A REAL-TIME KNOWLEDGE-BASED SIMULATION FOR SUPERVISORY CONTROLS AND PROCESS MONITORING OF A NUCLEAR POWER PLANT

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Abstract A Real-Time Knowledge-Based Simulation (RTKBS), which tests and evaluates SuperVisory Controls (SVCs), Process Monitoring (PM), and Man-Machine Interaction (MMI) in the Main Control Room (MCR) of a Pressurized Water Reactor (PWR) Nuclear Power Plant (NPP), is described. The RTKBS is approached by integrating knowledge-based agents in real-time. Real-time agents are designed to simulate a generic PWR NPP, while knowledge-based agents are designed for SVCs, PM, and MMI. SVC, monitoring of safety-critical functions, a set of emergency operating procedures and accident scenarios, an evaluation model of MMI, fault diagnosis, analysis of control automatics, and user interface, are designed as knowledge-based agents. The RTKBS is implemented using the Hayes-Roth's real-time performance architecture in intelligent agents, and is applied not only to test and validate SVCs and PM but also to evaluate MMI in a simulated CRT-based MCR. The current implementation of the RTKBS, which is at the initial stage of development, includes Direct Manipulation Process Interface (DMPI), a small set of SVCs, and simulated operating procedures. Our experience thus far shows that the knowledge-based simulation is very useful for evaluating various tasks of MMI and SVCs in a highly automated MCR and for testing a new control concept.

1. INTRODUCTION

Real-time simulation technology has been widely applied to process control and monitoring in engineering plants [Moor, et al., -; Penalva, et al., 1993; Shere, 1994]. Real-time AI systems design is approached by coupling real-time into AI, coupling AI into real-time, and cooperating real-time with AI [Musliner, et al., 1995]. These design approaches were applied to develop knowledge-based simulation environments for testing and evaluating SVCs, PM, and MMI in the MCR of a NPP at Oak Ridge National Laboratory (ORNL) [Otaduy, et al., 1991] and Halden Reactor Project [Owre, et al., 1994]. ORNL has developed an Experimental Control Research Test Facility with a hierarchical knowledge-based control concept, while the Halden Reactor Project has developed an Integrated Test and Evaluation Environment to evaluate MMI. Real-time expert system shell G2 [GenSym, Co., 1994] was utilized to develop operator support systems and control automatics analyzer, and to integrate a set of monitoring systems at the Halden Reactor Project. The concept of control automatics of a NPP is being changed by applying high technology to the NPP design and operation [Kisner, et al., 1990]. Correspondingly, the RTKBS to test and evaluate SVCs, PM, and MMI in the CRT-based MCR of a NPP is developed by cooperating real-time with knowledge-based simulation environment. RTKBS is also applied to evaluate DMPI, control algorithms, Computerized Operating Procedures (COPs), and alarm system. Real-time agents have been developed with mathematical models of a generic PWR NPP, and intelligent controllers are being developed for highly automated NPP control. These real-time agents are integrated with knowledge-based agents for SVCs, fault diagnosis, monitoring about trends and processes, execution of operating procedures, analysis of control automatics, and evaluation of MMI. The Hayes-Roth's real-time performance architecture in intelligent agents was used in designing and implementing the knowledge-based simulation. The RTKBS at the initial stage of development shall be extended to test and evaluate several more types of real-time and non real-time Man-Machine Interface Systems (MMISs) in the MCR of a NPP. KAERI-Compact Nuclear Simulator (KAERI-CNS) code, which can simulate a generic PWR NPP, is interfaced with knowledge-based agents of RTKBS. Finally, RTKBS is used to test and evaluate control automatics, SVC, PM, and MMI in the MCR of a PWR NPP within an experimental test facility.

