Immune System Engineering: Model Based Analysis for Anomaly Detection

New Paradigms for Continuous Monitoring

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Customer's Needs (Survey)

- Design
  - US OEM – Need to test design margins early in process.
  - >60% of warranty problems are NTF design problems
    - Need more comprehensive real-time diagnostics
- Development
  - Suppliers – Diagnostic System requirements are arriving later and later, leaving less time for development
  - OEM's – new more comprehensive OBD requirements
- Validation
  - US OEMs – Valuable resources squandered on fleets
- In-use
  - Truck OEMs, Auto OEM – Diagnose after MIL, prognostics
- Repair verification
  - US OEM – Verify that no problems exist after repair.
    - Avoid returns.
- Repair
  - Euro and US OEM's – Analysis of flight recorder data
    - Want data driven methods

Perceived Needs

- Quality
  - Design complex systems with high reliability
- Development Costs
  - Complete and qualify design in constrained time.
- Regulatory Requirements
  - Meet new requirements with high confidence
- Customer Recognition of Performance
  - Efficient and correct service of all problems
  - Increase sales based on customer appreciation

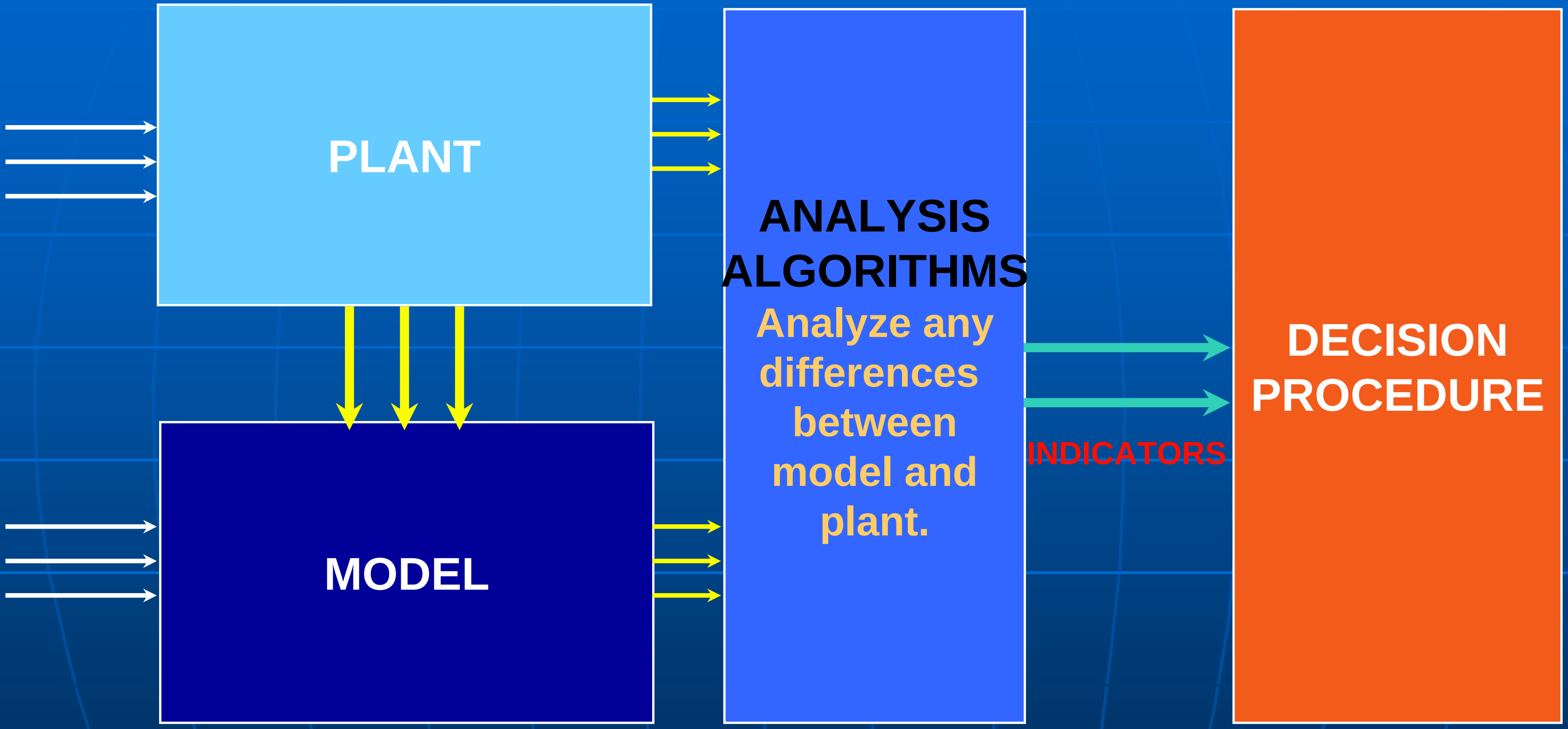
Proposed Solution:
Immune System Engineering

- Design diagnostics into the system at the earliest stages.
  - FMEA analysis is not completely effective
  - Diagnostics must detect ***any*** problem.
  - Need Anomaly Detection
- Eliminate design issues through comprehensive analysis of system performance against design intent
- Utilize same analysis for on-board, manufacturing testing and in-use testing to reduce resources required for system diagnostics.
  - Develop diagnostics ONCE in life-cycle.

