SE 165 “Principals of Structural Health Monitoring”

• Instructors:
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• Meeting times
  – Tu, Th 8:00-9:20 AM lecture (RM. 260, Galbraith Hall)

• This course is being taught from Los Alamos National Laboratory via ISDN link

• This course is part for a new UCSD/Los Alamos National Laboratory (LANL) education program in structural health monitoring and validated simulations
SE 165 Overview

• **Course text and Software**
  – None, I will provide copies of chapters from a book I’m developing.
  – Matlab (plus signal processing toolbox and statistics toolbox) is available in SE computer lab
  – You can buy student version of Matlab for your own computer

• **Course assessment**
  – Weekly MatLab programming assignments (9) **60%**
  – Small-group written term project **30%** (more on this later)
  – Final examination (project oral presentations) **10%** (Thu March 17, 8-11 AM)

• This course will use WebCT [http://webct.ucsd.edu](http://webct.ucsd.edu)
  • syllabus, schedule, homework solutions, lecture notes, other information will be uploaded to WebCT
SE 165 Lectures

• Course Introduction, SHM introduction (1)
• Operational Evaluation, Data Acquisition, Project (1)
• Signal Processing Basics (2)
• Feature Extraction (3)
• Data Normalization (3)
• Statistical Classification of Features (4)
• Vibration-based SHM (4)
• Applications (2)

TOTAL: 20 lectures
Other Course Logistics

• You can contact me by phone at 505-663-5330 4:00-5:00 M,W,F, and 3:00-4:00 T, Th. You can call at anytime, but I will make every effort to be in my office at the times listed.

• You can make arrangements for phone conversation at other mutually convenient times via e-mail.

• I’ll be at UCSD to teach classes live at UCSD on January 13th, Feb. 15th & 17th, and March 8th & 10th.

• I’m out of town Feb. 1 & 3 and March 1 & 3. We will make these classes up at alternate times.
Course Objectives

- Provide a brief history of structural health monitoring.
- Provide a systematic approach to structural health monitoring problems by defining the problem in terms of a statistical pattern recognition paradigm.
- Use a multi-disciplinary, data-driven approach to develop structural health monitoring solutions.
- Introduce students to the concepts of statistical pattern recognition and demonstrate the application of this technology to structural health monitoring.
- Introduce new sensing technology being developed specifically for structural health monitoring activities.
- Show applications and discuss current state of the technology.
Introduction to Structural Health Monitoring
Some Early Applications

- We were involved in several experimental projects that required damage detection:
  - Seismic Category 1 Structures Program
  - Containment Buckling.
  - Seismic Qualification of Glove Boxes
How We Got Started

- 1992 I-40 Bridge Test was our first project that focused specifically on structural health monitoring
Definition of “Damage”

• **Damage** will be defined as changes to the material and/or geometric properties of a structural or mechanical system, including changes to the boundary conditions and system connectivity, that adversely affect current or future performance of that system.

• Implicit in this definition of damage is a **comparison** between two different states of the system.

• Examples:
  – crack in mechanical part (stiffness change)
  – scour of bridge pier (boundary condition change)
  – loss of tire balancing weight (mass change)
  – loosening of bolted joint (connectivity change)
Definition of “Damage”

- All materials used in engineering systems have some inherent initial flaws.
- Under appropriate loading flaws will grow and coalesce to the point where they produce component level failure.
- Further loading may cause additional component failures that can lead to system-level failure.
  - In some cases this evolution can occur over relatively long time scales (e.g. corrosion, fatigue crack growth)
  - Other cases cause this damage evolution to occur over relatively short time scales (e.g. earthquake loading, impact-related damage)
- Must consider the length and time scales associated with damage initiation and evolution when developing a SHM system.
Definition of Structural Health Monitoring

• **Structural Health Monitoring** is the process of implementing a damage detection strategy for aerospace, civil and mechanical engineering infrastructure.

• The SHM process involves:
  – The observation of a system over time using periodically sampled dynamic response measurements from an array of sensors.
  – The extraction of damage-sensitive features from these measurements.
  – The statistical analysis of these features is then used to determine the current state of system health.

• Note: SHM can make use of Non Destructive Evaluation techniques (SE163)
Structural Health Monitoring (cont.)

• For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments.

