Bayesian Computational Sensor Networks for Aircraft Structural Health Monitoring

AFOSR DDDAS PI Meeting
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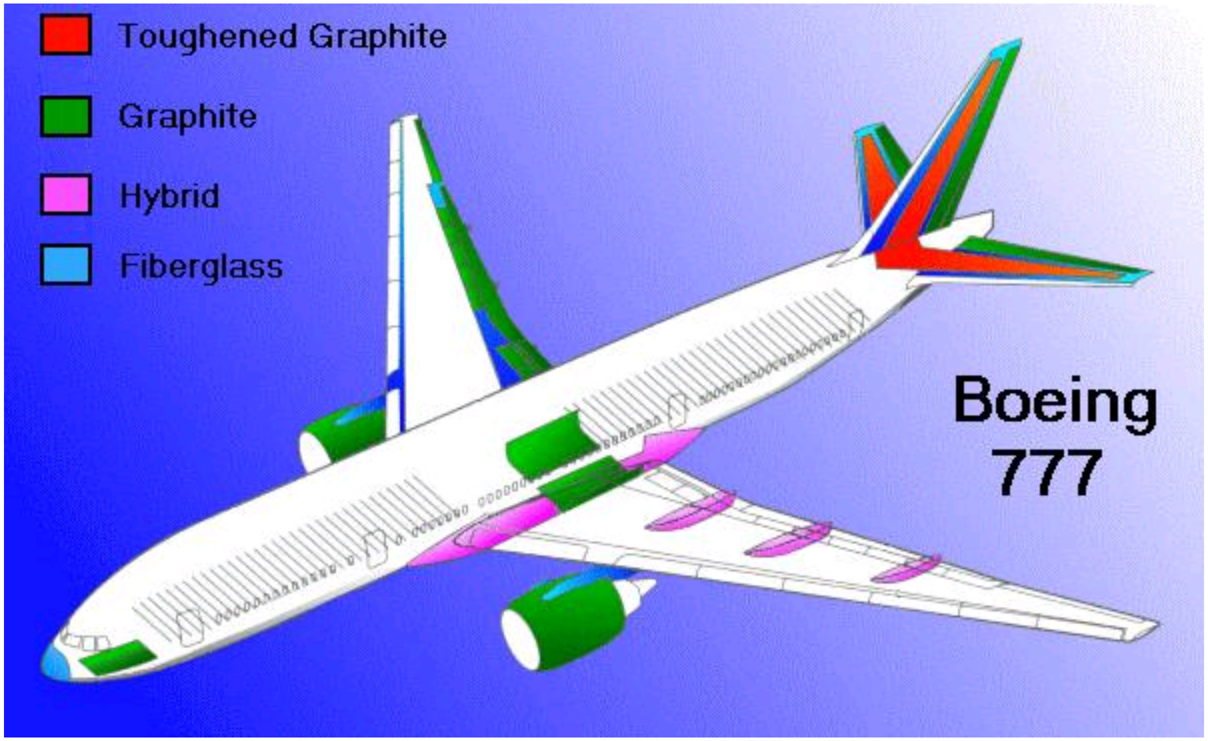
What is structural health monitoring?

Monitoring structures for changes in their characteristics, predicting their useful lifetime without maintenance, and recommending maintenance strategies that will increase useful lifetime and reduce downtime

The need for SHM in newer aircraft

Newer generation aircraft use significant amount of load bearing composite parts

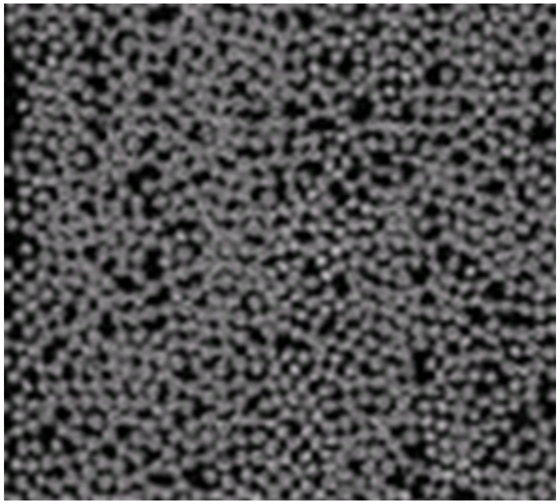
Composite use in past aircraft designs



www.aviation-history.com

Fiber-reinforced polymer matrix composites

Fiber layers are oriented differently in different plies, giving desired strength in all directions



