Structural Health Monitoring Using Statistical Pattern Recognition

Sample Viewgraphs

These slides are taken from various lectures

This set of slides is not intended to be a complete presentation

Outline

- Preliminaries
  - How we got started in this field
  - How we have evolved
  - Course evolution
- Course Philosophy
- Define Damage (Length scales, Time scales)
- Define Structural Health Monitoring
- Motivation for Structural Health Monitoring
- The Structural Health Monitoring Process
- Brief Historical Summary
- **Material in this presentation is covered in Chapters 1 and 2 of the Reference Book**

Course Philosophy

- 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.
- Introduce participants to the components of this paradigm and demonstrate its application to various structural health monitoring problem.
- Provide an implementation strategy for this statistical pattern recognition paradigm based on a Bayes risk formulation rooted in detection theory.
- Show applications and discuss lessons learned.
- Show participants freely available software tools for implementing many techniques presented in the course.

How We Got Started (Circa 1992)

- 1992 I-40 Bridge Test was our first project that focused specifically on structural health monitoring

Definition of "Damage"

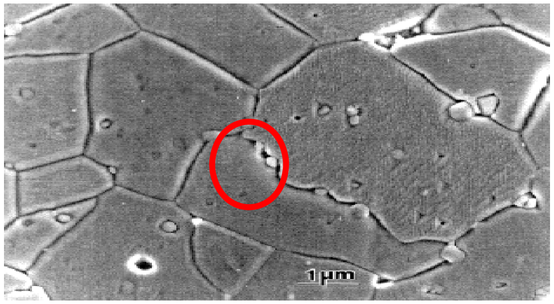
- **Damage** is defined as changes to the material and/or geometric properties of a structural that adversely affect its performance.

- 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 (aging vs. extreme event) are diverse!**



•Inclusions at grain boundary


•Welded Connection


•Department Store Collapse

Definition of Structural Health Monitoring

- **Structural Health Monitoring** is the process of implementing a damage detection strategy for aerospace, civil and mechanical engineering infrastructure.
- Implementation depends of specific application attributes, for example differences in time scale on which damage evolves:
  - 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.

How Engineers and Scientists "Study" Damage

- **What causes damage?**
  - Material science (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)
  - Engineering design strategies (design for inspectability)
  - Define operational and environmental limitations
- **Is damage present? (NDE, structural health monitoring)**
- **How fast will damage grow and reach a critical level?**
  - **NDE, 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")

What is NDE?

The American Society of Nondestructive Testing (ASNT) says:

"Nondestructive evaluation (NDE) is the examination of an object with technology that does not affect the object's future usefulness."

This is also known as nondestructive testing, nondestructive inspection, nondestructive examination, and nondestructive characterization.

Usually, this examination is conducted with the purpose of "health assessment" in mind:

Can the object safely and reliably perform its intended duty within appropriate economic constraints?

What is NDE?

NDE is nothing more than identifying a physical phenomenon (the interrogating parameter) that will interact with and be affected by the object in some way (the interrogated parameter) without altering the object's function.

Many NDE techniques do technically alter the object in some way, but the definition holds provided the object can still be returned to useful service.

The primary difference between NDE and SHM is that NDE requires the object be taken out of service for the inspection, while SHM does not.

The Structural Health Monitoring Process

- The Structural Health Monitoring process includes:

1. Operational evaluation

   Defines the damage to be detected and begins to answer questions regarding implementation issues for a structural health monitoring system.

2. Data acquisition & networking

   Defines the sensing hardware and the data to be used in the feature extraction process.

3. Feature selection & extraction

   The process of identifying damage-related information from measured data.

4. Probabilistic decision making

   Using statistical models to transform features into actual performance-level decisions

