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Title: Integrated Solutions to SHM Problems: An Overview of SHM Research at the LANL/UCSD Engineering Institute

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Integrated Solutions to SHM Problems: An Overview of SHM Research at the LANL/UCSD Engineering Institute.

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Abstract

- This seminar will provide an overview of structural health monitoring (SHM) research that is being undertaken at Los Alamos National Laboratory (LANL). The seminar will begin by stating that SHM should be viewed as an important component of the more comprehensive intelligent life-cycle engineering process. Then LANL's statistical pattern recognition paradigm for addressing SHM problems will be introduced and current research that is focused on each part of the paradigm will be discussed. In this paradigm, the process can be broken down into four parts: (1) Operational Evaluation, (2) Data Acquisition and Cleansing, (3) Feature Extraction, and (4) Statistical Model Development for Feature Discrimination. When one attempts to apply this paradigm to data from real world structures, it quickly becomes apparent that the ability to cleanse, compress, normalize and fuse data to account for operational and environmental variability is a key implementation issue when addressing Parts 2-4 of this paradigm. This discussion will be followed by the introduction a new project entitled "Intelligent Wind Turbines" which is the focus of much of our current SHM research. This summary will be followed by a discussion of issues that must be addressed if this technology is to make the transition from research to practice and new research directions that are emerging for SHM.

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A Vision for Engineering Research: Cognitive, Adaptive, Infrastructure Systems

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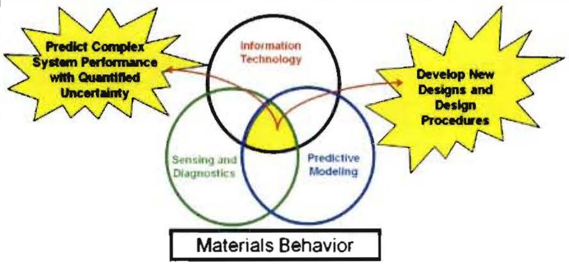

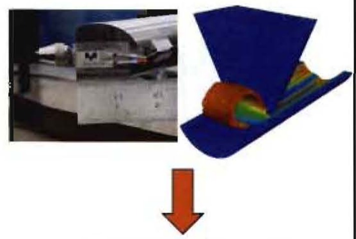

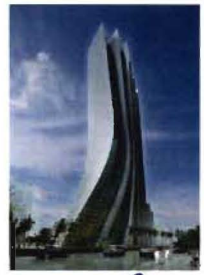

- Design system functionality in at the material and manufacturing level
- Monitor and assess in-service system condition (SHM)
- Intelligent System Retirement (SHM/DP)

Note: this vision is about a process, it is not specific to aerospace, civil or mechanical systems

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Cognitive, Adaptive, Infrastructure is achieved by building life systems functionality in engineered systems

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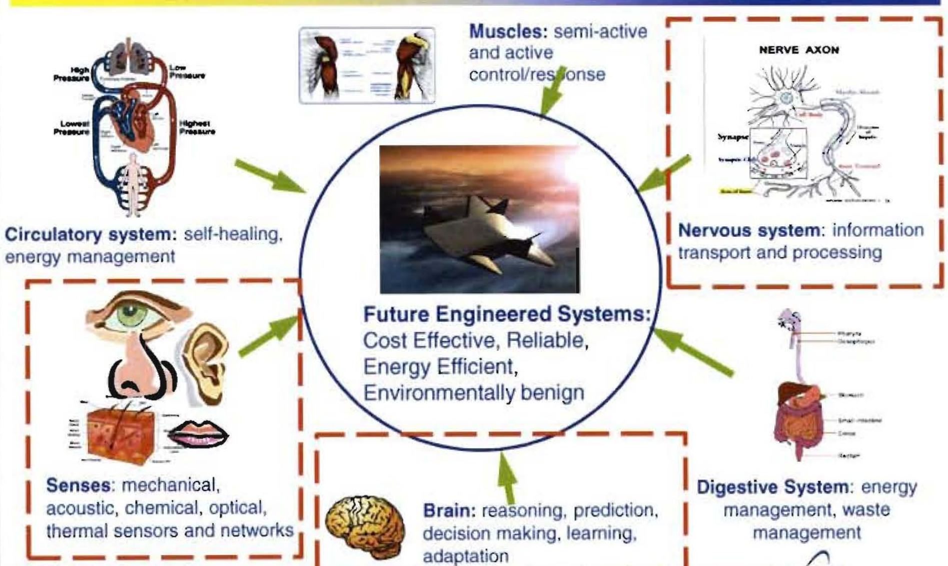

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Definition of "Damage"

- **Damage** is defined as changes to the material and/or geometric properties of a structural that adversely affect its performance.
- All materials used in engineering systems have some inherent **initial flaws**.
- Under environmental and operational loading flaws will grow and coalesce to produce **component level failure**.
- Further loading causes **system-level failure.**
- **The time and length scales of damage evolution (ageing vs. extreme event) are diverse!**

Inclusions at grain boundary

Welded Connection

Department Store Collapse

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How Engineers and Scientists "Study" Damage