2. FUNCTIONAL REQUIREMENTS OF RTKBS

NPP processes are continually monitored on CRT and Large-Scale Project Panel (LSDP), and controlled by supervisory controllers and human operators. SVCs are simulated by automating control tasks and a set of SVC commands such as startup, shutdown, power increase and decrease, and RCS pressure control. Major functions of RTKBS are classified as SVCs and PM, fault diagnosis, model-based MMI evaluation, execution of simulated COPs, analysis of control automatics, real-time data interface with external real-time simulation, and real-time execution of a simulated plant model. RTKBS is structured as three major subsystems of cognition system, perception system, and action system. Each subsystem communicates through Communication Interface (CI) in real-time. Simulated data for NPP events are sent to cognitive/conceptual events of cognition system. Human operators and SVC developers can interact with the external real-time simulation through DMPI, and the operator's response data are sent to cognitive/conceptual events of cognition system whenever their interactions occur. Cognition system performs fault diagnosis, control, monitoring, execution, and evaluation tasks. Control and diagnostic knowledge, multi-reasoning skills, and evaluation knowledge about MMI and control automatics analysis are designed for these tasks. Action system controls external real-time simulation, and drives several kinds of displays for control, monitoring, diagnosis, and evaluation. Control logics are implemented as a graphical object-oriented representation for test and evaluation of control automatics. Another knowledge in RTKBS is COPs which can execute the predetermined procedure for simulated accidents. Knowledge of COPs is also represented as graphical objects, and a set of rules and procedures. Knowledge-based agents are implemented with G2, and real-time agents for simulating a generic PWR NPP are implemented using FORTRAN 77 and C.

3. DESIGN AND IMPLEMENTATION

Figure 1 illustrates RTKBS structure and interactions with external simulation and RTKBS users.

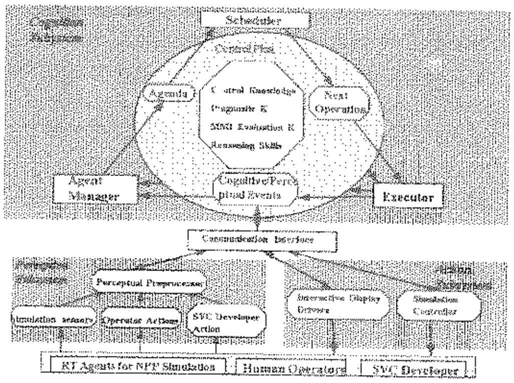

Figure 1: RTKBS Architecture

RTKBS is designed based on the Hayes-Roth's real-time performance architecture in intelligent agents and its knowledge-based agents are implemented using G2. RTKBS has an external simulation environment for simulating a generic PWR NPP, and interacting with human operators and SVC developers through DMPI and COPs.

3.1 Cognition System

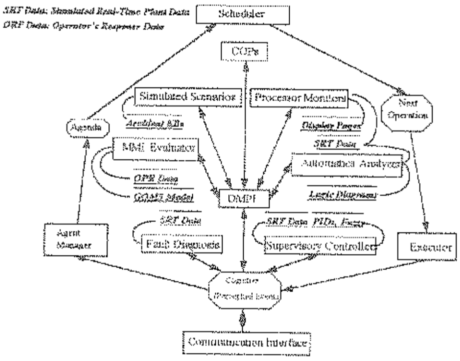

Figure 2: Knowledge-based agents architecture of cognition system

The architecture of Knowledge-based agents for cognition system is shown in Figure 2. RTKBS has the internal knowledge of safety-critical functions, control logics, dynamic processes, operating procedures for simulated accidents, MMI evaluation, and fault diagnosis. Control logics are referenced for control automatics analysis. Current control automatics analyzer of RTKBS performs its function on-line with control logic diagrams and monitors control automatics status. Control logic diagrams are structured with lower-level components of NPP, i.e., AND, OR logic gates, valves, etc. The control automatics analyzer can provide operators with a textual message for their request such as 'why a valve/pump will not open/start ?' [Winsnes, 1991]. Event-based and temporal reasonings are applied both to determine trends using real-time simulation data of a generic PWR NPP, and to diagnose safety-critical states. Model-based reasoning is applied to evaluate MMI and is implemented as a set of rules and procedures of G2. Event-based and forward reasonings are applied to perform COPs. COPs are represented as object-oriented and also implemented with a set of rules and procedures of G2. A small set of COPs for Small-Break (SB)-LOCA scenario is implemented and is integrated within emergency operating procedures. CI manages overall data communications between subsystems of RTKBS. CI gets interaction data from external simulation and human operators, and transfers the perceived data into the knowledge-bases of cognition system or directly to action system. Agenda manager identifies executable reasoning operations by using recent cognitive/perceptual events, and records on agenda. Scheduler determines which operation of executable reasonings is executed and when it is executed. Finally, executor performs the chosen operations.

