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Introduction

The Oak Ridge National Laboratory (ORNL), under sponsorship of the U.S. Department of Energy (DOE), is conducting research that will lead to advanced, automated control of new liquid-metal-reactor (LMR) nuclear power plants. Although this program of research (entitled the "Advanced Controls Program") is focused on LMR technology, it will be capable of providing control design, test, and qualification capability for other advanced reactor designs (e.g., the advanced light water reactor [ALWR] and high temperature gas-cooled reactor [HTGR] designs), while also benefiting existing nuclear plants. The Program will also have applicability to complex, non-nuclear process control environments (e.g., petrochemical, aerospace, etc.).

The Advanced Controls Program will support capabilities throughout the entire plant design life cycle, i.e., from the initial interactive first-principle dynamic model development for the process, systems, components, and instruments through advanced control room qualification. The current program involves five principal areas of research activities: 1) demonstrations of advanced control system designs, 2) development of an advanced controls design environment, 3) development of advanced control strategies, 4) research and development (R&D) in human-system integration for advanced control system designs, and 5) testing and validation of advanced control system designs. Discussion of the research in these five areas forms the basis of this paper. Also included is a description of the research directions of the program.

ORNL's Advanced Controls Program

Background

In 1985, the DOE established a task team to determine the need for, assess the feasibility of, and recommend an approach to the introduction of automation and advanced controls into the nuclear power industry. A primary recommendation of the task team was an Advanced Controls Program with a centralized, multi-user capability. As a result of this recommendation, the DOE provided support to ORNL to pursue research leading to advanced, automated control of new innovative LMR power plants. The overall goal of the program is to provide a U.S. center of excellence in R&D and testing of nuclear control systems employing the latest advances in automation, artificial intelligence (AI), expert systems, hierarchial computer architectures, human-system interfaces, and optimal control.

The Advanced Controls Program utilizes and advances state-of-the-art control technology through close interaction with other national laboratories, universities, industry and utilities. Its focus is to ensure improved operability, availability, reliability, safety, human-system interfaces, and competitiveness for advanced LMRs. Because of the relatively ambitious scope of the program and the increasing world-wide interest in advanced controls, automation, and advanced human-system interfaces, growth of the Advanced Controls Program has been envisioned to extend to research of an international nature.

The Impetus For an Advanced Controls Design Environment

Over the past decade, the essential elements for the development of a large-scale program focused on advanced controls was realized within the U.S. nuclear industry. Those elements involved: the existence of enhanced technological capabilities, a market that could readily implement enhancements offered by these capabilities, and a supportive research environment.

With respect to the existence of enhanced technological capabilities, the rapid introduction of innovations in the areas of digital technology and AI has recently allowed for a more serious focus on the development of advanced control systems. In particular, advances in computer-based digital data acquisition systems, process controllers, fiber-optic signal transmission, AI tools and methods, and small, inexpensive, fast, large-capacity computers (with both numeric and symbolic capabilities) have provided many of the elements necessary for developing large, practical, automated control systems.

With respect to the existence of a market that could readily implement enhancements offered by new technological capabilities, the U.S. nuclear industry of the 1980's was ready to embrace the benefits offered by technological innovation. One example is DOE's call for the use of digital technology in advanced reactor designs. It was clear that utilization of digital technologies had a potential to lead to: (1) improvements in plant availability, (2) lower operating costs, (3) simpler operation, and (4) a reduction of challenges to active and passive safety systems.

Digital technology impacts plant availability by providing an increased potential for the development of control algorithms that are better able to deal with nonlinear and discrete changes in parameters and redefinition of target states. Furthermore, it increases the self-checking potential for failures or decalibration.

Digital technology and advanced control strategies and architectures allow for increased levels of automation. Automated systems are envisioned to accomplish many of the routine activities of an experienced operator. When compared to a human operator without automated aid, automated control systems are envisioned to perform many functions more rapidly, manage more complex systems, and consider more situational characteristics in a shorter period of time.

