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Virtual Reality Used in the Ergonomic Evaluation of the Control Rooms of Nuclear Plants

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Abstract

The control room of a nuclear power plant (NPP) is a complex system that controls a nuclear and thermodynamic process used to produce electric power. The operators interact with the systems using graphic interfaces and panels that have implications to the safety of nuclear plant and influence in the operator activity. The ergonomic analysis considers the operation strategies, the operator's interaction, the system-operator interaction and the support groups and operator's interaction. The aim of this article is to describe how game engines can be used to model a NPP control rooms for ergonomic evaluation. The evaluation results provide information and data used to verify whether the control room complies with the legal requirements from the regulatory authority, aiding the nuclear licensing process.

Keywords: Ergonomics; human factors; control room; nuclear power plant; virtual reality.

1 Introduction

The control room contains the systems and the necessary instructions to control an industrial plant, to ensure its reliable operation and safe shutdown in normal situations and in accidents (ISO 11064, 2002).The control rooms of nuclear reactors are constituted of systems that controls nuclear fission process and thermodynamic processes used in the electric power production. Operators who are trained to monitor and control the plant systems use the main control room to operate the plant. The operators` interaction with the control room happens through interfaces and various monitoring stations. The interfaces must be arranged to assist operators in their handling, for both routine operations and for accident conditions. Control room operations are based in procedures used for starting and stopping the nuclear reactor, to handle emergency situations, to deal with alarm systems, communication systems, control systems, safety systems and to verify failures diagnosis. The control room systems were computerized with a considerable redundancy and interconnectivity and the high degree of reliability.

According to International Ergonomics Association IEA (2000), the ergonomics can be defined as the adaptation of work to man or, more precisely, as the application of scientific knowledge develop tools, machines and devices that can be used by people with maximum comfort, safety and efficacy. For Santos and Vidal (2003), the ergonomics uses the activity analysis of the operators to deal with the complexity of operators' work decomposing this activity into measurable and observable aspects such as posture, visual exploration, communication, and identification of parallel activities, which are not formulated within the framework prescribed in tasks and procedures. Santos e Vidal (2000b) proposed a broader approach, emphasizing the need for the incorporation of ergonomics and human factors in the life cycle of the control rooms of nuclear reactors. Santos (2003) suggests the use of the proposed methodology for evaluation of control rooms with more advanced technologies.

Considering the importance of ergonomics evaluations for a safer operation of NPP contro rooms this research has the following objectives:

- Evaluate the use of a game editor UnrealEd in modeling the main control room of a nuclear power plant;
- Propose the use of the game tool UnrealRuntime in the evaluation of a NPP control room layout trough the observation of operators' movements when they perform their tasks using emergency procedures;
- Use the UnrealRunTime to calculate the time of needed for each task during a postulated accident scenario.

2 Human factors

According to Nureg 711, the human factors human factors refer to the abilities, limitations and other human characteristics that belong to the system design. The human factors requirements involve items related to control room, such as layout, design of interfaces, operator training and procedures to be performed by them. Currently, the concepts ergonomic and the human factors are complementary, so that 1993 the Human Factors Society changed its name to Human Factors and Ergonomic Society. The definitions of ergonomic and the human factors refers to working activities of human being emphasizing the adaptation of working environment and the improvements that may occur.

3 Ergonomic evaluation of control rooms

According to Iida (2000), the ergonomics is the study of the adaptation of work to human, where the work involves the human being, the technical systems and the work organization. Wisner (1995) pointed out a series of factors that affect the human performance such as conditions of the workplace, conditions of the work practice, the furniture layout, equipment design, work organization, training, management policy, and policy in general.