- **What causes damage?**
  - Material science (initial imperfection, manufacturing and assembly, material aging and degradation processes)
  - Engineering analyses (exceeding allowable strength, deformation or stability criteria)
- **What can be done to prevent damage?**
  - Material science (new materials and/or manufacturing processes)
  - Engineering design strategies (design for reliability and manufacturability)
  - Define operational and environmental limitations
- **Is damage present? (NDE, structural health monitoring)**
- **How fast will damage grow and reach a critical level?**
  - **Structural health monitoring**
  - Damage prognosis
- **How do we mitigate the effects of damage?**
  - Change operational parameters (e.g. speed of operation)
  - Maintenance and repair
  - Self-healing structures ("smart materials")

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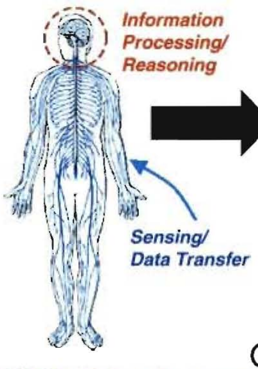
Structural Health Monitoring and Damage Prognosis

Structural Health Monitoring (SHM) is the process of developing a damage assessment capability for aerospace, civil, and mechanical infrastructure.
Damage Prognosis (DP) is the process of combining SHM assessments with predictive loading and damage evolution models to make decisions regarding the operation or maintenance maintenance of the infrastructure.




Pipelines


Buildings


Power


Offshore Platforms


Dams & Levees


Bridges

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SHM is a Problem in Pattern Recognition

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A Statistical Pattern Recognition Paradigm for SHM/DP

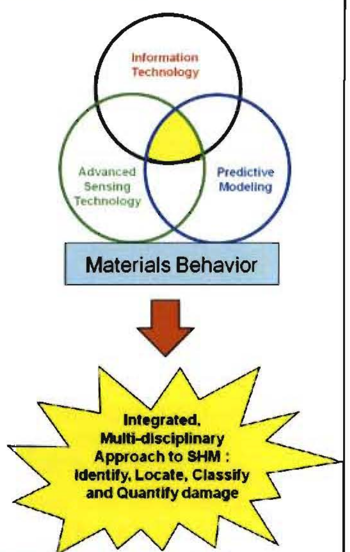
Operational Evaluation
Defining the damage to be detected and the monitoring length and time scales needed, and addresses implementation issues for the specific application (environmental/operational constraints, economics, regulatory influences, etc.).

Data Acquisition and Networking
Defining the sensing/actuation hardware and the data required for the feature extraction process.

Feature Selection and Extraction
Identifying and computing damage-related information from measured data and discarding irrelevant information.

Probabilistic Decision Making
Using statistical modeling of detection properties to transform features into actual performance-level decisions.

Prognosis
Combining assessments based on feature classification with probabilistic future loading models and damage evolution models to predict performance-level variables (remaining life, time to service, etc.)



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Operational Evaluation: Wind Turbine Example

- **Motivation for structural health monitoring is purely economic.**
  - For an initial investment of about \$1 -1.5 million/megawatt, then annual O&M costs using a 2% figure for 5 mw turbine are \$100-150K/year.
  - 20 yr overhaul might cost 15-20% of the initial investment (in this example, \$750 - 1500K).
  - **Defines allowable cost and service life of the SHM system.**
- **Damage to be detected:**
  - Delamination of composite turbine blades
    - **Need to define minimum area of delam that must be detected, expectable delam growth rates and critical delam area.**
  - Damage to gear box
    - Turns at 1000 rpm compared to 10 rpm of rotor
    - 4 yr life compared to 20 year life of rotor
- **Environmental and operation constraints on the SHM System: rotating device, wind, rain, lightning, temperature, electromagnetic fields, offshore**

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Challenges for Operational Evaluation

- **Many high-capital–expenditure structures are "one-of-a-kind" systems.**
  - Dictated by physical environment where they are built
  - More difficult to incorporate lessons learned from other nominally "similar" systems to define anticipated damage
- **Many structural designs are driven by low-probability, but extreme-impact events**
  - Earthquake, Hurricanes
  - Terrorist actions
  - Loss-of-coolant accidents
- **However, structural systems also degrade slowly under normal use**
  - Corrosion and fatigue cracking, Freeze-thaw/thermal damage, Loss of pre-stressing forces, Vibration-induced connectivity degradation, Hydrogen enbrittlement and nuclear irradiation (NPP)
- **There is no widely excepted procedure to demonstrate rate of return on investment in an SHM/DP system**

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Considerations for SHM Data Acquisition System

- **THERE IS NO SENSOR THAT MEASURES DAMAGE!**
  (and there never will be!!)
- **However, can't do SHM without sensing**
- Define data to be acquired and the data to be used in the feature extraction process.
  - Types of data to be acquired
  - Sensor types, number and locations
  - Bandwidth, sensitivity (dynamic range)
  - Data acquisition/transmittal/storage system
  - Power requirements (**energy delivery**)
  - Sampling intervals
  - Processor/memory requirements
  - Excitation source (**active sensing**)
  - **Sensor diagnostic capability**

- **<u>CAN NOT</u> develop the sensing/processing system independent of the feature selection and statistical model development portions of the process.**