Anomaly Detection

- Anomaly Detection is based on the principle that deviations in system performance can be detected if we have a sufficiently accurate model of the expected behavior of the system to compare with the actual performance of the system.
  - This is the foundation of model based reasoning
- The nature of the models and their representation of system behavior differs in the approaches we will discuss.
- Immune System Engineering is the capability to create analysis tools for the entire product lifecycle that can continuously monitor systems and detect and identify ANY system failures that appear.
  - ISE Tools applied early in the design and validation stages can drive out problems that otherwise would go to production, and thereby produce improvements in system robustness and reliability.

Model Based Reasoning



PLANT

MODEL

ANALYSIS ALGORITHMS

Analyze any differences between model and plant.

INDICATORS

DECISION PROCEDURE

WITH A PERFECT MODEL – ANY DEVIATIONS ARE ANOMALIES!

This scheme, in effect, is simply a redundant system for diagnostics.

If we don't use a physical replication of the plant for the "model" then we are utilizing "analytic redundancy" to accomplish what avionics applications seek when they use physical redundancy.

Note: without extensive analytics, triple hardware redundancy is needed.

Emerging Issues

- New control systems are much more complex than existing systems, as demands to create higher value for customers grow.
- Time to develop new systems has been reduced.
    - Little time in the process for new features OR diagnostics as designed by standard methods
- Stage gate processes have failed to provide adequately robust products.
    - >60% of warranty costs on these systems are due to engineering design problems which should have been detected, but diagnosis tools were not sufficiently sensitive.
- Authority of the control systems has increased.
    - VDC can control brakes and throttle.
- Legislative initiatives have emerged which suggest that OBD requirements for these systems will make demands far in excess of those seen for emissions OBD.

OBD II Experience

- OBD II was successful after >5 years.
  - Early problems have been resolved
  - Most exemptions for non-compliance have expired.
- OBD II was structured to detect only "findable, fixable, faults"
  - Many failures are not detected or flagged.
- Philosophy was to test for known and required failure modes.
  - All possible failure modes are defined in advance
- Failures must be severe and persistent to be detected.
  - Low level, intermittent problems are disregarded
- Failures are not deemed critical.
  - No immediate hazard is recognized for virtually all emissions problems.
- OBD is not a continuous, real-time monitor
  - Many monitors do not run more than once every several trips.
- Failure notification is not immediate
  - Multiple failures in succession are used to suppress alpha errors.
- Systems are not disabled in the presence of failure
  - No immediate operational consequences

Safety Critical Systems

New Needs

- Safety critical systems have the potential to introduce serious injury risk when failures occur.
- Governments have indicated a desire to require real-time monitoring (diagnostics) of designated safety critical systems.
  - ETC, vehicle stability, steer by wire etc.
- Diagnostic requirements are likely to be much more challenging.
  - Failure announcements should be immediate
  - Monitor must be full-time, real time.
  - Operational behavior should be impacted when failure is present.
  - ANY failure is a concern
  - Anomaly Detection appears to be a requirement

Typical Difficulties

- Problems are “wicked”
  - Very non-linear
  - Very little good data from production systems
  - Extremely skewed information profiles
    - Data which is usually captured emphasizes common operating conditions, not conditions which stress the plant.
  - Noise distributions unknown or complex
  - As the system converges, less than 0.1% of all the data provide any useful feedback for learning.
  - Systems are only partially understood
    - Vehicle stability systems have poor tire models
- Engineers who work on system designs claim it is impossible to “understand” individual systems without heavy investment of time to become an expert in the particular discipline.

Best Applications of Anomaly Detection

- Analysis of designs at early stages when problems are easiest to fix.
- Validation studies of test fleets when ALL the data should be analyzed.
- Search for simplest solution to diagnostic problems
  - Sensor fusion analysis can eliminate sensors
- Develop OBD monitors for emissions and safety critical systems.
  - Liability issues in US are dominant.
  - Major efforts at all companies getting underway.

