A CSA MODEL-BASED NUCLEAR POWER PLANT CONSULTANT

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ABSTRACT

An experimental computer-based nuclear power plant consultant is described. The inference procedures interpret observations of a particular plant situation in terms of a commonsense algorithm network model that characterizes the normal and abnormal events of a pressurized water reactor plant. This paper discusses the knowledge and control structures, and illustrates the operation of the system with situations from the accident at Three Mile Island.

INTRODUCTION

The concern for nuclear power plant safety on the part of the Nuclear Power industry, its Federal Regulators and the general public was increased by the accident at Three Mile Island. Among the recommendations of two committees [1,3] that studied that accident were that there be: new NRC requirements to ensure that qualified engineer supervisors with intimate knowledge of the plant be a part of the onsite supervisory management chain on every reactor operating shift, new mechanisms to incorporate operating experience into regulatory programs, and new programs for improved operator training.

A computer-based consultant could support the implementation of some of these recommendations. Namely, a knowledge base of nuclear power plant operation, procedures, and experience coupled with an automatic diagnostic capability might provide onsite expert advice. A committee of nuclear power plant experts could update the knowledge base on the basis of new experience. Coupled with a tutorial system the knowledge base might also be used for operator training.

Much of the knowledge required to diagnose nuclear power plant problems involves knowledge of the physical mechanisms of the nuclear power plant itself as well as its normal and emergency operator procedures. Commonsense Algorithms (CSAs) [2] have been used to model physical mechanisms but there have been no expert systems specifically designed to use CSA's as a knowledge base.

The purpose of the research described in this paper is to investigate the use of commonsense algorithms and expert systems technology in representing knowledge of nuclear power plants for use in problem diagnosis and intervention.

In the next section of this paper commonsense algorithms are reviewed and illustrated with a CSA model of a nuclear power plant subsystem. Then the inference rules and control strategy of a prototype computer-based consultant that uses the knowledge base is described. Next a sample consultation involving the Three Mile Island accident is sketched. Finally, the preliminary results are summarized and other factors in the ongoing development of the system are discussed.

COMMONSENSE ALGORITHM NETWORK MODELS

The Commonsense Algorithm (CSA) representation has been used for describing physical mechanisms [2], and as the basis for problem solving and language comprehension systems. The CSA representation for physical mechanisms consists of 4 event types and 9 relations. The events are actions (A), tendencies (T), states (S), and statechanges (SC). The 9 relations (or links) are oneshot causality (OS-CAUSE), continuous causality (C-CAUSE), repetitive causality (R-CAUSE), state coupling (S-COUPLE), equivalence (EQUIV), antagonism (ANTAG), enablement (C-ENABLE), threshold (THRESH), and rate confluence (RATE-CONFL). The first 5 types of relation can be "gated" by conditions that must hold for the causal relationship to continue to hold.

Some of the events and relations are illustrated in Fig. 1. In the explanation that follows the verbal description is cross-referenced with the event (En). The pilot-operated relief valve (PORV) could be explained in English as follows:

If there is a positive statechange in vapor pressure (E1) that thresholds at 2200 psi (E2), then the pressure switch closes (E3). As long as the solenoid wires are intact (E4), there will be EMF in the solenoid (E5) that will enable the tendency magnetism (E7) to continuously cause the solenoid plunger to be out (E9) provided it is not stuck in a closed position (E8). Because of a mechanical link to the PORV, the PORV will be open (E11) provided it is not stuck in a closed position (E10). This is equivalent to a negative statechange in vapor pressure (E16) and coolant in the reactor coolant system (E17) provided the block valve is open (E12). When the negative statechange in vapor pressure thresholds at 2100 psi (E18), the pressure switch will open (E19) so that there is no longer EMF in the solenoid (E20), and the solenoid plunger will retract (E22), closing the PORV (E23).

Note that both normal and abnormal states and processes are represented in the network. No claim is made that the CSA representation for this example is complete nor that all the events are at the same level of description.

The CSA network for the PWR power plant currently consists of a model of the primary coolant system including the coolant pumps, reactor, pressurizer (a part of which is the PORV previously described), steam generator, and emergency core cooling system. Events which are symptomatic of system problems and which cause alarms and automatic control actions are also represented in the model. Operator actions in response to alarms are represented as sequential commonsense algorithms.

