CHARACTERIZATION OF VALUE FOR SENSOR NETWORKS FOR PROCESS FAULT DIAGNOSIS

Sridharakumar Narasimhan and **Raghunathan Rengaswamy**(+*)

(+) Dept of Chemical Engineering, Clarkson University, Potsdam, NY 13699-5705. US

Abstract

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. While these design algorithms can provide the best design locations for a given cost, the value of the sensor network for fault diagnosis is usually not quantified. This is an important aspect that needs to be addressed if these algorithms have to be assimilated into industrial practice

Keywords

Fault Diagnosis, Sensor location, Network value

Introduction

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 (Bagajewicz, 1997, Rao et al., 1999, Bhushan and Rengaswamy, 2000). While these design algorithms can provide the best design locations for a given cost, the value of the sensor network for fault diagnosis is usually not quantified. This is an important aspect that needs to be addressed if these algorithms have to be assimilated into industrial practice

Economic Value of Fault Detection

*Author to whom correspondence should be addressed. Email: raghu@clarkson.edu

The monetary value of a sensor network can be decided by many methods. The simplest idea is to evaluate the cost of the sensors and the cost of maintaining/replacing faulty sensors. However, this does not quantify the benefits or the utility of the sensor network. For instance, from the perspective of fault diagnosis, it is necessary to ensure faults are detected and diagnosed as and when they occur. Bhushan and Rengaswamy (2000) have reported and developed procedures for designing sensor networks that ensure observabililty, single and multiple fault resolution and maximize the system reliability. However, a disadvantage with current approaches is that it is difficult to quantify the final benefit to the user. It can be contended that it is possible to assign a utility function, in terms of costs to any given problem. The aim of this contribution is to quantify the utility of a sensor network from a fault diagnosis perspective.

Sensor networks for fault diagnosis

We shall start with the assumption that a fault occurring in the system affects some (or all) of the process variables, some of which will be measured using the given sensor network. The Signed DiGraph (SDG) is a powerful technique that can be used to perform fault diagnosis based on limited quantitative information from the process. It will be assumed that it is possible to model the cause-effect behaviour of the system, that generates a set of variables that are affected whenever a particular fault occurs. In addition, the direction of deviation of the affected variable (in either the positive or negative direction from the nominal value) is needed for fault modeling using the SDG approach. Thus, we assume that a bipartite matrix (A) describes the fault effect behaviour of the system, where

$$\begin{aligned} a_{ij} &= +1 \text{ if fault } i \text{ affects variable } j \text{ in the positive direction} \\ &= -1 \text{ if fault } i \text{ affects variable } j \text{ in the negative direction} \\ &= \pm 1 \text{ if fault } i \text{ affects variable } j \text{ in an indeterminate manner} \\ &= 0 \text{ if fault } i \text{ does not affects variable } j \end{aligned}$$

Thus, corresponding to each fault f_i, we have a set of sensors $A_i = \{S_k\}$ which are affected by f_i and the direction in which the corresponding variable is affected. The observability problem is to pick a set of sensors $\{S_l\}$ such that there is at least one directed path from every root node f_i.

The above criterion ensures that no fault goes unobserved. However, it does not unequivocally specify which fault has occurred, i.e, it is not a sufficient condition for resolving between faults f_i. Resolution can be guaranteed by solving an augmented observability problem where the sets A_i are augmented with the symmetric difference of pair wise sets A_i and A_j, A_{ij}.

$$A_{ij} = A_i \cup A_j - A_i \cap A_j$$

The set A_{ij} contains of variables that are affected only by fault i or fault j, but not both. Thus, if the set A_{ij} is nonempty, the faults i and j can be distinguished if even one sensor in the set A_{ij} is chosen.

The augmented observability problem is solved for single fault resolution. The same approach can be extended to multiple faults by considering all possible multiple combinations of faults and the unions of the corresponding fault sets.