The main methodologies used for control rooms' ergonomic design are set out below:

- Analysis of the future activity: according to Luquetti e Vidal (2003), the analysis of the future activity aims to evaluate the work in a situation similar to the future design to understand how real operators' should cope with constraints and variability in this new setting.
- Ergonomics work analysis: this methodology has three major phases: demand analysis, activity analysis/task analysis, and validation. The analysis of demand should aims to understand the representativeness of the demand, its origin, which are the real problems and possible courses of action to solve the problems. Activity analysis is based on careful observation of work activity, identifying how work is actually performed. Task analysis includes the prescribed work and the conditions necessary to perform them. The validation occurs after the presentation and discussion of the analysis results with the workers.

4 Virtual Reality

The virtual reality describes a set of techniques and modes of interfaces that allow integration between the user and sensitive environment presented by the computer system. This combination leads the feeling of reality to one or more individuals (Augusto et al., 2007).

The scenarios replicated in virtual reality are called virtual environments, where an avatar can move around and interact with objects and elements, as well as interact with other avatars. The simulation of reality is made in the virtual environment where representative idealized scenarios are made (Stanney and Kay, 2002).

The program for modeling virtual environments chosen to meet the objectives of this study was the Unreal Engine from Epic Games, Inc., a game engine that can be modified to be adapted to different

projects (Augusto et al., 2007). The game engine was chosen for the following reasons: (i) it's free to be used for educational purposes and non-commercial objectives); (ii) it has a 3D engine of good quality and performance, producing virtual environments with sufficient realism, and (iii) the physical quantities are represented in good approximation, for example, the collision between solid and gravity.

5 Evaluation of a NPP control room

The control room chosen for the ergonomics evaluation controls a Pressurized Water Reactor (PWR) that uses light and pressurized water to uranium atoms fission, and subsequent electric power production and is located in Angra dos Reis, Rio de Janeiro.

5.1 Control room of nuclear plant PWR

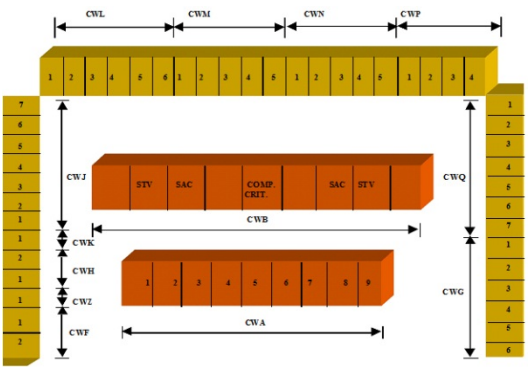
The main control room of PWR nuclear plant performs the following functions:

- Allow the control and monitoring of the plant in normal and emergency situations;
- Recognize and diagnose the transients that affect the safety;
- Initiate actions to maintain the safety condition of the nuclear reactor;
- Detect failures and start automatic action to reactor shut down.

The control room operators perform the following activities:

- Monitors the actual operational sequence, comparing them with predetermined functions;
- Check the individual functions and its relationship with other systems;
- Observe the variables representing the process;
- Interfere in the levels of certain variables, if there are deviations in set points;
- Have to be informed about the process using meters, gauges, dials and computer monitors, and adjust the process using controls.

The main control room under study has the following areas: primary control, turbine or secondary control, auxiliary control, communication, acquisition of data through computer processing, and documentation. Figure 1 shows a schematic view of the control room where the main control panels we use during the evaluation are presented.



CWA: MAIN CONTROL CONSOLE
CWB: AUXILIARY CONTROL CONSOLE
CWF: NUCLEO MONITORING
CWG: VENTILATION
CWH: NUCLEO INSTRUMENTATION
CWJ: REACTOR PROTECTION
CWK: ISOLATION OF CONTENTION
CWL: SECURITY SYSTEMS
CWM: PRIMARY AUXILIARY SYSTEMS
CWN: INDIVIDUALS CONTROLS
CWP: SECUNDARY SYSTEMS
CWQ: ELECTRIC SYSTEMS
CWZ: RESERVE
STV: SYSTEM PRESENTATION OF TREND OF VARIABLES
SAC: COMPUTERIZED ALARM SYSTEM

Figure 1: Diagram of a control room of a PWR nuclear power plant, showing the main control area, in orange, and auxiliary control area in yellow.