Advantages

Low weight, high strength

Better fatigue resistance than metals

Better resistance to corrosion

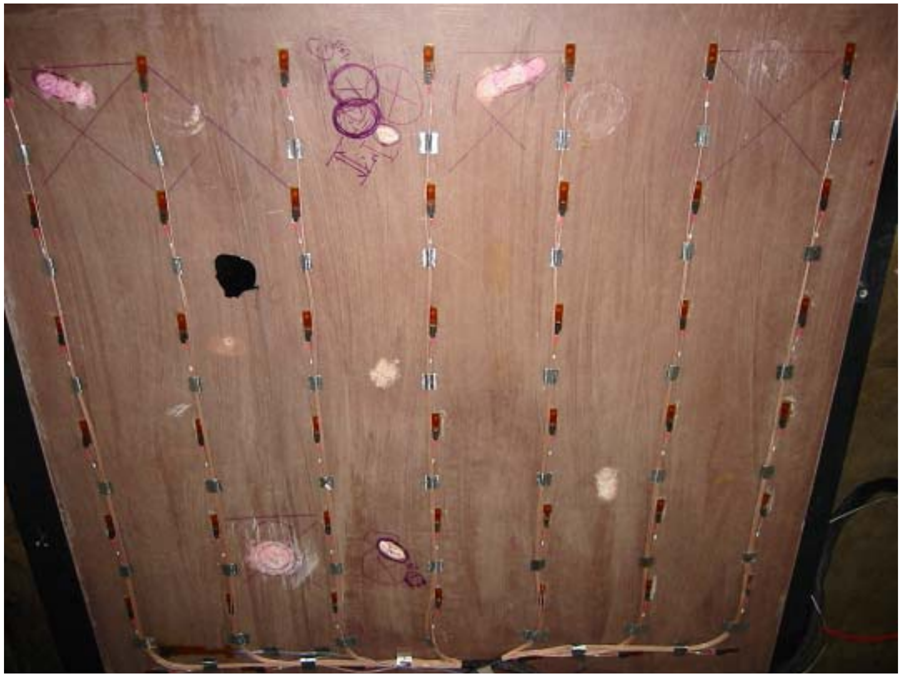
Reduced number of parts required

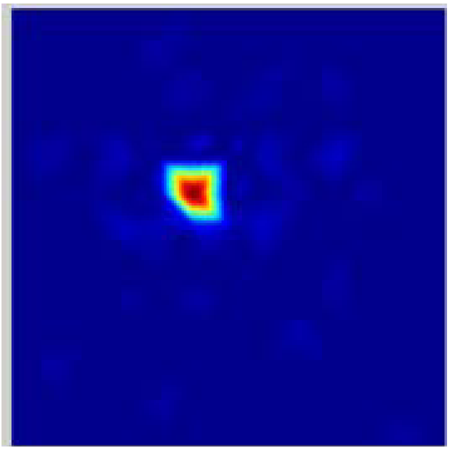
Disadvantage

Impact can cause internal damages with little or no external evidence

SHM needs in new composite airplanes

- Assess the flightworthiness of airplanes each time before they take off





http://www.stanford.edu/~gorin/papers/IWSHM2007OptEst.pdf

SHM needs in older aircraft

Monitor fatigue and corrosion related damages

Replace schedule-based maintenance with condition-based maintenance strategy

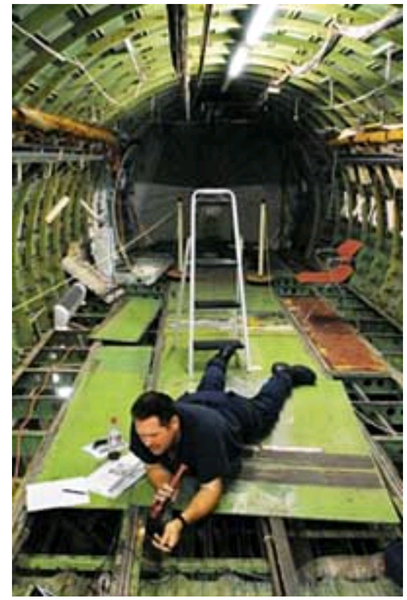
Non-destructive inspection – where we are now

Need experts

Time consuming

Need access to the areas being inspected

Expensive



Goal: Replace schedule-based maintenance with condition-based maintenance

Schedule-based

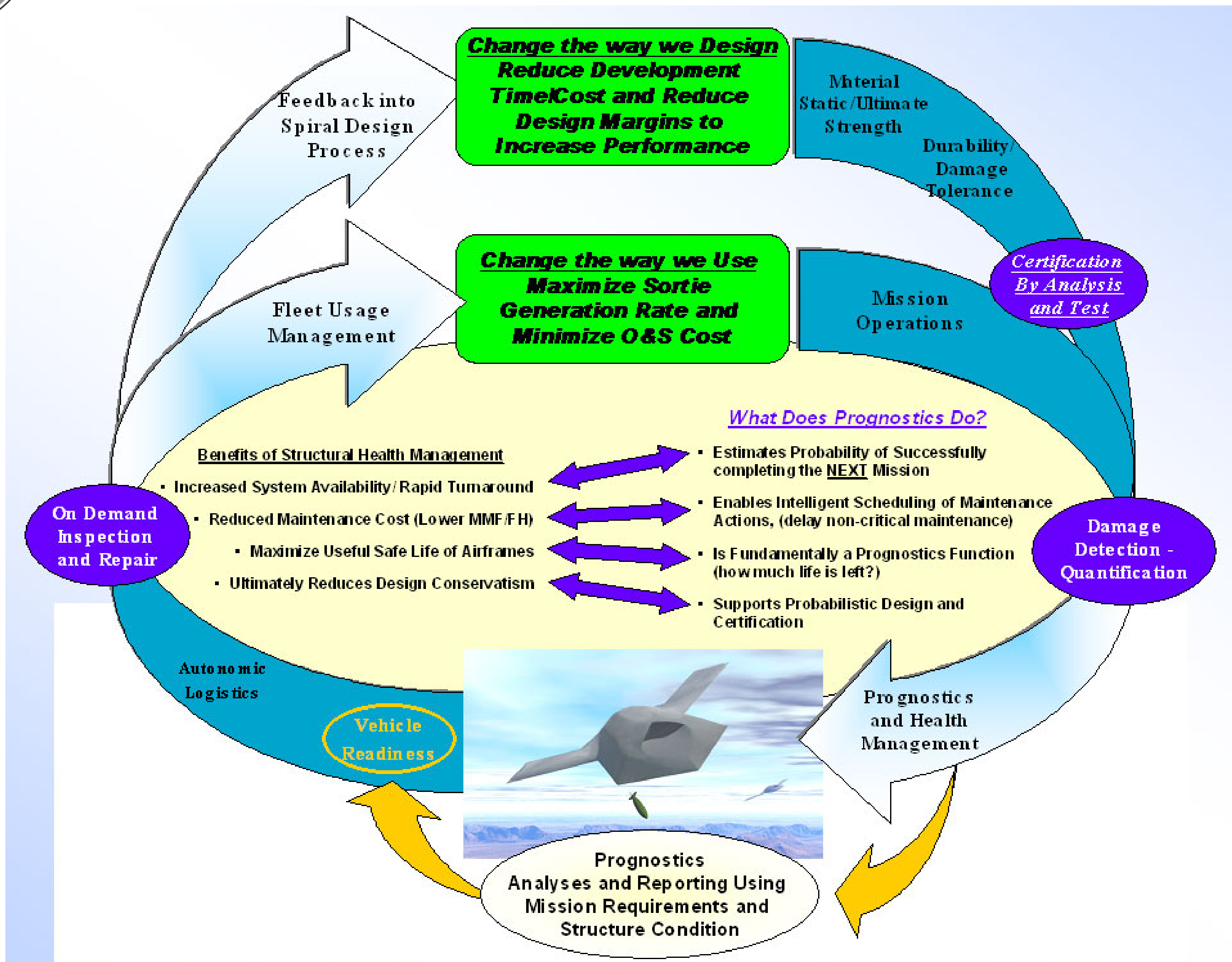
- Structural design
- Perform full-scale fatigue testing and identify problem areas
- Construct inspection schedule

