Redundant Sensor Calibration and Estimation for Monitoring and Control of Nuclear Power Plants

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INTRODUCTION

Performance, reliability and safety of nuclear power plants depend upon validity and accuracy of sensor signals that measure plant conditions for information display, health monitoring and control [1]. Validity of measurements is important because a sensor failure can have serious consequences. Thus, it is essential to regularly ensure correct operation of sensors, in particular for those having great importance for operating safety, to locate and identify any possible degradations and faults.

However, periodic maintenance strategies cause the unnecessary calibration of instruments that are operating correctly which can result in premature aging, damaged equipment, plant downtime, and improper calibration under non-service conditions. Recent studies have shown that less than 5% of process instrumentation being manually calibrated requires any correction at all. Therefore, plants are interested in monitoring sensor performance during operation and only manually calibrating the sensors that require correction [2].

Redundant sensors are often installed to generate spatially averaged time-dependent estimates of critical variables so that reliable monitoring and control of the plant are assured. For example, temperature, pressure, and flow sensors are installed with redundancy in nuclear power plants. Redundancy can be classified into two groups: direct redundant data and analytical redundant data (using mathematical models of the physical system). In practice, analytical measurements may be the only source of supplemental redundancy for detection of plant component and sensor failures.

This paper presents a calibration and estimation filter for redundancy management of sensor data and analytical measurements. The filter is validated based on redundant sensor data of primary coolant temperature collected from simulator of IRIS (International Reactor Innovative and Secure) Nuclear Power Plant.

METHODOLOGY

The online sensor calibration problem has been investigated by many researchers. Hines *et al.* [2] reviewed the on-line monitoring techniques for performance assessment. Dorr *et al.* [3] explored fault-detection methods using direct and analytical redundancy. In this paper, a methodology using adaptive recursive filter for real-time calibration of redundant signals consisting of sensor data is presented.

Most critical process temperatures in nuclear power plants are measured using resistant temperature detectors (RTD) and thermocouples. Due to inherent deficiency or aging, temperature sensors can suffer from large calibration shifts, erratic and noisy output, response-time degradation and saturated output [4].

Individual measurements in a redundant set may often exhibit deviations from each other after a length of time. These differences could be caused by slowly time-varying sensor parameters, plant parameters, transport delays, etc. Consequently, some of the redundant measurements could be deleted by a fault detection and isolation (FDI) algorithm if they are not periodically calibrated. On the other hand, failure to isolate a degraded measurement could cause an inaccurate estimate of the measured variable [1]. This problem can be resolved by adaptively filtering the set of redundant measurements as follows: (1) Simultaneously calibrate all measurements online to compensate for their errors; (2) Adaptively update the weights of individual online, based on their respective a posteriori probabilities of failure instead of being fixed a prior.

In the event of an abrupt disruption of a redundant measurement in excess of the allowable bounds, the respective measurement is isolated by the FDI logic, and only the remaining measurements are calibrated to provide an unbiased estimate of the measured variable. On the other hand, if a gradual degradation occurs, the faulty measurement is not immediately isolated by the FDI logic. Instead, the relative weight of the degraded measurement is gradually decreased [1]. Since the weight of a gradually degrading measurement is smoothly reduced, the eventual isolation of the fault would not cause any abrupt change in the estimate.

APPLICATION TO IRIS

The calibration filter has been validated in IRIS model. IRIS is a modular pressurized water reactor with an integral configuration. It is offered in configurations of single or multiple modules, each having a power rating of 1000MWt (about 335MWe). The nominal reactor core inlet and outlet temperatures are 557.6°F and 626°F,

