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SUPERVISORY, HIERARCHICAL CONTROL FOR A MULTIMODULAR ALMR*

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Abstract

This paper describes the directions and present status of research in supervisory control for multimodular nuclear plants at ORNL as part of DOE's advanced controls program ACTO. The hierarchical supervisory structure envisioned for a PRISM-like multimodular LMR is discussed first. The architecture of the supervisor closest to the process actuators and how it has actually been implemented for demonstration in a network of CPU's is presented next. Two demonstrations of supervisory control with an expert system are also described, one for control of a plant with a single reactor and turbine, the other for control of a plant with three reactors and one turbine. An appendix contains the mathematical basis for the novel approach to large scale system decomposition we have used in the demonstrations of supervisory distributed control of the single reactor plant.

Introduction

Significant technological advances warrant the consideration of new designs for nuclear power plants and their control systems. The nuclear plants of the future will most likely be modular and will consist of multiple reactor cores. The control systems of future reactors will undoubtedly be computer based and most likely be fully automated. The human operator will act as master supervisor and strategic policy decision maker with extensive monitoring facilities and limited direct control capabilities.

As part of ORNL's Advanced Controls Program (ACTO), the supervisory control task group is conducting research on computerized supervisory control issues relevant to the automatic control of multimodular nuclear plants. This research focuses on the integration of numerical and symbolic computation techniques to facilitate the implementation of intelligent controllers with algorithmic as well as human like analytical and model based problem solving and explanatory capabilities. Coparticipants in this effort are the University of Tennessee and the Massachusetts Institute of Technology.

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For incremental development and testing as well as for demonstration of supervisory control concepts we are using multimodular reactor models whose configuration resembles that of General Electric's Power Reactor Inherently Safe Modules (PRISM) concept sponsored by the U. S. Department of Energy. The PRISM multimodular concept considers a plant to be composed of three power blocks. Each power block consists of three inherently safe reactors attached to one turbine. Thus, a plant has a total of nine nuclear reactor cores and three turbine/generator sets.

In this paper we describe the directions and present status of our research in supervisory control for multimodular nuclear plants.

Research Directions

The supervisory control structure we envision for multimodular plants is of a hierarchical recursive nature. As shown in Figure 1 it has a supervisory controller in each node other than the bottom level actuator nodes.

Each supervisory module has the same philosophy of operation: it considers its children nodes as a plant to be controlled so that the goals specified by its parent node, to which it reports, are achieved. Each supervisory module embodies strategies to generate demand distributions, monitor plant performance, select control actions from a set of proposed control vectors (control law reconfiguration), diagnose the need for and implement controller gain adjustments, and avoid operation near safety and administrative limits.

In addition, every supervisory module provides for operator interaction. The operator must be informed by the supervisory module of impending control actions, the reasoning behind their selection and what plant response is expected and whether further control actions will be needed. With regard to control, the supervisory module views the operator as an optional control law generator - which includes manual control - constrained like the rest of the available automatic controllers to act within safety envelopes. In addition, the operator will be able to guide the supervisory module to a decision but it may not override the supervisor's logic in an unconstrained fashion.

In essence, the supervisory modules encode knowledge at three levels: operator information needs (man/machine engineering), economic and administrative policies, and plant physics. The man/machine engineering knowledge component is the same for all supervisory modules in the control hierarchy. However, the higher a supervisory module is in the hierarchy, the less concerned it is with plant physics versus administrative policies and vice versa. For instance, the top node is mostly concerned with electrical