Condition-based

- Monitor aircraft continuously for problems
- Do maintenance based on the state of the structure as need arises

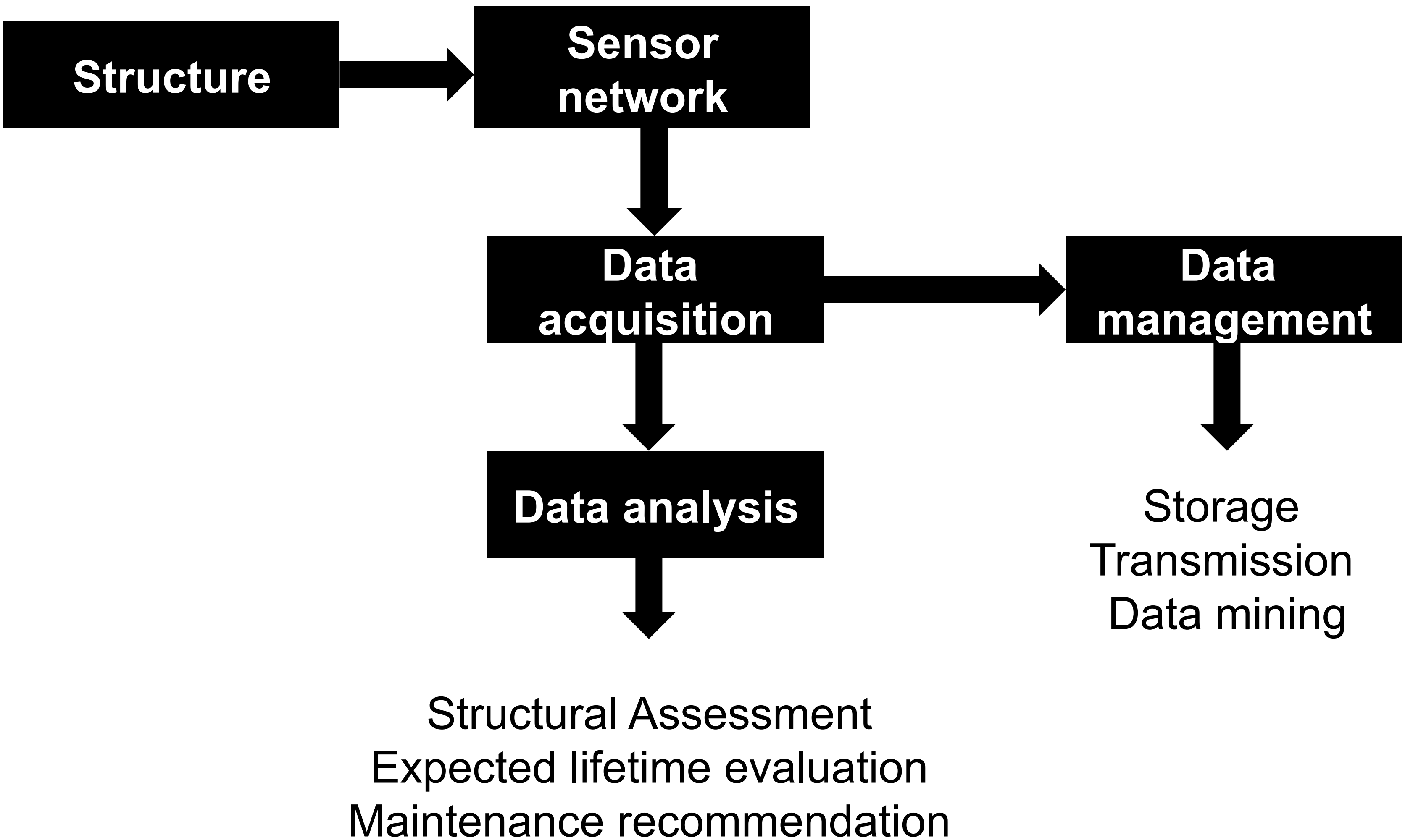
→ Increases availability
→ Reduces maintenance costs
→ Increases reliability (!!??!!)

