Automated Fault Detection and Diagnosis
an Introduction

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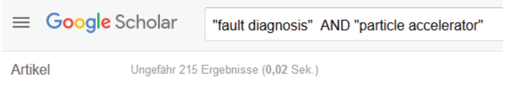
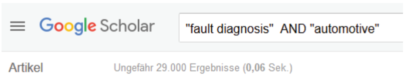
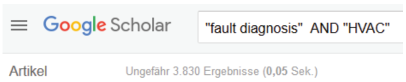
Why fault diagnosis?

- See Holger Schlarbs talk on August 11th, 2020
- Big data (streams) $> 30\,\mathrm{TB}/\mathrm{day}$
- Rising problem awareness in accelerator community

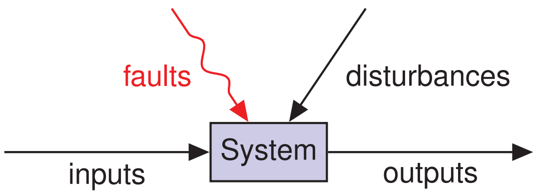


- Current hype of AI and ML methods
- Two academic waves interfere - will it be a Tsunami?
- Fact: Vulnerability rises with complexity of systems
- Demand for structured methods and processes
- Models of (sub)systems are available !
- Huge engineering research topic since decades ...



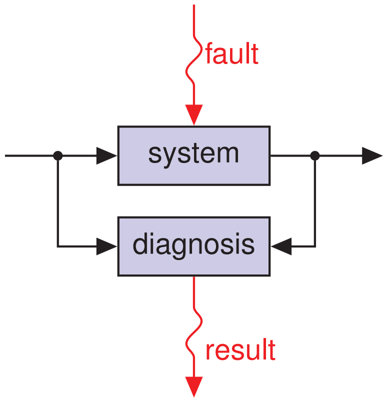


Fault Diagnosis



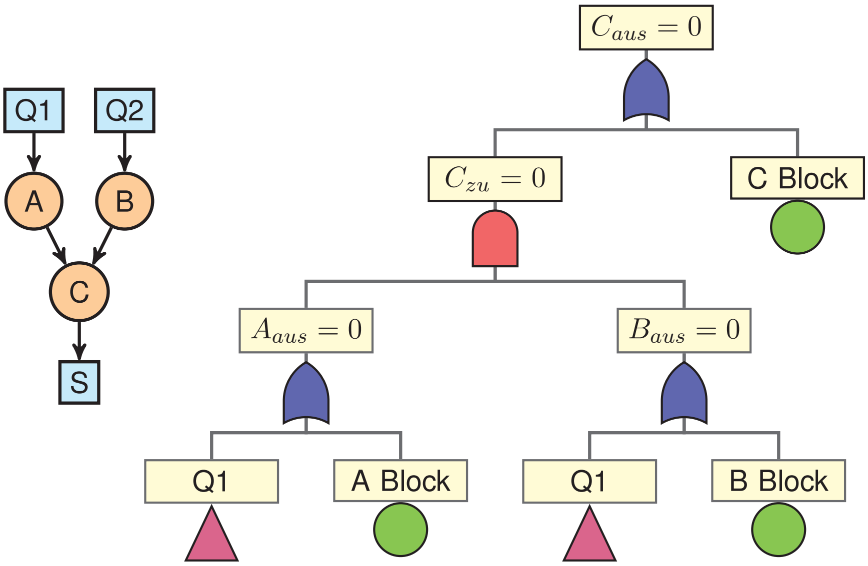
- system (dynamic)
- fault
- disturbace (e.g. noise, operator actions)
- problem: find fault from inputs and outputs

Fault Diagnosis



- system (faulty)
- diagnosis algorithm
- diagnosis result

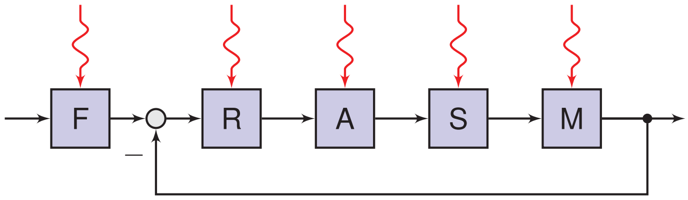
Fault Trees



Fault Trees

- old method [Watson, 1961]
- widely used standard
- reasoning against causal direction
- analysis of fault trees: failure probability
- often generated by expert knowledge
- very complex for realistic systems
- maintenance for complex systems very hard
- model-based methods are an alternative

Complex Systems



- system / actuator / sensor
- feedback / feedforward control
- fault can occure in each component
- faults in configuration, communication, design, ...