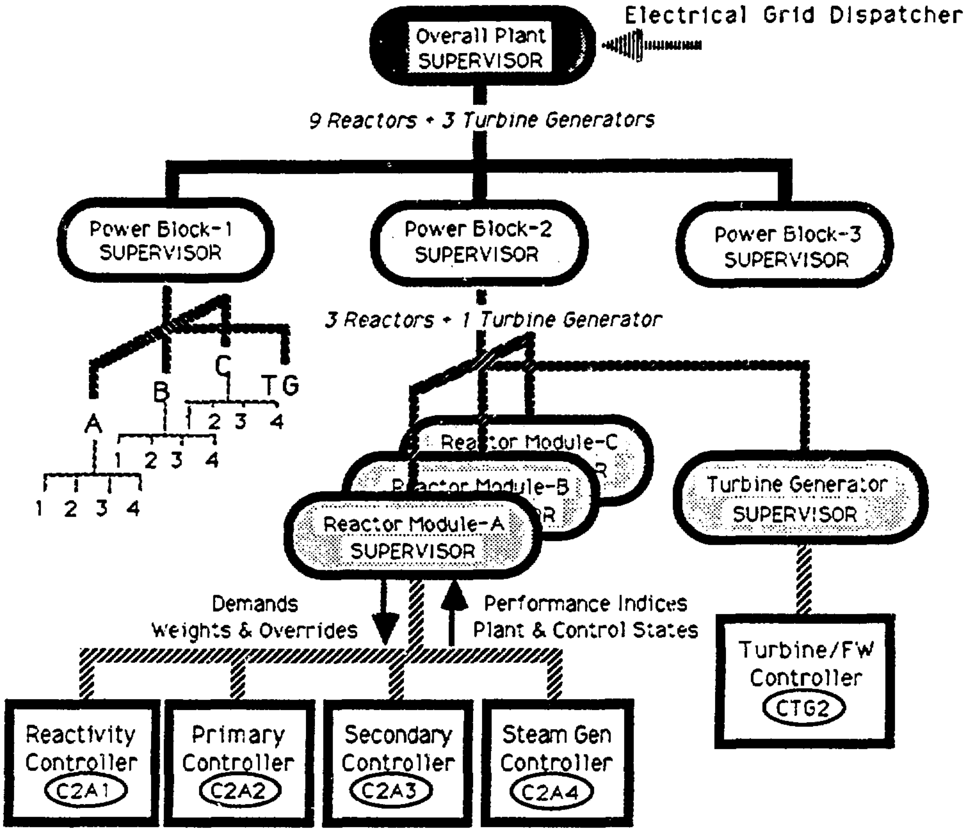

Figure 1
Supervisory Control Hierarchy

grid economics and overall maintenance and performance objectives of each power block. Meanwhile, the single reactor supervisor is mostly concerned with diagnostics of subsystem controller performance, control law reconfiguration, actuator responses, and state variable tracking.

At the bottom of the control hierarchy are the automatic control modules that interface directly to the plant signals and actuators. As shown in Figure 1 we have chosen to pursue a distributed control approach for each reactor and turbine. In this distributed approach each of the subsystem automatic control modules has three action levels: one monitors the status of the set of smart sensors and signal validators concerned with the data needs of the controller, another implements the control laws that generate the control vector appropriate to the plant state and demand setpoints, and the last monitors the status of the smart actuators to ascertain proper execution of the control vector. Each subsystem controller can have a variety of control laws available for generation of a set of tentative control vectors. The corresponding supervisory parent module will select the most desirable control vector.

Research on smart sensors is part of a parallel effort in the ACTO program to be incorporated in the future. Nonetheless the possibility of faulty data exists, thus we seek control algorithms that degrade gracefully with bad data, i.e. facilitate rapid diagnosis and correction.

The smart sensor work will be extended to generate smart actuators. The smart actuator - control rod, pump, or valve - will be aware of its performance characteristics, should follow up on how control demands are fulfilled, and will report to the controller's supervisor when deviations from expected behavior occur. Self tuning capabilities triggered by prior consent from the supervisor will be an integral part of the design of smart actuators.

Implementation of the described architecture for supervisory control will require fault tolerant parallel computer architectures and operating systems with parallel and distributed computing capabilities.

Present Status of Research

Implementation of the architecture shown in Figure 1 is proceeding in stages from the bottom of the hierarchy upwards. Most of the work during 1988 focused on the lowest level supervisory module and its subsystem controllers. Concepts were initially developed for a plant with a single reactor and are being extended to a three reactor plant.