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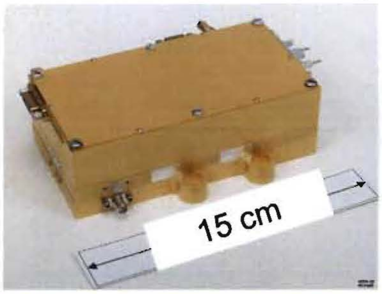
High Explosives Radio Telemetry System

- Develop a system for measuring, transmitting, and receiving data that verifies the flight and terminal-event performance of warheads in delivery environments
- This system consists of fiber optic pressure sensors, conventional strain and acceleration sensors, and the High Explosive Radio Telemetry (HERT) system
- 32 fiber optic sensors, 10 ns sampling resolution, 100 Mb/s transmission rate, sensor diagnostic capability, 0.6 kg



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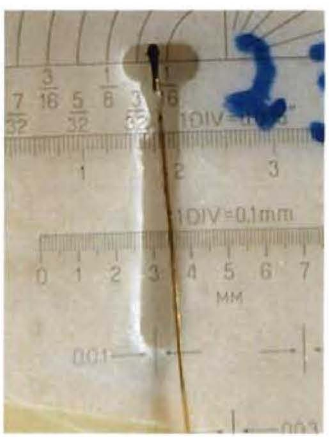
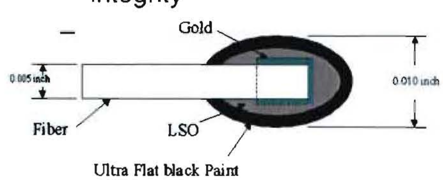
Fiber Optic Shock Sensors with Self-Check



Fiber Sensor

- Fiber Optic Shock Sensor
  - Placed in small machined groove in HE surface
  - Generates light upon arrival of shock wave, blinded from high explosive light
  - Prior to shock arrival all sensors are self-checked for integrity
  -



LSO: Cerium-Doped Lutetium Oxyorthosilicate

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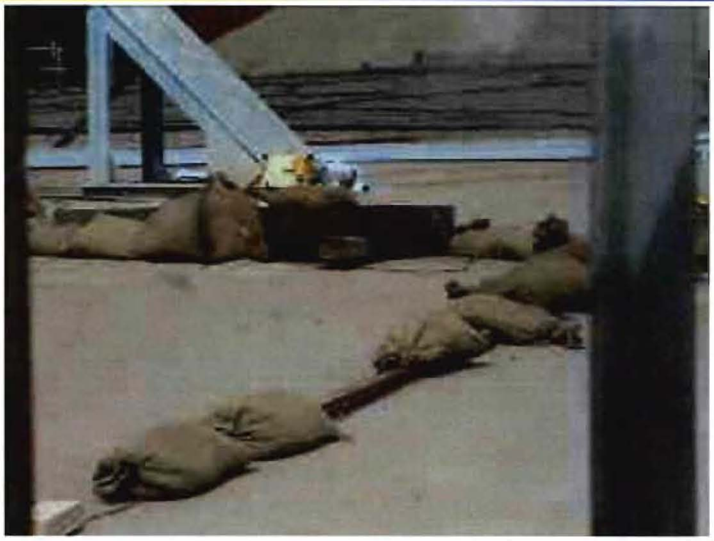
Ground HERT Explosive Test



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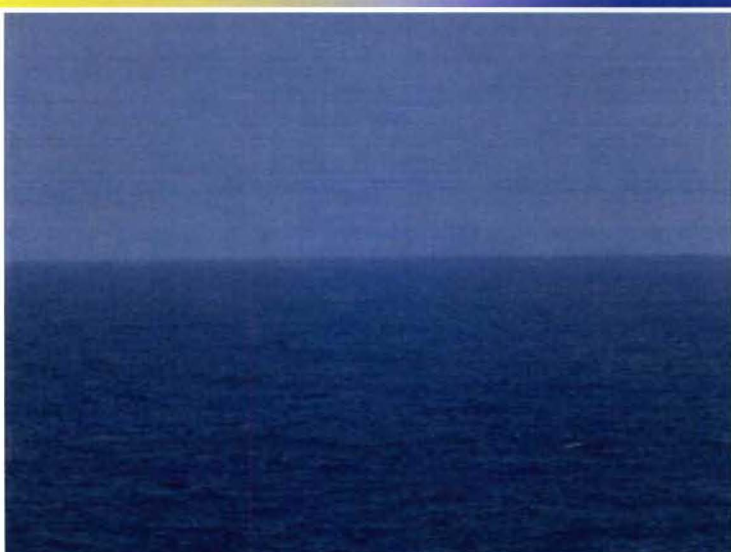
Sensor System Loading Environments



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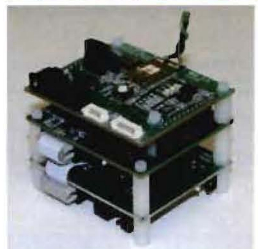
Wireless Telemetry and Power Delivery