Digital technology allows for the development of sophisticated diagnostics, alarm management, and graphical displays that will alert the operator to the plant status and any special actions that are needed by the operator. It will provide plant operators with information that is of greater value than that which is provided by displays within the current U.S. commercial reactor industry. Furthermore, increased employment of supervisory control, coupled with the trend in U.S. reactor designs toward a "natural" means of accommodating all aspects of a reactor's behavior, implies an operator role which is less burdensome (simpler) than the role of the operator in today's U.S. plants.

Regarding the minimization of challenges to active and passive safety systems, the use of supervisory control and distributed, multivariate, fault-tolerant control techniques will lead to automation that provides such a capability.

With respect to a supportive research environment, the DOE has recognized ORNL as a center of excellence for controls and has designated ORNL as the lead laboratory for advanced controls having the responsible for national program planning in this area.

Program Areas

Demonstrations of Advanced Control System Designs

The purpose of the advanced controls demonstrations are to provide timely illustrations of prototypic designs for control systems for selected aspects of the advanced LMR concept. They are intended to show how state-of-the-art research in advanced controls technology can be used to help accelerate the transition to fully automated control. Initially these demonstrations were implemented by computer simulation at ORNL. Future demonstrations are being scheduled to be carried out on existing DOE reactor systems.

Supervisory Control Demonstration: The supervisory control demonstration reflects on-going research in recursive, hierarchial control as applied to a multimodular LMR design. At the lowest level of the hierarchy, plant control functions such as reactivity and primary system coolant flow/state report their performance characteristics to a common supervisory module, i.e., if the control of one reactor module could be accomplished via the control of four plant functions, then four controllers would report the characteristics of their performance to one reactor module supervisor. Taking the example further, if there were three identical reactor modules, there would be three reactor module supervisors (one for each module), reporting to one power-block supervisor. Therefore, one or more supervisory modules at one level would report to a single supervisory module at a higher level (hence, the recursive nature of the structure).

For each supervisory module, there exists an operator interface capable of allowing a human operator to display data, information, and trends pertaining to plant state. A human operator may choose to interact at any level, or with any supervisory module desired. The lower in the hierarchy that a particular supervisory module is located, the more detailed is the interface content. This interface also functions as a means by which the human operator can potentially exercise manual plant control. For the current supervisory control architecture, any manual control action suggested by the human operator will be attempted. If, however, the supervisory module receives indications that the reactor is proceeding toward an unsafe state, it will initiate control actions which will ensure that an unsafe state is not reached. It should be pointed out that in the current architecture the relationship between the human operator and the supervisory control system (i.e., the supervisory control module having the ultimate control responsibility) can be viewed as opposite to that which is currently espoused within the nuclear community. The optimal role of the human operator within a sophisticated control environment, especially an environment where the human operator is not envisioned to have a safety role, is a research issue that is yet to be resolved. The supervisory module therefore can function as an arbitrator between proposed control activities emanating from responsible lower-level supervisors and automatic controllers, as well as proposed control activities from the human operator.

At the lowest level, proposed optimal control activities will stem from digital control packages that receive plant state information directly from sensors in the plant. For the demonstration and other simulations associated with the supervisory control effort, plant state information is provided by mathematical descriptions of the reactor. Automated control is done with a set of nonlinear controllers with provisions for unmodeled dynamics' to account for the inexactness that exists between modeled and real plant dynamics.

During U.S. Fiscal Year (FY) 1989 the supervisory control architecture for one power block (i.e., a power block supervisor module, three reactor module supervisors, a turbine/feedwater supervisor, and the associated controllers [13 in all]), were developed and successfully demonstrated in a network of nine CPUs on six computers. Future research will be directed toward development of the architecture to model an entire multimodular plant (three power blocks), to develop an enhanced capability to accommodate accident situations, and to develop the capability to dynamically reconfigure target goals, setpoints and control laws. Further details of the supervisory control research can be found in Reference 2.

Balance of Plant Control Demonstration: Balance of plant (BOP) control, and especially the control of the feedwater systems, tend to be one of the more difficult activities for operators in a nuclear power plant. Because of the relatively large potential for impacting overall operational effectiveness through the simplification of feedwater control, research toward the achievement of this goal, via advanced control techniques, is being pursued. The purpose of this demonstration is to illustrate simpler, fault tolerant, flexible control designs for the feedwater systems of advanced LMRs (and other steam producing power plants), as compared to existing feedwater controllers being used in the industry. Existing control systems for feedwater systems are almost exclusively analog in nature, are typically cumbersome to control, have almost no embedded intelligence, and are evidencing reliability and maintainability problems stemming from the vintage nature of their design and the increasing unavailability of spare parts.

