Model based diagnosis: a research agenda

Albert Benveniste (Inria-Rennes)

Synchron 2021

Diagnosis, health monitoring, and maintenance, are becoming more and more important

The case of aeronautic sector

Business model of aeronautic sector

Past: selling products

- Aircraft
- Engine
  - Selling with low margin,
  - Revenues from parts
- Landing system

Tomorrow: pay-on-use, services

- Airbus' Skywise Health Monitoring Platform
- Boeing: same
- Air France Industries: same

- Services from data analytics

ENGINE HEALTH FUNCTIONS

Engine Health Management is based on Safran Aircraft Engines Algorithms able to:

More HM for complex systems needed at Airbus & Boeing

Performance Analysis
- Performance Condition Monitoring
- Performance Health Monitoring

Mechanical Diagnostics
- Unbalance Modular Analysis
- Bearing Monitoring

Nacelle Monitoring
- Thrust Reverser Actuation System
- Nacelle Anti Ice Valve

Subsystem Supervision
- Actuator Loop
- Engine Oil Condition
- Engine Start Capability
- Sensors Intermittences
- Actuator Use
- Smart Filter
- Sensors Aging Drift
- Mission Cycle Count

Current Capabilities | In Development

9

Status of research

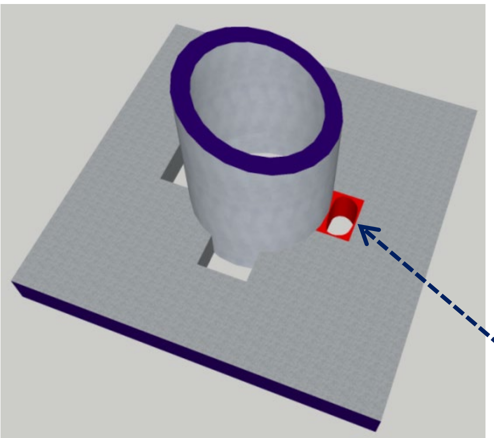
Academics

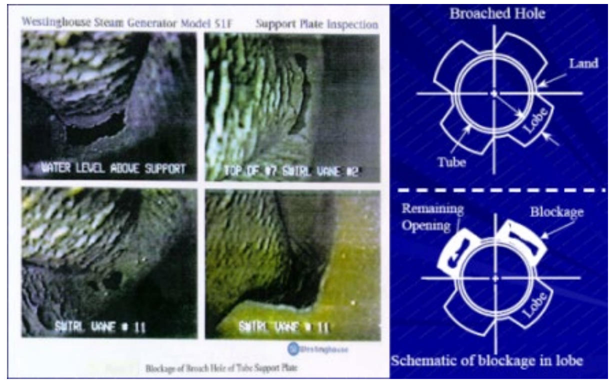
- Deep learning, data-based
- Indicator based diagnosis
  - Indicators from physical and system knowledge (manual)
  - Statistical analysis
- Model based diagnosis
  - OK for small systems

Industry

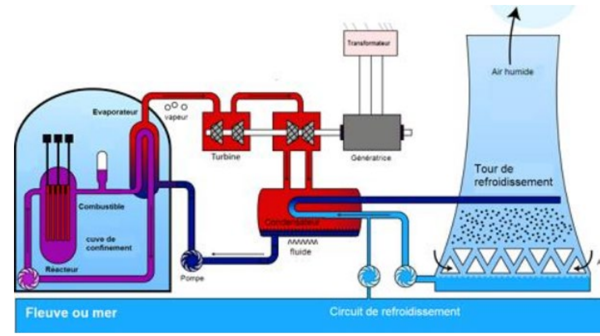
- Diagnosis and HM developed after system design (separately, different team)
- Indicator based diagnosis most commonly used
- Getting indicators is costly
  $\Rightarrow$ Data analytics preferred

Clogging of steam generators (EDF) beyond local diagnosis?