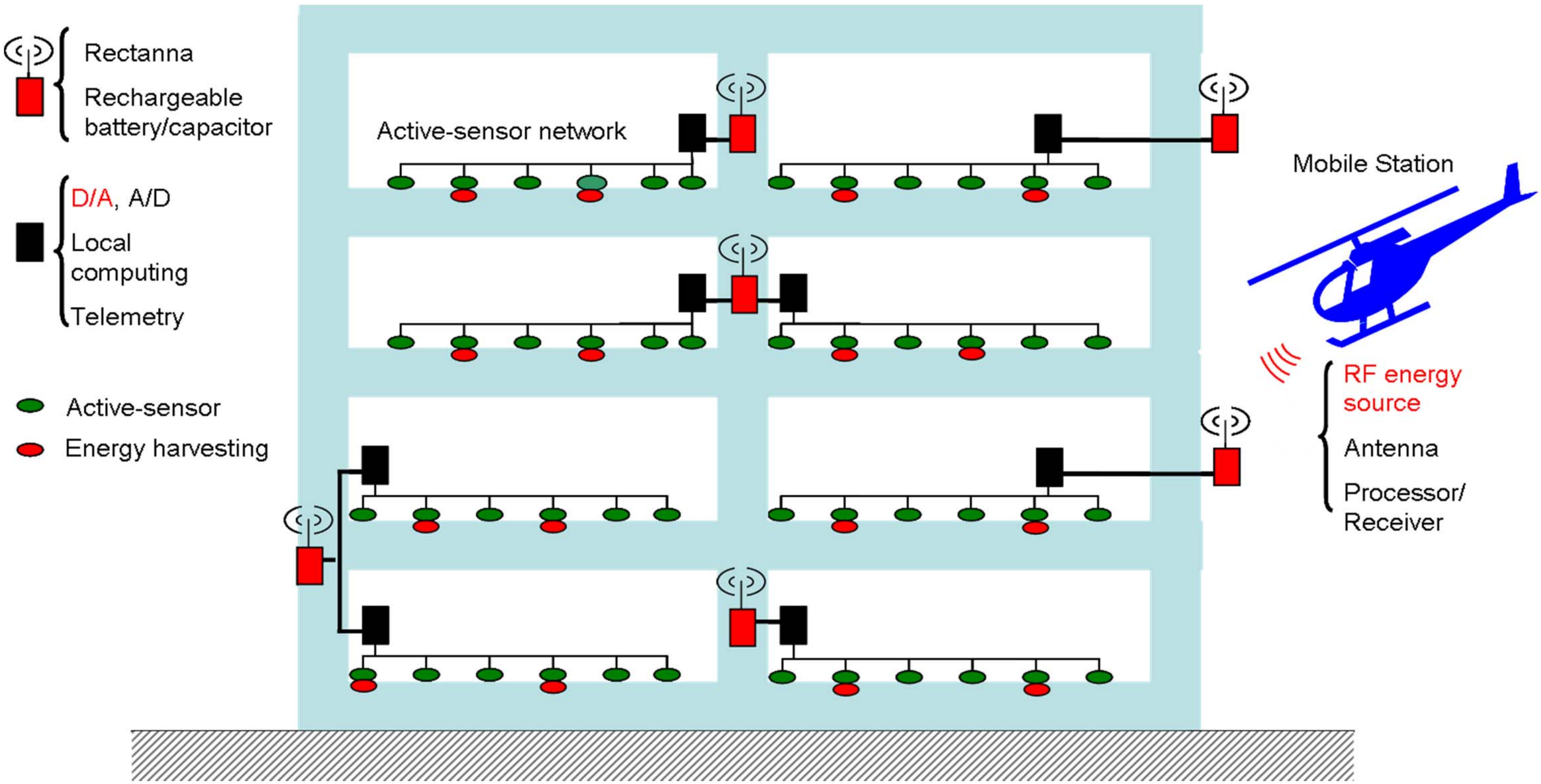
- Our goal is to first discuss each of these steps in more detail
- We will conclude the course by proposing a risk-based methodology to integrate these four steps

Operational Evaluation: Wind Turbine Example

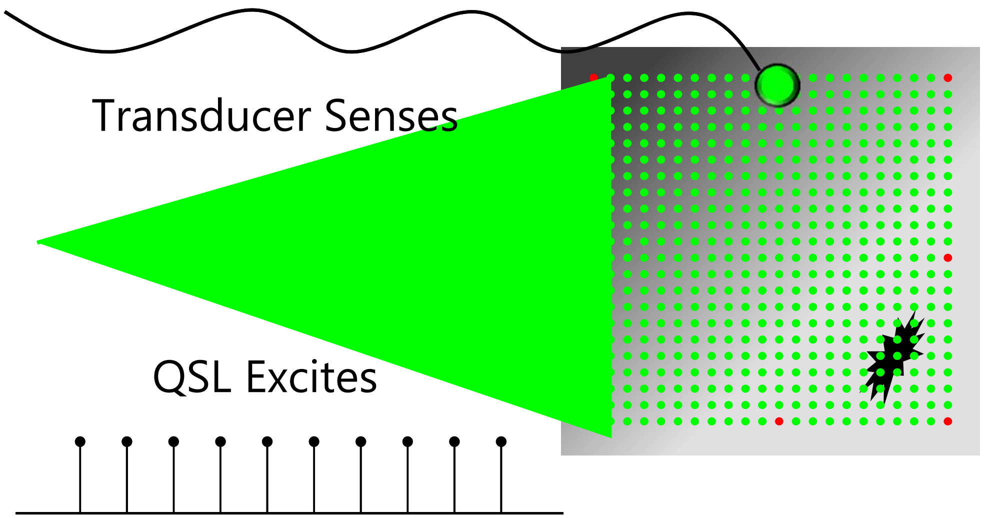
- Motivation for structural health monitoring is purely economic.
  - For an initial investment of about $1 -1.5 million/megawatt, then annual O&M costs using the 2% figure for 5 mw turbine are $100-150K/year.
  - 20 yr overhaul might cost 15-20% of the initial investment (in this example, $750 - 1500K).
  - **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