Anomaly Detection

- Basics of Current Strategy
- Performance
- Limitations
- Improvements

ETAS – University of Michigan

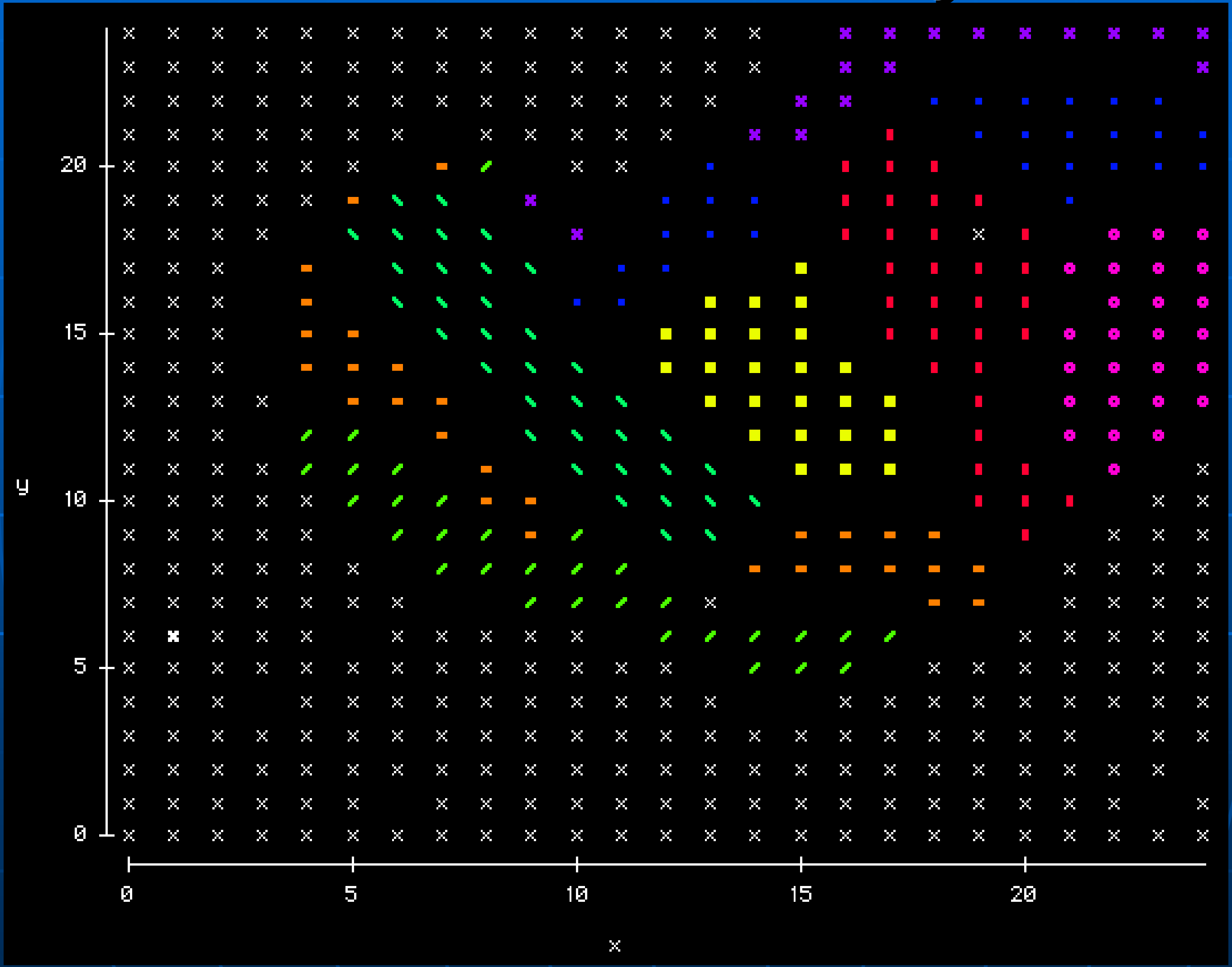
Anomaly Detection Using Self Organizing Maps

- Our strategy realizes MBR by regionalizing the operation of a complex system to narrow time domains (based on input sequences over a given interval) and analyzing the short-time Fourier transform of the output behavior of the system for same interval of time.
- This scheme is novel and pragmatic, although some computational complexity is introduced by the need to transform the information on the system to a different "feature space".
  - Introduces a "batch" process which causes small delays
- There are several interesting capabilities that this approach provides for engineers which make it VERY attractive for many applications.

Self-Organizing Map

- A simple, unsupervised learning scheme to recognize “natural” clusters of features in data.
- Maps high dimensional data into “visualizable” two (or 3) dimensional representation which captures two important elements of information from incoming data
  - Clusters
  - Similarity
- Examples
  - Faces
  - Galaxies
  - Messages
  - Conference Content
  - Diagnostic Analysis

SOM Analysis



Results are quite good, but not as good as needed for production use.

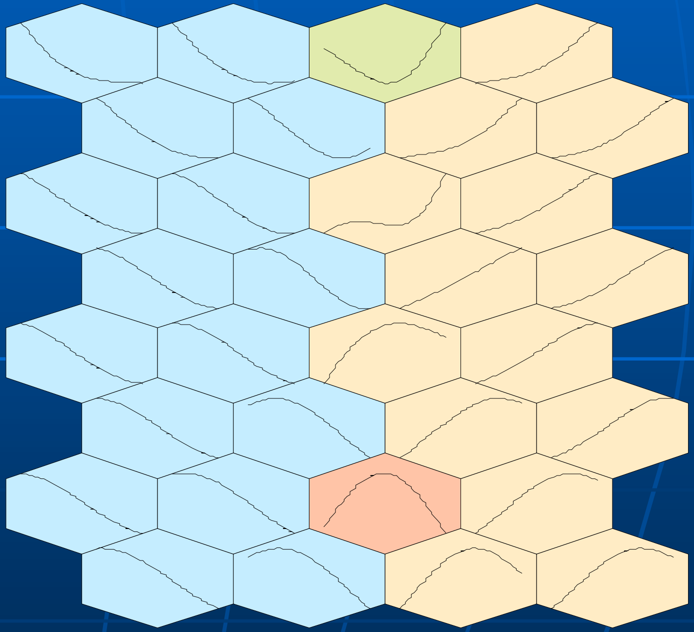
Can the technique be improved with some additional analysis?