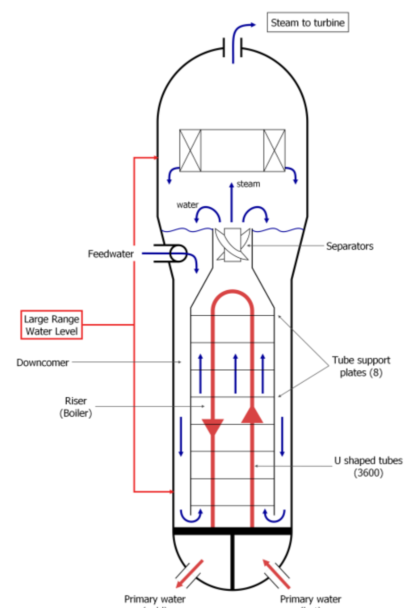




iron oxide deposits



- **Needed**: method to assess the SG clogging rate, better than current methods based on inspection at shutdowns
- **Success**: solved using physical modeling based diagnosis
- **Problem: this was possible because diagnosis problem kept local to the SG; for most problems, global effects exist**



Research needs

Academics

- Diagnosis Models from Design Models ?
- Indicator from Design Models ?
  - Indicators from design models (automatically)
  - Statistical analysis, machine learning

Systems Industry

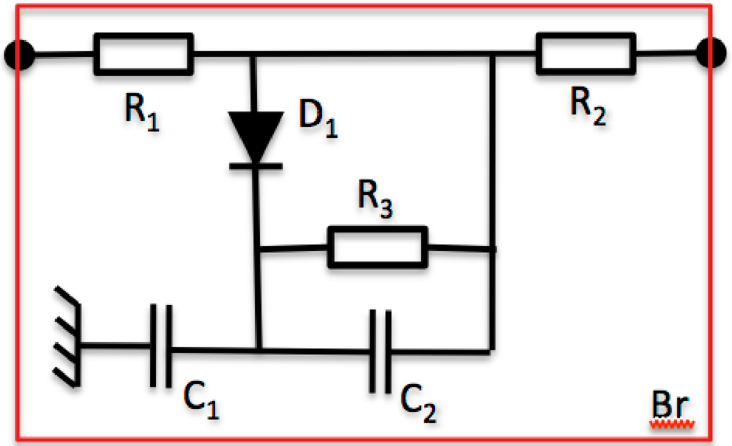
- {Data+Model}-based diagnosis:
  - OEM knowns his system: making a competitive advantage of this
  - Ex: Air France Industries / Safran
- Getting models?
- Improving statistics and machine learning by using models?

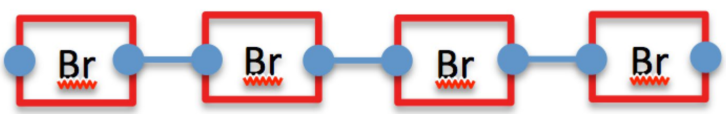
DAE based modeling & System wide Diagnosis

Automatic generation of fault indicators from design model

Albert Benveniste Synchron 2021

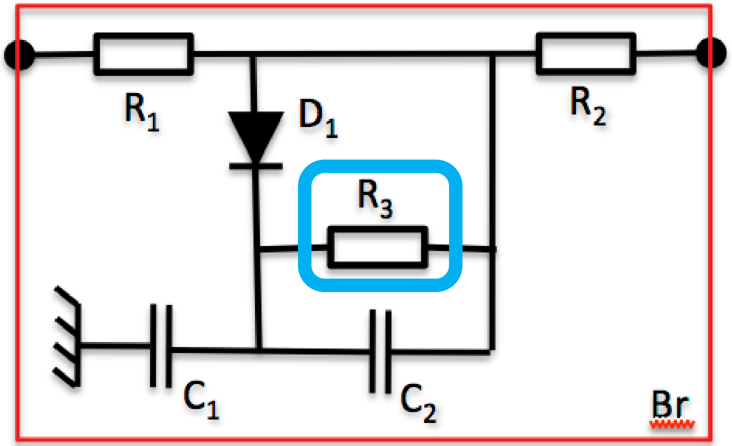
From design models to parity checks, automatically

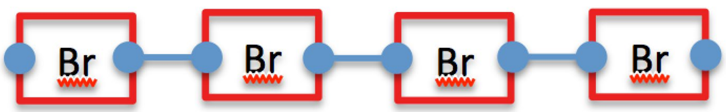




- Westinghouse braking system; control: pressure at the head of the train
- Each wagon induces two modes: valve D_1 open / closed
  - 2^n modes for a n wagons train
- Resistor R_3 captures possible leakage
  - Nominal / Leak : $R_3 = \infty$ / $R_3 < \infty$