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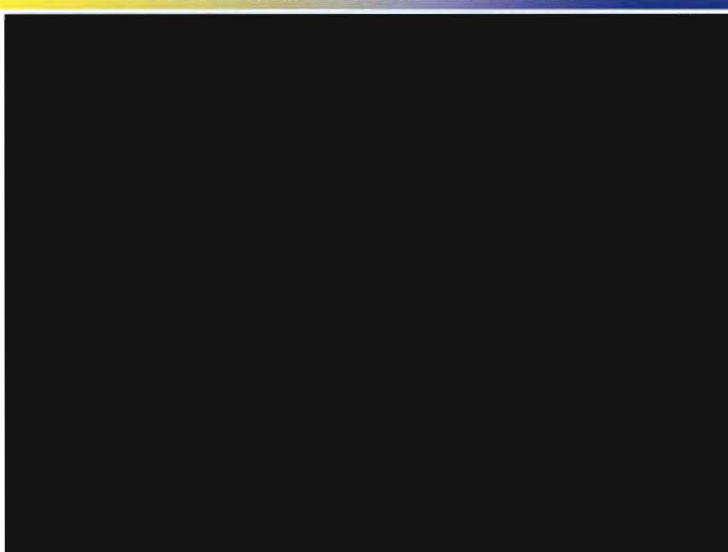
Field Test of Remote Power Delivery

(D. Mascarenas Ph.D. dissertation, UCSD)



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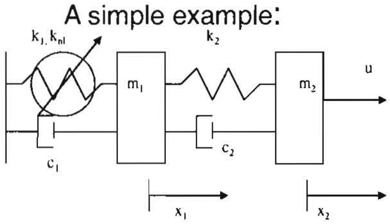
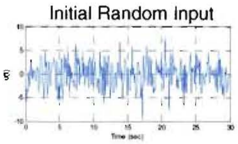
Excitation design optimization for active sensing

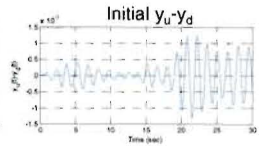
(M. Bement, LANL, C. Olson Ph.D. dissertation, UCSD)

What excitation (input) should we provide to best observe damage?

A simple example:





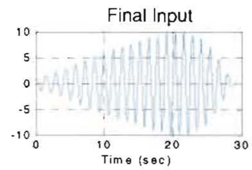


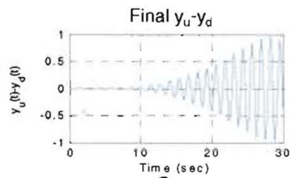
After 100 Iterations
1000 fold increase in y_u-y_d

- What types of input will make output the most different, when compared to the response of the undamaged system?

The solution: Solve an adjoint problem (basically some tricks with integration by parts)

$$\max J = \frac{1}{2}\int_0^T (y_u - y_d)^2 dt$$





Challenges for SHM Sensing Systems

- **Number of sensors**
  - Instrumenting large structures with thousands of sensors still represents a sparsely instrumented system!
  - Large sensor systems pose many challenges for reliability and data management
- **Ruggedness of sensors**
  - Sensing systems must last for many years with minimal maintenance
  - Harsh environments (thermal, mechanical, moisture, radiation, corrosion)
  - Need sensor diagnostic capability
- **The sensing system must be developed integrally with the feature selection/extraction and classification.**
- **There is no accepted sensor design methodology**
  - **Optimal Sensor placement (need models)**
  - **Optimal waveform design for active sensing (need models)**

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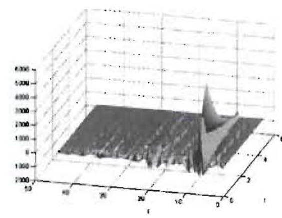
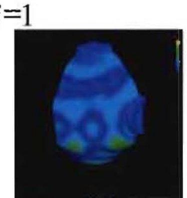
Damage-Sensitive Features

- **What do we mean by a Feature?**
  - A feature is some characteristic of the measured response that is correlated to damage
    - Waveform or image comparison
    - Model parameters
    - Residual errors
- **Primary Characteristics of Features**
  - **Sensitivity** - sensitive to damage and completely insensitive to everything else (rarely occurs)
  - **Dimensionality** - Want the lowest dimension possible (influences statistical modeling)
  - **Computational Requirements** - minimal assumptions and CPU cycles (embedded systems)
  - **Consistency** - feature's magnitude should change monotonically with damage level
- **Want to use the simplest feature possible that can distinguish between the damaged and undamaged system**



$$x_i = \sum_{j=1}^{n} a_j x_{i-j} + \varepsilon_i$$



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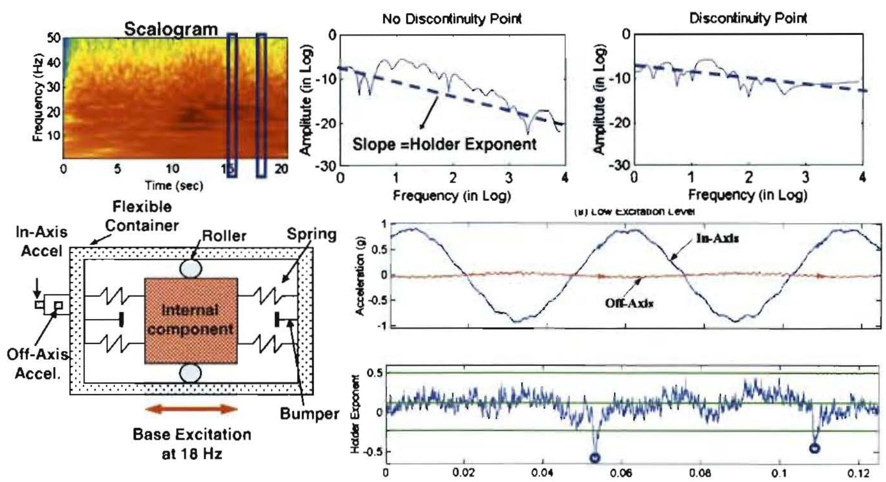
Feature Extraction Example: The Holder Exponent

