MURI IPD Introduction and Project Overview

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14 August 2000

ONR GRANT NO.: N00014-95-1-0461

Form SF298 Citation Data

Report Date ("DD MON YYYY") 14062001	Report Type Final	Dates Covered (from... to) ("DD MON YYYY") 01031995 30092000

Title and Subtitle MURI Integrated Predictive Diagnostics (IPD)	**Contract or Grant Number** N00014-95-1-0461
	Program Element Number URI
Authors Hall, David L.; Byington, Carl S.	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) THE PENNSYLVANIA STATE UNIVERSITY 110 TECHNOLOGY CENTER BUILDING UNIVERSITY PARK, PA 16802-7000	**Performing Organization Number(s)**
Sponsoring/Monitoring Agency Name(s) and Address(es) Office of Naval Research	**Monitoring Agency Acronym**
	Monitoring Agency Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Prepared in cooperation with Rensselaer Polytechnic Institute and Tennessee State University	
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Subject Terms condition-based maintenance (CBM); Multidisciplinary University Research Initiative (MURI); Integrated Preditive Diagnostics	
Document Classification unclassified	**Classification of SF298** unclassified

Classification of Abstract unclassified	**Limitation of Abstract** unlimited
Number of Pages 27	

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
14-06-2001	Final Technical Report	01-Mar-1995 - 30-Sep-2000

4. TITLE AND SUBTITLE
MURI Integrated Predictive Diagnostics (IPD)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-95-1-0461

5c. PROGRAM ELEMENT NUMBER
URI

6. AUTHOR(S)
David L. Hall, Carl S. Byington

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE PENNSYLVANIA STATE UNIVERSITY
110 TECHNOLOGY CENTER BUILDING
UNIVERSITY PARK, PA 16802-7000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A, Approved for Public Release, Distribution is Unlimited.

13. SUPPLEMENTARY NOTES
Prepared in cooperation with Rensselaer Polytechnic Institute and Tennessee State University

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16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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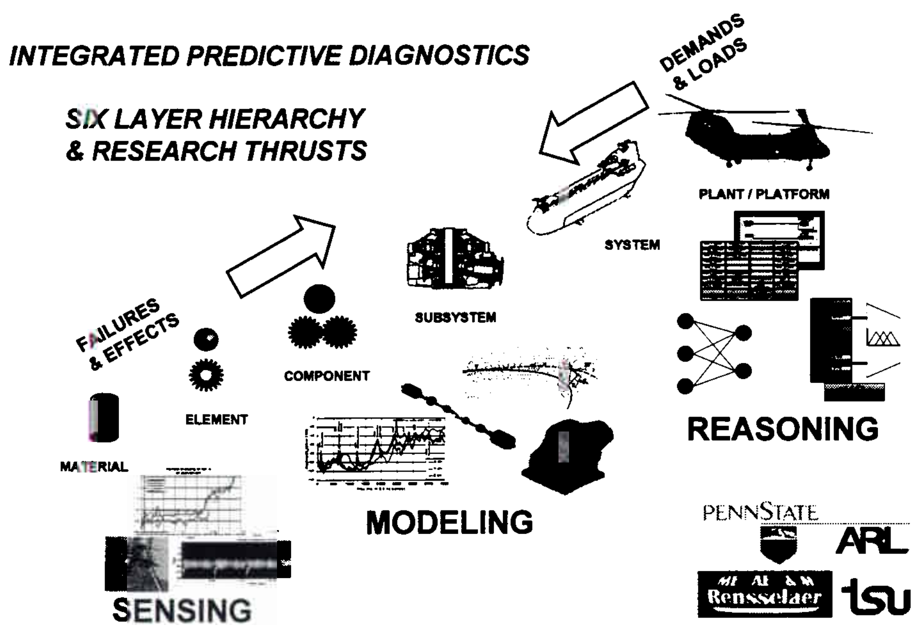
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	SAR		(703) 6964503

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Multidisciplinary University Research Initiative (MURI) for Integrated Predictive Diagnostics

March 1995 – August 2000



MURI Objective

Mission-oriented predictive diagnostics for mechanical systems with emphasis on consequence-driven sensing, modeling, and reasoning. Demonstrate end-to-end processing for CBM on mechanical diagnostics test bed (MDTB).

Enhanced DoD Capabilities

Reduced lifecycle maintenance costs for weapons platforms with enhanced mission effectiveness, increased reliability and improved human safety.

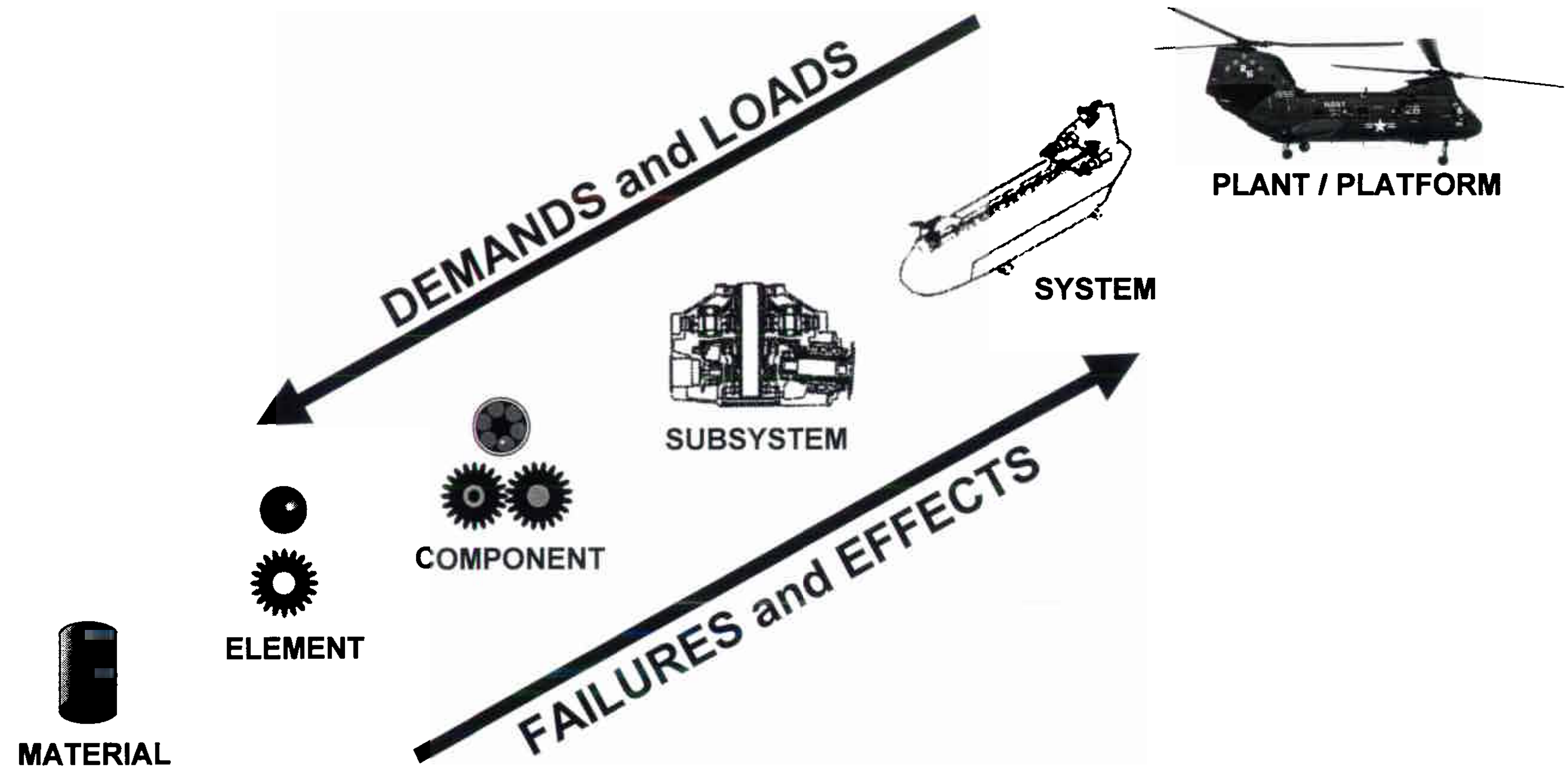
Accomplishments

- Test beds to collect calibrated fault transitional data
- *Smart*, self-calibrating sensors
- Advanced sensing methods: torsional, magnetic
- Advanced signal processing and data fusion
- Nonlinear prognostics to track failure evolution
- Hierarchical models for MDTB
- Advanced hybrid automated reasoning techniques
- Collaboration with CHI Systems: intelligent agents for helicopter aircrew decision support

Scientific/Technical Approach

- Three research areas: sensing, modeling, reasoning
- Vertically integrated facilities and models to link materials-level failure phenomena to platform-level effects
- Data collection and demonstration on MDTB
- Workshops and data archival for CBM community
- Research supports both helicopter and shipboard-based programs