Classes of diagnosis problems

Fault Detection, Isolation, and Identification (FDII)

- Detection: has a fault occured ?
- Isolation: where has the fault occured?
- Identification: which fault has occured?

Fault dynamics

- static: always faulty or nominal
- temporal: time-varying

[Isermann: Fault-Diagnosis Systems]

Classes of diagnosis problems (FDII)

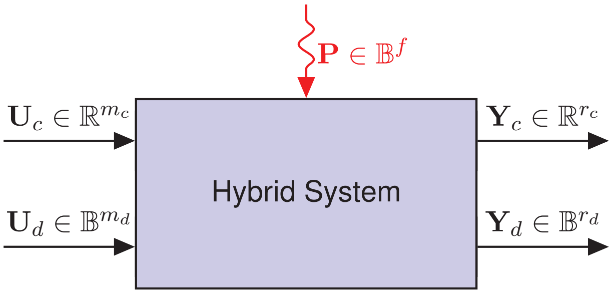
Model-based fault diagnosis needs ...

- Detection: nominal overall system model
- Isolation: nominal subsystems models
- Identification: fault models

Fault models

- static: parameter (sets)
- temporal: signals

Dynamical Systems



- Modeling task: represent the bahaviour

$$\mathcal{B} = \{\mathbf{Y}, \mathbf{U} \mid \text{all signals possible for the system}\}$$

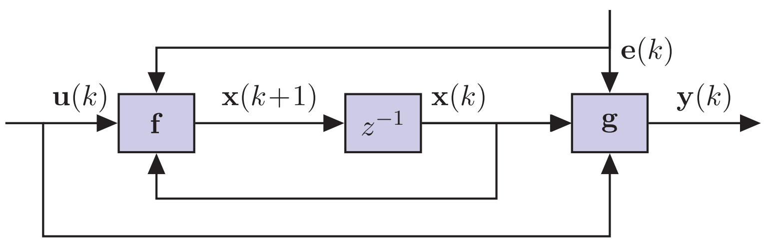
- Fault models represent the faulty behaviour

State Space Models

- controllability & observability
- design methods
  - state feedback
  - optimal control
  - predictive control
  - feedforward control
  - learning control
- supervisory control
- fault diagnosis
- parameter identification (ARX, N4SID, ...)
- EASY to implement and simulate
- different classes: linear, nonlinear, discrete-event, ...

[Åström & Murray: Feedback Systems]

State Space Models: Block diagram



- next-state function

$$\mathbf{x}(k+1) = \mathbf{f}(\mathbf{x}(k), \mathbf{u}(k), \mathbf{e}(k))$$

- output function

$$\mathbf{y}(k) = \mathbf{g}(\mathbf{x}(k), \mathbf{u}(k)), \mathbf{e}(k))$$

State Space Models: Classes

- nonlinear, stochastic

$$\begin{aligned} \mathbf{f} &= \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{e}) \\ \mathbf{g} &= \mathbf{g}(\mathbf{x}, \mathbf{u}, \mathbf{e}) \end{aligned}$$

- linear deterministic stochastic

$$\begin{aligned} \mathbf{f} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{E}\mathbf{e} \\ \mathbf{g} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} + \mathbf{F}\mathbf{e} \end{aligned}$$

- differential algebraic models (DAE)

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{e}) \\ \mathbf{0} &= \mathbf{h}(\mathbf{x}, \mathbf{u}, \mathbf{e}) \\ \mathbf{y} &= \mathbf{g}(\mathbf{x}, \mathbf{u}, \mathbf{e}) \end{aligned}$$

Modelling and Simulation Tools

- MATLAB / SIMULINK
- Scilab / XCos / Octave
- OpenModelica / DYMOLA
- Phython
- Julia
- ...

