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Virtual Control Desks for Nuclear Power Plants

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1. Introduction

Nuclear power is a very important option that meets the global needs for power generation. But nuclear plants' operation involves high safety requirements, due to all the potential risks involved. Nuclear power plants (NPP) must be operated under safety conditions in all stages, since its start up, and during all the process. For this reason, control desks and rooms must be designed in such a way operators can take all the procedures safely, with a good overview of all variable indicators and easy access to actuator controls. Also, operators must see alarms indication in a way they can easily identify any abnormal conditions and bring the NPP back to normal operation. These matters have been taken into account through the years in NPP control desks and rooms design, through ergonomics or human factors evaluations, to help design safer NPP control systems (Hollnagel, 1985; Pikaar, 1990; ANSI ANS-3.5, 1993; Foley et al., 1998; Feher, 1999).

Operator training routines used to be carried out in full-scope simulators that resembled real control desks with high fidelity. Then, a new concept emerged, using control systems simulators based on synoptic windows interface, with NPP dynamics computer-based simulation system. These later usually include all the dynamics involved in a NPP operation. All variables are affected by operators' actions in the synoptic windows-based interface, with responses to their actions readily presented on screen. Although the high fidelity in the NPP dynamics simulations, synoptic windows-based interfaces does not resemble much real NPP control desks, since operators have to deal with graphical diagrams on computer screens.

Virtual reality technology help NPP operation simulation, since it enables virtual control desks (VCD) prototyping, thus adding to NPP dynamics computer simulation the design of control desks with high visual fidelity with real ones. Operators can now take advantage of both the online simulation capabilities of NPP dynamics computer-based simulation systems, with a more suitable interface such as VCDs, which resemble more closely the real

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ones. This approach have been under development and upgrading at *Instituto de Engenharia Nuclear* (IEN, Nuclear Engineering Institute) an R&D center of *Comissão Nacional de Energia Nuclear* (CNEN, Brazilian Commission of Nuclear Energy). This R&D enabled dynamic simulations and online operator interaction.
An existing NPP simulator, originally designed with a synoptic windows-based interface, was then interconnected with the developed VCD through network, either local or through the Internet, by using TCP/IP protocol. First tests were reported earlier (Aghina et al., 2008), showing the remote operation of the computer-based NPP dynamics simulator through the VCD.
Our staff has lately made improvements to this VCD, to turn its design an easier task, through the use of modules that can be added, deleted or modified. Besides this, new interaction modes have been included for an easier interfacing. There is a 3 × 2 m projection screen in one of our Labs, which can be used for the VCD simulation, among other ones. With friendlier interaction modes, users can interact with the VCD in front of this projection screen without using computer keyboard and mouse.
One of these new modes makes use of speech recognition-based commands. Also, an alternative interaction mode makes use of head tracking, with or without visual markers.
This Chapter spans many topics related to this R&D, ranging from the VCD development and the interfacing with the existing computer-based NPP dynamics simulator, to the new interactions modes. Thorough the chapter, related topics will be commented, such as the importance of ergonomic evaluations for safe NPP operation.

2. Nuclear power plant operation

NPP operation involves high safety requirements, due to the nature of this power source itself. Nuclear (fissile) materials must be dealt with very safely to achieve the desired objective, – that is, to generate power –, through the use of highly efficiency control systems. The nuclear fission reactions must be taken in very controlled conditions.
In NPP, fission takes place by inserting or removing control rods from the NPP core, where is the fissile material. The more operators remove the control rods from the core, the higher the operating power level.
In the following, a simplified description of pressurized water reactor (PWR) NPP is given, since this is a very common type of NPP currently in operation. PWR NPP resemble much thermoelectric power plants, in that water is heated by a power source, to move turbines associated with electric generators. The main difference is that nuclear fissile material is used as power source, instead of coal or gas.
A PWR NPP consists basically of three main parts, named: (i) primary, (ii) secondary, and (iii) tertiary. But one can consider also the electrical part, to suppy power to transmission lines. Fig. 1 illustrates a PWR NPP with its three main parts and the electrical part.
Primary includes the NPP core, that contains the fissile material and the control rods, and also the associated primary circuit, – indicated as “reactor vessel”, in Fig. 1 –, where water is heated through the nuclear fission reactions. There is a pressurizer, which keeps the pressure high enough to prevent water to vaporize above 100 degrees Celsius; this is the reason for the term “pressurized” in PWR. In the primary circuit, water – shown in red, in Fig. 1 –, may have nuclear contamination. Thus, the primary and secondary water circuits are completely isolated from each other, to prevent nuclear contamination among them.

Heat is transfered from the primary to the secondary by a heat exchanger, named steam generator, the interface between both isolated circuits. This water in the secondary circuit is not kept at high pressure, but vaporizes itself to move the turbines, that are also part of the secondary.