Six-Layer Hierarchy
for Integrated Predictive Diagnostics



Challenges for Condition-Based Maintenance

- **Sensors**
  - Sensor selection and location
  - Size and cost
  - Robustness and self-calibration
  - Smart in-situ processing
- **Signal processing/data fusion**
  - Detection of rare events
  - Poor signal-to-noise ratio
  - Signal characterization and feature selection
  - Fusion of non-commensurate sensors
  - Archival quality data sets
- **Intelligent reasoning and control**
  - Combined implicit/explicit reasoning
  - Hierarchical reasoning
  - Incorporating negative information
  - Uncertainty and knowledge representation
  - Incorporation of operational context
- **Micro-mechanical modeling**
  - Incipient fault models
  - Fault progression models
  - Impact of environmental factors
- **Dynamic modeling and prognostics**
  - Link of micro failure to macro observables
  - Nonlinear dynamics
  - Intrinsic limits of predictability
  - Life cycle modeling

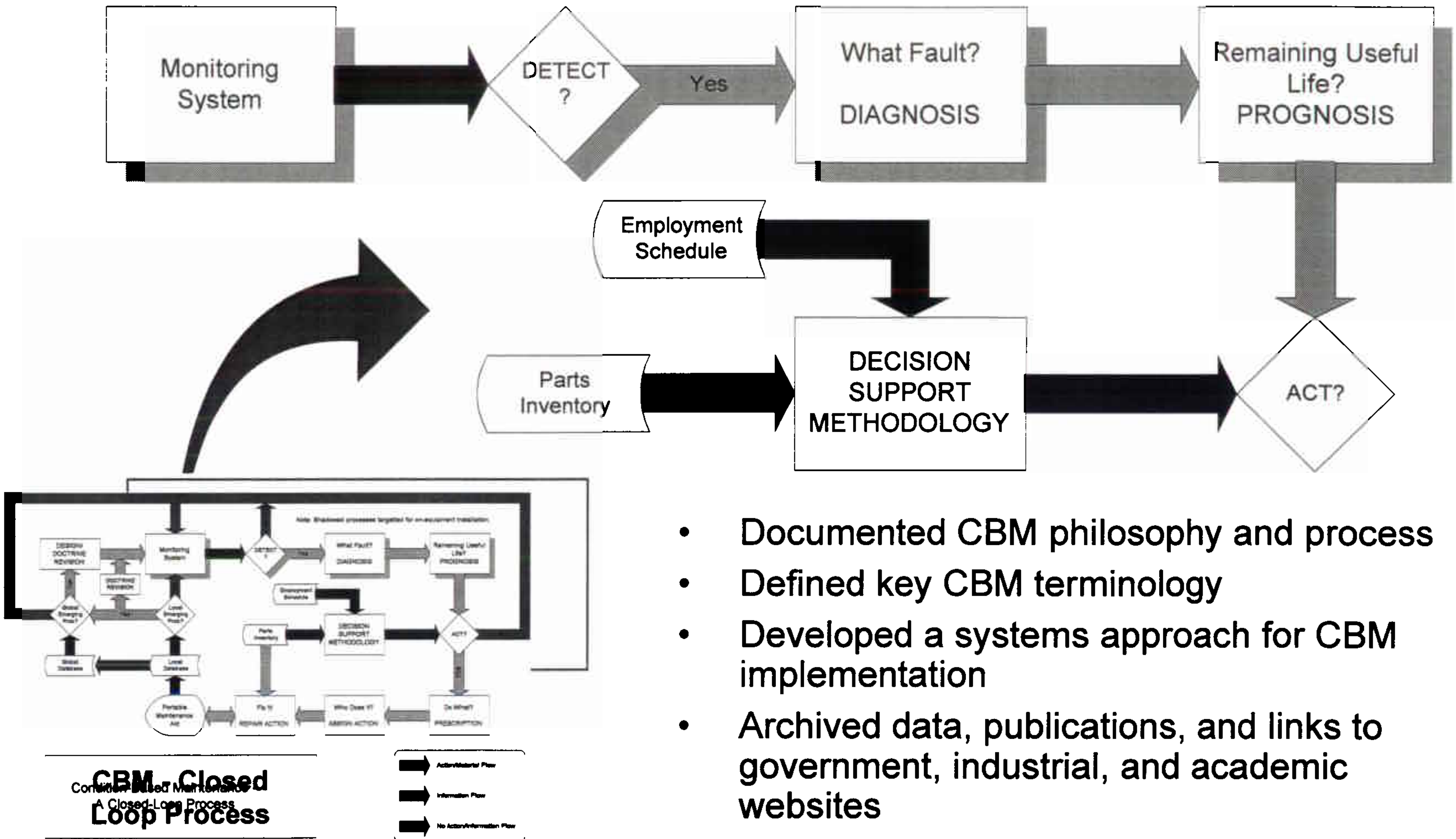
What the MURI Team Proposed…

Micro-Mechanical Failure Models	• Wear progression and failure models • Fatigue failure processes/progression models • Role of hydrogen embrittlement in high strength steels • Vertically integrated test facility and data sets
Dynamic Modeling	• Reliable prediction of damage state from macro-observables • Diagnostics based on dynamical responses • Prediction of remaining useful life
Sensors and Sensing Systems	• New architecture for smart self-calibrating sensors • New noncontact ultrasonic sensors • Nanofabricated smart sensors • New adaptive noise canceling sensors
Signal Processing and Multisensor Data Fusion	• New wideband, coherent signal processing techniques • Advance pattern recognition methods for recognizing failure events • A general multisensor data fusion processor • New active/passive sensor processing approach
Intelligent Reasoning and Control	• New knowledge representation/inference methods • Linked explicit/implicit approximate reasoning • Hierarchical architecture for intelligent prognostics • Life-extending control approach

What We Achieved

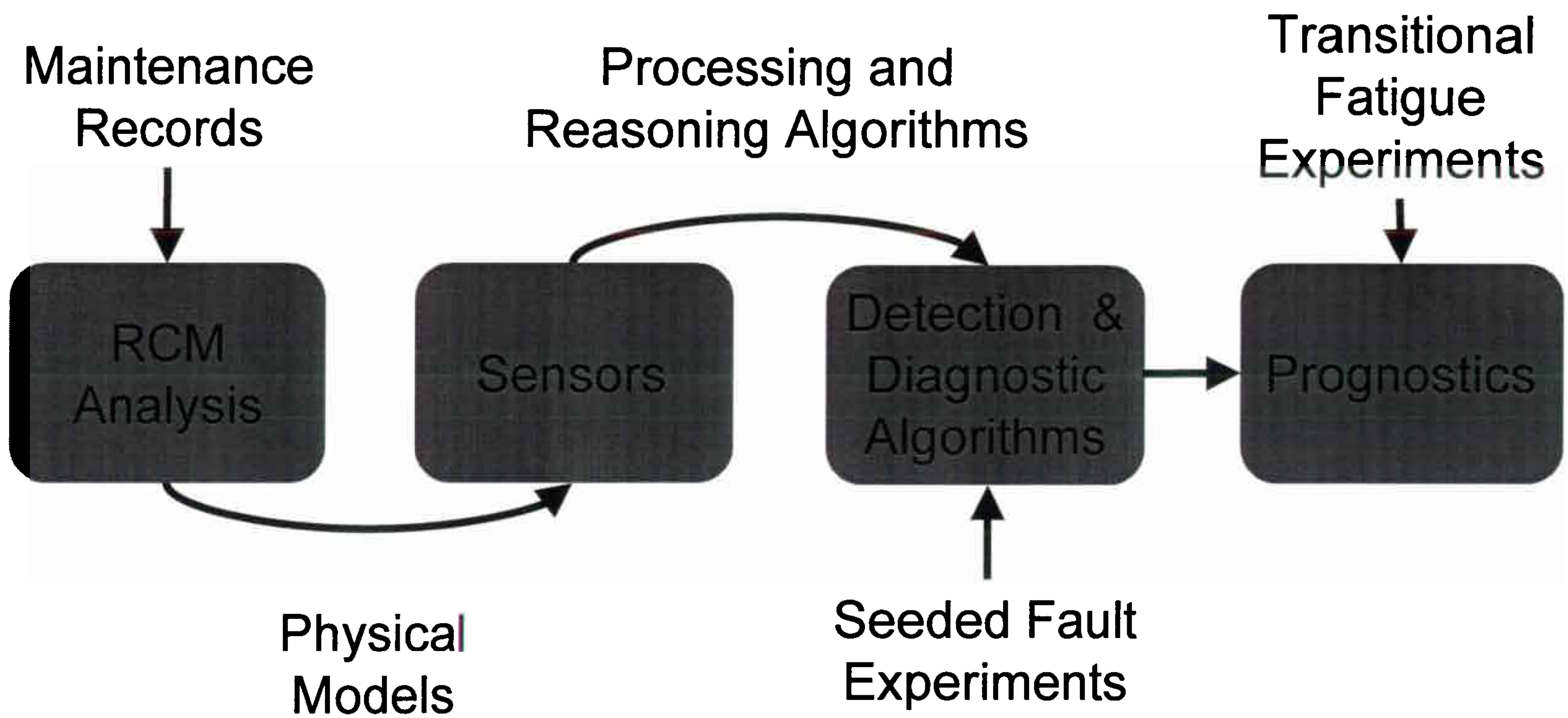
- A formalization of the CBM problem
- A suite of test beds and toolkits to analyze transitional failure data
- CBM system advances
  - Implementation of advanced sensors and new sensing techniques
  - Robust signal processing & feature extraction methods
  - Fusion methods for multisensor CBM data
  - Hierarchical models for mechanical components and subsystems
  - Prognostic models at the observation and state-vector level
  - New architectures and hybrid methods for automated reasoning
- Education of multiple undergraduate and graduate students
- An S&T base of training materials, papers, and data
- Technology transition to multiple programs