A. Robertson



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Challenges for Feature Selection and Extraction

- **Developing an analytical approach to feature selection.**
  - Feature selection is still based almost exclusively on engineering judgment
- **Quantifying the features sensitivity to damage**
- **Quantifying how the feature's change with damage level.**
- **Understanding how the feature will change with changing environmental and operational conditions**
  - **One of the biggest barriers to *in situ* deployment of SHM systems!**

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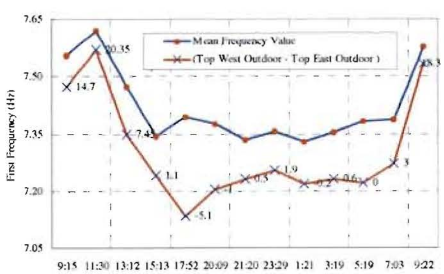
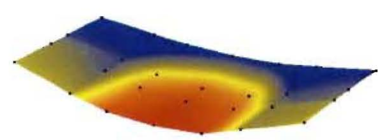
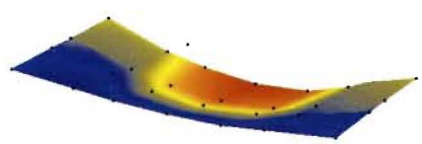
Environmental Variability





First mode, 10 AM



First mode, 5:30 PM

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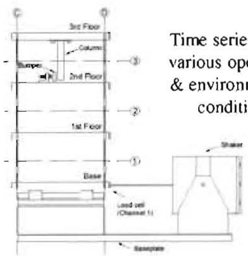
Machine Learning Approach to Normalization

(Elói Figueiredo Ph.D. dissertation, U. of Porto)

1. COLLECT BASELINE DATA

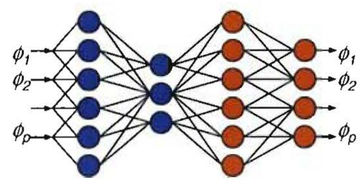


Time series from various operation & environmental conditions

2. AR-MODELING

$$x_i = \sum_{j=1}^{p} \phi_j x_{i-j} + \varepsilon_i$$

3. DATA NORMALIZATION



4. NORMALIZED FEATURES

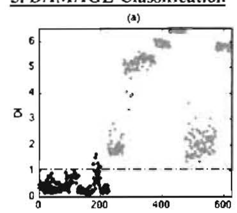
$$[E] = [\phi] - [\hat{\phi}]$$

$$DI(j) = \sqrt{\sum_{i=1}^{m} (E_{i,j})^2}$$

5. ESTABLISH THRESHOLD

95% cut-off value over the training data

5. DAMAGE Classification



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Probabilistic Decision Making

- **Supervised learning**: data are available from undamaged and damaged system.
- **Unsupervised learning**: data are available only from the undamaged system.(Typical for SHM)
- **Three general types of statistical models for damage detection:**
  - Group classification (supervised, discrete)
  - Regression analysis (supervised, continuous)
  - Identification of outliers (unsupervised)
- Statistical models are used to answer four questions regarding the damage state of the system: **Existence, Location, Type, Extent.**

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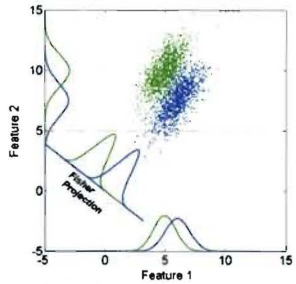
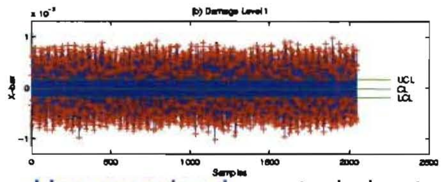
Probabilistic Decision Making Examples



Supervised: Fisher's descriminant



Unsupervised: control charts

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Challenges for Probabilistic Decision Making

- **Analytical approaches to defining threshold levels**
  - Must balance tradeoffs between false-positive and false-negative indications of damage.
  - Minimize false-positives when economic concerns drive the SHM application (e.g. wind turbines)
  - Minimize false-negatives when life-safety issues drive the SHM application (e.g. nuclear power plant)
- **Updating statistical models as new data become available**
- **Managing the large volumes of data that will be produced by an on-line monitoring system**
  - Learn how others are do it (credit card fraud detection)

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Bayesian Experimental Design For Evaluating/Designing SHM/DP Systems (E. Flynn Ph.D. dissertation, UCSD)

