

A virtual reality learning platform for steam generators

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Abstract. Virtual reality (VR) has proven to be an effective tool for industrial training, offering immersive and interactive learning experiences. However, it is important to accurately simulate the behavior of the equipment in order to provide realistic training activities to the users.

On these premises, the PITSTOP project aims at developing an immersive learning tool, based on the integration of dynamic models and a VR environment. Following this methodology, the first learning platform for industrial-scale steam generators was created. Adopting a mixed physics-based data-driven approach, a fast but accurate dynamic model was developed and calibrated on real data of the auxiliary steam generator of the gas turbine combined cycle plant of Tirreno Power in Vado Ligure, Italy.

Accessible through an Oculus Quest VR headset, the platform allows learners to interact with a virtual steam generator and adjust control parameters to observe the effects on the system. In this way, learners can gain a better understanding of steam generation principles and practice problem solving and decision-making skills in a safe, controlled environment. The platform also provides teaching materials and an evaluation mode such that learners can assess their knowledge and estimate the correctness of their actions. This article presents an overview of the VR learning platform, with a focus on the specific features of an industrial scale application. The capabilities of the tool are demonstrated through the recreation of real operational procedures of the Tirreno Power steam generator within the VR platform.

1 Introduction

The attention towards workplace safety has grown over time, resulting in more automated and remotely controlled processes to reduce worker interactions with dangerous equipment. However, some devices still require human intervention and operators must be properly trained for their operation. National laws often require specific licenses and mandatory

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training on the field, but standard training does not prepare trainees for emergencies or malfunctions, and inexperienced workers handling hazardous systems can lead to dangerous scenarios. Therefore, simulators have emerged as an innovative and interesting solution for the training of personnel in various fields, including workers of industrial plants [1] and crews of transportation systems [2]. The most recent advancements of virtual reality (VR) and augmented reality (AR) systems have greatly expanded the features a virtual simulator can offer, making it possible to provide an immersive and more effective learning experience [3]. Various studies have quantified the positive impact that VR has in terms of teaching effectiveness [4,5].

For example, Al-Adawi et al. [6] created a VR simulator to train workers on how to extinguish fires in electric cabinets, which could be accessed by wearing an HTC Vive headset. Pérez et al. [7] developed a VR environment in Unity 3D for the training of operators working with industrial robots. Similarly, in this case, the platform uses a VR headset.

Following these experiences, the PITSTOP project, supported by the Italian National Insurance Institute for Work safety – INAIL, aims to create an immersive VR simulation platform for training workers of hazardous equipment, integrating an immersive 3D VR environment with a real-time model. Focusing on the case study of steam generators, the authors have already developed and successfully tested the simulator of a small-scale boiler [8]. The system was designed both to train the user, providing learning material and instructions within the VR environment, and to test their knowledge of the plant. The adoption of reusable smart elements to define actuators and control devices made it possible to simplify the development of the training platform [9].

This article shows how the methodology proposed by the PITSTOP project can also be easily adopted for the simulation of more complex systems. Following the same workflow, the first VR simulator of an industrial-scale steam generator is created. The model is developed considering the case study of a 20 bar water-tube boiler and it is tested to recreate the operative procedures of the real system.

2 Steam Generator

The system considered for this study is an industrial-scale water-tube boiler installed in the gas turbine combined cycle (GTCC) power plant of Tirreno Power (Quiliano, SV, Italy). It is an auxiliary system, and its purpose is to provide steam to the plant during the startup and shut-down phases. It has an internal capacity of about 13.2 m³ and it can reach a maximum pressure of 20 bar. Its main components are upper and lower cylindrical bodies (CB), economizer, superheater and a burner fed by natural gas. It also includes two water pumps and a wide set of valves for its regulation, including some venting valves that can be used to limit its pressure. An illustration of these elements is present in Figure 1. Even if it is possible to interact with some of the components directly, the steam generator is mostly controlled and monitored through remote consoles.

Multiple control loops act on various actuators to guarantee the proper operation of the system. Through the digital control panel, the user can control a steam valve to modify the amount of steam to be provided to the GTCC. From the same panel, they can also switch between manual and automatic controls, and read various measurements of the most significant parameters. Regarding the automatic controllers, they are all based on a proportional-integral-derivative (PID) structure, and their logics are described hereafter:

- The fuel mass flow \dot{m}_f is regulated, acting on the fuel valve, to follow the steam pressure setpoint (which can be set by the user on the control panel).
- The air mass flow \dot{m}_a is regulated, acting on the air damper, to obtain an air/fuel ratio compliant with the emission requirements.