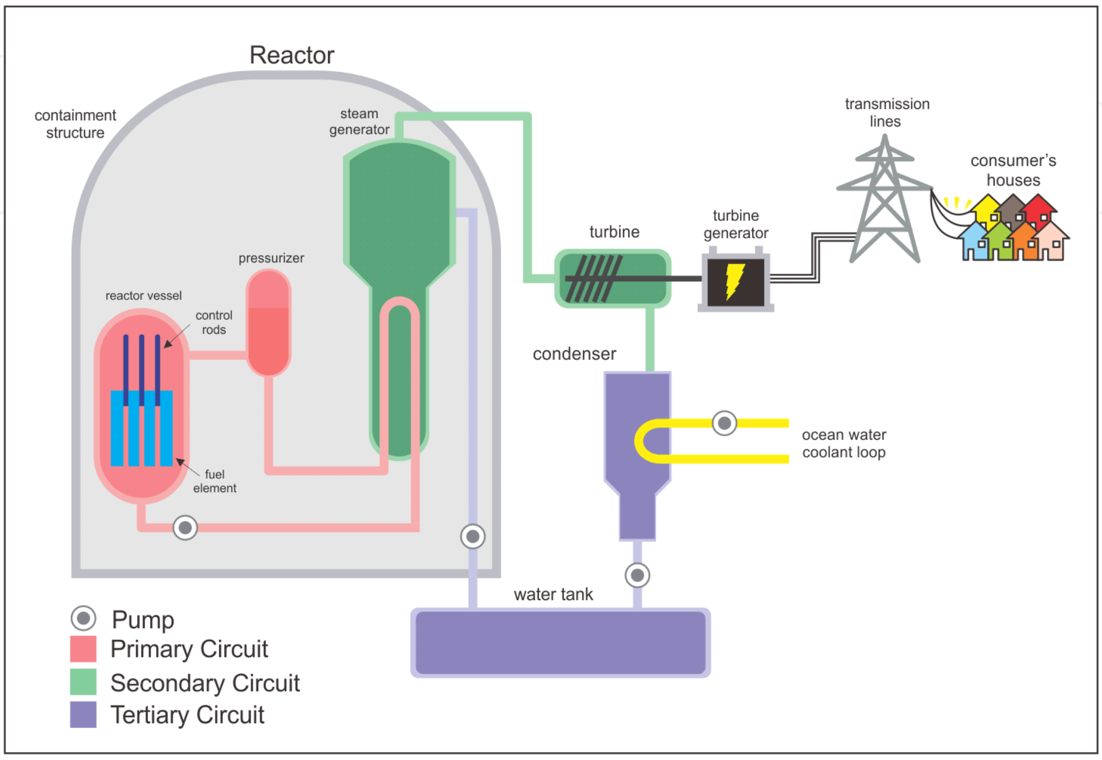


Fig. 1. PWR NPP simplified diagram[1].

As shown in Fig. 1, there is a containment structure for the nucler plant core, all the primary, and the steam generator. It consists, in the plants currently in use, of two containers, in fact, an inner container made of steel, resistant to high pressures and to corrosion, and an outer container made of concrete. This is an advancement in relation to older nuclear plants where only a concrete contaniment structure was used.

The vapour at the secondary, after moving the turbines, is condensed back to water at the condenser, a heat exchanger that is another isolated interface between the secondary and the tertiary. The water used for this purpose comes in some cases from a nearby sea or other natural water source, by pumps.

The electrical part after the NPP consists of the electrical generators coupled with the turbines axes, and all further devices and systems needed to supply power to the transmission lines, as transformers, power back-up and the frequency and phase synchronization controls.

All these parts, – primary, secondary, tertiary and the electrical part –, and related equipment, have their associated control subsystems, with all sensors, displays, actuator controls and alarm indicators. Operators are given specific tasks in NPP operation, and a supervisor must coordinate their actions. They all have to set operational conditions and monitor variables and any possible malfunctioning through the displays and alarms indicators. Once any abnormal conditions detected, they must identify fast and correctly

[1] This figure was made at IEN/CNEN with CAD software.

their cause, and mitigate their effects, bringing the NPP back to normal operational conditions. This is carried out through pre-defined procedures that must be followed during any incident or accident.
The following subsections give an overview on some topics related to this R&D, and on related R&D run by other groups.

2.1 Nuclear power plant simulators

Given the high safety requirements for NPP operation, operators must run very efficient training programs. These are usually carried out by using full-scope control desks and rooms, which resemble the real ones with high visual fidelity, with associated NPP computer-based simulation systems. The former requires the physical construction of control desks, similar to the real ones, what involves high costs and time. For this reason, only a few of such full-scope simulators are constructed, meaning operator trainees usually have to wait for some time to be trained, among other teams, besides to the need of travelling to the training site.
Fig. 2 shows, as an example, a reduced-scale full-scope simulator, in that the developed virtual control desk was based. The leftmost module is dedicated to neutron flux monitoring, control rods and general alarms. The central (and main) module is dedicated to the monitoring and control of nuclear plant's core, pressurizer, stem generator and turbines, among other tasks. The rightmost module is dedicated to the monitoring and control of the electrical power generation besides other general alarms.