USE OF SELF-ORGANIZING MAPS TO ANALYZE SYSTEM INPUTS and SYSTEM STATE

ASSUME: System outputs are determined by system inputs and initial conditions

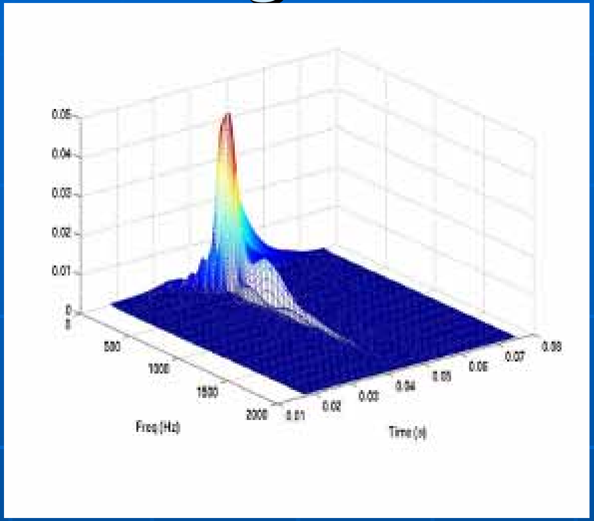
$$[\mathbf{y}(t_0), \frac{d\mathbf{y}}{dt}|_{t=t_0}, \frac{d^2\mathbf{y}}{dt^2}|_{t=t_0}, \cdots, \mathbf{u}(t_0), \cdots, \mathbf{u}(t_0+\tau)]^T$$

- Use the Machine Learning methods to break the problem down into manageable pieces and eliminate need for software "invention"
- Provide a process which works when system complexity is very high.
- Provide a system whose computational requirements can be accommodated in production hardware.



Example of SOM created using input signals

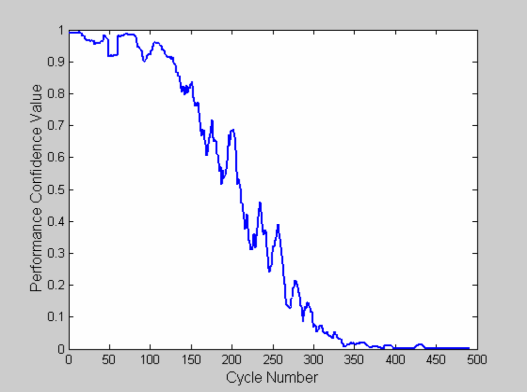
TFA Based Performance Assessment for High Accuracy Diagnostics



Time-Frequency Energy Distribution of Output

Dimensionality Reduction

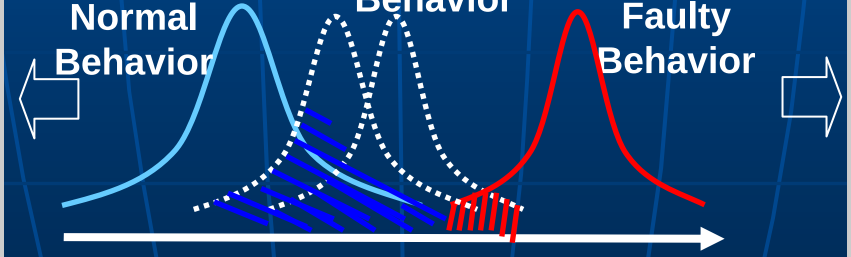
2-3 Parameters (Gaussian)



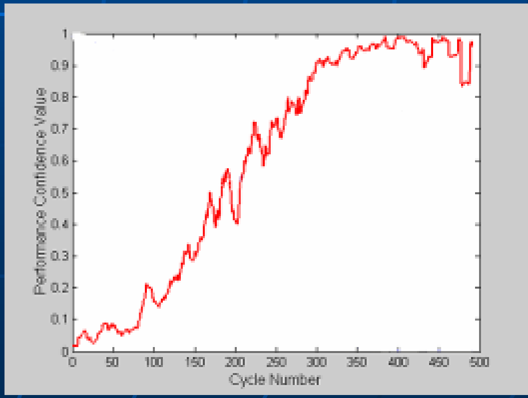
Most Recent Behavior

Normal Behavior

Faulty Behavior



Feature Space



Major Advantages

- Simple, understandable procedure
  - Methods incorporated are modifications standard machine learning, signal processing and statistical analysis tools.
- Prescriptive
  - The method does not require inventing new algorithms for each diagnostic problem
- Efficient
  - Makes maximum use of data from “normal” systems
- Intuitive means of separating known operating conditions from unseen conditions.
  - The SOM determines whether or not the input conditions are known or novel.
  - False alarms due to “uncharted” operation are thereby avoidable.
- Incorporates detailed analysis of system output behavior to achieve high performance in diagnostic analysis.
  - Avoids limitations of purely UL approach.

