Model Based Fault Detection and Isolation

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Lecture Main Topics

- General introduction
  - State-of-the-art review
- Main methods for fault diagnosis
  - Parameter estimation methods
  - Observer and filter approaches
  - Parity relations
  - **Neural networks and fuzzy systems**
- Application examples
- Concluding remarks

Programme Details

- Introduction: Course Introduction
- Issues in Model-Based Fault Diagnosis
- Fault Detection and Isolation (FDI) Methods based on Analytical Redundancy
- **Model-based Fault Detection Methods**
- The Robustness Problem in Fault Detection
- Fault Identification Methods
- Modelling of Faulty Systems

Programme Details (Cont'd)

- Residual Generation Techniques
- The Residual Generation Problem
  - **Disturbance de-coupling for linear systems**

- **Fault Diagnosis Technique Integration**
- **Fuzzy Logic for Residual Generation**
- **Neural Networks in Fault Diagnosis**

Programme Details (Cont'd)

- Output Observers for Robust Residual Generation
- Unknown Input Observer (UIO)
- FDI Schemes Based on UIO and Output Observers
- Kalman Filtering and FDI from Noisy Measurements
- Residual Robustness to Disturbances
- Application Examples

Introduction

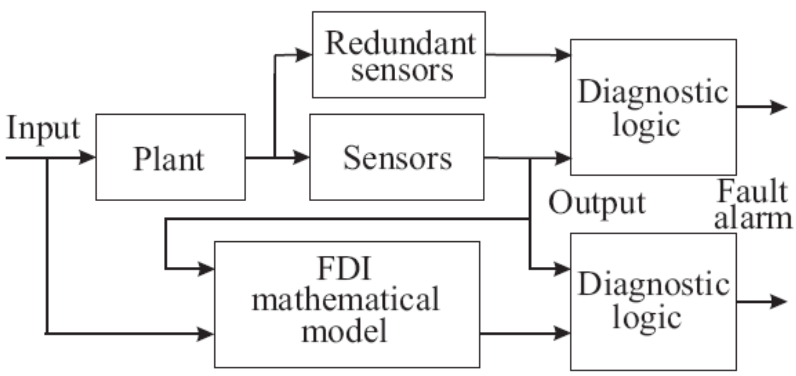


Figure 1.1: Comparison between hardware and analytical redundancy schemes.

Introduction (Cont'd)

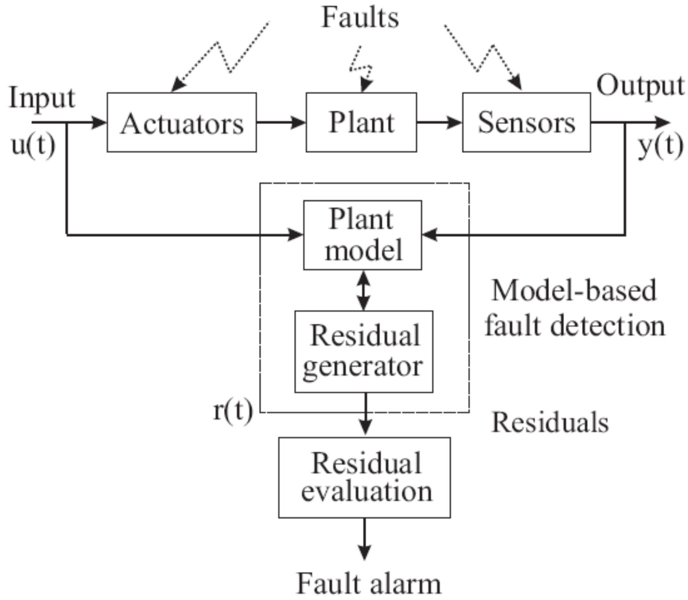


Figure 1.2: Scheme for the model–based fault detection.

