

A Customizable Immersive Training System for Operators of Dangerous Equipment

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Immersive virtual reality systems allow simulating realistic situations in which the user can learn the use of dangerous machinery through structured paths and actively learn how to manage dangerous situations in total safety. The use of VR for training of industrial equipment while not new is not as widespread due to the cost of creating and adapting it to address various equipment and situations. To overcome this limitation, this paper proposes a VR simulator for training steam generator operators and verifiers focusing on the easy of customizing the VR system to suit new learning paths and different equipment while reducing the implementation efforts by ITC experts.

1. Introduction

Despite the increasing attention to safety aspects and the development and integration of automation and remote control processes, work environments that involve hazardous material or high-risk exposure maintain an intrinsic risk that can be reduced but not cancelled. Many accidents that occur in the workplace are caused by human errors due to poor knowledge or inadequate maintenance of the working tools and underestimation of the risks related to the activities performed. It is therefore essential that the worker has the necessary skills to minimize the possibility of error or malfunction of the equipment used. For this reason, current regulations require participation in specific training courses aimed at creating awareness and knowledge of the procedures to follow. Furthermore, for the management and maintenance of dangerous equipment, the possession of the relevant qualification is generally required. Often, this qualification also requires practical training in the field, the duration of which varies depending on the type of equipment. This on-the-job learning phase is inherently dangerous and is generally limited to carrying out activities in regular situations. Therefore, even if it is adequate to learn the procedures for the daily operation and periodic maintenance of the equipment; learning to deal with critical situations, emergencies, malfunctions, or with the consequences of incorrect operations is generally (and hopefully) limited to theory and lacks effective feedback in practice. Although the simulation of critical situations is particularly useful for guaranteeing the safe use of work equipment, it is however true that it is particularly complex to simulate critical or error situations in particular those which could be dangerous for the operator. However, thanks to the most recent technological advancements in the fields of virtual reality (VR) and real-time simulation, it is possible to overcome these limits. Combining the simulation of physical, chemical, and mechanical phenomena with an immersive VR systems, offers the possibility of reproducing situations in realistic environments that the user feels to be part of (Patle et al., 2019), (Pirola, 2021). Simulations offer the advantage of creating a "protected environment" in which it is possible to actively learn from mistakes (Nazir and Manca, 2015). In a virtual environment it is possible to simulate situations at different degrees of complexity, thus favouring the realization of a structured learning path, in which it is easy and immediate to access demonstrative, technical and regulatory material while carrying out operations. Based on these premises, training systems using immersive VR have been presented over the past years, addressing different applications in scientific literature and in commercial solutions. Among them, aeronautics and military sectors (Liu et al.,

2018) have been the pioneering ones, while engineering and medical applications are the most addressed (Vergara et al., 2017). In the manufacturing sector, Knoke and Thooben (2021) identify that the processes more addressed by VR training systems, either desktop, VR or augmented reality (AR), are assembling, cutting, welding, disassembling and liquid coating, motivating the choice with the more effective applicability. Many activities are devoted to address dangerous activities (Zhao and Lucas, 2015), (Nazir and Manca, 2015) (Nazir et al., 2013). In (Patle et al., 2019) various works addressing the training of operators in chemical plant and laboratories activities are presented, highlighting the need of realism for enhancing the training effectiveness. One of the main issues in the development of such training systems is the cost for the creation of alternative learning scenarios, which normally requires the simultaneous involvement of the training expert for its design, and the IT specialist for its realization in the VR environment (Rilling et al., 2010) (Fracaro et al., 2021). To reduce this effort, in this paper we propose a customizable immersive training system for certifiers and operators of boilers, which allows the training expert to directly specify the training scenarios using familiar tools. Moreover, the system is conceived to be easily adapted for the training and simulation on different devices. The simulation relies on a dynamic model of the equipment, composed of various modular elements. These elements are developed to simulate the functionality of the real devices, while accurately reproducing the effect of user interactions. The paper will briefly describe the main objectives and requirements of the PITSTOP project funding the presented research. Then, the main characteristics of the under-development solution are described (section 3). Finally, some concluding remarks and an outlook of future works will conclude the paper.

