Robust Methods for Autonomous Fault-Adaptive Control of Complex Systems

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Autonomous Fault-Adaptive Control

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Goal: Develop autonomous fault-adaptive on line control for complex systems.

Objectives:

- Develop **modeling techniques** for distributed hybrid systems that handle interactions efficiently.
- Perform Robust **Fault Detection and Isolation (FDI)** in a distributed hybrid system environment using a combination of Beard-Jones filters, hybrid diagnosis schemes, and Failure Propagation Graphs.
- Design **controller tuning** and **controller reconfiguration** methods for reliable fault-adaptive control.

Key Innovations:

- Distributed hybrid modeling techniques.
- Monitoring and mode identification in hybrid systems.
- Fault detection and isolation with hybrid models; integrate hybrid diagnosis across subsystems
- Online controller tuning and controller selection and reconfiguration

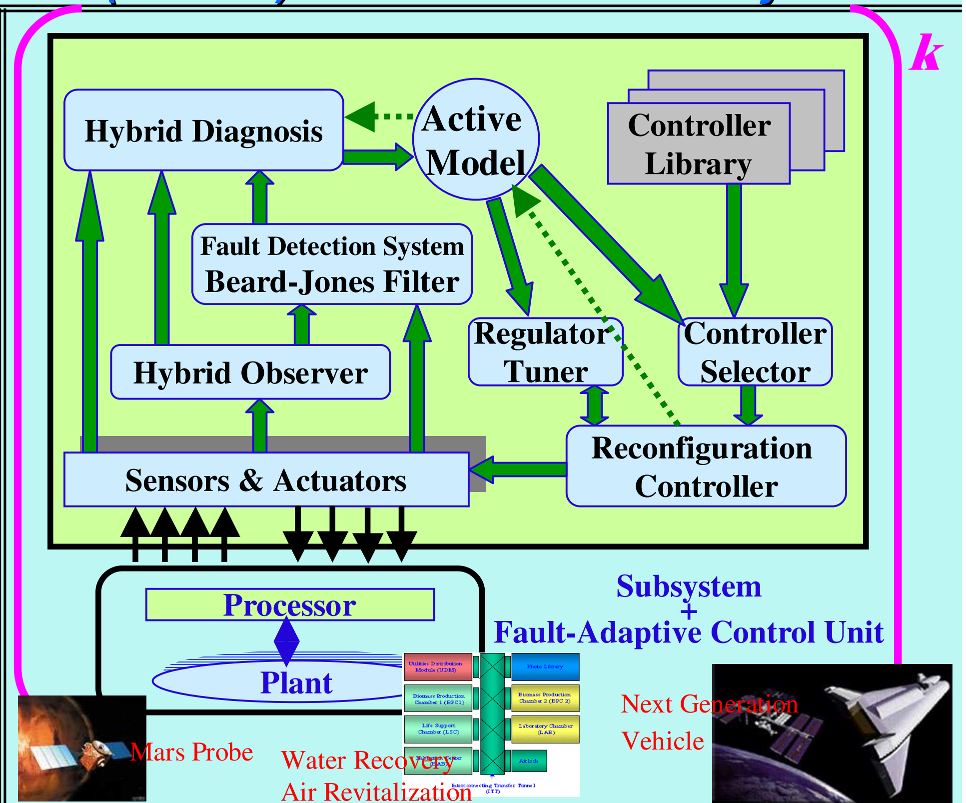
NASA Relevance:

- Develop technology for long-term autonomy of complex dynamic systems using model-based, distributed, intelligent online algorithms
- Contribute to autonomous operation of NASA missions.

Accomplishments to date:

- Hierarchical Hybrid modeling: Bond Graphs + Discrete Event Systems
- Comprehensive FDI applied to real applications
- Online safety control by incremental analysis
- Multi-layered architecture for FDI and Control
- Modeling and analysis of WRS of Bioplex system (in conjunction with NASA JSC)
- Publications

10/8/2002:
NASA-IS Meeting (Monterey)



Schedule:

- **Year 1: Foundations**

  Modeling (Hybrid + Interactions), Hybrid Observer

  Prototype B-J filters, hybrid diagnosis, and FPG diagnosis
- **Year 2: Prototype**

  Refined and integrated modeling of system, interacting hybrid observers, integration of diagnostic modules, prototype controller selector; NASA application
- **Year 3: Integrated System**

  Complete model of NASA application, integrated run-time system (observers + FDI units + reconfigurable controller), Demonstration of NASA application

Key Technical Challenges for Autonomous, Fault-Adaptive Control

- Complex, Embedded Systems: Tasks
  - **Modeling**
    - Component based modeling + composition
    - Hybrid models: controlled + autonomous transitions
    - Tuning models to track real system behavior
  - **Tracking**
    - Complex continuous processes with discrete changes in uncertain environments (Kalman filters + hybrid automata)
    - Systems with large mode spaces: online model generation
  - **Fault Detection and Isolation**
    - On line (real time?) FDI: detect small changes at onset + analyze transients in the face of mode changes + online parameter estimation
    - Robustness issues: dealing with model disturbances + measurement noise
  - **Controller Reconfiguration**
    - Online safety control as a search process

Online

Complete Architecture for Transient Detection and Analysis

Fault Detection – robust detection of small changes + detecting fault onset

Abrupt change detection theory + statistical signal detection

Optimal detector based on time frequency analysis of signal (wavelets) + energy detection in transients

Subsampling methods to accurately define onset

Signature Generation – signal to symbol transformation

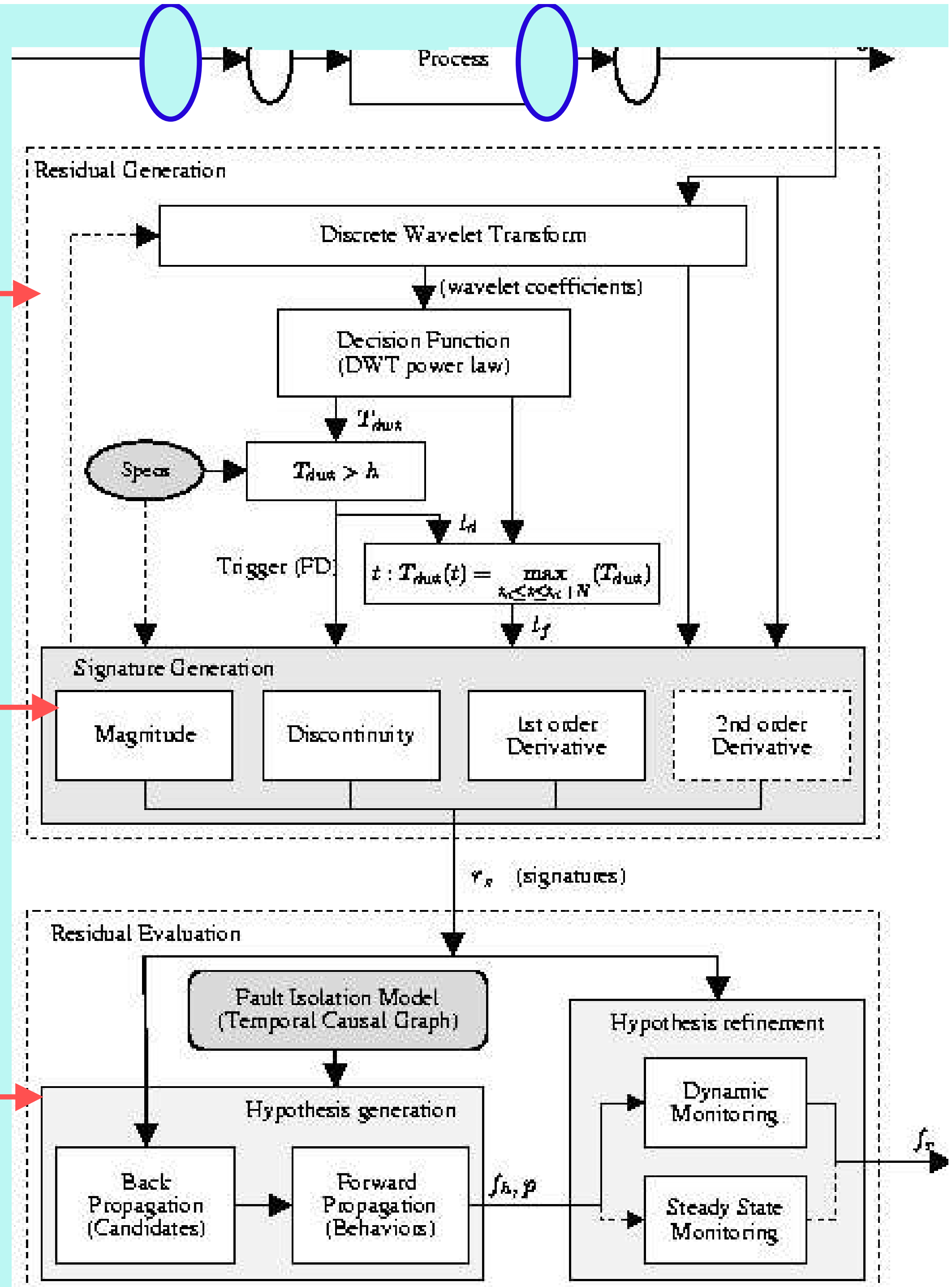
setting of thresholds: partly signal theory + partly experimental

derivative estimation from discrete time approx. of signals in noisy environments: implemented as linear estimation problem with FIR filter

