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Qualitative Model Based Diagnosis of Abrupt Faults

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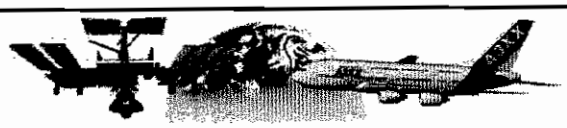

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Presentation Outline

The Diagnosis Problem

Fault Detection and Isolation (FDI) Approaches

Our Qualitative Continuous Approach

- bond graphs
- temporal causal graph analyses
- monitoring

Model Configuration Changes (Hybrid Systems)

Fault Detection and Isolation (FDI), Diagnosis

Engineered Systems

- complex
- safety critical (e.g., aircraft, nuclear plants)

Hardware Redundancy

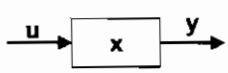
- expensive

Functional Redundancy

- exploit system *model*, i.e., model-based diagnosis

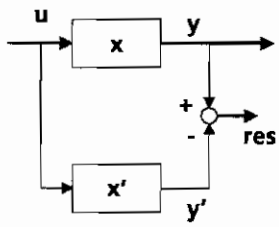
The Diagnosis Problem

System With Nominal (Designed) Behavior



To Detect Anomalies Requires a Reference (Model) of Nominal Behavior

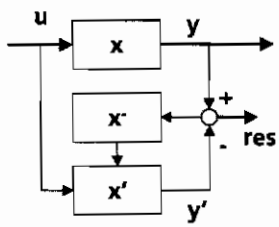
- nominal values from design specification (e.g., for stationary processes)!
- compute nominal behavior from a model



Model Imperfection

In General, the Estimated State Differs and Diverges From Actual State

- **closed loop required**
- **observer (e.g., Kalman filter)**



Observer

Prevents Estimated State From Diverging

- **convergence gain**

High Gain

- **no spurious residuals**
- **however, adaptation to *incipient* fault behavior**

Assumption

- **all faults are abrupt**

Fault Detection and Isolation (FDI)

Fault Detection Determines Whether a Fault Occurred

- compute deviation from nominal
- apply (intelligent) thresholding

Fault Isolation Identifies Deviating Model Parameter(s)

- match faulty system behavior with modeled faulty behavior
  - i.e., requires *fault models*
- fault types
  - sensor, actuator, component, structure
- map parameter deviations to actual components

The FDI Model

Values: Qualitative vs. Quantitative

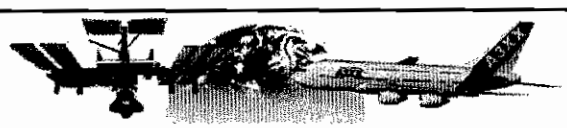
- qualitative models do not require numerical parameter values but diagnosis is less precise
- computational complexity of qualitative methods may be less

Temporal Behavior: Discrete vs. Continuous

- discrete methods may be easier to design but are less precise, coarser
- spurious results

	CONTINUOUS	DISCRETE
QUANTITATIVE	parameter estimation, state estimation	De Kleer & Reiter (combinational circuits)
QUALITATIVE	Mosterman & Biswas	discrete event methods, e.g., Lunze, Sampath *et al.*

Our Qualitative Continuous Approach



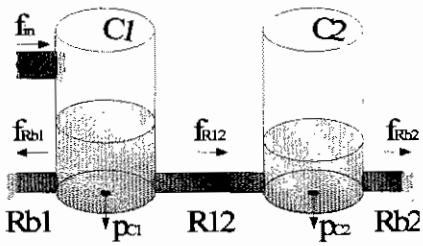
A Continuous Representation

Model Represented as a Temporal Causal Graph (TCG)

- **automatically derived from a *bond graph* (Paynter, 1961) by HYBRSIM**
  - **inherent physical conservation constraints**
    - suppress spurious behaviors
  - **multi-domain (electrical, mechanical, hydraulic)**
  - **qualitative through quantitative behavior**
- **TCG contains**
  - **system parameters (possible component faults)**
  - **temporal effects**