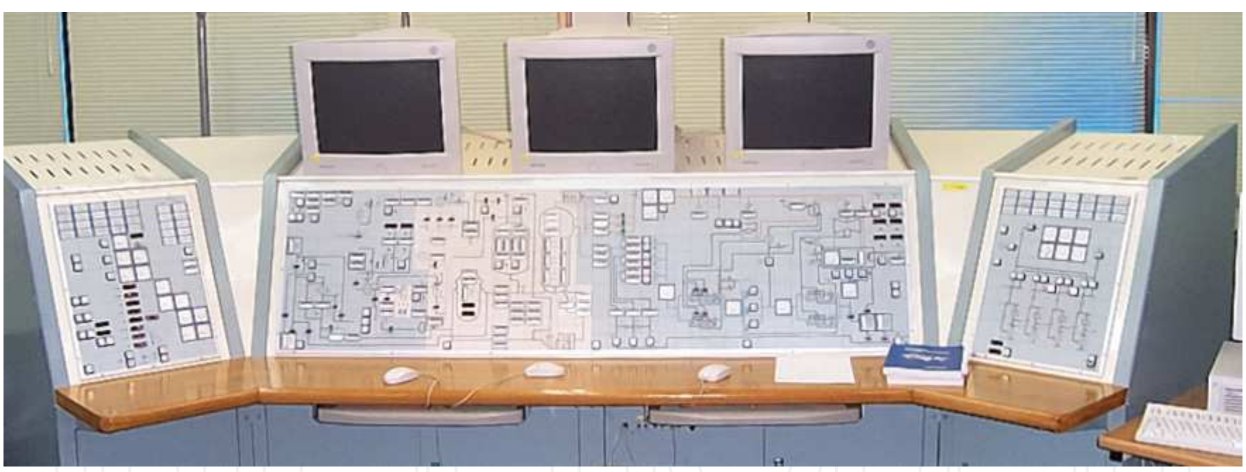


Fig. 2. Reduced-scale full-scope NPP simulator[2].

Computer-based simulators perform numerical simulation of a NPP dynamics, – in general, a simplified modelling of its dynamics, online (IAEA-TECDOC 995, 1998). This involves all the mathematical models related to neutronics, thermohydraulics, chemical, and other NPP dynamical subsystems. It deals also with all input and output variables, the former set by operators, and the later monitored by them.
Through the years, the use of physical full-scope simulators tended to be surpassed by the use of synoptic windows-based interfaces, where the NPP control desk is represented

[2] This photo was obtained by IEN/CNEN's staff during a visit to Korea Atomic Energy Research Institute.

through diagram views in computer screens. This approach is an upgrade relatively to the full-scope interfaces, but it lacks the visual fidelity with real control desks, since diagrams have quite different appearance, instead.

2.2 Virtual control desks and rooms

More recently, a new approach has come to use by some R&D groups, in which computer graphics and virtual reality technology are used to simulate control desks and rooms as visual interfaces (Drøivoldsmo and Louka, 2002; Nystad and Strand, 2006; Markidis and Rizwan-uddin, 2006; Hanes and Naser, 2006). This new approach thus combines both the NPP computer based simulator systems functionality with high visual fidelity with real control desks and rooms. These virtual interfaces become then virtual prototypes of real ones, for operator training or for ergonomics evaluation.

The fields of ergonomics and human factors have become very important topics in the design of control desks and rooms (Hollnagel, 1985; Pikaar, 1990; ANSI ANS-3.5, 1993; Foley et al., 1998; Feher, 1999). The relevance of these fields is independent of the end user application, either for nuclear plants, or for any other industrial plants, as chemical, petrochemical or industrial plants in general. The following explanation concentrates in the design of control desks, but it could be applied to control rooms too.

Ergonomics analyses enable the evaluation of the control desks' design, relatively to the location of displays, actuator controls and alarms indicators, for a safer operation. A design which does not consider these factors may turn operation a more difficult and unsafe task for personnel, due to possible misallocation of all the above mentioned devices in the control desks, so operators may not act properly in the case of incidents or accidents. A design that considers these factors takes into account the evaluation of operators' behaviour through many simulations, before a final decision about their location. Besides new control desks design, existing ones can be also evaluated and modified, to meet ergonomics requirements for safe NPP operation conditions.

3. IEN's nuclear power plant simulator

IEN's staff had been involved in a computer-based NPP simulator R&D, in a cooperation with the Korea Atomic Energy Research Institute (KAERI), and with the International Atomic Energy Agency (AIEA). This cooperation resulted in a new laboratory at IEN in 2003, named *Laboratório de Interfaces Homem-Sistema* (LABIHS, Human-Systems Interface Laboratory), (Carvalho and Obadia, 2002; Santos et al., 2008). This simulator comprises a computer-based PWR NPP dynamics simulation system, with synoptic windows-based interface, and is used mainly for operator training and ergonomics evaluation.

