ADVANCED OPERATOR TRAINING SIMULATION

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This manuscript is dedicated to the curiosity of Sauro on Operator Training Simulation, OTS, and specifically on the virtual reality and augmented reality environments that have excited his attention and interest in last months. Several times Sauro asked us to describe the features and concepts at the basis of an advanced approach to OTS. This paper tries to satisfy his interest and to describe our vision on future developments and improvements of such a fascinating topic.

1. INTRODUCTION

This paper presents and discusses an innovative training methodology targeted to the field operators of the chemical and processes industry. The key-point is improving and enhancing the operators' training in terms of process knowledge and plant understanding by means of a virtual experience of what may happen in case of either a process anomaly or an accident in order to make the field operators aware of the key parameters of the process and its dynamics in terms of characteristic times and response amplitudes. The iterative revision of specific events allows increasing the process understanding, while testing a number of occurrences that usually do not happen throughout the plant life and that, as a consequence, cannot be learnt on the job. The methodology is designed to be embedded into a final product that can be defined as an advanced Operator Training Simulator (OTS).

Human errors due to operational, judgment or job-related errors may account for as high as 3̃040% of industrial accidents, including those caused by inexperienced and unskilled workers (OECD, 2003; Spencer, 2000). Enhancing safety and health practices at work is vital for employees and companies across all industries and the operator training is ultimately important to support the implementation of minimum safety standards, and health and safety regulations. While automation and decision support systems can increase safety due to rapid diagnosis and response, these systems address only known and predictable abnormal events. Conversely, events that were not predictable need to be analyzed by the operators and may require a manual intervention. Therefore, full automation is neither realistic nor optimal from a safety perspective, and the presence of well informed and well-trained operators is indispensable.

In designing the safety systems, a great attention should be devoted to the dynamic simulation of both nominal and unforeseen conditions to assess a priori the flexibility of the process as well as to examine its behaviour in case of accident (*i.e.* in case of release of chemicals in the environment). Once the process layout and control system have been validated and tested for disturbance rejection, it is time to train the operators for conventional and unconventional process operations. For this purpose, in recent years a steadily increasing number of chemical facilities have installed OTSs. Section 2 describes the conventional OTS approach and the solution proposed in this paper to include the possibility to train operators to cope with chemical accidents, whilst Section 3 discusses the use of virtual and augmented reality.

2. ADVANCED OPERATOR TRAINING SIMULATORS

Respect to a dynamic simulator, which usually runs off-line for design purposes, an OTS is a software tool developed for the on-line simulation of chemical processes. It can be run in real time and it may be either sped up or slowed down to gather the complex nuances of process dynamics. An OTS may also comprise some pieces of hardware that recall the layout of the control room to increase the realism.

The driving force that moves the management to install an OTS is the lack of qualified manpower capable of facing the intrinsic problems of process control such as start-ups, shutdowns, transients, grade-changes, disturbance rejections, alarms). An OTS allows training the unskilled operators and deepening the process understanding by means of a dedicated simulator that resembles the process flow diagram, with the same labels of the field equipment. At the same time, an OTS is of paramount importance for skilled operators because it allows simulating unconventional operations and unexpected conditions that may happen rarely. A further advantage of OTS is that the trainee neither damages nor causes malfunctions to the real plant.

Conventional OTSs are focused on the learning of control room operators and rarely, if not ever, they implement any features for the field operators. However, when an accident occurs in an industrial site, the most challenged, exposed, and involved people are field operators.

To train both control room and field operators in case of chemical accidents occurring within the battery limits of an industrial site, one needs to couple two distinct dynamic software tools: a process simulator and an accident simulator. The former simulates the dynamic evolution of the process and is not able to describe what happens outside of a process unit once a chemical substance is released in the environment. Conversely, the latter receives some input data (*i.e.* information concerning the release) from the process simulator and models the accident outcomes (*e.g.*, gas dispersion). It also quantifies the effects of the accident on the surrounding equipment and operators. To close the connection, the process simulator receives as input data the quantities determined by the accident simulator (*e.g.*, thermal fluxes) and modifies the process variables according to the plant model. The data exchange between the process simulator and the accident simulator allows tracking the dynamic evolution of the process when an accident occurs, and quantifying the possible effects and damages on the structures, and equipment, as well as the injuries of field operators.