Formalization of the CBM Problem

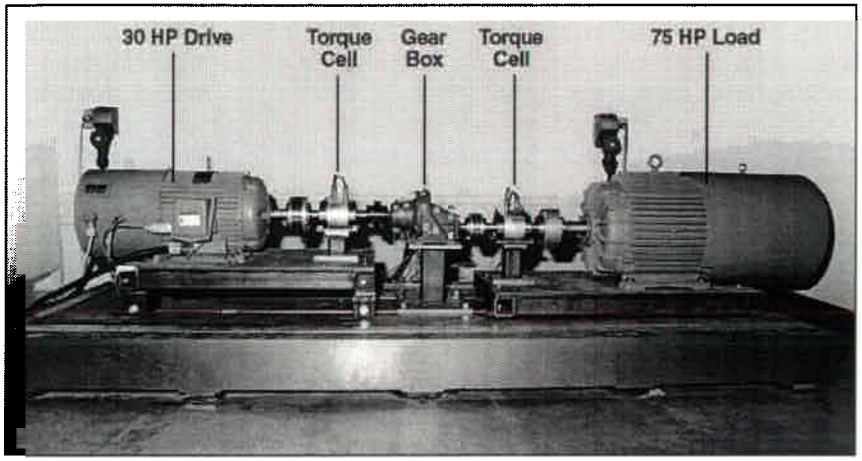


- Documented CBM philosophy and process
- Defined key CBM terminology
- Developed a systems approach for CBM implementation
- Archived data, publications, and links to government, industrial, and academic websites
- Analyzed CBM cost benefits and technology tradeoffs

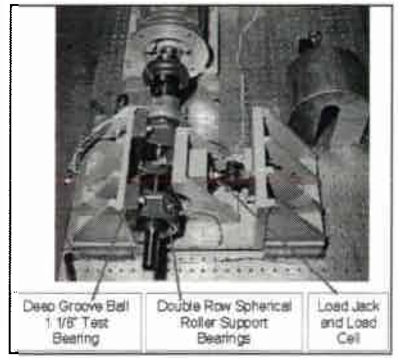
Role of Transitional Data



Test Beds



Mechanical Diagnostic Test Bed (MDTB)

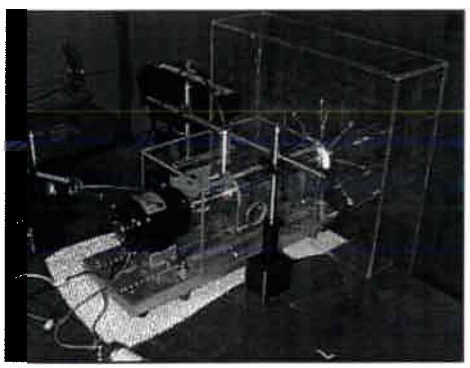


Bearing Test Rig

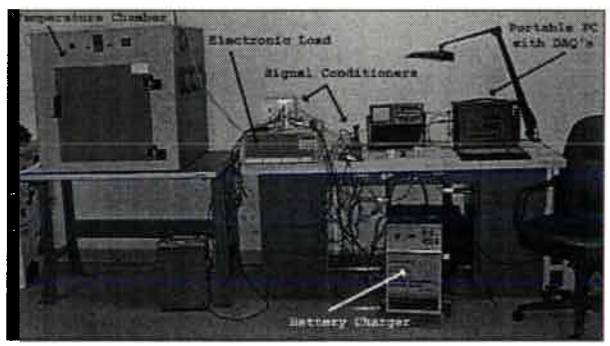
Lubrication Test Bed

New in 2000:

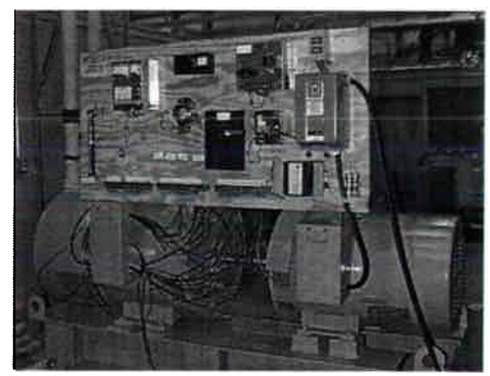
- **Diesel-Enhanced MDTB**
- **High-Speed Gearbox Rig**



Shaft Torsional Test Rig

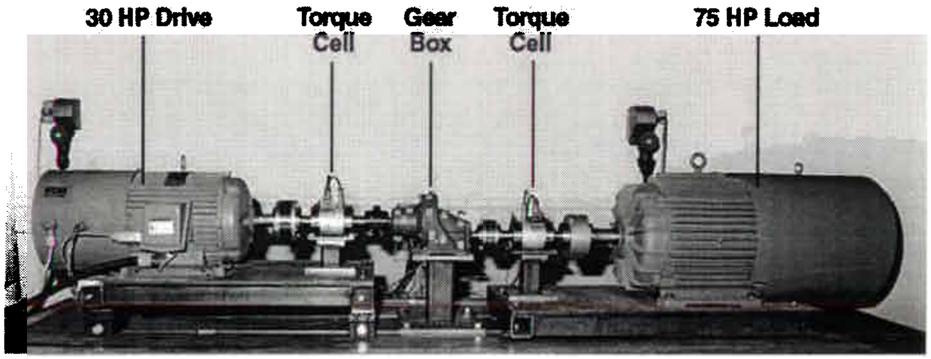


Battery Diagnostics Test Bed



Electric Generator Test Rig

Mechanical Diagnostics Test Bed

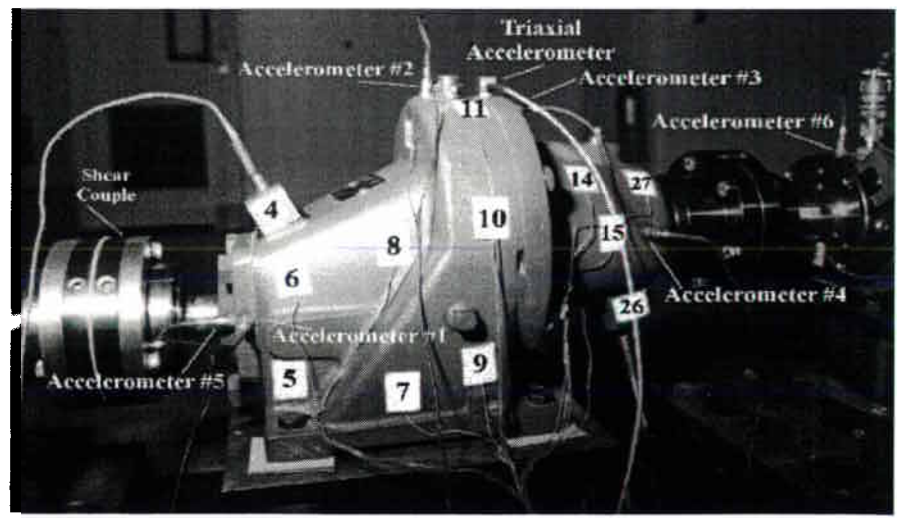


Data Acquisition and Management

- Standard process for data acquisition management, archival and distribution
- Standard approach for CBM data acquisition, calibration, documentation, and storage