- What are the **relevant damage states, θ,** and their **probability** of occurring P(θ)?
  - "Undamaged" / "Damaged", Continuous states: extent, location
- What are the **system costs** associated with the SHM design?
  - Hardware cost, Maintenance cost, Operation cost
- What **actions, *d*,** does the SHM/DP system dictate in response to observing a damage state?
  - Continue/reduce/stop operation; Inspect component or entire structure; do nothing
- What are the **costs** of taking each of those response actions?
  - Cost of inspection vs missing damage, detecting damage in the wrong location

$$E(L)=\sum_{\theta,d} L_d(d,\theta)P(d|\theta,e)P(\theta)+L_e(e)$$

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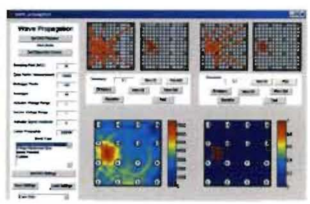
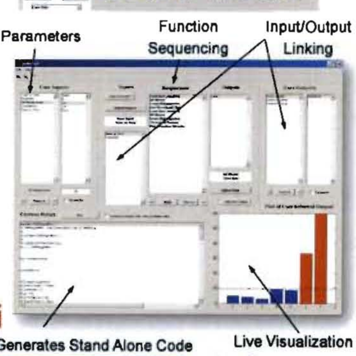
SHMTools Software

Eric Flynn, Dustin Harvey, Samori Kuofu, Stuart Taylor, Elói Figueiredo

- Standardized
  - Naming
  - Documentation
  - Function arguments
  - Experimental data
  - Usage examples
- Easy to Use
  - Modular
  - Extensive Documentation
  - Example Usage
- Expandable
  - Open Source
  - Flexible Structure
- Hardware Embeddable
  - Efficient
  - Converts to Compilable Code
- Research Orientated
  - Freely available
  - Open source
  - Useful to the SHM community
  - Serves as reference material
  - Cites research literature





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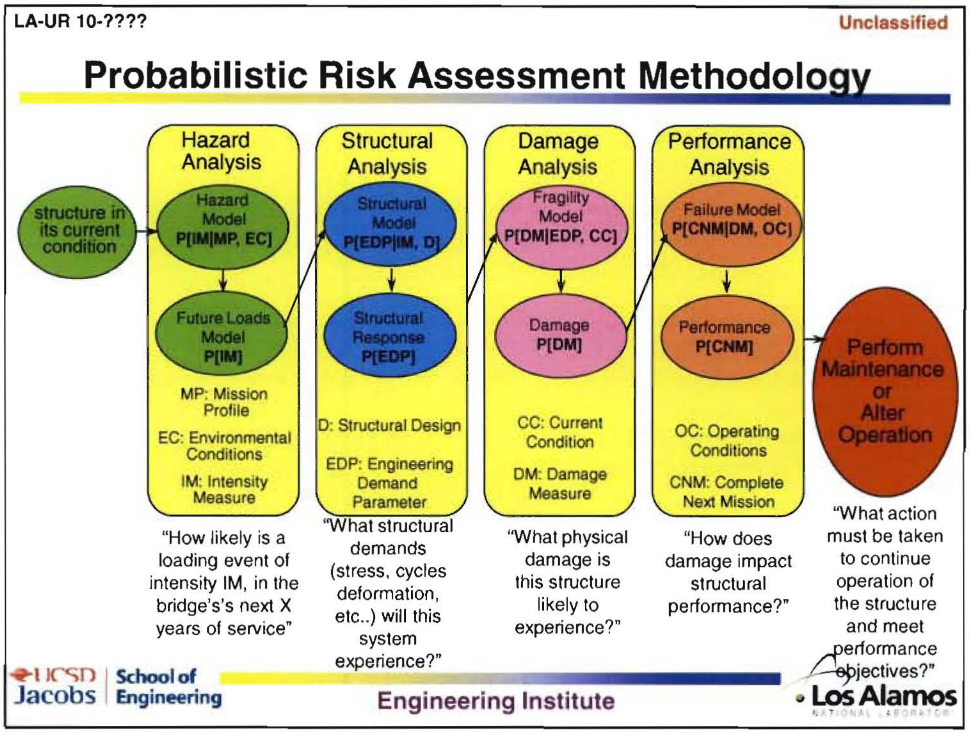
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Probabilistic Risk Assessment Methodology
structure in its current condition
Hazard Analysis
Hazard Model P[IM|MP, EC]
Future Loads Model P[IM]
MP: Mission Profile
EC: Environmental Conditions
IM: Intensity Measure
Structural Analysis
Structural Model P[EDP|IM, D]
Structural Response P[EDP]
D: Structural Design
EDP: Engineering Demand Parameter
Damage Analysis
Fragility Model P[DM|EDP, CC]
Damage P[DM]
CC: Current Condition
DM: Damage Measure
Performance Analysis
Failure Model P[CNM|DM, OC]
Performance P[CNM]
OC: Operating Conditions
CNM: Complete Next Mission
Perform Maintenance or Alter Operation
"How likely is a loading event of intensity IM, in the bridge's's next X years of service"
"What structural demands (stress, cycles deformation, etc..) will this system experience?"
"What physical damage is this structure likely to experience?"
"How does damage impact structural performance?"
"What action must be taken to continue operation of the structure and meet performance objectives?"
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DOE's Goal: Reduce O&M Costs by 40%
• Wind power currently costs 5-to-8 cents per kilowatt-hour, which is more than twice the cost of electricity generated by burning coal
• Wind turbines are designed to last 20 years but fail on average 2-3 times per year during their first 10 years of operation
Designed for this...
...but experience this.
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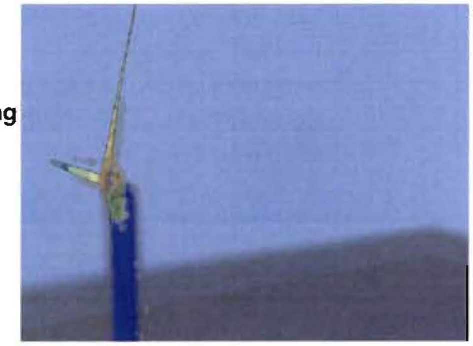
Innovative R&D Is Required to Drive Down Cost of Wind Energy

