have been defined, the script that allows the simulation of the dynamic response of the plant is implemented. For this, the behavior is modeled through an equation that involves the parameters of a real plant. In this way, the behavior of the plant is approximated through a mathematical model which allows a simulation in real time for the testing of controllers. The data produced by the simulation in each sampling period is reflected in the corresponding instruments and is used to reproduce the animations previously configured. In Fig. 13, it is possible to observe the output of the system (water level) before a step input and the data corresponding to each process variable in the respective instruments and in the HMI.

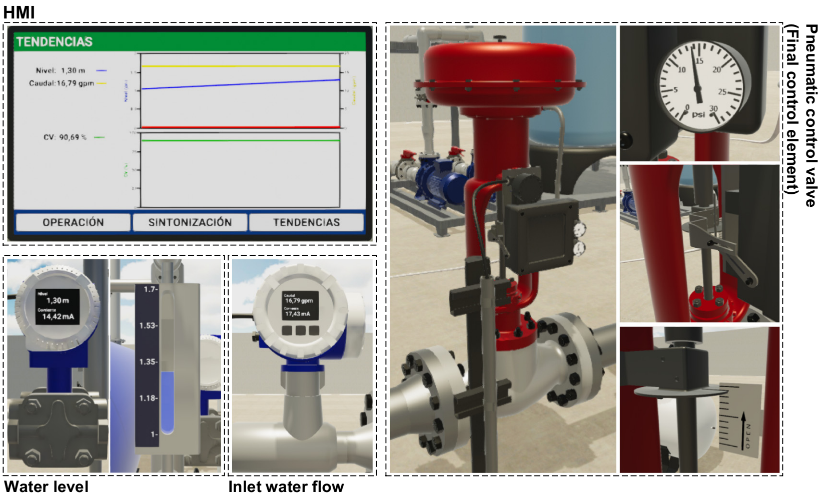

Fig. 13. Step response of the system

In this way, a suitable virtual industrial process is obtained to be used in tests with controllers of all kinds.

3.2 Data Reading and Writing

For testing purposes, a communication interface is required that allows data exchange between the physical controller and the implemented simulation. For this case, an Arduino MEGA 2560 board is used due to the features it offers and its availability in the market.

The simulation data is sent to the Arduino through serial communication, this data is transformed into DC electrical signals to be used by the controller. In the same way, Arduino is capable of reading DC signals to transform them into numerical data usable in the simulation. At this stage, it is necessary to implement signal conditioning since Arduino generates voltages as PWM and these are not suitable to be read by some controllers. In Fig. 14, a diagram is shown describing the data exchange between the simulation in Unity3D and the controller. These numerical data are transformed into character strings for transmission, in this way the sending is optimal and the resolution of the data is maintained.

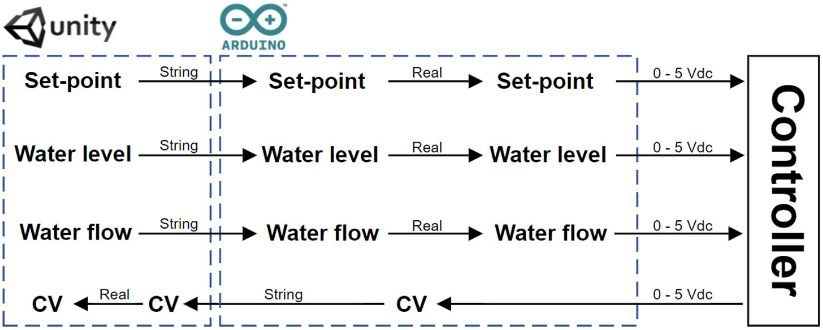

Fig. 14. Data management between Unity3D and Arduino

4 Results

The developed application focuses on testing controllers based on Hardware-In-The-Loop simulation. This application uses an interactive virtual environment as a graphical interface, which allows to recreate the possible critical scenarios of the process in real time. In addition, this system can be used for engineering education, mainly in the teaching of automation and control of industrial processes, given the characteristics of the application.

To validate the operation of the system and its performance, a classical single-loop control and a cascade control are implemented as a case study in a Siemens S7–1200 PLC to perform tests on the system and evaluate the performance of each control strategy in a comparative way. To carry out the analysis of each control method, the data of the variables of interest of the process have been obtained and graphs have been generated to comparing the results, in addition, a disturbance is applied to the process that consists of the closure of a manual valve in the steam boiler feed pipe, see Fig. 15.

