APPLICATIONS OF FUNCTIONAL REDUNDANCY
TO
INSTRUMENT FAILURE DETECTION IN NUCLEAR REACTORS

A consulting report to the
Nuclear Regulatory Commission
by
Robert W. Albrecht
July 17, 1979

requested by
William S. Farmer
Reactor Safety Research
Nuclear Regulatory Commission

Contents

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Background

At the Surveillance and Diagnostics Review Group meeting held June 8, 1979 in Bethesda, this consultant suggested that the techniques of functional redundancy showed promise in applications to instrument failure detection in nuclear power plants. It was further suggested that instrument failure detection based on functional redundancy would have warned the TMI operators that the pressurizer level indication was not to be relied upon as an inference of water level in the primary system. Mr. W. S. Farmer suggested that this consultant prepare a brief report on the application of functional redundancy to instrument failure detection in nuclear reactor systems.

Subsequent to this meeting the subject of instrument failure detection by methods of functional redundancy was raised by this consultant and by Prof. R. N. Clark of the University of Washington Electrical Engineering Department at the International Colloquim on Two-Phase Flow Instrumentation held in Idaho Falls, Idaho, June 10-14, 1979. Prof. Clark made a presentation to the contractor's meeting at the invitation of Dr. G. D. McPherson on Wednesday, June 13. Minutes of this meeting were transmitted by R. D. Wesley to participants on July 2, 1979 including recent papers by Prof. Clark.

Prof. Clark was asked to prepare a brief proposal and bibliography for support of investigations in this area by Mr. D. J. Hanson of E. G. & G. A copy of his proposal and bibliography (dated July 11, 1979) is attached.

Technical Possibilities

The principles of instrument failure detection by functional redundancy are covered in Prof. Clark's attached proposal. Broadly, the idea is to compare signals from dissimilar sensors using a plant model to generate estimates of significant state variables of the plant. Redundancy is achieved by a computer model that compares state estimators from various sensors. Tests for consistency with the physics of the plant may signal sensor failure if a sensor is inconsistent with others.

Hardware redundancy and voting logic is common to nuclear plant instrumentation and control systems. To this consultant's knowledge, functional redundancy for instrument failure detection has never been applied to a nuclear power plant.

Functional redundancy may be viewed in a nuclear power plant as supplemental to hardware redundancy. A well-constructed functionally redundant instrument failure detection system may provide operators with additional information not available from the hardware redundant system. The outstanding example of this is the pressurizer level indication at TMI. No number of (hardware) redundant level sensors would have given an indication that a false inference of primary system coolant level was to be expected from the pressurizer level reading. However, since a functionally redundant system would have automatically required consistency between primary and secondary pressures and temperatures and known mass flows into and out of the primary system with pressurizer level it would have sensed and reported that pressurizer level was inconsistent with other state variables of the plant. Following relatively simple logic based on HPI, letdown, leakage, and break flows and using standard instrument readings supplemented by steam tables and tabulated correlations it appears quite probable that a consistent model of coolant inventory in the post-trip state could be economically constructed and used for instrument failure detection.

Since functional redundancy depends on plant modelling and implementation of the model in a digital computer the mere act of implementing a functionally redundant instrument failure detection system increases the understanding of the interrelationship between various instrument responses and the state variables of the plant. It is now clear that further understanding of the plant response and the associated instrument responses is valuable to enhancing safety.

It should be emphasized that the application of functional redundancy to instrument failure detection is not only a specific response to the TMI incident but this technique is broadly applicable to both accident states and normal operation of nuclear power plants. Also the models required for implementation of this technique can be continually improved as experience is gained. Still another fringe benefit is that it may be useful to have real-time computational models of the plant or of subsystems on call to operators for projecting potential response to changes in operating state or for assistance in the diagnosis of anomalous behavior.

An attractive aspect of the application of functional redundancy to instrument failure detection is that it requires no retrofitting or additional sensors in a power plant. It may require some signal conditioning and buffering to bring plant process signals to the dedicated instrument failure detection computer. Because of this minimal disturbance to the plant, functional redundancy can be implemented in operating nuclear power plants with little or no interference with normal operation.

Algorithms and models for functionally redundant instrument failure detection can be devised using basic physical data for the plant and components. The parameters in the models and the operating characteristics of the instrument failure detection system may be tested using power plant simulators.