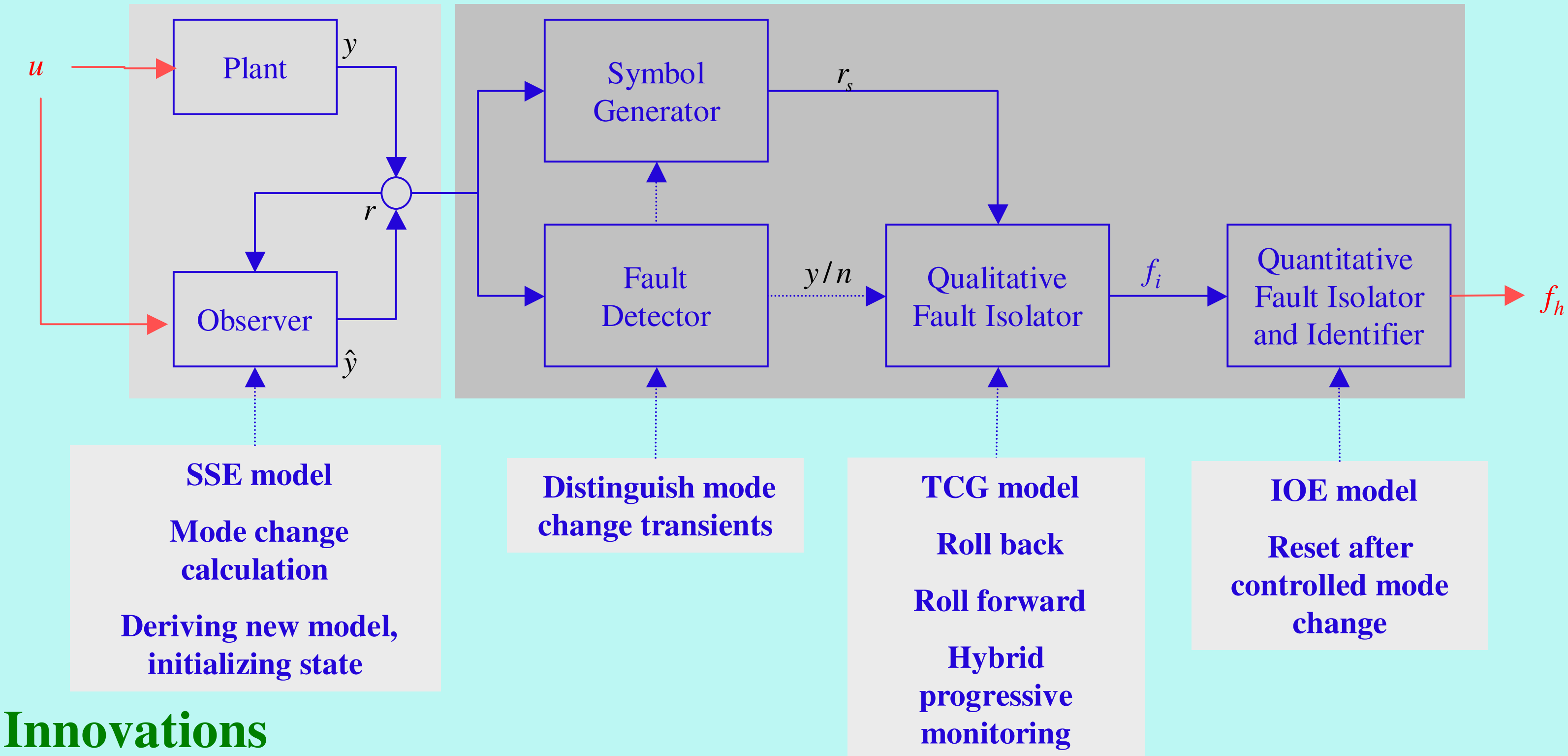
Fault Isolation – (hypothesis generation + refinement) + parameter estimation

dynamics of transient captured by TCG

linked to Taylor series expansion of signals



Hybrid FDI Architecture



Key Innovations

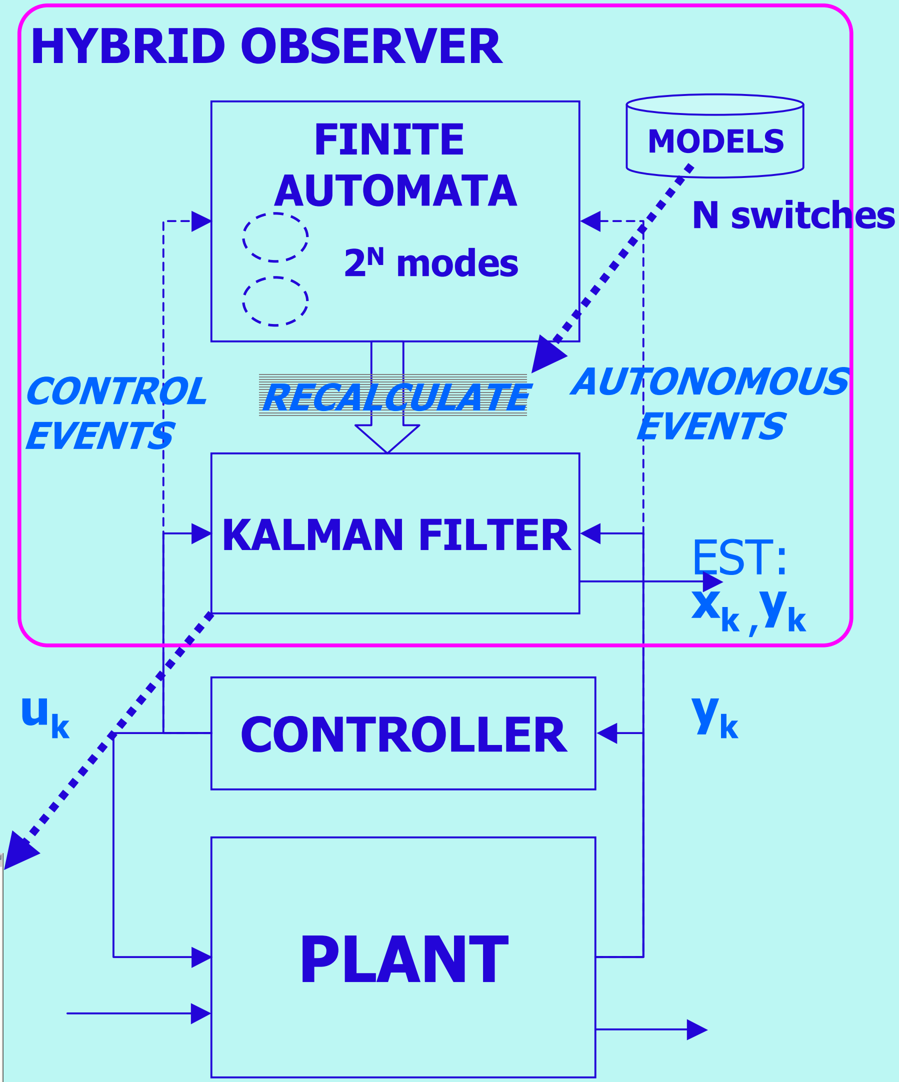
- Component based modeling using Hybrid Bond Graphs + decision functions to implement mode transitions
- Used to systematically derive State Space Equations (SSE), Temporal Causal Graph (TCG), and Input Output Equations (IOE)

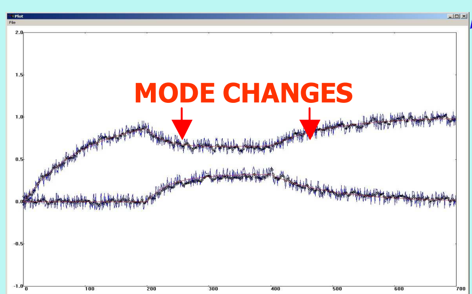
Hybrid Observer

Key Innovations:

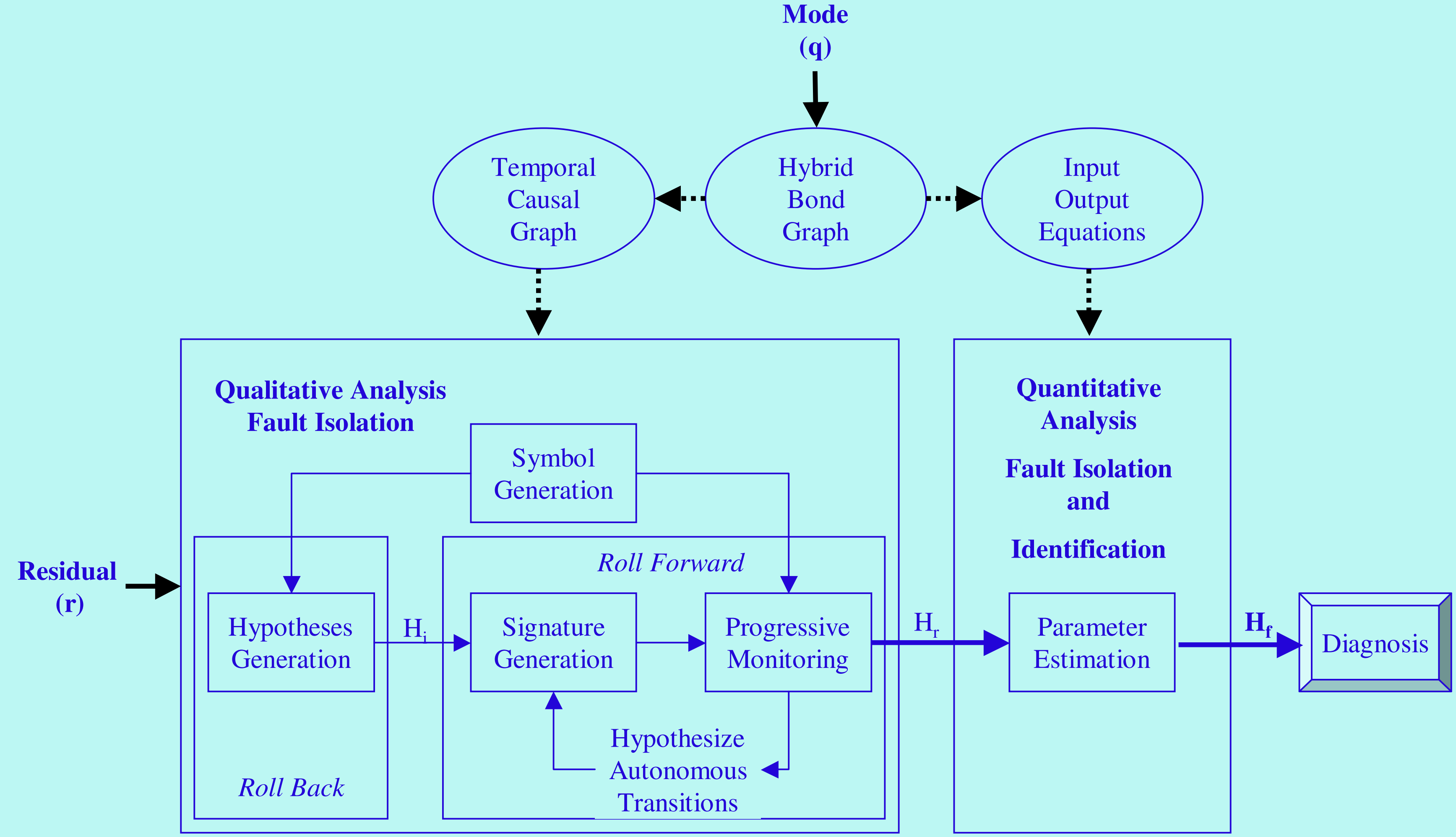
Observer is composed automatically from component models

- Dynamic update of model after mode changes
- Track autonomous changes
- Tracking of noisy signals





