Controller System to Aid Diagnostics

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Topics

- Background on MIT control research.
- Vision for controller structure.
- Supervisory control of neutronic power.
- Model-based control law.
- Rule-based control.
- Progress towards automated diagnostics.

Note: Several figures in these notes have been removed for copyright reasons.
Readers are referred to the following U.S. Patents by Dr. J. A. Bernard for more information:
1) Apparatus and Method for Closed-Loop Control of Reactor Power:
Standard Dynamic Period Equation (No. 4,637,911)
2) Apparatus and Method for Closed-Loop Control of Reactor Power:
Alternate Dynamic Period Equation (No. 4,710,341)
3) Apparatus and Method for Closed-Loop Control of Reactor Power in Minimum Time
(No. 4,781,881)

Background

- Project began in late 1970s. Principal areas of research include:
  - Modeling of system components.
  - Signal validation with analytic redundancy.
  - Fault-tolerant operation.
  - Reactivity constraint approach.
  - Closed-loop digital control experiments.
  - Rule-based control.
  - Period-generator control.
  - Use of predictive displays.
  - Expert systems.
  - Real-time PWR model (space-time).
  - Steam generator level control.
  - Multi-modular control.
  - Spacecraft reactor control.

Goals

- Develop theoretical basis for generic methodologies for the closed-loop digital control of nuclear reactors:

  a) Neutronic power
  b) Core temperature
  c) Steam generator level

- Demonstrate these methodologies under conditions of closed-loop digital control on several research/test reactors:

  a) 5 MWt MIT Research Reactor
  b) SNL's Annular Core Research Reactor

- Control techniques are to be based on rigorous models of reactor dynamics.

  a) For research and test reactors, this has meant deriving non-linear space-independent models, the dynamic period equations.

  b) For large PWR cores, this has meant developing numerical codes that describe spatial and temporal behavior both accurately and in real time.

Anticipated Benefits

- Large PWR Cores:
  - Improved reliability.
  - Maintain competitiveness with non-U.S. vendors.
  - Alter man-machine interface so that reactor operation is monitored by both man and digital surveillance system.
  - Reduce incidence of challenges to safety system.
- Research and Test Reactors
  - Generate experimental evidence of the validity of the control concepts.
  - Provide a generic method for the closed-loop, digital control of these reactors.
- Space Reactors
  - Provide the enabling technology for space nuclear propulsion.
- Multi-Modular Reactors
  - Allow operation with unbalanced loads so as to avoid need for simultaneous refueling of all modules
  - Contain costs by limiting number of operating crews.

Major Accomplishments

1970s — Real-time model of reactor components.

1981 — Signal validation and instrument fault detection.

1983 — Reactivity constraint approach.

1985 — Rule-based control.

— Rigorous derivation of dynamic period equation.

— NRC license approval of reactivity constraint approach.

1986 — MIT-SNL minimum time laws.

— On-line reconfiguration of control laws.

1987 — Achievement of time-optimal control of neutronic power.

— Demonstration of MIT theories on SNL's Annular Core Research Reactor.

1988 — Development of near real-time codes for the determination of neutronic and thermal-hydraulic behavior in cores characterized by spatial dynamics.

Major Accomplishments (Cont.)

1988 — Derivation of conditions for global stability and stability against oscillations about a specified trajectory.

— The incorporation and extensive evaluation of proportional-integral-derivative feedback in the MIT-SNL period-generated minimum time control laws.

1989 — Preliminary efforts for the control of system temperature.

— Design of a controller for power and temperature in cores characterized by spatial dynamics.

— Incorporation of a fixed source term in the nodal code QUANDRY to permit the study of source effects on reactor power increases from subcritical.

1990 — A comparative assessment of the merits of spatial versus point kinetics as a means of properly describing a reactor's dynamics during startup.

1992 — Experimental studies to illustrate need for controller self-diagnostics.