Major Advantages

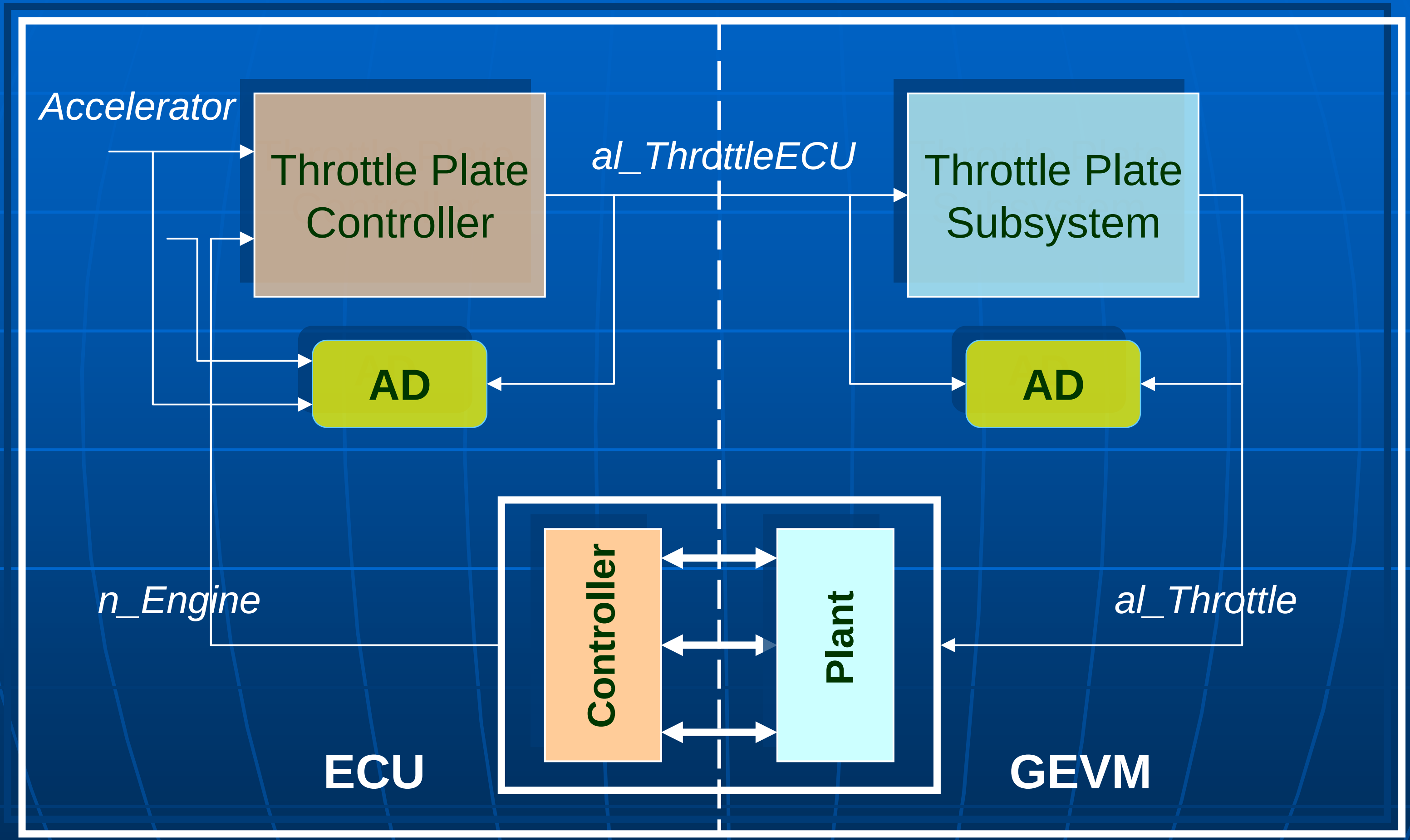
- Process is structured to fit the process of creating OBD monitors
    - The pre-conference workshop laid out WHAT needs to be done to develop effective monitors for OBD.
    - The method outlined here shows HOW to do the job.
    - Trucks, hybrids and AFV can use this feature now!
- Can accommodate handling “rare events”.
- Outputs have desirable statistical properties which facilitate calibration
- Hardware accelerator is available
- Lifecycle compatible
    - Diagnostic design serves the entire system lifecycle