3.2 Perception System

Cognitive system gets its new data by sending a request message to perceptual preprocessor. Perceptual preprocessor gets two types of plant data and operator's action data. It classifies the perceived plant parameter data into data value classes and trends. About 1000 plant parameters are perceived at the rate of 200 ms while operator's response data are immediately perceived by conceptual preprocessor.

3.3 Action System

Several kinds of display drivers are designed for managing communications with the external simulation environment, monitoring parameter values, trends, alarms, and safety-critical functions, and providing information of operating procedures and control logics. Plant overview is designed at the highest level of displays with monitoring and communication purposes between operating crews. Figure 3 shows a G2 prototype for an Integrated Process Status Overview (IPSO) of a NPP.

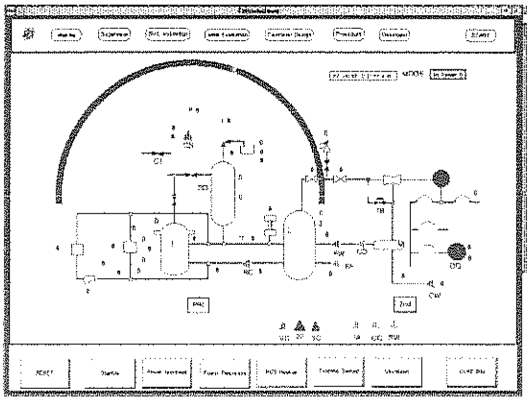

Figure 3: A G2 Prototype for IPSO Display

Displays are represented as object-oriented graphics with G2. DMPIs are designed for human operators and SVCs developers, and control functions are integrated into displays. Human operators can diagnose and control an activated function with DMPI which several kinds of CRT displays are interfaced with. DMPI for level control of a steam generator is shown in Figure 4.

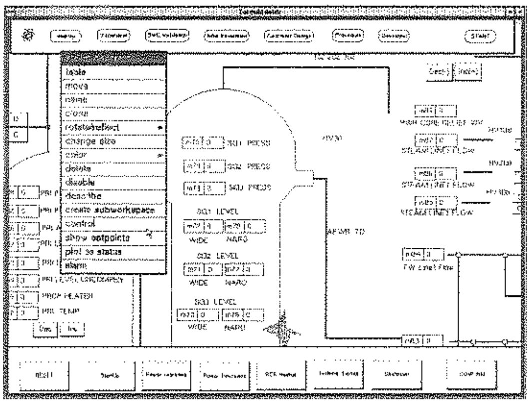

Figure 4: A DMPI for S/G level control

3.4 External Environments

KAERI-CNS code is used to simulate a generic PWR NPP. KAERI-CNS source code has been developed by STUDSVIK Energiteknikk, and modified by I&C department of KAERI for design, test, and evaluation of automatic controls and PM. We used the modified KAERI-CNS code for the external simulation of RTKBS. RTKBS has the overall functions for SVCs and PM, operator interface displays control, simulated scenario runs, execution of simulated operating procedures, and presentation of alarm information. DMPI can enable human operators and SVCs developers to interact with RTKBS. SVCs developers can interact with DMPI which allows menu- and button-based access to control logic diagrams.

4. PERFORMANCE EVALUATION

Experimental scenarios with accidents and incidents are supplied to evaluate SVC and PM. Representative accident scenarios of SB-LOCA and steam generator tube rupture are widely used to simulate a complex operation of NPP. COPs for SB-LOCA are designed and utilized to test and evaluate process control and MMI. A page of COP is shown in Figure 5.

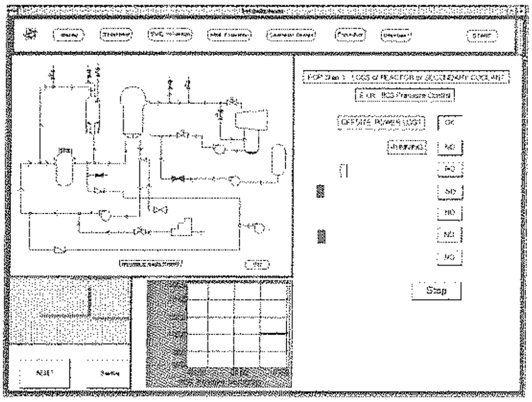

Figure 5: A page of COP

MMI with SVCs and simulated COPs is evaluated with Goals-Operators-Methods-Selection (GOMS) hierarchy and plant's generic control tasks. GOMS hierarchy for the simulated CNS main control panel was developed for evaluating control tasks in the MCR of a NPP. Figure 6 shows the GOMS hierarchy.