Reports

1. Fault-Tolerant Systems Approach Toward Closed-Loop Digital Control of Nuclear Power Reactors, (Jan. 1988/NSF)

    - Reactivity Constraint Approach

2. Formulation and Experimental Evaluation of Closed-Form Control Laws for the Rapid Maneuvering of Reactor Neutronic Power, (June 1989/SNL-DOE).

    - Development of MIT-SNL Control Laws

3. Startup and Control of Reactors Characterized by Space-Independent Kinetics, (April 1990/SNL-DOE).

    - Applications of MIT-SNL Control Laws

4. Closed-Loop Digital Control of Power and Temperature in Reactors Characterized by Spatial Kinetics, (Sept. 1990/DOE)

    - Extension of MIT Control Concepts to PWR Cores

5. Studies on the Closed-Loop Digital Control of Multi-Modular Reactors, (Nov. 1992/DOE-ORNL).

    - Control of Multi-Modular Reactor and Steam Generator Level

6. Bernard, J.A. and T. Washio, Expert Systems Applications Within the Nuclear Industry, American Nuclear Society, La Grange Park, IL (Oct. 1989).

Vision for Controller Structure

1. Features

   - Separation of safety and control systems.
   - Multi-tiered structure.
     - — Supervisory loop.
     - — Control law loop.
   - Signal validation.
   - Use of reconfiguration logic to select control law.
   - Automated reasoning to identify reactor state and evaluate controller performance.

2. Status

   - All components developed and demonstrated experimentally except for the automated reasoning.

Supervisory Control of Neutronic Power

- Reactivity Constraint Approach
  - Developed in 1983.
  - Demonstrated on-line under closed-loop control for MIT Research Reactor in 1983.
  - Demonstrated on-line under closed-loop control for SNL's Annular Core Research Reactor in 1988.
  - Under patent (U.S. /Canada) to MIT.

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Effect of Reactor Dynamics on Reactor Control

- Changes in reactor power are determined by the behavior of the prompt and delayed neutron populations.

  (a) Prompt Neutrons:

  - Produced directly from fission.
  - Generation time is typically 100 microseconds.
  - Directly proportional to the fission rate.
  - Subject to immediate control by altering the fission rate.

Effect of Reactor Dynamics on Reactor Control
(continued)

(b) Delayed Neutrons:

- Produced from daughter nuclides that result from the beta decay of certain fission products.
- Generation time averages 12.2 seconds.
- Not proportional to the fission rate but rather a function of the power history.
- Not subject to immediate control.

- If power overshoots are to be averted, it is essential to limit the delayed neutron contribution so that, upon attainment of the desired power, the insertion of the control mechanism will make the rate of change of the prompt neutrons sufficiently negative so as to offset the continued increase in the delayed neutrons.

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Non-Linear Model of Reactor Dynamics

- Dynamic Period Equation:
  - Gives the instantaneous reactor period as a function of the rate of change of reactivity, the reactivity, and the rate of redistribution of the delayed neutron precursors.
  - Obtained by differentiating the neutron kinetics equation and then substituting to eliminate terms containing precursor concentrations.
  - The in-hour relation is a specialized form of this equation.
- Advantages to its use:
  - Rigorous within limits of space-independent kinetics.
  - Describes all reactor behaviors from subcritical to prompt critical.
  - Explicitly shows each physical process that can affect the reactor period.

Dynamic Period Equation

1. It is useful to relate reactivity to period. Most text books do this by use of the Inhour Equation which is valid only a long time after reactivity changes. A more general relation, one that is valid under all conditions, is the dynamic period equation. (This relation was developed at MIT in the mid-1980s and is the basis of MIT's very successful program on digital control of reactors.) A simplified version is:

$$\tau(t) = \frac{\bar{\beta} - \rho(t)}{\dot{\rho}(t) + \lambda_e(t)\rho(t)}$$

where $\tau(t)$ = is the reactor period,

$\bar{\beta}$ = is the effective delayed neutron fraction,

$\rho(t)$ = is the net reactivity,

$\dot{\rho}(t)$ = is the rate of change of the net reactivity, and

$\lambda_e(t)$ = is the standard, effective multi-group decay parameter.