- The water mass flow \dot{m}_w is regulated, acting on the water valve, to maintain the level of liquid water inside the CB over an acceptable threshold.

The steam generator is also integrated with various emergency logics, designed to stop its operation in case of anomalous or dangerous situations. If one of the emergency logics is activated, the system can be restarted only after all its parameters are brought back to an acceptable condition and the user has pressed the “reset” button on the control panel.



Figure 1 – The water-tube boiler of the Tirreno Power combined cycle plant of Quiliano (SV), Italy; front view (on the left) and side view including the water pumps (on the right).

3 Simulation Model

3.1 Development

The model was developed in Matlab-Simulink, according to a real-time execution approach, keeping in mind its training and testing purposes. Therefore, it includes all the significant components the user can interact with (Figure 2), both manually and through the remote consoles, as well as the measurement displays and sensors that can be read within the VR simulator. To provide a seamless stream of data, the simulation time step is set equal to 1 s.

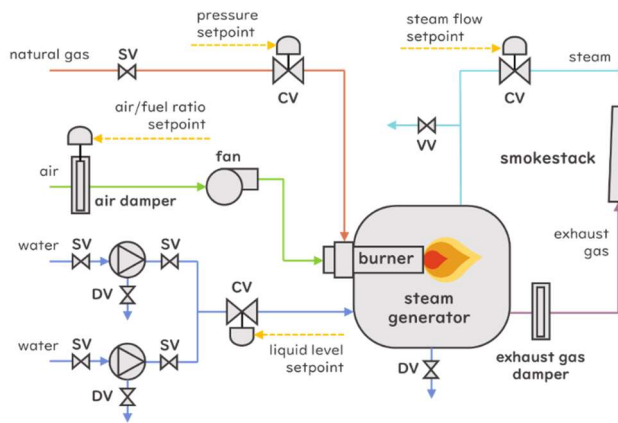


Figure 2 – Simplified layout considered for the dynamic model of the steam generator to be integrated within the VR simulator (SV = shut-off valve, DV = discharge valve, CV = controlled valve, VV = venting valve), including the setpoints of the various control logics.

The modeling process is based on the physics-based data-driven mixed approach proposed by Rossi et al. [10], already successfully adopted for the small-scale steam generator model of the PITSTOP project [8]. This approach provides physically accurate results and real-time simulation, which is a critical requirement for this application. Real data collected on the plant was analyzed to understand how variations of fuel, water, air, and steam mass flows affect the performance of the boiler. This information was used to create steady-state maps of the system. The maps were then embedded in Matlab-Simulink and combined with the numerical solution of mass and energy balance equations to guarantee physical consistency. To provide a realistic simulation of the steam generation, the model simulates economizer, evaporator and superheater separately, considering the heat transferred through each section. Thermophysical properties of water and steam are computed by the opensource tool Coolprop [11], which was integrated with the dynamic model. The molar composition of the fuel is assumed equal to 95% CH₄ - 5% N₂ to determine the heat released by its oxidation. The dynamics of the system are simulated by means of transfer functions, estimated on the basis of the real transient historical data of the plant. The Matlab-Simulink model simulates also the controllers described in Section 2, including the emergency ones. In this way, all the control logics are reproduced within the model, and the user can learn about their effect while being in the VR environment. Final validation with experimental data has been performed, mainly targeting the main trend reproduction, rather than the absolute values of parameters, in order to ensure realistic experiences by the trainees (Figure 3).