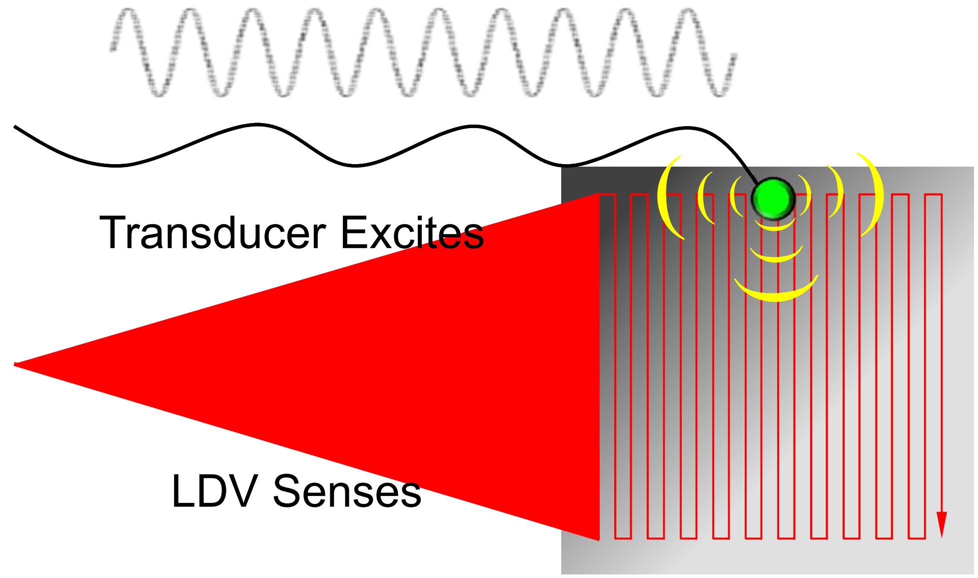
Networking: Active Wireless Sensing and Energy Delivery

Demonstrated by Mascarenas, 2008, Taylor et al., 2009



Full Wavefield Imaging (Hybrid SHM/NDE)





- Excite with pulsed-laser
- **Pulsed** excitation
- Sense with embedded transducer
- Measure **transient** response

- Excite with fixed transducer
- **Continuous** harmonic excitation
- Sense with laser Doppler vibrometer
- Measure **steady-state** response

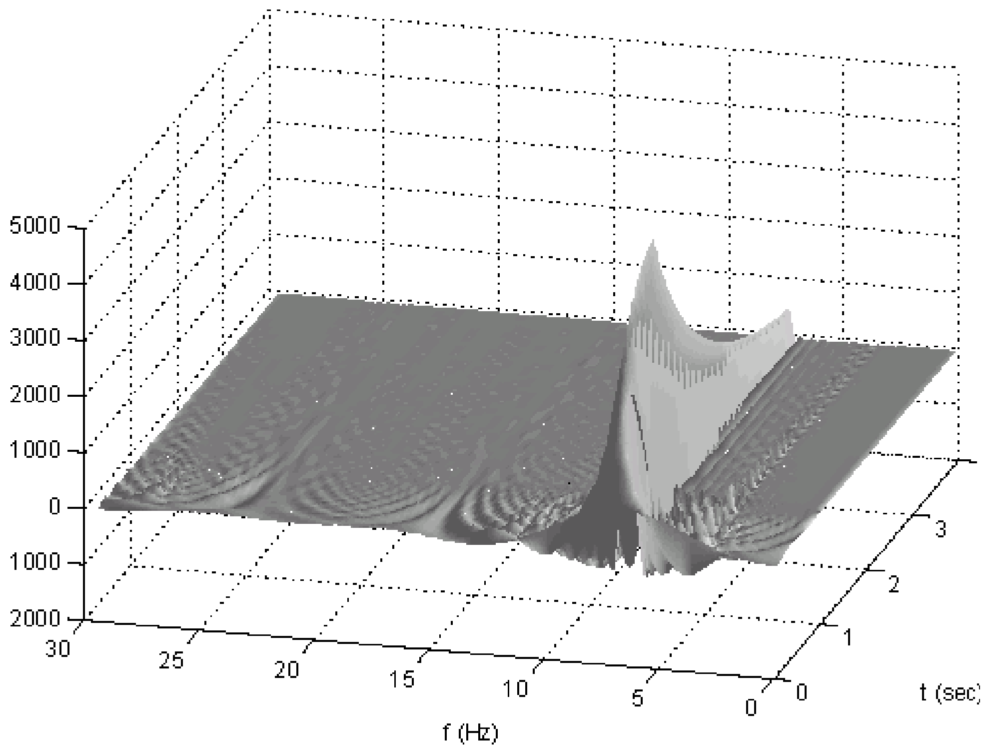
LANL–CBNU Engineering Institute Korea EST. 2011