Sensor network value

As mentioned earlier, it is necessary to quantify the utility of a sensor network from a fault diagnosis perspective. This will be done by assigning a cost to the benefits or utility gained by the sensor network in diagnosing a fault or set of faults. Before determining the value of a sensor network, it will be necessary to quantify the value of detecting a particular fault. While there are many issues that need to be addressed, here we outline a methodology for identifying the value of a sensor network for fault diagnosis. Only the single fault assumption will be considered here. Faults in a process can be classified as structural, parametric or sensor faults (Venkatasubramanian et al., 2003). 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 controlled 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 (Bagajewicz et al 2004). Gross errors in sensor faults can lead to loss of resolution property of the corresponding sensor network. The value of detecting this fault can be quantified through the loss that one will incur due to the loss in resolution property. This would relate to the economic value in detecting the other parametric faults. A methodology for identifying the value for networks that detect parametric faults will be discussed next.

Before quantifying the network cost, it is necessary to determine the efficacy of the sensor network for fault diagnosis. Given a sensor network containing l sensors $L=\{S_1,S_2,\ldots,S_l\}$ and set of n observable faults $F=\{f_1,f_2,\ldots,f_n\}$, and the symmetric difference sets A_{ij}, a consistent enumerative procedure (Narasimhan and Rengaswamy, 2004) is used to determine the set of resolvable faults (under single fault assumption) F_{end} .For example, if at the termination of the enumeration, for the given sensor network, $F_{end}=f_1,f_2,\{f_3, f_4\}$, the sensor network f_3 and f_4 have the same symptoms on the measured sensors and so unresolvable, which is different from that of f_1 or f_2. Corresponding to all possible operating points x, compute the average profit function c(x) using an assumed probability distribution function and treating unresolvable faults as described in Narasimhan and Rengaswamy (2004). Ideally, the set of unresolvable faults should be disjoint, however, because of the qualitative ambiguities in the SDG modeling approach, this may not be always possible. Techniques to handle such ambiguities using fuzzy logic or multi-valued logic will be investigated.

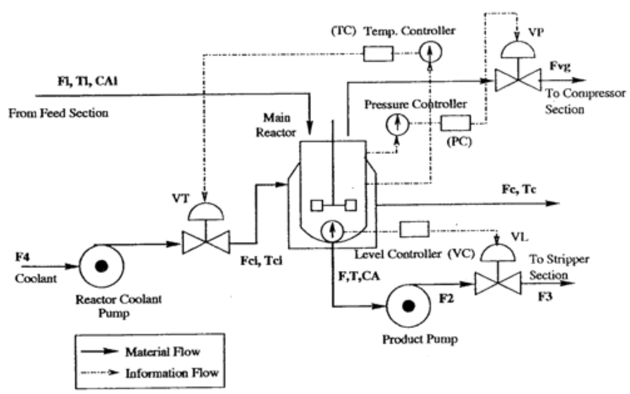

Figure 1: CSTR process schematic.

Example from the Fault Diagnosis Perspective

The value from the fault diagnosis perspective will be demonstrated on the CSTR case study, which has been widely used as a test-bed for fault diagnosis. A highly exothermic reaction

$A_l \rightarrow B_l + C_g$

is carried out in a jacketed CSTR. Three controllers are used to control the reactor pressure, reactor liquid level and reactor temperature respectively by manipulating the outlet gas flow rate, outlet liquid flow and cooling water flow rate respectively. The following faults are considered:

Cai^+, Cai^-, Fi^+, Fi^-, Cd^-, U^-, Ti^+,Ti^-, Tci^+, Tci^-, which correspond to faults (positive or negative deviations as indicated by the signs) in inlet concentration of A, inlet flow rate, catalyst deactivation (as measured by catalyst activity), heat exchanger fouling (reduction in overall heat transfer coefficient or a fouling factor), inlet temperature of A and cooling water respectively. The nominal operating values, normal operating range, higher and lower limits for the faults

It is assumed that the original sensor network consists of [Ca, F, Cai, P, V, T]. Possible sensor networks will include some subset of [Fc, Tc, Ti, Tci, Fvg] along with the existing choice of [Ca, F, Cai, P, V, T].

The following costs and operational figures are assumed in calculation of the profit function.