Dynamic Period Equation (cont.)

Quantity	Meaning
$\dot{\rho}(t)$	— Rate of change of reactivity. This is proportional to the prompt neutron population. Changes in the velocity of a control device therefore have an immediate effect on the period.
$\lambda_e(t)\rho(t)$	— This term is proportional to the delayed neutron population. Reactivity can not be changed on demand. Rather, a control device's position has to be altered or the Burnable poison concentration has to be adjusted. This takes time.

Dynamic Period Equation (cont.)

2. It is important to note that the reactor period depends on both the rate of change of reactivity ($\dot{\rho}$) and the total reactivity (ρ). The former corresponds to prompt neutron effects; the latter to delayed ones. Hence:

   (i) The speed at which one changes reactivity alters the period. This is the basis of power cutbacks that involve high speed rod insertions.

   (ii) The reactor period is a function of the power history because the decay term reflects the power level that existed when the delayed neutron precursors were created. This is one reason why it is important to approach a final power level slowly.

   (iii) The relation between period and reactivity is not readily solved. Hence, operators may find predictive displays to be of use.

Dynamic Period Equation (cont.)

$$\tau(t) = \frac{\left(\overline{\beta} - \rho(t)\right) + 1^{*}\left[\dfrac{\dot{\omega}(t)}{\omega(t)} + \omega(t) + \lambda_e(t) - \dfrac{\dot{\lambda}_e(t)}{\lambda_e(t)}\right]}{\dot{\rho}(t) + \lambda_e(t)\rho(t) + \dfrac{\dot{\lambda}_e(t)}{\lambda_e(t)}\left(\overline{\beta} - \rho(t)\right)}$$

where the standard, effective, multi-group decay parameter is defined as:

$$\lambda_e(t) \equiv \Sigma\lambda_i C_i / \Sigma C_i(t) \quad \text{for } i = 1, N$$

and where symbols not previously defined are:

$\dot{\omega}(t)$	is the rate of change of the inverse of the dynamic reactor period,
$\omega(t)$	is the inverse of the dynamic reactor period,
$\dot{\lambda}_e(t)$	is the rate of change of the standard, effective, multi-group decay parameter,
$C_i(t)$	is the concentration of the i<u>th</u> precursor group normalized to the initial power, and
N	is the number of groups of delayed neutrons, including photo-neutrons.

Supervisory Control

- Traditional function of a control algorithm is to specify plant trajectory and, if the actual state differs from the desired one, generate a feedback signal to reduce the error.

- For safety-constrained systems, the control algorithm should also both define the envelope of conditions under which it will be possible to halt the transient and preclude operation beyond that envelope.

- Supervisory control is especially important for non-linear or time-delayed systems.

Feasibility of Control

- A system is controllable if it is possible to transfer "any initial state to any final state in a finite time by some control sequence". This property places no restrictions on the trajectory taken between the initial and final states.

- A reactor is 'feasible to control' is it can be transferred from some initial power level and rate of change of power (i.e., period) to a desired steady-state power level without overshoot. This concept limits the allowable trajectories.

  – Excludes trajectories involving actual overshoots.

  – Excludes states from which overshoots could not be averted by manipulation of the specified control mechanism.

- 'Controllability' concerns only the capability to change from one state to another. 'Feasibility of control' is more restrictive because it also concerns the capability to remain in the final state. That is, can the transient be halted?

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Constraint Approach

- Implementation of supervisory control is achieved by utilizing constraints that take the form of inequalities:
    - The time required to establish conditions under which the force driving the transient can be negated must be less than the time remaining to attain the limiting condition.

- No use is made of predictive models.