Engineering Institute LANL•UCSD

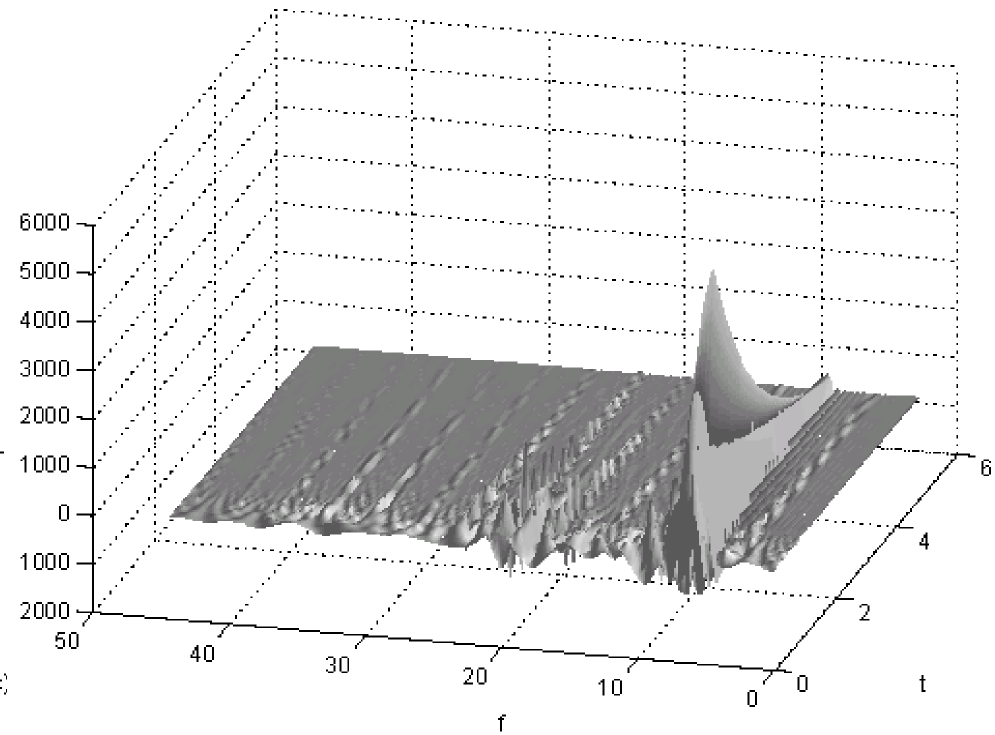
Introduction to Features

- What is a Feature?
  - A feature is some characteristic of the measured response that is well correlated with damage
  - Feature selection: what is the best feature to use?
  - Feature extraction: how do we calculate the feature from the measured data?
- Primary Characteristics of features
  - **Sensitivity** – Ideally, the feature should be very sensitive to damage and completely insensitive to everything else (rarely occurs)
  - **Dimensionality** - Want the feature to have the lowest dimension possible
  - **Computational Requirements** - Features should be extracted with minimal assumptions and CPU cycles
  - **Consistency** -Ideally, the features should change monotonically with damage level.
- Feature vs metric
  - A metric is used to quantify the difference between features
- Want to use the simplest feature possible that can distinguish between the damaged and undamaged system