Fault Isolation & Identification

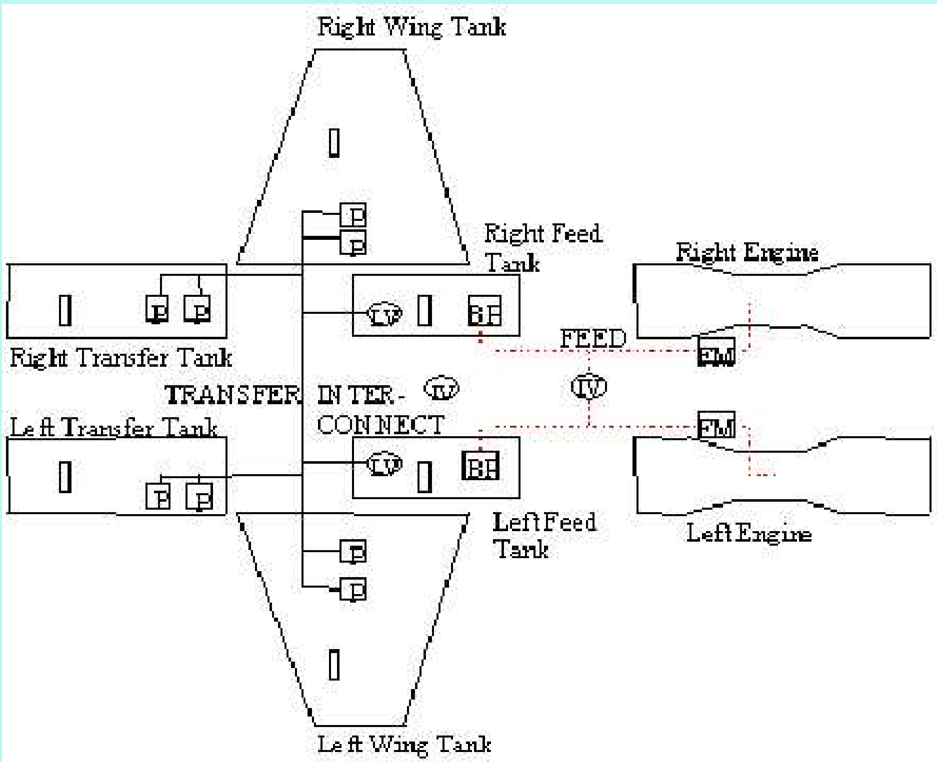


Key Innovations

Roll back and Roll forward process; dealing with mode transitions

Combining qualitative with parameter estimation

Fuel System Configuration

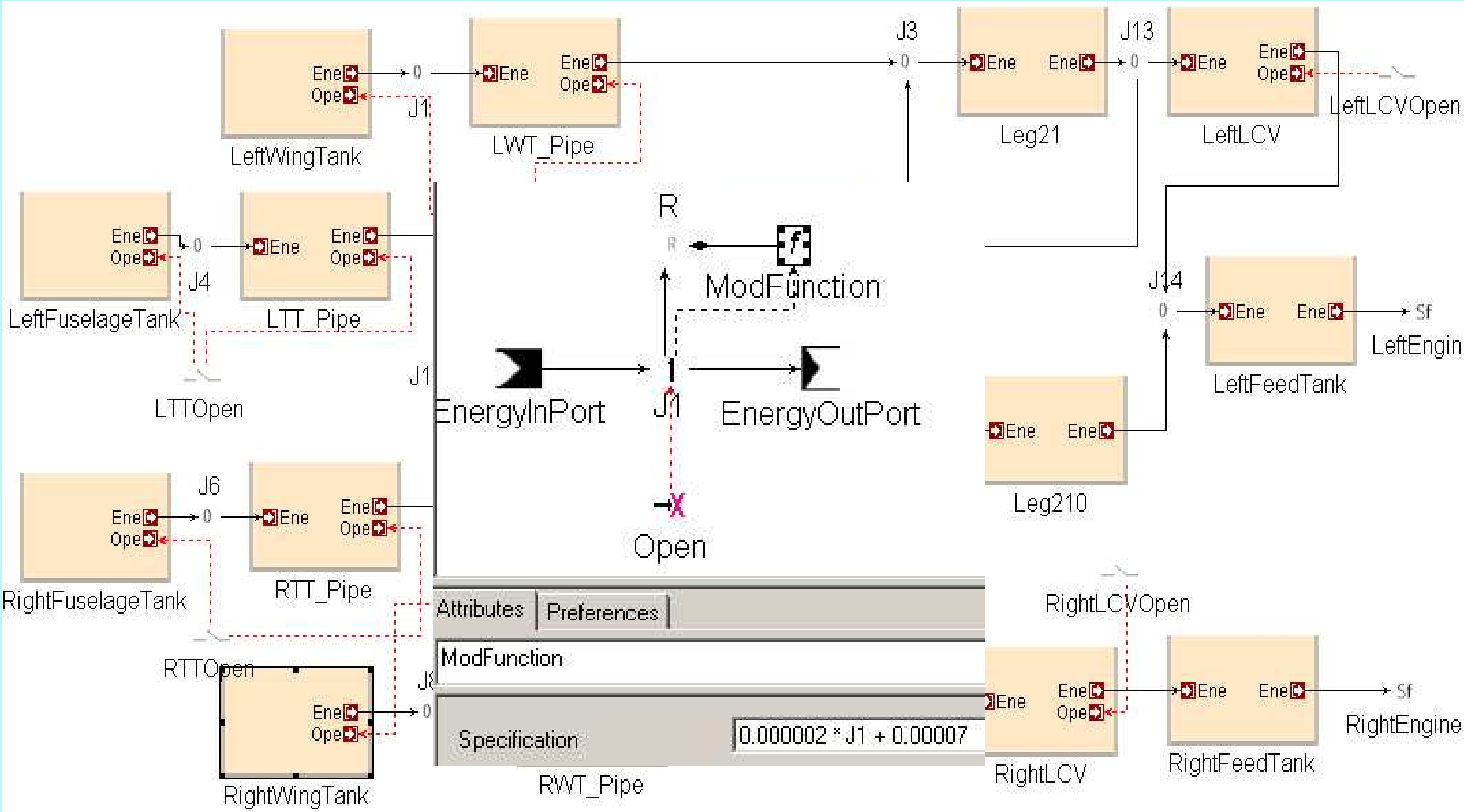


P **Transfer Pump**
LV **Level Control Valve**
IV **Interconnect Valve**
BP **Boost Pump**
FM **Flow Meter**
Fuel Quantity Sensor

Components with non-linear behavior

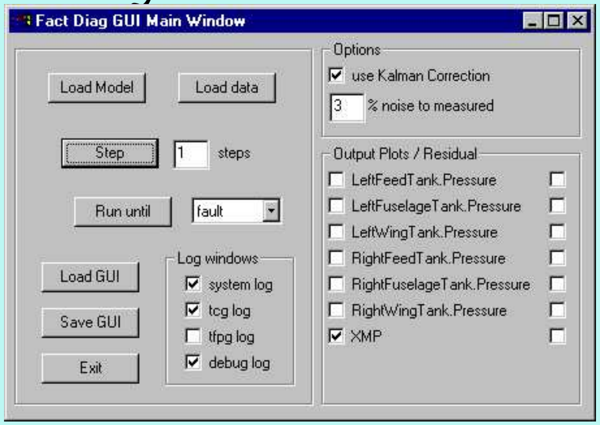
- Modeling with modulating functions
- Modified tracking algorithm to solve non-linear equations
- Causality based on non-linear relations
- Only controlled transitions, no autonomous transitions