ORNL is developing multivariate control strategies coupled with smart sensors as an alternative to the traditional analog control of feedwater trains. Such strategies offer increased fault tolerance, robustness, and flexibility to accommodate changes in hardware and software. Multivariate control strategies implement/utilize multiple sources of data and information (D&I) to control a particular entity (component or subsystem). These sources of data include exogenous D&I from upstream or downstream from the controlled entity. Utilization of multivariate control strategies can be viewed as a model-based control methodology. Such strategies allow for a control environment that is much less susceptible to the failure or degradation of one particular control signal (the model-based controllers [MBCs] are designed to function with any single failure in the related instrumentation). In addition, the availability of information related to the status of the multiple data and information sources allows for easier inference of system/plant condition (a good source of integrated diagnostic information for the human operator). By the end of U.S. FY-1989, four local MBCs had been developed. They were: (1) steam generator level control, (2) turbine steam admission valve control, (3) low pressure feedwater heater level control, and (4) moisture separator level control.

The development of smart sensors, functioning in conjunction with MBCs, is another research area supported by the Advanced Controls Program. The desire is to ensure that the signals being provided to the MBCs have a high degree of reliability. Smart sensors are being designed to perform local tests that allow discrimination between: (1) instrument or signal failures, (2) a change in the process with which the sensor is associated, or (3) a change in condition of the sensed values due to changes in plant states (e.g., start-up or full-power).

In order to facilitate a high degree of robustness with respect to the control of particular plant/system entities, control architectures are being developed to accommodate other control techniques such as the linear-quadratic-Gaussian (LQG) or the proportional-integral-derivative (PID). Strategies for selection of the appropriate control technique will be the focus of future research. One of the overall goals of the current research in the BOP area is to provide the lower level control interface for a BOP supervisor (turbine/feedwater supervisor) of the supervisory control system (described earlier). Further details of the BOP research can be found in Reference 3.

Automated Start-Up Demonstration: This demonstration has an ultimate objective of showing that advanced LMR plants can be operated from low to full power using computer control. A phased approach is being taken in this research. That is, initial capabilities are being developed that will allow for computer-assisted manual start-up of a LMR. In particular, this effort involves the development of operator aids that will support manual start-up by the human operator. The computer will support the human operator by displaying start-up procedures, issuing prompts for hold points, providing checksheet capabilities and performing data reduction and integration for the generation of supportive graphical displays. Such initial advancements in the operator interface area are being developed by ORNL with cooperation from staff members of the Experimental Breeder Reactor-II (EBR-II) operated by Argonne National Laboratory (ANL). Subsequent to completion of the interface prototypes, operators within the EBR-II control room will provide evaluation of the start-up aids.

Another automated start-up activity being carried out at ORNL is the development of control strategies and algorithms for optimal start-up. Such development will be in support of the supervisory control research and is currently being developed to be functional with a simulation model of the EBR-II facility. An inverse dynamic control methodology has been developed to control power ramps during start-up and is being compared to the performance of PID and LQG controller designs. As the control strategies and algorithms are implemented within the simulation model of EBR-II, the manual control requirements of the human operator will be diminished, as compared to the computer-aided manual start-up phase described earlier. Eventually, as the supervisory control capabilities and the control strategies and algorithms are ported to the EBR-II facility (and, if available, the EBR-II simulator), automated start-up will be demonstrated for a real facility. Furthermore, lessons learned from this experience and other controlled experiments will contribute significantly toward automated start-up capabilities for advanced LMR designs. Further details of the automated start-up research can be found in Reference 3.