Figure 2 shows schematically the functional implementation philosophy of the actuator controller supervisory module.

A prototype of the supervisory control concept was built according to Figure 2 for demonstration in 1988. The supervisory module was implemented using an in-house modified version of the expert production system OPS5 running under Lucid Lisp on a SUN4 computer.

The supervisory module contains sets of rules that demonstrate the capabilities for dynamic interaction of an expert system with plant simulators, the operator, and automatic controllers. There are rules to monitor upper and lower parameter limits, block and unblock the operator and/or the automatic controller from operating groups of actuators as needed, respond to operator demands for manual, automatic, and heuristic control, set demand setpoints, and change the values of the cost function weights of the automatic controllers.

The plant simulator package consists of simulations of two LMR type plants: one consisting of a single nuclear reactor and its turbine, and the other consisting of three nuclear reactors sharing a single turbine. Both simulations are written in the Advanced Continuous Simulation Language (ACSL) and run on a SUN3 computer.

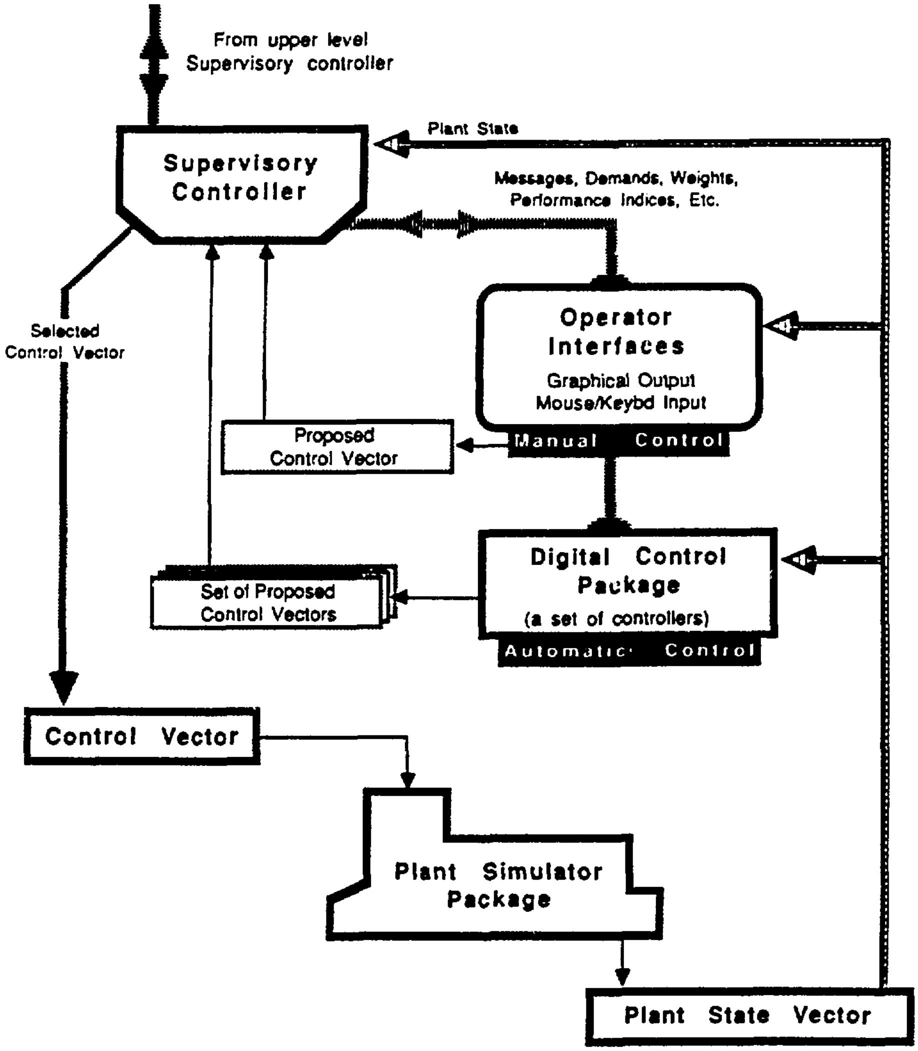

Figure 2
Implementation Philosophy for the
Actuator Controller Supervisory Module