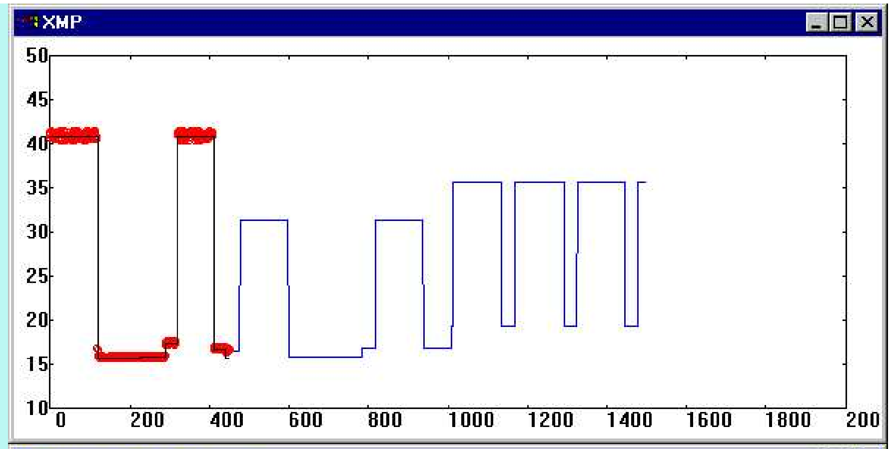
Fuel System GME model

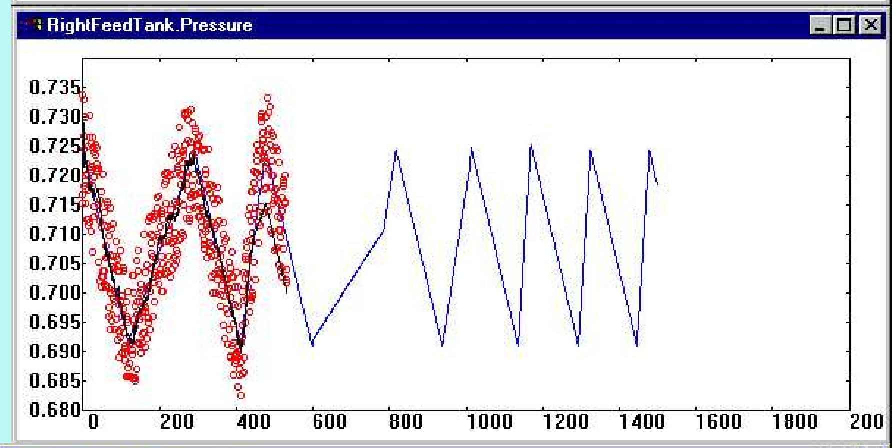


Key issue in model building: matching model parameters to real System behavior

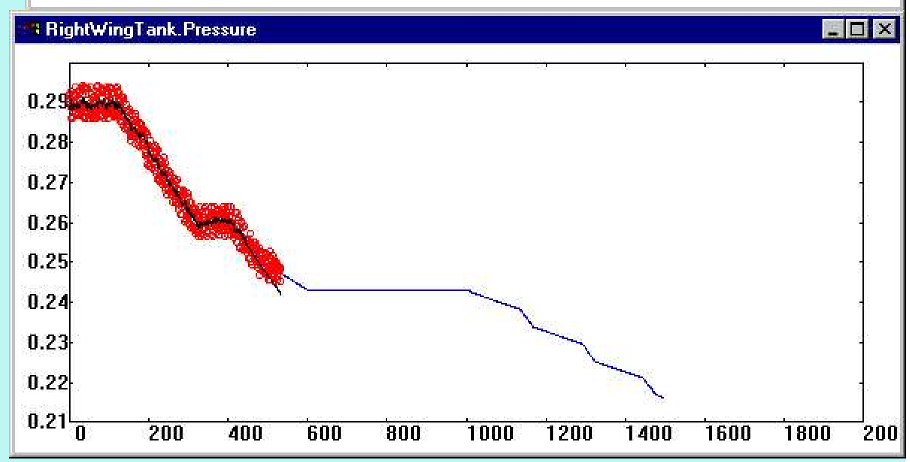
Fuel System Demo

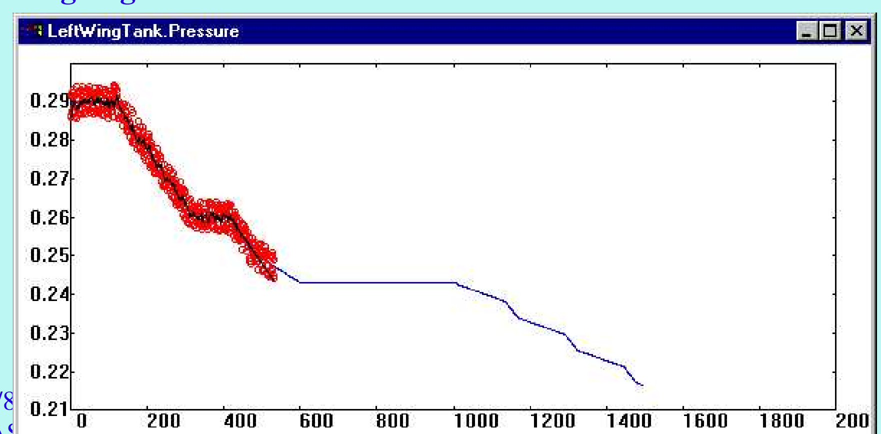




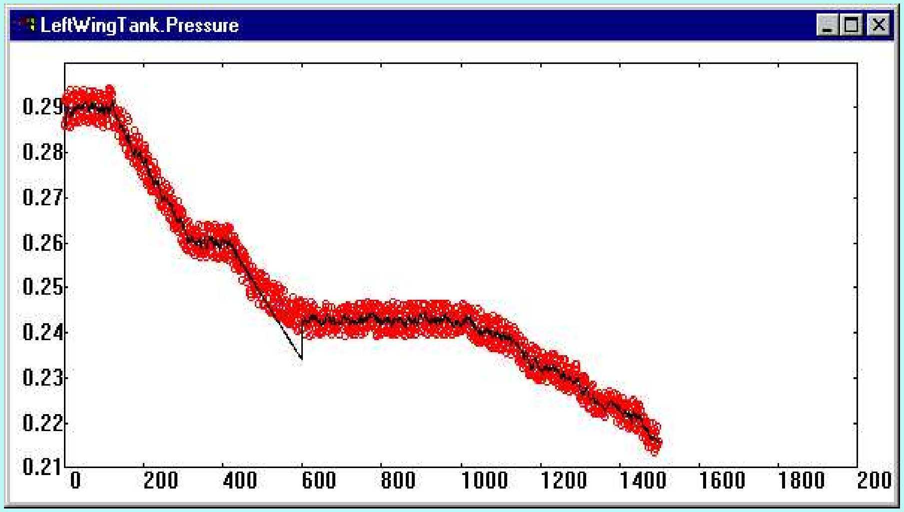


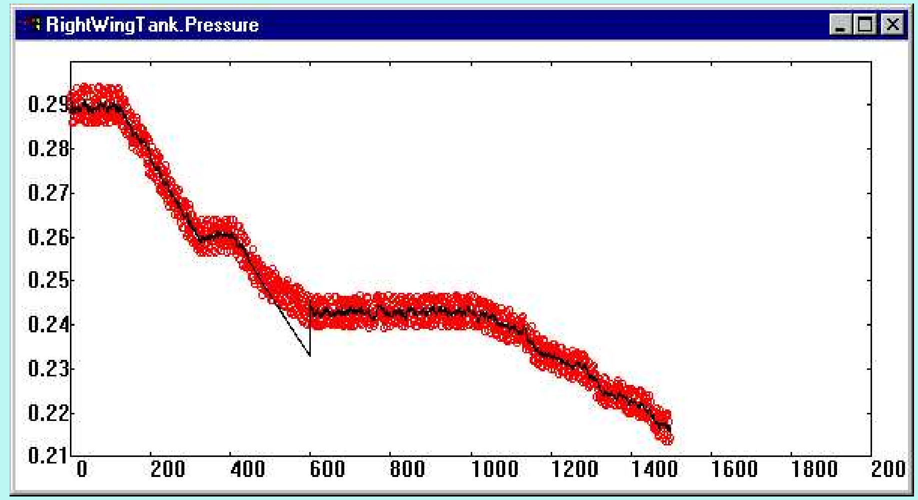
- **timestamp (453.0)** LWT_Pipe.R-, LeftWingTank.R-, LeftWingTank.TF+, Leg21.R+, Leg210.R+, Leg25.R+, Leg26.R+, RWT_Pipe.R-, RightLCV.R+, RightWingTank.R-, RightWingTank.TF+
- **timestamp (476.0)** Leg21.R+, Leg210.R+, Leg26.R+
- **timestamp (530.0)** Leg21.R+, Leg210.R
- **timestamp (597.0)** TCG has finished, in 151 steps, starting parameter estimation for: [Leg210.R+ Leg21.R+]
- For Leg210.R+...finished, error: 18999
- For Leg21.R+...finished, error: 7.17291
- Setting Leg21.R's fault coefficient to 99.3068

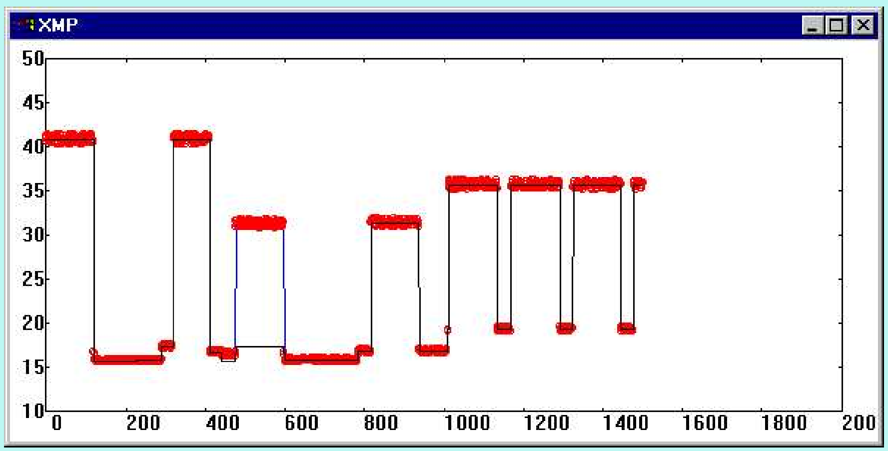


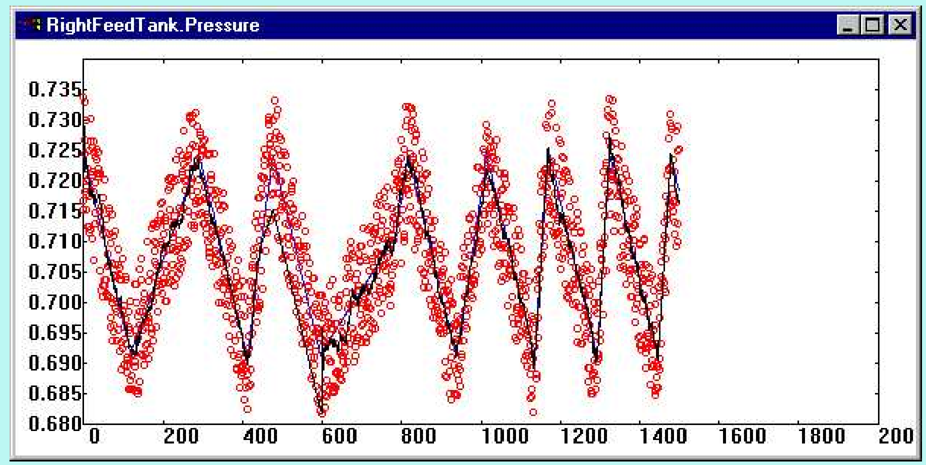


Fuel System Demo (contd. …)





