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Original Article

Modified parity space averaging approaches for online cross-calibration of redundant sensors in nuclear reactors

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ABSTRACT

To maintain safety and reliability of reactors, redundant sensors are usually used to measure critical variables and estimate their averaged time-dependency. Nonhealthy sensors can badly influence the estimation result of the process variable. Since online condition monitoring was introduced, the online cross-calibration method has been widely used to detect any anomaly of sensor readings among the redundant group. The cross-calibration method has four main averaging techniques: simple averaging, band averaging, weighted averaging, and parity space averaging (PSA). PSA is used to weigh redundant signals based on their error bounds and their band consistency. Using the consistency weighting factor (C), PSA assigns more weight to consistent signals that have shared bands, based on how many bands they share, and gives inconsistent signals of very low weight. In this article, three approaches are introduced for improving the PSA technique: the first is to add another consistency factor, so called trend consistency (TC), to include a consideration of the preserving of any characteristic edge that reflects the behavior of equipment/component measured by the process parameter; the second approach proposes replacing the error bound/accuracy based weighting factor (W^a) with a weighting factor based on the Euclidean distance (W^d), and the third approach proposes applying W^d, TC, and C, all together. Cold neutron source data sets of four redundant hydrogen pressure transmitters from a research reactor were used to perform the validation and verification. Results showed that the second and third modified approaches lead to reasonable improvement of the PSA technique. All approaches implemented in this study were similar in that they have the capability to (1) identify and isolate a drifted sensor that should undergo calibration, (2) identify a faulty sensor/s due to long and continuous missing data range, and (3) identify a healthy sensor.

1. Introduction

Redundant sensors are generally used in nuclear reactors to measure safety-related parameters for monitoring plant conditions during operation, start-up, and shutdown. Redundant sensors such as resistance temperature detectors, thermocouples, pressure transmitters, etc., are usually installed in reactors to check critical variables, and to assure reliable monitoring and control of the plant, their signals undergo adequate processing to estimate the averaged time-dependent signal [1]. These sensors are subject to long-term exposure to heat, humidity, vibration, and other effects that can cause damage to sensor bonding, response time, or measurement accuracy [2]. The degradation of these sensors is a major concern as they can give inaccurate records, especially in nuclear reactors where safety, reliability, productivity, and maintenance cost are major concerns.

To ensure safe and reliable operation, calibration of safety-related parameter sensors in nuclear reactors is performed regularly, for instance, once every fuel cycle. These calibration activities consume significant resources and time to isolate the instruments, calibrate them, and then return them to service. However, high-quality sensors maintain accurate measurements for more than 1 or 2 years and, therefore, calibrating them may mean wasting money [3,4]. Hence, using performance-based calibration rather than time-based calibration was introduced, leading to the development of on-line drift monitoring and cross-calibration (CC) techniques [2].

In online CC, redundant sensors' outputs are monitored during operation and then averaged to identify any deviation of the sensor signal from the estimated average. If the sensor signal is drifting

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outside the acceptable limits [5–7], the sensor either undergoes calibration, if possible, or must be isolated and replaced if it is no longer operable. CC is applicable to all types of process redundant sensors; it provides a better approach for pressure, level, and flow transmitters [2].

The CC method has four main averaging techniques: straight averaging, band averaging, weighted averaging (WA), and parity space averaging (PSA) [8].

Straight averaging is a simple averaging technique that does not consider weights for signal points; it simply calculates the sum of redundant signals and then compares each sensor signal to the average obtained. Band averaging is an averaging technique that involves applying an outlier band prior to the averaging process to eliminate the influence of outliers on the estimated average [3]. WA and PSA are averaging techniques based on weighting factors that can be calculated by including, distance-based weighting, as in the WA, or error bounds and band consistency–based weighting, as in PSA. Then, each weighting value is multiplied by its corresponding estimated sensor reading, aggregated with the others, and then used to generate an adequate estimated average [3,7–11].

PSA determines the consistency between redundant signals based on signals' error bounds; redundant measurement values are combined with the measurement error band; consistent signals that share bands are given consistency weights of 2, 3, 4, etc.; and inconsistent signals that have no shared band with any other signal points are given a consistency weight of 1 [3,5,9,11].

To improve calculations of the PSA, some factors such as characteristic edges and distance between signal points need to be considered. Edges in signal processing may indicate a transition between states or the occurrence of interesting/abnormal events [12] that may be signs of equipment failure. Therefore, these edges should be preserved in the calculation of the estimated average. To deal with this problem, the consistency of the signals, based on dynamic trends, can be considered. On the other hand, a distance-based weighting factor would be better to make the model totally data-driven model.

