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Sensor placement for fault detection and localisation

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Abstract

A general approach is proposed for designing the cheapest sensor network able to detect and locate a set of specified faults. The method is based on the sensitivity of process residuals with respect to faults. A genetic algorithm is used to select the sensors and their locations. Results are shown for two water networks.

Keywords: sensor network, genetic algorithm, fault detection and isolation.

1. Introduction

Nowadays, the interest for chemical process monitoring becomes more and more important. Indeed, environmental and safety rules must be satisfied and the required product quality must be achieved. Moreover, fluid leakages are expensive and must be detected as quickly as possible. Fault detection can only be done if a suitable sensor network is installed in the process. However, all measurements are corrupted by noise and the sensor precision has a great influence on the detectability and isolability of process fault. Therefore the sensor precision must be taken into account when a network is designed.

In this study, a general method to design the cheapest sensor network able to detect and locate a list of faults in a given process is proposed. The method is based on the fault detection method proposed by J. Ragot and D. Maquin [4]. Those authors use the notion of fault sensitivity to decide whether a residual is influenced or not by a specified process fault.

As the problem is multimodal, not derivable and involves many binary variables, the sensor network optimization is done by means of a genetic algorithm (Goldberg [3]). Indeed, the efficiency of this optimization algorithm has been proved for similar problems, such as the design of efficient sensor networks for data reconciliation (Gerkens [2]).

The method is illustrated for two water networks of different sizes. The detected faults are leakage in pipes and storage tanks, but other fault types could also be simulated and detected.

2. Fault detection and isolation

The objective of fault detection is to determine whether the measurements remain in a normal range of values, as predicted by a process model for a given operating mode of the plant. If the distance between measurements and estimations is too large, a fault is detected. The fault detection and localisation techniques are carried out in two steps: the estimation of the residuals and the decision. In order to make sure that all the faults that can occur in a process are detectable, the signature matrix must be analysed. This matrix is the occurrence matrix of the potential fault variables in the model equations, expressed in residual form. As an example, let us consider the following system, characterizd by four residuals and six variables at time t:

$$r_1(t) = f_1\left(x_1(t), x_2(t), x_5(t), x_6(t)\right)$$

$$r_2(t) = f_2\left(x_1(t), x_2(t), x_3(t), x_5(t), x_6(t)\right)$$

$$r_3(t) = f_3\left(x_3(t), x_5(t), x_6(t)\right)$$

$$r_4(t) = f_4\left(x_2(t), x_4(t), x_5(t)\right)$$

The corresponding signature matrix has the form:

$$\Sigma = \begin{pmatrix} X & X & 0 & 0 & X & X \\ X & X & X & 0 & X & X \\ 0 & 0 & X & 0 & X & X \\ 0 & X & 0 & X & X & 0 \end{pmatrix}$$

A fault is detectable if the corresponding column in the signature matrix contains at least one non-zero element. A fault can be located if the corresponding column in the signature matrix is different from all other columns of the signature matrix. The fault localisation consists of deducing what is the fault from the values of the residuals. For that purpose, fuzzy rules are elaborated from the signature matrix. They are linguistic “if-then” constructions of the general form “if A then B” where A are the premises and B the consequence of the rule.

As noise influences the value of the residuals, some random perturbations in the measurements may be large enough to trigger a fault detection even when no fault occurs. Taking into account temporal persistence allows to improve the detection procedure. For that purpose, instantaneous measurements are replaced by averages calculated over several time steps.

The sensitivities of residuals to a given fault are different so that the magnitude of the residual deviations allows to characterize and isolate a fault. The detectability and isolability of faults can then be improved by using this difference of sensitivity. Let y be the measurement of a variable of the process. It is the sum of the true value x, the noise ε and the fault *f*:

$$y = x + \varepsilon + f$$

The true value satisfying completely the process model, the residual is composed of two terms: the contribution of the noise r_ε and the contribution of the fault r_f so that the effect of the fault can be masked by the effect of the noise according to their relative magnitudes. The noise contribution to the i^{th} residual is defined as follows:

$$r_{\varepsilon,i} = \sum_{j=1}^{n} m_{ij}\,\varepsilon_j$$

where m_{ij} are the elements of the matrix of the derivatives of the residuals with respect to the variables. If the errors are replaced by the precision of the sensors e_j, one obtains the upper bound of the contribution of the noise on the ith residual:

$$r_{\varepsilon,i} = \sum_{j=1}^{n} |m_{ij}| e_j$$

In the same way, the contribution of a unique fault f_j affecting the ith residual is defined as follows:

$$r_{f_j,i} = m_{ij} f_j$$

The lowest magnitude of the ith residual that allows to distinguish between the noise and the fault f_j is defined by the bound:

$$\tau_{ij} = \frac{\sum_{j=1}^{n} |m_{ij}| e_j}{|m_{ij}|}$$

So, the ith residual is sensitive to fault f_j if the magnitude of that fault is higher than τ_{ij}.