The operator interface consists of two consoles. The main console shows live data in windows over color-coded plant schematics and permits the operator to display trend data and exercise plant control by means of active actuator icons (with consensus of the supervisory controller). It was developed with the object oriented graphics package DVTools and runs in a SUN3 computer. The second console allows the operator to change demands, weights, and control modes from the keyboard and to display their present settings in alphanumeric form. It is written in Lucid Lisp and runs in a SUN4.

The digital control package consists of an optimal nonlinear distributed controller, developed for the single reactor LMR as part of the research on decomposition of large scale systems and nonlinear control techniques, and it is described in the appendix. Additional implementation and management strategies are being considered for nonlinear, fuzzy, heuristic and classical controllers such as PID, LQG, LQG/LTR etc. for incorporation into this module. Both ACTO staff and universities are contributing in this subject area.

The control algorithms used in the supervisory control demonstration presume that the signals are noise free and validated and that the actuators perform their functions as told. Nevertheless, as indicated earlier, the algorithms have an inherent capability for signal and actuator failure diagnosis.

We are presently working on the extension of the single reactor plant achievements to a three reactor power block and in speeding up the simulations. To this end we are migrating the simulation software to the C language on ACTO's ENCORE parallel computer. To derive the control equations from the dynamic equations we use the symbolic mathematics package Mathematica[5]. To solve the resulting set of nonlinear differential equations we use the numerical package SLATEC. Figure 3 shows the target implementation goal for 1989.

Based on SUN's Remote Procedure Call (RPC) specifications, software links have been implemented across a network of SUN computers and the ENCORE parallel computer. This distributed computational network mimics the functionality of the real plant and its controllers. With it, we have run simulations of plants consisting of up to three reactors, a turbine, operator interfaces and a supervisory controller, wherein each component runs on its own CPU and shares access to data such as state and control vectors with the rest of the processes in the network. This, not only allows faster execution of the programs promotes modularity and permits dynamic reconfiguration of the simulation.

Conclusions

The proposed hierarchical architecture supervisory control of multimodular plants is rather suitable for implementation in a network of distributed computers.

A new approach to large scale system decomposition has been used to implement the lower level supervisory controller of a single core LMR. In this approach the subsystem interaction terms are automatically generated by the optimal control algorithm as it matches plant signal data with its internal model predictions. This provides a set of time dependent parameters that can be used for online diagnosis by an expert system, thus transforming the black box coordinator module typical of classic distributed systems[6] into an intelligent supervisor.