Incorporating functional redundancy in addition to hardware redundancy can aid in verifying that an apparent (hardware) instrument failure is truly an instrument failure rather than an anomalous change in plant conditions. Therefore, false alarms due to instrument failures can be reduced.

The logic of implementing instrument failure detection by functional redundancy naturally forces the designer to consider the natural grouping of interrelated variables. One of the weaknesses identified in the design of reactor control rooms is the format for display of interrelated information to operators. By using plant models based on the interrelationships of variables in a real-time situation it is likely that new and innovative methods for presenting the essential state variables of the plant will emerge. These new methods of information presentation can be tested for their qualities in enhancing the man-machine interface through simulators.

It is not necessary for an entire nuclear power plant to be modelled in detail in order to apply this technique. The method may be applied to relatively isolated subsystems (examples: feedwater system, start-up instrumentation, coolant inventory at shut down, reg rod position-reactivity-burnup interrelationships, fuel handling systems, etc.). In some cases highly accurate modelling may be required to detect subtle differences that signal a lack of consistency between sensors but in other cases the modelling requirements may be quite modest.

State of the Art

The technique of instrument failure detection by functional redundancy has been a subject of academic research for several years. Prototypical systems have reached a proof-of-principle stage in the aero-space industry. The technique depends upon computer modelling and interfacing the computer to the plant and sensors. Preliminary indications are that fault detection by this method may be accomplished reliably with tolerable false alarm rates.

An attractive aspect of the state of the art is that the computer field is progressing very rapidly and one may anticipate quite large capacity, reliable, fast, small size, computer facilities will be available to implement this technique at a power plant site.

An ultimate configuration that one could envision is a parallel computer model for plant components with detailed modelling for diagnostic purposes and a general purpose model for overall plant model comparisons.

Serious effort will be required to apply the methods of functional redundancy in the nuclear power plant field. One current limitation is that essentially all of the reported investigations of this technique have been to linear, lumped parameter systems. In many cases the reactor system to which the technique may be applied may be reasonably modelled linearly or it may be modelled by some piecewise linear approximation about nominal operating states. On the other hand, cases probably exist that are strongly nonlinear and basic investigations of the applicability of functional redundancy will be required to determine if the method can be applied.

Statistical investigations of tolerable system noise and the tolerance of the methods to model inaccuracies will by required in order to produce a robust instrument failure detection system that is minimally susceptable to false alarms.

Recommendations

It is recommended that NRC initiate an investigation of the potential applications of functional redundancy to instrument failure detection in nuclear power plants. This investigation should include specific trial applications using simulators and/or actual plant demonstrations. The applications should focus on those safety issues for which operator information is most sensitive (small break LOCAs, for example). Vendors and utilities should have a vested interest not only in enhancing safety through application of these techniques but also in using these methods for plant optimization. Naturally academic researchers have an interest in studying the fundamentals of these techniques and in applying them to prototypical situations. In addition it is important to carefully define limitations of the methods due to model errors, nonlinearities, noise, etc.

Because of the potential of these methods for contributing to reactor safety with a minimal disturbance and because of the wide range of interested organizations, it is recommended that NRC seek assistance of national laboratories, industry and universities in formulating a goal oriented program to enhance reactor safety by application of the techniques discussed above.

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11 July 1979

Mr. D. J. Hanson
Manager
Semiscale ES & A Branch
EG & G Idaho, Inc.
Idaho Falls, Idaho 83401

Dear Mr. Hanson:

At your request of June 14, 1979 I am submitting this informal letter proposal for support of investigations into methods of applying the techniques of functional redundancy to certain nuclear reactor instrumentation systems. This work is intended to enhance reactor safety by providing means to detect instrumentation failures as they occur. When you are prepared to go ahead with this work I can have an official proposal ready in two working days.

FAILURE DETECTION BY FUNCTIONAL REDUNDANCY

Sensor failure detection in automatic systems is normally accomplished by some form of logical comparison of redundant signals. The simplest form of redundancy employs multiple sensors of identical type. The signals from these sensors are compared in a voting logic scheme. This is known as "hardware redundancy" because the redundant signals are generated by the redundant sensors installed in the plant. In recent years it has become clear that redundant signals can be generated from non-redundant instruments, using the techniques of estimation theory, coupled, in some cases, with statistical decision theory. These methods are known as "functional redundancy", "analytical redundancy", and other terms. They have been developed in the aerospace industry and to some extent also in the electric power industry. A bibliography of literature in this field is appended herewith.