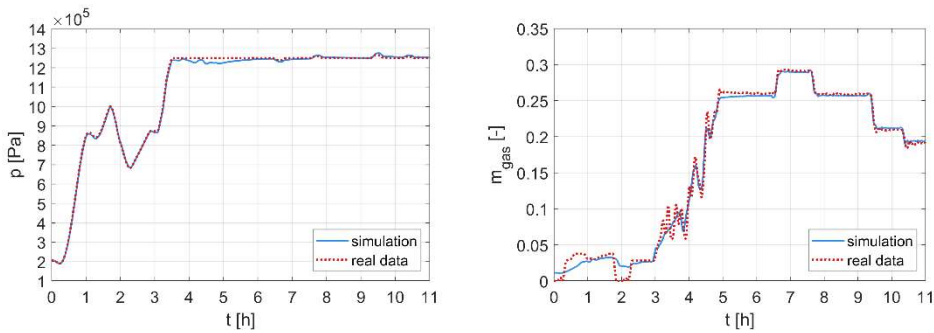


Figure 3 – Validation on real historical trends of steam pressure (left) and fuel mass flow (right).

3.2 Test

From the analysis of the technical procedures of the real plant, three significant training scenarios were identified:

- *purge* – starting from a turned off system, the user must reach an acceptable level of water inside the CB, reset the system, turn on the air fan and control the air damper opening, and finally start the purging procedure.
- *startup* – starting from a purged system, the user must activate the automatic air controller, ignite the pilot flame and gradually open the fuel valve until a pressure of 6 bar is reached, while avoiding excessive temperature gradients and maintaining the water level in an acceptable range.
- *normal* – starting from a system at 6 bar, the user must increase the opening of the fuel valve up to 40%, turn on the main burner, activate the automatic fuel controller and gradually increase the pressure setpoint, until a pressure of 13 bar is reached.

The model was successfully tested on the three scenarios, following all the operations required for the completion of each one of them. For sake of brevity, in this section only the results obtained testing the model on the startup and normal operation scenarios are presented (Figure 4 and Figure 5, respectively).

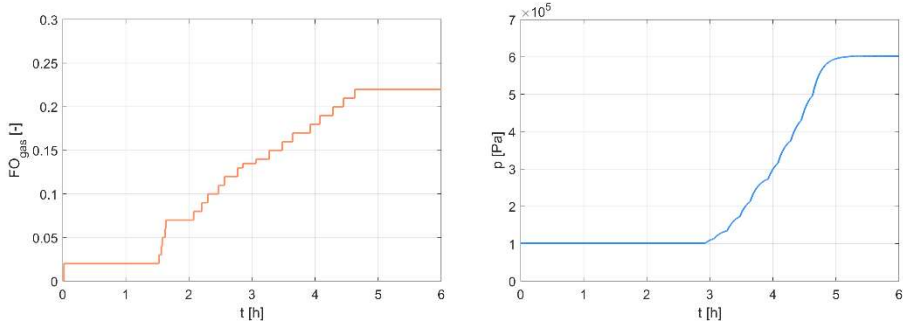


Figure 4 – Simulation of the startup scenario: fuel mass flow (left), pressure of the steam flow (right).

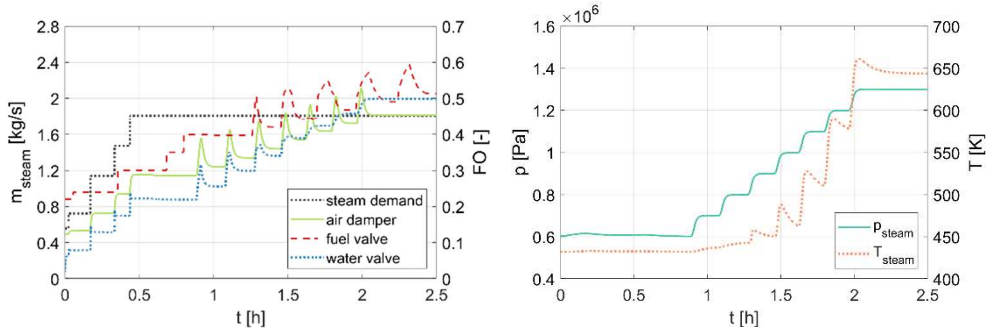


Figure 5 – Simulation of the normal operation scenario: steam demand, fractional openings of fuel valve, water valve and air damper (left), pressure and temperature of the steam flow (right).

In the first 0.5 h of this simulation, the steam demand is gradually increased, and the user manually opens the fuel valve to maintain an internal pressure of about 6 bars. Then, the pressure controller is switched to automatic mode, and the user varies the pressure setpoint multiple times, until 13 bars are reached. Therefore, the system regulates the fuel valve opening to obtain the desired pressure. Both the air damper and the water valve are automatically controlled to maintain the air/fuel ratio and the CB level on acceptable values. The steam is in saturated conditions for the first 1.2 h. Therefore, temperature variations are directly related to the saturation pressure. After 1.2 h, the gas flow is high enough to superheat the steam, and the temperature increases become more significant. This behavior is consistent with the expected physics of the plant and confirms the realism of this tool. The simulation was executed in about 30 s, demonstrating the real-time capabilities of the model.