Residual Generation

- This block generates residual signals using available inputs and outputs from the monitored system
- This residual (or fault symptom) should indicate that a fault has occurred
- Normally zero or close to zero under no fault condition, whilst distinguishably different from zero when a fault occurs

Residual Evaluation

- This block examines residuals for the likelihood of faults and a decision rule is then applied to determine if any faults have occurred
- It may perform a simple threshold test (geometrical methods) on the instantaneous values or moving averages of the residuals
- It may consist of statistical methods, e.g., generalised likelihood ratio testing or sequential probability ratio testing

Introduction (Cont'd)

- Model-Based FDI Methods:

1. Output observers (OO, estimators, filters);
2. Parity equations;
3. Identification and parameter estimation.

Introduction (Cont'd)

- Signal Model-Based Methods:
  1. Bandpass filters;
  2. Spectral analysis (FFT);
  3. Maximum-entropy estimation.

- Change Detection: Residual Analysis
  1. Mean and variance estimation;
  2. Likelihood-ratio test, Bayes decision;
  3. Run-sum test.

Introduction (Cont'd)

- Model Uncertainty and FDI
  - Model-reality mismatch
  - Sensitivity problem: incipient faults!
- Robustness in FDI
  - Disturbance, modelling errors, uncertainty
  - UIO and Kalman filter: robust residual generation
- System Identification for FDI
  - Estimation of a reliable model
  - Modelling accuracy
  - Disturbance estimation (recall: ARX, ARMAX, BJ)

Introduction (Cont'd)

- Fault Identification Methods
  - Fault nature (type, shape) & size (amplitude)

1. Geometrical distance and probabilistic methods;
2. Artificial neural networks;
3. Fuzzy clustering.

- Approximate Reasoning Methods:

1. Probabilistic reasoning;
2. Possibilistic reasoning with fuzzy logic;
3. Reasoning with artificial neural networks.

Introduction (Cont'd)

- FDI applications status & review

Table 1.1: FDI applications and number of contributions.

Application	Number of contributions
Simulation of real processes	55
Large-scale pilot processes	44
Small-scale laboratory processes	18
Full-scale industrial processes	48

Table 1.2: Fault type and number of contributions.

Fault type	Number of contributions
Sensor faults	69
Actuator faults	51
Process faults	83
Control loop or controller faults	8

Introduction (Cont'd)

- FDI applications status & review

Table 1.3: FDI methods and number of contributions.

Method type	Number of contributions
Observer	53
Parity space	14
Parameter estimation	51
Frequency spectral analysis	7
Neural networks	9

Table 1.4: Residual evaluation methods and number of contributions.

Evaluation method	Number of contributions
Neural networks	19
Fuzzy logic	5
Bayes classification	4
Hypothesis testing	8

Introduction (Cont'd)

- FDI applications status & review

Table 1.5: Reasoning strategies and number of contributions.

Reasoning strategy	Number of contributions
Rule based	10
Sign directed graph	3
Fault symptom tree	2
Fuzzy logic	6

Table 1.6: Applications of model–based fault detection.

FDD	Number of contributions
Milling and grinding processes	41
Power plants and thermal processes	46
Fluid dynamic processes	17
Combustion engine and turbines	36
Automotive	8
Inverted pendulum	33
Miscellaneous	42
DC motors	61
Stirred tank reactor	27
Navigation system	25
Nuclear process	10

Model-based FDI Techniques

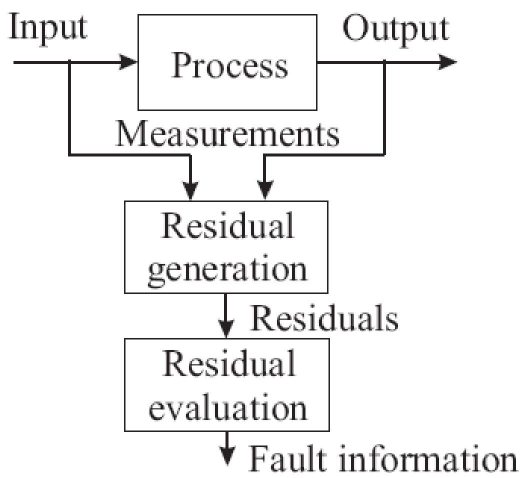


Figure 2.1: Structure of model-based FDI system.