Basically these techniques employ a sub-system, consisting entirely of computers operating on-line, which have one (or several) state estimators each of which generates a multidimensional signal (the estimated state vectors). These several estimated state vectors, along with the sensor signals themselves, constitute the set of redundant signals used for detection of failures in the hardware components of the plant. In most cases a considerable excess of redundant signals are available, which allows a designer certain freedoms in both the design of the state estimators themselves and in his choice of logical schemes to accomplish the failure detection.

Failure detection by functional redundancy is still the subject of much research effort, but some applications of it have already been accomplished and much of the research results have indicated the feasibility of some specific approaches to the failure detection sub-system design. It is therefore feasible to attempt an application of these techniques in nuclear reactor instrumentation systems, as is proposed here.

POTENTIAL APPLICATIONS TO NUCLEAR REACTOR SYSTEMS

At the meeting of June 14, 1979 three problem areas were identified as candidates for possible application of functional redundancy to failure detection and other instrumentation problems. These three are Reactor Vessel Liquid Inventory (RVLI), Subcooling Meter (SM), and Maximum Linear Heat Generation Rate (MLHGR). The first two of these problems seem to be important in emergency circumstances, such as a loss of coolant accident, whereas the third problem seems to pertain more to normal operations of the reactor, to achieving optimal fuel efficiency, for example. From the viewpoint of promoting reactor safety it therefore seems that the first two of these problems should receive priority in these studies. Beyond this consideration there appear to be other reasons as well for attempting to apply functional redundancy initially to these first two problem areas. Among these reasons is that the plant model in emergency circumstances could be relatively simple as compared to a model of a fully operating plant.

PROPOSED INVESTIGATION

Because the SM problem is essentially one of establishing a sophisticated thermodynamic model that relates the estimated subcooling to many pressure and temperature measurements it appears to be a less tractable application of the existing techniques of functional redundancy than does the RVLI problem. The instrumentation problem of determining mass flow from indirect measurements of liquid level, pressure differences, etc., each measurement carrying its own noise, is related to the problem of estimating the state of a dynamic system with a Kalman filter, as in a functionally redundant failure detection scheme. For these reasons attention will be focused on the RVLI problem, at least at the inception of these studies.

A reasonable starting point is to establish a model of the primary cooling loop which is valid for some significant conditions of break flow and ECC flow and at the same time is amenable to the techniques of functional redundancy. This model should include decay heat generation, heat transfer to the coolant, coolant fluid mechanical conditions, pressure drops and temperatures, as well as primary coolant geometries and reactor operating conditions (charging flow, letdown flows, RCS pump status, leakage flows, etc.). Integrated with the system model the instrument responses to the dynamic state of the reactor must be represented. Very simple system and instrument models will be adopted initially in order to investigate the feasibility of using functional redundancy to identify instrument failures during accident conditions. During the Three Mile Island incident the failure of the pressurizer level indicator to properly reflect the coolant inventory was a major factor leading to fuel failure. It may be possible, even with simple models, to utilize functional redundancy to alarm in cases with such large errors as were present at Three Mile Island.

The plant and instrumentation models will be implemented on the University of Washington digital computer. Assistance with establishing an appropriate model for these studies will be sought at EG & G and other interested laboratories and industries. These models will be evaluated by standard techniques. The aim of this research is to augment the plant and instrument models with an instrument failure detection sub-system designed with the principles of functional redundancy. The total system will be tested to determine the efficiency of the instrument failure detection scheme (i.e., failure detection without false alarms) under different types of primary system breaks.

Because nuclear reactors consist of a large number of relatively independent sub-systems it is possible to monitor the instruments in a particular sub-system (such as the feedwater system, the control rod drive system, or the condensate system) by a failure detection sub-system which is identified with only that particular sub-system. During the course of the research on the main problem described here it is anticipated that opportunities for applying failure detection techniques in these other sub-systems will become evident, and perhaps will be pursued.

I will look forward to proceeding with you further on these studies.