Instrumentation

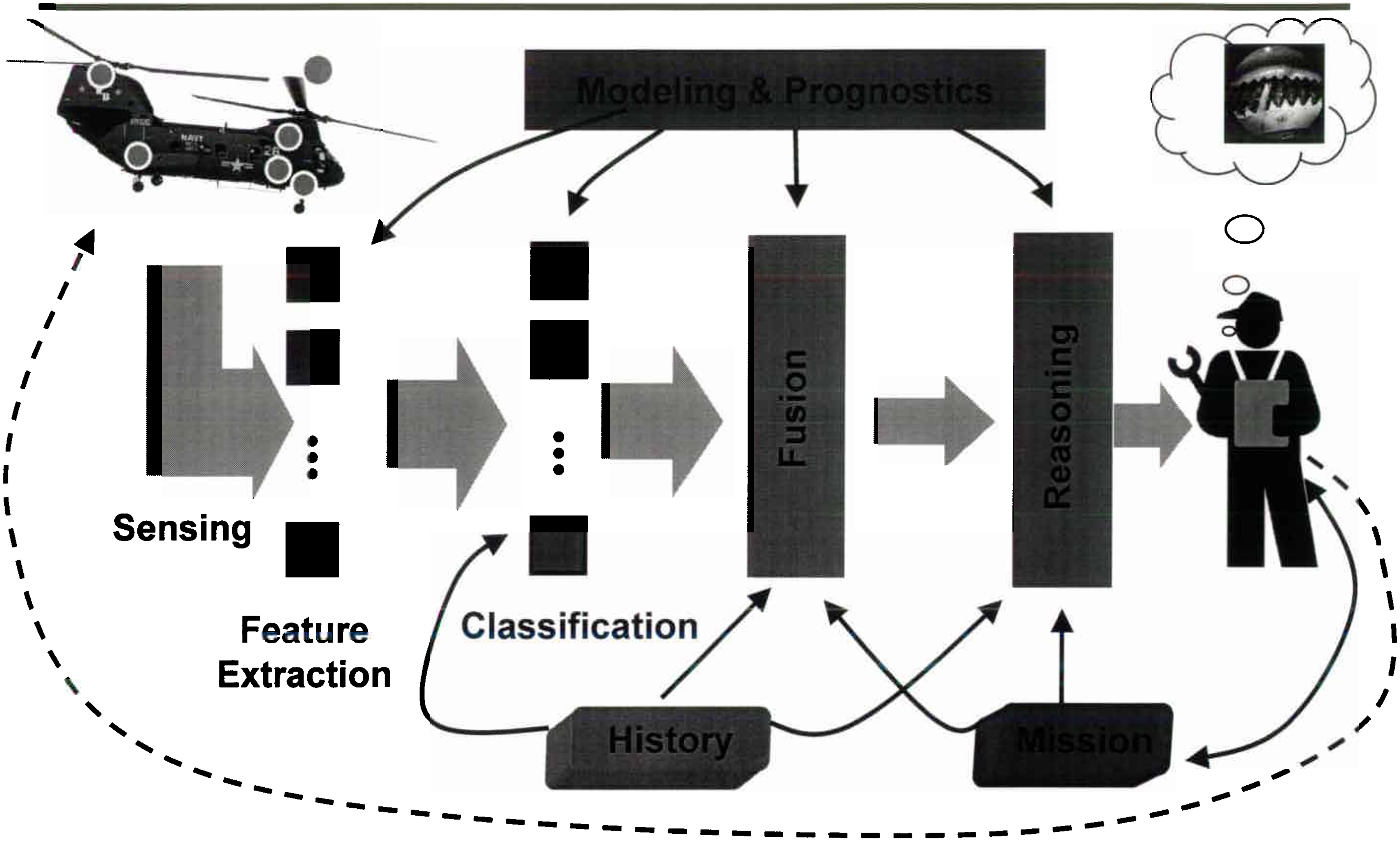
- Vibration (accelerometer, laser vibrometer)
- Acoustic emission events
- Strain gauges
- Multi-point temperatures
- Oil quality and sampling (dielectric and debris)
- Multiple torque & speed
- Motor monitoring
- Shaft encoder



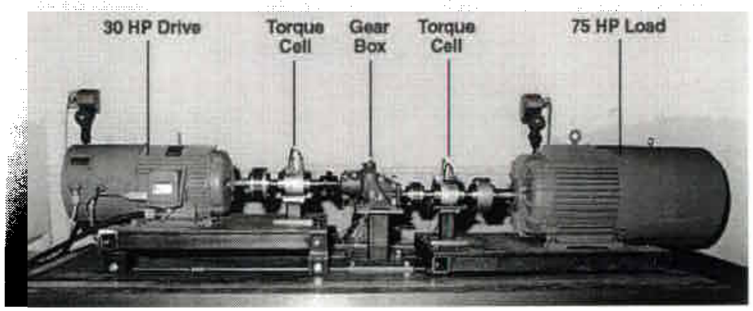
Analysis Facilities and Tools

- FMECA/Pareto Analysis ➡ RCM Analyst, ItemSoft RAMS
- Failure/Evaluation Testing ➡ MDTB, Diesel, Battery and Fluid System
- Data Acquisition/Archival ➡ Labview, CVI, DAMAD
- Vibration Analysis ➡ Torsional, MDTB,Turbine, Bearing
- Oil Analysis and Testing ➡ LASERNET, MDTB, LSTB
- Power Systems Modeling ➡ ANSYS, TELSS, Simulink
- Feature/Decision Fusion ➡ Data Fusion Toolkit
- Diag/Prognostic Algorithms ➡ Matlab, C, C++
- Blackboard and Reasoning ➡ iGEN, Neural Net & Fuzzy Logic Tool
- CBM Cost Benefit Analysis ➡ ItemSoft RAMS, Price

CBM Processing Flow



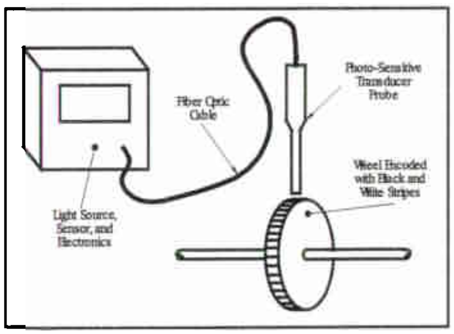
Advanced Sensing



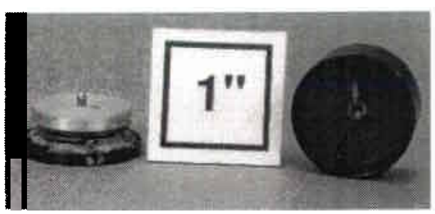
Mechanical Diagnostic Test Bed (MDTB)

