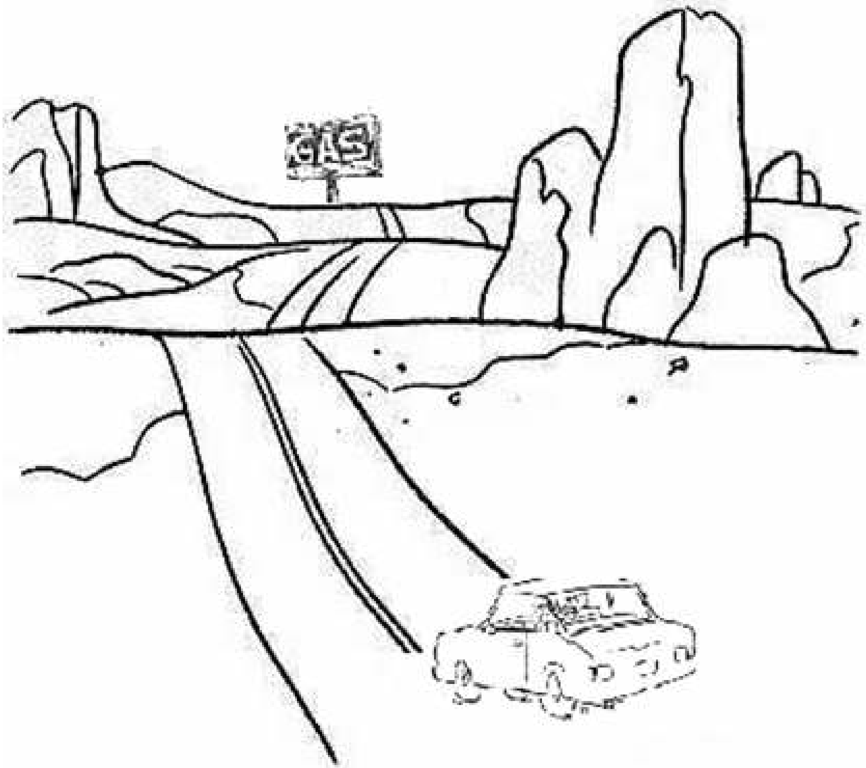
Using Prognostic Information for Reconfigurable Control

Dr. George Vachtsevanos /PI
Georgia Tech and Impact Technologies
Douglas Brown / GRA
Brian Bole / GRA

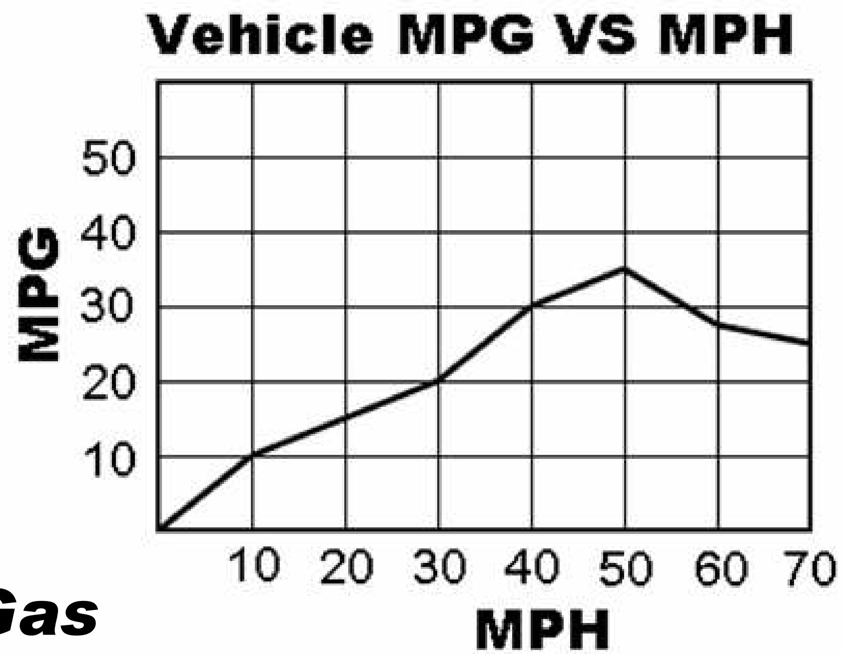
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0250

PHM 2009 Conference Tutorial

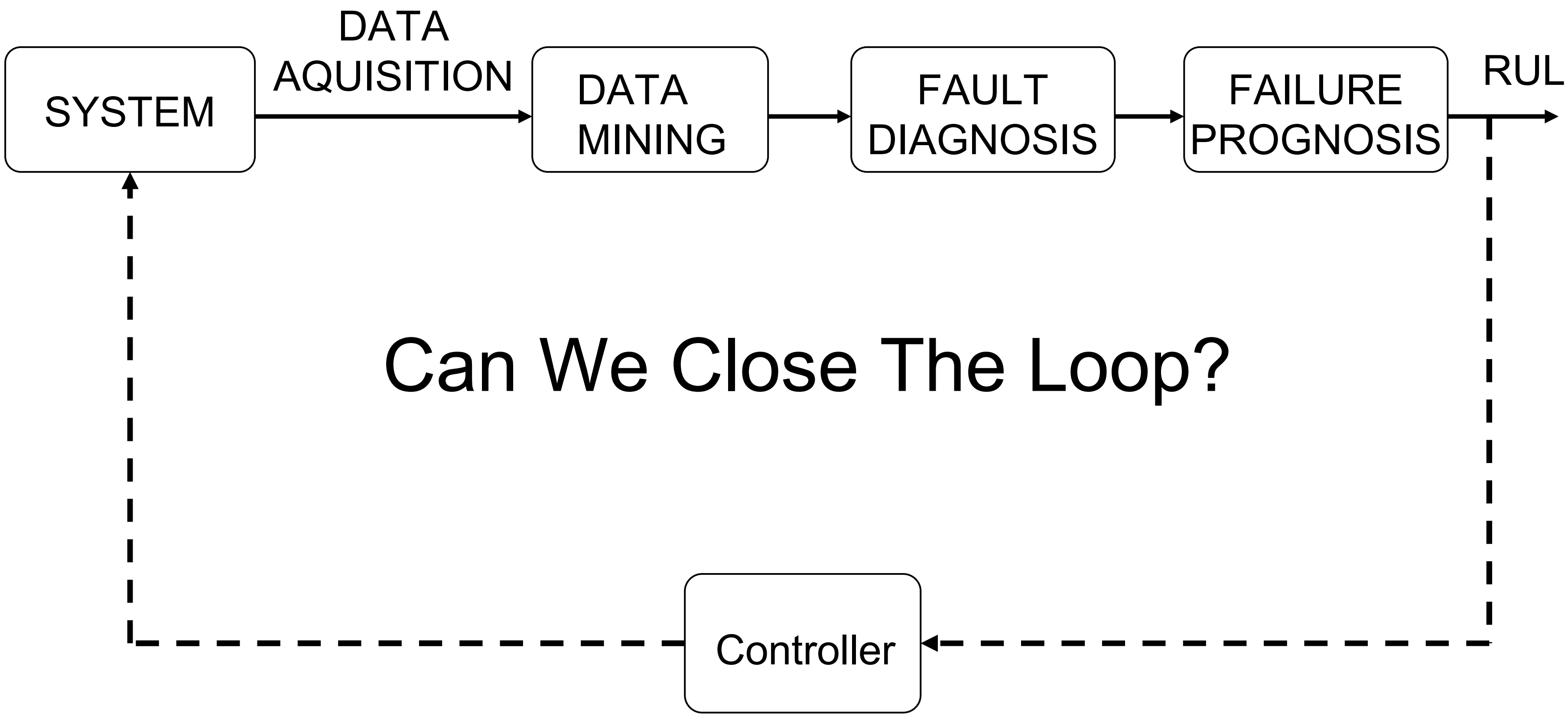


We have 1 GAL left in the tank

THE NEAREST STATION IS
30 MI AWAY!!!



Can We Make It To The Gas Station?



Can We Close The Loop?

ENTER

Fault – Tolerant Control

(Fault Mitigation, Fault Accommodation, Reconfigurable Control)

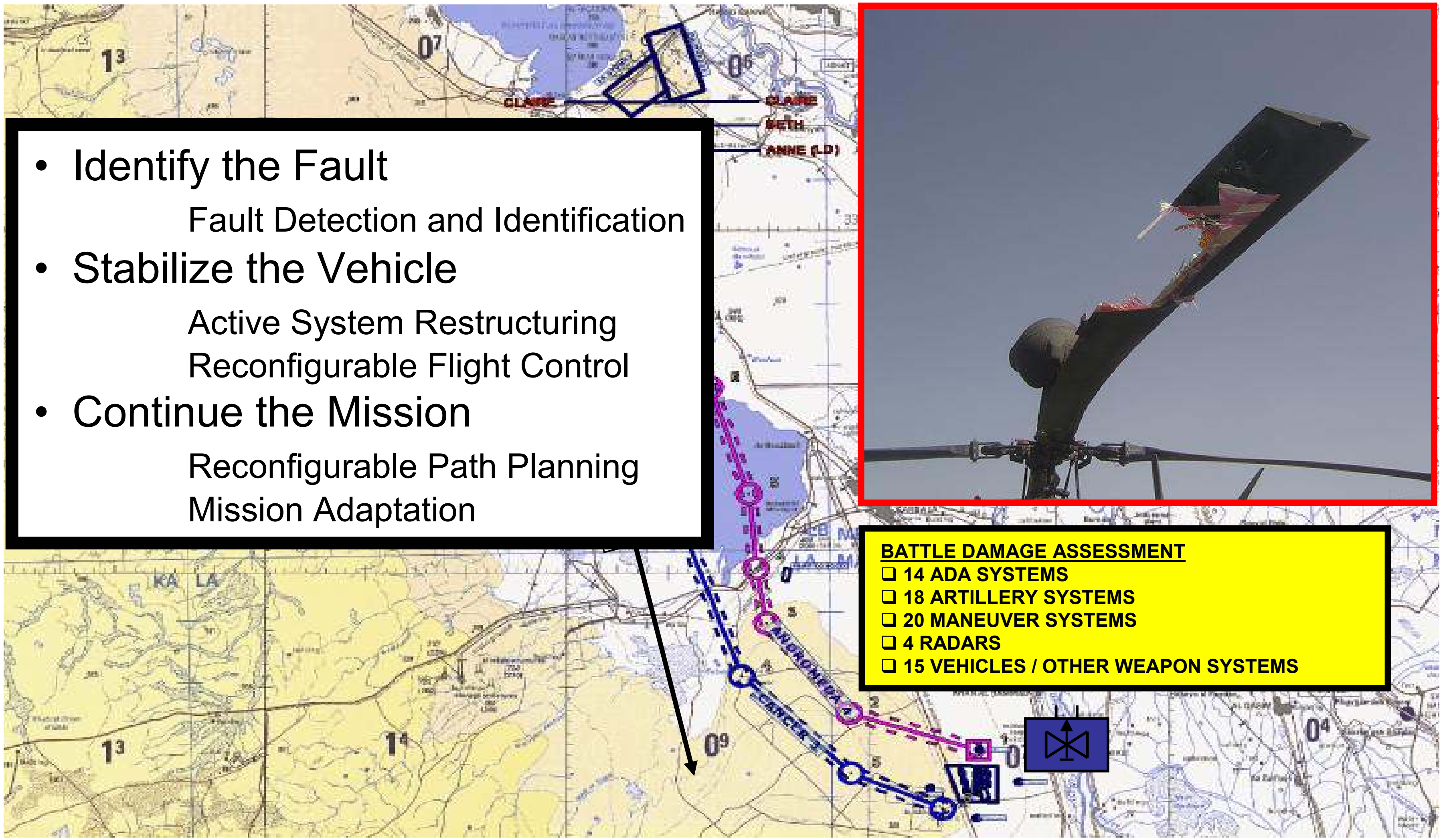
The Caveat: With Prognostic Information

The Link between PHM and Control

The Problem

Case Study

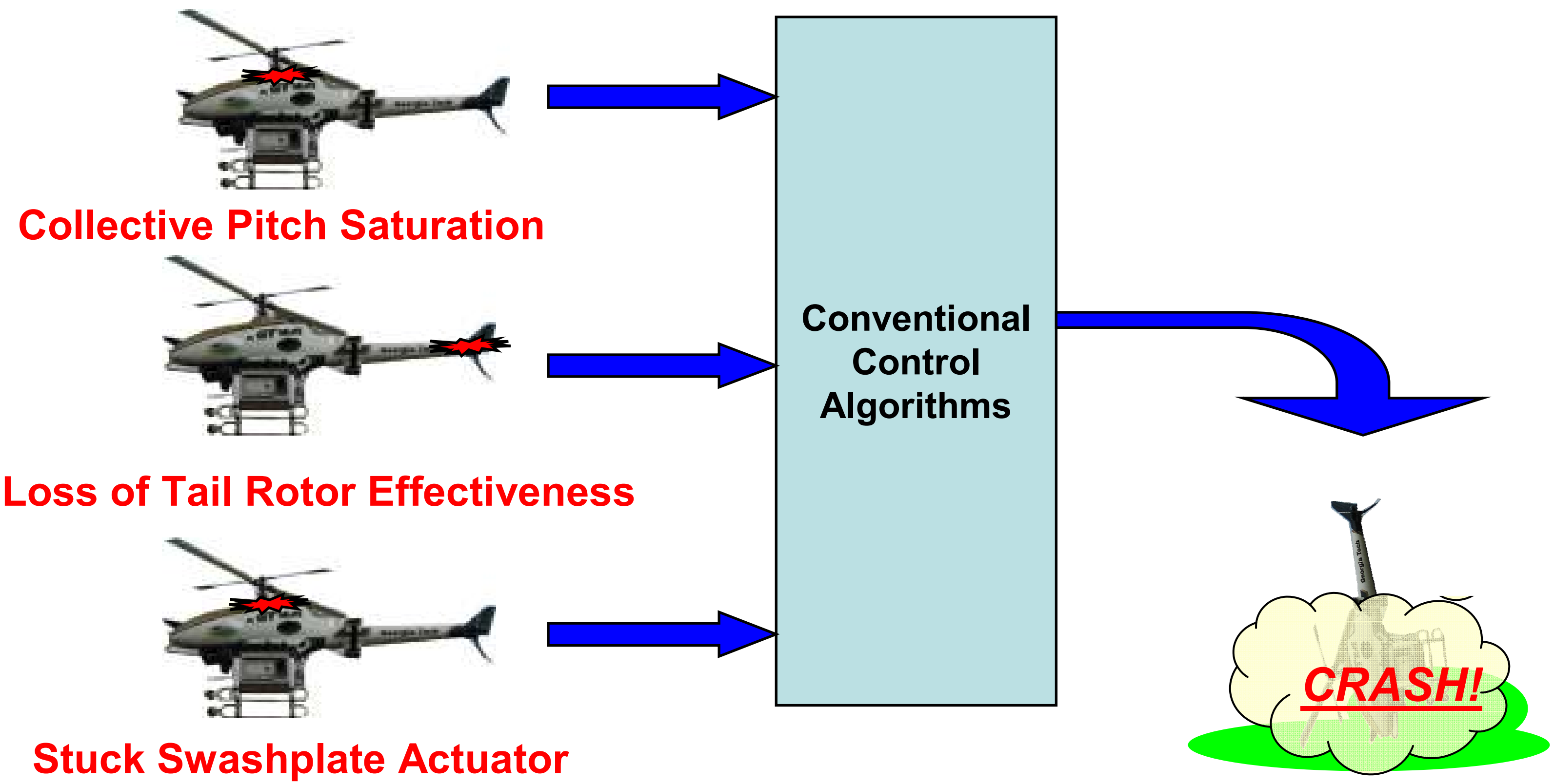
- Identify the Fault
  - Fault Detection and Identification
- Stabilize the Vehicle
  - Active System Restructuring
  - Reconfigurable Flight Control
- Continue the Mission
  - Reconfigurable Path Planning
  - Mission Adaptation



Gabram, Doug. "AH-64D Longbow Operations in Iraq". HELICON: Rotorcraft in Transformation, Washington, DC, November 9-10, 2004.