To compare the modified PSA approaches with the PSA approach applied by Electric Power Research Institute (EPRI) in the Instrument Calibration and Monitoring Program (ICMP) report, hydrogen pressure data sets from the cold neutron source (CNS) of a research reactor were used in the verification and validation [5].

2. Materials and methods

To make a justified comparison between the PSA approach implemented in the ICMP and the modified PSA approaches proposed in this article, the same data sets were used for all approaches, all signals were subject to the same preprocessing technique, and the same statistical implementation was used for defining the threshold and the uncertainty intervals. The data sets were collected from the CNS of a research reactor and qualified using the cross moving median (CMM) filter [13] to attenuate noise and outliers, as well as to recover the missing data needed to generate an estimate signal for each sensor. The reduction of noise and outlier effects is not only important for smoothing the signals but also to minimize the uncertainty estimate, which can exceed the drift allowance even when no drift is present [14].

Now, let us assume that we have a group of redundant signals from 1 to m (where m is the number of redundant signals, $m \geq 3$); they have been cleaned and estimated as $S_1, S_2, S_3, \cdots S_m$, and their weighting factors have to be determined and calculated for each specific signal (k) for a sample that has a time period from 1 to n. The ICMP PSA approach and three modified PSA approaches and their related statistical limits are explained in the following subsections.

2.1. Parity space averaging

A parity space approach defines the consistency relationship between pairs of measurements in the space; the distinct pairs of measurements with their measurement errors can be found in the consistency regions where intersections occur [11].

In the ICMP report [5], the PSA method was applied by obtaining two weighting factors: the accuracy weighting factor, which is named W^a in this study and is obtained by calculating the weights based on the signal accuracy (B) and the band consistency weighting factor C, obtained by determining how many signals are sharing their bands with others (see Fig. 1).

W^a is a weight that considers the instrument accuracy; this weight can allow the giving of greater weight to more accurate and narrow-range instruments than to wide-range instruments. In the ICMP report, W^a was calculated as in Equation (1) using the sensor accuracy [5]. However, in this study, the accuracies of redundant sensors under processing were unknown, and as the accuracy of an instrument is sometimes equal to its signal error bound, it was decided to use the confidence interval (CI), which represents the estimated signal error, instead. CI is a quantified limit of uncertainty degree around the measurement of parameter of interest; this limit adds a margin of error to the parameter [15].

$$W_k^a = \frac{1}{B_k^2} \tag{1}$$

where W_k^a is the weight of signal. (S_k)

B_k is the accuracy/error bound of the signal in Equation (3) and can be interpreted from the definition of 95% CI [16] in Equation (2), as follows:

$$95\%CI_k = mean(S_k) \pm 1.96\left(\sigma_{S_k}/\sqrt{n}\right) \tag{2}$$

$$B_k = 1.96\left(\sigma_{S_k}/\sqrt{n}\right) \tag{3}$$

σ is the standard deviation of the signal. (S_k), n is the sample length, $k = 1, 2, 3, \ldots$ m, and m is the number of redundant signals.

To determine the relationship between pairs of signals and their error bounds, as in the ICMP report [5], the condition of consistency check was applied to identify the consistency between any two signals from the redundant group based on the relation between them and between their error bounds; where the difference

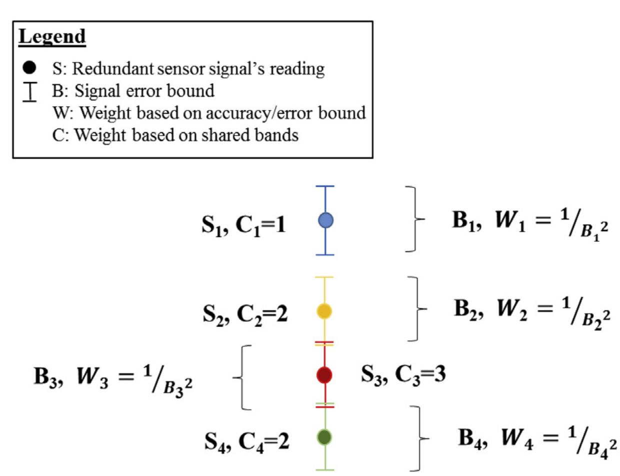

Fig. 1. Parity space averaging technique as implemented in the ICMP.
ICMP, Instrument Calibration and Monitoring Program.