2. The PITSTOP project

Among the potentially dangerous equipment requiring a specific skill for their operation and verification, steam generators are subjected to dedicated regulations, which establish rules to be respected for their installation, working conditions, monitoring and verification. In addition, the current Italian regulations (DM, 2020) require the acquisition of a specific qualification, which is obtained attending specific training courses aimed at creating awareness and knowledge of the proper procedures to follow. Depending on the characteristics of the equipment, four levels of qualifications are defined, requiring increasing knowledge on the underlying functional and theoretical aspects. Moreover, for high capacity and thus potentially more dangerous generators, a practical training period on the field is mandatory, for a number of training days dependent on the producibility of steam supplied by the generator. Unfortunately, the availability of very high capacity boilers is limited, reducing the possibility for new operators to find a location for their training.

Due to the intrinsic risk of this kind of equipment, current regulations require also periodic verifications of their correct setup, working conditions and maintenance. These procedures are performed by specific authorized organizations, whose professionals learn the verification operations via theoretical studies of the latest regulations without trainings on the field.

To overcome the limitations mentioned above, the PITSTOP project (PITSTOP, 2021), funded by INAIL, the Italian Workers' Compensation Authority (INAIL, 2021), aims at developing an immersive virtual reality simulator for the acquisition of the skills necessary for the management and verification of boilers in a structured and, at the same time, safe way.

To follow a learning-by-doing approach and to satisfy the training needs for both the boiler operators and the professionals in charge of the periodical verification, the system must satisfy several requirements. In fact, it should achieve a high level of realism and provide many practice and learning activities. In particular, the system has:

- to provide tailored learning paths for the two considered professional profiles, characterized by different tasks to be performed;
- to provide coaching capabilities, supporting the understanding of the actions to be executed to meet the assigned targets;
- to present the learner several different scenarios, corresponding to standard working procedures as well as anomalous conditions, in particular those caused by incorrect settings of the system actuators. In this way, the learner can observe and understand the consequences of possible mistakes, and learn how to take the necessary countermeasures;
- to simulate the real behavior of the equipment in response to the user actions, thanks to realistic simulation tools capable of real-time dynamic execution;
- to allow natural interaction with the equipment, so that the learner can become acquainted with the gestures and operations to perform in real life;
- to support the verification of the trainee learning;
- to be easily adaptable for the training on different devices, considering the specific requirements necessary to acquire the corresponding certification.

3. The training system for steam boiler operators and verifiers

3.1 The system usage modes and learning paths

To guarantee both knowledge acquisition and verification functionalities, the simulator offers two different usage modalities: (i) learning and (ii) testing. In learning mode, the trainee is supported by the system while executing various tasks:

- getting contextualized information on the elements of the equipment in order to have a better comprehension and fast recognition of its main components and auxiliary elements;
- getting explanations on the causes of the encountered equipment anomalies and on the proper countermeasures to overcome them;
- accessing many documents, which can be used to recall the previously learnt concepts, for understanding and memorizing procedures to be respected and to visualize the actions to be performed. The documentation includes notes provided during the theoretical courses, relevant regulations and specific information of the generator used for the training (e.g. user manual);
- being guided during the task execution, allowing a better comprehension of the instructions contained in the boiler documentation and aiding their memorization.

When in learning mode, the system is somehow playing a role similar to the instructor during the on-site training, while allowing for reference documentation to be consulted directly in the immersive 3D virtual environment, avoiding the need to switch from VR to reality to seek advice in documents elsewhere available.

In testing mode, the learner:

- has to execute the task without suggestions, while having access only to the documentation of the specific equipment;
- can get feedback/corrections of their performance once he/she has completed the task.

To aid the learning process and to evaluate the learner performance, the system saves a list of the various actions done to fulfill the given tasks, together with the information of the number of trials necessary to correctly complete each action.

Whereas general concepts and information on the equipment are of interest of both professional profiles, their duties and the tasks they are expected to execute are different. Therefore, when using the system, it is necessary to specify the user profile, in addition to the specification of the usage modality (learning or testing). The list of meaningful tasks for each profile are shown in Table 1. For the verifier the four tasks are mandatory in the case of first periodic verification, that is when the equipment is subjected to the periodic verification for the first time after commissioning.