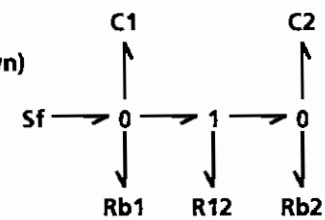
A Second-Order System

Two Tanks



Bond Graph

- 0-junctions are common pressure points
- reversible process, C, state variables (known)
- irreversible process, R
- context, Sf, input (known)
- 1-junctions are common flow points



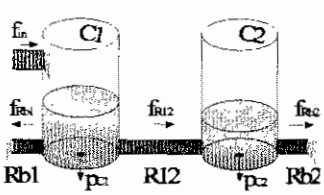
Assign Causality

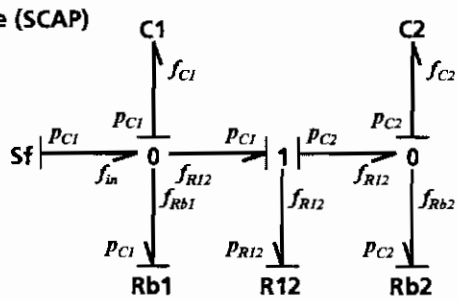
Each Power Connection, *Bond*, Has Two Variables

- ***effort*** **(pressure) and** ***flow*** **(volume flow)**
- **product,** *effort* $\times$ *flow*, **is power**

Sequential Causality Assignment Procedure (SCAP)

- **algorithmic variable ordering**



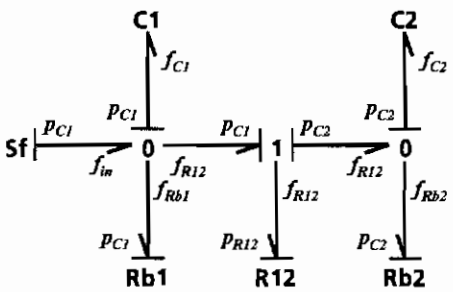


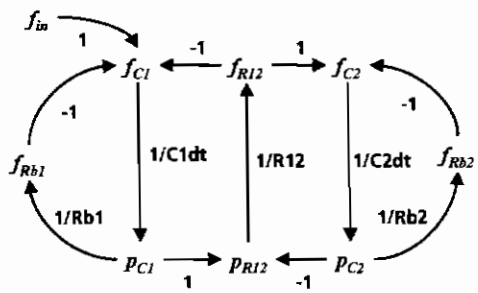
Generate Temporal Causal Graph (TCG)

Allows Additional Processing Based on Boundary Value Analyses

Straightforward From Causal Bond Graph

- **temporal effects break algebraic loops with negative feedback**





Qualitative Diagnosis

TCG Still Covers Quantitative to Qualitative Behavior

Represent Signals in Basic Qualitative Terms

- **-, below nominal**
- **0, at nominal**
- **+, above nominal**

Requires Corresponding Signal-to-Symbol Transformation

- **sophisticated signal processing algorithms**

Diagnosis Stages

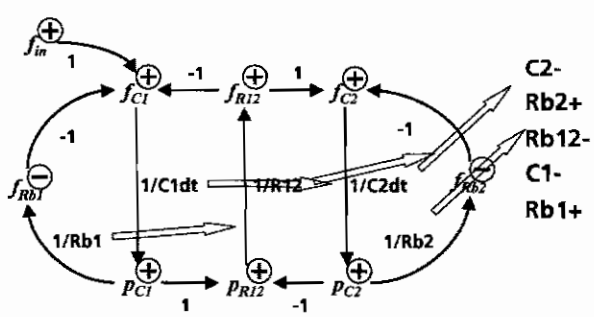
1. Detect Fault
2. Generate Hypotheses
   - generate all possible (sets of) fault candidates
3. Refine Hypotheses
   - prune the fault candidates based on additional information
   - requires
     - predictions of future behavior
     - monitoring to generate symbols
4. Suspend Diagnosis