Residual General Structure

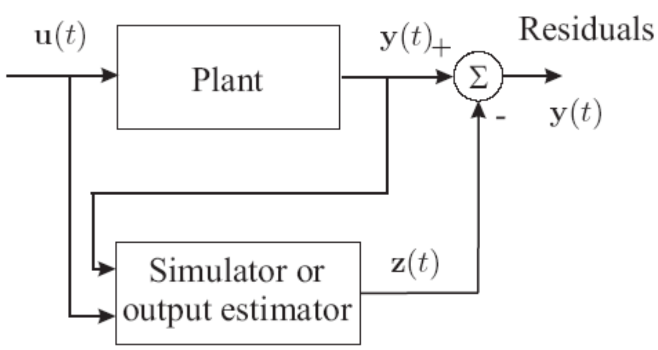


Figure 2.9: Residual generation via system simulator.

Residual generation via system simulator

$$\mathbf{r}(t) = \mathbf{z}(t) - \mathbf{y}(t)$$

z(t) is the simulated plant output

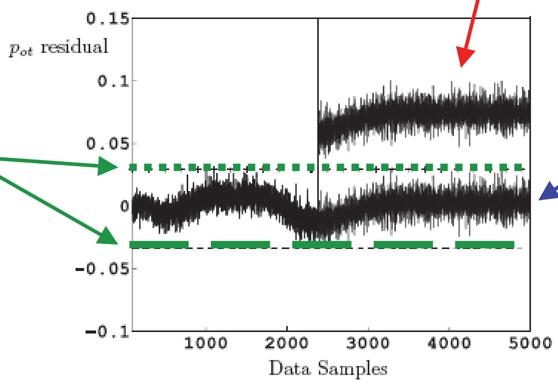
General Residual Evaluation

$$\begin{cases} J(\mathbf{r}(t)) \le \varepsilon(t) & \text{for} \quad \mathbf{f}(t) = \mathbf{0} \\ J(\mathbf{r}(t)) > \varepsilon(t) & \text{for} \quad \mathbf{f}(t) \neq \mathbf{0} \end{cases}$$

Faulty residual

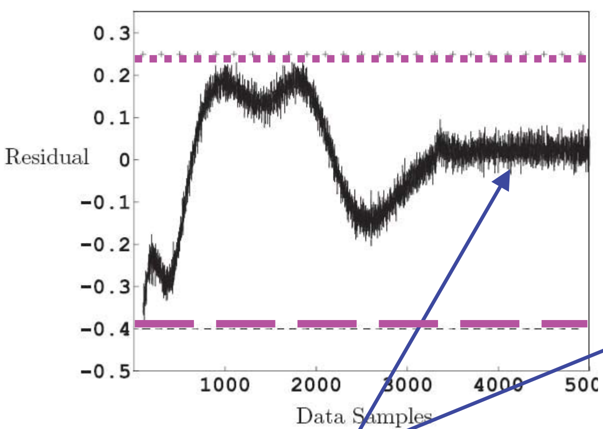
Fault free residual

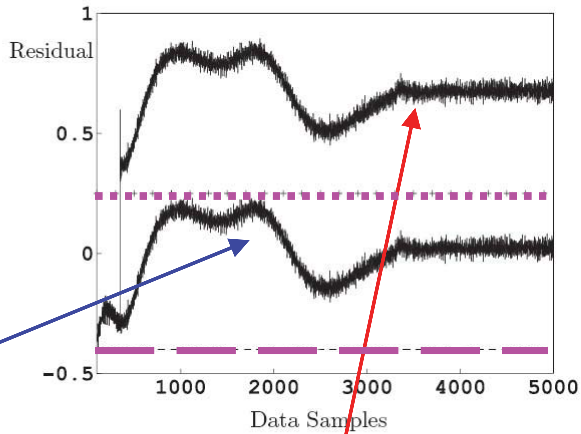
Detection thresholds
ε(t)



General Residual Evaluation *(example)*

Detection thresholds





Fault free residual

Fault-free & faulty residuals

Fault Diagnosis Technique Integration

FDI Technique Integration

- Several FDI techniques have been developed and their application shows different properties with respect of the diagnosis of different faults in a process
- To achieve a reliable FDI technique, a good solution consists of a proper integration of several methods which take advantages of the different procedures
- Exploit a knowledge-based treatment of all available analytical and heuristic information