Fault Tolerant Control

Conceptual Illustration

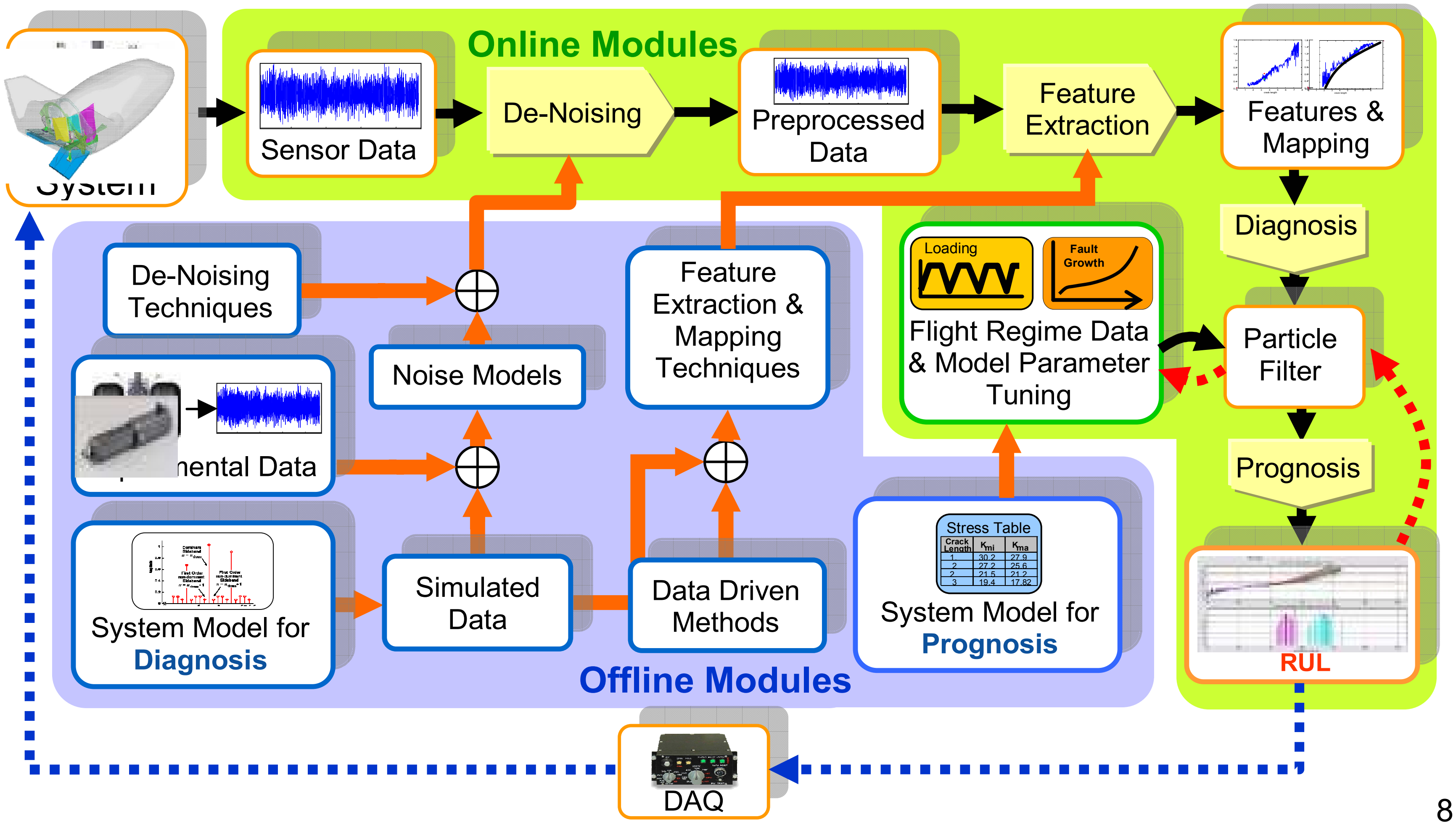


Flight Results - Stuck Collective

PHM Architecture

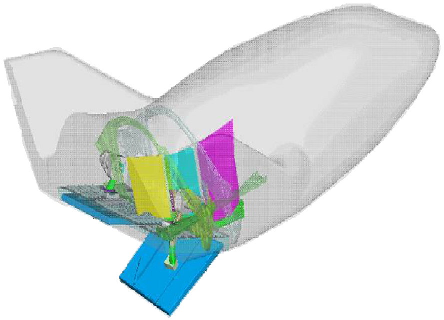
General Overview

Overall Architecture for Implementation of Fault Diagnosis and Failure Prognosis Algorithms

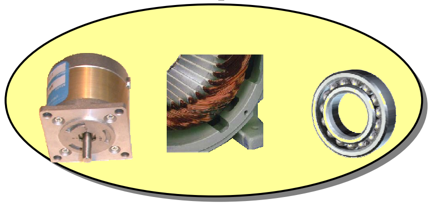


Testing, Modeling, and Reasoning Architecture

Electromechanical Actuator

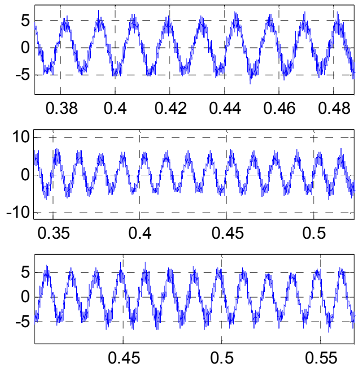


Components

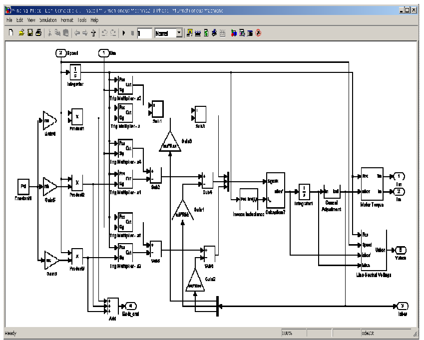


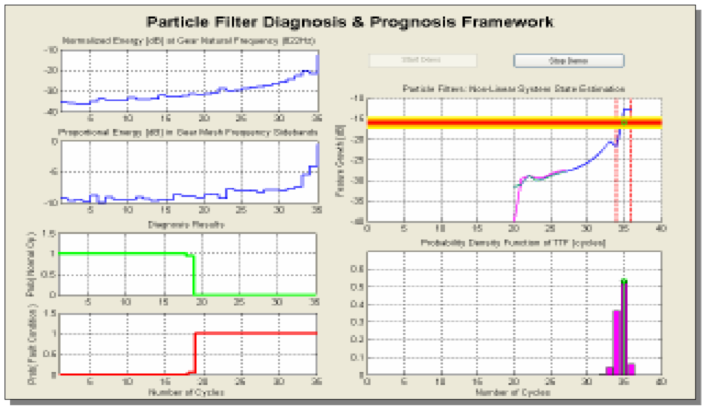
HUMS modules

Testing / Seeded Fault Data



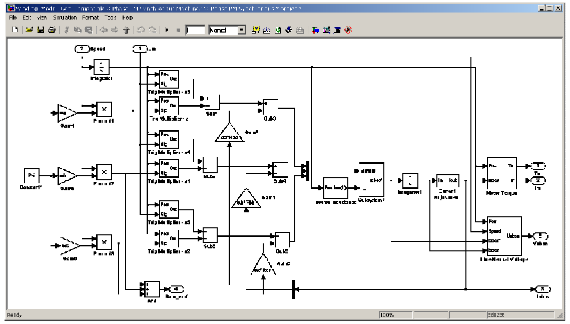
Modeling





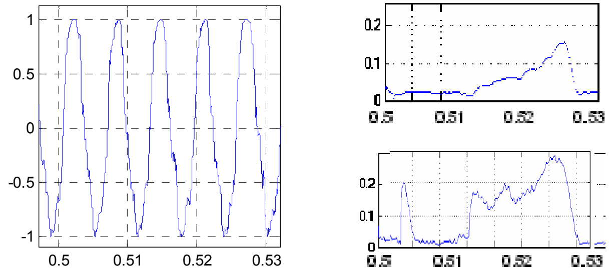
Reasoning Architecture for Diagnosis-Prognosis

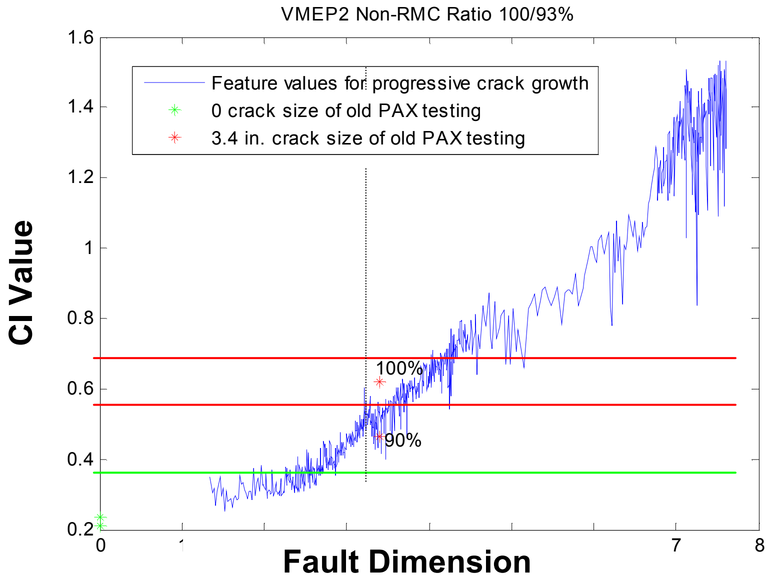
Understanding the Physics of Failure Mechanisms



Fault Model

Feature Selection and Extraction



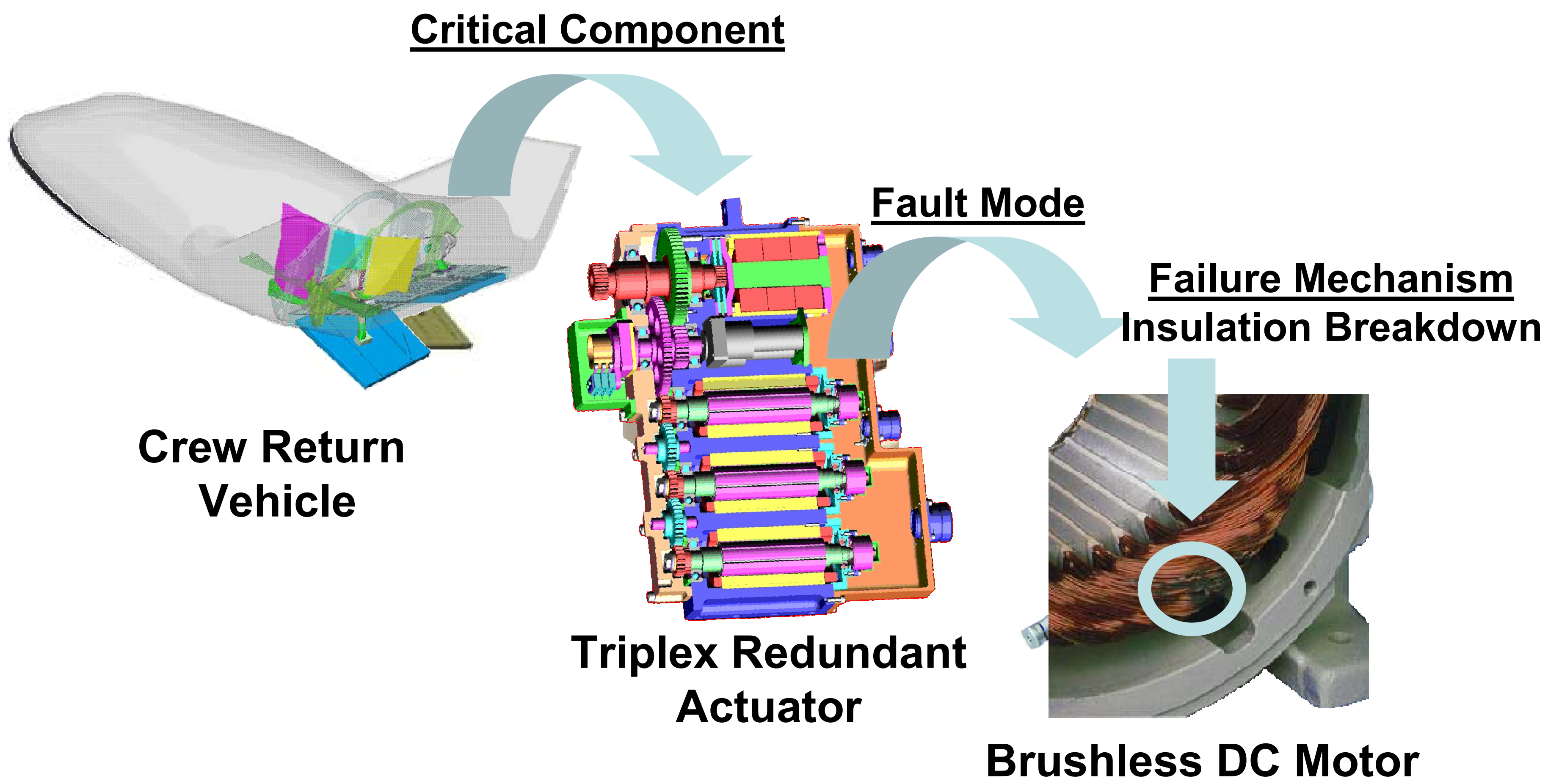


- Optimum Feature Selection
- Mapping of Features vs. Fault Dimension
- Utility in Diagnosis / Prognosis