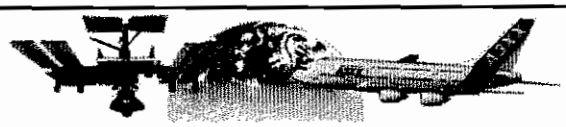
Interpretation by Graph Propagation

Backward Propagation of Detected +/- Deviation in TCG

Example; Too High Pressure in C2, p_{C2}^{+}

- hypothesized faults: C2-, Rb2+, R12-, C1-, Rb1+



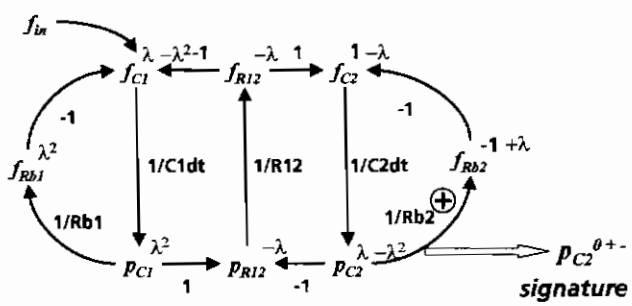


Prune Set of Fault Hypotheses

Forward Propagation of Each Parameter Deviation in TCG

- **prediction, signature, of future measurements for each fault**
- **develop polynomial in λ (*dt*) to take temporal effects into account**

Example; Rb2+



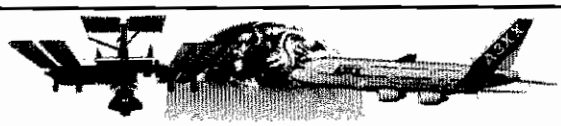
Hypothesis Refutation

Validate Each Fault By

- **comparing with other measurements (not just the one that generated it)**
- **information from each individual measurement**
  - **magnitude change**
  - **discontinuous change**
  - **first order effect**
  - **additional information**
    - second order effect
    - steady state

Requires Time Window to Generate These Symbols Because of Noise

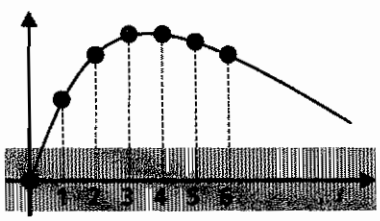
- **monitor during transient after fault ⇒ *progressive monitoring***



Progressive Monitoring

System Behavior Convolutes the Predicted Transient at Time of Failure

- dynamically change the signature



k	measure
0	0
1	+
2	+
3	+ +
4	+ 0
5	+ -
6	+ - -

k	signature1
0	0 + -
1	+ + -
2	+ + -
3	+ + -

match!

k	signature2
0	+ - +

no match!

Only Model Observable Behavior!

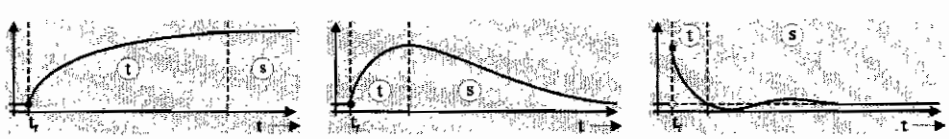
Final Diagnosis

Suspend When One of Three Classes of Behavior Is Detected:

- compensatory response
- reverse response
- inverse response

Per Signal

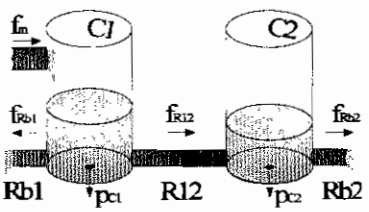
- not all feature detection simultaneously suspended

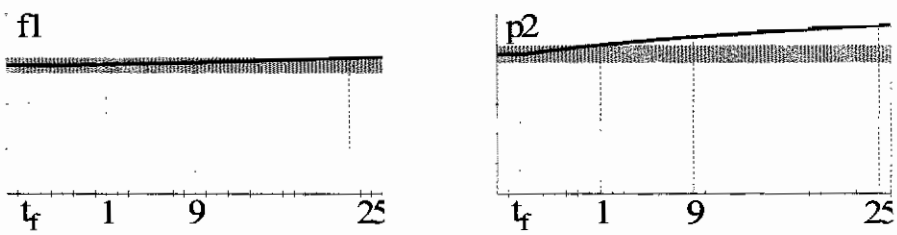


Two Tank Diagnosis

Monitoring Example

- Rb2+





Two Tank Symbols

Diagnosis Output

(1) ACTUAL =>
f1: 0 .
p2: 1 .