1. Cost of product B: $0.375/mol
2. Cost of cooling water: $0.015/ft^3 cooling water
3. Cost of transporting vapour product C: $0.00225/ ft^3 vapour
4. Operating hours per year: 8760 hr/yr
5. Cost of sensor: $1000 a sensor

The fault sets based on the SDG model (Bhushan and Rengaswamy, 2000) are presented in Table 1. The set of resolvable faults is determined for different sensor possible sensor networks is determined (Ref Table 2) and the network value is reported in Table 3.

Table 1 Fault sets

Tag	Fault	Set A
F1	Cai^+	Ca^+, Fc^+,Tc^-,Fvg^+,Cai^+
F2	Cai^-	Ca^-, Fc^-,Tc^+, Fvg^-,Cai^-
F3	Ti^+	Fc^+,Tc^-,Ti^+
F4	Ti^-	Fc^-,Tc^+,Ti^-
F5	Fi^+	Ca^+, F^+, Fc^+, Tc^-, Fvg^+,Fi^+
F6	Fi^-	Ca^-, F^-, Fc^-, Tc^+, Fvg^-,Fi^-
F7	Tci^+	Fc^+,Tci^+
F8	Tci^-	Fc^-,Tci^-
F9	Cd^-	Ca^+, Fc^- , Tc^+, Fvg^-
F10	U^-	Fc^{-+} , Tc^-

Table 2 Resolvable faults

Sr no	Sensor network	Resolvable faults
1	[Ca, F, Cai, P, V, T, Tci, Ti]	{F1}{F2}{F3}{F4}{F5}{F6}{F7}{F8}{F9}{F10}
2	[Ca, F, Cai, P, V, T, Fc,Tc, Ti]	{F1}{F2}{F3}{F4}{F5}{F6}{F7}{F8}{F9}{F10}
3	[Ca, F, Cai, P, V, T, Tc, Tci]	{F1}{F2}{F3,F10}{F4}{F5}{F6}{F7}{F8}{F9}
4	[Ca, F, Cai, P, V, T, Fc, Tc]	{F1}{F2}{F3,F10}{F4}{F5}{F6}{F7}{F8}{F9}

Table 3 Network value

No	New Sensors	Value ($/yr)	Sensor Costs ($/yr)	Value - Sensor Costs ($/yr)
1	T_{ci}, T_i	7,810	2,000	5,810
2	F_c, T_c, T_i	7,810	3,000	4,810
3	T_c, T_{ci}	4,720	2,000	2,720
4	F_c, T_c	4,720	2,000	2,720

References

Bagajewicz M. (1997). Optimal Sensor Location in Process Plants. AIChE Journal. Vol. 43, No. 9.

Bagajewicz, M., D.Chmielewski and R. Rengaswamy (2004). Integrated Process Sensor Network Design. To be presented in the 2004 Annual AIChE Meeting, Austin, TX.

Mani Bhushan and R. Rengaswamy, "Design of Sensor Network based on the SDG of the process for Efficient Fault Diagnosis in Complex Chemical Plants", *I & EC Research*, 39(4), pp 999-1019, 2000

Mani Bhushan and R. Rengaswamy, "Comprehensive Design of Sensor Network based on Reliability Criteria Part I: Formulation", *I & EC Research*, 41, 1826-1839, 2002

Mani Bhushan and R. Rengaswamy, "Comprehensive Design of Sensor Network based on Reliability Criteria Part II: Applications", *I & EC Research* 41, 1840-1860, 2002.

Narasimhan, S. and R. Rengaswamy, "Quantification of sensor network value for fault diagnois" To be submitted. 2004.

Rao Raghuraj, Mani Bhushan and R. Rengaswamy, "An algorithm for Location of Sensors in Complex Chemical Plants Based on Various Fault Diagnosability Criteria", *AIChE J.*, 45(2), pp 310-322, 1999

Venkatasubramanian V., R. Rengaswamy, K. Yin and S. N.Kavuri, "Review of Process Fault Diagnosis - Part I: Quantitative Model-Based Methods", *Computers and Chemical Engineering,* 27(3), pp 239-311, 2003.