Optimum mapping of CI's to Fault Dimension

System Background

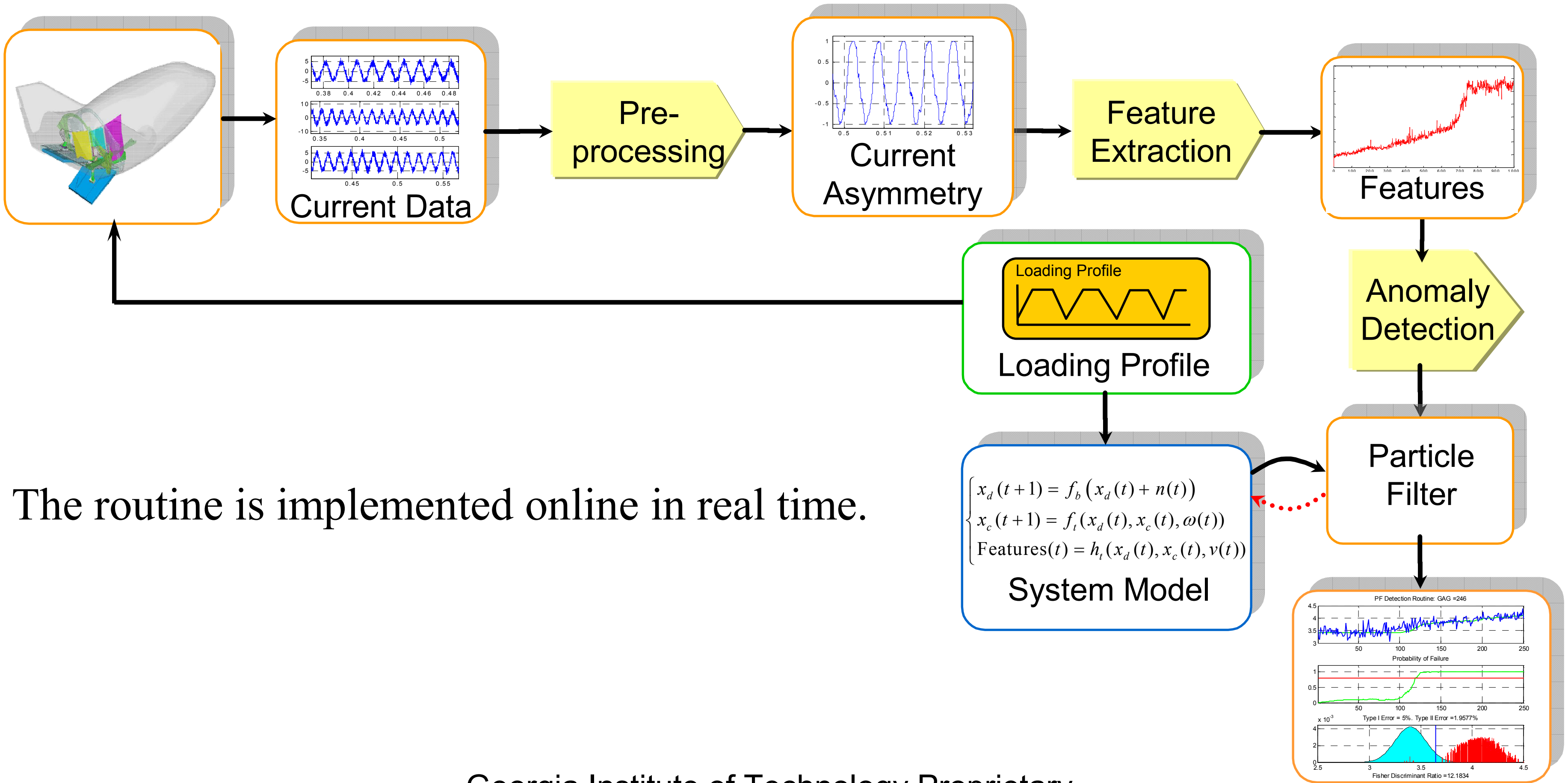
Fault Hierarchy (Top–Down)



Fault Detection Architecture

Anomaly Detection

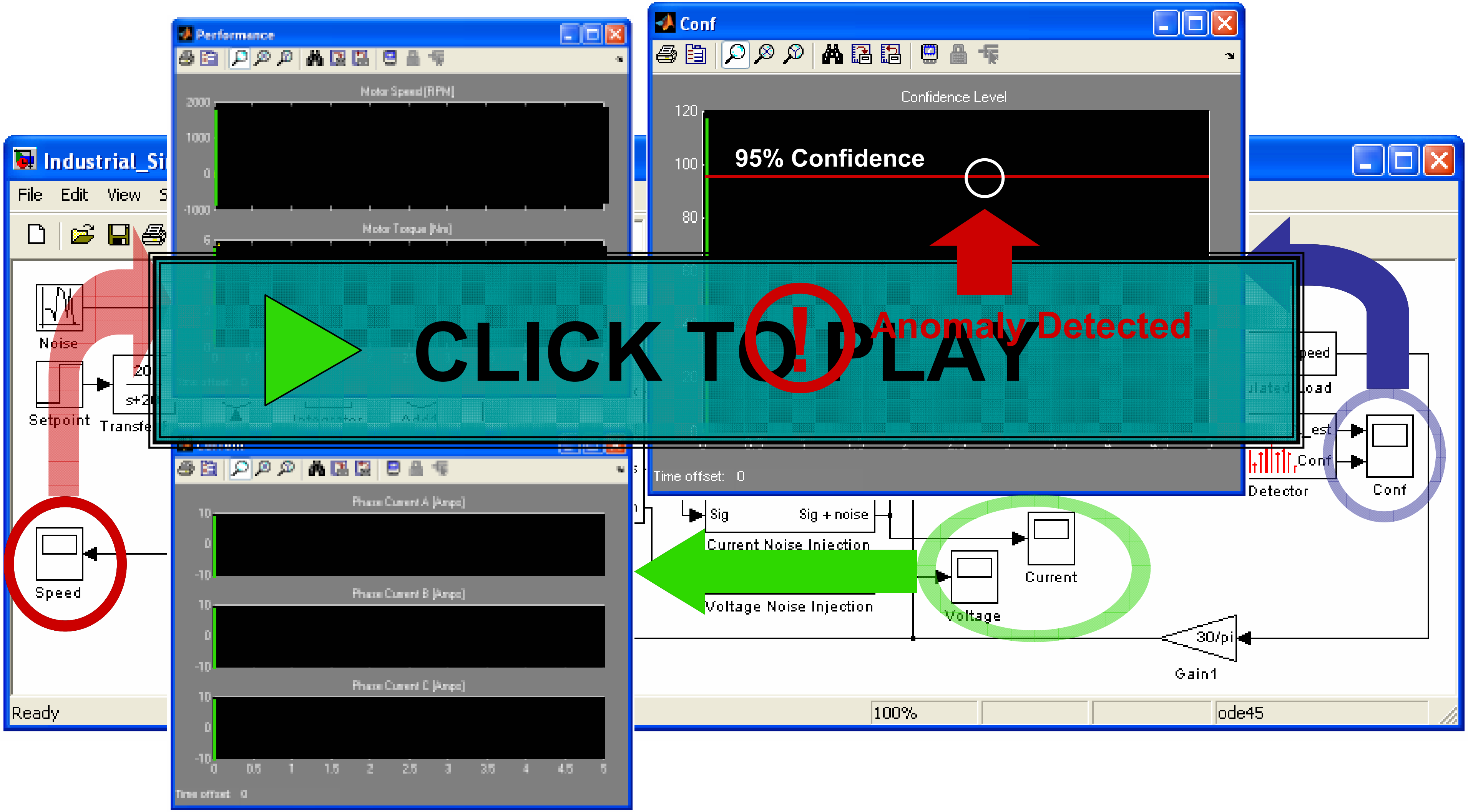
Objective: Detect a fault (without isolating the faulty component; without assessing the severity of the fault) as early as possible with specified confidence level and given false alarm rate.



The routine is implemented online in real time.

Anomaly Detection

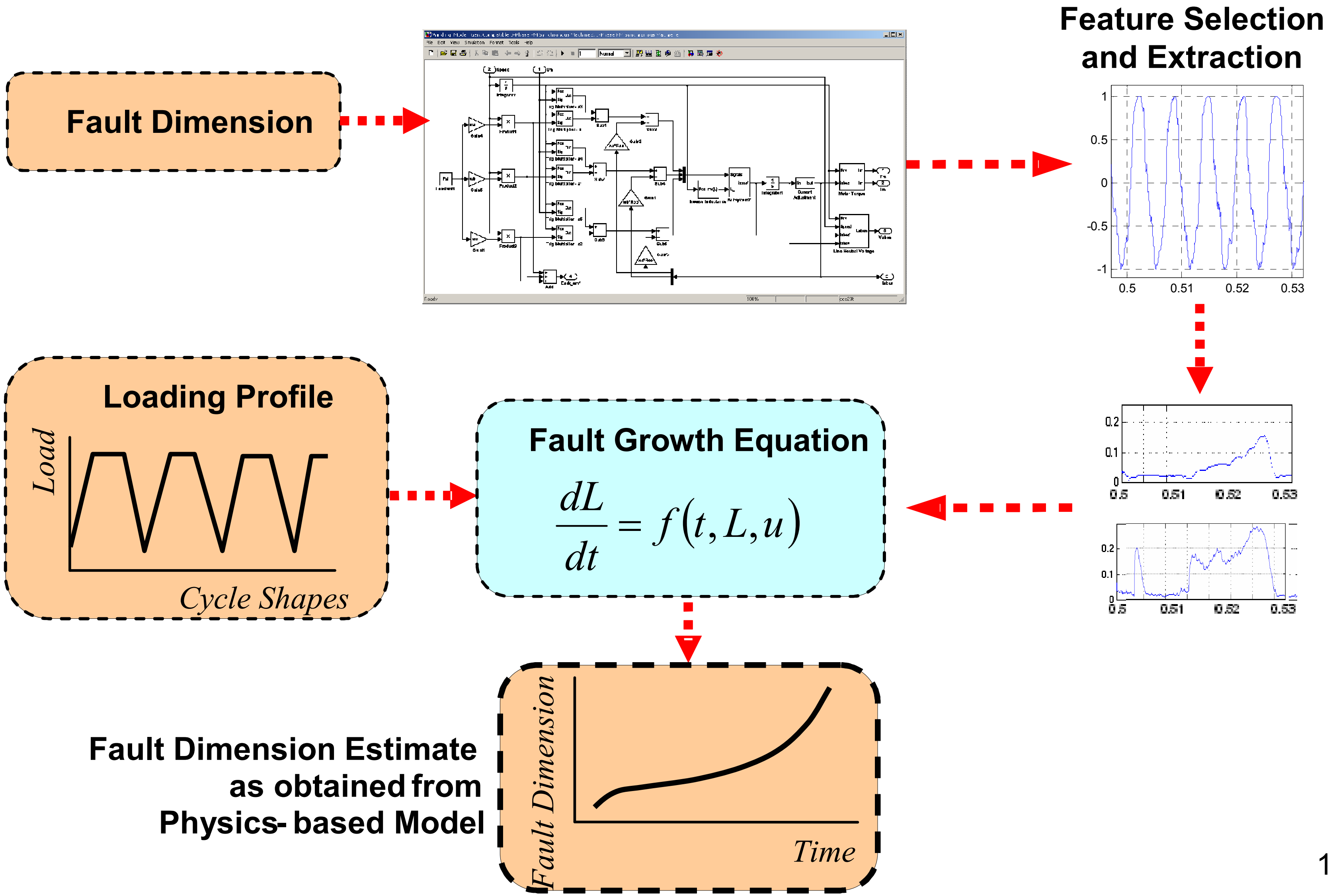
Anomaly Detection Results



Failure Prognosis

- Objective
  - Determine time window over which maintenance must be performed without compromising the system's operational integrity
  - Estimate time-to-failure and provide information to operator/pilot
- Enabling Technologies:
  - Data Driven
  - Model-Based
- A Model/Measurements Based Approach