C2- =>
f1: 0 1 -1
p2: 1 -1 1
Rb2+ =>
f1: 0 0 1
p2: 0 1 -1
R12- =>
f1: 0 -1 1
p2: 0 1 -1
C1- =>
f1: 1 -1 1
p2: 0 1 -1
Rb1+ =>
f1: -1 1 -1
p2: 0 0 1

(9) ACTUAL =>
f1: 0 0 .
p2: 1 1 .

Rb2+ =>
f1: 0 0 1
p2: 1 1 -1
R12- =>
f1: 0 -1 1
p2: 1 1 -1
C1- =>
f1: 1 -1 1
p2: 1 1 -1
Rb1+ =>
f1: -1 1 -1
p2: 1 1 1

(10) ACTUAL =>
f1: 0 0 .
p2: 1 0 . (-> S)

Rb2+ =>
f1: 0 0 1
p2: 1 1 -1
R12- =>
f1: 0 -1 1
p2: 1 1 -1
C1- =>
f1: 1 -1 1
p2: 1 1 -1
Rb1+ =>
f1: -1 1 -1
p2: 1 1 1

(23) ACTUAL =>
f1: 1 0 .
p2: 1 0 . (-> S)

Rb2+ =>
f1: 1 1 1
p2: 1 1 -1
C1- =>
f1: 1 -1 1
p2: 1 1 -1

(25) ACTUAL =>
f1: 1 1 .
p2: 1 0 . (-> S)

Rb2+ =>
f1: 1 1 1
p2: 1 1 -1

(26) ACTUAL =>
f1: 1 0 . (-> S)
p2: 1 0 . (-> S)

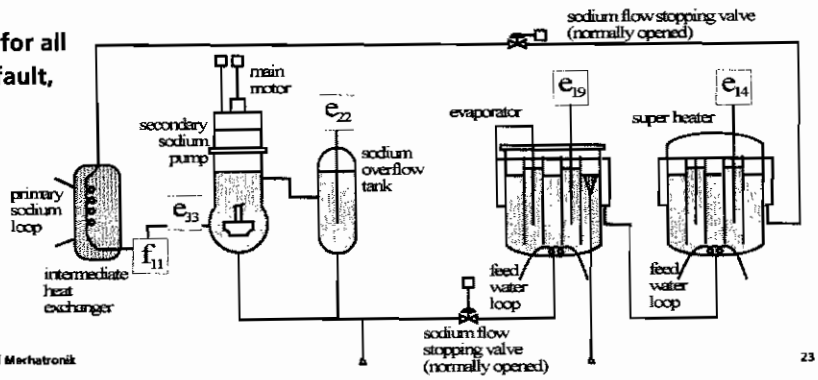
Rb2+ =>
f1: 1 1 1
p2: 1 1 -1

Secondary Sodium Cooling Loop

Sixth Order Nonlinear Model

22 Faults

- **accurate for all but one fault, i.e., Cev-**



Combustion Engine Cooling System

Noise

- **model**
- **measurements**

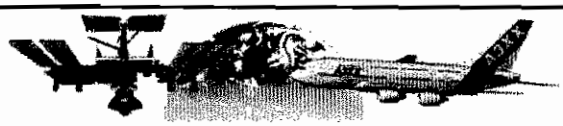
Difficult to Model

- **algebraic loops**

Mode Switching

- **large leak**
- **small leak**

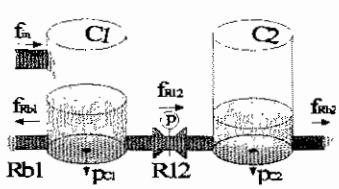
Parallel FDI



Hybrid Diagnosis

Structural Changes

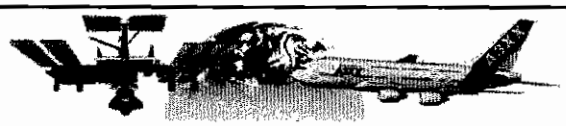
Consider a Pressure Controlled Connecting Valve



For Rb2- (leakage) the Valve may Close and the Prediction Changes

- **OPEN:** $p_{C2}^{0\,0-}$
- **CLOSED:** p_{C2}^{0+-}

This Could Lead to Incorrect Diagnoses



Causal Changes

Closing the Valve Changes Causality in the System

- **OPEN:** $f_{RI2} = p_{RI2} / RI2$
- **CLOSED:** $p_{RI2} = f_{RI2} * RI2$

Generate All TCGs?