- Wind industry is experiencing tremendous growth
- LANL is delivering a comprehensive wind turbine engineering R&D program that provides
  - **Turbine/plant simulation with realistic wind loading**
  - **Real-time structural health monitoring**
  - **Large-scale experimental validation**
  - **Damage-mitigating control**
  - **V&V with uncertainty quantification**
  - **Data interrogation/visualization**
  - **LANL/NREL/SNL wind collaboration**



Supports LANL's Energy Security Mission and Aligned with DOE's 2030 Goals

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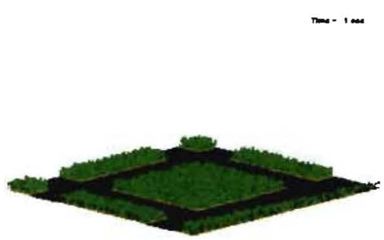
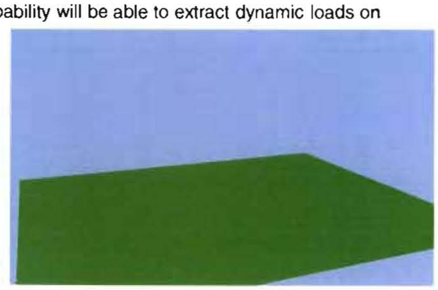
WindBlade: LANL's Turbine and Plant Fluid-Structure Interaction Simulation Code

- Couples R&D 100-winning HIGRAD/FIRETEC with LANL's new turbine/wind interaction modeling technique, **WindBlade** (*patent pending*)
- Provides capability to study realistic wind interactions with rotating turbines
  - fully compressible atmospheric hydrodynamics code
  - Lagrangian tracking scheme that **accounts for 2-way feedback between winds and moving solid objects**
  - resolves complex environments: topography, unsteady winds, severe weather, solar heating/unstable mixing
  - aeroelastic, fluid-structure interaction (FSI) capability will be able to extract dynamic loads on blades and towers



***HIGRAD/FIRETEC* Wildland Fire Simulation**



***WindBlade* 9-Turbine Simulation Showing Turbulence-Induced Vorticity**

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Our Research Is Centered On Turbine Blades

- We have a comprehensive engineering R&D program focused on wind turbines that is delivering
  - turbine/plant simulation with realistic wind loading
  - structural health monitoring (SHM) with damage prognosis
  - multi-scale sensing for damage detection and shape reconstruction
  - model validation and uncertainty quantification
  - damage-mitigating control
  - large-scale technology integration
  - LANL/NREL/SNL wind collaboration
- Why start with the turbine blades?
  - blades have high failure rates
  - blades continue to grow in size, thus encounter more severe dynamic loading
  - true wind loads on blades are not accounted for in design process
  - blades are the origin for loads on the hub, gearbox, and generator

LANL FE Model of Composite Blade

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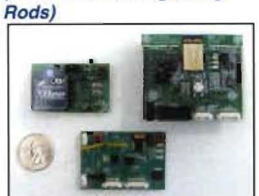
SHM: Anticipating Failure, Rather Than Reacting To Failure

- We are developing low-cost sensing systems to monitor blade health
- Embedded in each blade, this system will
  - Identify structural damage and monitor its progression
  - Predict remaining useful blade life

LANL Wireless Sensor Nodes
(No Wires = No Lightning Rods)



Energy Harvesting (No Batteries)

Active Sensor Patches Are Both Senders and Receivers

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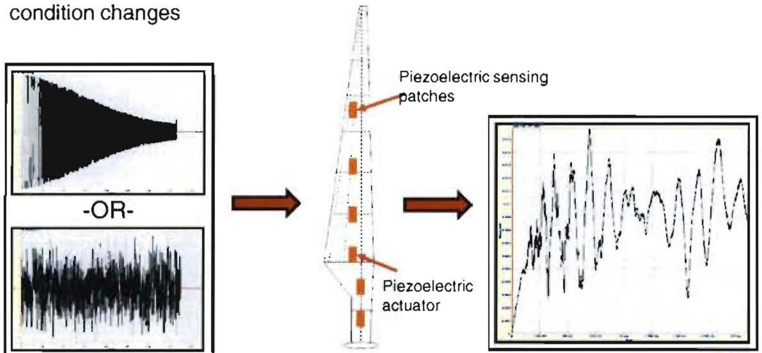
Blade Fatigue Test at NREL