• After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.
Related Technologies

- **Non-Destructive Evaluation**
  - Local off-line inspection (SE 163)

- **Structural Monitoring**
  - Acquiring data (usually kinematic response) from a structure, but no assessment of structural condition

- **Structural Health Monitoring**
  - On-line, more global inspection with condition assessment

- **Condition Monitoring**
  - SHM for rotating machinery

- **Health and Usage Monitoring Systems (HUMS)**
  - Rotor craft

- **Statistical Process Control**
  - Monitoring plant processes

- **Damage Prognosis**
  - Adds prediction of remaining life capability
Motivation for Structural Health Monitoring

- Local damage detection methods, referred to as Non-Destructive Evaluation (NDE), are well developed and widely used.
- These methods have difficulty when large surface areas need to be inspected and when the damage lies below the surface.
- Need more global and automated damage detection methods.

Recent (2001) failure of offshore oil platform near Brazil
Motivation for Structural Health Monitoring

• Economic and life-safety advantage
  – Move from time-based maintenance to condition-based maintenance
  – Combat asset readiness
  – New business models
    • Manufacturers of large capital investment hardware can charge by the amount of life used instead of a time-based lease.

• Allow owner & operators to make more informed decisions
The Statistical Pattern Recognition Paradigm for SHM

1. **Operational evaluation**
   Defines the damage to be detect and begins to answer questions regarding implementation issues for a structural health monitoring system.

2. **Data acquisition**
   Defines the sensing hardware and the data to be used in the feature extraction process.

3. **Feature extraction**
   The process of identifying damage-related information from measured data.

4. **Statistical model development for feature discrimination**
   Classifies feature distributions into damaged or undamaged category.

- Data Cleansing
- Data Normalization
- Data Fusion
- Information Condensation
  (implemented by software and/or hardware)
Defining Some Terms

• **Data Cleansing**
  - The process of selectively choosing data to pass on to, or reject from, the feature selection process
  - Example: discarding data from a faulty sensor

• **Data Normalization**
  - The process of separating changes in the measured system response caused operational and environmental variability from changes caused by damage
  - Example: Temperature compensating circuit for strain measurements.

• **Data Fusion**
  - The process of combining data from multiple sensors in an effort to enhance the fidelity of the damage detection process
  - Example: Estimating a mode shape from sensor array data

• **Data Compression**
  - Reducing the dimensionality of the data
  - Example: Estimating modal frequencies from sensor data
Pattern Recognition vs. First Principles

<table>
<thead>
<tr>
<th>Amount of Data</th>
<th>Strength of Model</th>
</tr>
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<tbody>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
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- Low
  - Pattern Recognition
  - Prayer? Voodoo? More research?

- High
  - First Principles

Note: Models of complex failure mechanisms tend to be weak
Statistical Model Building

- **Supervised learning**: Data are available from undamaged and damaged system.
- **Unsupervised learning**: Data are available only from the undamaged system.
- Three general types of statistical models for structural health monitoring:
  - Group classification (supervised, discrete)
  - Regression analysis (supervised, continuous)
  - Identification of outliers (unsupervised)
- Statistical models are used to answer five questions regarding the damage state of the system.
Statistical Model Building (cont.)

- Statistical models are also used to avoid incorrect diagnosis of damage
  - False-positives
    - Damage indicated when none is present
  - False-negatives
    - Damage is not identified when it is present

- Establishing statistical bounds for classifying features as corresponding to a damaged condition will be based on the relative consequences of false-positive vs false-negative indications of damage.
  - When life-safety is the primary motive for SHM, false-negative will typically control
Questions to be Answered

1. Is the system damaged?
   – Group classification problem for supervised learning
   – Identification of outliers for unsupervised learning

2. Where is the damage located?
   – Group classification or regression analysis problem for supervised learning
   – Identification of outliers for unsupervised learning

3. What type of damage is present?
   – Group classification
   – Can only be answered in a supervised learning mode

4. What is the extent of damage?
   – Can only be answered in a supervised learning mode
   – Group classification or regression analysis

5. What is the remaining useful life of the structure? (Prognosis)
Are These Systems Damaged?

Did you use pattern recognition?
Concluding Remarks

• There is no sensor that can measure damage!
  – Sensors measure the response of a system to some stimulus
  – Must integrate data interrogation procedures with sensing technology to develop effective structural health monitoring solutions

• Structural Health Monitoring is the process of transforming sensor data into information about the damage state of the system.

• In most cases Structural Health Monitoring technology is not as mature as Non-Destructive Evaluation.

• Currently, lots of research efforts underway to develop structural health monitoring technology for a wide variety of aerospace, civil and mechanical engineering applications.

• **Course Theme**: Structural Health Monitoring is a problem in **statistical pattern recognition**.