- The intent is to allow a real-time decision to be made as to the need to alter the present control signal in order to avoid a future challenge to a limiting condition.

Controller Design

-- If power is to be leveled smoothly, must limit the delayed neutron contribution so that, upon attainment of the desired power, the insertion of the control mechanism will make the rate of change of the prompt neutrons sufficiently negative so as to offset the continued rise in the delayed neutrons.

$$[\lambda_e(t)\rho(t)+\frac{\dot{\lambda}_e(t)}{\lambda_e(t)}(\overline{\beta}-\rho(t)] \leq |\dot{\rho}_c|$$

where $|\dot{\rho}_c|$ is the maximum available rate of reactivity change.

Note that $|\dot{\rho}_c|$ is always a positive number regardless of whether or not the control mechanism is moving.

Contraint Approach Applied to Nuclear Reactors

- Constraints have been developed for reactors subject to limitations on:
  - Neutronic power
  - Energy production
  - Temperature
- If power is to be leveled smoothly, must limit the delayed neutron contribution so that, upon attainment of the desired power, the insertion of the control mechanism will make the rate of change of the prompt neutrons sufficiently negative so as to offset the continued rise in the delayed neutrons.

$$[\rho(t) - |\dot{\rho}_c| / \lambda_e(t)] / |\dot{\rho}_c| \leq \tau(t) \ln(P_F / P(t))$$

where $|\dot{\rho}_c|$ is the maximum available rate of reactivity change.

Model-Based Control Laws

1. Investigated a number of techniques for the control of reactor power.

    - Proportional control (no model).
    - Feed forward control.
    - State-space methods (linear).
    - Time-optimal.

2. Method of choice is "period-generated" control which is analogous to the "computed-torque" method in robotics.

Background

1. Period-generated control was developed for purpose of adjusting nuclear reactor power in a very rapid yet safe manner.

2. Intended application is control of spacecraft reactors that will be used for manned expeditions to Mars.

3. Principal result of research is the MIT-SNL Period-Generated Minimum Time Control Laws which have been shown through experiment to be capable of safely raising reactor power by five-seven orders of magnitude in a few seconds.

Period-Generated Control

- Method for tracking trajectories that are defined in terms of a demanded rate.
- Control signal is computed by first using feedback to generate a demanded inverse period (a velocity) and then substituting that inverse period into a system model.
    - Use of feedback compensates for perturbations and modeling errors.
    - Use of model compensates for non-linear dynamics.
- Characteristic feature is rapid change of control signal upon transient initiation and termination.
- Advantages are that the technique is:
    - Readily implemented.
    - Applicable to non-linear systems.
    - Capable of near time-optimal response.

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Basis of Period-Generated Control

- Define error signal by comparison of demanded and observed trajectories.

- Compute demanded inverse period in terms of the error signal.

- Process the error signal through an inverse model of the system dynamics to obtain control signal.

- Apply control signal to actual system.

$$e(t) = \ln[n_d(t + j\Delta t)/(n(t)]$$

$$\omega_d(t) = [e(t) + (1/T_i) \int e(t)dt + T_d\dot{e}(t)]/j\Delta t$$

$$\dot{u}_c(t) = \widehat{R}(t)\,\omega_d(t) - \hat{r}(t) + [\omega_d(t) - \omega(t)]/k\Delta t$$

$$\omega(t) = \left(R(t)\right)^{-1}[\dot{u}_c(t) + r(t) - \dot{\omega}(t)]$$

MIT-SNL Period-Generated Minimum Time Control Laws

Standard:

$$\dot{\rho}_c(t) = (\overline{\beta}-\rho(t))\omega(t) - \lambda_e(t)\rho(t) - (\dot{\lambda}_e(t)/\lambda_e(t))(\overline{\beta}-\rho(t)) - \dot{\rho}_f(t)$$

$$\ell^*\dot{\omega}(t) + \ell^*((\omega(t))^2 + \lambda_e(t)\omega(t) - (\dot{\lambda}_e(t)/\lambda_e(t))\omega(t))$$