- **combinatorial explosion**

Parametrize TCG With Mode!

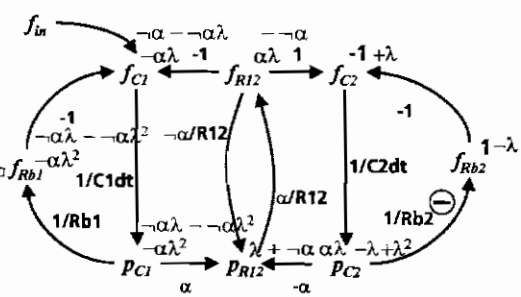
- **parametrized signatures**
- **constraint satisfaction problem (CSP)**

Causal Changes

For Two-Tank

- **two modes**
  - **OPEN:** α
  - **CLOSED:** $\neg\alpha$
- **leakage, Rb2-**

f_{Rb1}: $\neg\alpha\lambda - \lambda^2$ *signature*



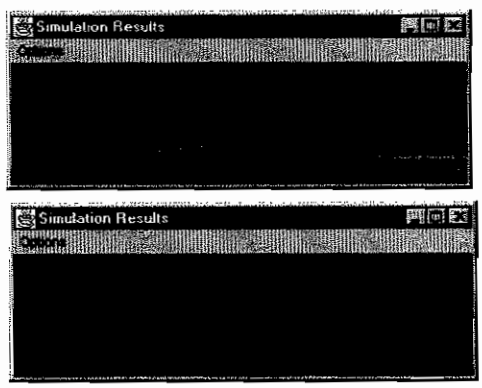
Mode Transition Contraints

One Fault Has Multiple Possible Behaviors

- **Rb2-(α): 0 0 -**
- **Rb2-(¬α): 0 + -**

k	measure
0	0
1	0
2	-
3	- -
4	- -

k	measure
0	0
1	+
2	+ +
3	+ +
4	+ +



Interaction Stops Diagnosis

3	- +

Constraint Satisfaction Problem

For Each Prediction

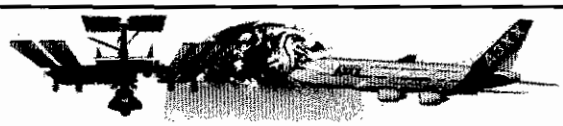
- **e.g., Rb2-** $\neg\alpha\ \lambda - \lambda^2 \Rightarrow \{0, 1-\alpha, -1\}$

Find α Such That Observation Is Satisfied

- **e.g., {1, 1}**

Under the Assumption That Higher Order Effects Propagate Down

- **only overwrite nominal, 0, values**
- **e.g., Rb2-** $\Rightarrow \{1-\alpha, 1-\alpha, -1\}$ **can be satisfied by** $\alpha = 0$ **(valve closed)**



Conclusions

Model-Based Diagnosis Systems

- method classification
  - qualitative vs. quantitative
  - discrete vs. continuous
- close interaction between a number of fields
  - modeling
  - instrumentation technology
  - signal processing
  - analyses (constraint satisfaction)

A Qualitative Continuous Method Can Be Successful

- accurate but less precise than quantitative approaches (pre-processing)
- for stationary processes an observer may not be required

TRANSCEND

Bond Graph Based Approach

- highly constrained continuous models

Graph Propagation

- fault hypotheses
- predictions

Signal-to-Symbol Transformation for Pruning

- discontinuities
- magnitude deviations
- first-order behavior
- second-order behavior?
- steady-state?

Current and Future Work

Hybrid (Continuous and Discrete) Systems

- engineered systems combine
  - physical plant, continuous
  - controller, discrete
- complex models
  - piecewise simpler
  - adapted to data acquisition bandwidth

Bond Graph Based Diagnosis Extended by Using Parametrized Causality

Still, Lots to Be Done!