Fig. 3 shows a view of the LABIHS simulator room, while Fig. 4 shows its layout. There is a projection screen with a window showing an overview of the whole system. One can see two operators, – the primary (or reactor) operator and the secondary (or turbine) operator –, near these projection screens and a supervisor in the back part of the room. There is also an instructor, not shown in this figure, who stands at "Simulator Set-up Controls", shown in Fig. 4, that starts operation and may insert malfunctions into the system, which operators do not know in advance. One can also notice the use of multiple computer screens in front of operators, to minimise the need of switching among different views.

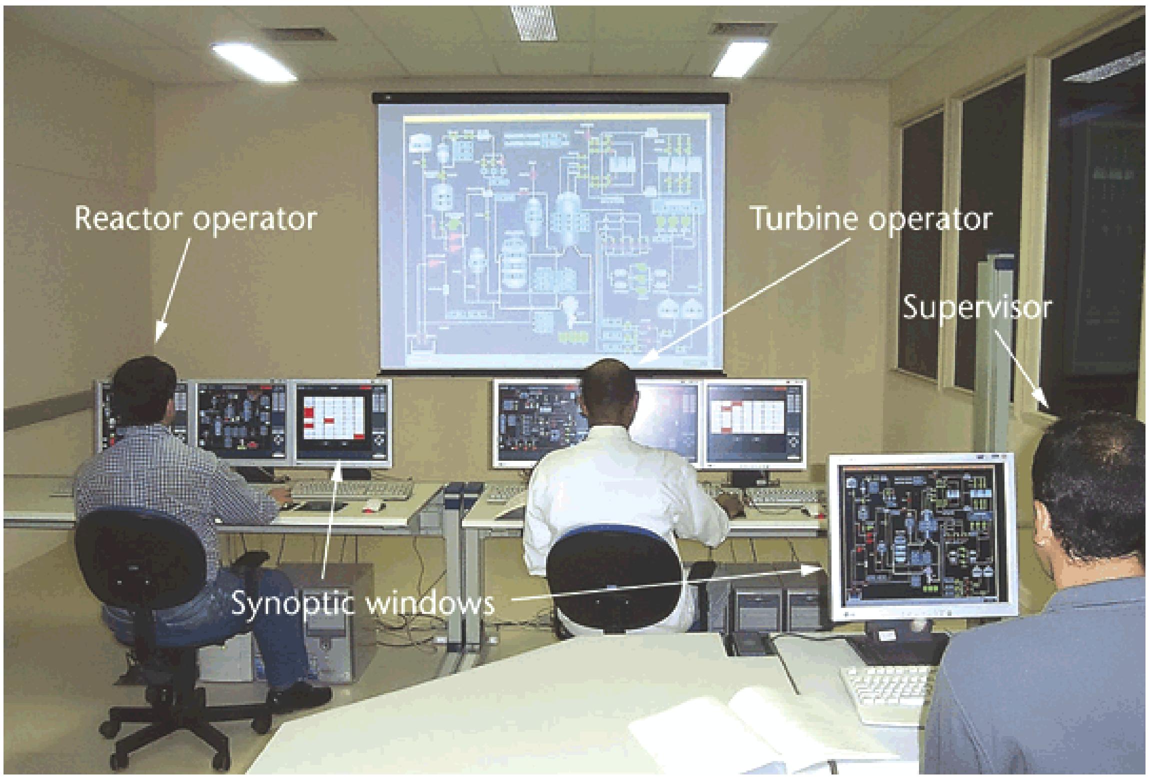


Fig. 3. LABIHS simulator room's view.