Self-calibrating

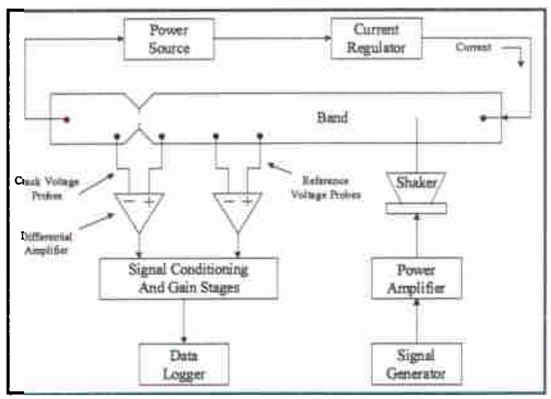
Nanoscale



Torsional



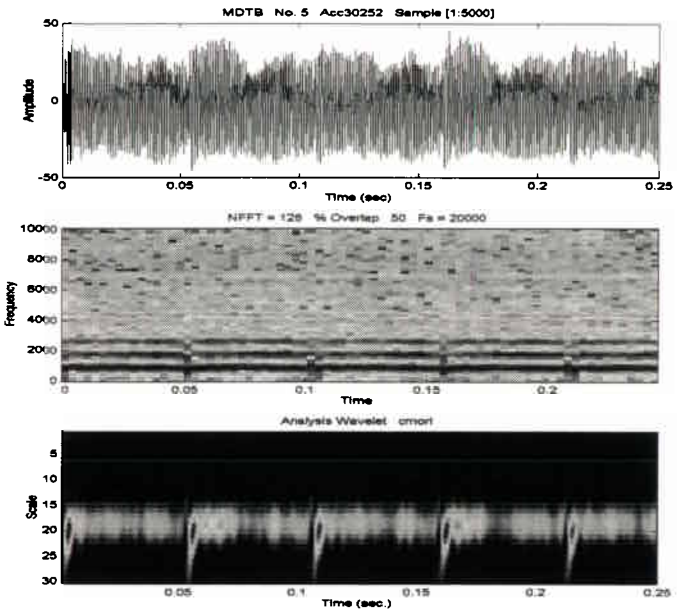
Fiber optic

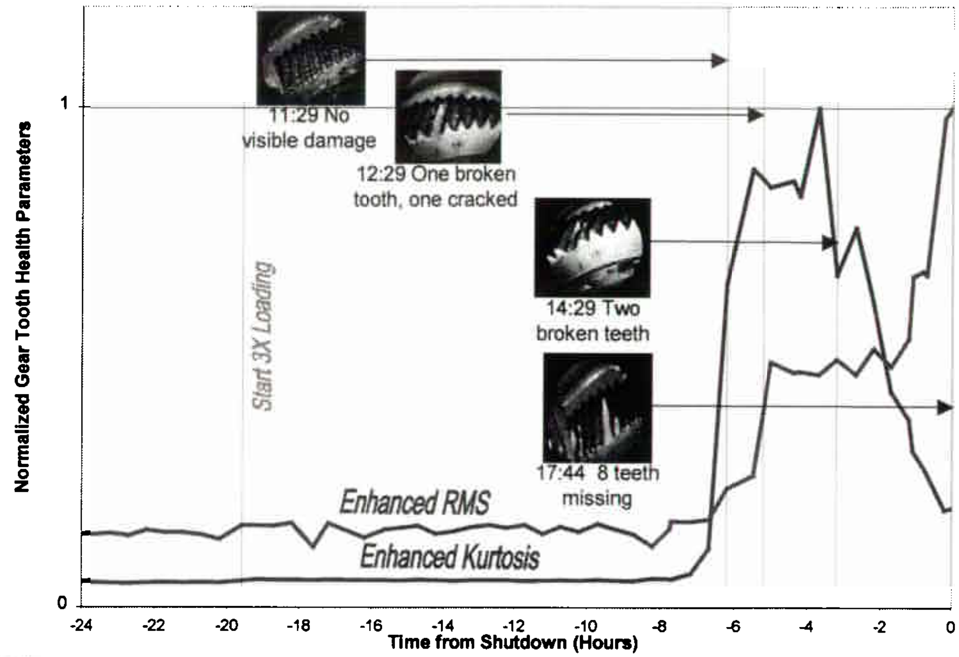


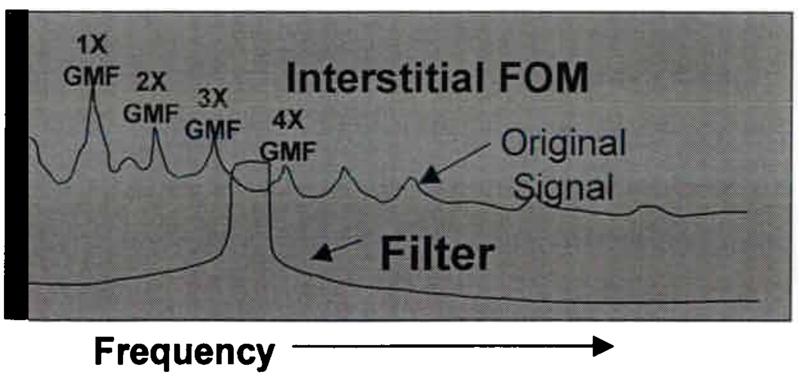
Electric Potential Difference (EPD)

- Investigated wide range of sensing phenomena
- Invented a self-calibrating accelerometer
- Designed and fabricated a nano-scale MEMS sensor
- Used magnetic sensors in novel manner
- Developed new torsional vibration sensing systems
- Calibrated sensors on multiple test rigs
- Established benchmark data sets

Signal Processing and Characterization

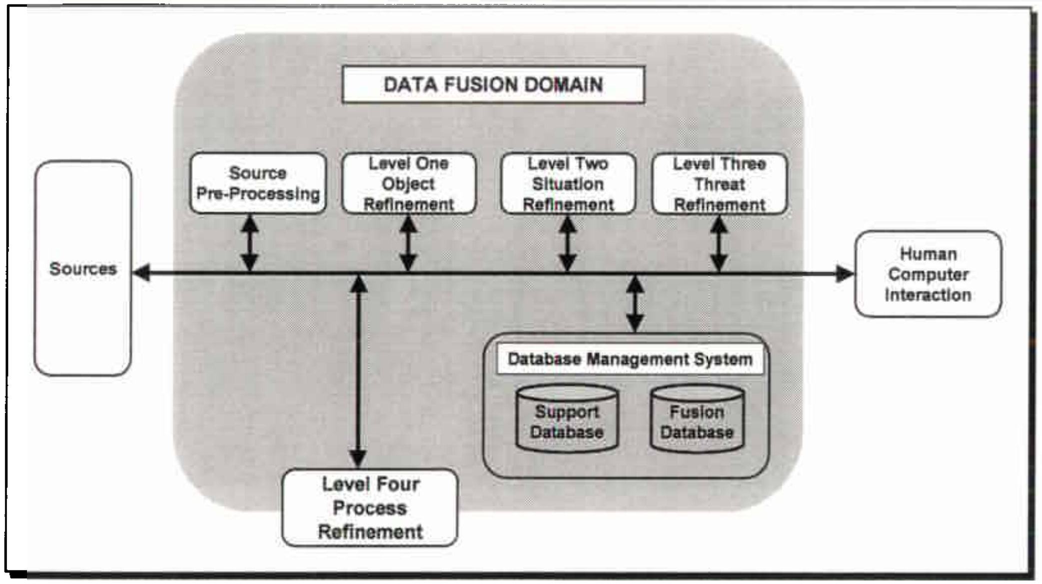


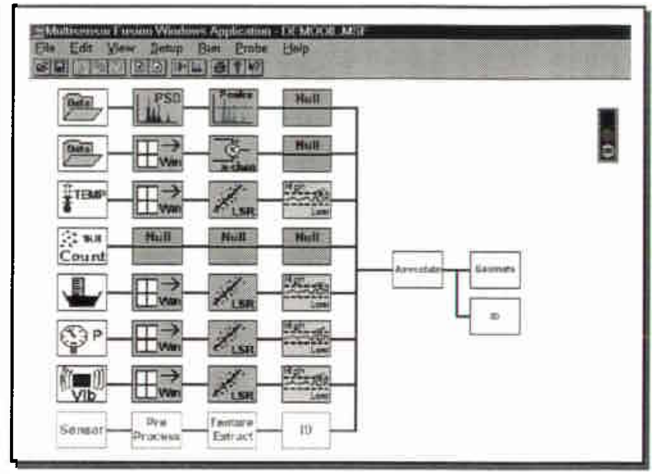




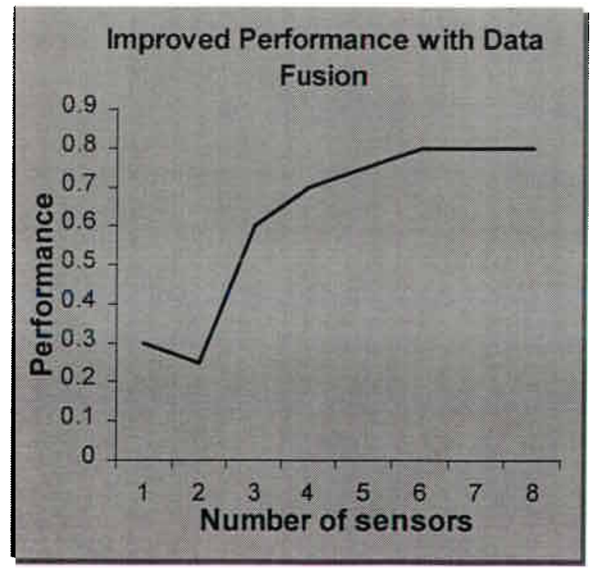
- Developed CBM Features Toolbox
- Implemented time-based, frequency-based, and time-frequency algorithms
- Identified robust features for fault characterization
- Calibrated CBM algorithms

Multisensor Data Fusion

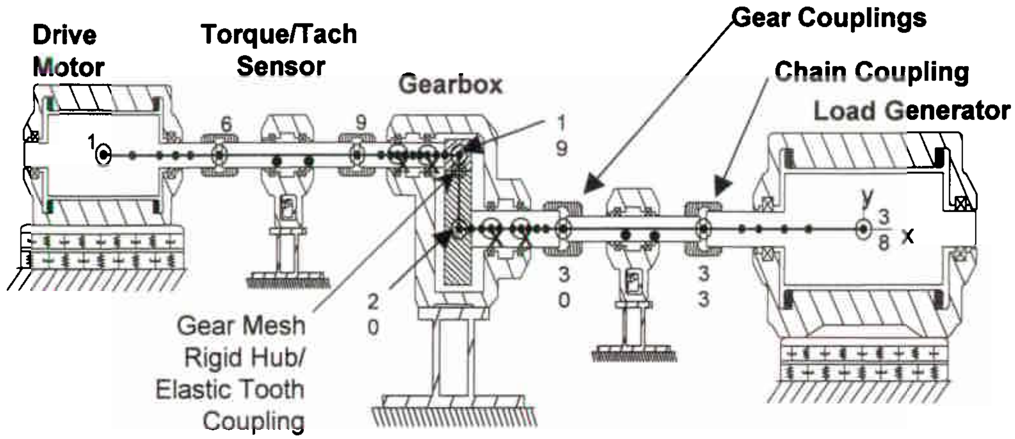




- Leveraged JDL data fusion process model
- Developed Multisensor Fusion Toolkit
- Demonstrated feature- and decision-level algorithms
- Derived critic adjudicated voting
- Quantified the value of data fusion