An example can clarify the importance of the data exchange between the simulators. Let us consider the case of a liquid outflow from a hole in a pipe with the formation of a pool on the ground (see for instance the case study in Brambilla and Manca, 2011). When a spark ignites the vapors evaporating from the pool, a pool-fire generates. The radiative flux impinging on the surrounding process units must be acknowledged by the process simulator to understand if the process (*i.e.* the equipment) can tolerate the consequent temperature and/or pressure increase. The toxic substance concentration that is inhaled and/or the radiation that is absorbed by a field operator allow also assessing his/her capability to endure and withstand a crisis while, for instance, operating on manual valves to cut off the outflow. By observing and understanding both qualitatively and quantitatively the accident consequences on the involved people and on the process dynamics, the control room and field operators can get a real advantage from the advanced OTS solution.

These bits of information increase the detail and fidelity of the simulation of malfunctions and accidents. The operators' understanding of the process under emergency conditions is also increased. Eventually, the dynamic simulation of industrial accidents allows updating and improving a posteriori the design of the plant, by identifying the most efficient start-up and shutdown procedures (either programmed or emergency), and by verifying the consistency of the mitigation systems.

As far as the software solution is concerned, the adopted process simulator is UNISIM® (Honeywell, 2009), a commercial program widely spread in the industry.

At present, there are no accident simulators that address the dynamic attribute for all the possible accident scenarios. Consequently, AXIM™ was developed (Brambilla and Manca, 2009a-b) in order to simulate both single and interlinked accident events such as liquid/gaseous outflows, spreading of pools, their evaporation and boiling, ignition and consequent pool-fire, and dispersion of gases (either dense or neutral). AXIM™ does not implement any CFD (Computational Fluid Dynamics) models due to the high computational time that would affect the performance of the advanced OTS. Respect to other accident simulators (available either on the market or freeware) AXIM™ is characterized by the dynamic attribute, where this term is referred to the capability of simulating releases that may change dynamically, without any previous advice or knowledge, according to the operating conditions and to the accident feedbacks. AXIM™ unifies and improves several models from a large number of sources, *e.g.*, Webber (1990) for the spreading and evaporation of liquid pools, Raj (2007) for pool fires; Scire and Strimaitis (2002) and Hankin and Britter (1999) for the dispersion of neutral and dense gases, respectively. Finally, AXIM™ exchanges input and output data with UNISIM® by means of a Visual Basic™ graphical user interface that exploits the "object linking and embedding" (OLE) automation paradigm. The OLE automation exposed by the objects of UNISIM® (*i.e.* the process units and the process streams) made the software linking rather straightforward. Actually, the properties and methods of the UNISIM® objects can be browsed by the object browser of Visual Basic™ and reduce the coding efforts while achieving rather effective and tangible results.

3. BETWEEN VIRTUAL AND AUGMENTED REALITY

A training program for field operator calls for an interactive software environment that should be the most realistic as possible in order to render the industrial site. Therefore, a possible effective solution is the implementation of a virtual reality (VR) environment where the operator (for instance wearing 3D goggles) can move through a 3D rendered site and gather the structure of the plant. The inclusion of the 3D VR in the advanced OTS solution is not mandatory even if recommended.

The 3D environment offers the realistic rendering of the surroundings so that the operator/trainee can feel the process units in terms of their layout, color, material, superficial aging, emitted noise, as well as daylight, nighttime, and meteorological conditions (see also Leva *et al.*, 2009; Shang *et al.*, 2009), *i.e.* all the aspects that may influence the operator behavior (Okapuu-von *et al.*, 1996; Pouliquen *et al.*, 2007). The effective preparation of the operator/trainee can be tested by asking him/her to walk through a virtual environment to check how a process unit is working, to switch on/off a keylock, to open or close a valve identified by a specific label. The resulting immersive experience is of paramount importance in increasing the operator's knowledge since s/he is not only involved in a theoretical study but also in an emotional multisensory experience.

The main objective of a VR simulator is the human formation centered on the experience and on recalling concepts, sensations, and visions already experienced somewhere else. The reduction of human errors, which are one of the most important causes of malfunctions and, possibly, of industrial accidents, is therefore the real objective of an advanced OTS based on VR, whose impact and efficiency on the field operators may be of orders of magnitude higher than a conventional OTS based only on the process flow diagram of the plant.

The link between the process and the accident simulators increases even more the wide range of information available and the amount of quantitative output data. The challenge is even higher respect to VR visualization since a lot of process and accident variables are referred to quantities that are either inside the equipment or not visible at all. This is the case of temperatures, pressures, levels, flowrates, but also of isorisk curves, radiative fluxes, concentration of toxic chemicals, inhaled doses, *i.e.* information that a field operator has not access to in the real world. Since what can be experienced in the real world is exceeded, the expression "augmented reality" (AR) describes the additional bits of information that a dedicated user interface provides to the field operators (as shown in Figure 1 and discussed in O'Shea *et al.*, 1999, and Stedmon and Stone, 2001).