From design models to parity checks, automatically





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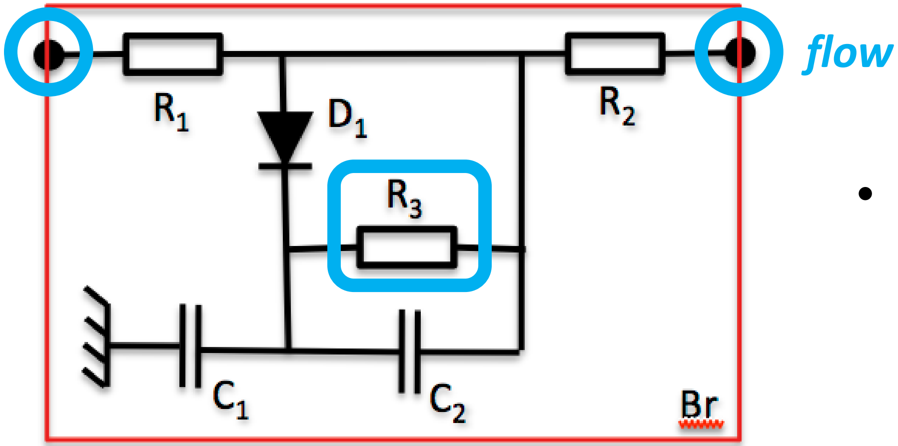
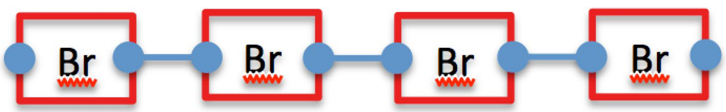
  - Nominal / Leak : $R_3 = \infty$ / $R_3 < \infty$
- **Goal: monitoring for a possible leakage**
  - *What should we measure?*
  - *Where to put sensors?*
- **Getting all of this from model, automatically**

From design models to parity checks, automatically

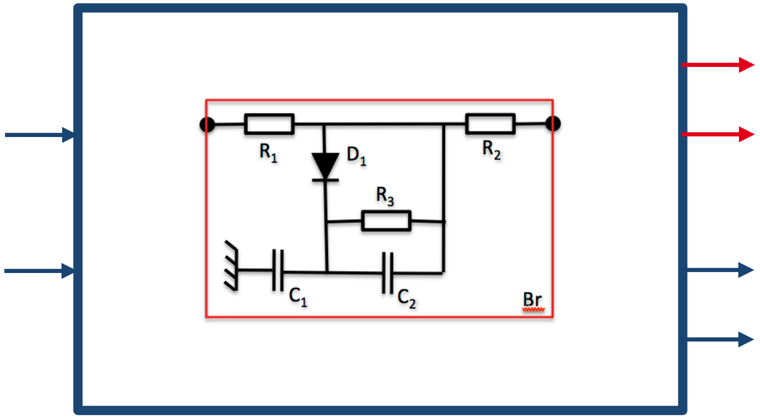




- Failure non detectable when D_1 open (no breaking mode)
  - (no flow traverses R_3 in this case)
  - Diagnosticability is mode-dependent

- How to generate parity checks
  - To monitor all possible leaks
  - By measuring (some or all of) the ***flows***?

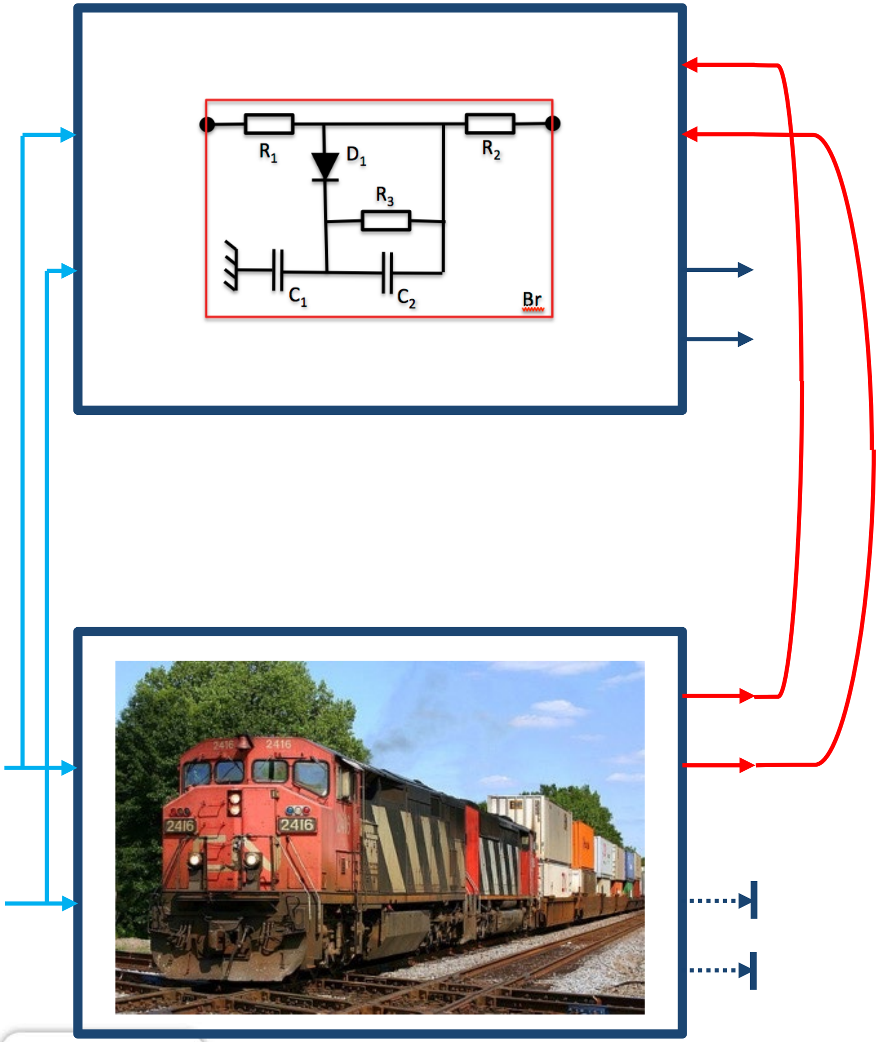
From design models to parity checks, automatically