2020 Vision for SHM

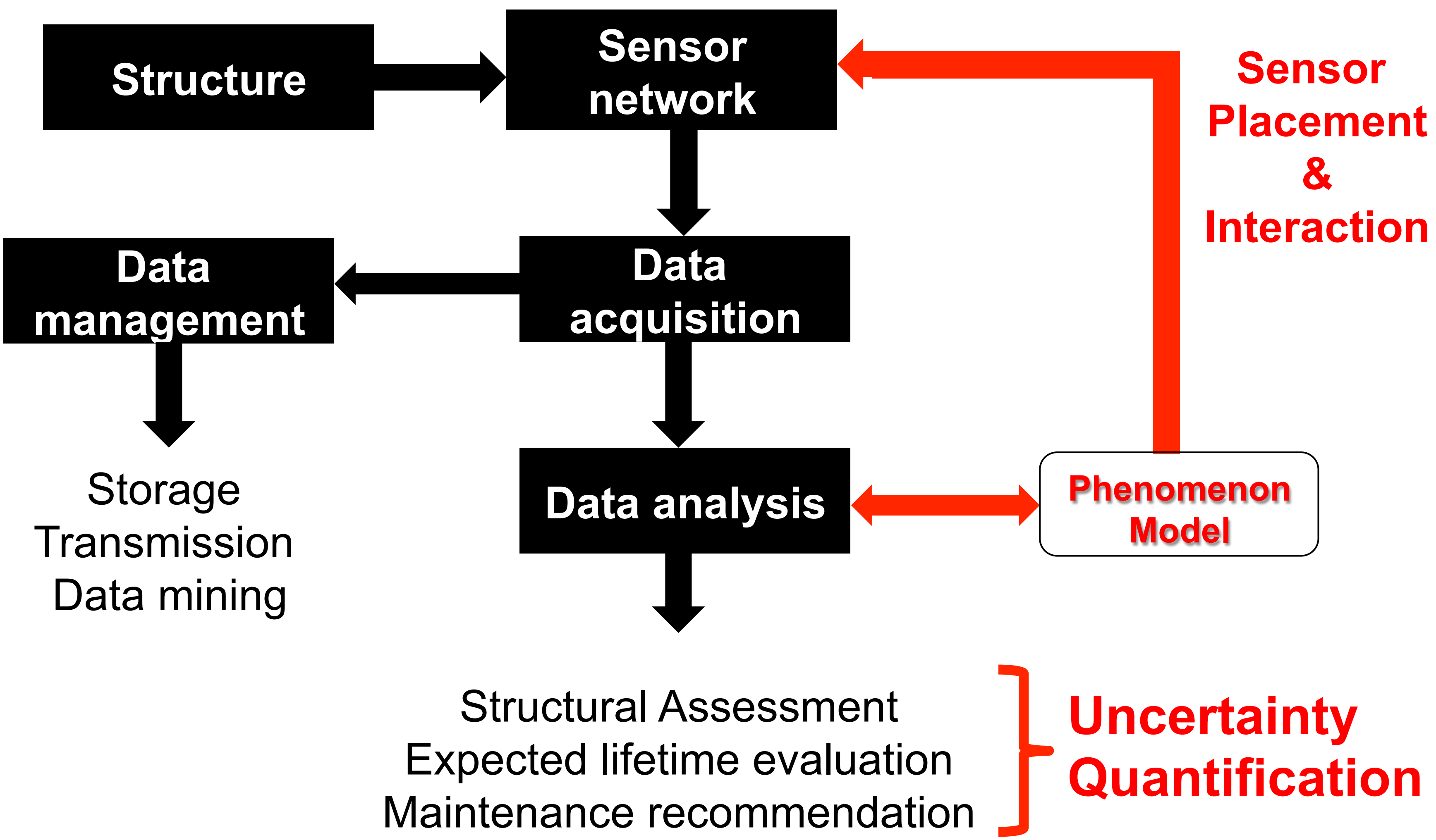


http://www.cs.wright.edu/~jslater/SDTCOutreachWebsite/pic13.pdf

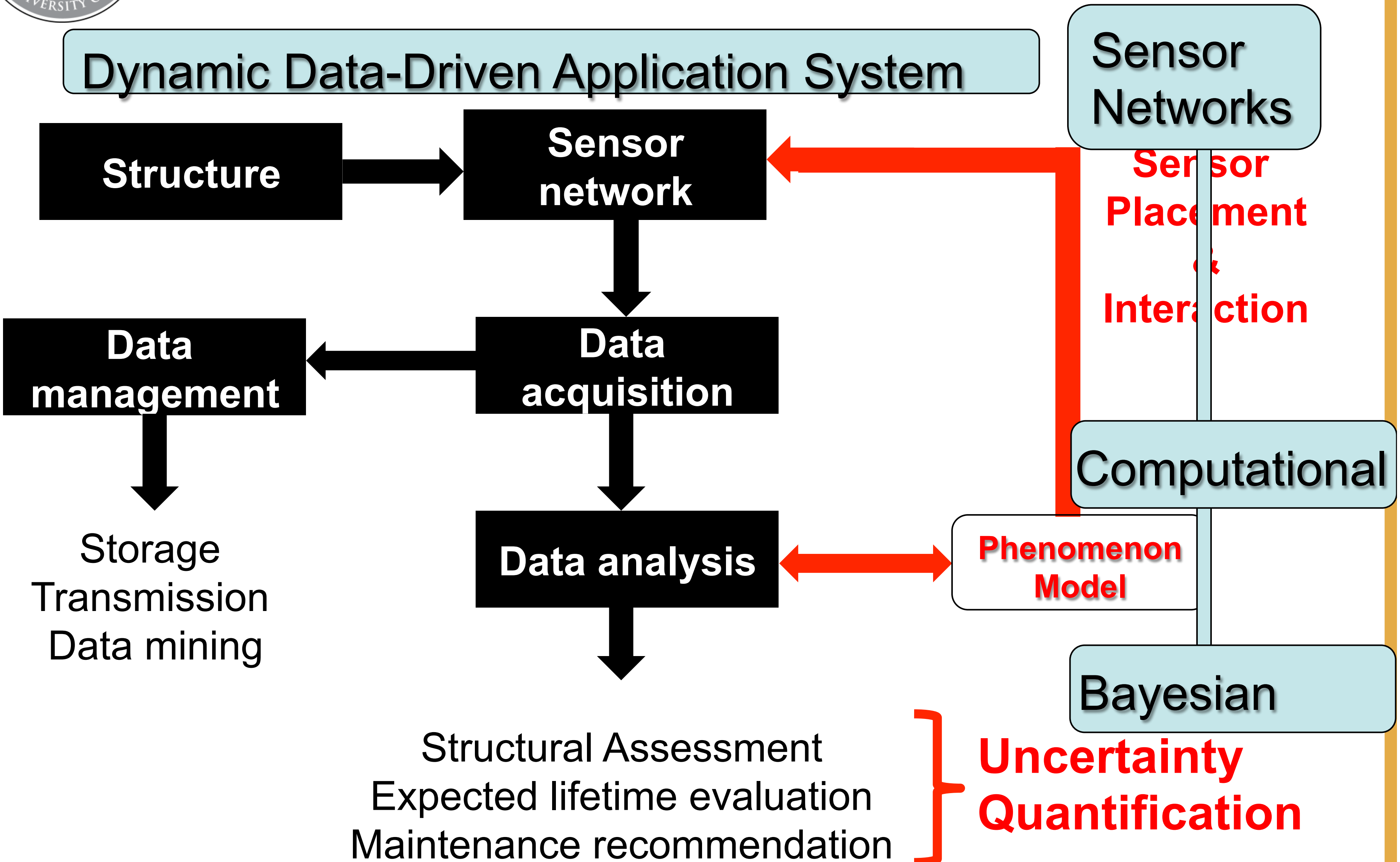
Components of an SHM system (current)