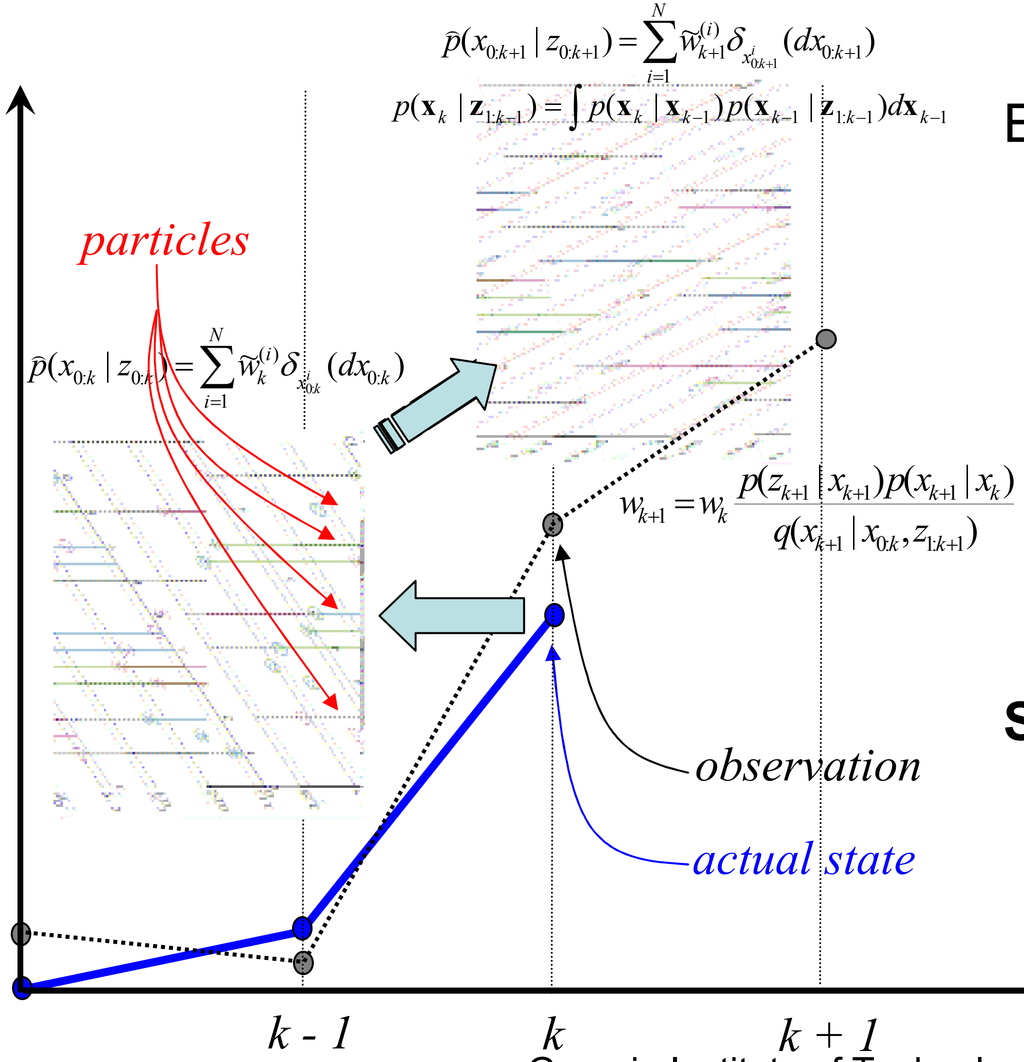
Prognosis: Fault Growth Characterization



Georgia Institute of Technology Proprietary

The Particle Filter Framework

Particle: Possible realization of the states of a process.



Every particle is associated with a **weight**

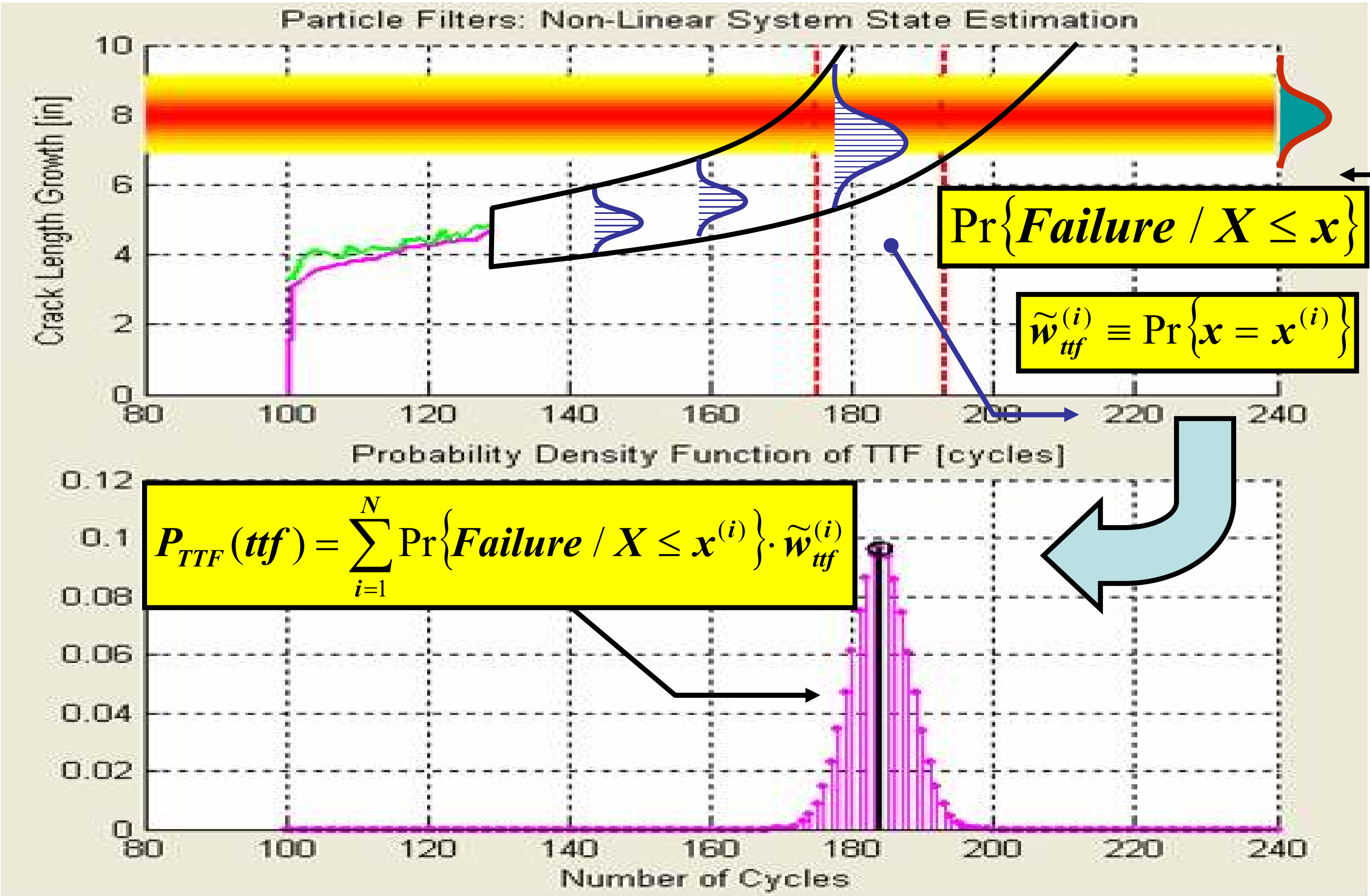
- Particles, together with their weights, represent a sampled version of the PDF.

We only need to study the propagation of weights in time!

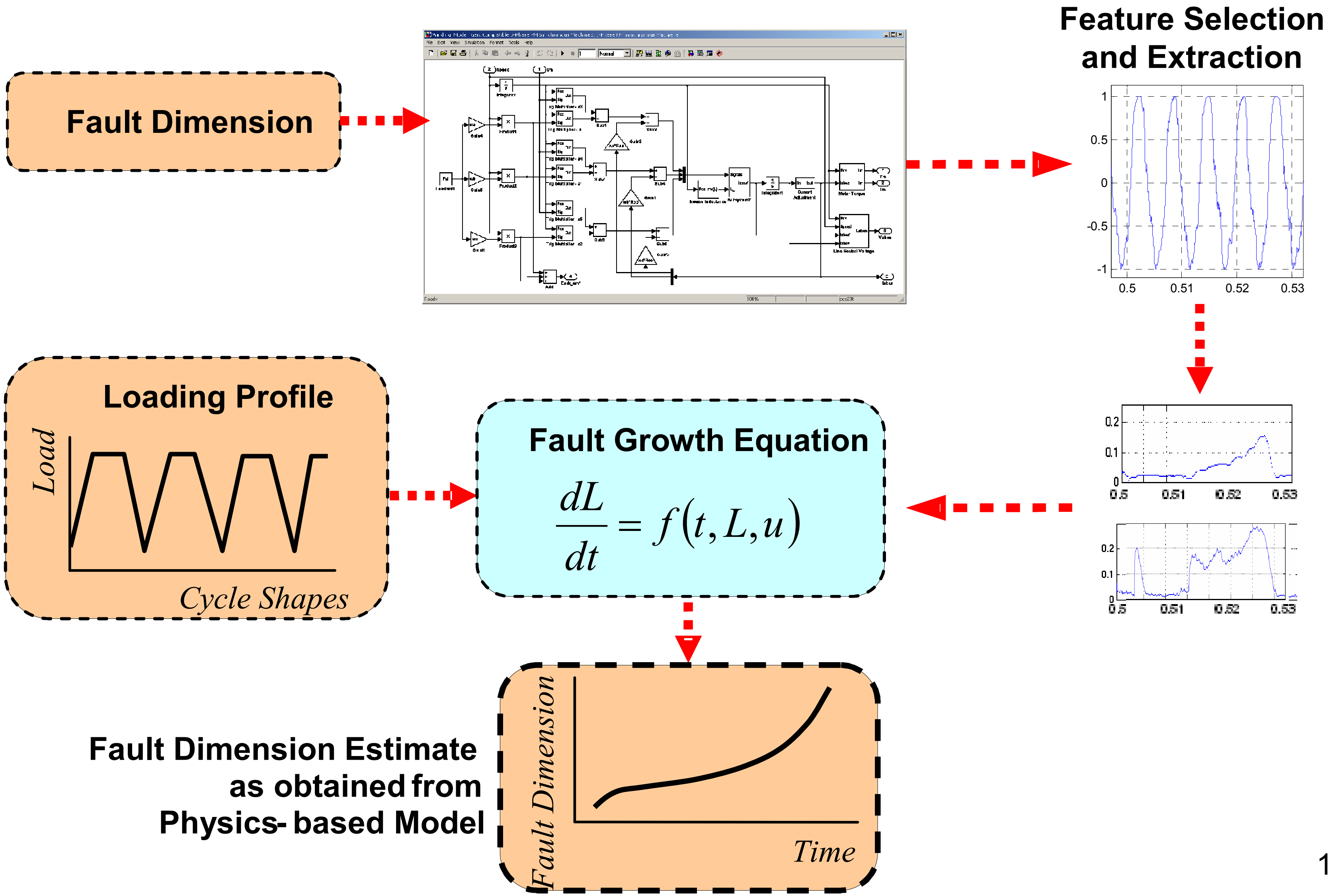
Steps:

- Predict the "*a priori*" PDF parameters, using the model
- Update parameters, given the new observation

The Particle Filter Framework

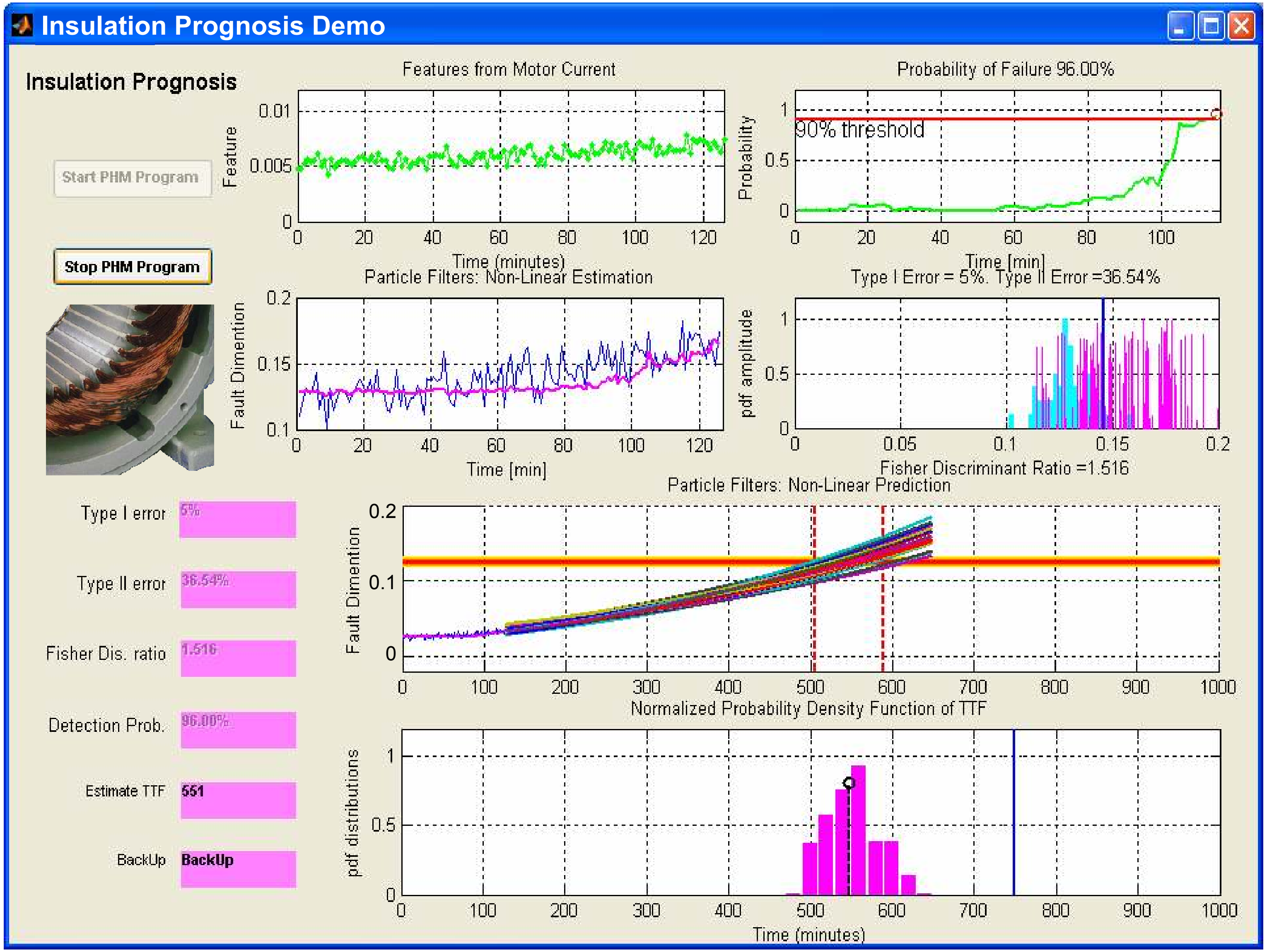


Prognosis: Fault Growth Characterization



Prognosis

Preliminary Simulation Results



Reconfigurable Control – State of the Art

Boeing[1,2]

- LQR design methodology using long-term prediction as a design constraint.
- Single parameter ρ used to trade-off importance between tracking error and control effort.

$$J = \int_0^\infty \left(\left(\mathbf{x} - \mathbf{x}^*\right)^T \mathbf{Q} \left(\mathbf{x} - \mathbf{x}^*\right) + \left(\rho R\right) u^2 \right) dt$$

- Feedback gain computed solving the Algebraic Riccati Equation:

$$\mathbf{P}\mathbf{A}_x + \mathbf{A}^T\mathbf{P} - \mathbf{P}\mathbf{B}_u \left(\rho R\right)^{-1} \mathbf{B}_u^T \mathbf{P} + \mathbf{Q} = 0$$

$$u^* = -\left(\rho R\right)^{-1} \mathbf{B}_u^T \mathbf{P}\left(\rho\right) \mathbf{x}$$

[3] A. Bogdanov, S. Chiu, L. Gokdere, and W. Vian, J., "Stochastic optimal control of a servo motor with a lifetime constraint„" in Proceedings of the 45th IEEE Conference on Decision & Control, December 2006, pp. 4182–4187.