Fault f_j will be located if for all non-zero elements of the signature matrix, the absolute value of the corresponding residual is larger than the corresponding bound τ_{ij} and for each zero element of the signature matrix, the absolute value of the corresponding residual is smaller than a fixed upper bound. For example, if one takes the derivative matrix of the process previously described:

$$\Sigma = \begin{pmatrix} 1 & -0.5 & 0 & 0 & 1 & -2.5 \\ 2 & -4 & 2 & 0 & 3 & 1 \\ 0 & 0 & 3 & 0 & -2 & -1 \\ 0 & 6 & 0 & -5 & -4 & 0 \end{pmatrix}$$

For the following error vector $e = (0.5, 1, 0.8, 0.4, 1, 0.4)^T$, the corresponding bounds matrix is given by:

$$\tau = \begin{pmatrix} 3 & 6 & \infty & \infty & 3 & 1.2 \\ 5 & 2.5 & 5 & \infty & 3.3 & 10 \\ \infty & \infty & 1.6 & \infty & 2.4 & 4.8 \\ \infty & 2 & \infty & 2.4 & 3 & \infty \end{pmatrix}$$

So, the third fault will be detected and located if the second residual has an absolute value larger than 5 and the third one an absolute value larger than 1.6.

3. Method description

The optimal sensor network that allows to detect and locate all the specified faults is carried out in four steps:

- simulation of the process and of the faults that should be detected and located;
- specification of the sensor database and the sensor requirements;
- verification of the problem feasibility;
- optimisation of the sensor network.

3.1. Simulation of the process and of the faults that should be detected and located

The process is first simulated for typical operating conditions. Then, for each possible fault one decides the minimal magnitude of the fault that should be detected by the sensor network, for example a leakage of 1% of a stream flow rate. The faults are simulated one by one by increasing progressively the leakage until the minimal fault that should be detected is reached. The values of the variables at the beginning and at the end of each pipe obtained during the k last simulations are kept for each fault. No noise is added to the variables at this step because the noise depends on the precision of the measurement tools. The number of samples used to calculate the moving average of the variables depends on the frequency of the measurements and the speed at which the fault should be detected. If the number of measurement times is higher, the fault detection and location is slower but more reliable. If this number is too small, the noise influences more the magnitude of the residuals and the fault detection is more difficult. In the examples of paragraph 4, a value of 5 has been chosen.

3.2. Specification of the sensor database and the sensor requirements

3.2.1. The sensor database

For each sensor type, the database contains the following information:
- the name of the sensor;
- the annualised cost of the sensor, i.e.the annualised sum of the purchase, installation and operating costs;
- the type of variable that can be measured by the sensor;
- the domain of validity of the measurement;
- the accuracy of the sensor, as defined by the following equation:

$$\sigma_j = a_i + b_i X_j$$

3.2.2. The sensor requirements

In this file, the sensors that exist and don't have to be replaced are listed as well as the sensors that can not be placed at a particular location in the process.

3.3. Verification of the problem feasibility

The problem feasibility check starts by enumerating all the sensors that can be placed in the plant. For each sensor of this list, a binary gene is created. It has the value of 1 if the sensor is chosen and 0 either. The set of genes forms a chromosome whose length is equal to the number of possible sensors. It may appear that a variable is measured by more than one sensor so that the precision of the most accurate one is taken into account for the bounds calculation. The residual bounds and the residuals are estimated for the initial sensor network: indeed, a noise bounded by the accuracy of the sensor is added to each variable for each measurement time before the mean of the variables and the residuals are calculated. The noise on the variables and then their values depend thus of the sensor network as well as the residual bounds.
To ensure that the design problem accepts a solution,: the initial sensor network has to be able to detect all the simulated faults. If it is not the case, new sensor types that are

more precise should be added to the data base or the minimal magnitudes of the faults to be detected should be set higher.