5.2 Choice of postulated accident for the simulation

The accident chosen for this simulation was the Small-Break Loss of Coolant (LOCA), with an area of 30 cm2 leak (internal diameter drain approximately 60 mm), consider the following boundary conditions:

- All systems operate normally;
- No power supply in an emergency;
- All systems of residual heat removal operate normally.

The LOCA accident occurs when there is a leakage of the reactor coolant due a rupture of pipe or malfunction of valve, as occurred in the Three Mile Island accident. Under such situation the reactor is shut down and the heat removal system is used to refrigerate the reactor.

5.3 Data for the simulation script

To handle a postulated accident as a LOCA, the operators use several instructions and procedures. Therefore, to develop the simulation script we used data from:

- The instructions regarding a postulated LOCA accident type "Small - Break", appearing in an operations manual (Angra 2 NPP - Operating Manual, 1999);
- Texts describing the tasks to be performed by workers for the control room;
- As a time reference for comparison was used the data published by Oliveira (2001) for the same accident.

5.4 The control room modeling

First, we analyzed some pictures of the reference control room and the together with room floor plan. The analysis took place at all angles of the control room, including their equipment. The objective of this analysis was to estimate the measures to be used to draw the control room. The preparation of these drawings was the basis for modeling the control room in UnrealEd 2.0. Figure 2 shows the main screen in UnrealEd modeling of the control room.

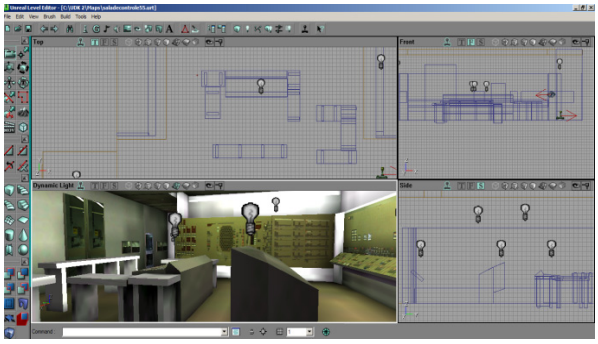


Figure 2 - UnrealEd editor showing the environment modeling.

After modeling, the Unreal Runtime is used for "navigation" in the modeled environment, using one or more avatars. At this time, the objective is to use the virtual environment to evaluate the ergonomic aspects of control room trough the observation of movements that operators perform during emergency procedures. For this purpose, each avatar is controlled by one user (one plant operator) who defines the path depending on the action to be performed. The figure 3 illustrates the Unreal Runtime avatar inserted into the environment, and figures 4 (a), 4 (b), 5 (a) and 5 (b) show view of the control room.

Figure 3: Illustration showing the Unreal Runtime avatar inserted into the environment already modeled.

(a) (b)

Figure 4: (a) View of the control room, where it can be seen the left auxiliary panel, the auxiliary panel plant, the CWA and CWB; (b) View of the control room, where you can see the central auxiliary panel and part of the auxiliary right panel.

Figure 5: (a) View of the control room where the right auxiliary panel and the supervisor's door room (the smallest one, to the right) are viewed; (b) View of the control room where the left auxiliary panel and access door to the control room (the biggest one, to the left) are viewed.

6 Simulation Procedure and Results

Initially the time an operator spent to carry out each action prescribed for the LOCA simulation were measured. We perform five simulations, and for each simulation, the actions were recorded separately.