Fuzzy Logic for Residual Generation

- Classical fault diagnosis model-based methods can exploit state-space of input-output dynamic models of the process under investigation
- Faults are supposed to appear as changes on the system state or output caused by malfunctions of the components as well as of the sensors
- The main problem with these techniques is that the precision of the process model affects the accuracy of the detection and isolation system as well as the diagnostic sensitivity

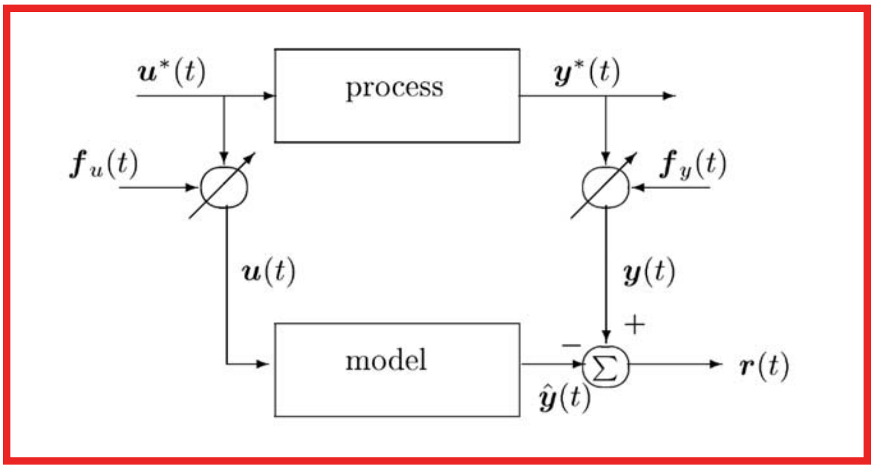
Fuzzy Logic for Residual Generation (Cont'd)

- The majority of real industrial processes are nonlinear and cannot be modelled by using a single model for all operating conditions
- Since a mathematical model is a description of system behaviour, accurate modelling for a complex nonlinear system is very difficult to achieve in practice
- Sometimes for some nonlinear systems, it can be impossible to describe them by analytical equations

Fuzzy Logic for Residual Generation (Cont'd)

- Sometimes the system structure or parameters are not precisely known and if diagnosis has to be based primarily on heuristic information, no qualitative model can be set up
- Because of these assumptions, fuzzy system theory seems to be a natural tool to handle complicated and uncertain conditions
- Instead of exploiting complicated nonlinear models, it is also possible to describe the plant by a collection of local affine fuzzy models, whose parameters are obtained by identification procedures

Residual Generation via Fuzzy Models



Resisual signals: $r(t) = y(t) - \hat{y}(t).$

Neural Networks in Fault Diagnosis

- Quantitative model-based fault diagnosis generates symptoms on the basis of the analytical knowledge of the process under investigation
- In most cases this does not provide enough information to perform an efficient FDI, *i.e.*, to indicate the location and the mode of the fault
- A typical integrated fault diagnosis system uses both analytical and heuristic knowledge of the monitored system

Neural Networks in Fault Diagnosis (Cont'd)

- The knowledge can be processed in terms of residual generation (analytical knowledge) and feature extraction (heuristic knowledge)
- The processed knowledge is then provided to an inference mechanism which can comprise residual evaluation, symptom observation and pattern recognition

Neural Networks in Fault Diagnosis (Cont'd)

- In recent years, neural networks (NN) have been used successfully in pattern recognition as well as system identification, and they have been proposed as a possible technique for fault diagnosis, too
- NN can handle nonlinear behaviour and partially known process because they learn the diagnostic requirements by means of the information of the training data

Neural Networks in Fault Diagnosis (Cont'd)

- NN are noise tolerant and their ability to generalise the knowledge as well as to adapt during use are extremely interesting properties
- FDI is performed by a NN using input and output measurements
  - NN is trained to identify the fault from measurement patterns
  - Classification of individual measurement pattern is not always unique in dynamic situations, therefore the straightforward use of NN in
- Fault diagnosis of dynamic plant is not practical and other approaches should be investigated