- We have our simulation model

- And the actual system for monitoring
- Some (but not all) states or outputs are measured

From design models to parity checks, automatically

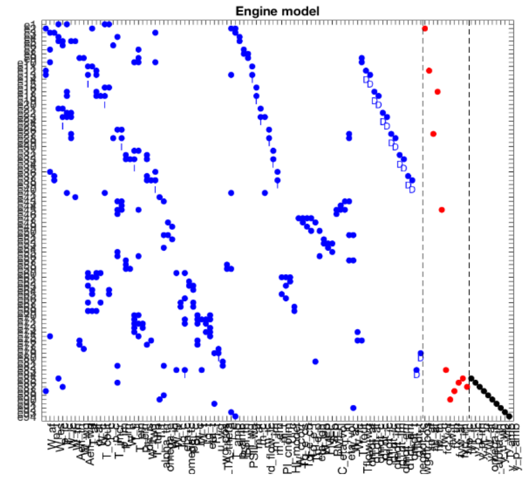


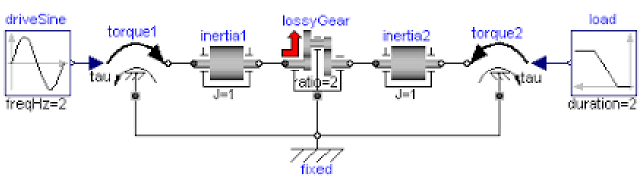
- Feed the model with measured data
- Yields an over-constrained (multimode) DAE model
- Generate automatically (via structural analysis) **parity checks**: minimal structurally singular subsystems (MSSS)
- Each parity check yields a **residual**, serving as fault indicator