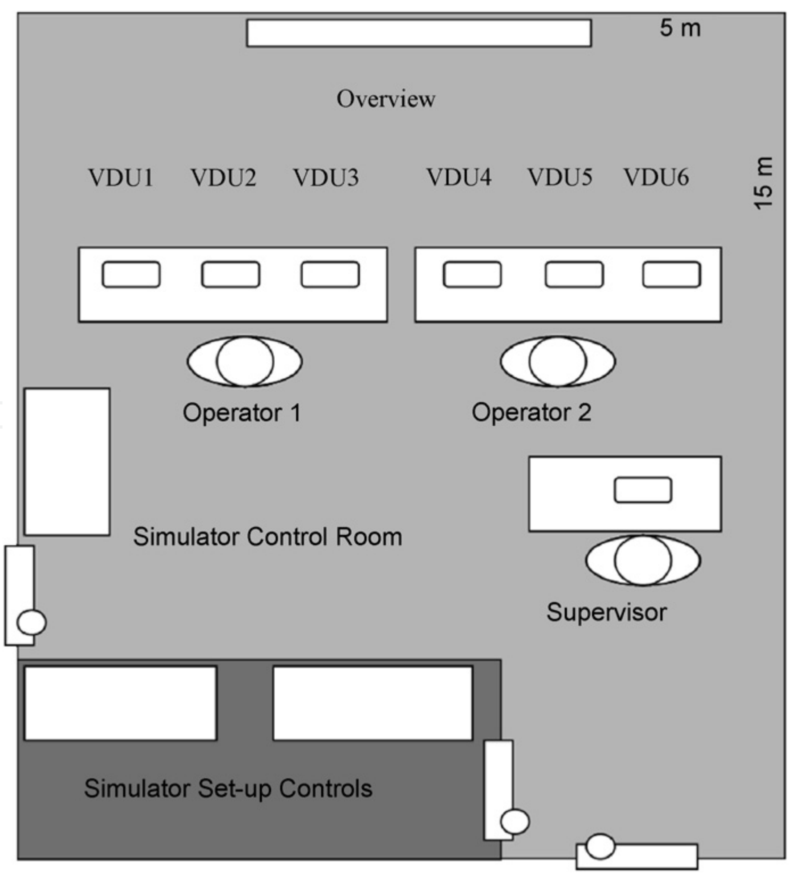


Fig. 4. LABIHS simulator room's layout.

3.1 Synoptic windows

Synoptic windows, as already briefly explained in section 2.1, mean the NPP control desk is represented through many diagram views on computer screens. This approach consists, from a point of view, in an upgrade relatively to the full-scope interfaces, which consisted of physical control desks construction. But, from another point of view, this approach lacks the visual fidelity with real control desks, since diagrams are used instead. Operator trainees have to switch among many windows, to see different parts of the NPP, to monitor variable indicators and also alarms. Multiple computer screens reduce this effort, – as can be noticed in Fig. 3 –, but even so this can be a confusing task, besides the poor appearance, far from that of a real control desk (Carvalho et al., 2008).
Some R&D have been carried out to improve these synoptic windows, following recommendations from ergonomic evaluations performed by IEN’s staff, which are detailed in the references (Carvalho et al., 2008; Santos et al., 2008; Oliveira et al., 2007).
Fig. 5 shows a close view of an original synoptic window in a computer screen.

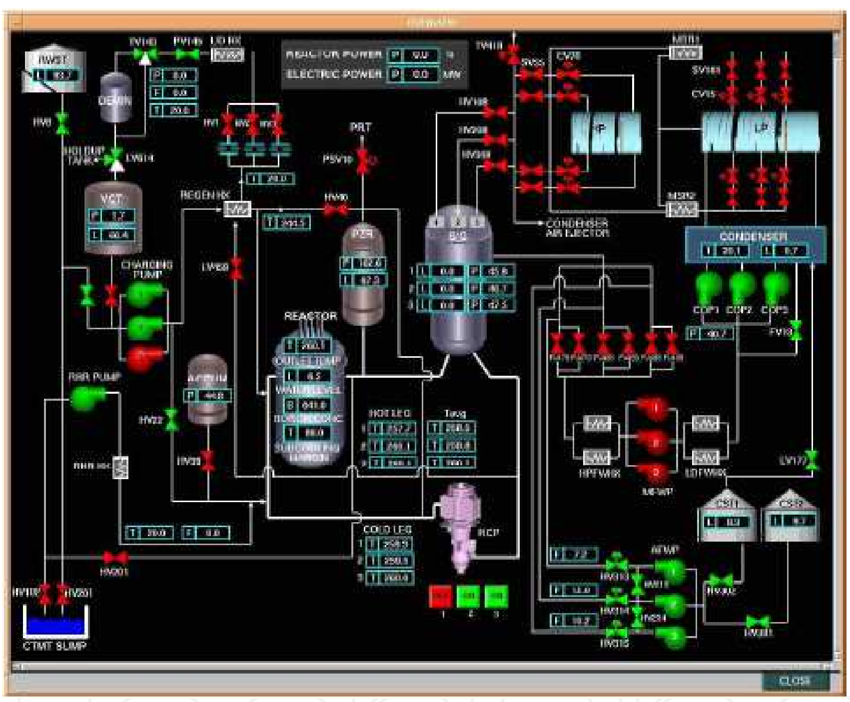


Fig. 5. Example synoptic window.

3.2 Networking

The LABIHS simulator networking can be represented in the following form (Carvalho et al., 2008). There is an interface between the simulator code and the synoptic windows, the shared memory. The later keeps updated values of all input and output variables that can be accessed by both sides, from the simulator side, or from the synoptic windows one.
Variables values, as temperature, pressure, flows, among others, are updated periodically as simulation runs, and feed the synoptic windows to inform personnel about operation conditions. Also, they can modify some other variables through actuator controls, such as “close valve A”, “open valve B”, “remove rods”, “insert rods”, and so on. These actions are readily input to the simulator code, that in turn updates simulation computation based on these new instructions.