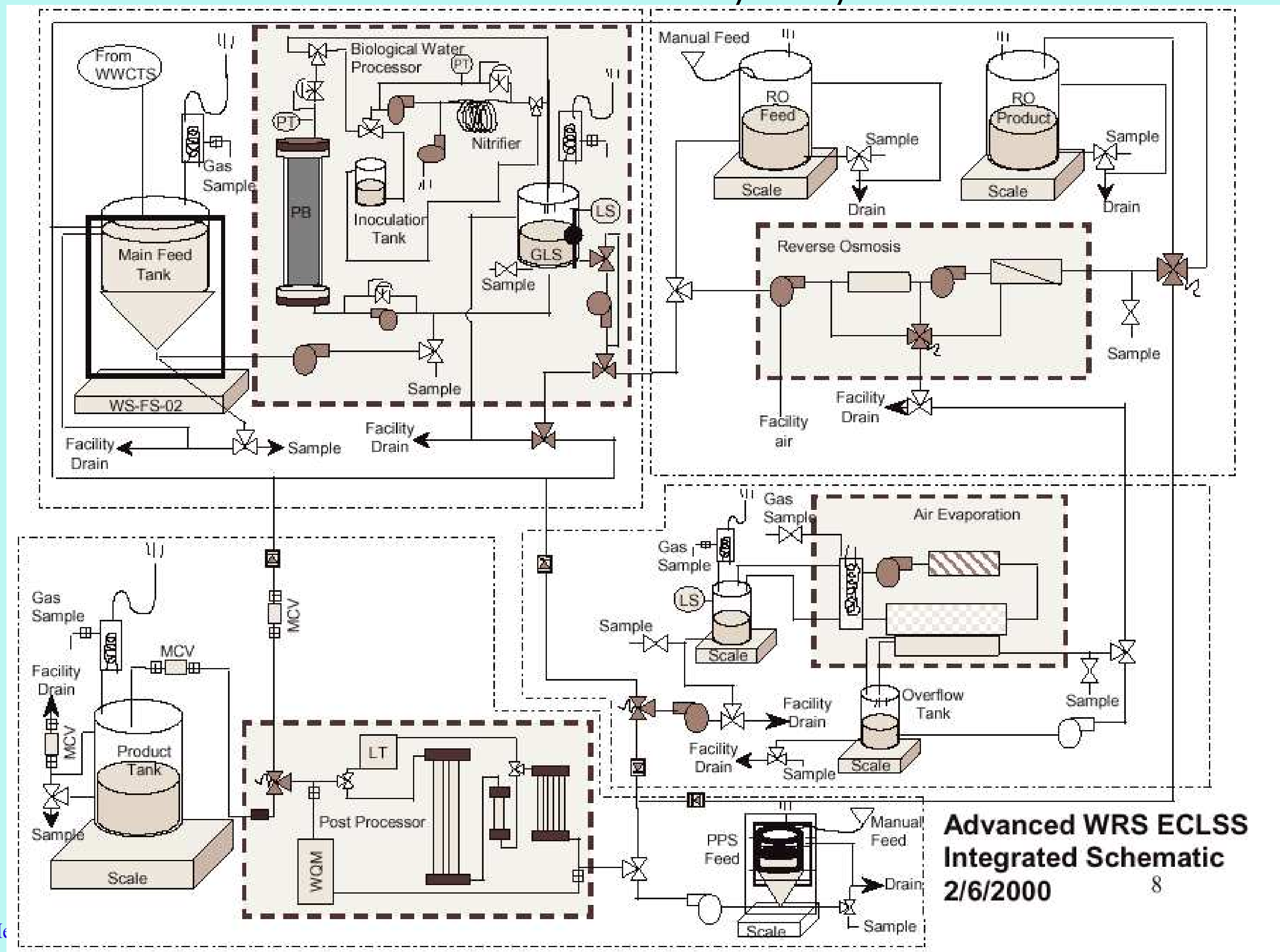




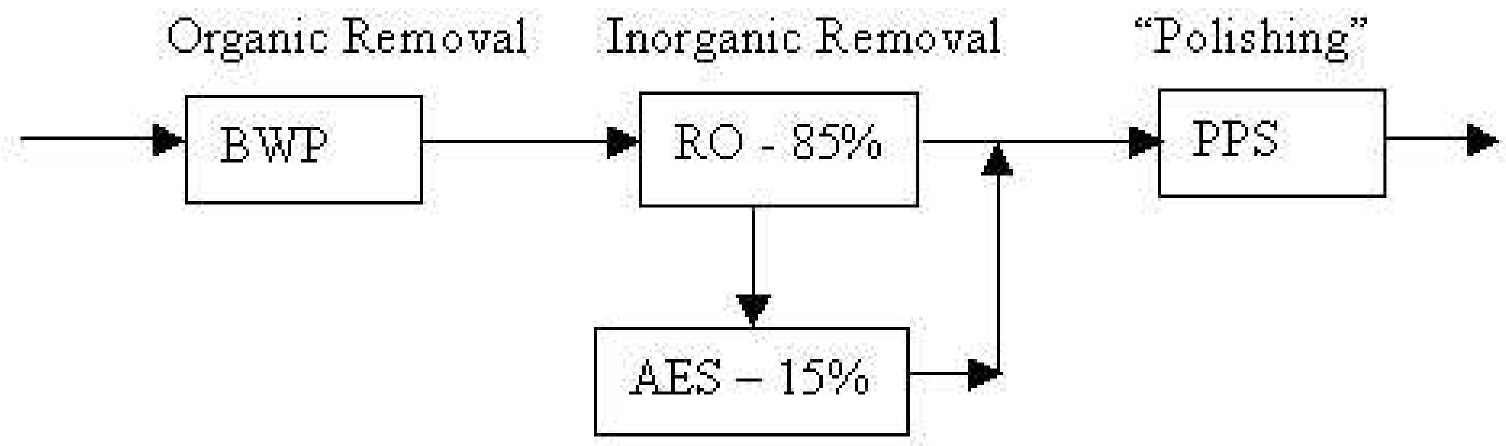
After FDI & identification, Kalman filter turned on with updated model – accurate tracking resumes; can use this model for prediction and fault-adaptive control (e.g., online safety control)