- Collect measurement data from the system in operation

Frisk & Krysander, Linköping, Sweden

Incidence graph generated from Simulink or Modelica

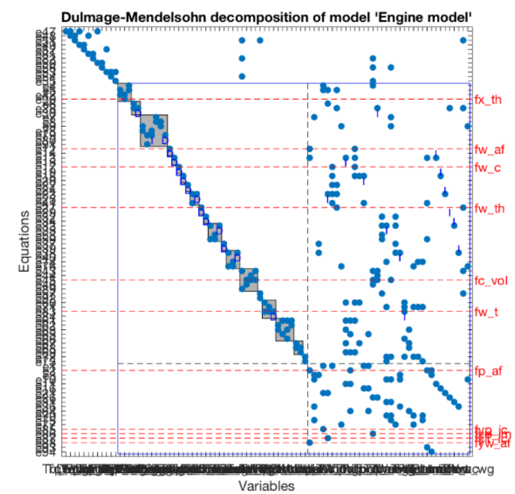




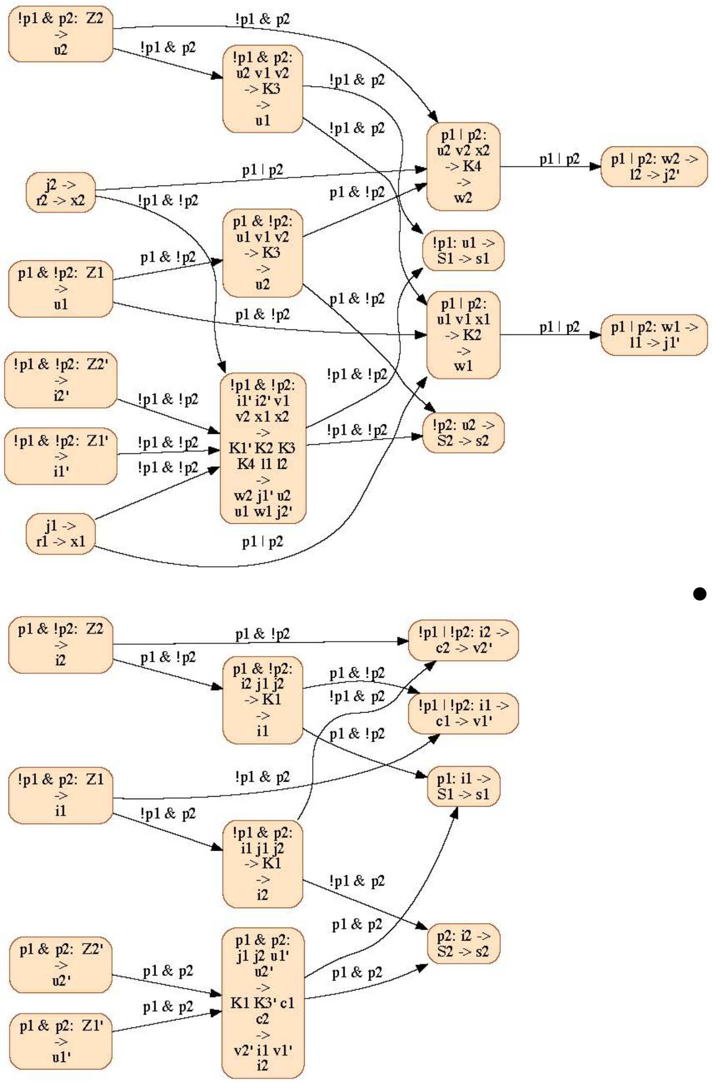
https://faultdiagnosistoolbox.github.io/usecase/