Examples of Performance

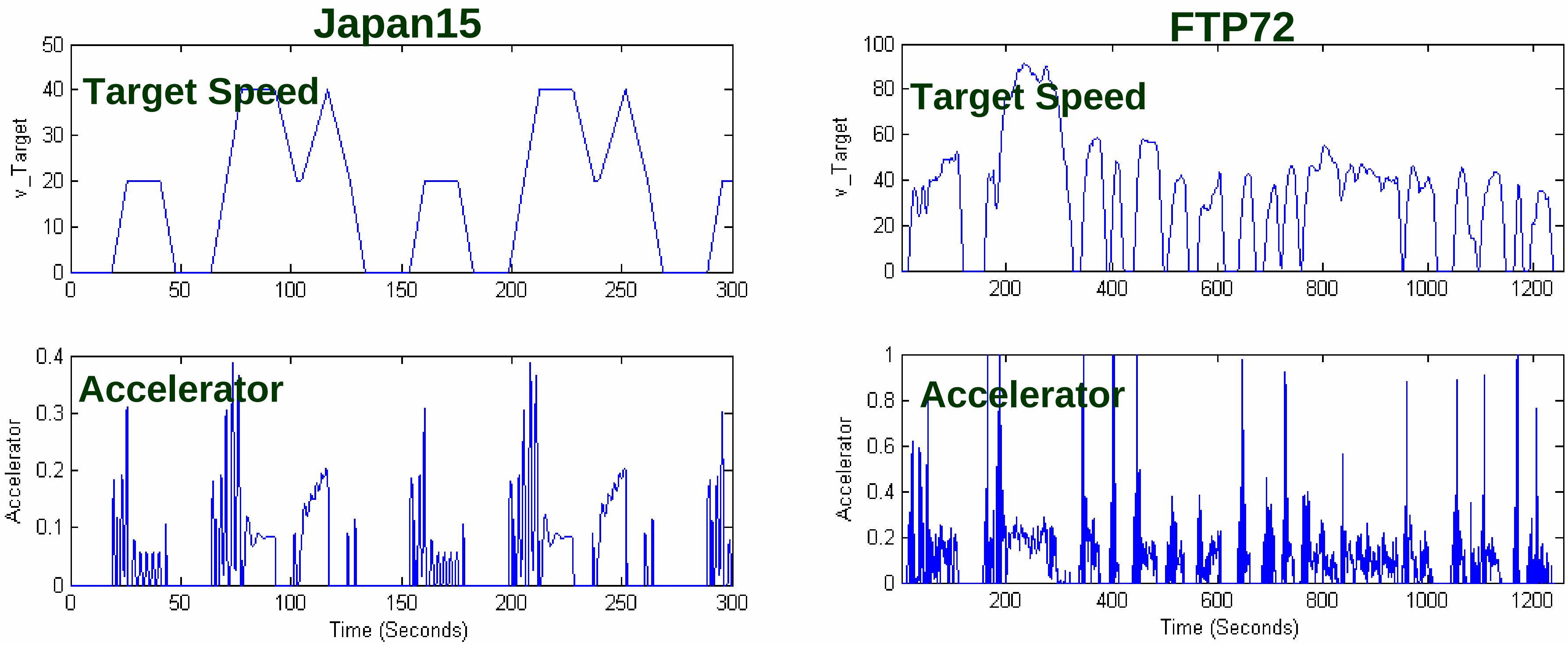
Application Example

- Application to Electronic Throttle Control System
  - Analysis has also been applied to detection of anomalous behavior of machine tooling systems.
- Must have real-time operation with high sensitivity for small errors of any nature.
- Must isolate problems between controller and plant.

Anomaly Detection Schematic



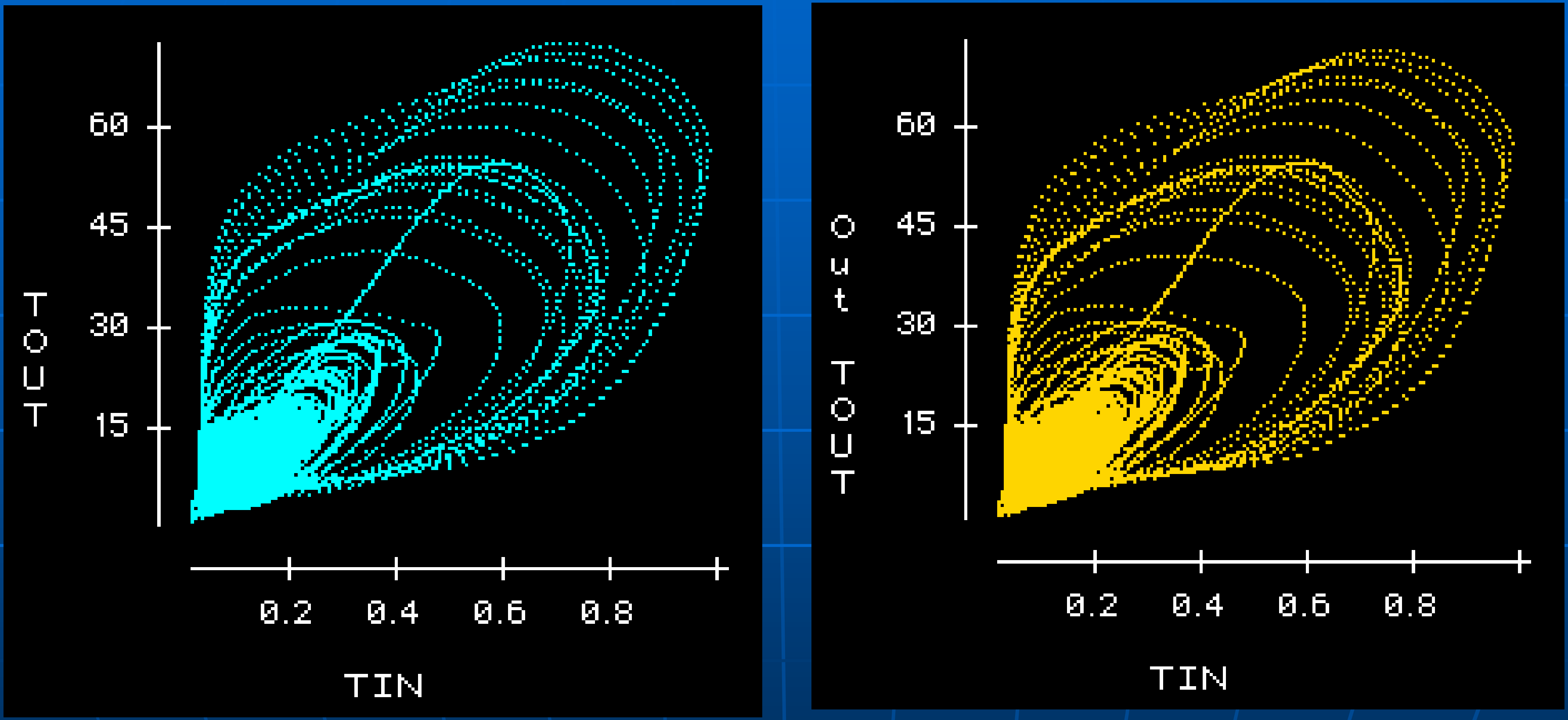
Demonstration



	Name of test cycles
Training data set	**•Japan15 & Japan 11:Japanese Cycles** **•FTP72: USA (Federal Test Procedure of 1972)** **•Manual Driving Profiles**
Testing data set	**•FTP75: USA (Federal Test Procedure of 1975)** **•ECE2: New European Test Cycle of the ECE**