Example: Bioplex System

Water Recovery System



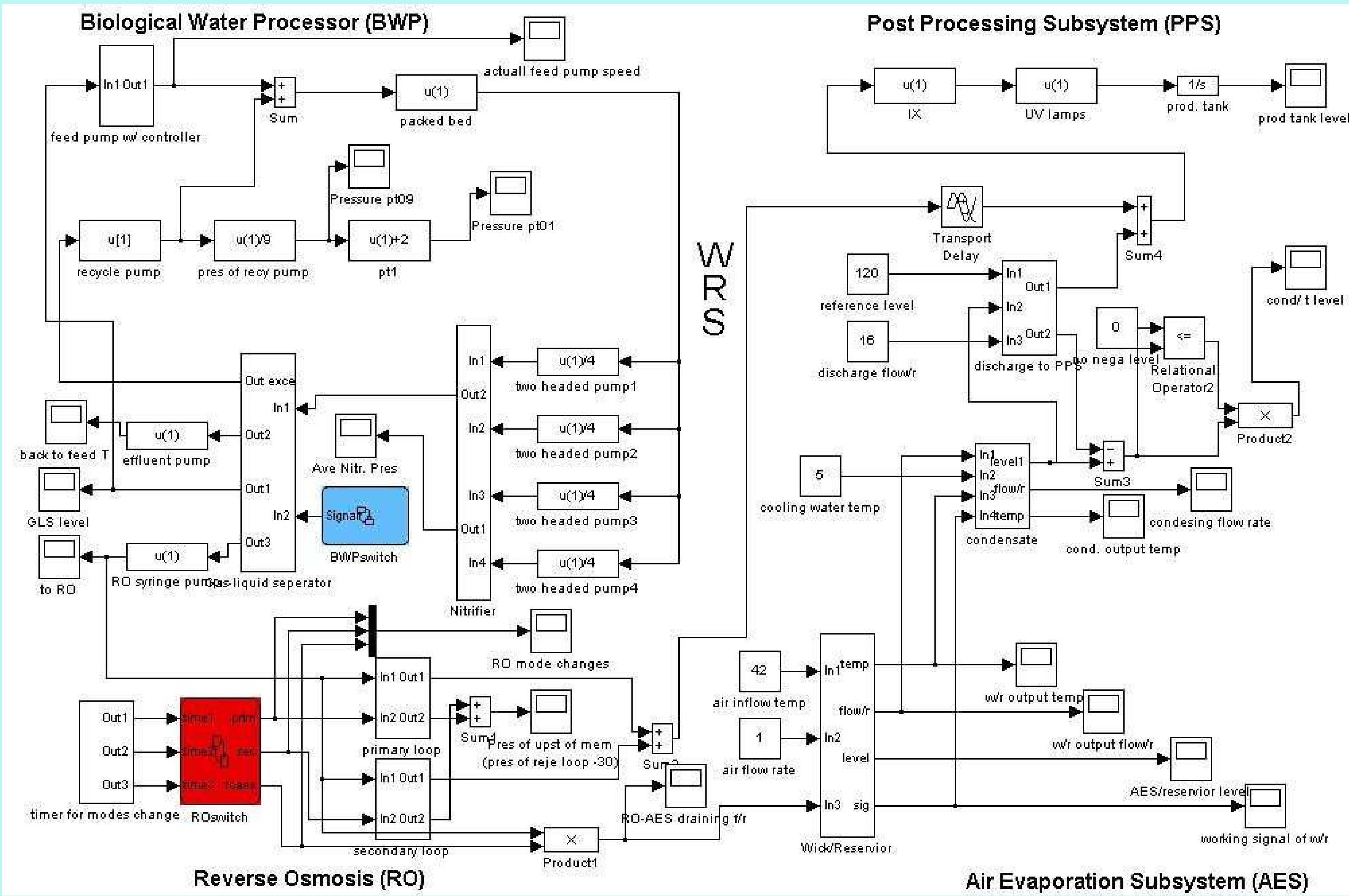
Water Recovery System



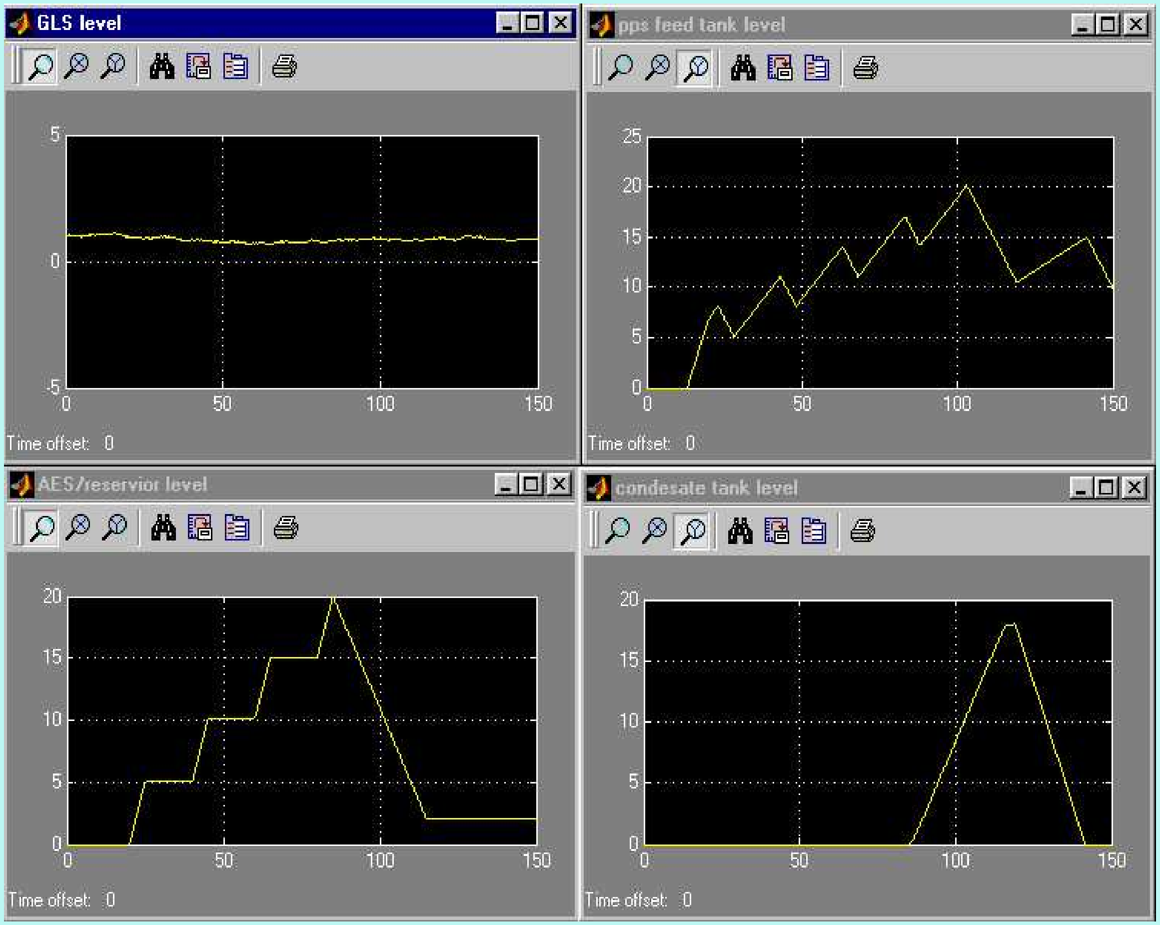
The schematics of Water Recovery system

- Loosely coupled
- Goes through multiple modes of operation
- Complex nonlinearities in individual components
- How do we achieve horizontal and vertical compositionality to assist the FDI and distributed control tasks

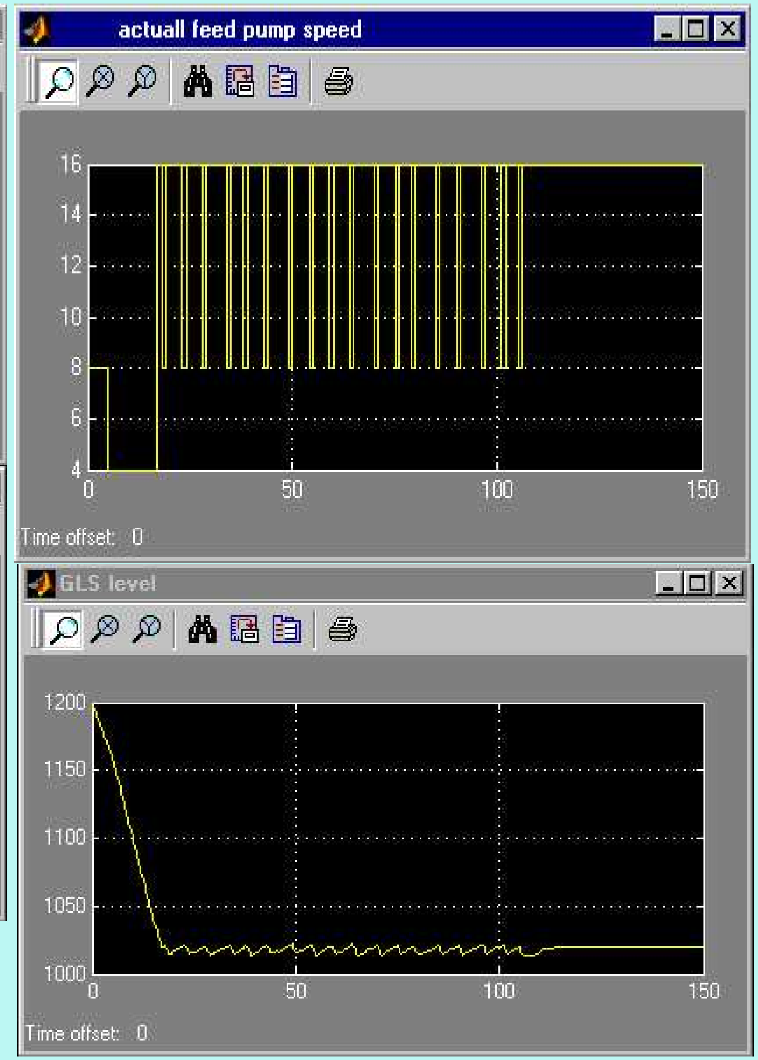
WRS Simulink-Stateflow Model



WRS simulation
Preliminary Results

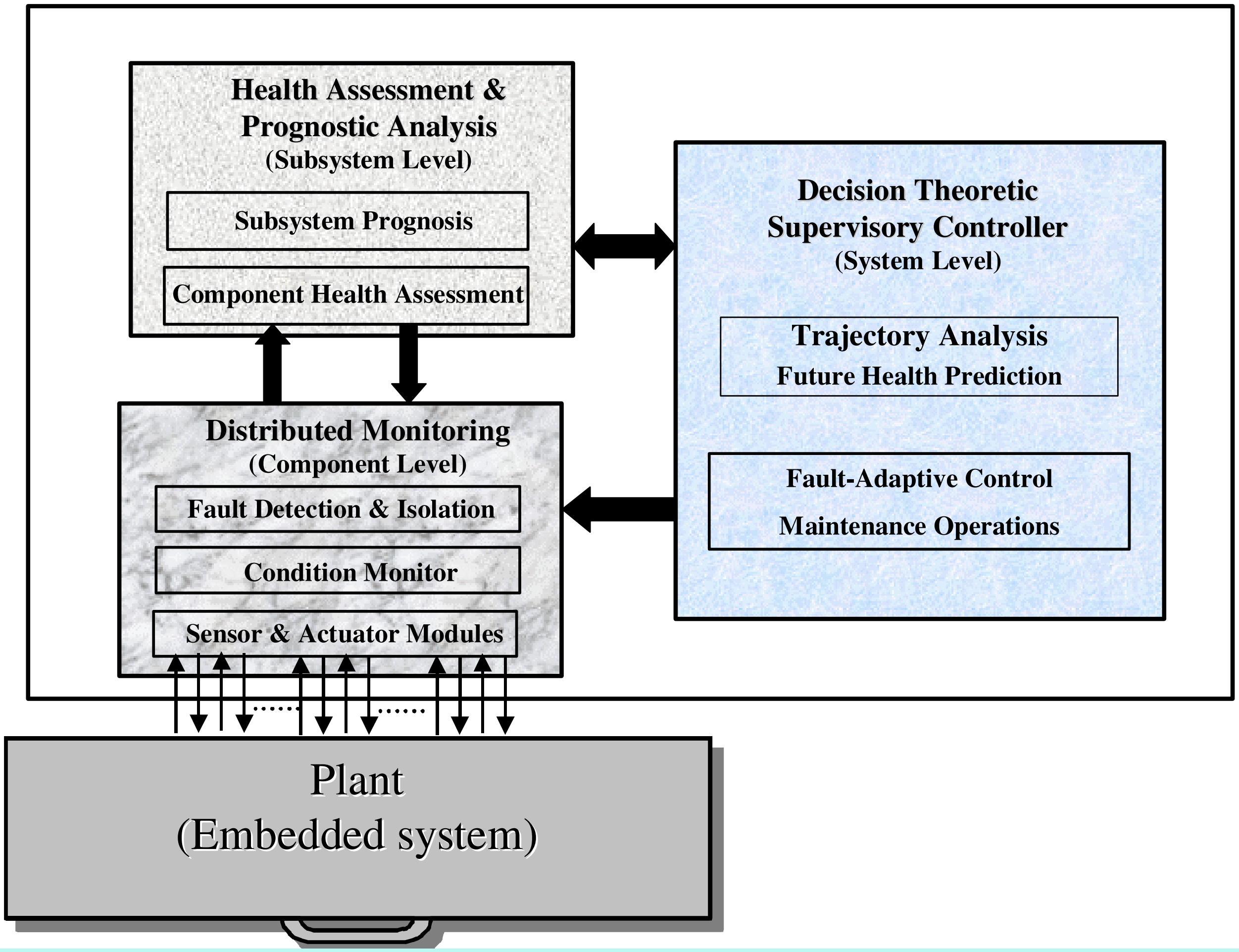


Nominal Operation



Controller Actions

Next Steps/ Future Work
Advanced Control Architecture
(Multi-layered)



- Multi-layered architecture
- Incipient Faults
- Health Assessment
- Prognostics
- Decision-theoretic supervisory control

Key Innovations

- Hybrid modeling techniques for complex systems with distributed subsystems
- Robust online monitoring and mode identification in hybrid systems
- Robust online fault detection and isolation with hybrid models (statistical + qualitative fault isolation + quantitative parameter estimation)
- Fault isolation extended to hybrid systems (roll back + roll forward)
- Online incremental safety control
- Integrated system for real applications

Publications: Hybrid Systems '02, Diagnosis (DX) '02, Book Chapter (Samad & Balas), Trans. IEEE SMC (special issue), CDC '02

NASA Relevance

- Develop technology for long-term autonomy of complex systems
  - Model-based
  - Distributed, On line
  - Intelligent
  - Robust
  - Comprehensive
- Contribute to autonomous operation of Life Support System processes
  - Air revitalization system
  - Advanced Water recovery System
  - Other NASA missions
- Vehicle Health Management
- Rover (?)