4 VR Environment

To provide an engaging and realistic simulation of the on-job training, the 3D model of the steam generator and of the remote consoles was designed and then imported into the immersive virtual environment. The learner can interact with it by using bare hands commands as in the real environment. All the actuators, and control elements activating or

affected by the dynamic model parameters have been created as separate geometric entities to allow their colour/position modification in response to learner's actions. Thus, for example, valves can be rotated, buttons pressed, while alarm LEDs change their colour according to the values returned by the dynamic model. Figure 6 provides a view of the modelled steam generator and consoles. The user can physically move within the VR environment. However, due to the large dimensions of the generator and the need to operate on elements positioned at various floor levels, teleporting capabilities were implemented to reach the actuator elements independently of their position and of the real available game space. The teleport places are made visible to the learner through the black feet icons visible in Figure 6 and selectable by pointing at them with the right forefinger. Finally, a desktop has been equipped with a tablet where the user can look for different documents of the steam generator or teaching material.

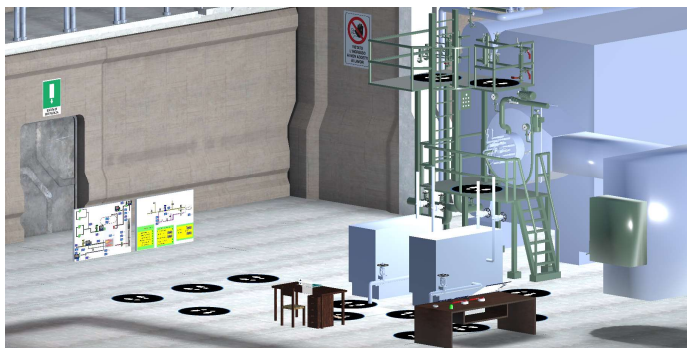


Figure 6 – The immersive 3D virtual environment.

The VR application provides two usage modes: *learning* and *verification*. In the first mode, the learner can have information about the task and the sequence of actions to accomplish it. The system provides real-time feedback in case of wrong actions by activating sound and visual alarms and highlighting the wrongly set actuators with regards to the requested sequence. In addition, the learner has access to training material in the form of documents and descriptions of the various equipment and console elements. In verification mode, the system provides feedback on the correctness of the performed tasks only when the learner considers the task completed. A counter of the wrongly and correctly accomplished tasks is generated for evaluation purposes.

Actuators and control elements are characterised by a *state* value, which changes based on the user's action and the dynamic model results, respectively. The communication between the VR environment in Unity 3D and the dynamic model in Matlab-Simulink is based on the exchange of statuses via User Datagram Protocol (UDP) over an IP network.

5 Conclusions

This article presents the first VR training platform of an industrial-scale steam generator. The results obtained testing the simulator showed that the integration of dynamic models and VR environments, already adopted for small scale systems within the PITSTOP project, is also suitable for more complex industrial plants. The model was designed to include all the main components the user can interact with, both directly on the plant and through a remote virtual control panel. The simulation also recreates all the standard and emergency control logics and makes it possible to switch between manual and automatic controllers, as well as to change the setpoints of the automatic logics. Thanks to these features, it was possible to

identify three relevant training scenarios (purge, startup, normal) that can be reproduced by the model. A simulation of normal operation was carried out and presented to assess the capabilities of the model.

In the future, the integration of the dynamic model with the VR environment will be completed. The model will use the action of the user in the VR environment as inputs of the simulation, providing direct feedback of the system response through the measuring equipment and the control panel. On the long term, the simulator could replace on-field training and evaluation of steam generator operators for the Italian scenario and be adapted according to other countries regulations.

Acknowledgments

The presented work has been partially supported by the project “PITSTOP: Piattaforma Immersiva per il Training STrutturato dell’OPeratore”, funded by INAIL, call BRIC 2019.

The authors would like to thank the personnel of Tirreno Power for their support.

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