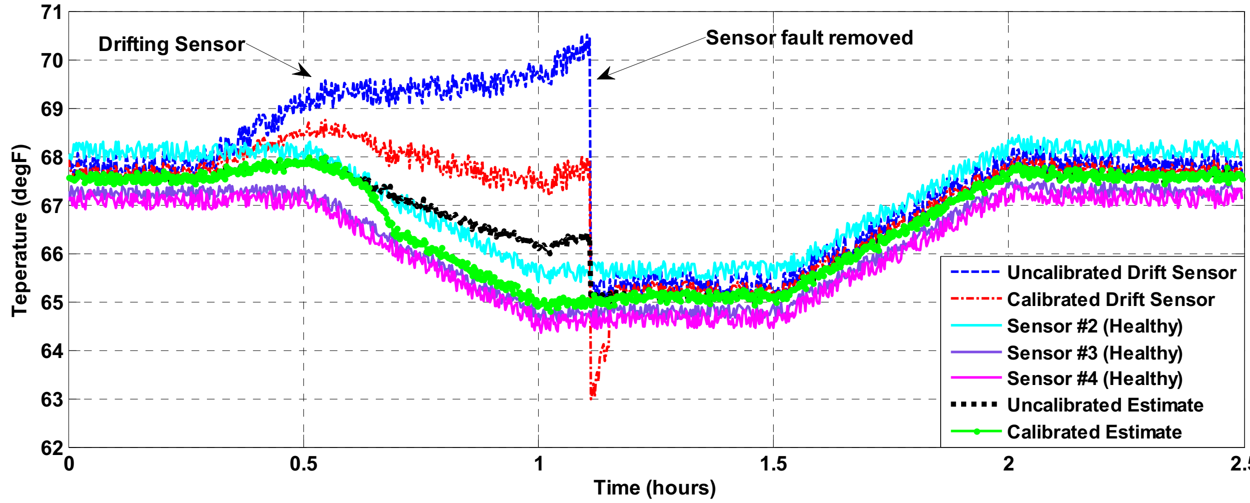

Fig. 1. Uncalibrated and Calibrated Sensors and Estimates

respectively. The set of redundant measurements is temperature sensors. The filter simultaneously calibrates the sensors to generate a time-dependent estimate of the temperature difference that is spatially averaged. This information on the estimated average temperature is used for health monitoring and damage prediction as well as for resilient control of the nuclear power plant under emergency operation, such as primary coolant pump failure [5].

The data has been collected from the IRIS simulator over a period of 2.5 h at the sampling frequency of once every 1 min. The nuclear power plant was under various output power load demand changes within the period. To simulate the sensor degradation, starting 0.3 h, a drift error was injected into the data stream of Sensor #1 in the form of additive ramp at the rate of 10°F/h. The injected fault was brought to zero at 1.1 h signifying that the faulty amplifier in the sensor hardware was corrected and reset.

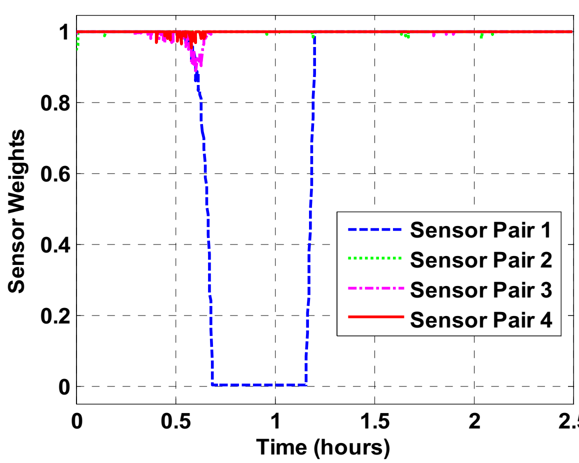

Fig. 2. Weights for Sensor Calibration.

Simulation results in Fig. 1 shows the response of the drift sensor, healthy sensors, as well as the estimate generated by weighted averaging of these four pairs at each sample. The calibrated estimate stays with the remaining three of healthy sensors even though Sensor #1 is gradually drifting. Fig. 2 shows the weight of the four sensor pairs. The weight of the drifting sensor reduces to zero as the deviation grows, and returns to normal when the fault is removed.

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