Components of an SHM system (BCSN)



Components of an SHM system (BCSN)



Major Objectives

1. **Bayesian Computational Sensor Networks**
   - Detect & identify structural damage
   - Quantify physical phenomena and sensors
   - Characterize uncertainty in calculated quantities of interest (real and Boolean)

Major Objectives (cont'd)

2. Active feedback methodology using model-based sampling regimes

- Embedded and active sensor placement
- On-line sensor model validation
- On-demand sensor complementarity

Major Objectives (cont'd)

3. Rigorous uncertainty models of stochastic uncertainty of:

- System states
- Model parameters
- Sensor network parameters (e.g., location, noise)
- Material damage assessments

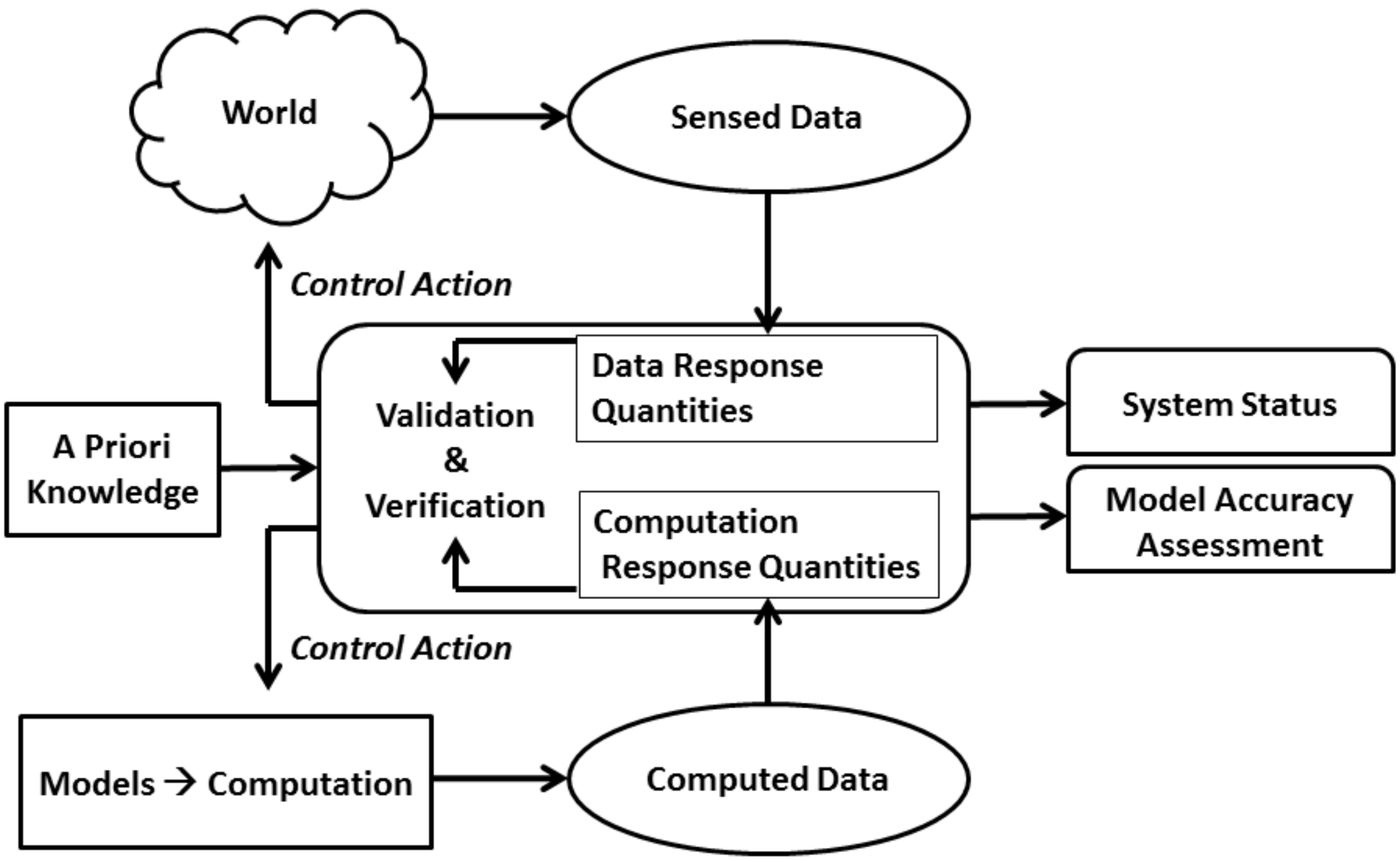
DDDAS Aspects

Addresses 3 of 4 DDDAS components:

- Applications modeling
- Advances in mathematics and statistical algorithms, and
- Application measurement systems and methods

VVUQ for Sensor Networks

Dynamic Data-Driven Model Accuracy Assessment



Current Specific Goals

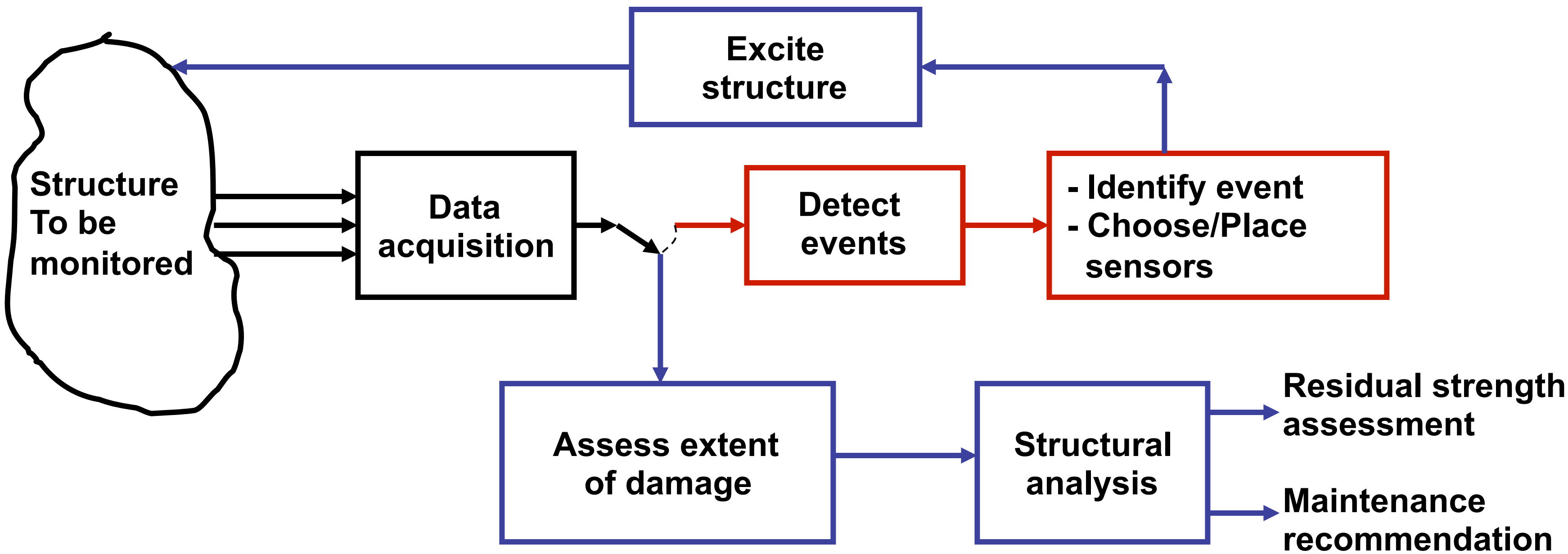
1. Determine **prior joint pdf's** describing knowledge of model parameter distributions.
2. Provide **proof of robustness** and stability of models under the various sources of perturbation (algorithmic, data, etc.).

Current Specific Goals

3. **Quantify validation processes** to assess the appropriateness of the calibrated model for predictions of quantities of interest (e.g., damage existence, damage extent, model and sensor parameter values).

4. Obtain piezoelectric active sensor network **experimental results** on metallic plates

A Generic SHM System



Damage assessment through active SHM

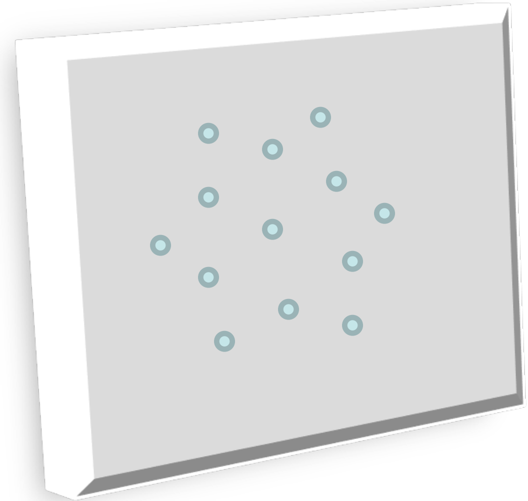
Excite the structure with ultrasonic waveforms.