- An amplified chirp or burst random signal is applied to the actuator
  - Response measured by Sensor Patches are used to assess the condition of the blade during the fatigue test
  - A known and repeatable input is applied to the structure, which makes the subsequent signal processing easier and efficient
  - A high frequency excitation (>5kHz): immune to operation vibrations or any other condition changes



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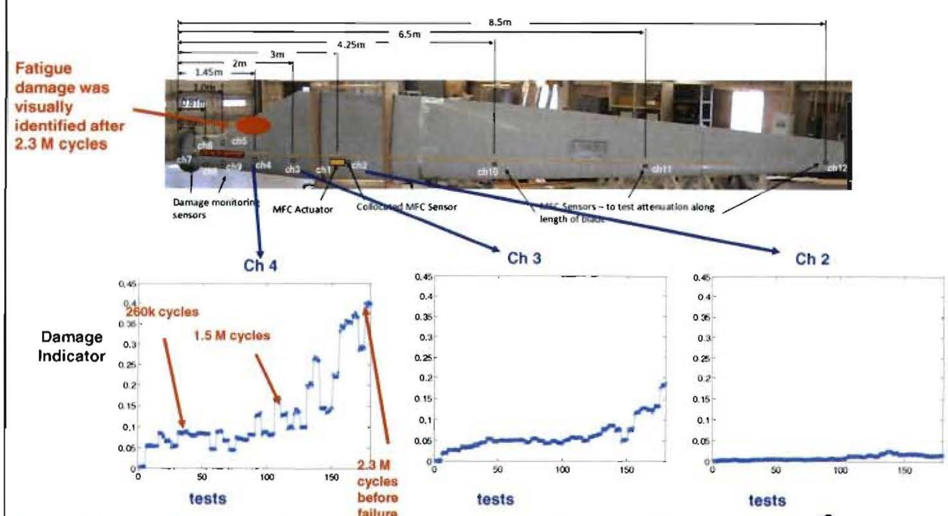
Blade Fatigue test at NREL



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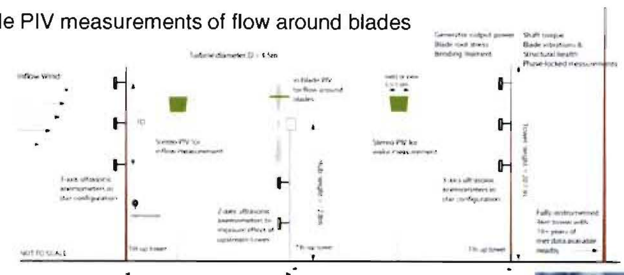
Improved Design Tools

- FY11: Fully instrumented field test of 4.5m-diameter turbine at LANL to include:
  - Stereo PIV measurements of inflow and outflow
  - In-blade PIV measurements of flow around blades



- FY12: In-blade PIV measurements on 20m-diameter turbine with LANL 9m blades

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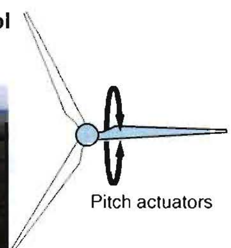
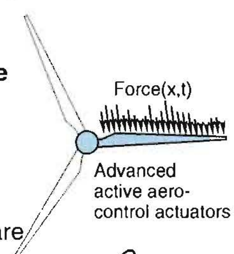
Damage-Mitigating Control

- **Today's Turbines: Do the best we can with pitch control**
  - Maximize performance while minimizing damage progression
  - Couple damaged system state with damage accumulation model to develop control laws
  - Demonstrate on full-scale turbine at NREL CART facility →



- **Future Turbines: Re-configure blade control on the fly**
  - Adjoint-based optimization employing LANL **WindBlade** code
  - Allows gradients of a cost function to be calculated with respect to time-varying and spatially-varying forces
  - Assessing advanced actuation concepts (e.g. twist, microtabs, active flow control) before paying for hardware



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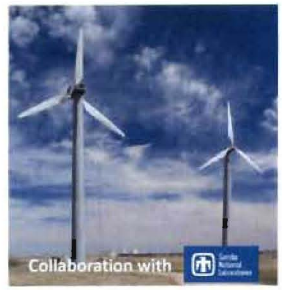
Project Will Culminate In Full-Scale Test of Relevant Structures and Flowfields

- Full range of instrumentation on three, 9-m blades
  - **Blade 1**: High-frequency SHM techniques to monitor blade transition region, and bolted joints at blade root
  - **Blade 2**: In-blade, rotating PIV system
  - **Blade 3**: Low-frequency sensing (e.g. fiber-optic, camera-based)
  - **All Blades**: Strain and acceleration sensors for shape reconstruction and energy harvesting
- Tower-mounted sensors to monitor upstream and downstream flow conditions
- Results fed into prognostic analyses and visualization algorithms to validate WindBlade and FE codes
- Proof of concept for validating embedded sensing



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Our Team

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