Diagnostic rules are also represented in the CSA network. For example, the three states "containment pressure greater than normal", "radiation level greater than normal", and "recirculation sump level greater than normal" are all continuously caused by the accident state "loss of reactor coolant" which would be caused by any number of abnormal states.

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($MECHANISM
  (NAME PORV_SYSTEM)
  (EVENTS
    (1 SC (PRESSURE VAPOR X 2200 POS))
    (2 S (PRESSURE VAPOR 2200 POS))
    (3 S (PRESSURE SWITCH CLOSED))
    (4 S (SOLENOID WIRE INTACT))
    (5 S (EMF IN SOLENOID))
    (6 S (INDICATOR LIGHT ON))
    (7 T (MAGNETISM))
    (8 S (SOLENOID PLUNGER NOT STUCK))
    (9 S (SOLENOID PLUNGER OUT))
    (10 S (PORV NOT STUCK))
    (11 S (PORV OPEN))
    (12 S (BLOCK VALVE OPEN))
    (13 S (BLOCK VALVE CLOSED))
    (14 A (OPEN BLOCK VALVE))
    (15 A (CLOSE BLOCK VALVE))
    (16 SC (PRESSURE VAPOR 2200 2100 NEG))
    (17 SC (COOLANT IN RCS NEG))
    (18 S (PRESSURE VAPOR 2100 POS))
    (19 S (PRESSURE SWITCH OPEN))
    (20 S (NO EMF IN SOLENOID))
    (21 S (INDICATOR LIGHT OFF))
    (22 S (SOLENOID PLUNGER IN))
    (23 S (PORV CLOSED)))
     (LINKS (THRESH (1 2))
            (S-COUPLE (2 3))
            (S-COUPLE (3 5) (4))
            (S-COUPLE (5 6))
            (C-ENABLE (5 7))
            (C-CAUSE (7 9) (8))
            (S-EQUIV (9 11) (10))
            (S-EQUIV (11 16) (12))
            (OS-CAUSE (14 12))
            (OS-CAUSE (15 13))
            (ANTAG (12 13))
            (S-EQUIV (16 17))
            (THRESH (16 18))
            (S-COUPLE (18 19))
            (ANTAG (3 19))
            (S-COUPLE (19 20))
            (S-COUPLE (20 21))
            (ANTAG (6 21))
            (EQUIV (20 22) (8))
            (EQUIV (22 23) (10))
            (ANTAG (11 23)))
     (PURPOSE (2 18))
     (NORMAL (19 4 21 8 10 23 13))
     (TRIGGER (2)))
```

Figure 1. CSA Representation of a Pilot Operated Relief Valve.

CONTROL STRATEGY

A consultation usually begins with a human operator requesting diagnosis of the cause of some abnormal event such as a negative statechange in pressurizer pressure, a positive statechange in containment pressure, or a containment temperature greater than normal. The consultation may also begin with a request for diagnosis of the cause of some automatic action of the control system in response to the previously mentioned abnormal events. Such actions include "reactor trip", "safety injection", and containment isolation".

The control strategy first indexes into the CSA net to locate these events. There are only four types of accidents to be diagnosed: loss of reactor coolant, loss of secondary coolant, steam generator tube rupture, and spurious actuation of safety injection. Hence a forward chaining control strategy is used. When a causal event is infered that has immediate effects that are observable but not verified, the control strategy asks the operator to verify these in order to further confirm the inference.

An operator is sometimes faced with the task of interpreting observations that are seemingly contradictory. The CSA network model can be used to interpret the meaning of these observations and thus resolve many of the apparent conflicts. If conflicting observations are received, the conflict is noted, and the diagnosis is undetermined until additional observations on the basis of the causal model can be obtained and additional inferences can be drawn from the model to resolve the conflict.

SAMPLE CONSULTATION

A sample consultation between an operator and the consultant system is shown in Fig. 2. The operator asks for advice on abnormally low vapor pressure in the coolant system. The consultant diagnoses the problem as loss of coolant (LOCA), and predicts that the Emergency Core Cooling System (ECCS) will come on. When the operator reports that the ECCS is on, the consultant predicts that it will cutoff. When the operator reports rising water level in the pressurizer, the consultant suspects that the PORV is open. When the operator asks whether the ECCS can be turned off, the consultant says not, and explains that since coolant is being lost from the system, if the ECCS is turned off, the reactor core will eventually become uncovered.

