374d Development of a Utility Function for Sensor Networks from a Fault Diagnosis Perspective

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Safety and optimality are crucial requirements in every industrial process. Modern day chemical plants, in particular, require comprehensive fault diagnosis procedures to function smoothly. The success of any fault diagnosis technique depends critically on the sensors measuring the important process variables. With thousands of possible measurements in a typical plant, the selection of variables for sensor placement is not an easy task. There has been considerable amount of work that has been done on developing algorithms for sensor network design for fault diagnosis based on qualitative graph models. Various objectives such as cost, reliability and fault resolution have been used in the sensor network design [1]. These design algorithms can provide the best sensor locations for a given cost, or minimize the cost required to achieve a target performance. While such networks are optimal with respect to the specified objective, the utility or benefit of the network is not quantified. Hence, the efficiency of the design is not transparent to the practising engineer.

In addition to fault diagnosis, the sensed data can be used for (i) optimizing process operation for maximizing productivity and (ii) controlling the process for enhancing product quality. Bagajewicz [2], in his book, reviews techniques for sensor selection based largely on state estimation and material accounting. Reviews of the hardware selection literature for controlled systems have also been published [3,4]. The above approaches are essentially optimal solutions to sensor network design problems, with the objective function or constraints arising from a single perspective, viz., material accounting, control or fault diagnosis. However, a single sensor network will be used in the field that may be used for all the above functions. Hence, the sensor network design problem is inherently a multi-objective optimization problem rather than a single objective one. The performance indices for sensor networks from differing perspectives (material accounting, control or fault diagnosis) are inherently incommensurate. One technique of solving multi-objective optimization problems is to build a suitable utility function. Thus while carrying out integrated sensor network design that simultaneously addresses these requirements, the economic value of the sensor network serves as a natural utility function for addressing such multi-objective problems. This will be the approach employed in this effort to build a suitable utility function for sensor networks from a fault diagnosis perspective.

Faults in a process can be classified as structural, parametric or sensor faults. Structural faults, in general, lead to shut-down and the value of a network that can diagnose structural faults can be calculated by the loss incurred during downtime. The value of detecting faults in control loop sensors can be calculated by quantifying unnecessary control effort that leads to loss in utility and the loss incurred from the products being off-spec. Biases in non-control variables are related to loss incurred through loss of precision. Gross errors in sensor faults can lead to loss in the ability of the network to detect and isolate faults. The value of detecting this fault can be quantified through the corresponding loss that one will incur. Parametric faults are characterized by measurable or inferable quantities. For example, changes in temperature, pressure etc. are measurable, while catalyst deactivation or heat exchanger fouling can be inferred by computing the catalyst activity or heat exchanger coefficient. This paper addresses the question of quantifying the value of a sensor network when parametric faults are assumed to occur.

A two step procedure for determining the value of a given sensor network from a fault diagnosis perspective is described in this contribution. In the first step, the set of resolvable faults for the given sensor network is determined. Resolvability refers to the property of the sensor network to identify the exact fault that has occurred based on available symptoms. This is a function of the chosen sensor network, the mode of occurrence of the faults and the fault diagnosis strategy employed. Subsequently, the value of the sensor network is determined using a probabilistic approach. The quantities used to parameterize the faults are treated as stochastic quantities. When a fault occurs, the plant operating conditions change and so does the operating profit. Depending on the sensor network, the resolvable faults can be detected and isolated in time. Hence, corrective steps can be taken to mitigate the effects of the faults and the plant can be restored to normal operation, if possible. Certain faults cannot be detected by the chosen sensor network, while certain other faults can be detected, but not isolated and so, the corrective action that one can take is limited. Thus, the operating profit of the plant is a random variable and is a function of the operating conditions, operating, control and diagnosis strategies, fault probabilities and various costs involved. More importantly, the operating profit is also a function of the chosen sensor network. The value of the sensor network, from a fault diagnosis perspective is thus chosen to be equal to the expected value of the operating profit.

The above procedure can be applied, in principle to any process and fault diagnosis strategy. To illustrate the procedure, a Signed DiGraph is used to model the cause effect relationship in the fault variables in this contribution. Techniques have been published to perform fault detection and isolation using the SDG [1]. These ideas are used to determine the set of resolvable faults using an enumerative algorithm for a given sensor network. It is assumed that only single faults can occur at a time. This assumption, while simplifying the analysis does not limit the power or applicability of the proposed approach. It is assumed that a resolvable fault is detected, isolated and corrected in time and the cost and time for correction is neglected while no action is taken when faults cannot be isolated. Monte Carlo calculations are performed to simulate the realization of the random quantities in a manner that is consistent with the above assumptions. The expected value of the operating profit is calculated using the above generated information and operating costs.

This procedure is illustrated by considering a simulated example of 10 parametric faults in an exothermic Continuous Stirred Tank Reactor. 9 potential process measurements are considered and so there are 511 non-trivial, non-redundant sensor networks possible. Quantifying the value of each of 511 sensor networks clearly brings out the trade-off between being able to detect and isolate a fault on one hand and its “usefulness“ on the other hand. Analysis of the sensor network value reveals that not all faults are equally important, and some are more valuable than others. Such conclusions are difficult to draw based on existing sensor network design strategies. This approach will provide a rational method for solving integrated sensor network design problems.

References

[1] Bhushan, M.; Rengaswamy, R. 2002, Comprehensive design of a sensor network for chemical plants based on various diagnosability and reliability criteria: I. framework. Ind. Eng. Chem. Res. 41, 1826.

[2] Bagajewicz, M., Process Plant Instrumentation. Design and Upgrade. Technomic Publishing Company, Now CRC Press. 2000.

[3] Kubrusly, C. S.; Malebranche, H. 1985, Sensors and controllers location in distributed system-a survey. Automatica 21, 117

[4] Peng, J.; Chmieleski, D. 2004, Covariance based hardware selection, part 1: Full state information actuator selection. Submitted to IEEE Trans Contr. Syst. Tech