[4] L. U. Gokdere, A. Bogdanov, S. L. Chiu, K. J. Keller, and J. Vian, "Adaptive control of actuator lifetime," in IEEE Aerospace Conference, March 2006.

Model-based Adaptive Flight Control

NNs for modeling and system identification.

Online model corrections using the adaptation scheme

Structure learning modeling algorithm

Receding horizon optimal control to maximize performance and safety

Modified least squares for model parameter identification

IAG&C

[1] D. G. Ward, J. F. Monaco, R. L. Barron, and R. A. Bird, "System for improved receding-horizon adaptive and reconfigurable control," US Patent 6,208,914, March 27, 2001.
[2] J. F. Monaco, W. D.G., and A. J. D. Bateman, "A retrofit architecture for model-based adaptive flight control," in AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, USA, September 20-22 2004.

- Artificial intelligence
- Active (Direct) adaptive control
- Expert systems
- Intelligent controls (NNs and Neuro-Fuzzy)
- Model Reference Adaptive Control (MRAC)
- Robust control design
- Robust adaptive control
- Supervisory / Hierarchical control

What is missing?

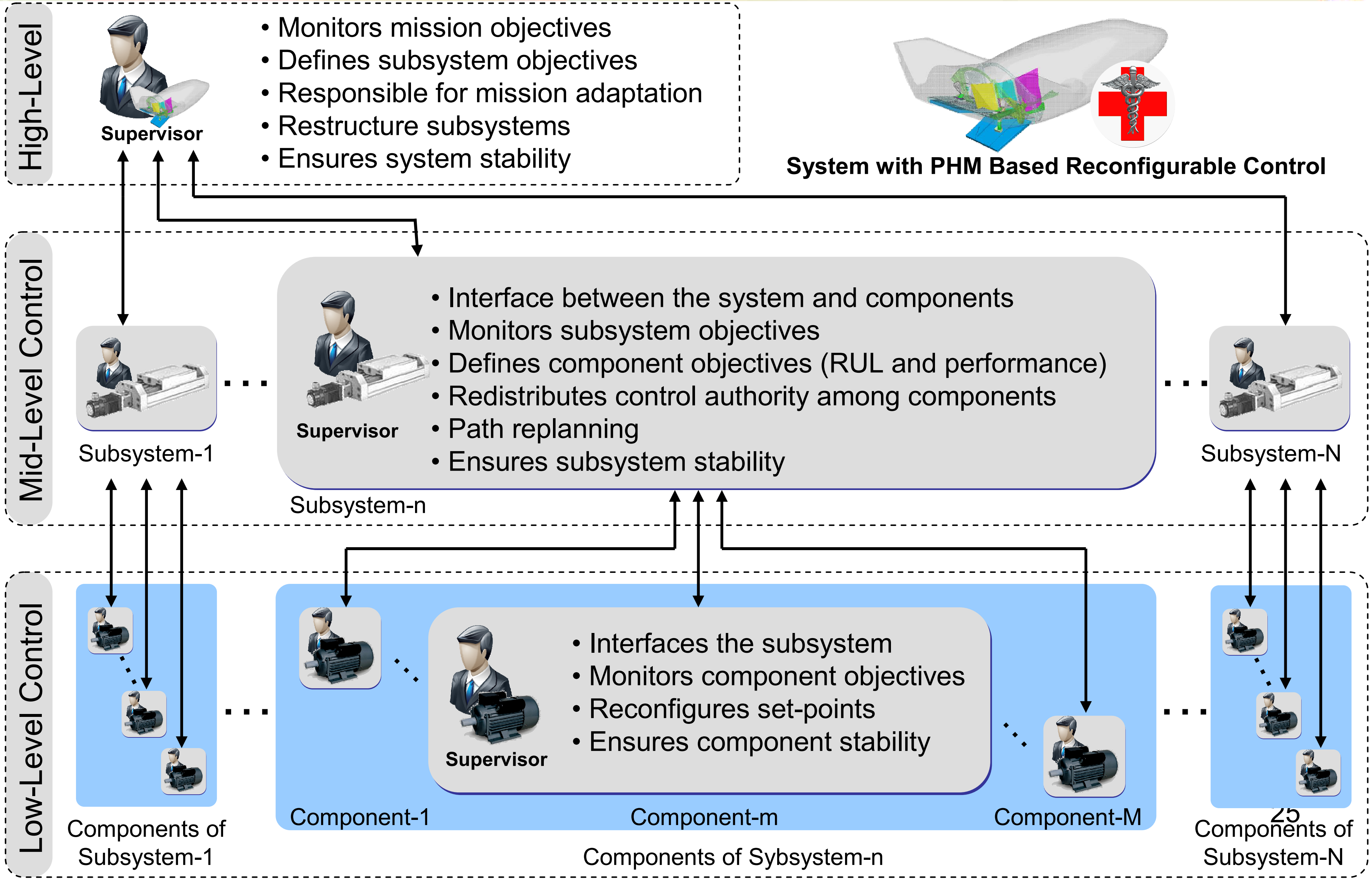
Control reconfiguration with prognostic information → real-time implementation issues.

- Computational Complexity
- Latency
- Satisfy Performance Requirements
- Stability
- Optimality
- Uncertainty Representation and Management

Reconfigurable Control – State of the Art
Our Approach

- Rigorous fault (or degradation) modeling and particle filtering for fault detection and diagnosis
- Early diagnosis and accurate prognosis with uncertainty management
- Optimization using MPC with constraints

Reconfigurable Control Architecture
Functional Relation in the Hierarchy



Reconfigurable Control

The three level hierarchy (continued)

The High-Level:

- Mission adaptation – adapt mission profile (way points in aircraft case, control objectives in EMA case) to meet hard mission objectives under impairment constraints.

Methodology: Minimize the following objective function

$$J\left(\overline{u}\right) = f^T \left|\overline{y} - \overline{y}_c\right|$$

where $\overline{y}_c$ = Flight path generated from waypoints

$\overline{y}$ = Desired flight path

f^T = Weighting vector

Reconfigurable Control

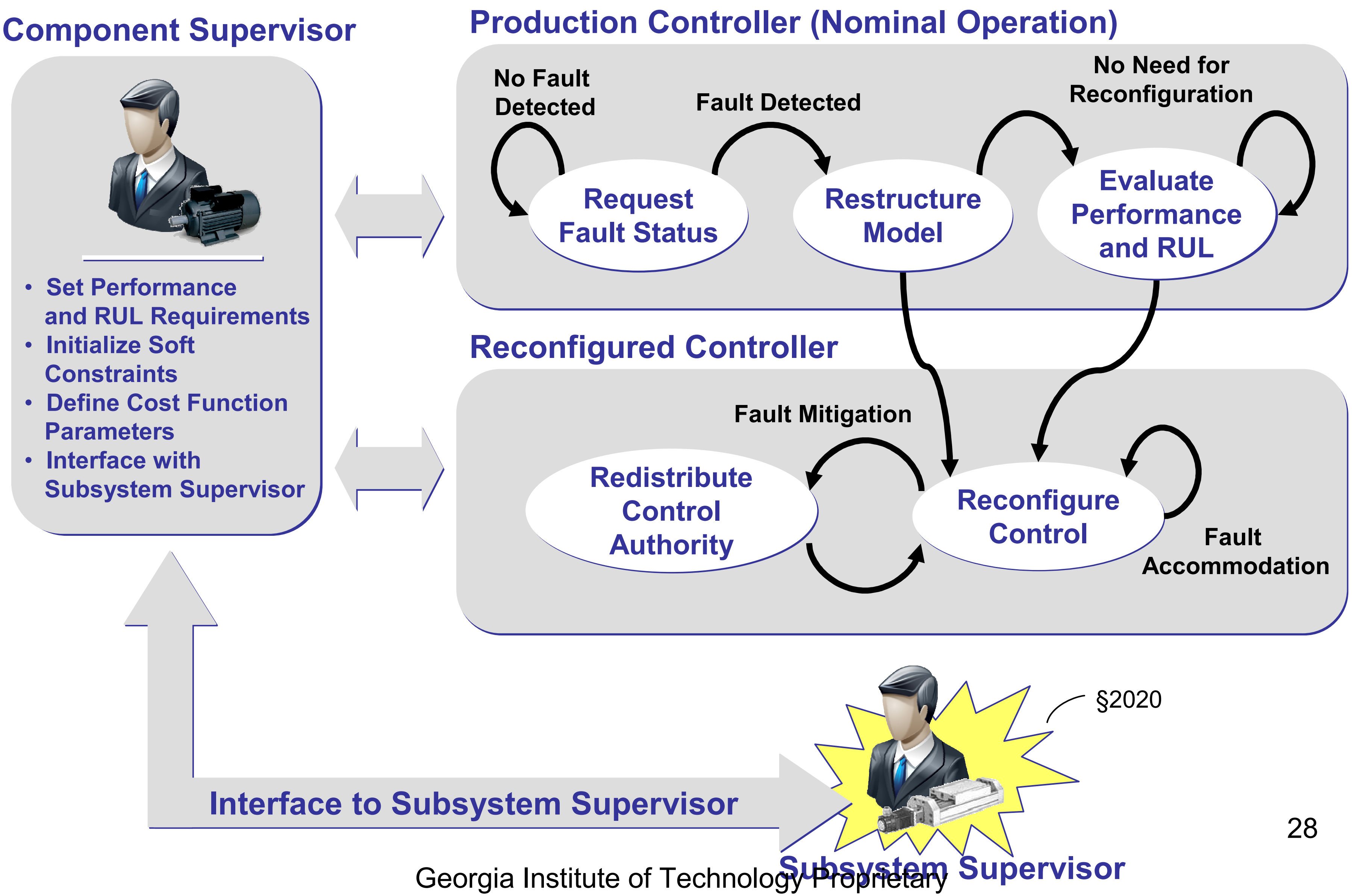
The three level hierarchy

The Middle-level:

- Trajectory re-planning: Find optimal path (trajectory), in least cost sense, that meets mission objectives under system impairment conditions. Example: Aircraft trajectory re-planning
- Re-distribution of control authority: Re-distribute available control authority (under impairment constraints) to meet hard mission objectives. Example: EMA with triple motor redundancy; or, flight control re-distribution.