Kortenkamp & Bonasso NASA JSC

Dearden & Narasimhan NASA Ames

Schedule

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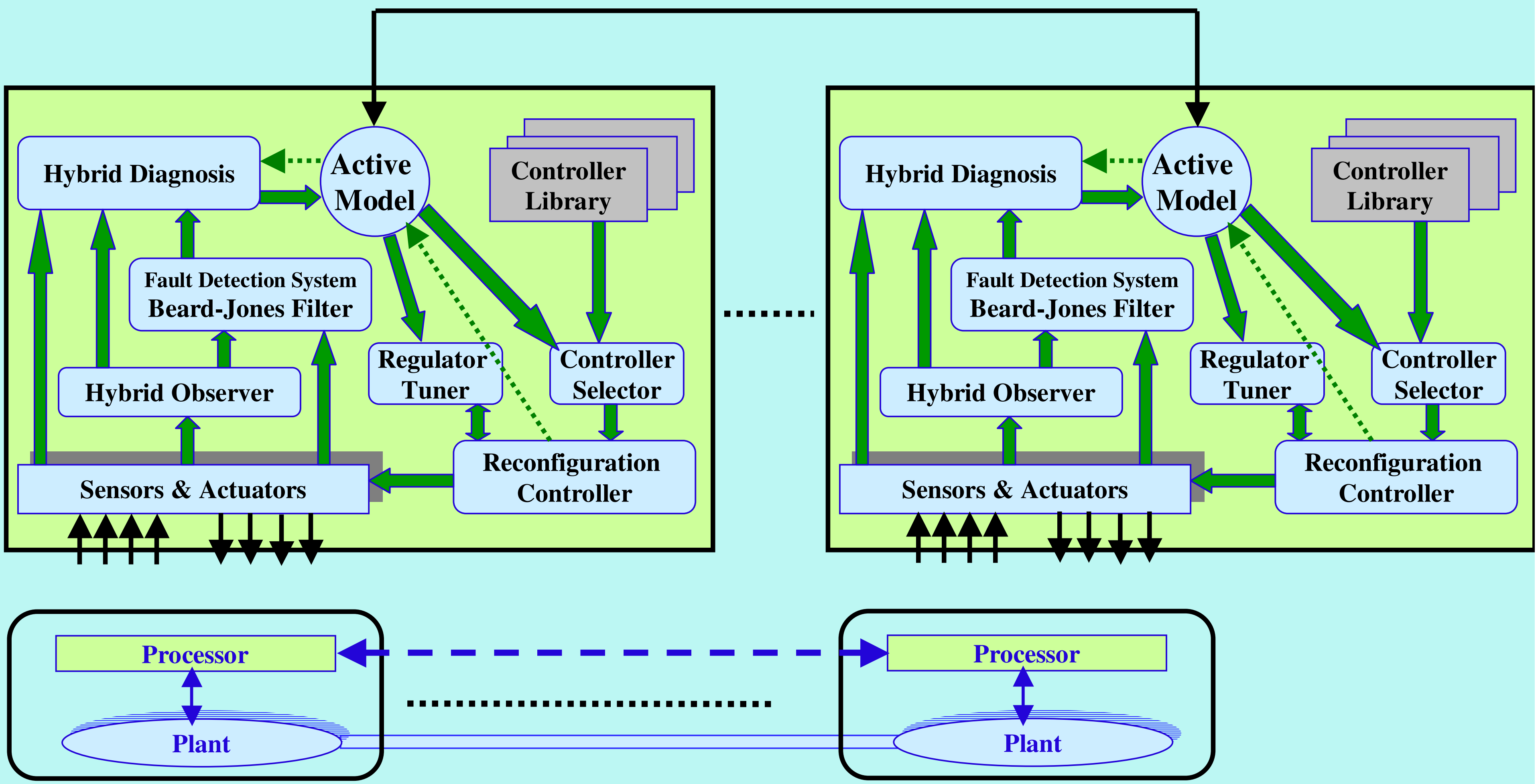
  - Hybrid Observer
  - Prototype B-J filters, hybrid diagnosis, and FPG diagnosis
- **Year 2: Prototype**
  - Refined and integrated modeling of system
  - Interacting hybrid observers
  - integration of diagnostic modules
  - Prototype controller selector
  - NASA application
- **Year 3: Integrated System**
  - Complete model of NASA application
  - Integrated runtime system (observers + FDI units + reconfigurable controller)
  - Demonstration of NASA application

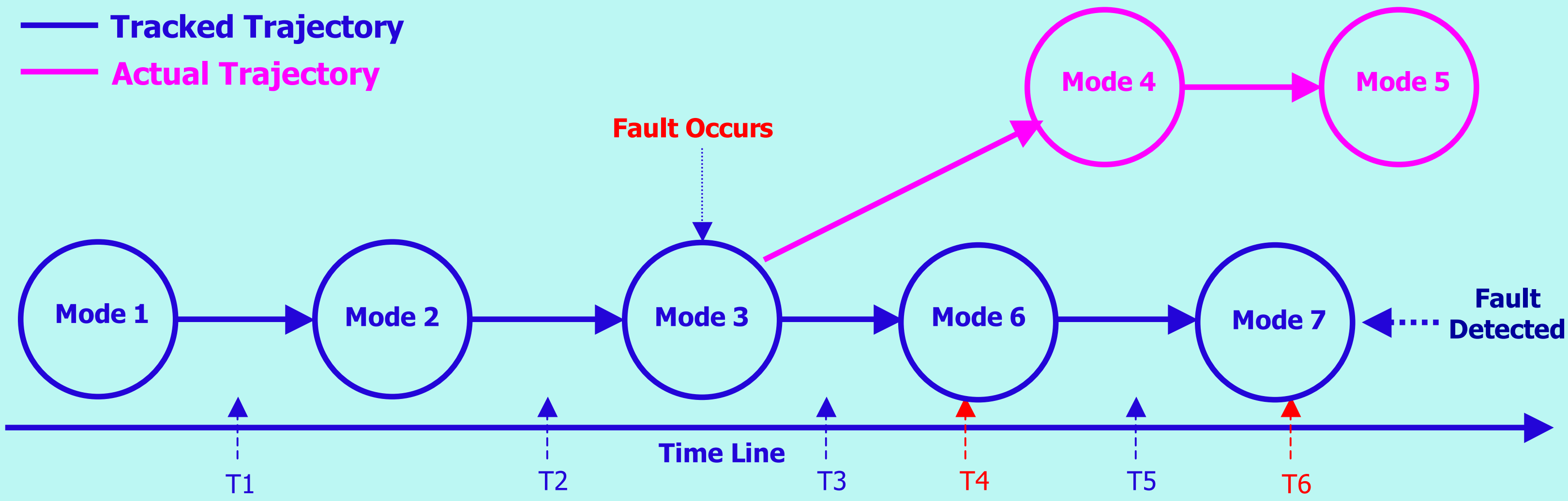
Extra Slides

Fault-Adaptive Control Architecture



Model-based approach to design and implementation of Tools and Components

Fault Isolation Task
Hybrid Systems



Presence of fault invalidates the tracked mode trajectory
Have to backtrack to find fault hypotheses

Fault Hypothesis: <mode,parameter,Δparameter>
Qualitative Fault Hypothesis: <mode,parameter,✏>

Fuel System Diagnosability Results

	WTP	WTR	TTP	TTR	TMR	SPR	FTP	FTR
WTP	–	X	√	√	√	√	√	√
WTR	X	–	√	√	√	√	√	√
TTP	√	√	–	X	√	√	√	√
TTR	√	√	X	–	√	√	√	√
TMR	√	√	√	√	–	√	√	√
SPR	√	√	√	√	√	–	√	√
FTP	√	√	√	√	√	√	–	X
FTR	√	√	√	√	√	√	X	–

WT – Wing Tank

TT – Transfer Tank

TM – Transfer Manifold

FT – Feed Tank

P: Pump

R: Resistance