Examples of Performance

Virtual Plant



ACTUAL PLANT

NN MODEL

The actual plant behavior is indistinguishable from the “Model” Plant

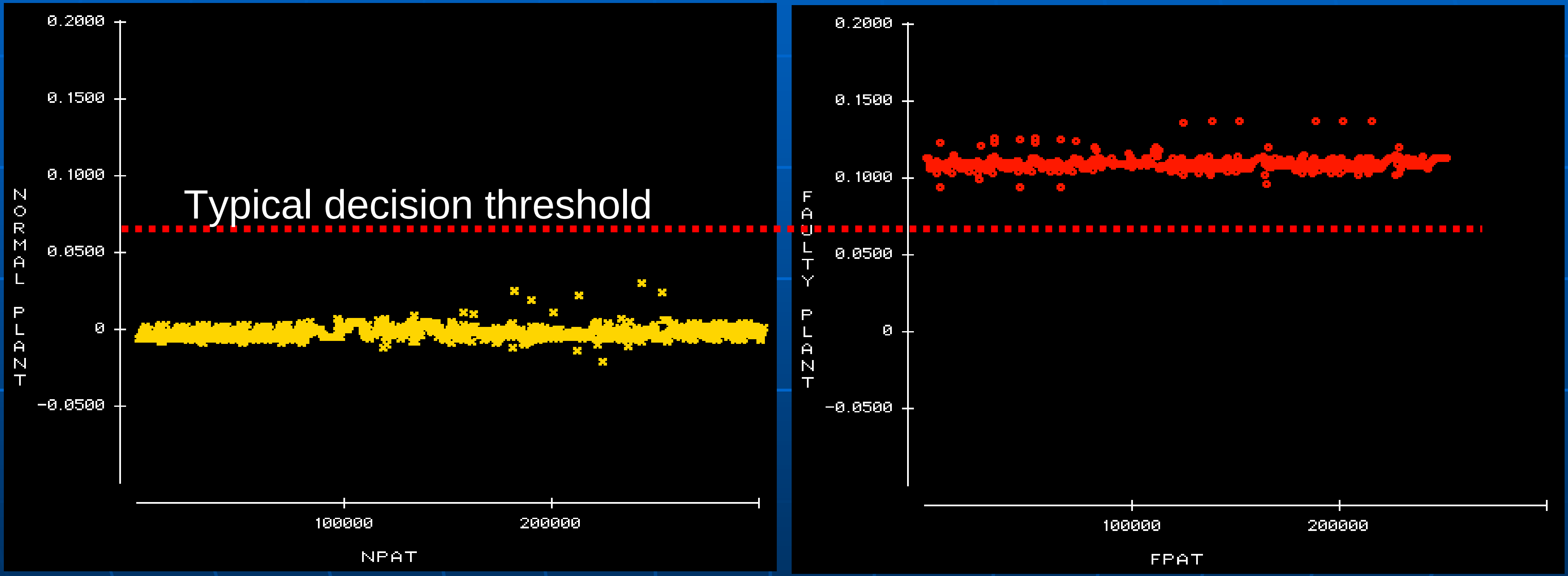
Examples of Performance

Anomaly Detection

Analysis of Throttle System Demonstration for AD

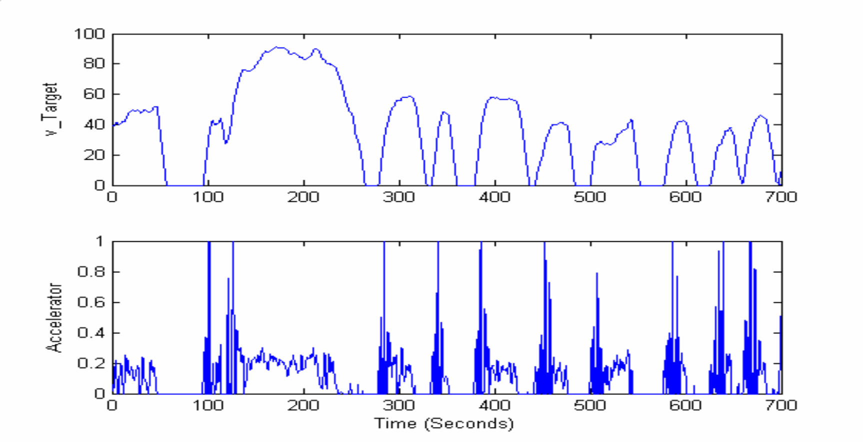
Decision performance at 3 second intervals for marginal perturbation.