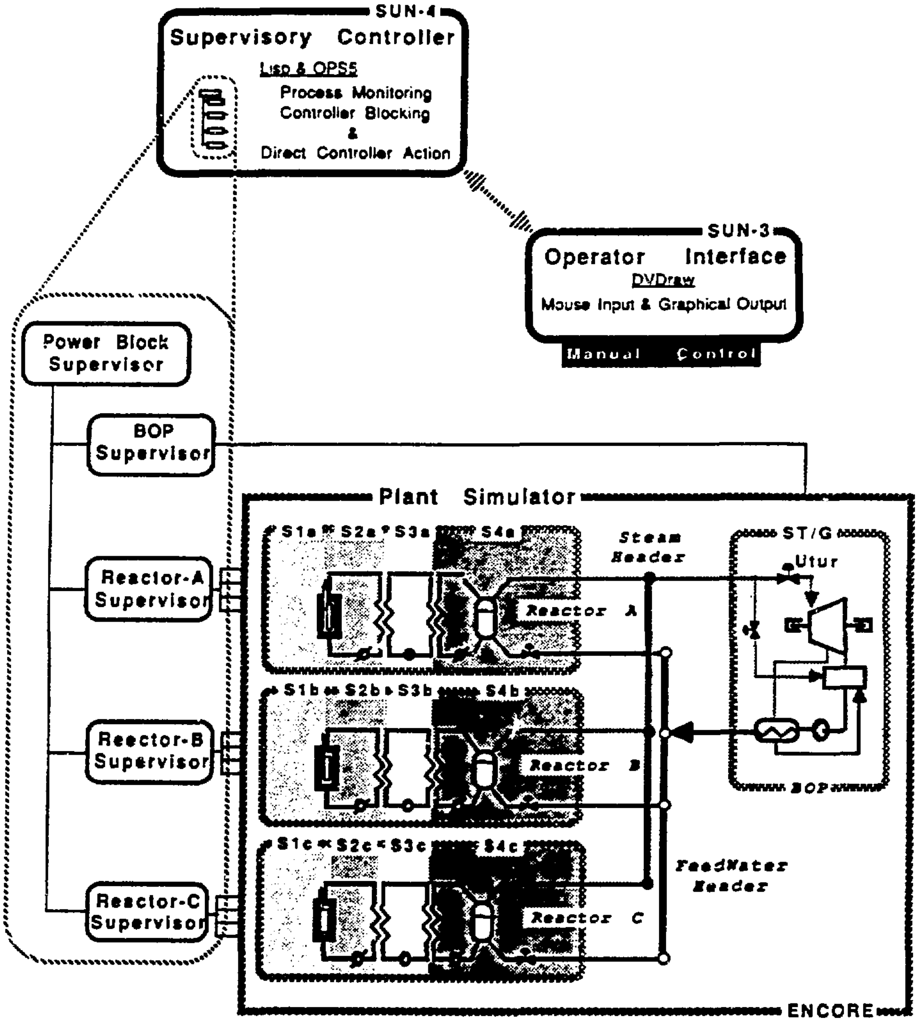

Figure 3
Implementation Goal for 1989

Implemented as an expert system, the supervisory module interacts with operator interfaces and distributed controllers to perform heuristic control, monitor subcontroller performance, establish demand distributions and change control weights to synchronize changes of control laws on the run.

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Appendix
Results of nonlinear control research work

The goal of our research on decomposition of large scale systems and nonlinear control techniques is to develop control algorithms with a good potential for robustness and for online performance monitoring and reconfiguration management. To this end we have concentrated efforts in the area of optimal control of nonlinear systems with unmodeled dynamics[4], i.e. based on mathematical descriptions that account for the inevitable fact that models are never exact representations of the real plant dynamics.

A novel approach[2] to system decomposition has been developed on the basis of the following mathematical formulation: let **F** be the exact descriptor of the state variable vector **X** of a process whose dynamics are governed by

$$\frac{d\mathbf{X}}{dt} = \mathbf{F}(\mathbf{X},\mathbf{U})$$

where **U** is the control vector, and let **F'** represent the best mathematical description available for that process, and **X'** be the corresponding state variable vector, such that

$$\frac{d\mathbf{X}'}{dt} = \mathbf{F}'(\mathbf{X}',\mathbf{U})$$

An optimal control algorithm for the process governed by **F** can be found using **F'** by incorporating a time dependent unknown term into the controllers model. That is, rather than relying on **F'** alone, the control algorithm can be derived using

$$\frac{dX'}{dt} = F'(X', U) + U_{nk}$$

where U_{nk} represents a time dependent term which will end up accounting for dynamic interactions and other effects unknown to **F'**. Note that these U_{nk} terms automatically generate an operation performance index suitable to online analyses by means of artificial intelligence techniques. As discussed later, the temporal behavior of the unknown terms can be monitored with an expert system to diagnose plant reconfiguration and controller and sensor performance.