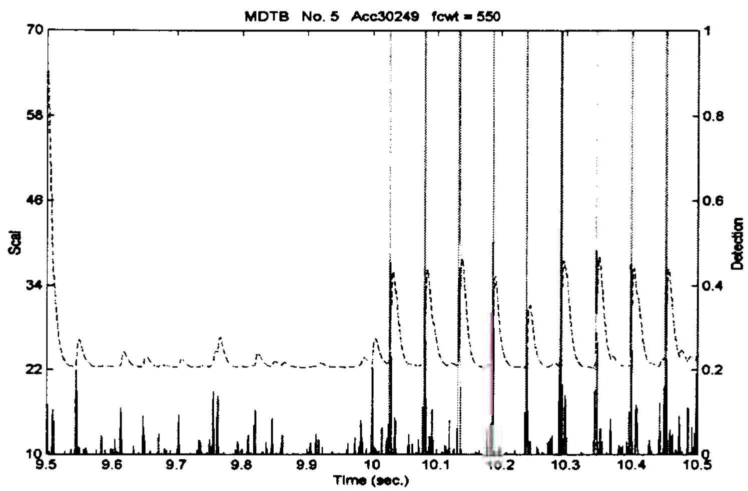


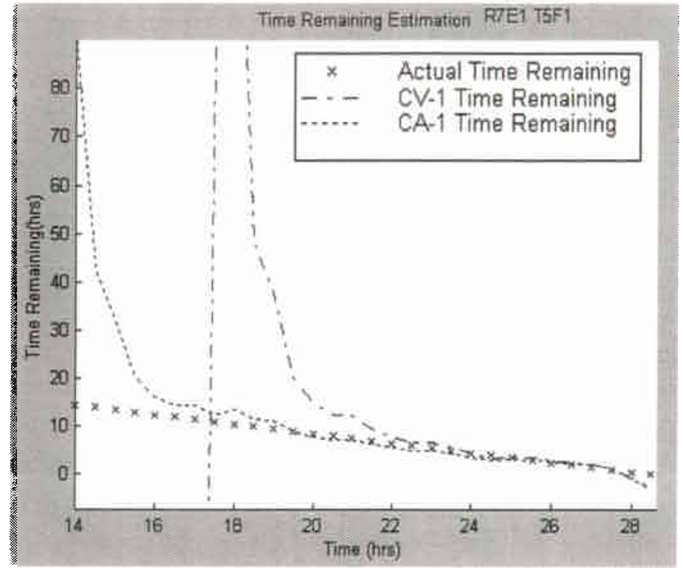
Mechanical System Modeling

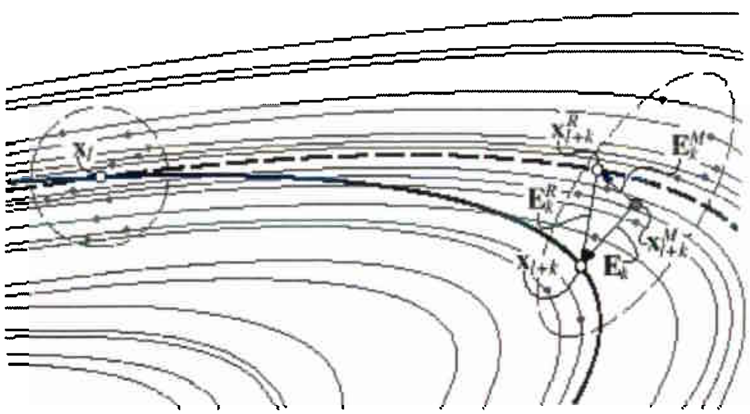


- Developed multi-level models for a wide variety of systems
- Created extensive Finite Element Models for MDTB subsystems and systems
- Developed models for load and environmental effects
- Calibrated models against test bed data
- Developed a model to predict macro-observables due to mechanical flaws

Prognostic Modeling

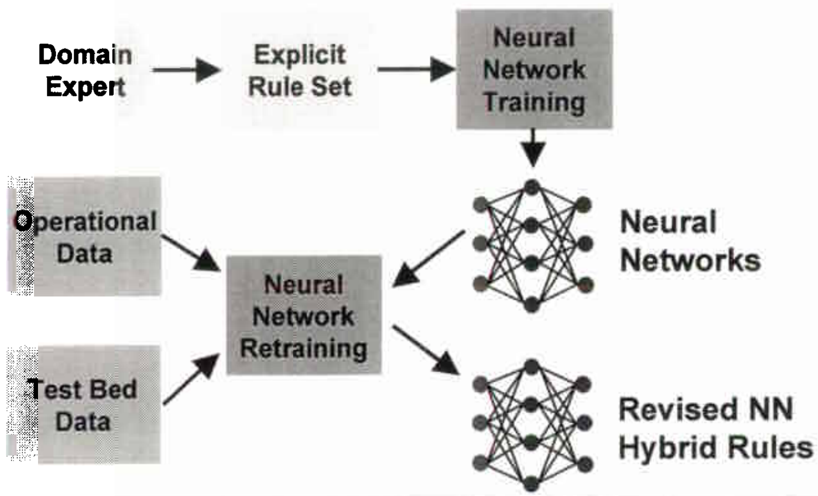


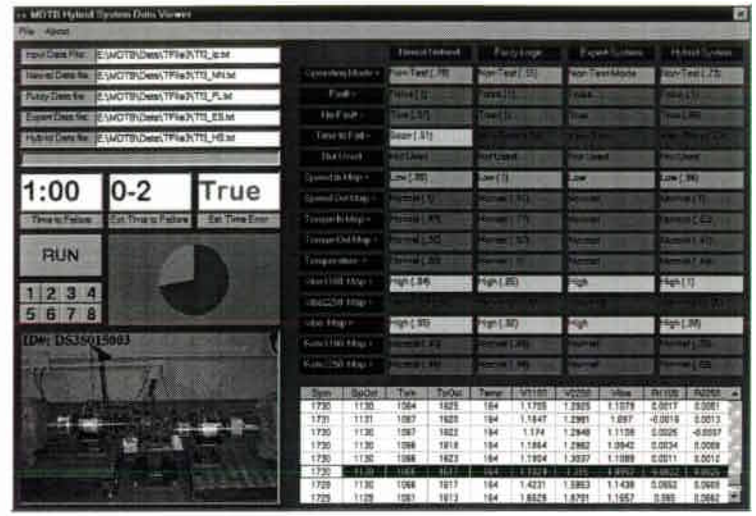




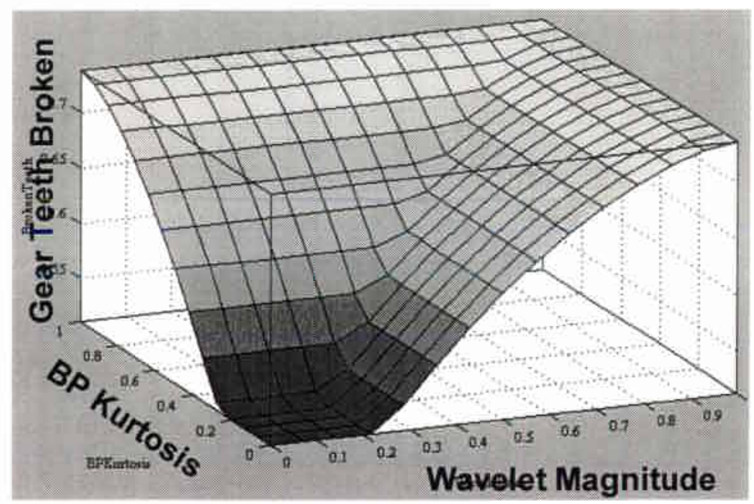
- New mathematical formalism for state-space prognostics
- Formulation of observation space prognostics and tracking
- Comparison and validation against multiple test stand data sets
- Limited materials-level prediction models