Parity checks

Clustering faults that cannot be distinguished given sensor setup

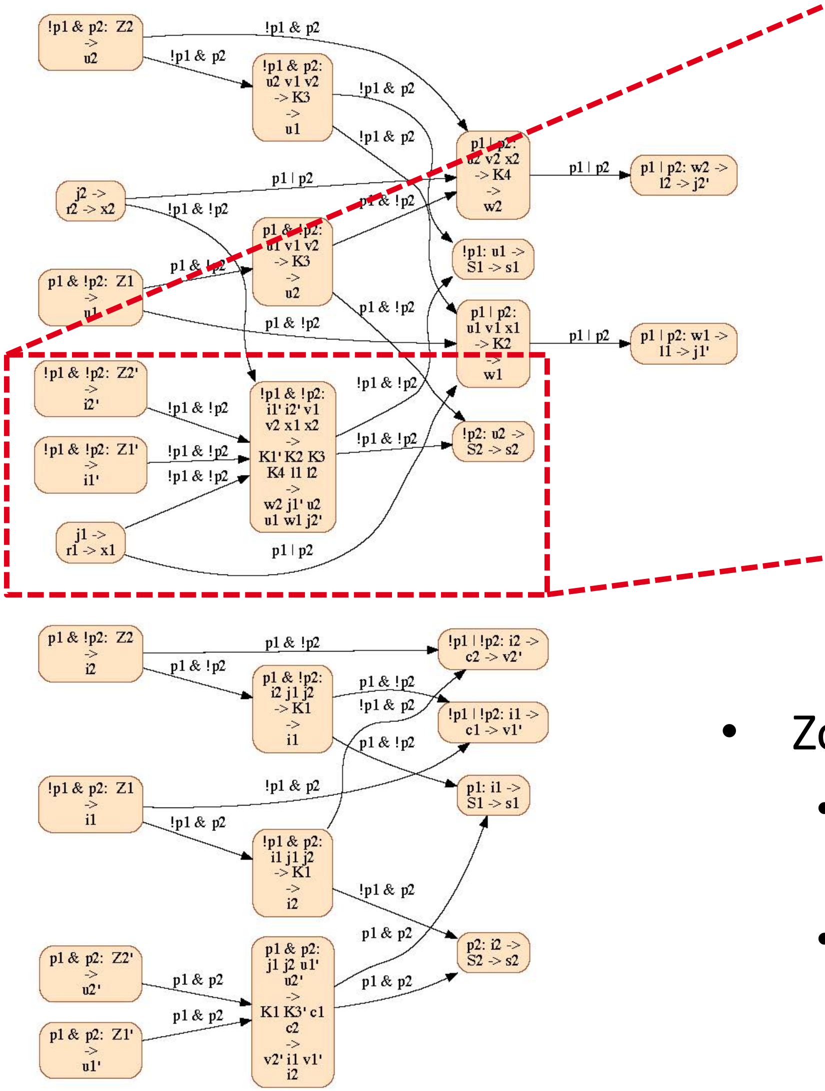


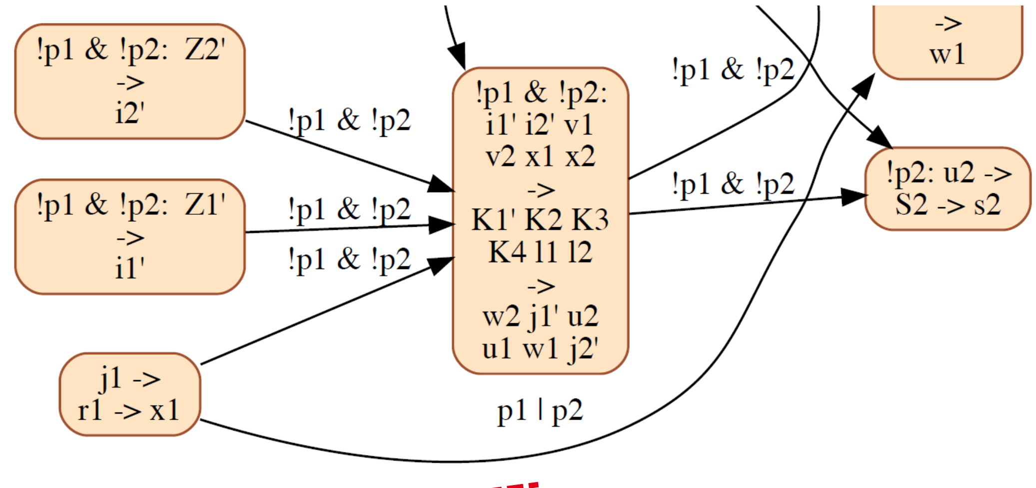
Using IsamDAE [Caillaud,Malandain]



- Conditional dependency graph between blocks

Using IsamDAE [Caillaud,Malandain]





- Zooming on a block
  - Measuring “s2” turns it into an “input” ⇒ (mode dependent) Over-Constrained Subsystem
  - Minimal OCS : mode dependent parity check

Putting statistics and machine learning on top of this

Probabilistic programming?

Sketch

$$\text{If P then} \begin{cases} f_1(\dot{x}_1, x_1, \dots, \dot{x}_n, x_n) = 0 \\ \dots \\ f_m(\dot{x}_1, x_1, \dots, \dot{x}_n, x_n) = 0 \end{cases} \text{satisfied/violated?}$$

- Parity check: DAE based overconstrained model used as test case: testing for equality is non robust

Sketch

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$$\text{If P then} \begin{cases} |f_1(\dot{x}_1, x_1, \dots, \dot{x}_n, x_n)| \leq \varepsilon \\ \dots \\ |f_m(\dot{x}_1, x_1, \dots, \dot{x}_n, x_n)| \leq \varepsilon \end{cases} \text{satisfied/violated?}$$

- Tuning threshold ε using Machine Learning, based on statistics in nominal status

Sketch

If P then $\begin{cases} f_1(\dot{x}_1, x_1, \ldots, \dot{x}_n, x_n) = 0 \\ \ldots \\ f_m(\dot{x}_1, x_1, \ldots, \dot{x}_n, x_n) = 0 \end{cases}$ satisfied/violated?

- Difficulty: some of the (differentiated) variables are unknown
- How to compute them, particularly when the model is violated?
- In control: **observers**; but difficult to design in general (KF, EKF, non-linear…); worse if multimode
- Alternative approach needed

Conclusion

- Model based diagnosis needed, data based not enough
- "Model based": getting the model manually is too costly
- DAE models $\Rightarrow$ fault indicators automatically: test cases
- Making this robust: model uncertainties and noises, statistical analysis

- **Go for {DAE models} + {probabilistic programming}?**

Thanks

Inria
INVENTEURS DU MONDE NUMÉRIQUE