The unknown terms and optimum control vectors result from the application of Pontryagin's Maximum Principle to two Hamiltonian functions, one with a term weighing the difference between state variable values **S** observed in the actual plant (provided by sensors) and **X'** generated by the internal model of the controller, i.e.

$$H_T = \frac{1}{2}(S - X')^2 Q_T + \frac{1}{2}(U_{nk} - U_{nk0})^2 R_T + \lambda^T (F'(X', U) + U_{nk})$$

and the other with a term weighing the difference between the demands **D** and the actual status of the corresponding state variables **X'**:

$$H_c = \frac{1}{2}(D - X')^2 Q_c + \frac{1}{2}(U - U_0)^2 R_c + \omega^T (F'(X', U) + U_{nk})$$

where:

U_{nk}	is the unknown terms vector
U	is the control vector
Q_T, R_T, Q_C, R_C	are weight matrices, and
λ, ω	are adjoint state vectors, respectively.

The following system of nonlinear differential and algebraic equations results,

$$\frac{dX'}{dt} = F'(X', U) + U_{nk}$$

$$\frac{d\lambda}{dt} = -\frac{\partial H_T}{\partial X'} \qquad \frac{d\omega}{dt} = -\frac{\partial H_c}{\partial X'}$$

$$\frac{\partial H_T}{\partial U_{nk}} = 0 \Rightarrow U_{nk} = U_{nk}(X', \lambda) \qquad \frac{\partial H_c}{\partial U} = 0 \Rightarrow U = U(X', \omega)$$

$$H_c(X'(T_r), U(T_r), \lambda(T_r)) = 0 \qquad H_T(X'(T_r), U_{nk}(T_r), \omega(T_r)) = 0$$

The above approach can be used for the development of controllers with a variety of features by treating the feature of interest as an unknown term. Algorithms for multivariate optimal control with parameter tracking capabilities can and have been implemented on this same mathematical basis[3].

Of particular interest is the case in which one purposely discards state variables from the plant model in order to decompose a large scale system into subsystems in a unique manner[2]. Then the total plant dynamics are described by a set of subsystems which are governed by equations such as

$$\frac{dX'_i}{dt} = F_i(X'_i, U_i) + U_{nk_i}$$

in which the subindex i represents a particular subsystem and $\mathbf{U_{nk}}$ represents that part of the interaction dynamics with the rest oi the system which are unaccounted for by the subsystem's model. The set of differential and algebraic equations for the distributed optimal controllers and synthesis of the interaction vectors are similar to those for the full plant shown above. Since there is no coupling between the internal model equations of each subsystem's controller, different integration time steps and/or CPUs can be used for each subsystem.

The application of this innovative decomposition technique to reactor control[3] is discussed below with the help of Figures 4 and 5.

Figure 4.a shows an schematic of a power plant consisting of a single reactor, its turbine, a set of sensors (where T, P, F, L, N, and Z stand for temperature, pressure, flow, level, neutron power, and control rod position respectively), and a set of control actuators (where U1, U2, U3, U4 and Utur represent control rod drive, primary pump, intermediate loop pump, feedwater valve, and turbine admission valve respectively). A multivariate nonlinear centralized optimal controller for this plant was developed based on the knowledge of the equations governing the plant operation. This centralized controller required the solution of a set of 87 nonlinear differential equations (NDE) and 13 algebraic equations (AE) every time step. It runs 20% slower than real time with ACSL on a VAX 11/780.

Figure 4.b shows the structure of the four subsystem controllers obtained by decomposing the centralized controller into a set of local controllers and the resulting unknown terms. Each controller generates its own control vector every time step while simultaneously computing the unknown term, which permits matching the plant measurements and the internally computed states. Demand coordination between the local controllers and