Alternate:

$$\dot{\rho}_c(t) = (\overline{\beta}-\rho(t))\omega(t) - \lambda'_e(t)\rho(t) - \Sigma\overline{\beta}_i(\lambda_i-\lambda'_e(t)) - \dot{\rho}_f(t)$$

$$\ell^*\dot{\omega}(t) + \ell^*((\omega(t))^2 + \lambda'_e(t)\omega(t))$$

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Real-Time Calculation Of Delayed Neutron Precursor Concentrations

- Calculation of precursor concentrations requires simultaneous solution of the neutron and precursor kinetics equations. This is difficult because of the extreme stiffness of the first of these equations.

- Solution is to decouple the neutron and precursor kinetics equations by assuming a particular shape for the neutronic response during each sampling interval. Precursor equations, which aren't in themselves stiff, are then solved using time steps on the order of the sampling interval (0.05 s - 1.0 s).

- Studies were made of the method's accuracy using linear, polynomial, and exponential shapes. Linear was chosen because it is simplest to program and quite accurate.

- Technique is referred to as 'Time Integration Method with An Assumed Power Profile.'

Accurate Tracking of Non-Linear Systems

- The feedback signal is computed from a comparison of the demanded and observed values of the system output. This signal is then input to an inverse dynamics model of the process that is being controlled. The solution is a form of feedforward control in the sense that the output of the inverse dynamics calculation is the actuator signal which, upon application to the actual process, will cause the system output to track the demanded trajectory.

$$e(t) = \ln[n_d(t + j\Delta t)/(n(t)]$$

$$\omega_d(t) = [e(t) + (1/T_i) \int e(t)dt + T_d \dot{e}(t)]/j\Delta t$$

$$\dot{\rho}_c(t) = \widehat{R}(t)\,\omega_d(t) - \hat{r}(t) + [\omega_d(t) - \omega(t)]/k\Delta t$$

$$\omega(t) = (R(t))^{-1}[\dot{\rho}_c(t) + r(t) - \dot{\omega}(t)]$$

- The combination of the inverse dynamics calculation and the feedforward action results in a canceling of the system dynamics:

$$\omega(t) = \omega_d(t) + (R(t))^{-1}\Big[[\omega_d(t) - \omega(t)]/k\Delta t - \dot{\omega}(t)\Big]$$

$= \omega_d(t)$ once acceleration effects die out.

Near Time-Optimal Behavior

- Most techniques for achieving time-optimal control are computation-intensive. Even with modern computers, a time-optimal trajectory must often be computed off-line and applied in an open-loop manner. No use of feedback is possible.

- Period-generated control combines feedback with a system model to generate the control signal that corresponds to movement along a given path. If a system is limited by a certain rate, then selection of the path that corresponds to that rate will result in a response that is very close to time-optimal.

- Period-generated control therefore offers near time-optimal performance with the corrective action of feedback.

Rule-Based Control

1. Study of rule-based control is useful in order to appreciate human capability to do diagnostics.

2. Study was done at MIT in 1984-1985 to answer certain questions.

   - Should rule-based systems be used for process control?
   - Can rule-based and analytic approaches be merged?
   - Can diagnostic expert systems be developed for controllers?

Human Approach to Process Control

1. Planning
   - Goal formulation.
   - Evaluate options.
   - Determine desired response.
2. Prediction
   - Form expectation of plant response based on mental models, knowledge of trends, equipment status.
3. Implementation
   - Initiation of the control action (often automated).
4. Assessment
   - Characterized by two feedback loops.
     - — Was the control signal implemented?
     - — Was the control signal properly formulated?
   - The operator must decide if his or her mental model is valid.
   - Must compare current observation with previously-made predictions. Was the model in error or has the plant changed?