In the TMI accident the operators could not decide that they were encountering an LOCA. Instead they were confronted with what they thought was contradictory information. The pressure of the coolant system was low, indicating a loss of coolant, but the water in the pressurizer was rising, indicating (they thought) a surplus of coolant. Using the CSA model the system is able to generate pathways to the observed states and gives alternative explanations to the asserted and denied states.

Thus the escape of steam from the top of the pressure vessel is determined to be an explanation of the rising water level in the pressurizer, so that rising water level in one part of the system does not contradict loss of coolant in the overall system.

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]CSANET
TYPE EVENT FOR WHICH YOU WANT ADVICE.
* (SC (PRESSURE VAPOR * * NEG))
  (S (PRESSURE VAPOR ?))
* 1800
  (S (TEMP CONSTANT))?
* YES
  (S (REACTOR TRIP))?
* YES
  IMMEDIATE OPERATOR ACTIONS COMPLETED?
* YES
  DIAGNOSIS:  LOSS OF COOLANT ACCIDENT
  PREDICT:
   (S-COUPLE (S (PRESSURE VAPOR 1600))
             (S (ECCS ON)))
  SUGGEST:
   IMPLEMENT EMERGENCY PROCEDURE FOR
   LOSS OF COOLANT ACCIDENT
* (S (ECCS ON))
  (S (PRESSURE VAPOR ?))
* 1700
  PREDICT:
   (THRESH (S (PRESSURE VAPOR 2000))
           (S (ECCS OFF)))
* (SC (LEVEL COOLANT-IN PRESSURIZER
        * * POS))
  (S (PORV OPEN))?
* NO, (A (TURN OFF ECCS))?
  NO
* WHY?
  (S-COUPLE
     ((SC (AMT COOLANT 2000 1600 NEG))
      (S (ECCS OFF)))
     (S (REACTOR-CORE UNCOVERED)))
*
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Figure 2. Sample Consultation

RECOMMENDED INTERVENTIONS

Knowledge of the emergency procedures and possible interventions by the operators can also be represented by CSA networks. In some cases the CSA net representation of emergency procedures can be associated with the diagnostic category. In other cases the system may search the CSA model for the location of the specific source of the problem to determine the corrective intervention for the problem. Intervention may introduce factors that were not considered in the original diagnosis, so that it is appropriate to infer the effects of remedial actions prior to recommending them. History of other problems or progression of the diagnosed problem may be factors in selecting which alternative procedures to recommend. It may also be necessary to reason as to why the procedures may not be correcting the problem.

RESULTS AND DISCUSSION

Expert system technology and commonsense algorithms provide a useful framework for organizing knowledge of nuclear power plants. The current knowledge base is a subset of the knowledge required for useful advice on actual plant operation.

The current system consists of a 350 event CSA model of a PWR coolant system constructed by a nuclear engineering expert, a CSA network simulator for designing and testing the models, and a diagnostic program that uses a forward chaining control strategy. Of the various expert systems this prototype most closely resembles CASNET or EXPERT [4]. It differs from those systems primarily in the use of CSA nets, the integration of the diagnostic rules into the CSA nets, and in its simulation capability.

Data on frequency of component failure or abnormal events can be included in the model to aid in determining certainty of competing hypotheses. Since some of the "facts" that the operators report are inferences or beliefs they may be asked to associate a certainty factor with their assertions.

The models of plant operation, event diagnosis and plant intervention will be experimentally validated using the methodology used to test MYCIN [6]. This involves comparing the results of the computer-based consultant with results obtained from nuclear power plant operators and nuclear engineers with varying levels of experience presented with the same case studies. Independent human experts in nuclear plant operation would then evaluate the results and rank the computer-based consultant at the appropriate level of expertise.

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