The actions defined in the Small-Break LOCA emergency procedure are:

1. Verify the state of the plant. To do so the operator has to move to the following places: Main Control Console, Nuclear Instrumentation System, Safety Systems, Auxiliary Systems, Electrical Systems, Ventilation System, and Reactor Protection System. Therefore to accomplish their task, the operators move themselves along the entire control room many times;
2. Verify if the plant is in electric emergency feeding, visualizing the Main Control Console. The two operators have to pass by the control room furniture to reach this console;

3. Verify the existence of LOCA looking at the pressurizer data. The two operators have to look at the Main Control Console;
4. Verify if the primary circuit temperature is less than 160 ºC and if the steam pressure is less than 4 bars. The primary circuit operator visualizes this information in the Main Control Console;
5. Verify if Residual Heat Removal pumps are in operation, that is, if the pressure fell below of the 9 bars. The primary circuit operator visualizes this information in the Primary Auxiliary Systems, passing few times by the furniture;
6. Verify if LOCA occurs according to pressurizer information. The primary circuit operator visualizes the information in the Main Control Console, passing by the furniture;
7. Verify if the level of the pressurizer is minor that 2,28 meters. The primary circuit operator visualizes this information in the Main Control Console;
8. The operations are made by the primary circuit operator in the Reactor Protection System, and he passes few times by the furniture;
9. The operators have to raise the pressurizer level using Extra Borating System spray. The operations are made by the primary circuit operator in the Reactor Protection System and Safety Systems. He needs to pass some times by the furniture;
10. The class S alarm is activated. The primary circuit operator visualizes the information in the Main Control Console, Ventilation System and the Security Systems. He executes longer passages by the furniture to recognize the alarm;
11. The pressurizer is full and the operators have to stop spray from the Extra Borating System. Moreover, a pump of borating additional is disconnecting. The primary circuit operator walks until the Safety Systems, passing some times by the furniture;
12. The operator has to rearm the Safety Coolant Signal. The information is visualized by the primary circuit operator in the Reactor Protection System, and to do so he passes few times by the furniture;
13. Verify if the plant is with electric emergency feeding. This task is carried out by secondary circuit operator in the Electrical Systems, and he passes by the furniture;
14. The operator has to start the Residual Heat Removal system pump. This task is carried out by the primary circuit operator in the Safety Systems, and he needs passes by some furniture;
15. The operator has to disconnect the first Safety Injection pump. This task is carried out by the primary circuit operator in the Main Control Console, Safety Systems, Primary Auxiliary Systems and Reactor Protection System. The operator also needs to pass by the furniture.
16. The operator has to disconnect the second Safety Injection pumps. This task is carried out by the primary circuit operator, passing by the same places of the previous action. The operator also needs to pass by many furniture. In the end of this action, it is necessary to wait 5 minutes for the pressurizer level to fall;
17. Operations were carried out to turn off the third Safety Injection Pump. The task are made by the primary circuit operator, through actions in the same places of the actions 15 and 16. The operator must walk through furniture;
18. Operations were carried out to raise the pressurizer level using the Extra Borating Spray System, "JDH". This task is performed by the primary circuit operator in the Main Control Console, Safety Systems and Auxiliary Primary Systems. The operator must walk through furniture.
19. Operations were carried out to stop the pressurizer level raise, disconnecting the Extra Borating System spray "JDH". This task is performed by the primary circuit operator in the Main Control Console and Safety Systems;
20. Operations were carried out to turn off the fourth Safety Injection Pump. These tasks are performed by the primary circuit operator in the Main Control Console, Safety Systems, Auxiliary Systems, and Reactor Protection System.

The Table 1 presents the time in seconds for each action. The script time was taken as a benchmark, and it was obtained using a different simulation method (Oliveira, 2001; Carvalho et al., 2009).

Table 1: The simulation times, measured in seconds.