Within this training framework, the operators can experience and understand the complex dynamics and features of an accident event, for instance by visualizing in false colors, within the 3D VR/AR environment, a toxic cloud dispersing through the plant according to the local wind field. This methodology allows assessing the operator knowledge about safety by taking into account the decisions, actions, movements, and protections adopted in case of accident. Indicators such as the absorbed/inhaled dose play a role similar to the stamina level (*i.e.* endurance) displayed in conventional video games. Moreover, the trainer can decide either to visualize or to remove the AR information from the 3D VR environment to test the preparation degree of the trainee.

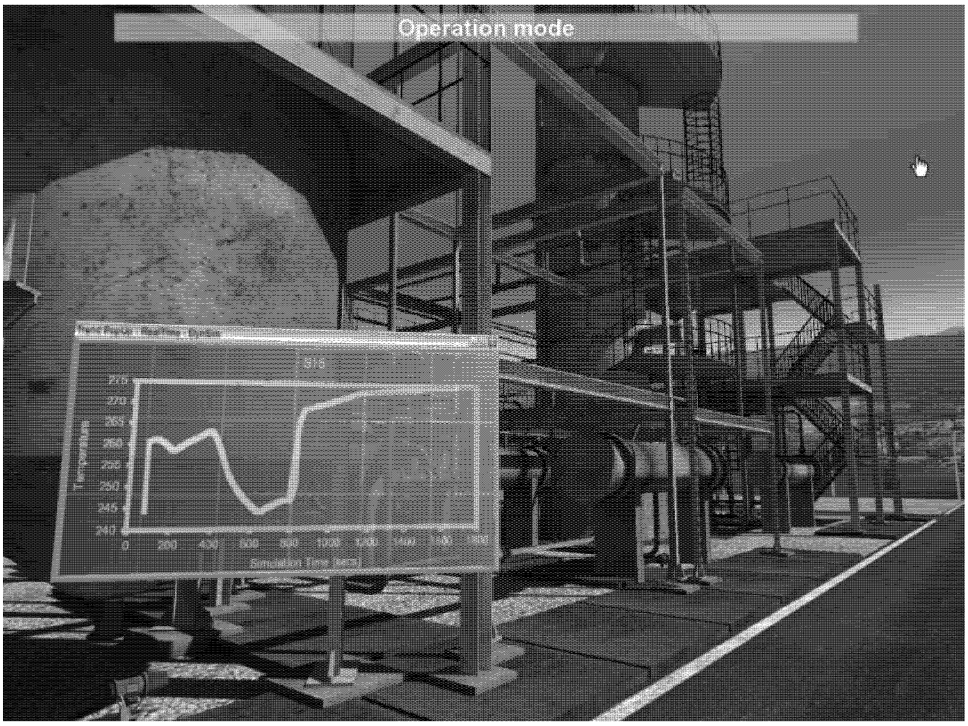

Figure 1. The operator can walk through the 3D environment where the AR feature can be of support to access a lot of data that is not visible in a real plant (e.g., the temperature profile in the bottom left diagram of the figure) (courtesy of the EC Virthualis project, www.virthualis.org)

In the AR framework, information about the plant conditions comes from the dynamic process simulator, whilst that concerning the accident and its consequences is determined by the dynamic accident simulator. It is therefore straightforward to understand the significant improvement in the training of operators due to the link between the process and the accident simulators that allows analyzing and quantifying the outcomes of an industrial accident. Actually, an accident event may be quite rare and cannot be reproduced in the real plant for training purposes. The availability of the aforementioned advanced OTS allows training both the control room and field operators to reduce and overcome the consequences of either a process malfunction or an accident event.

4. AN APPLIED EXAMPLE

Let us consider the example cited above, concerning the release of a liquid from a hole in a pipe, for instance of toluene at ambient conditions. Since toluene is a heavy component (normal boiling point 383.8 K), the liquid released from the hole spreads on the ground forming a pool, which evaporating vapors can be ignited generating a pool fire. The operating conditions of the surrounding process units change dynamically according to the changes of the flame radiation.