All the tasks are performed in a local network, in which there is a central computer, operated by the instructor and where the simulator also runs, and other terminals operated by the trainees. Fig. 6 illustrates the networking scheme used, showing the shared memory rule.

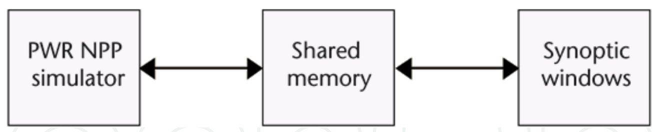


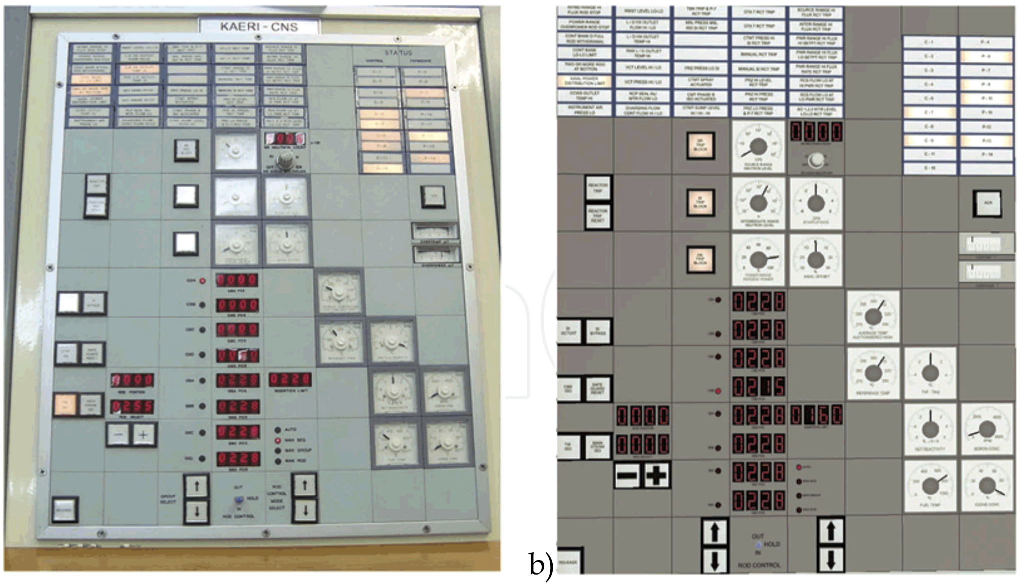
Fig. 6. The networking scheme used at LABIHS simulator.

4. IEN's virtual control desk

4.1 Visual interface

Due to the interactive nature of this R&D, the VCD makes use of programming, with the OpenGL graphics library, what enabled online operation training and dynamical ergonomics evaluation. The VCD developed was based on the reduced-scale full-scope physical control desk shown in Fig. 2 (Aghina, 2009).
OpenGL is a free, public domain, and high performance 3D graphics function library written for C/C++ languages. It is dealt with directly by graphics card, setting the computer processor free of tasks. It can be defined as interfacing software for graphics hardware. There is also an auxiliary library, OpenGL Utility Toolkit (GLUT), for user interaction tasks through interface devices such as computer keyboards, mouses, among others.
The VCD consists of more than five hundred graphic components, belonging to seven classes, as plane displays, cylindrical displays, buttons, switches, among others. The VCD panel is mapped in discrete Cartesian coordinates, for component location. As inserting text boxes in OpenGL is not so easy a task, textures are used instead, by pasting images from the real control desk, for the front panel's background and for the displays and buttons, for a more realistic appearance. Fig. 7 shows an overall view of the VCD; compare it with Fig. 2. Fig. 8a and 8b show a comparison of partial views of the real and the corresponding virtual versions. This partial view corresponds to the leftmost module shown in Fig. 7. Fig. 9 shows a close perspective view of the VCD, showing the realistic impression one can have by interacting with it.

Fig. 7. Overall view of the VCD.



a) b)

Fig. 8. a) Partial view of the real control desk; b) The corresponding virtual model.

Fig. 9. A perspective view of the VCD.

4.2 Networking

The VCD now substitutes the former synoptic windows-based interface, and thus must communicate with the shared memory, for both reading variable values and feeding the simulator with input operator commands (Aghina, 2009; Aghina et al., 2008). This was done through networking, using TCP/IP protocol. Therefore, the VCD is able to communicate with the simulator not only through local networks but also remotely, through the Internet. Fig. 10 illustrates the new networking scheme adopted. Comparing it with Fig. 6, one can see the VCD along with the TCP/IP socket now play the role formerly played by the synoptic windows-based interface.

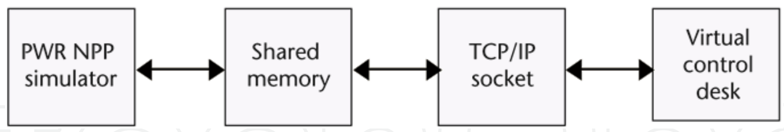


Fig. 10. The networking scheme used at LABIHS simulator.