diagnostics were done by means of an internal supervisory

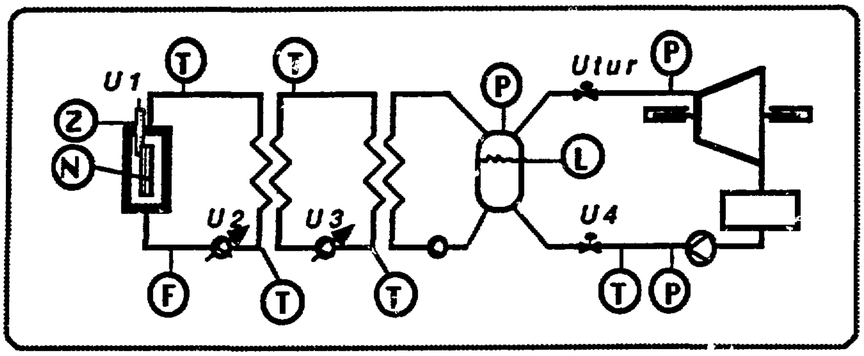

Figure 4.a
Single Reactor and Turbine Plant Schematic

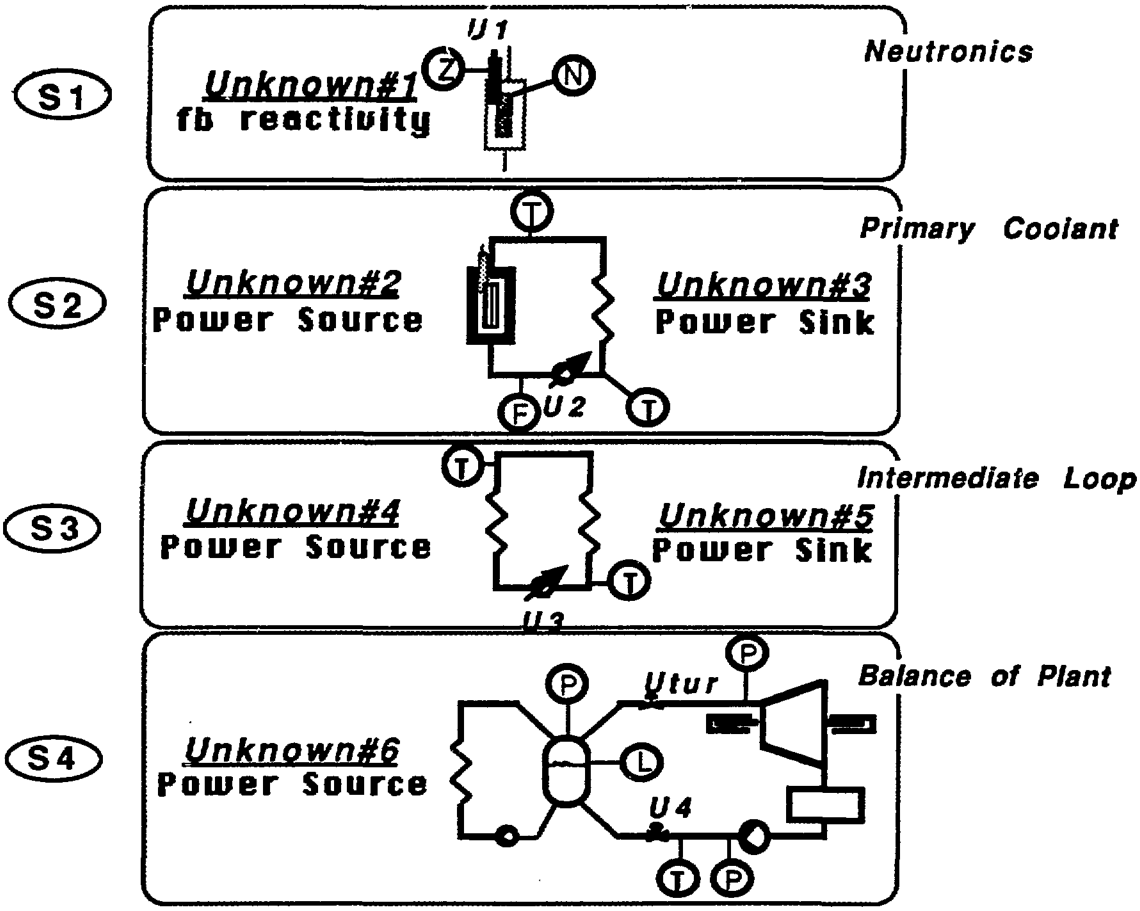

Figure 4.b
Single Reactor Plant Subsystem Decomposition

subroutine. The overall number of equations for this case was 48

NDEs and 13 AEs and their solution runs 40% faster than real time with ACSL on a VAX 11/780.