In the case of the operator, “activation” refers to the first time the equipment is switched on, while “switch on” refers to the restart of the equipment after a switch off. For the “switch on” and “solve problem” tasks, the equipment can be set up in many different configurations, i.e. its actuators can have different statuses. Dealing with initial configurations which can be either correct or not, the learner has to understand if the device is ready to be operated and, if not, how to fix the wrong configurations.

The task regarding verification of the environment is common to both professionals. For safety reasons, current regulations define constraints for the rooms where the equipment is located (UNI/TR11752). For instance, they impose the presence of specific signage in the work area, and require a suitable empty space around the devices that must be accessed by the operator. It is therefore extremely important that both specialists know the directives.

Table 1: Lists of the considered tasks for the two professional profiles

Learner profile	Verifier	Operator
Tasks	<ol style="list-style-type: none"> 1. Compilation of the technical sheet 2. Checks and tests of the equipment accessories 3. Environment check 4. Reporting 	<ol style="list-style-type: none"> 1. Environment check 2. Activation 3. Switch on 4. Solve problem 5. Switch off

The task “Solve problem” refers to many different equipment configurations. The ones here considered are mainly related to wrong setups of the system actuators: misplaced valves, wrong positions of buttons and switches, inadequate pressure settings. Based on the current configuration, the system simulates the behavior of the equipment, showing the consequences of the incorrect setup in VR. In learning mode, upon learner

request, the system communicates the type of problem and its cause, together with the sequence of actions to carry out to solve it.

To complete the training, the learner must complete all the required tasks in both learning and testing modes, until the equipment is properly configured. Anyhow, the effective requirements and modalities on the usage of the systems to guarantee the effectiveness of the training can be better specified by the persons in charge of the learning verification.

3.2 The simulator system components

To reproduce faithfully the behavior of a real boiler, the PITSTOP training system is composed of two simulation modules, shown in Figure 1:

1. a VR simulator that supports the 3D spatial and audio immersive experience of the learner;
2. a functional simulation module based on of a real-time dynamic model of the equipment, simulating its behavior in response to the learner actions on the equipment actuators.



Figure 1: the simulator organization

These two modules communicate with each other by exchanging information regarding the status of safety, control, or measurement components that are modelled both in the 3D environment and in the dynamic model. Actuators can be directly manipulated by the learner to alter the operation of the equipment; they can modify their position (e.g. turning a switch) and appearance (e.g. internal light turned on). Differently, the modification of control elements depends on the functional simulator and, in particular, on the control system embedded within. Also safety elements, e.g. safety valves, are activated by the functional simulator, but they can be also acted by the learner to verify their working conditions.

The first module has the objective to provide a sense of presence to the learner, who should be able to act on the equipment actuators as in real life. To meet this goal, big attention has been paid in the design of the user interaction modalities, avoiding the use of controllers and allowing natural gestures to interact on the actuators. Voice commands, in alternative to menu items available on user request, are also exploited with the provision of gaze tracking for the element selection for the information visualization.

The VR simulator has been developed on the top of the game engine Unity, using HTC Vive head mounted display for the immersive experience and Leap Motion controller for the gesture acquisition and detection. The choice has been made considering the best compromise between costs, detection capabilities and movement freedom for the user. The dynamic model of the functional simulator has been developed in Matlab-Simulink environment, following the physics-based data-driven mixed approach proposed in (Rossi et al., 2018), (Rossi et al., 2019). To ensure high fidelity, the model was calibrated and validated on real data collected on a real boiler, which will be presented in the next paragraph.

3.3 Use cases

To reproduce faithfully the behavior of the boiler and to simulate the actions to be performed in a realistic way the system has been developed as a sort of digital twin of a real steam generator installed in the laboratory of the project partner Università di Genova, at the Savona (Italy) campus. This boiler generates steam thanks to electrical resistances installed inside its main tank. It is a quite simple device, but it is well suited for a didactical experience, making it possible to test all its functionalities and to perform all the planned training activities. A more complex system is going to be modelled during the next phase of the project, using as reference a dismissed secondary boiler at the Tirreno Power plant in Vado Ligure (Italy). Figure 2 depicts the real boiler and its virtual counterpart used in the system current version.