TCP/IP protocol was chosen because it suited very well in the communication needs for this R&D. It enables friendly bi-directional data transmission between two computers, besides the versatility to be used locally or remotely through a global medium such as Internet. This is very attractive for training, as it avoids unnecessary trainees travelling to the training site where the simulator is installed, since the VCD is portable and can be used in the end-user site.

4.3 Interaction modes

In a first moment, interaction was carried out through usual interaction modes as computer keyboard and mouse. But soon our staff planned to develop other friendlier interfaces through other mode such as voice, to set user free from keyboard and mouse, and turn user interaction with the VCD a more natural task. In IEN's Labs there is a 3 × 2 m projection screen, where user can visualise different applications in an environment that enables immersion, in some sense. It would be very desirable if users could be stood up in front of this projection screen, interacting directly with the VCD, free from wired interfaces such as the ones cited before.

First, an automatic speech recognition (ASR) system was developed and implemented (Jorge et al., 2010). Lately, other interaction modes were implemented, based on head tracking, with and without visual markers. Also, a head-up display was also tested as an alternative form of visualisation, besides the projection screen or simply desktop computer screens.

All interaction modes in use are explained in the following sections.

4.3.1 Automatic speech recognition

An ASR system was developed based on well-known signal processing techniques, as cepstral analysis (Furui, 1981; Oppenheim and Schafer, 1989) of the spatio-temporal speech signals, and neural networks (NN), (Haykin, 1999; Cichocki and Unbehauen, 1993), for the pattern recognition stage. The good system's performance has been demonstrated by tests, and was published elsewhere (Jorge et al., 2010). It was first implemented offline, thus partially online by using OpenAL library and also OpenGL, for integration with the VCD. But then, it was implemented as a self-contained system, for full online operation. Other purpose was to perform direct interaction with the operating system (OS), independent of the application, so it could be used for any other application in our Labs, besides the VCD. This was achieved by using MS Windows Application Programming Interface (API). The computer thus receives the spoken command inputs as they were keyboards' or mouse's ones.

Tests were performed, showing also good performance of the system for changing views of the VCD through spoken commands, as moving it for left, right, up or down, or zooming it in or out, as examples of possible commands.

4.3.2 Head tracking

Head tracking was implemented through two approaches, with and without visual markers, as described next. But, independently of using or not markers, the main purpose of head tracking is to turn interaction a much more natural task, because an user can turn his or her head towards the specific scene location he or she needs to see with more detail.

Considering the current R&D, some examples might be: (i) one might need to look towards the leftmost VCD module (see Fig. 7) to see an alarm or any other indication; he or she needs simply to move head to the left, and the image on the projection or computer screen turns to that side. (ii) one might need to look in more details a variable indication in a specific display; he or she needs simply to approach head towards the screen (projection screen or computer screen), and the projected image zooms in. Other examples might easily be thought of, for moving to the left, up or down, or for zooming out.

These tasks can be also executed by spoken commands, as former tests that we performed. Of course spoken commands is a more natural interaction mode than using keyboard or mouse. But head movement seems a more natural interaction mode than that supplied by the developed ASR system, so our staff moved towards this type of interaction too. In fact, each interaction mode has its own advantages and disadvantages, as will be discussed later.

4.3.2.1 Head tracking with markers

After the acquisition of a head-mounted head-up display, it soon became an alternative for visualisation, besides the projection screen and desktop computer screen. Coupling of visual markers in this head-mounted display readily enabled the use of an available computer code for head pose estimation, with the use of an infrared sensor, – Natural Point's Trackir5 –, attached to a fixed location in front of user.

The tracking system with markers does not need to be used with the head-up display, as the markers can be fixed in user's head by other means. But the head-up display can not be used with the face tracking system without markers, as will be explained in the following section.

This tracking system makes use of three reflective markers filed at user's head (in the head-mounted display or by other means). The pose is estimated based on their positioning, through projective geometry computation, by a freeware library, supplied by the same company, – Natural Point. This library is OptiTrack, and performs tracking with six degrees of freedom.

This approach has a strong advantage related to accuracy in head pose estimation, due to the precise markers position detection by the fixed infrared sensor. The disadvantage, if one could mention it, is the need to use the markers at one's head.

4.3.2.2 Head tracking without markers

Another approach is the use of a code for head pose estimation based on tracking some points detected in user's face. This code is a proprietary library named FaceAPI, by Seeing Machines. The source code is not available, and the company does not supply any details about the tracking methodology used. Thus, it has been used as an executable called by our application. It also performs tracking with six degrees of freedom, and operates with either webcams or infrared cameras, as described in section 4.3.2.1.