NORMAL ANGLE DISTURBANCE

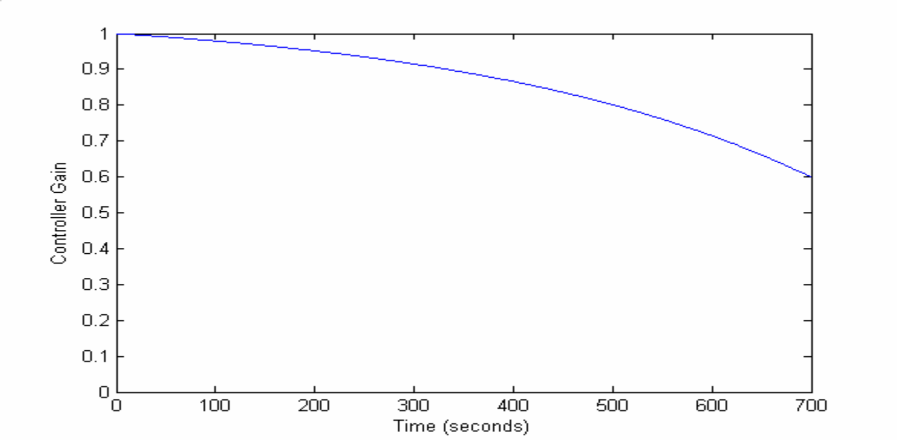


Results shown apply to analysis of plant performance.

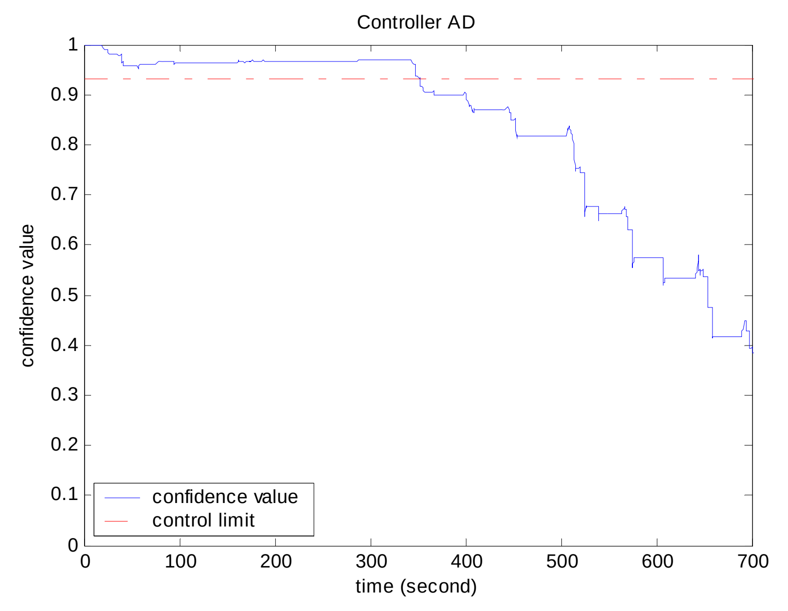
Time Varying Parameters (Controller)



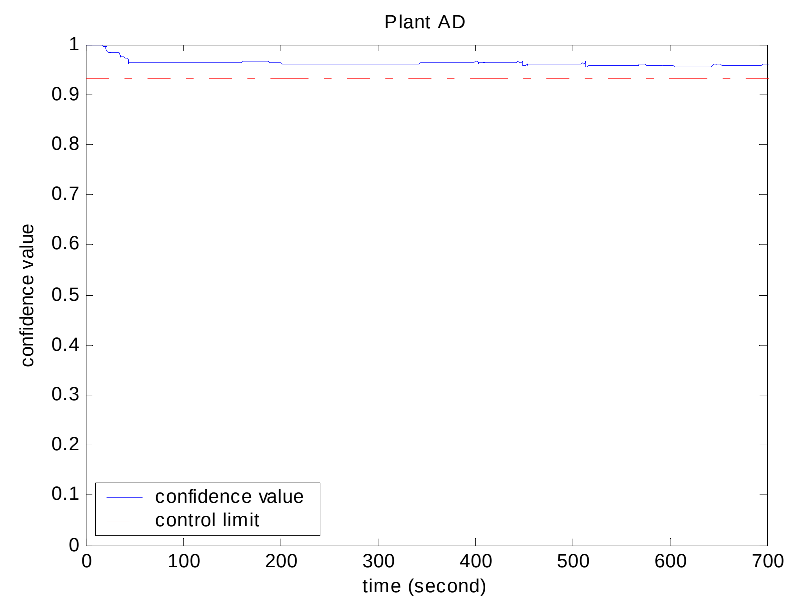
Driving Profile:FTP75



Gain factor decreases from 1 to 0.6



Controller AD



Plant AD

Anomaly Detection Application

- Performance was analyzed on 4 types of failures introduced into system
    - Three failures in plant.
    - One failure in controller.
- Anomaly Detectors were used for plant and controller.
    - In all cases, the anomaly detector isolated the problem to the correct system.
- For the plant, the AD scheme was able to isolate the problem to the correct cause with FMEA analysis.
    - Root cause analysis still an important issue in diagnostics.
- Multiple AD's address the issue in a effective manner.

CONCLUSIONS

- We have shown how machine learning methods may be used to construct real-time monitors for complex systems.
- A straightforward means of using simple unsupervised learning in combination with statistical analysis and information compression was shown which is suitable for emissions OBD applications.
- A more sophisticated approach has been developed which we feel may be ultimately appropriate for the more severe requirements mandated for safety critical systems.
- All the methods demonstrated were prescriptive and followed the principles for development of diagnostics as discussed in the workshop preceding the TOPTEC.