Figure 2: The real steam boiler (<10bar) and the virtual twin exploited in the training system

3.4 Adaptability of the system

As previously mentioned, the current directives (DM, 2020) require an on-site training period for conducting a steam boiler of the potentiality corresponding to the target habilitation degree. This means that the system has to provide the simulation of at least a boiler for each degree level. This might be expensive in terms of man effort if all the information and actions are hardcoded within the program. In fact, the implementation of the previously described functionalities requires the involvement of various expertise, in particular, the in-depth knowledge of the equipment to correctly specify the actions to carry out, the engineering knowledge to specify the dynamic functional model, and the ability to program in the development environment of the VR platform to import this knowledge into the VR system. Therefore, it is important to devise modalities to reduce as much as possible the equipment-specific implementation. Even if the different degrees of accreditation for steam generators involve different types of equipment with increasing hazard levels, it can be noted that they are characterized by similar activities to perform and components to interact with (e.g. buttons, valves). Then, it is of utmost importance that the system is flexible enough to be easily adapted to different equipment and scenarios, requiring only the involvement of experts of the scenario itself, i.e. the equipment expert and engineers for the dynamic model specifications.

Here, the term scenario refers to the task the learner has to perform, the environment in which the equipment is working, the status of the equipment before and after the conclusion of the task, the correct sequence of operations to complete the task. When performing these tasks on a steam generator, each operation always results in the status change of one actuator, possibly depending on the status of control and safety elements. Therefore, both the initial and the final status can be expressed in terms of the actuators' status, whose possible values belong to a limited set. Examples of status are "closed" and "open" for a valve, "on" and "off" for a switch. Moreover, there is a limited number of types of these kinds of components (actuators, safety and control elements), each one with a predefined and predictable behavior. Their modelling allows the possibility of adapting the system when changing the equipment on which the learner has to be trained. Based on these assumptions, the developed system adopts an Object-Oriented organization and uses files for the specification of the scenarios and operations sequences in terms of the components' statuses. When a new boiler has to be included, its 3D models corresponding to the actuators, safety and control elements have to be annotated according to the corresponding type; thus some type-specific default attributes and characteristics are automatically associated. They include, for instance, the type of modifications (e.g. color change) allowed, the interaction foreseen (e.g. grasping, rotation), number of possible statuses, produced sound. When annotating the elements, the expert has to associate a unique name, that is then used to specify the actions to be performed to achieve a task. For each task, the domain expert has to specify the actuators to act on and in which order, and the status value to which they have to be set. For each actuator status change, it is also necessary to specify which actuators must necessarily have a specific value and what this value is. Moreover, the expert has to specify the expected statuses of the actuators when the task is correctly completed. The expected statuses are used by the system to check the correctness of the single actions and of the overall task. In case of mistakes, in the learning mode, the results of the check (wrong setting of actuators) are communicated at each action step, while in the testing mode they are communicated only once completed the task.

4. Conclusions and future work

This paper proposes a training system for the acquisition of the expertise necessary for conducting and verifying steam boilers, which represent a specific class of industrial pressurized vessel devices. The long-term objective

is the use of immersive VR simulators for acquiring the necessary knowledge in periodic verification and conducting activity, and thus shortening or even substituting the on-the-job training required for the conducting qualification degree acquisition.

The key characteristics of the presented training system are (i) the adoption of virtual “twins” of real boilers, by coupling the dynamic model for the functional simulation of the boiler with its 3D representation in the VR environment; (ii) a VR environment allowing natural free hand interaction with the virtual environment mimicking the operations in real world; (iii) the easy adaptation of the system to deal with different equipment avoiding the need of additional VR code through the adoption of the concept of actuators, control and safety elements’ classes allowing the re-use of the characterizing attributes and behavior, together with the use of external text files for the scenario and tasks specification.

To validate the approach, a more complex steam boiler is going to be included in the system. Currently the system has been tested internally to the project; more in-depth and structured testing sessions are being organized to verify the usability and the clarity of the communicated information.

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