Uncracked vs. Cracked Beam Response: Wigner-Ville Transform



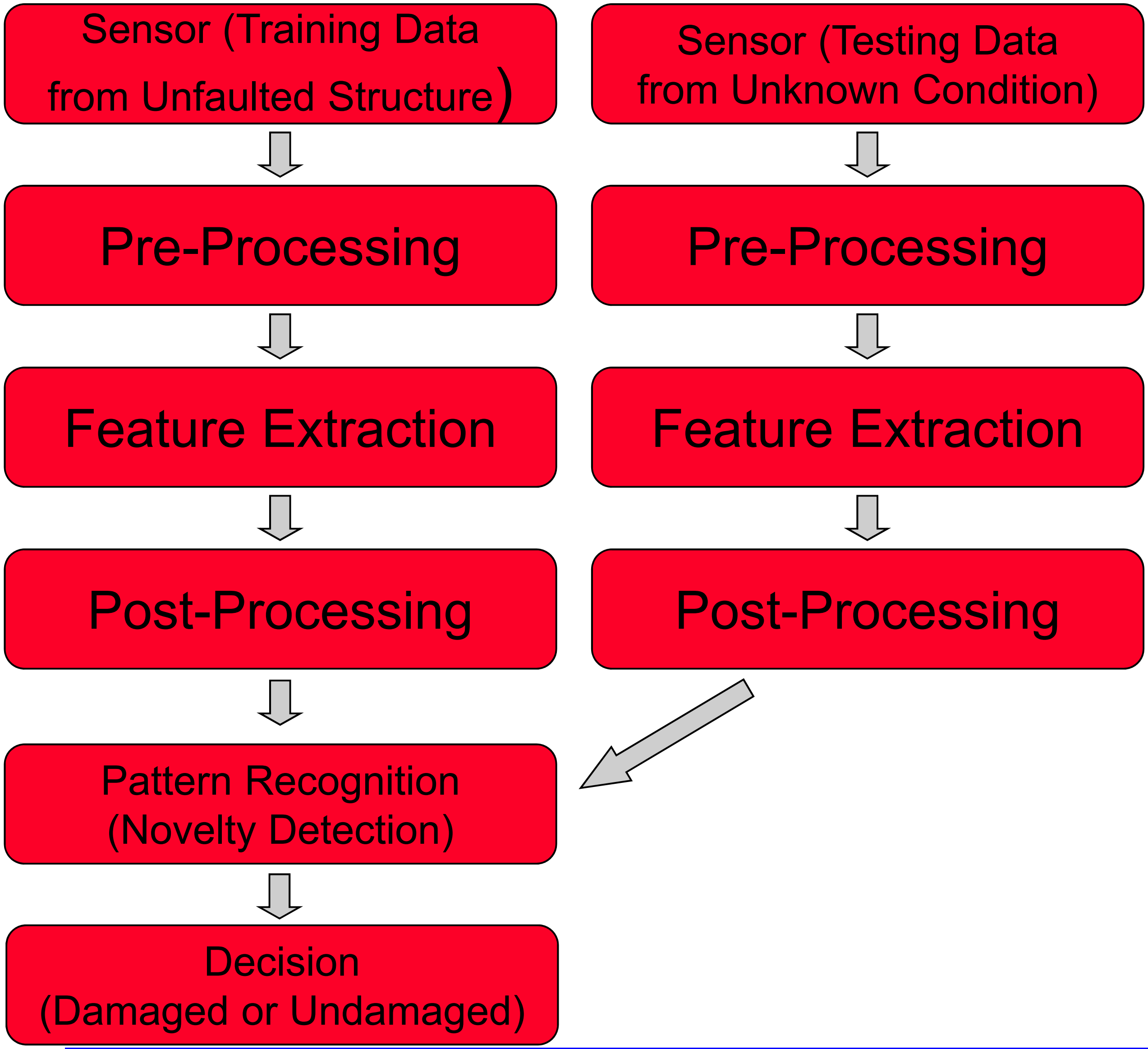
Uncracked

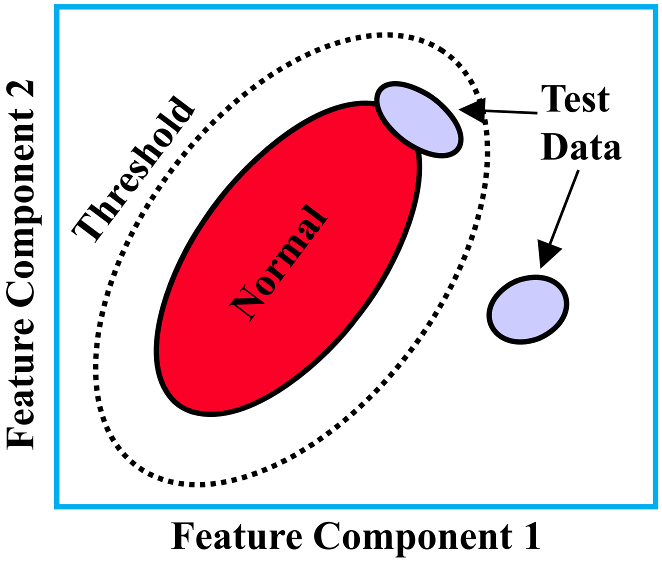


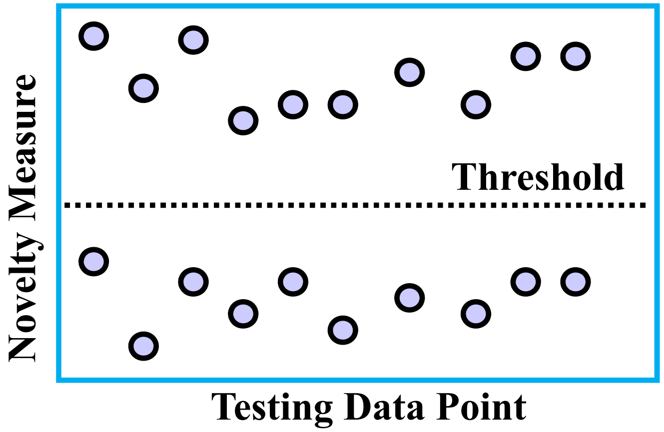
Cracked

Feature

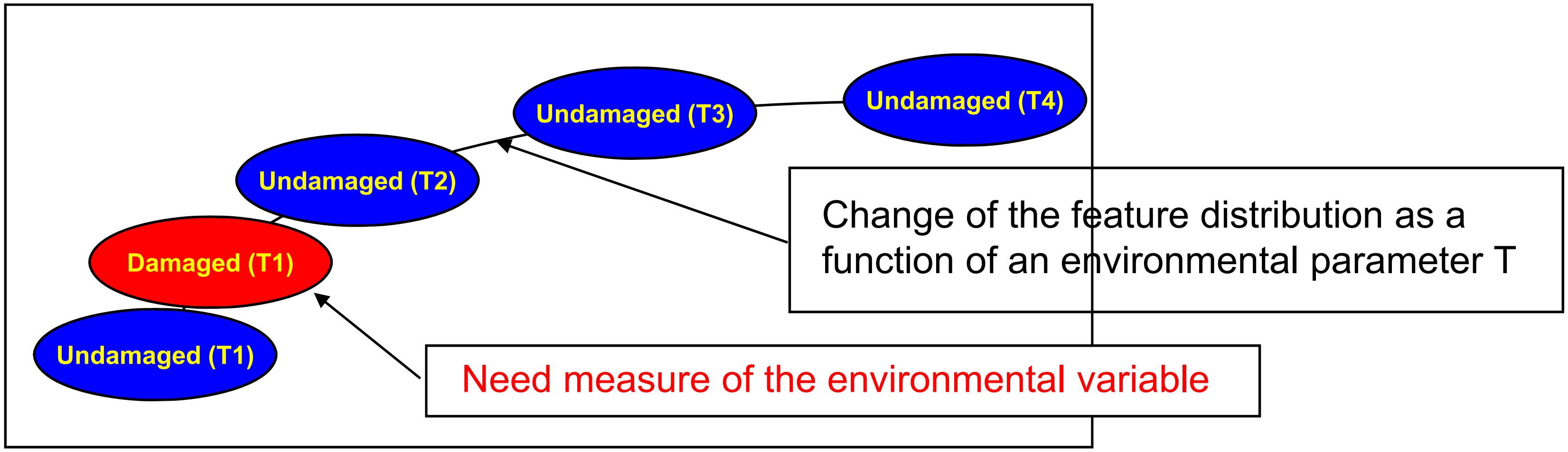
Novelty Detection



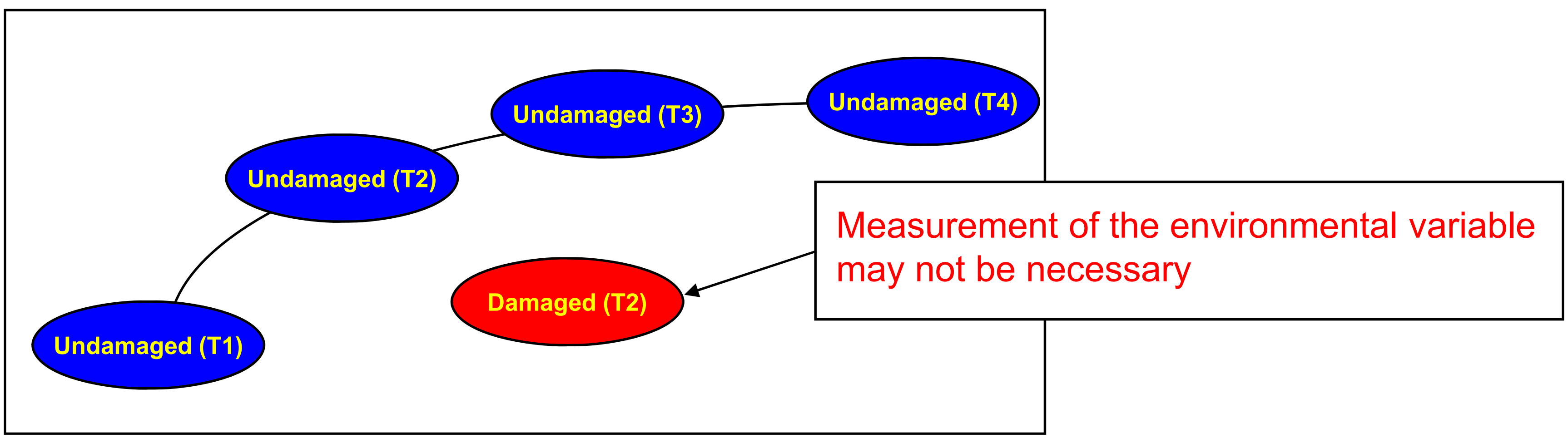