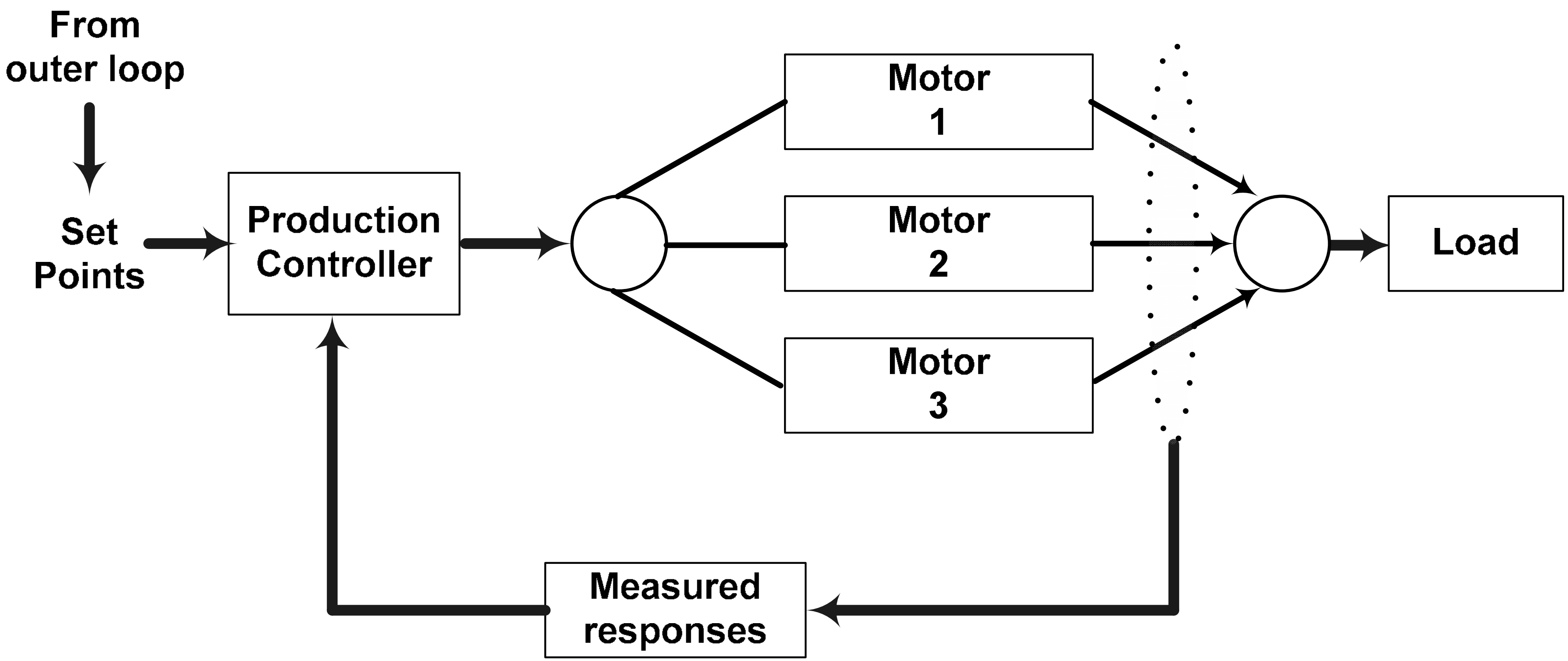
Reconfigurable Control

Low Level – State Transition Diagram

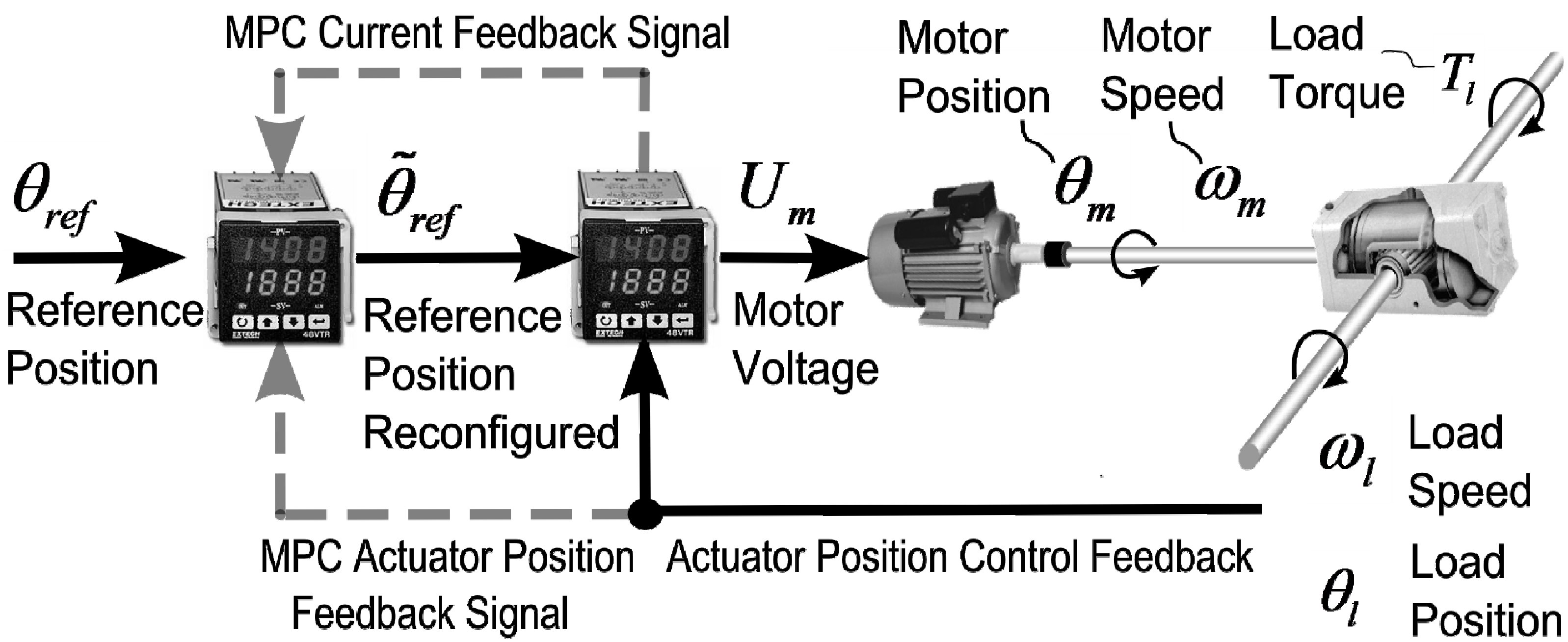


Evaluation Platform / Validation

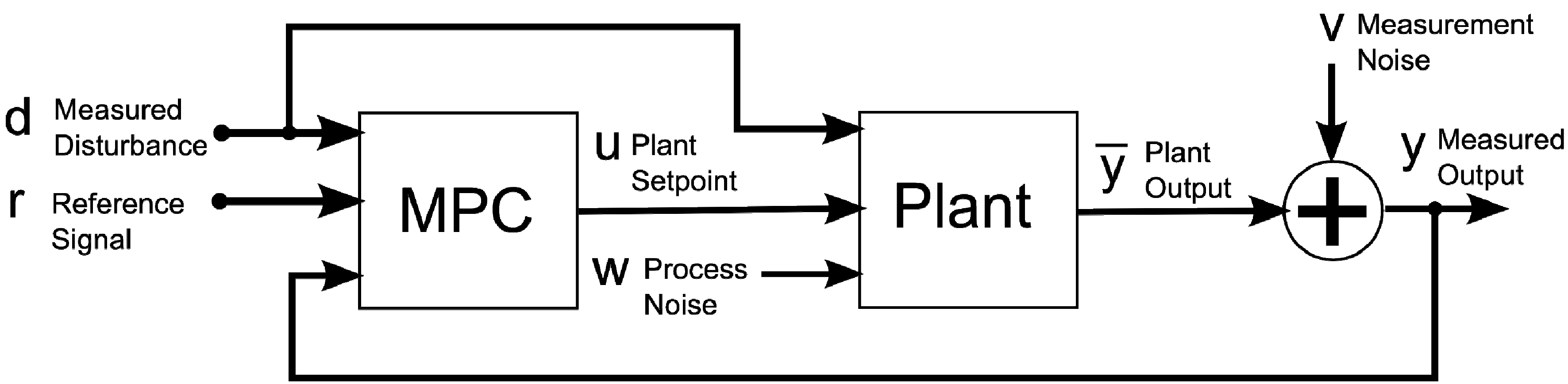
The EMA – Nominal system



The Actuator Testing Configuration

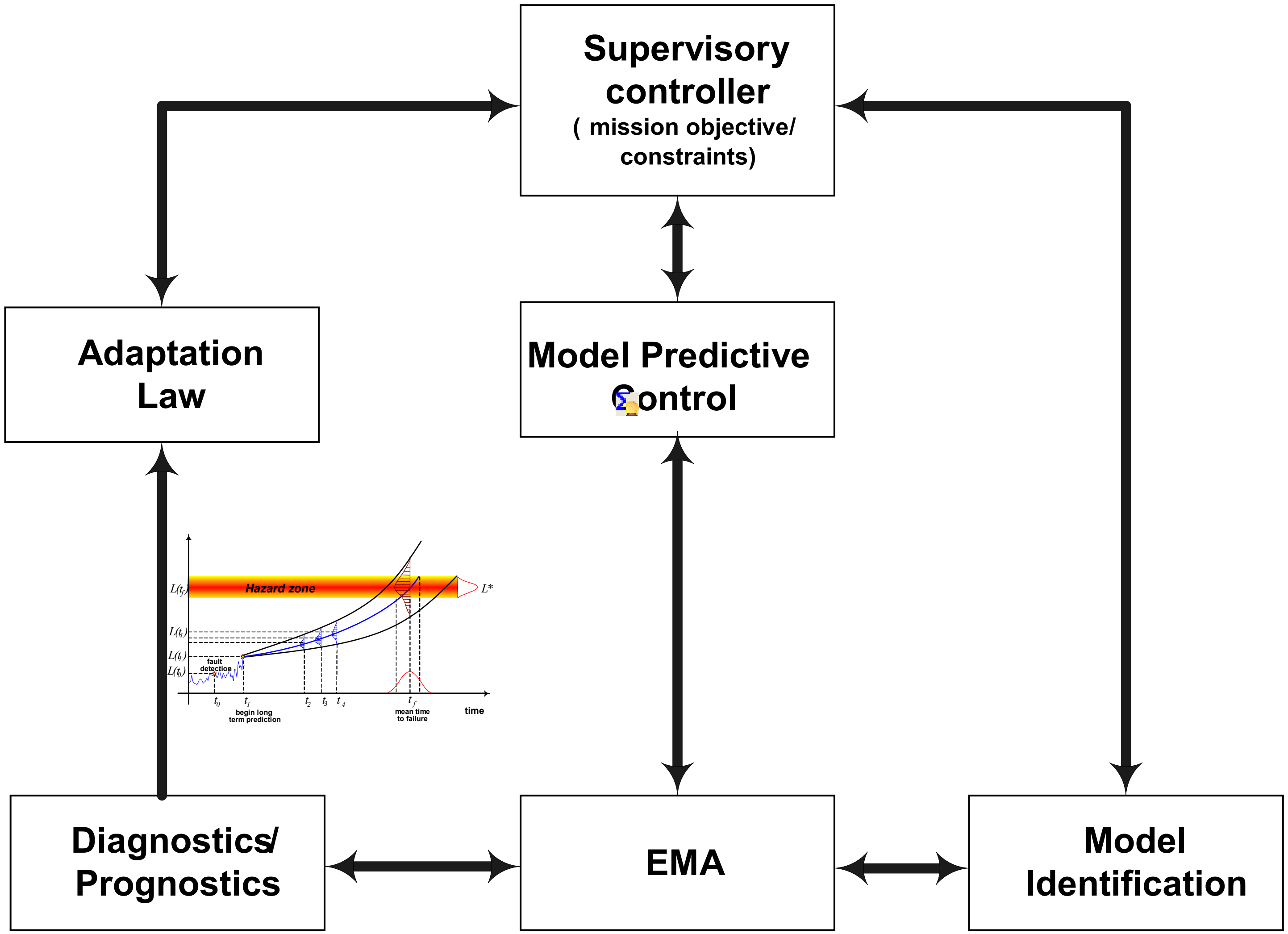


The Model Predictive Control Framework



Technical Approach

Control Reconfiguration Architecture



Model Predictive Control

Problem Definition

Minimize the cost function *J* subject to control offsets Δu(k|k)…, Δu(m-1+l|k),

$$\min_{\Delta u(k|k),\cdots,\Delta u(m-1+k|k),\varepsilon} \left[J\left(\Delta u, r, y\right) \right]$$

where *J* is defined as,

$$J\left(\Delta\tilde{\mathbf{u}}_p, \tilde{\mathbf{r}}_p, \tilde{\mathbf{y}}_p\right) = \left(\tilde{\mathbf{y}}_p - \tilde{\mathbf{r}}_p\right)^T \mathbf{W}_y^2 \left(\tilde{\mathbf{y}}_p - \tilde{\mathbf{r}}_p\right) + \Delta\tilde{\mathbf{u}}_p^T \mathbf{W}_{\Delta u}^2 \Delta\tilde{\mathbf{u}}_p + \rho_\varepsilon \varepsilon^2$$

where

$$\tilde{\mathbf{y}}_p = \left[y(1|0) \quad y(2|0) \quad \ldots \quad y(p|0) \right]^T$$ – Predicted plant outputs

$$\tilde{\mathbf{r}}_p = \left[r(1) \quad r(2) \quad \ldots \quad r(p) \right]^T$$ – Desired set-points

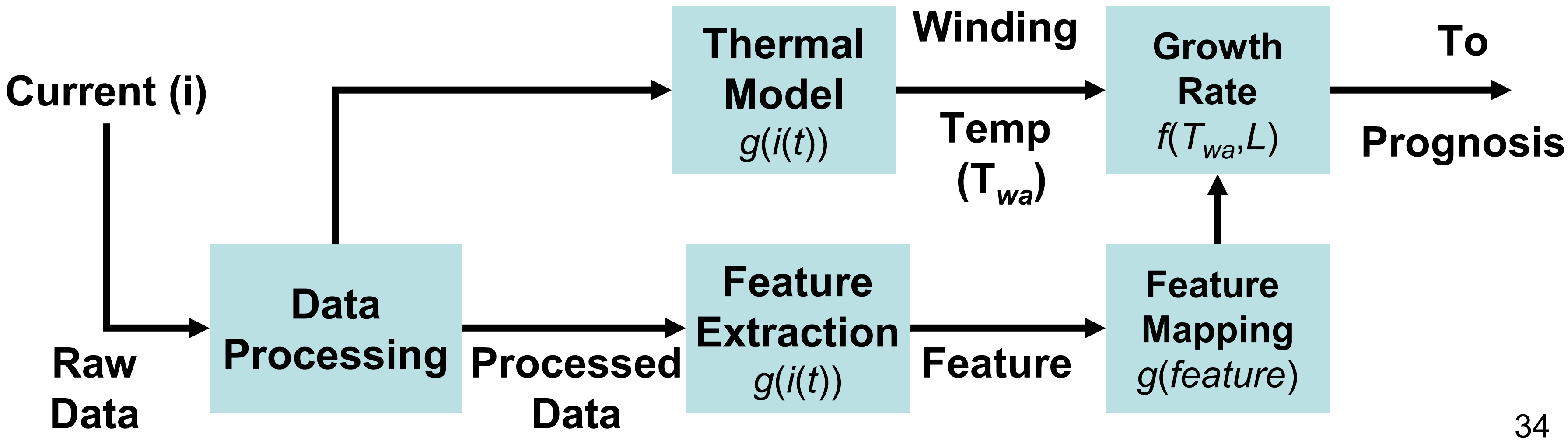
$$\Delta\tilde{\mathbf{u}}_p = \left[\Delta u(0) \quad \Delta u(1) \quad \ldots \quad \Delta u(p-1) \right]^T$$ – Reconfigured set-points

[1] A. Bemporad, M. Morari, and N. L. Ricker, Model Predictive Control Toolbox for Matlab, The Mathworks, Inc., 2004.