Automated Reasoning

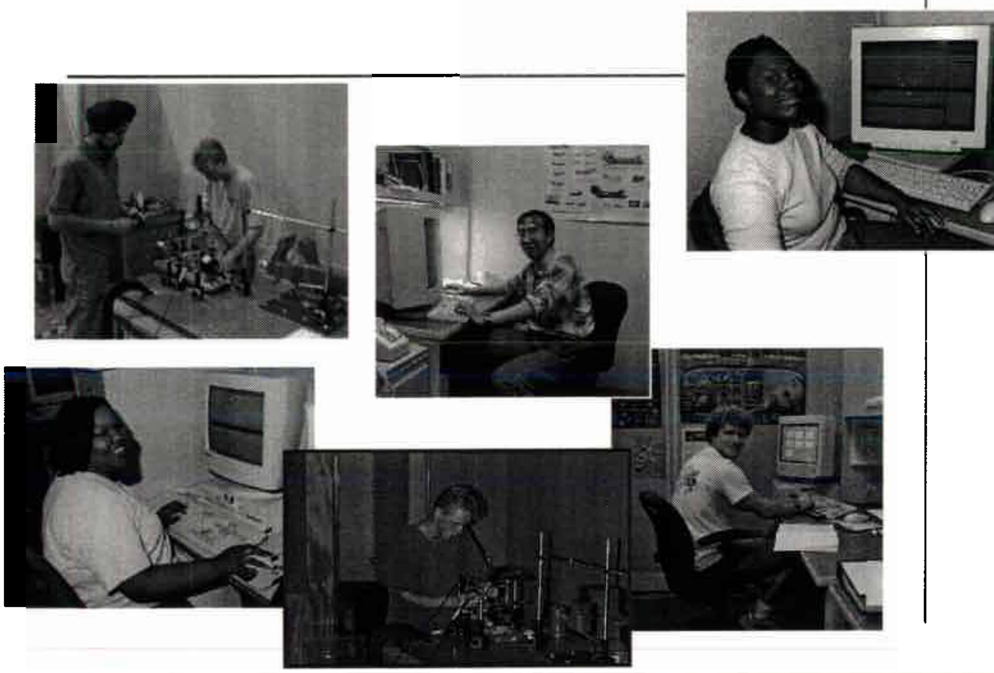




- Performed technology assessment of automated reasoning
- Developed new architecture for automated reasoning
- Compared performance of alternative reasoning techniques
- Developed new techniques for hybrid reasoning

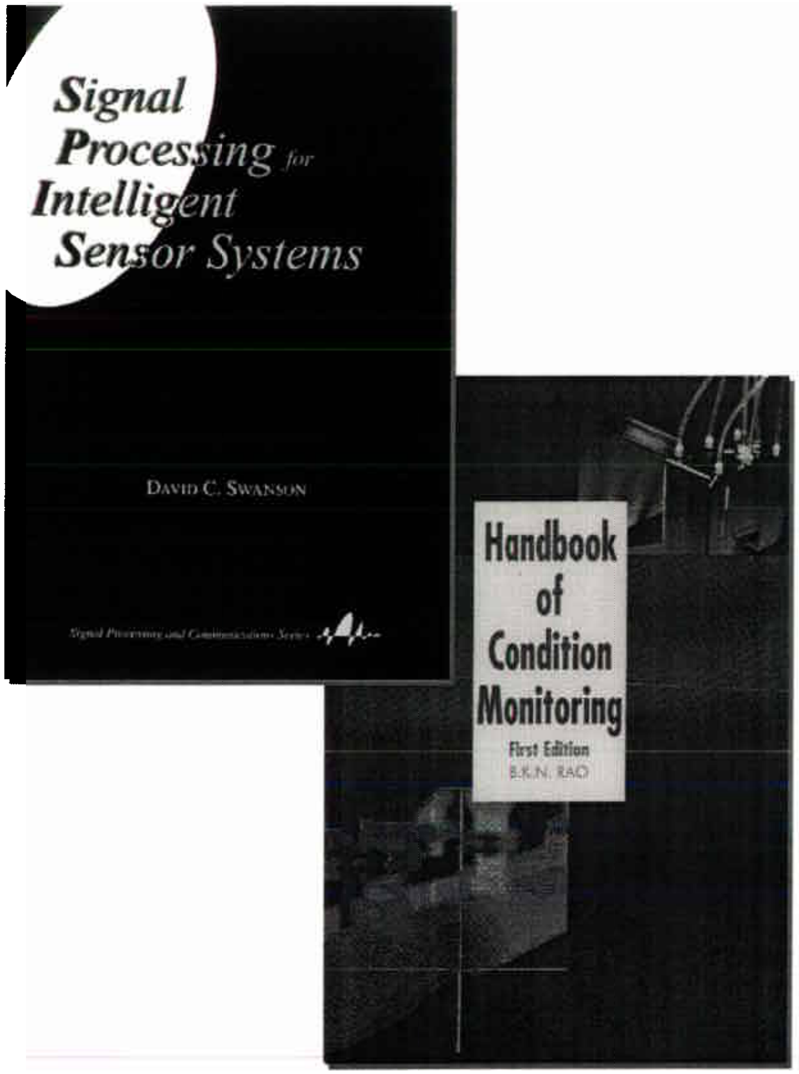


Educational Activities



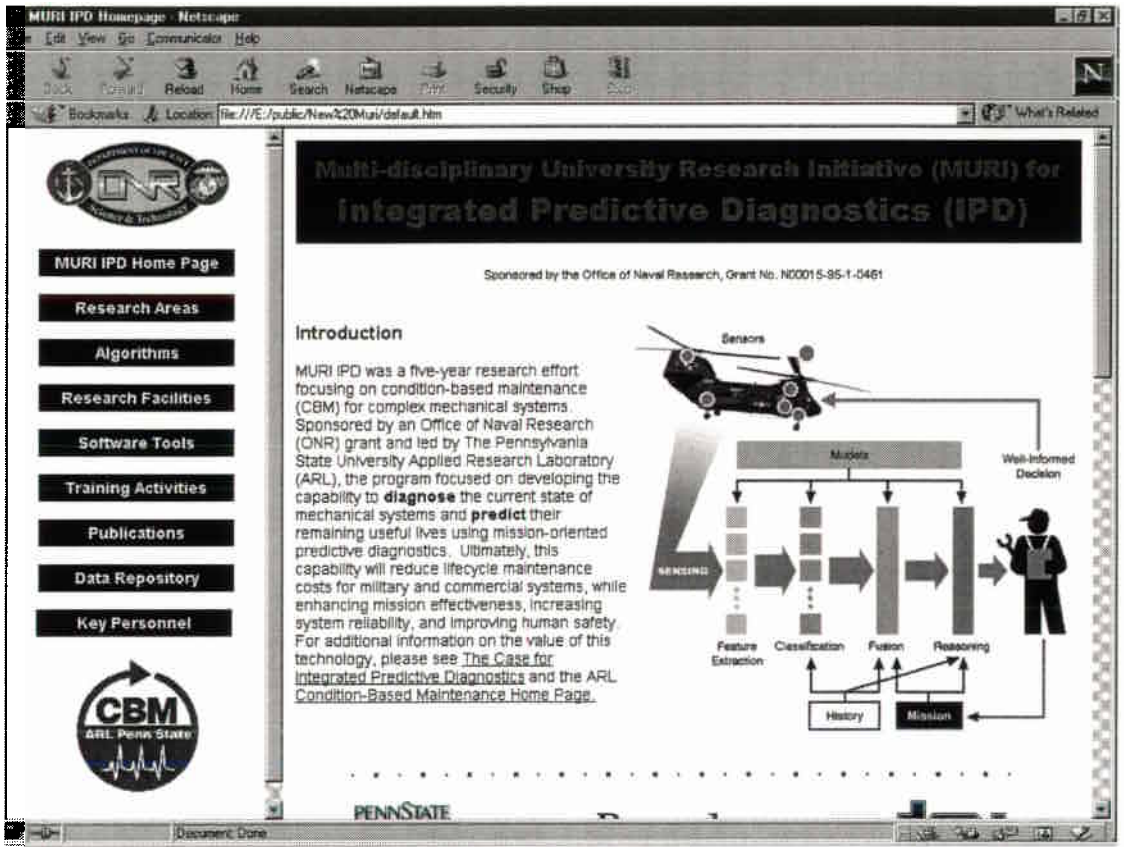
- Multi-university partnership
- Undergraduate, graduate and post-doctoral support (100+ students)
- Workshops, seminars, multi-day tutorials
- Online information and data
- Papers (including 14 theses)

Publications and Presentations



- Books (3)
- Book chapters (3)
- Refereed publications (20+)
- Conference publications (80+)
- Conference presentations (50+)
- Tutorials and workshops (8)