3.4. Optimisation of the sensor network

When the existence of a solution has been verified, it can be optimized. The objective function to be minimized is evaluated this way:

- if all the faults can be detected and located, the objective function is the sum of the costs of all the sensor in the network;
- if at least one fault can not be detected or located, the objective function is set to a large value (twice the maximum costs).

The goal function being generally multimodal, the problem being not derivable and containing only binary parameters, a genetic algorithm [2] has been used as the optimization method. The algorithm that has been used is based on the one developed by Caroll [1]. In this algorithm, the individuals are selected using tournament selection. A shuffling technique allows to choose randomly pairs for mating. A new population is generated by applying single-point cross-over and the jump mutation mechanisms. Individuals of the first population are chosen randomly, by activating randomly 80% of all each genes. The size of the population is set to 20 individuals. The probability of reproduction is fixed to 50%, the probability of single-point cross-over to 50% and the probability of jump mutation to 1%.

The fitness function is evaluated for each individual of the new generation. The best one is then kept and duplicated in the case it would be subject to mutation in the following generation. The calculation is stopped when the objective function of the best individual remains unchanged during a specified number of generations.

4. Cases studies

Two water networks have been studied. The first one is composed of five storage tanks and ten connection pipes (figure 1). The fifteen faults that should be detected and located are water leakages in the storage tanks or in the pipes. Each storage tanks can be fitted with a level meter, and the flow rate can be measured at both ends of each pipe, which means 25 possible sensors.

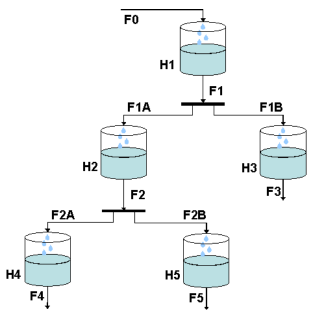

Figure 1

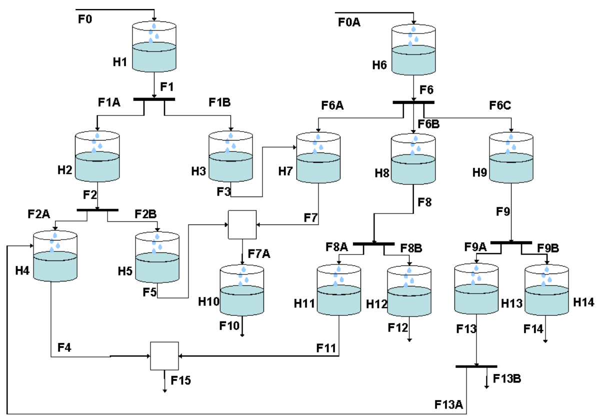

Figure 2

In the sensor database three level meters are available with different accuracies and prices, and 10 flowmeters with different accuracies, prices and measurement domains. With this database, it is possible to place 135 sensors. That corresponds to a solution space of 2135 = $4.4*10^{40}$ solutions. This measurement system has a total cost of 11950 cost units.
Obtaining the solution requires 14770 generations (295421 goal function evaluations) for a stop criterion of 6000 generations. The optimal sensor network is obtained after 301 seconds on a 1.6GHz computer. This optimal network costs 1860 units and counts 25 sensors, one for each possible sensor location. It allows to detect and locate all the 15 faults. The initial and most expensive network costs 3100 units (1240 cost units more than the optimal one).
The second water network (figure 2) is composed of 14 storage tanks and 31 pipes so that there are 76 possible sensor locations. The sensor database contains three level meters with different accuracies and prices, and 15 flowmeters with different accuracies, prices and measurement domains. The initial network counts 392 possible sensors. This corresponds to a solution space of 10^{118} solutions. This sensor network has a total cost of 34100 units.
Obtaining the solution requires 26104 generations (522101 objective function evaluations) for a stop criterion of 6000 generations. The optimal sensor network is obtained after 5667 seconds on a 1.6GHz computer. This solution costs 6200 units and requires 76 sensors: one for each possible sensor location. It allows to detect and locate all the 45 faults. In order to detect and locate all the faults, one sensor is required at each location, but the network cost can be minimized by selecting the cheapest sensor that provides the required precision.. The most expensive of those network costs this time 9000 costs units (2800 cost units more than the optimal one).

5. Conclusions

The proposed method allows to determine a sensor network that is able to detect and locate a specified list of tank and pipe leakages. This network is much cheaper than the initial one but due to the optimization method, there is no guarantee that is the best one. This method could be transposed for other types of faults such as the catalyst deactivation or the loss of efficiency in a compressor.

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