Very truly yours,

Robert N. Clark
Professor and Associate Chairman

RNC:mk
Enclosures:
(1) Resumé of Principal Investigator
(2) Bibliography on Instrument Failure Detection
(3) Budget

RESUME OF PRINCIPAL INVESTIGATOR

NAME:	Robert N. Clark
TITLE:	Professor and Associate Chairman of Electrical Engineering, University of Washington
BIRTH:	April 17, 1925, Ann Arbor, Michigan
EDUCATION:	BSE-EE University of Michigan, 1950 MSE-EE University of Michigan, 1951 Ph.D. Stanford University, 1969

Professional Societies

IEEE, Senior Member
AIAA, Associate Fellow

Professional Experience

1957 - Present	University of Washington, Department of Electrical Engineering. Research on pulse-modulated systems, instrument failure detection, stability of nonlinear systems, and linear systems. Teaching undergraduate and graduate courses in circuits and systems, mechanics, electromagnetic fields. Consulting for various firms in aerospace control systems and electromechanical system design.
1976 - 1977	Fraunhofer Gesellschaft, Institut für Informationsverarbeitung in Technik und Biologie (IITB), Karlsruhe, West Germany. Visiting Scientist, research on instrument failure detection methods in automatic control systems.
1966 - 1968	NSF Fellowship and Lecturer, Stanford University. Studies in applied mathematics and optimization. Research in stability of pulse-modulated systems.
1951 - 1957	Honeywell, Inc., Research Engineer. Analysis and development work in electromechanical and hydraulic systems, and inertial systems and components.

Military Service

1943 - 1946	U.S. Marine Corps., Radar Technician

RESUME OF PRINCIPAL INVESTIGATOR (Page 2)

NAME: Robert N. Clark

Publications (Recent Journal Articles and Book)

1. Clark, R. N., "A Simplified Instrument Failure Detection Scheme," IEEE Trans. Aero. and Elect. Syst., Vol. AES-14, No. 4, July 1978, pp. 558-563.
2. Clark, R. N., "Instrument Fault Detection," IEEE Trans. Aero. and Elect. Syst., Vol. AES-14, No. 3, May 1978, pp. 456-465.
3. "Control of Lateral Motions of the TERRAFOIL Transit Vehicle" (with J. E. Furman and B. J. Hartz), AIAA Jour. Spacecraft and Rockets, Vol. 14, No. 2, pp. 118-123, February 1977.
4. "Stability of Ultimate Motion in an Attitude Control System with Unbalanced Thrusters" (with H. A. Kolve), AIAA Jour. Spacecraft and Rockets, Vol. 13, No. 9, pp. 513-514, September 1976.
5. Clark, R. N., Masreliez, C. J., and Burrows, J. W., "A Functionally Redundant Altimeter," IEEE Trans. Aero. and Elect. Syst., Vol. AES-12, No. 4, July 1976.
6. Clark, R. N., Fosth, D. C., and Walton, V. M., "Detecting Instrument Malfunctions in Control Systems," IEEE Trans. Aero. and Elec. Syst., Vol. AES-11, No. 4, July 1975, pp. 465-473.
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Professor Robert N. Clark
University of Washington
July, 1979

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Also included in this list are a few references in linear control and estimation theory, Kalman filters, and Luenberger observers (Ref. 48-53).

No attempt is made here to cover the literature in allied fields such as fault tolerant computers, redundancy management, or system reliability.

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PROPOSED BUDGET

FAILURE DETECTION IN NUCLEAR REACTOR SYSTEMS

9/16/79 -- 9/15/80

	% of TIME	AMOUNT REGUESTED
SALARIES AND WAGES:		
Principal Investigator --		
R.N. Clark, 3 Mos.	50	$ 4,971.
R.N. Clark, 2 Mos.	100	6,628.
Predoctral Research Associate II, 12 Mos.	50	7,144.
Research Assistant, 12 Mos.	50	6,385.
		$ 25,128.
FRINGE BENEFITS:		
Faculty @ 16%		1,856.
Students @ 8%		1,082.
		$ 2,938.
SUPPLIES:		
Miscellaneous Electronic Supplies		1,000.
TRAVEL:		
1 trip to East Coast to National Conference (Air Fare, $434., Per Diem, 5 days @ $50. per day, and Ground Transportation.)		700.
5 Trips to Idaho Falls, R.T. Air Fare, $175. 10 days Per Diem at $40.per day, Ground Transportation		1,300.
		$ 2,000
OTHER EXPENSES:		
Computer Time		$ 1,000.
Secretarial Services		3,000.
Postage, telephone, duplicating, etc.		250.
		$ 4,250.
TOTAL DIRECT COST:		$ 35,316.
Indirect Costs, 57% of Direct Salaries		14,323.
TOTAL AMOUNT REQUESTED:		$ 49,639.

Addressees for Letter dated AUG 28 1979

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