Human Operator Model Demonstration: A phased approach to nuclear plant automation necessarily impacts the role of the human operator within the control environment. In particular, some of the effects will be lower levels of operational staff, less direct control interface, decreased levels of low detail D&I, increased levels of integrated D&I, and in general, an elevation of the role of the operator from a manual controller to that of a high-level system manager. Unfortunately, estimates of the functionality of a human operator within such an environment can only be speculation given the existing tools for assessing human performance within complex control environments. For this reason, the Advanced Controls Program at ORNL is supporting the development of a state-of-the-art model of human cognitive functionality. This model, entitled INTEROPS[SM] (Integrated Reactor Operator System), addresses such operator functions as planning, system observation, fault management, fault diagnosis, scheduling execution, information interpretation, trend estimation, failure detection, alarm analysis, parameter analysis, scheduling, and task execution. The INTEROPS model is a hybrid architecture whose main components are written in the SAINT (Systems Analysis For Integrated Networks of Tasks) simulation language and common LISP. The human cognitive model is coupled to a sophisticated Fortran-based thermal hydraulics code of a single-module LMR.

The primary purpose for development of INTEROPS was to provide a tool for addressing allocation of function issues related to advanced control design. The value of INTEROPS has broadened beyond the original intent. Not only is it capable of providing data related to operator workload, stress and other measures of human performance, it can be used as a means for assessing the quality of various control environments from a human performance perspective (i.e., used within trade-off analyses). Furthermore, the model can be used to identify human-error-likely, or near human-error-likely situations for control strategists on an a-priori basis. The wide applicability of INTEROPS stems from its characteristics of being a descriptive and predictive model of human functionality.

In order to facilitate a better understanding and applicability of INTEROPS, a first demonstration of the model is being developed and will be completed by the end of U.S. FY-1990. The demonstration will show the time dependent nature of a number of human performance measures, including stress and cognitive workload, as various reactor transients are run within the thermal hydraulics code. Important plant parameters will also be displayed for correlational purposes and elements of the simulated human operators' fault diagnosis process will also be displayed.

Development of an Advanced Controls Design Environment

The development of advanced and intelligent control systems requires an environment (and a set of tools) that facilitates high-level decision-making and allows the consideration of all facets of plant operation (e.g., plant operation and maintenance). One means of achieving such an environment is through the development of a controls analysis workstation capable of automating, documenting, and testing all aspects of a design, its analysis, and its specification. The workstation being developed within the Advanced Controls Program will provide a centrally located, user friendly design environment. The environment will consist of the following areas: (1) networked, intelligent computer workstations and integrated software tools, graphics capabilities, on-line design guidance, on-line documentation capabilities, and interface capabilities to large reactor simulation code (2) plant and component models and databases useful for control system design and plant simulation, (3) human-system interaction models, guidelines for designing human-control system interfaces, and human performance databases to support the design process, and (4) information resources concerning control system strategies for automated control. ORNL professional staff members from the Advanced Controls Program will also be available to assist in the transfer of technology to end users. With respect to Area (1) above, a controls analysis workstation environment for efficient engineering of control systems has been a principal research area that has, as yet, not been discussed. The workstation will provide a control system designer an enhanced capability for the overall design, simulation, as well as code generation. Advantages of the workstation will be: (1) productivity enhancement through improved tools and design environment error reduction, (2) centralization of project management responsibilities, (3) automated record keeping, (4) standardization of methods for controls analysis, and (5) a [illegible] communication environment within and between design teams. Because the workstation is envisioned to be intelligent, it will have the capability to advise users of appropriate control techniques, the operation of particular plant components, and the use of the control design workstation itself.

The control design workstation will be developed as an integrated group of four modules. These are:

(1) The Control System Analysis Package provides analysis tools for the development of modern (state-space) linear and nonlinear control systems. It will provide reference to other methodologies not currently addressed within the workstation environment.

(2) The Control System Database provides a centralized repository for all information relevant to the control system analysis package. It will include: (1) control system design data from vendors, (2) logbooks for users of the workstation, (3) input/output files associated with analysis software, (4) help files and documentation for analysis software, and (5) a continually updated bibliography related to control system methods supported by the analysis package.

(3) The Interactive Simulation Package provides a user-friendly modeling environment for testing control systems at various stages during the development cycle. Features will include: (1) an interactive nature that provides quick feedback on any changes made to the control or system models (this feature encourages experimentation and supports creative thinking), (2) hierarchial capabilities that will provide the designer a means for the selection of models at various levels of granularity depending on his particular and current need (such a feature allows the designer to effectively consider required simulation speed, performance and stage of control system design), and (3) graphical capabilities to display plant, control system, operating conditions and variables, likely human operator performance measures, and other parameters and features as required (such graphical interfaces reflect an integration of large amounts of D&I and embody many implicit operational characteristics of value to the designer).