Fault Growth Model for Prognosis

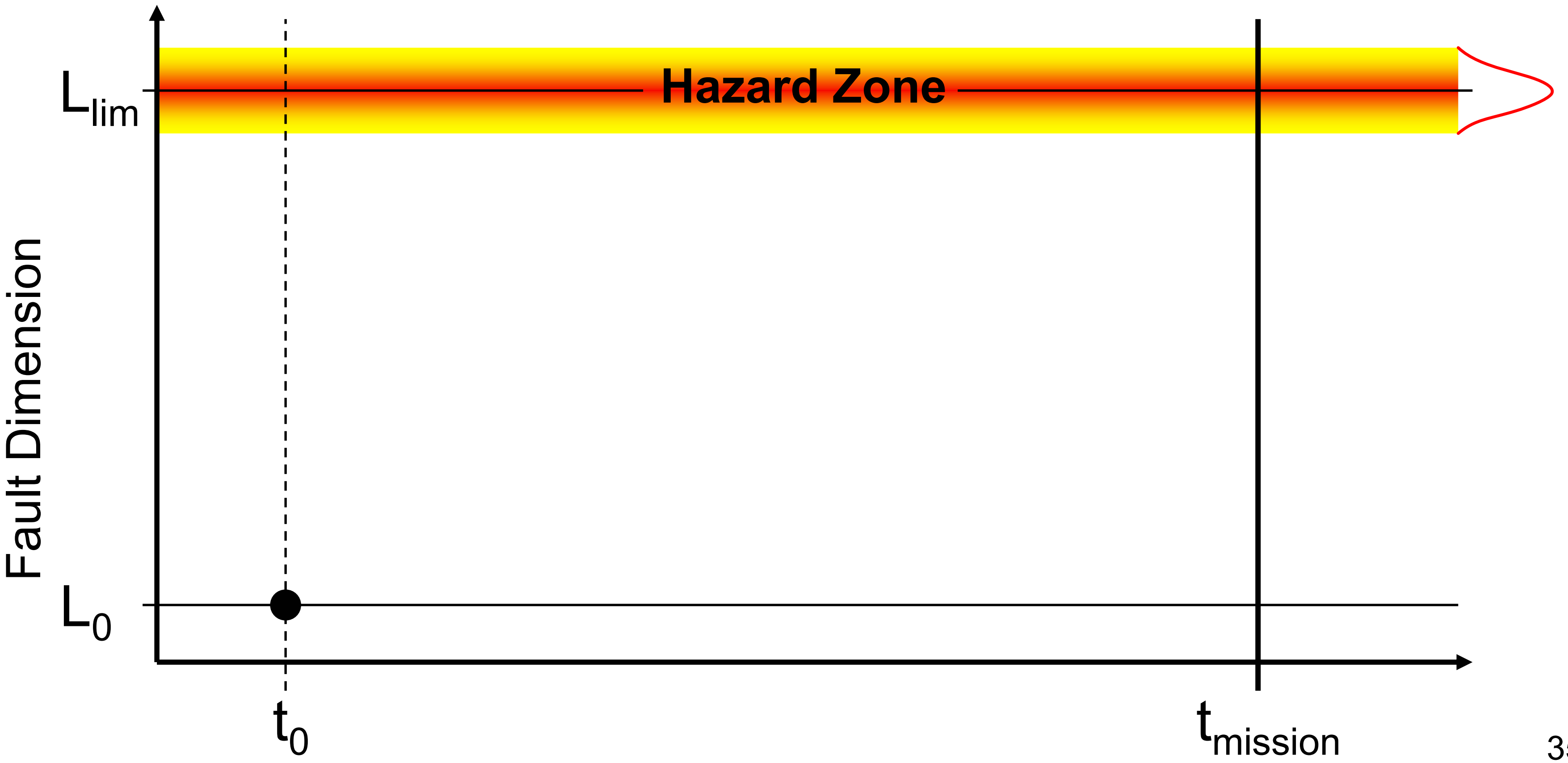
Outline

- **Describes how the primary feature evolves with the turn-to-turn winding fault**
- **Principle assumptions**
  - **Time rate of growth (*dL/dt*) increases with the current fault dimension (*L*)**
  - **Time rate of growth (*dL/dt*) increases with winding temperature (T_{wa})**
  - **Current (i) is related to winding temperature (T_{wa})**



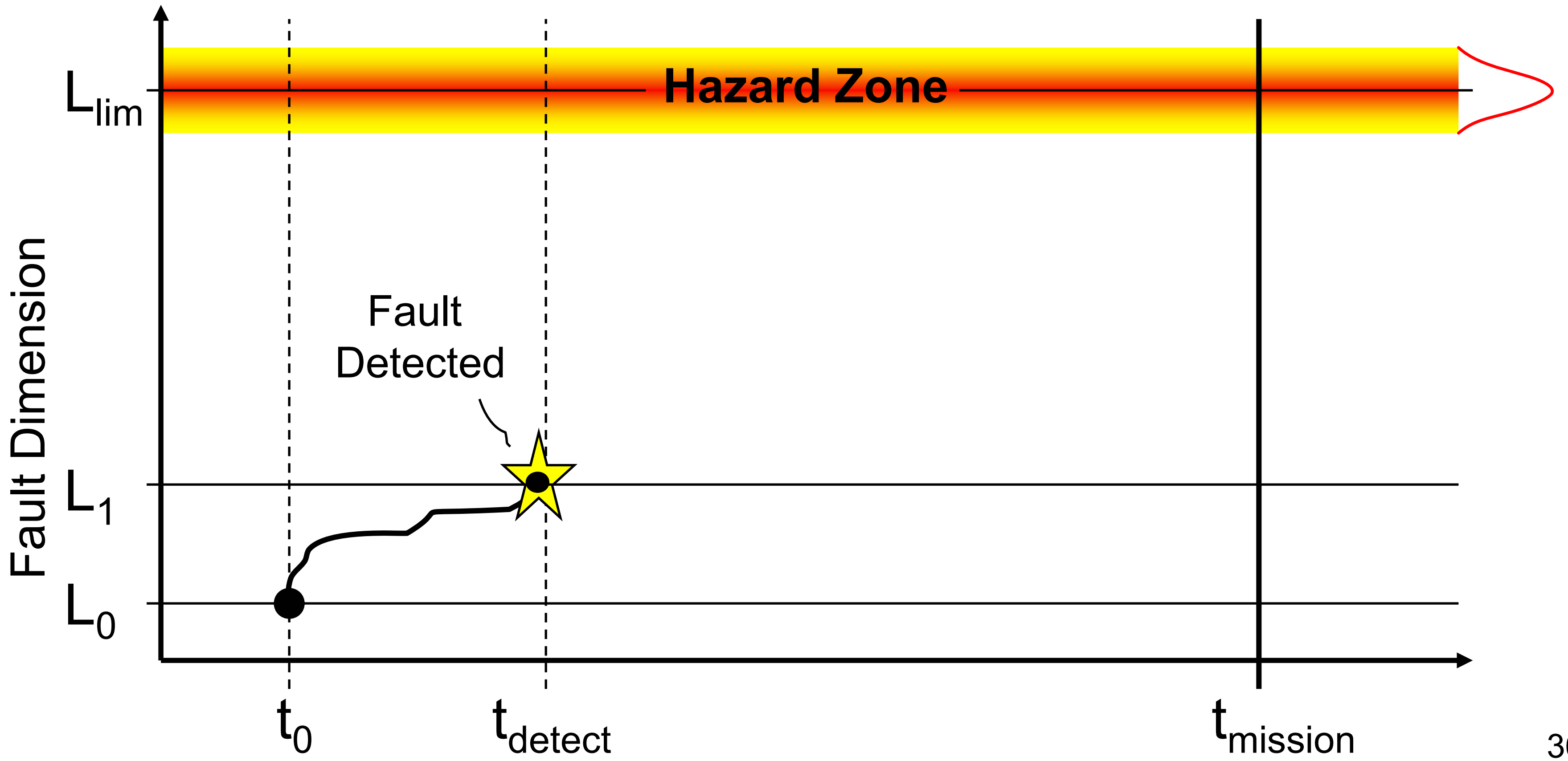
Step 1. Initialization

- Load initial fault dimension L_0
- Define fault detection criteria for diagnosis