Methods for Fault Diagnosis

Classification

- model-based / signal-based
- qualitative / quantitative
- offline / online

Properties

- trade-off: false positive (alarms) - false negative
- backwards reasoning against causal direction
- prerequisite: diagnosability $\Leftarrow$ redundancy

[Mouzakitis: Classification of Fault Diagnosis Methods for Control Systems]

Quantitative model-based Diagnosis

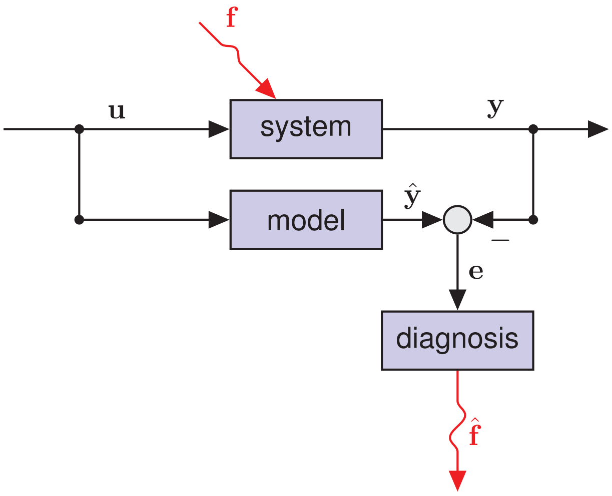
Generation of Residuals

- compare simulation vs. measurements
- parameter identifikation
- state estimation
- parity equations
- ...

Classification of Residuals

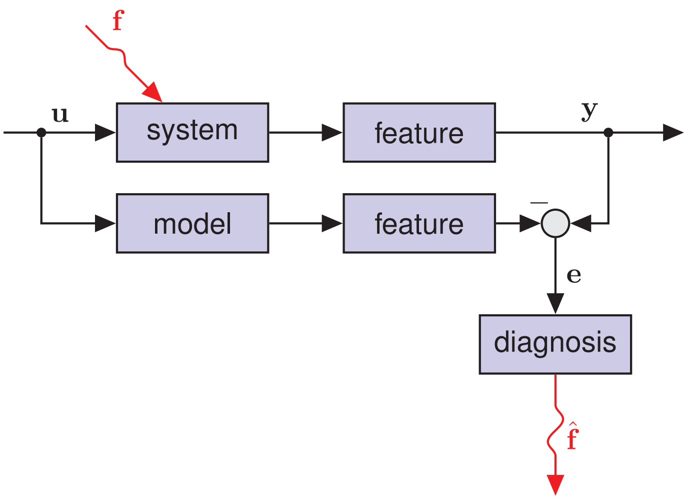
- support vector machines (SVM)
- fuzzy logic
- artificial neuronal networks (ANN)
- other classifiers (k-means, PCA, ...)

Signal Comparison



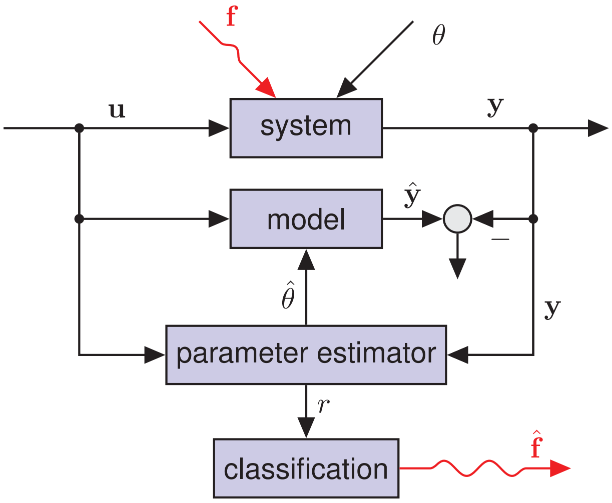
Problem: Diagnosis depends on initial state of the model