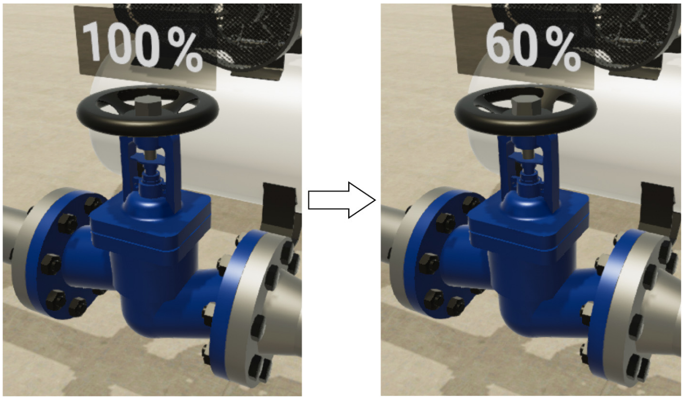

Fig. 15. Application of a disturbance in the water inflow

It was used the PID algorithm for the implemented controllers in both control architectures. In Table 1, the controllers tunning constants are presented, it was used the Lambda tunning method for all cases. This method uses an intermediate parameter which allows the user to adjust the output until achieve the required performance.

Table 1. Tunning constants for each control architecture

Control architecture	Kp	Ti	Td
Single loop control	12.4326	15.4	1.0214
Cascade control			
Primary controller	6.4292	15.4	1.0214
Secondary controller	0.399	2.28	0.5614

In Fig. 16, the results of a test performed to evaluate the response of the system for the single loop control strategy and for the cascade control are presented. The tests were carried out under the same conditions and the data were exported to interpret them graphically and analytically. In addition, the reaction of the system to the applied disturbance can be observed, which complements the analysis.

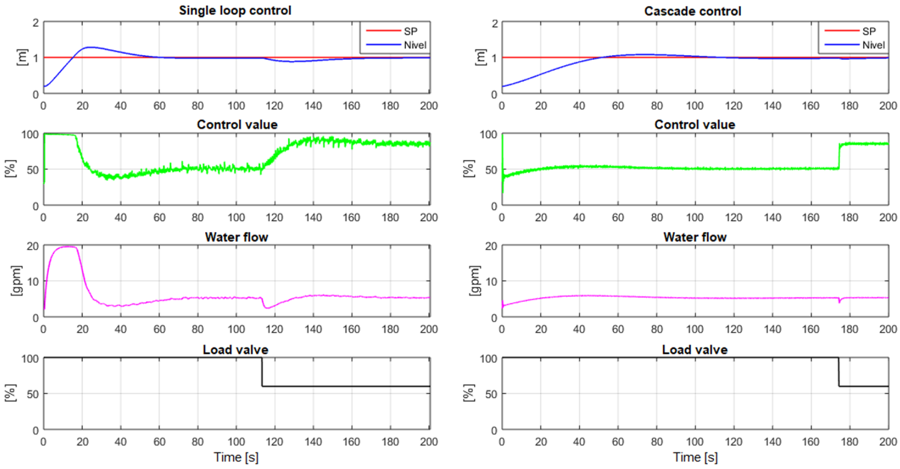

Fig. 16. Single loop control vs. Cascade control

From this test, performance parameters can be calculated that will allow choosing the ideal control algorithm for regulating the water level of the boiler drum. Table 2 shows the parameters that allow evaluating the performance of each control strategy, this values can be calculated through the previous graph or using a software to analize a data set.

Table 2. Performance parameters for each control strategy

Control strategy	Overshoot	Establishment time	IAE
Single loop control	30.61%	62.27 s	18.62
Cascade control	6.93%	102.1 s	24.56

As has been seen, the system allows the control algorithms to be tested to be widely evaluated since their performance can be observed in real time and it is also possible to export the data corresponding to the process variables for a detailed analysis.

5 Conclusion

The developed application allows to test controllers in a satisfactory way, through the simulation of the dynamic characteristics of a steam generation system using a boiler. This simulation, which uses the Hardware-In-The-Loop paradigm, use an interactive virtual environment as a graphical interface, which allows manipulating various elements of the plant to widely evaluate the performance of a control algorithm, as observed in previous sections. It should be noted that the system allows the testing of all types of controllers in a transparent way, without requiring additional programming thanks to the use of electrical signals, which also makes the system scalable and provides a starting point for a broader architecture.

The level of detail of the virtual environment, the simulation of the dynamics of the process in real time and the data acquisition method constitute an efficient system to carry out tests with controllers, since there are no significant delays in the exchange of data and the variables are presented in a clear way.

In addition, the virtual environment offers several applications for the system, such as teaching automatic control, training industrial plant operators, learning about industrial instrumentation, among others, in a much more optimal and complete way than with traditional educational methods.

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