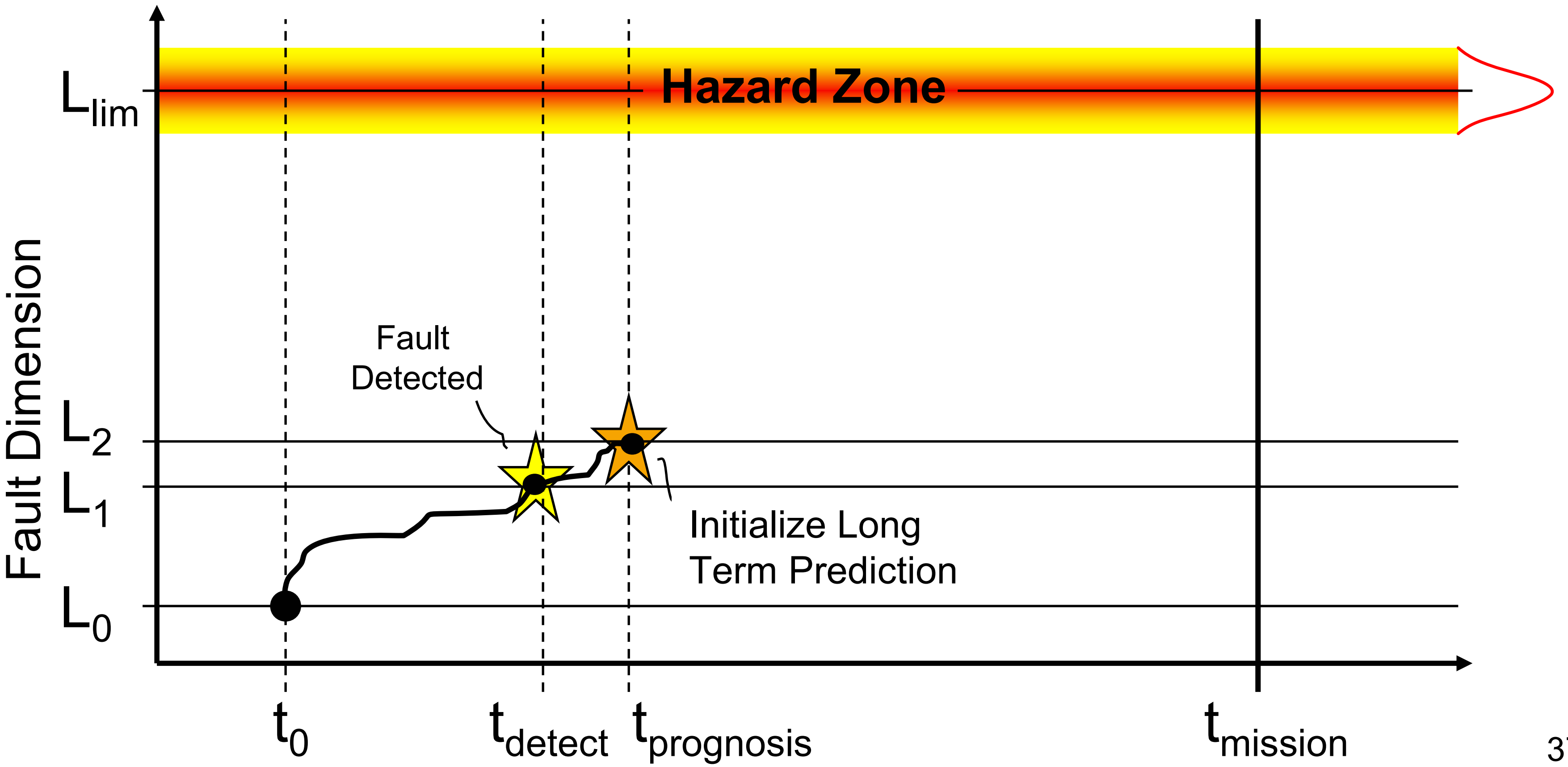
Step 2. Fault Detection

- Continuously monitor for fault



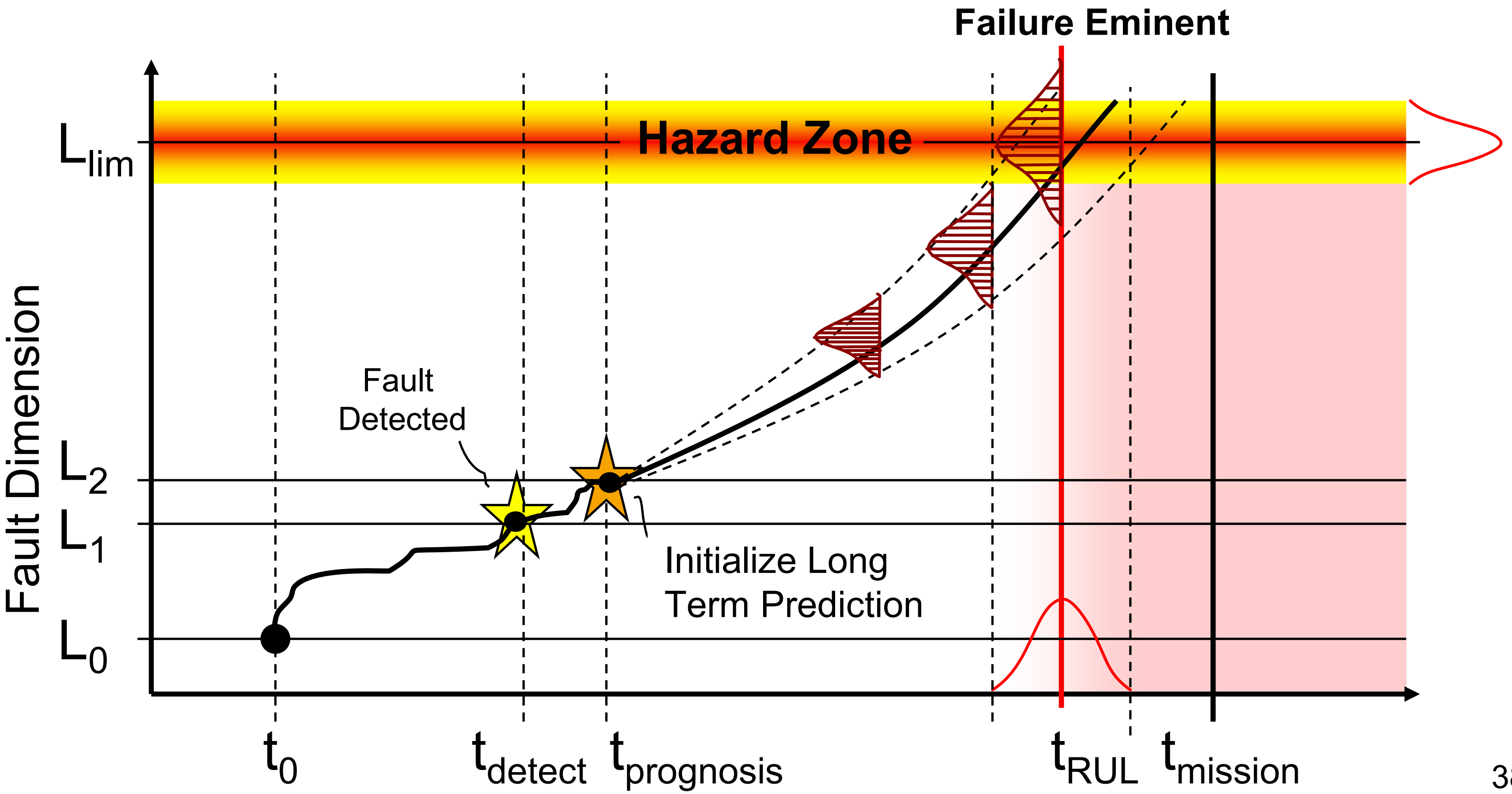
Step 3. Initialize Prognosis

- Initialize long term prediction



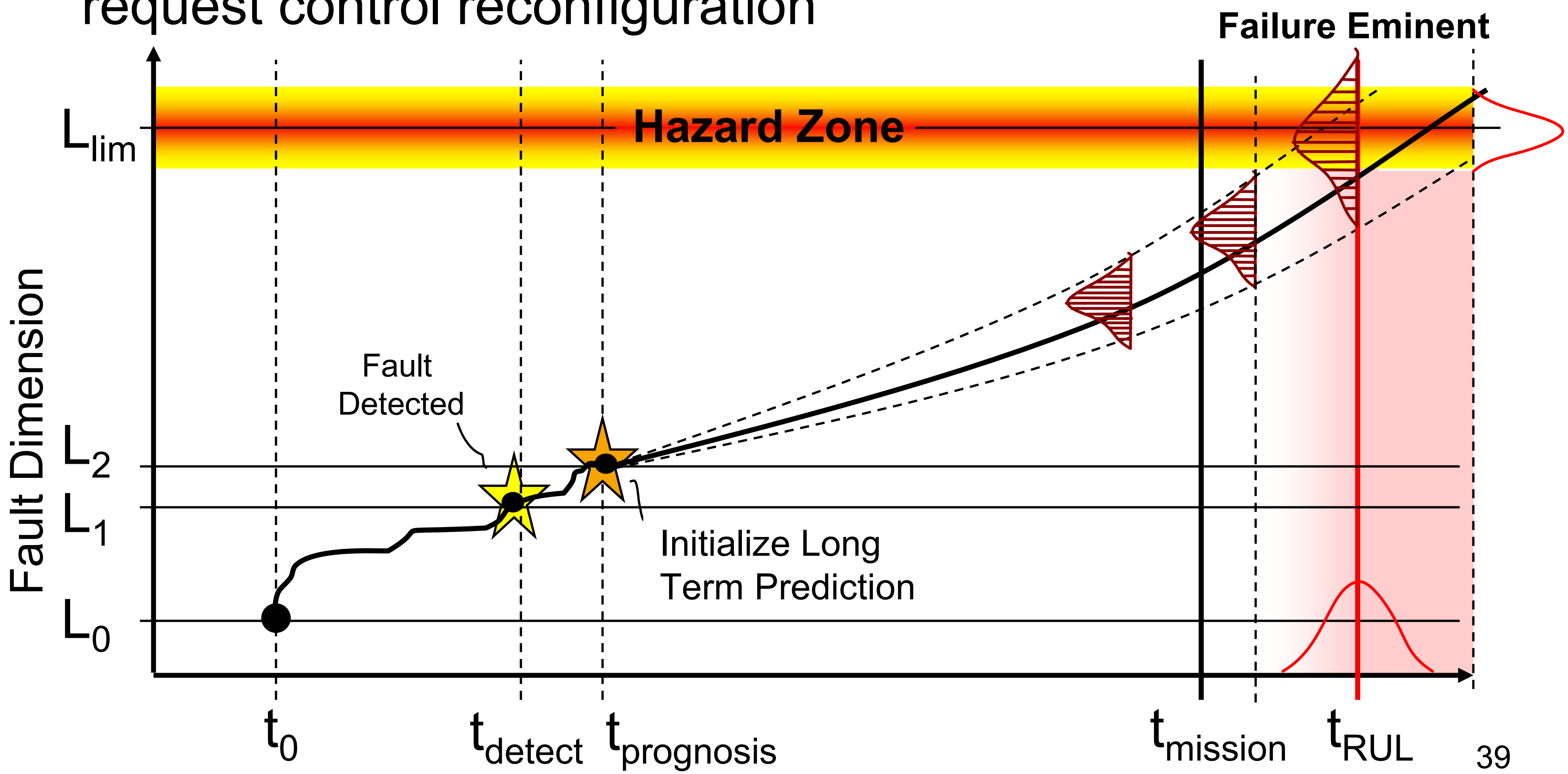
Step 4. Calculate RUL

- Predict fault dimension using fault-growth model
- Project hazard-zone crossing onto the time axis for RUL



Step 5. Compute u_{RUL}

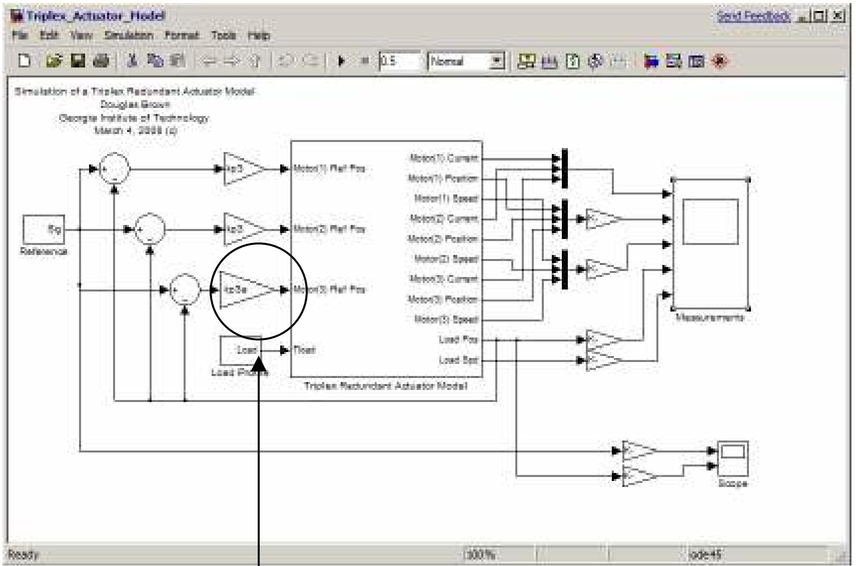
- Find constant control input U_{RUL} required to achieve the desired t_{RUL}
- If performance and RUL restraints cannot be satisified request control reconfiguration

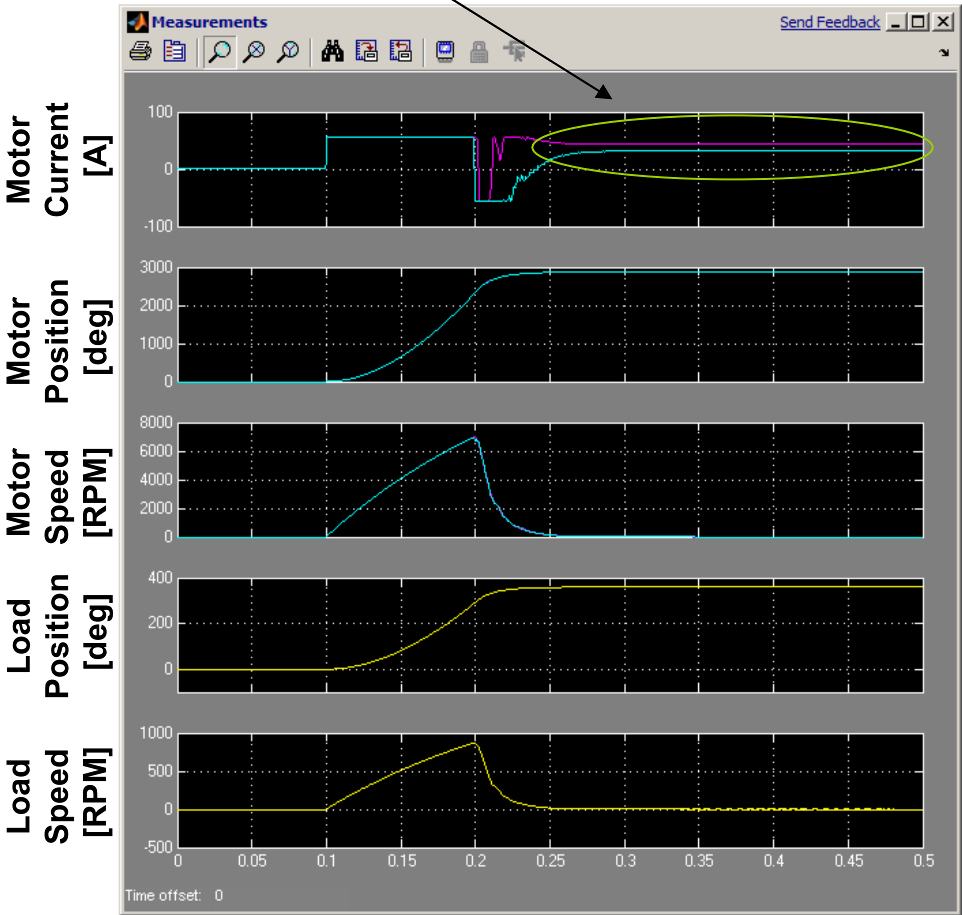


Triplex Redundant Actuator Model

Load Torque Redistributed

Simulink Triplex Actuator Model

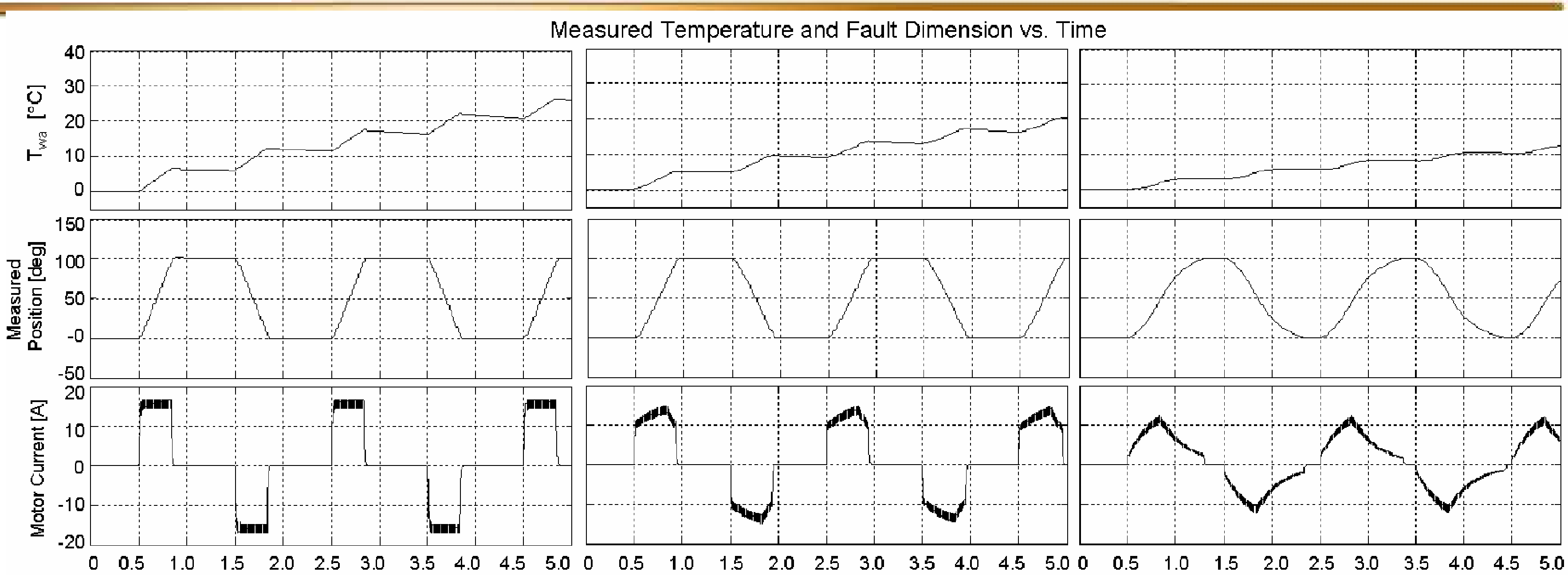




Feedback gain adjusted

Preliminary Results

Various Fault Dimension / Constant $T_{mission}$



(a) $L = 1x10^{-6}$ (b) $L = 1x10^{-2}$ and (c) $L = 1x10^{-1}$

Simulation results for the fault growth model

Operating Current [A]	Expected RUL [min]	RUL Increase
20	2200	2444
25	310	344.4
30	41.0	45.56
35	6.00	6.667
40	0.90	1.000

Reconfigurable Control

Benefits of Reconfigurable Control with PHM

- Capability to enhance mission effectiveness in the presence of contingencies
- Means to complete mission while satisfying performance constraints and assuring system stability
- Ability to optimize reconfigurable control and PHM algorithm requirements for specific components / subsystems under degraded operation in order to meet mission objectives

Reconfigurable Control

Benefits of Reconfigurable Control with PHM (Cont.)

- Full functionality for reconfiguration / fault tolerance via an intelligent hierarchical architecture
- Ability to perform failure prognosis and reconfigurable control in almost real-time avoiding latency problems
- Uncertainty representation and management through a particle filtering approach.

Reconfigurable Control

Benefits of Reconfigurable Control with PHM (Cont.)

- Mission capability updates through the integration of reconfigurable control and Integrated Adaptive Guidance and Control Systems
- Ability to provide engineering justification for adding new reconfiguration, control and communication system upgrades with technical and economic benefits clearly identifiable
- Provision of feedback to system designers of design information that will lead to fault-tolerant high-confidence systems.

CONCLUSIONS – FUTURE WORK

- Linking PHM To Controls – The Added Value
- Need To Mature Prognostic Algorithms
- Computational Issues
- V&V – Qualification
- Opportunity For New R&D