Feature Extraction & Comparison

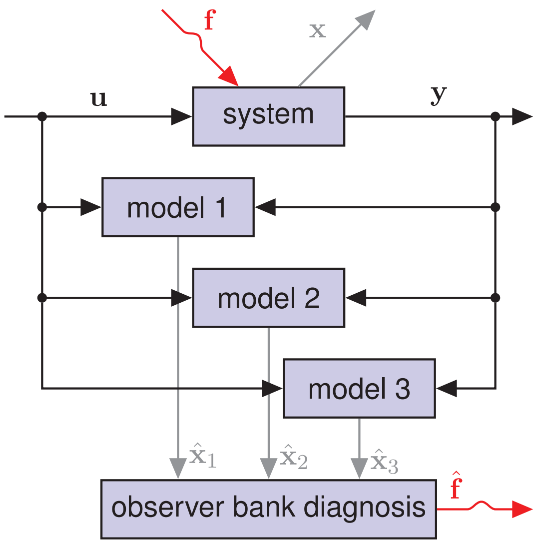


Features from sensor signals: e.g. energy consumption

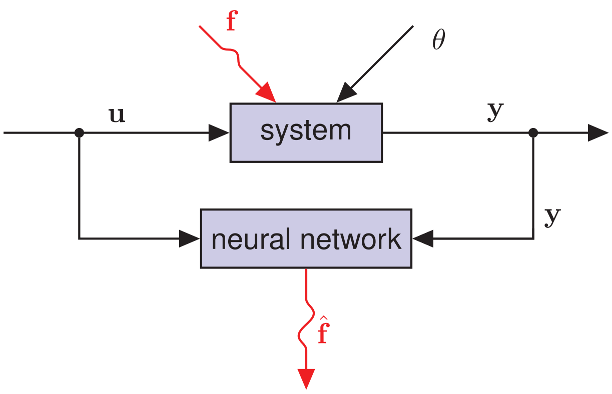
Parameter Identification



State Observer / Kalman Filter



Machine Learning



- learning $\Leftarrow$ data
- supervised learning $\Leftarrow$ classified data
- runtime $\Leftarrow$ learned model

Quantitative Methods

- signal comparision
  - usually thresholds for difference
  - unkown initial state of the system
  - model uncertainties
- feature extraction
  - decreasing dependency on initial conditions (linear stable systems)
  - model is used in simulation
- parameter identification
  - input and outputs similarily used
  - model only gives structure and parameter regions
  - no initial value problem
  - improvements e.g. parity equations
  - fault identification by parameter classification
- observer banks
  - input and outputs similarily used
  - models used for state estimation
  - fault identification by multiple fault models

Qualitative model-based Diagnosis

Models

- logical models
- *Discrete Event Systems* (DES)
- nondeterministic automata (stochastic)
- hybrid models, Petri nets, ...

Algorithms

- rule-based expert systems (AI)
- *Supervisory Control Theory*
- qualitative modelling
- data mining, assumption based truth maintenance (ATMS)

[Müller: Fault Detection with Qualitative Models reduced by Tensor Decomposition]

Qualitative Models

- abstract from details (describing sets)
- use inputs and outputs (and states)
- are understood in system theory (discrete-time multilinear)
- use Markov property (easy implementation)
- are identifiable from measurements (relative frequency)
- can be derived from quantitative models (Monte Carlo)
- are directly interpretable (automaton graph)
- have combinatorical complexity
- are decomposable to overcome this problem
- solve diagnosis problem (measured $\subseteq$ modelled)
- can use qualitative observer banks for fault diagnosis
- give fault probabilies (easy matrix or tensor computations)

Fault Diagnosis for Accelerators

- which faults are detectable?
- which models are available (and useful)?
- how to integrate data (especially unclassified)?
- which methods are working (best - for which cases)?
- how to detect anomalies (e.g. rare events)?
- which subsystems are influenced by a fault (most severely) ?
- how to use diagnostic results (in operation, for reconfiguration)?
- ... yours ?

A lot of open questions ... and first answers ...

[Nawaz: Anomaly Detection for XFEL using a Nonlinear Parity Space Method]

Summary

- FDII: Fault Detection, Isolation, Identification
- Diagnosis: measurement + algorithm (+ model)
- Quantitative methods: residual generator + classifier
- Qualitative methods: automaton + observer bank
- AI methods: expert system + knowledge aquisition
- ML methods: artificial neural network + classified data

Take Home Message
Basic problem properties depend on systems, not methods!

THANK YOU FOR YOUR ATTENTION