ACTION	SCRIPT TIME	SIMUIATION 1 (sec)	SIMULATION 2 (sec)	SIMULATION 3 (sec)	SIMULATION 4 (sec)	SIMULATION 5 (sec)	AVERAGE TIME OF SIMULATIONS (sec)
1	805,4	809,2	809,2	810,2	799,2	822,2	810
2	28,5	29,5	28,5	29,5	29,5	27,5	28,9
3	12,9	16	15	15	14	14	14,8
4	41,8	43,2	45,2	44,2	44,2	40,2	43,4
5	31,2	28,5	30,5	28,5	27,5	27,5	28,5
6	27,9	24	26	25	26	25	25,2
7	15,8	16,2	17,2	16,2	16,2	15,2	16,2
8	211,2	188	172	177	220	236	198,6
9	146	136,2	136,2	133,2	136,2	137,2	135,8
10	113,7	111,3	107,3	106,3	106,3	114,3	109,1
11	264,2	250,5	245,5	242,5	247,5	249,5	247,1
12	93,9	75,4	75,4	74,4	71,4	77,4	74,8
13	38,4	40,5	38,5	38,5	37,5	38,5	38,7
14	47,6	40,8	40,8	38,8	38,8	37,8	39,4
15	464,5	467,9	467,9	459,9	461,9	463,9	464,3
16	467,1	455,9	443,9	436,9	436,9	442,9	443,3
17	252,4	252	254	248	253	250	251,4
18	463,8	456,7	456,7	450,7	449,7	452,7	453,3
19	362,4	360,7	360,7	350,7	354,7	356,7	356,7
20	193,3	189,9	190,9	182,9	184,9	187,9	187,3
TOTAL	**4082**	**3992,4**	**3961,4**	**3908,4**	**3955,4**	**4016,4**	**3966,8**

The table 2 presents the relative error of each action compared with the benchmark in the following fields:

- Actions;
- Script time- time of each action which was developed in the script;
- Average time of the simulations – average time of 5 (Five) simulations, separated by each action.
- Relative error – error in relation to the benchmark script, for each action, and the medium time for each simulation (percent unit).

Table 2: Relative error in each action

1	805	810	0,57%
2	28,5	28,9	1,40%
3	12,9	14,8	14,73%
4	41,8	43,4	3,83%
5	31,2	28,5	8,65%
6	27,9	25,2	9,68%
7	15,8	16,2	2,53%
8	211,2	198,6	5,97%
9	146	135,8	6,99%
10	113,7	109,1	4,05%
11	264,2	247,1	6,47%
12	93,9	74,8	20,34%
13	38,4	38,7	0,78%
14	47,6	39,4	17,23%
15	464,5	464,3	0,04%
16	467,1	443,3	5,10%
17	452,4	251,4	0,40%
18	463,8	453,3	2,26%
19	362,4	356,7	1,57%
20	193,3	187,3	3,10%
TOTAL (sec	**40**	**3966,8**	

7 Conclusions

Complying with procedures is one of the most cultivated values in the nuclear industry. NPP operators like to have everything under control in advance (planning) and to know exactly what to do in a timely manner (follow the procedures). However, sometimes, the operators faced situations where it was very difficult to follow the procedure as a script in a timely manner, and in many of these situations, the problems are in the procedures. This research addresses the modeling and ergonomic evaluation of NPP control rooms and specially the time available to the operators to control such safe-critical system. Time

availability is clearly a factor that influences control, and it is not considered in most of the operators' tasks modeling research that focus on problem solving strategies, decision making, human error modeling, and so forth. However, operators' activities takes place in time and the available time is one of the most important determinants of whether an action is going to be successful or not. Few research address the actual work situation and problems faced by the operators of safe-critical systems that have to follow procedure scripts rapidly, and understand the plant evolution at the very same moment. In some situations, due to the complex nature of the work, already prepared plans and procedures, does not met the dynamic requirements of the operators cognition, making the operators' control tasks unnecessarily difficult. To achieve the active monitoring attitude to become a good operator, he/she needs spare time to think about the situation and plant processes. Therefore, time is always in short supply and more research on the subject is still needed. This applies to many different areas, such as industry, military operations, traffic, etc. The results we obtained indicated that the UnrealEd is useful to modeling control rooms, using the small resources normally available to research. The comparison of the operators' action times measured in our simulation with the reference action times showed that the UnrealRunTime can be a valid tool for estimating the operators' action time during a scenario of postulated accidents.

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