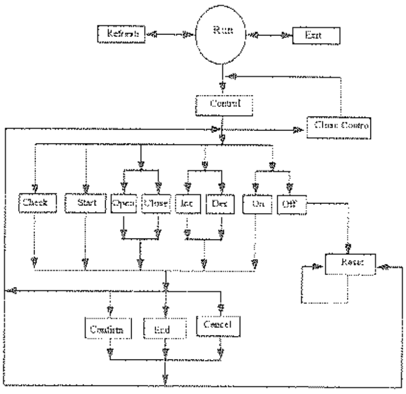

Figure 6: GOMS Hierarchy for CNS Main Control Panel

The GOMS hierarchy is implemented with a set of rules and procedures with G2. A safety-critical event is simulated and then the operator's interaction for the control task is evaluated with GOMS knowledge. The result of this evaluation is depicted in Figure 7. Predicted states and goal of control tasks were selected from written operating procedures.

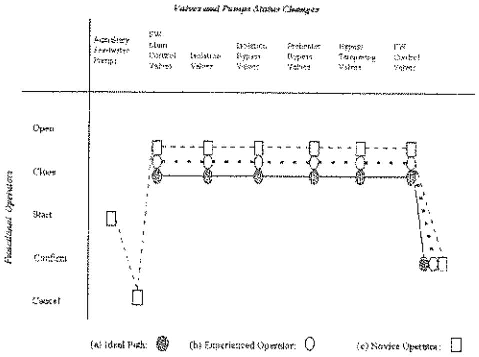

Figure 7: GOMS Analysis of Operator's control interaction with control tasks

Validation of SVCs is performed with control logic diagrams, experimental scenarios, and DMPI. A control logic diagram used for validating SVCs is depicted in Figure 8. These analyses are at the initial stage of test and evaluation and will be extended with more SVCs, PMs, COPs, and control logics.

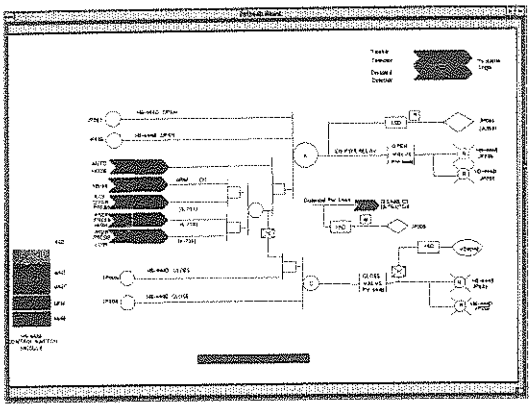

Figure 8: Control Logic Diagram

5. CONCLUSIONS AND FUTURE WORK

The RTKBS, developed by applying the Hayes-Roth's real-time performance architecture in intelligent agents , satisfies the real-time requirements for SVCs and PM in the MCR of a NPP. It also enables new control concepts and operator support systems to be easily tested and evaluated with dynamic simulation capability and flexibility. Our experience thus far shows that knowledge-based simulation is very useful for evaluating various tasks of MMI and SVCs in a highly automated MCR and for testing a new control concept.

The following further work is planned:

(1) Control Logic Diagrams
Small sets of control logics and operating procedures have been designed and tested with the RTKBS prototype. More control logic diagrams should be provided for RTKBS.

(2) SVCs
SVCs will also be extended for more SVC functions and intelligent controls. Supervisory commands for KAERI-CNS code should also be extended.

(3) COPs
COPs will be improved by considering operator's experiences. An example is the backtrack of an operating sequence when operators fail to implement an intermediate operating step before reaching the last one. Guiding to a proper operating step will be considered in COPs by applying knowledge-based system technology. COP design is approached by employing multimedia interface technology, such as sounding and voice presentations, and various help functions with hypertexts.

(4) Performance Data Analysis of Human Factors Experiments
The RTKBS will also be extended to support a knowledge-based analysis of operator performance data in evaluating SVCs, PM, and MMI.

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