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Design of Rule-Based Controller

1. Identified the rules that operators use by use of questionnaires and observation.

2. Translated these rules into mathematical statements via fuzzy logic.

3. Assembled a set of 21 rules and used that set as a closed-loop controller on the MIT Research Reactor in 1985.

"Fuzzy" Logic

1. Humans express themselves in linguistic terms. For example, the reactor period is "too short."
2. Fuzzy logic is a means of describing and combining these linguistic terms in a manner suitable to a digital system.

Example:

- An observed reactor period might be described with the labels "too short," "short," or "negative." Transitions between labels are not abrupt and a given reading might belong to several groups. Thus, a positive period of 90 seconds might be "too short" to degree 0.2, "short" to degree 1.0 and "negative" to degree 0.0.
- The parameter being classified (the period) is a "universe of discourse."
- Individual labels ("too short") are "subsets" of that universe.
- The degree to which a measured value belongs to a subset is its "grade of membership."

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Assessment of Rule-Based Controllers

1. Rule-based controller achieved control over a wide range of initial conditions, including non-equilibrium ones.

2. Rule-based and analytic approaches were of comparable accuracy, with analytic one slightly better.

3. Response time of analytic system superior.

4. Rule-based system insensitive to high frequency noise.

5. Rule-based system very difficult to maintain.

6. Rule-based system more tolerant of sensor failures.

Possible Role of Rule-Based Systems

1. Rule-based systems are robust. Use to return plants to a safe condition on failure of analytic controls.

2. Provide "reasoning" behind decisions of analytic controllers to human operators.

3. Further research is necessary to develop efficient methods for the calibration of rule-based systems. In particular, uniform methods for defining the functions that describe the linguistic variables are needed.

Progress Towards Automated Diagnostics

1. Method being explored emulates the human approach to diagnostics.

    - Did system respond as expected? This requires availability of predictive model.

    - If not, what are the symptoms of the problem?

    - Once a symptom is identified, what are the possible causative agents?

2. One of the last publications from the MIT-SNL Program reprinted a series of experiments that illustrated the need for automated diagnostics:

    - Bernard, J.A. and F. J. Wyant, "Experiments Illustrating the Importance of Automated Reasoning," IEEE Control System Magazine, Vol. 12, No. 2, April 1992, pp 84-92.

Survey of 1992 Experiments

1. Normal Response: Power increase 3.0 kW - 12 MW on a demanded period of 0.60 s. Spectacular Result.

2. Effect of initial rod bank height an ability to complete a transient: If the available rate of reactivity change is insufficient, the controller fails. (Too slow and achieved wrong power level).

3. Effect of incorrect reactivity estimate: Degraded performance results.

4. Effect of failed sensor: Controller functions adequately because of signal validation.

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Automated Diagnostics

1. Each of the three experiments shown corresponds to a problem with a different parameter.
    - Rate of change of reactivity
    - Reactivity
    - Power Level

2. This suggests an approach to automated diagnostics. Express the system in state-space and try to identify each aberrant behavior as initiating from a particular state variable.
    - Assumes all state variables are measurable.
    - Assumes each is identifiable. This may not be achievable given signal noise.
    - Requires linearized system.

Diagnostics

1. The diagnostic analysis would be done using a multi-layered approach.

    - Evaluation of system response.
    - Symptom identification.
    - Fault identification.

2. System response is judged by means of comparing desired and actual response.

3. System identification may perhaps be done using the state-space representation.

4. Fault identification may be done using expert system approach subject to assumption that all causes for a symptom deviation are pre-identified and instrumented so as to be detectable.

Inpact of Automated Diagnostics

1. Two experiments are shown:

   - For first one, an error in a safety command caused a premature halt of the control device, and the run failed.

   - For the second, the run was completed successfully despite a dropped rod.

2. This raises another major unresolved issue. To what extent should an automated diagnostic system be allowed to implement corrective action when safety is involved?

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