(4) The Plant Model Database provides a centralized repository for all information relevant to plant modeling work. Specific D&I related to a particular design may be stored along with the results of data files that support a current design effort.

In the near term future (U.S. FY-1991 or FY-1992) research in support of the development of the workstation environment will provide a focus for much of the other research of the Advanced Controls Program. It will provide a forum for the integration of research in the areas of supervisory control, human-system modeling and design guidelines, BOP control, and control strategies. The workstation may prove to be useful in research to be carried out in support of the testing and validation of advanced control system designs (to be discussed later in this paper). Further details of the workstation environment research can be found in Reference 8.

Development of Advanced Control Strategies

Control strategies that facilitate safe, reliable, and efficient operation, as well as increased component lifetimes, efficient maintenance, and improved human-system interactions, require the integration of a number of advanced control concepts. These include: (1) tight control of continuous-variable type (CVT) subsystems, (2) coordination of many interacting CVT subsystems, (3) control of discrete-event type subsystems, (4) decision-making for fault avoidance and mitigation, and (5) high-level decision making for planning and coordinating the many facets of plant operation. Techniques of control (which include multivariate, optimal, model algorithmic, hierarchial coordination, disturbance accommodating, discrete event, operations planning, and system-wide automation) are being examined for their potential benefits in reactor control and operations. In addition, decision-making for degraded conditions and the effective distribution of control intelligence for normal, dynamic, and degraded plant conditions are being investigated.

R&D in Human-System Integration For Advanced Control System Designs

Human-system integration research is being carried out to impact all phases of advanced control system development. In particular, three design phases (preliminary, detailed, and final) are utilized as a basis for the human-system research. During the preliminary design phase, little integration will have been achieved with respect to a particular design concept and only high-level decisions will have been made concerning design specificity. Also in this phase, human-system research can best support ongoing efforts by providing general guidelines related to the role and potential functionality of humans in complex control environments. Furthermore, advice can be provided concerning the types of D&I that must be made available to support human-system research in subsequent design phases. During U.S. FY-1989, ORNL completed an in-depth literature review of the human factors aspects of allocations of function. The lessons learned from the review led to the formulation of 32 guidelines and 69 corollaries for human-system integration[6]. A systems engineering approach involving active participation of human factors experts is strongly recommended.

For the more detailed design phase, several feasible design alternatives will emerge. Such alternatives will reflect proper attention to the design guidelines and expert high-level advise provided by design team members with human factors expertise. More detailed and integrated human-system considerations will be focused on the role of the operator, allocations of function, responsibility and control, level of automation, etc. In order to address such issues within complex control environments, detailed models of human-system interaction are necessary. In order to provide a capability for the Advanced Controls Program at ORNL to provide support for the detailed design phase, the INTEROPS model (described earlier) was developed. The model allows for the generation of a time-based profile of operator performance for various off-normal scenarios. Its stochastic nature accounts for the inherent variability associated with human performance. Furthermore, the model accounts for human limitations and bias in cognitive processing. For example, the INTEROPS model exhibits the following behavioral characteristics: cognitive tunneling, confirmation bias, and decay of data stored in short-term memory.

Prior to U.S. FY-1989, INTEROPS reflected a model of human functionality that operated exclusively within a rule-based domain. That is, the model could only adequately address cognitive performance when the operational situation was well-defined (i.e., procedurally-based) on an *a-priori* basis. The model could not address required cognitive behavior for operational scenarios that require innovative thinking which arises when operators are confronted with operational situations not covered by procedures. In order to replicate operator functionality during tasks which require knowledge-based behavior, the simulated operator must be capable of constructing and testing plans by utilizing its own "mental model" of the internal structure of the system. Initial efforts to achieve such a capability were realized during U.S. FY-1989 through the development of a qualitative simulation model (QSM) of a LMR[7]. The QSM will be accessed by the simulated operator when the operational situation cannot be handled by the rule-based planner, or when procedural non-compliance is preferred for some other reason. As such, the model can be viewed as a model of an operator's mental model. The QSM is written in Common LISP and utilizes the object-oriented language extension called Flavors. Details of the QSM are beyond the scope of this paper; however, it has been designed to provide a means (a mental model) for replicating an operator's systematic attempts to understand plant states through propagating the likely effects of perceived initial plant conditions. Although the QSM has allowed initial penetration into the regime of modeling knowledge-based behavior, much more research is needed to understand the characteristics and dynamics of mental models. It should be pointed out that as the role of the human operator is elevated to that of a high-level system manager, it becomes increasingly important to design control and display interfaces that support an operator's mental models and minimize the cognitive distance between the operator and the process being controlled. The initial version of the INTEROPS model will be completed in U.S. FY-1990. Validation efforts will be carried out in U.S. FY-1991 and beyond.