The subsystem's decoupling points were selected on the basis of either physical boundaries, such as heat exchangers, in which energy but not mass transfer occurs, or processes similarities, such as heat sources and heat sinks, as is the case of subsystems S2 and S3 in Figure 4.b. Consequently, the unknown terms represent the coupling effects between systems and have a physical meaning thus providing an insight on the process being controlled. Note that in reality, the unknown terms, in addition to reflecting the temporal behavior of their associated physical parameters, include contributions from abnormally faulty signals and mismatches between the process and the subcontroller's internal model. It is the role of the supervisory module of these four local controllers to monitor the consistency and temporal dependence of the unknown terms, diagnose abnormal behavior and take corrective action as appropriate.

The overall controller structure for this single reactor plant supervisory system is shown in Figure 5. Note that this is equivalent to the bottom level of the hierarchical structure shown in Figure 1.

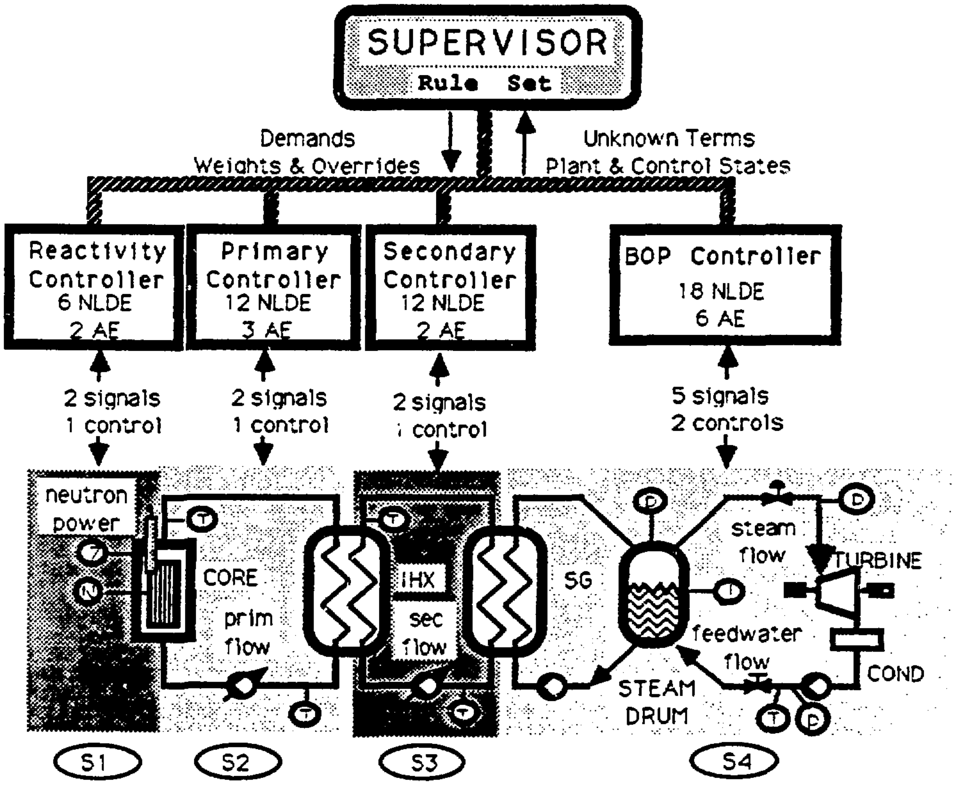

Figure 5
Supervisory Distributed Control