If the Distributed Control System (DCS) is able neither to detect automatically the liquid outflow from the pipe, nor to alarm the control room operator, s/he must detect the accident due to abnormal deviations from the nominal operating conditions and decide/select the proper emergency procedure. In this case, a possible countermeasure can consist in shutting down the pumps that transfer the toluene from one section to another of the plant in order to cut off the pipe outflow. In addition, field operators have to wear the protective devices to intervene on two valves in order to isolate the damaged pipeline. This operation may require a considerable amount of time (*i.e.* some minutes) to remove the locks and eventually close the valves (TNO, 1999). While

executing this task, the field operators must pay attention to the radiative heat flux emitted by the pool-fire to avoid any injuries, from blistering to more serious burns.
The role played by the dynamic process simulator consists of computing the variations of the operating conditions due to the toluene leakage from the hole and the heat radiation from the pool fire. Conversely, the accident simulator evaluates the source term (*i.e.* the flow rate from the hole) and the accident consequences (*i.e.* the radiative heat flux emitted by the burning pool and the fraction that arrives on the operators and on the equipment). The input/output data are exchanged dynamically between the simulators at each time step of the simulation through the Visual Basic™ interface that is responsible for the synchronization of the simulators.
In order to simulate the presence of an accident scenario, the UNISIM® flow sheet must be modified. In case of a hole in a pipe, a splitter can be added on the broken pipe to divide the main stream into two currents: the first corresponds to the flux in the pipe under normal conditions; the second is the leakage when the hole forms. To simulate the formation of the hole, a valve can be set on the leakage stream. This valve is initially closed, while it is opened when the accident occurs to account for the outflow. Accordingly, the flow rate in the pipe is reduced. The liquid outflow from the hole may vary dynamically due to either the perturbation of the process variables (*e.g.*, pipe pressure) or deliberate actions of the operators (*e.g.*, shut down of the pump on the feed line).
AXIM™ uses the leakage information (*e.g.*, flow rate, thermodynamic state) to evaluate the pool spreading dynamics in terms of diameter, temperature, height, and evaporation/burning velocity (Brambilla and Manca, 2009a). The characteristic quantities of the flame are the diameter, height, tilt, and the surface radiation. These data, together with the position of the operators and the equipment, allow evaluating the view factors and, then, the radiative fluxes, and radiative doses and thermal fluxes on both the equipment and field operators.
The consequences experienced by the field operators intervening on the accident scene depend on a number of factors. One approach consists in considering the heat flux from the fire. The literature (*e.g.*, EPA and NOAA, 2006) reports that a 60 s exposure to a radiative heat flux of 10 kW/m^2 is potentially lethal; a 5 kW/m^2 flux produces second degree burns; a 2 kW/m^2 flux causes pain. Consequently, depending on the thermal flux at the operator position, s/he either can or cannot close the valve safely. In should be considered that conventional clothing reduces the radiative heat flux incident on the skin by a factor of two, the skin reflects 20% of the incident energy, and only 60% of the energy penetrating the skin is effectively absorbed and eventually produces burns (Raj, 2008). This means that only 24% of the heat incident on the operator contributes to increase his/her skin temperature, so the aforementioned thresholds can be too conservative. Another approach consists in considering the cumulative effect instead of the thermal fluxes (TNO, 1989):

$$L = \int_0^{\overline{t}} I^{4/3} dt \qquad (1)$$

where L $\left[s\left(W/m^2\right)^{4/3} / 10^4 \right]$ is the thermal load, I $\left[kW/m^2\right]$ is the specific radiative heat, and $\overline{t}$ $[s]$ is the exposure time. According to Lees (2004), second-degree burns occur for a thermal load of 1200, third-degree burns for 2,600, unpiloted clothing ignition for 3,000, and lethality for 4,500 $s\left(W/m^2\right)^{4/3}/10^4$. The threshold for unpiloted clothing ignition is assumed to be 3,000 $s\left(W/m^2\right)^{4/3}/10^4$ even if wearing specific overalls may raise significantly this value up to 10,000 $s\left(W/m^2\right)^{4/3}/10^4$ (Lees, 2004), and therefore may reduce the probability of severe injuries. With this approach, even for radiative fluxes on the skin lower than 2 kW/m^2, the cumulative effect (*i.e.* thermal load) can produce serious injuries to the field operators.

5. CONCLUSIONS

At our knowledge, there are not any commercial OTSs capable of accounting for and quantifying the process dynamics in case of accident events. The paper discussed the necessity to couple an accident simulator to a conventional OTS to get the whole and quantitative picture in case of either malfunctions or industrial accidents.

An example discussed the effects of a liquid release from a hole in a pipe and the possible injuries suffered by the field operators who are called to work close to the fire. By observing the process response in terms of simulated dynamics, it is also possible to quantify the temperature and pressure increases of equipment situated near the fire epicenter. The modification of the operating conditions (produced by the radiative heat flux from the pool fire) influenced on its turn the liquid outflow from the hole in the pipe.
The interaction and the exchange of input/output data between the process and the accident simulators pointed out how an advanced OTS can be used effectively for hazard assessment, consequence analysis, and training of field (and control room) operators.

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