Data Normalization Issue: Two Different Situations

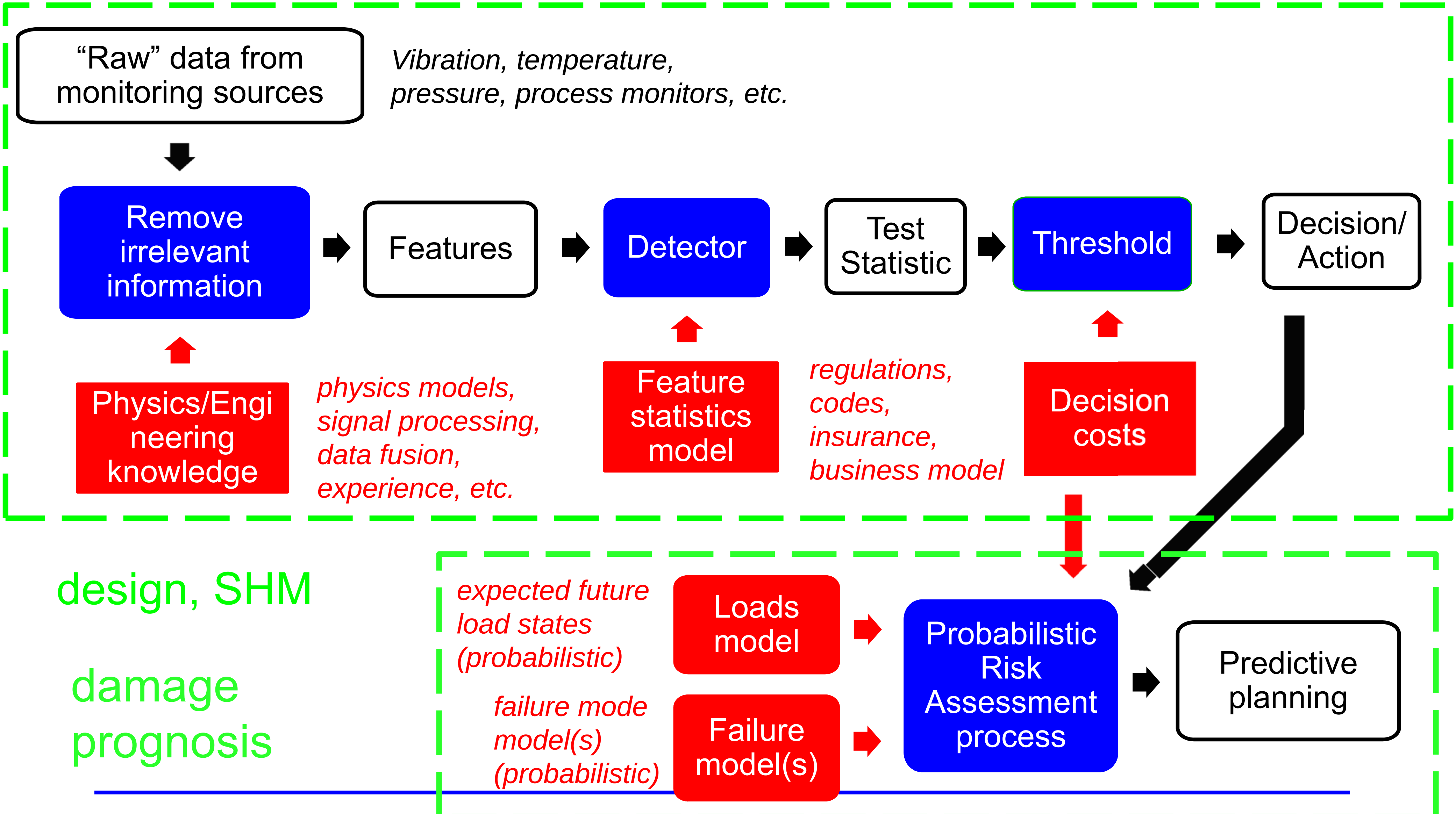


2 dimensional feature space

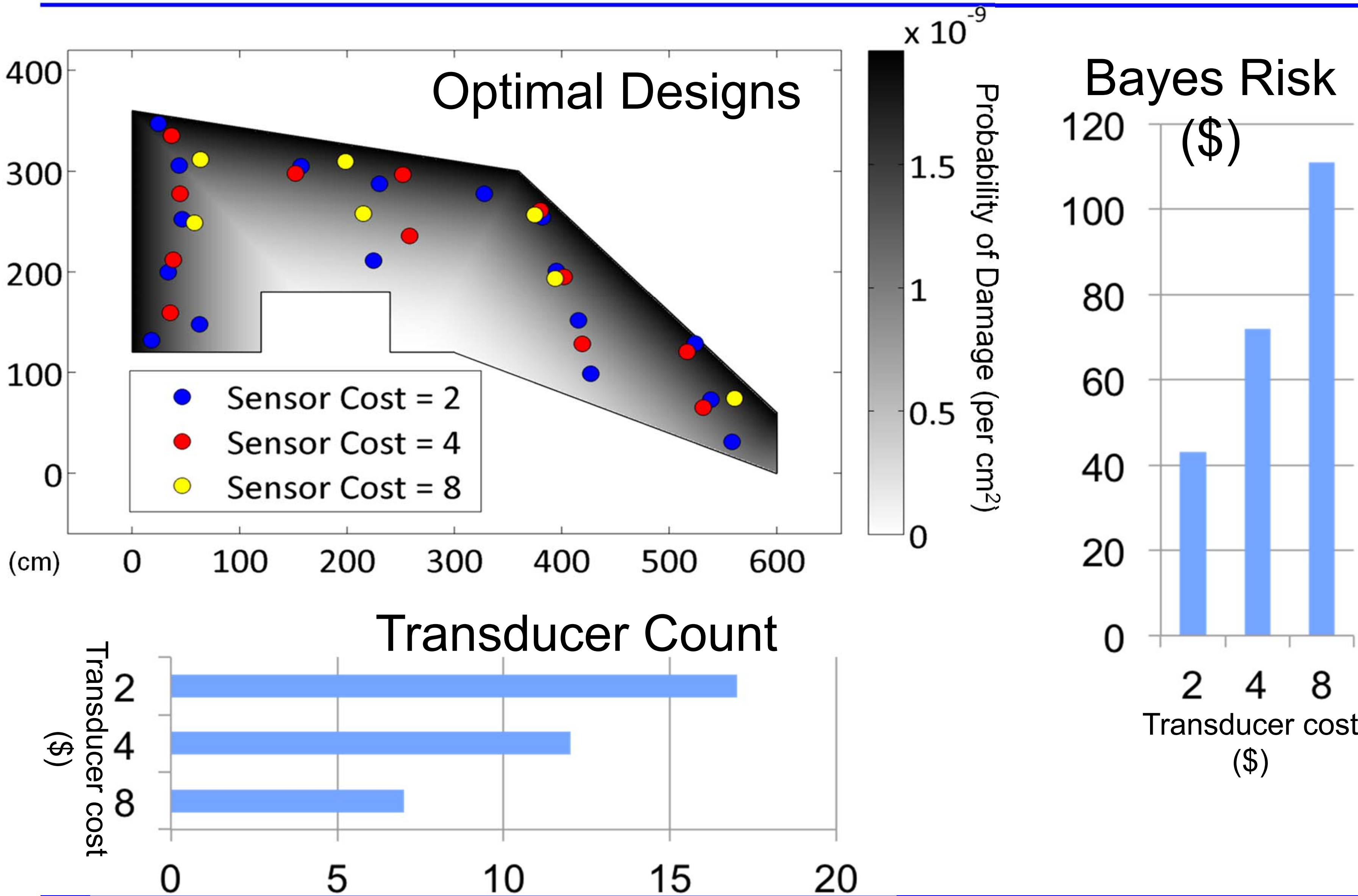


2 dimensional feature space

Better Execution of This SHM/DP Paradigm: Transforming Data into Information that Facilitates Decision-Making



Example #1: Optimized Design Results



FUNDAMENTAL AXIOM 2

- Many researchers state that they have developed a SHM method that “does not require baseline data” or is “baseline free”
- We contend this statement is **NEVER** true!
- However, the confusion often stems from what is meant by “baseline data”
- All pattern recognition approaches require training data
  - Novelty (outlier) detection requires examples of normal system condition
  - Higher levels of damage assessment (type of damage, severity) require examples of the candidate types and data from systems with different levels of damage severity