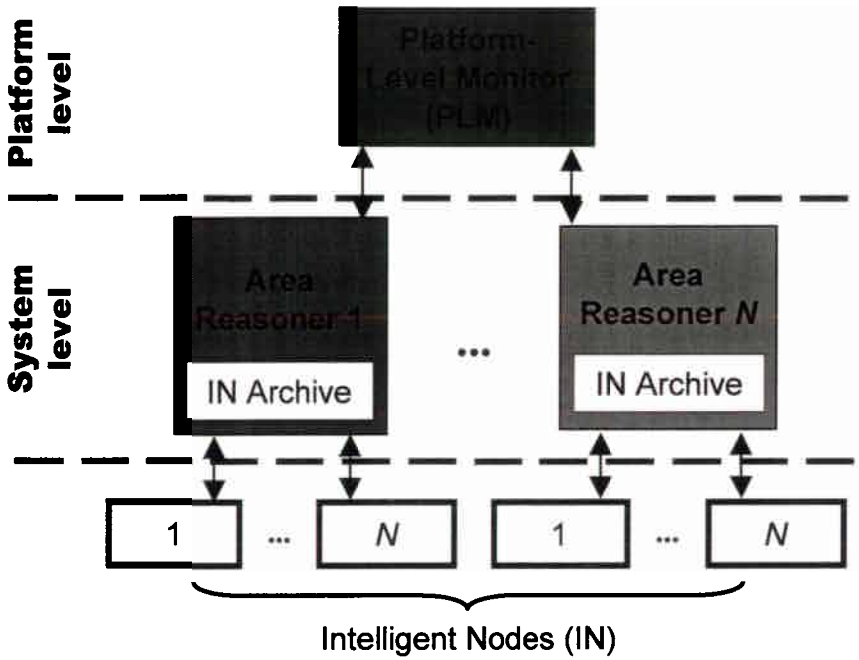
Online MURI Resources

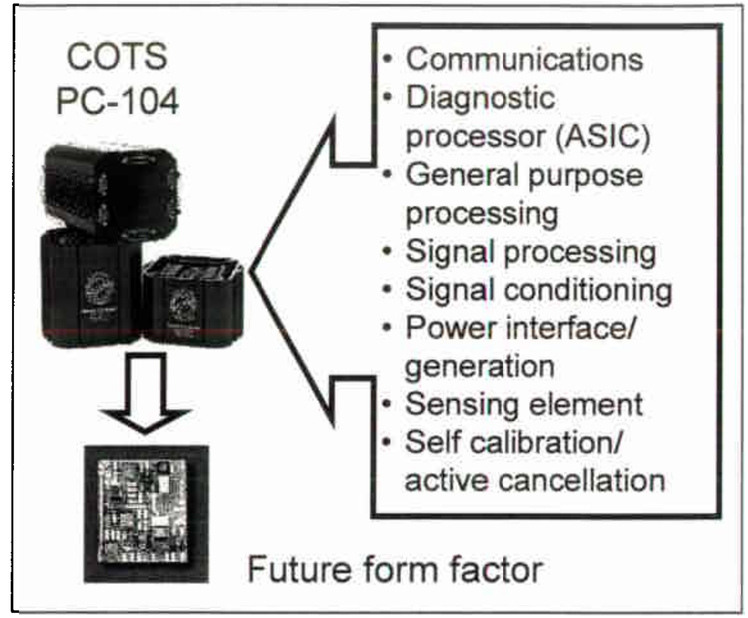


http://www.cbm.arl.psu.edu/IPD/Welcome.html

- Progress in research areas (sensing, modeling, reasoning)
- Information on algorithms
- Summary of testing facilities and software tools
- Publications and other resources
- Key personnel
- Data samples and forms to request MDTB and Westland Helicopter data

Evolving CBM Architecture





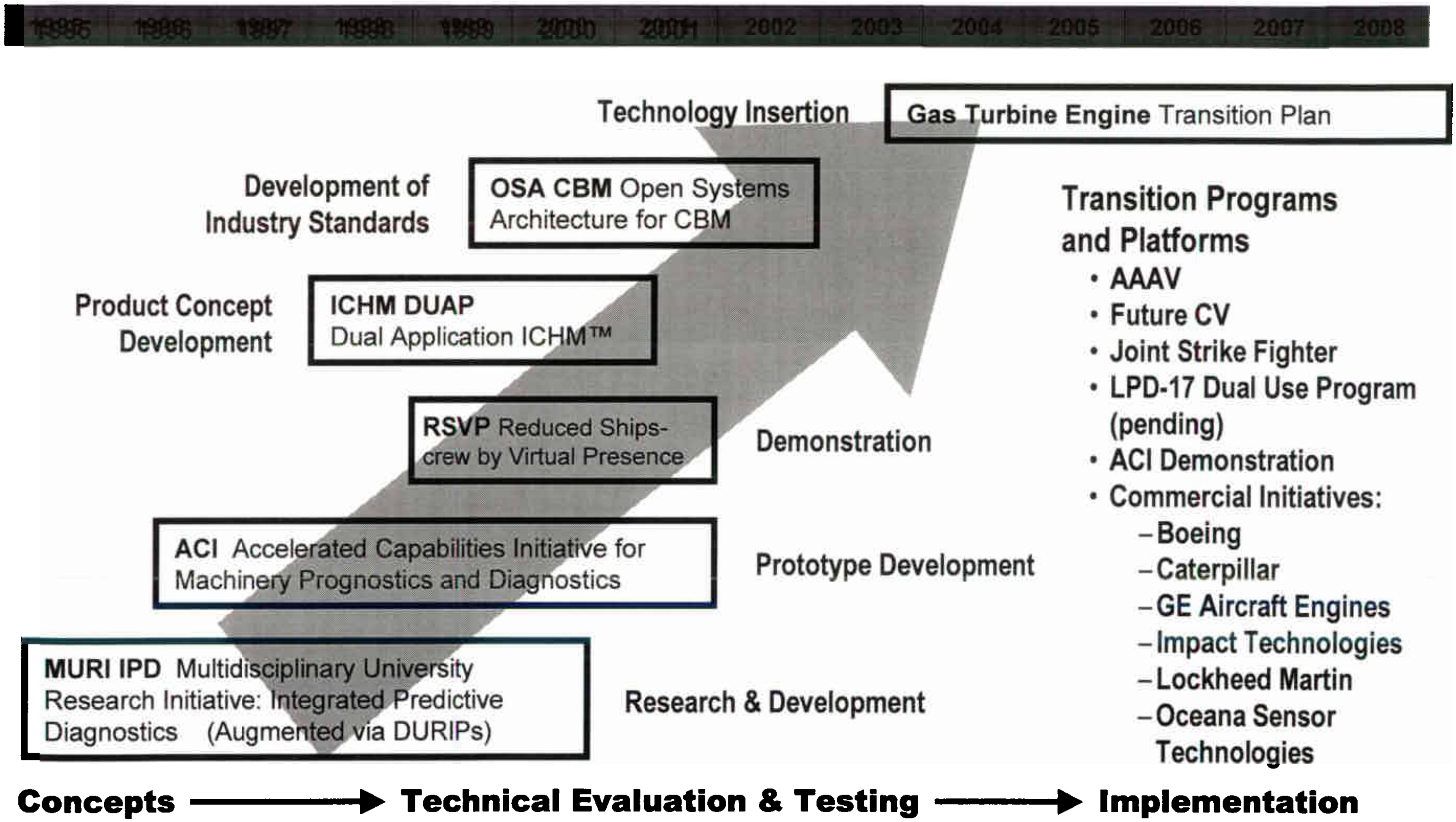
MURI Contributions

- DSP/data fusion algorithms
- Test beds for architecture evaluation
- New sensor concepts
- Automated reasoning for system and platform levels
- Prognostic modeling concepts for all levels

Evolution to an Open System Architecture (OSA)

- Generalized formalism led to ACI three-level architecture
- Fusion and reasoning models define functionality in OSA CBM
- Smart, self-calibrating sensors provide foundation for net-centric CBM/PHM

Program Inter-relationships and Transition Paths



Continuing Challenges

- Sensing Challenges
  - Well-calibrated transitional data for CBM
  - Autonomous intelligent multisensor systems
  - Self-powered, self-calibrating sensors with wireless communications
- Modeling Challenges
  - Physics-based models for failure phenomena and progression
  - Accurate prediction of macro-scale observables from micro-scale phenomena
  - General theory of uncertainty and failure prediction
  - Automated feature extraction/selection for processing sensor data
  - Integration of non-commensurate sensor data
- Prognostics
  - Scaling laboratory-based models to fielded systems and platforms
  - Continued evolution of prognostic theory and applications

(continued)

Continuing Challenges (cont'd)

- Automated Reasoning Challenges
  - Cognitive-based automated reasoning methods to mimic capability of expert mechanics
  - Hierarchical hybrid methods incorporating physics-based models
  - Integration of explicit and implicit knowledge and negative information
  - MOPs and MOEs for data fusion and reasoning
- System Control and Resource Utilization Challenges
  - Tasking and optimal use of 10^N sensors
  - Adaptive context-based sensing
  - Feedback and control of load conditions to extend life span
- Evolution of CBM to asset readiness for intelligent mission planning
  - Spanning the dimension from physics of failure to system capability and platform readiness
  - Translating mission profile demands to system loads and failure prognostics

Summary of Achievements

- Developed a formalization of CBM technology and engineering
- Established test beds, tools, and processes for CBM
- Created new methods for observing, detecting, and characterizing mechanical failures
- Developed new architectures and methods for automated reasoning
- Developed new mathematical formulations and models for failure prediction
- Demonstrated viability of hierarchical machinery prognostics
- Established enabling technology for CBM transition and implementation using an open system architecture
- S&T base of data, models, tools and training material available to CBM community