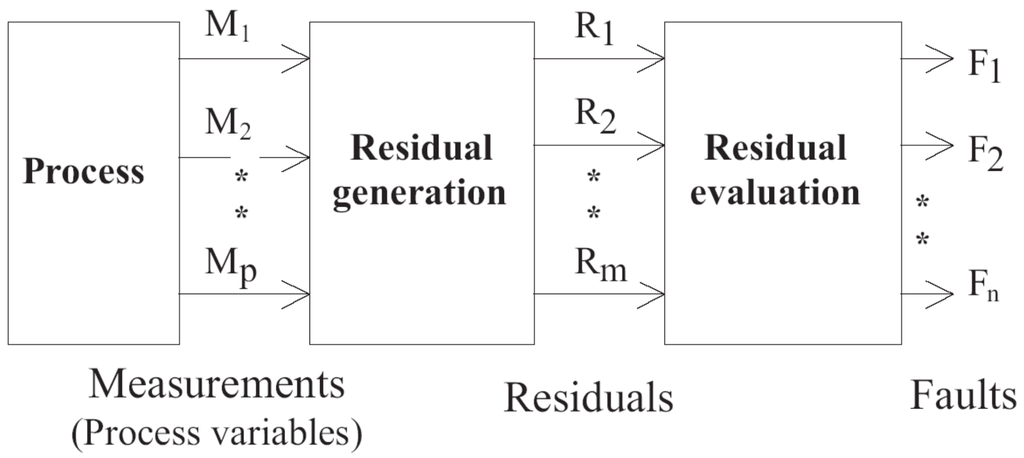
Neural Networks in Fault Diagnosis (Cont’d)

- A NN could be exploited in order to find a dynamic model of the monitored system or connections from faults to residuals
- In the latter case, the NN is used as pattern classifier or nonlinear function approximator
- NN are capable of approximating a large class of functions for fault diagnosis of an industrial plant
- The identification of models for the system under diagnosis as well as the application of NN as function approximator will be shown

Neural Networks in Fault Diagnosis (Cont’d)

- Quantitative and qualitative approaches have a lot of complementary characteristics which can be suitably combined together to exploit their advantages and to increase the robustness of quantitative techniques
- Partial knowledge deriving from qualitative reasoning is reduced by quantitative methods
- Further research on model-based fault diagnosis consists of finding the way to properly combine these two approaches together to provide highly reliable diagnostic information

FDI with Neural Networks



FDI with Neural Networks (Cont'd)

- As described in the figure, the fault diagnosis methodology consist of 2 stages
- In 1st stage, the fault has to be detected on the basis of residuals generated from a bank of output estimators, while, in the 2nd step, fault identification is obtained from pattern recognition techniques implemented via NN
- Fault identification represents the problem of the estimation of the size of faults occurring in a dynamic system

FDI with Neural Networks (Cont'd)

- A NN is exploited to find the connection from a particular fault regarding system inputs and output measurements to a particular residual
- The output predictor generates a residual which does not depend on the dynamic characteristics of the plant, but only on faults
- NNs classify static patterns of residuals, which are uniquely related to particular fault conditions independently from the plant dynamics

FDI with Neural Networks (Cont'd)

- NNs have been used both as predictor of dynamic models for fault diagnosis, and pattern classifiers for fault identification
- The most frequently applied neural models are the feed-forward perceptron used in multi-layer networks with static structure
- The introduction of explicit dynamics requires the feedback of some outputs through time delay units

FDI with Neural Networks (Cont'd)

- Alternatively to static structure, NN with neurons having intrinsic dynamic properties can be used
- On the other hand, NN can be effectively exploited for residual signal processing, which is actually a static patter recognition problem

FDI with Neural Networks (Cont'd)

- Fault signals create changes in several residuals obtained by using output predictors of the process under examination
- A neural network is exploited in order to find the connection from a particular fault regarding input and output measurements to a particular residual

FDI with Neural Networks (Cont'd)

- The predictors generate residuals independent of the dynamic characteristics of the plant and dependent only on sensors faults
- Therefore, the neural network evaluates static patterns of residuals, which are uniquely related to particular fault conditions independently from the plant dynamics

Conclusion

- ✓ Model-Based FDI
- ✓ Analytical Redundancy
- ✓ State-Space Models
- ✓ Residual Generation
  - ✓ Unknown Input Observers UIO
  - ✓ Dynamic Observers / Kalman Filters
- ✓ Residual Evaluation/Change Detection