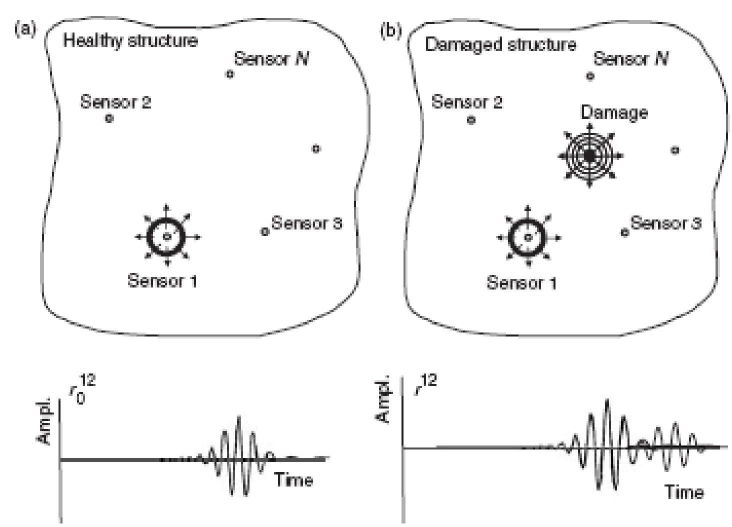
Collect signals that arrive at sensors distributed on the structure from the actuating transducer.

Evaluate the health of the structure based on the properties of the collection of signals.

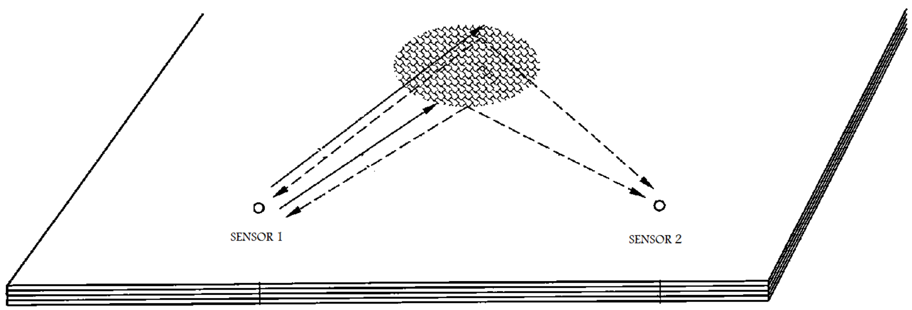
Once the system is installed, automated inspection possible.

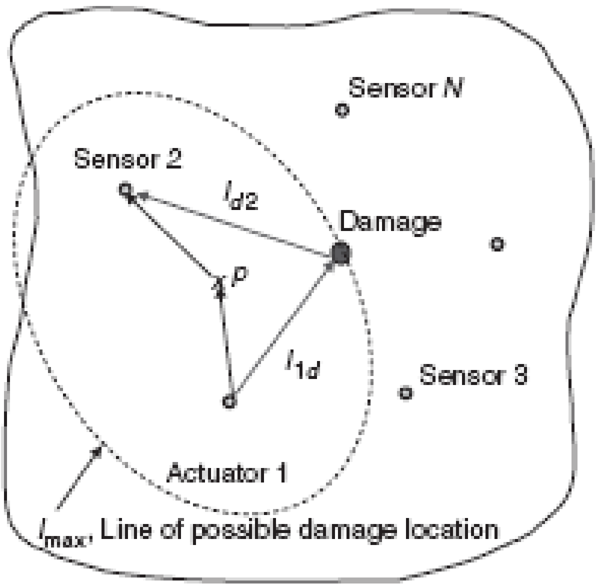
Physical access to inspection areas not needed during test.





Estimation of Damage Extent





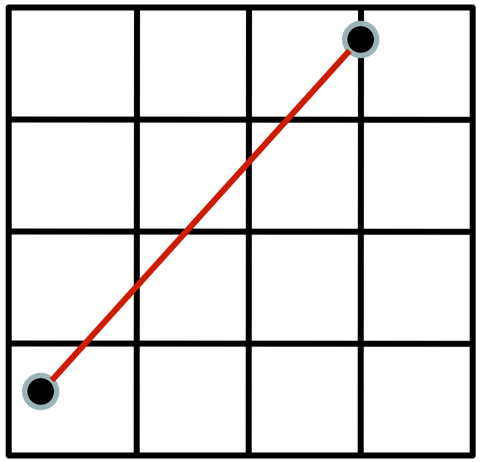
Surface waves propagating through the structure get reflected from both the front and back edges of the damage

Knowing the wave velocities and the time differences between transmitted and received signals for multiple transmitter-sensor pairs will allow estimation of the damage edges.

Anomaly mapping without knowledge of wave velocities

Abnormalities at each point in the path contribute to the dissimilarity index in accordance with the severity of the "damage"

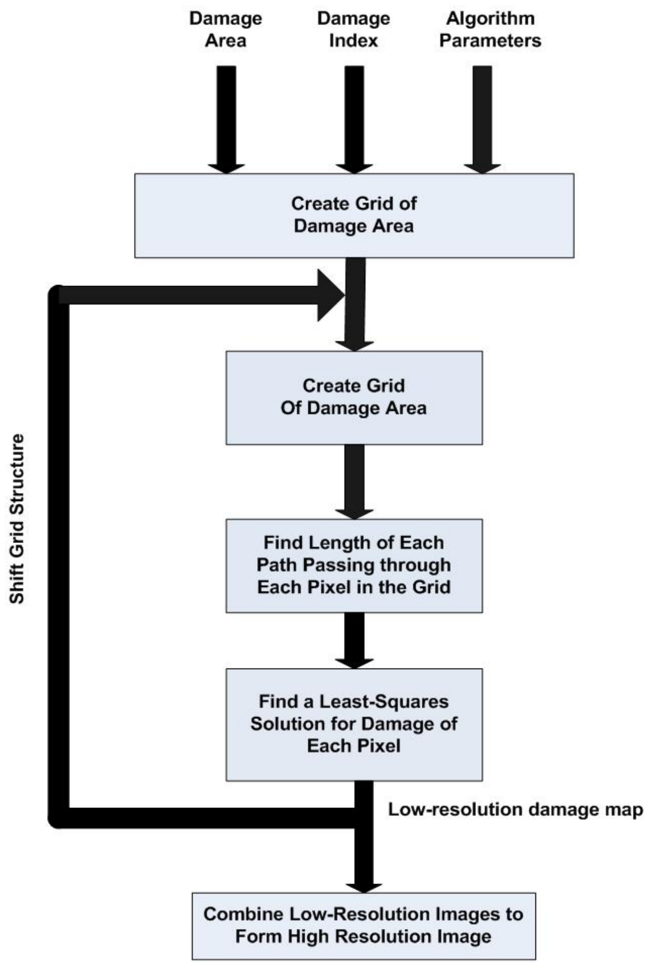
$$D(i,j) = \sum_{m,n} d(m,n)\, l(m,n,i,j)$$