After some tests, evaluation showed it did not offer good accuracy when user turns his or her head to the sides; at twenty degrees to both sides, the estimation of head angle, – its pose –, sometimes oscillates, making the VCD image on screen to shake for both sides. The

advantage is that there is no need to use any markers at one's head, turning interaction more natural.
This system can not be used with head mounted display, because it comes trained to detect faces, and thus any other device in one's head makes face undetectable by the code.

4.3.3 Combining the interaction modes

After many tests with the interaction modes explained above, our staff has noticed each one had its own advantages and disadvantages, and thus could be combined, each one used for those tasks where it performs better. It results, therefore, in a more complete and friendlier interfacing. More specifically, the combination is performed between the ASR and head tracking (with or without markers), not between both head tracking approaches.
The ASR system performs very well when one needs to switch quickly among different VCD views, as for example, switching from an overall view, as shown in Fig. 7, to a partial view, as shown in Fig. 8a, or to return to a previous view. One has to speak simple commands such as "left module" (or simply "left"), "up", "down", or "back", to return to a previous view.
Once switched to the desired view, through the ASR system, the head tracking system enables the user to see details in that view, by simply moving head a just bit for each side, up or down, to direct sight to a specific part of interest. User can also zoom the view in or out by approaching or apparting his or her head just a bit from the VCD image.
Using head tracking to switch among different views can be not so easy and natural a task, because one would have to move not a bit, but a lot, his or her head for both sides, up, down, approaching or apparting from screen.
From another point of view, using speech to move a bit for any position within a VCD module's view would also be not so easy a task, as user would have to speak many times for little movements.
Thus, combining ASR and head tracking results in a more natural interaction for users than using each of the modes alone. Table 1 summarises this combination.

		Task	
		Switching views	Seeing details
Interaction mode	ASR	Applies	–
	Head tracking	–	Applies

Table 1. Interaction modes choice according to the desired task.

4.3.4 The head-up display

Tests also indicated the advantages and disadvantages of using the head-up display. It is good to remind that using head markers does not mean necessarily using also head-up display. The disadvantage, if one could mention it, is the need to use such a device in his or her head.
But there is a strong advantage. When one uses head tracking (with or without visual markers), he or she must turn his or her head to the sides, or up, down, as examples, to direct sight towards a specific VCD module. But then, he or she must keep head in that position to keep looking at that module. This cause discomfort because he or she must direct only his or her eyes towards the desired detail, keeping the head turned to the sides, or up

or down. Eyes become directed towards the opposite head position, say, head turned to the left, and eyes turned to the right side.
By using the head-up display, when turning head to the desired position, that module's view is projected in the glasses in front of his or her eyes in a frontal angle, so anyone needs to direct eyes to the opposite head position. Thus, this is an important factor to be considered, if one has to keep interacting with the VCD for a long term.

5. Concluding remarks and perspectives

The developed VCD proved to be a very good alternative relatively to the synoptic windows-based approach, by aggregating both the high fidelity visual appearance with the corresponding real control desk, to the computer-based PWR NPP simulation system's functionality.
Relatively to the interaction modes, after developing and testing only the ASR system, in a first moment, and then the head tracking approaches, it suddenly turned out to be that a combination of ASR with head tracking would result in a more natural users' interaction with the VCD. Each interaction mode is used for the tasks it fits best, with ASR performing better for switching among different VCD views, or what one could call macro movements; head tracking performing better for small movements within a particular VCD module or region, or what one could call micro movements.
Another conclusion was related to users' better comfort when using the head tracking approach with head-up displays, in relation to projection screen or computer screens. But the head-up display can only be used with the visual marker approach.
The matters related to the markerless head tracking closed algorithm could be surpassed in the future, by using another methodology available in the literature.

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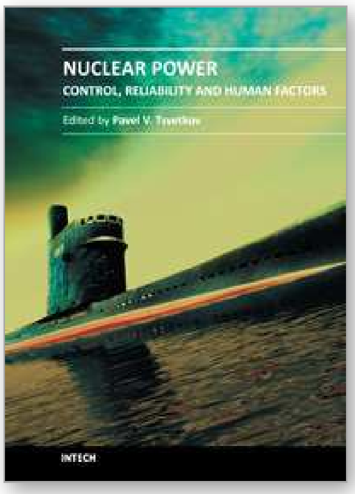

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Advances in reactor designs, materials and human-machine interfaces guarantee safety and reliability of emerging reactor technologies, eliminating possibilities for high-consequence human errors as those which have occurred in the past. New instrumentation and control technologies based in digital systems, novel sensors and measurement approaches facilitate safety, reliability and economic competitiveness of nuclear power options. Autonomous operation scenarios are becoming increasingly popular to consider for small modular systems. This book belongs to a series of books on nuclear power published by InTech. It consists of four major sections and contains twenty-one chapters on topics from key subject areas pertinent to instrumentation and control, operation reliability, system aging and human-machine interfaces. The book targets a broad potential readership group - students, researchers and specialists in the field - who are interested in learning about nuclear power.