For the testing and evaluation phase, the set of design alternatives from the previous design phase are tested and evaluated for the purpose of selecting a candidate final design. From a human-system integration perspective, this will involve an assessment of the functionality of the human operator(s) within the existing design alternatives. In general, such activities will involve carefully designed and controlled human performance experiments, carried out in full- and part-task simulator environments to: (1) assure effective design of the human-system interface, (2) resolve specific human performance issues for which little research exists, (3) gain a better understanding of the nature of human performance, (4) provide an initial source of human performance D&I, and (5) support continuing validation of INTEROPS. Other testing and evaluation phase efforts will be focused on the compilation of human factors D&I within a human factors data system and utilization of INTEROPS as a basis for the development of prescriptive operator aids. Another suggestion for the use of INTEROPS during the testing and evaluation phase calls for incorporating the model into a training simulator environment. The model could be utilized as a "partner" to a human operator, and through the ability to control its performance characteristics, human operator performance can be studied as a function of the ability of the co-team members.

Testing and Validation of Advanced Control System Designs

As a control system design comes to fruition, requirements for integrated simulation capabilities become necessary in order to "verify" and fine-tune the final design. Requirements to achieve integration include real-time simulation capabilities for a wide variety of reactor subsystems, integrated systems, and controllers. Surveys and investigations of computer hardware and software capabilities for satisfying the full-plant simulator requirements have been initiated. Special attention is being given to current and projected availability of expert system tools, object-oriented programming systems, computer-aided systems engineering tools, database management systems, and graphics-animation capabilities. Furthermore, methods are currently being developed to ensure that the software developments being carried out within the Advanced Controls Program conforms with industry standards (i.e., American National Standards Institute [ANSI], Institute of Electrical and Electronics Engineers [IEEE], U.S. Nuclear Regulatory Commission [NRC] Regulatory Guides).

Future Research Directions

Integration of the research areas within the Advanced Controls Program will provide the focus for much of the near-term effort. Generation of an integrated design environment with the capability to support user needs in areas of concept development, generation of design alternatives, evaluation of design candidates, iteration for design optimization, and testing and evaluation will require sophisticated and flexible architectures. As described in this paper, the Advanced Controls Program is moving toward the accomplishment of the required R&D.

Experimentation for test and evaluation will also receive increased attention. Environments for full- and part-task experimental application will be designed and developed to assess the total system functionality of the designed system. Such an assessment capability necessarily includes assessment of hardware, software, and subsystem and system performance as well as understanding the nature of human performance for the given design.

Research with cooperative and supportive organizations in the U.S. and with other countries will also be investigated. The advanced controls environment at ORNL provides a great opportunity for joint research associated with intelligent automation. Since the scope of the Advanced Controls Program involves complex non-nuclear control environments, cooperative research with such organizations will also be pursued.

Summary

The Advanced Controls Program at ORNL is sponsored by the U.S. DOE to support effective technological innovation in the area of advanced LMR controls. Applicability of the program, however, goes beyond the LMR community. ORNL is providing a center of excellence for this research and is providing an environment for the conceptualization, design, testing and evaluation of advanced control concepts. The program is organized to provide: (1) demonstrations of advanced control systems designs, (2) development of an advanced controls design environment, (3) development of advanced control strategies, (4) R&D in human-system integration for advanced control system designs, and (5) testing and validation of advanced control system designs. Application to international research programs is being considered.

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