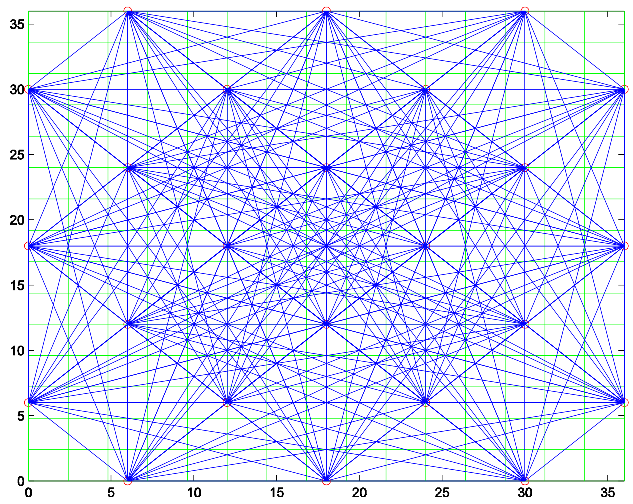


Solve for $d(m,n)$ from an over-determined set of linear equations

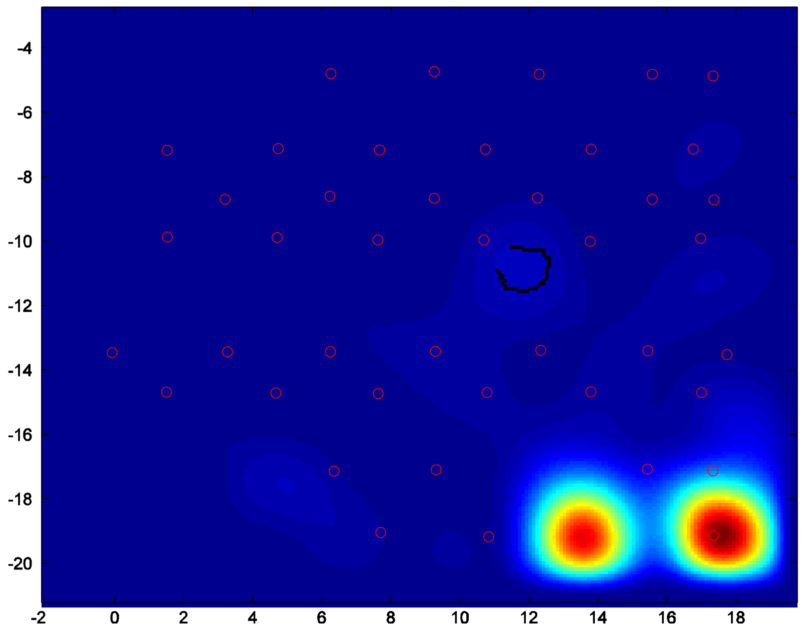
Same idea as that of tomographic reconstruction of medical images.

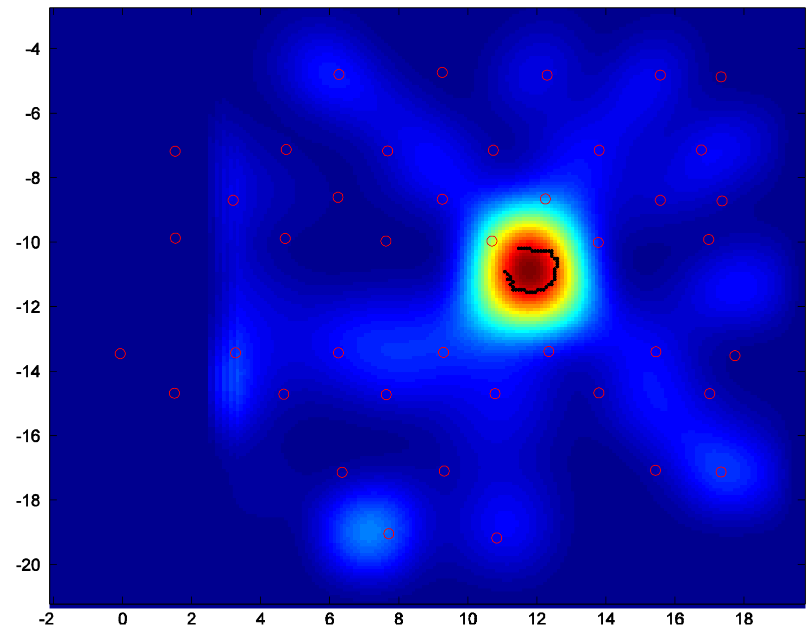
Block diagram of anomaly mapping algorithm





Robustness to sensor damage





The performance of the algorithm does not suffer significantly if a few damaged sensors are removed from the calculations.

We have developed a method for identifying the damaged sensors by analyzing the “local” statistics of the damage indices.

A damage mapping example for a series of damaging impacts

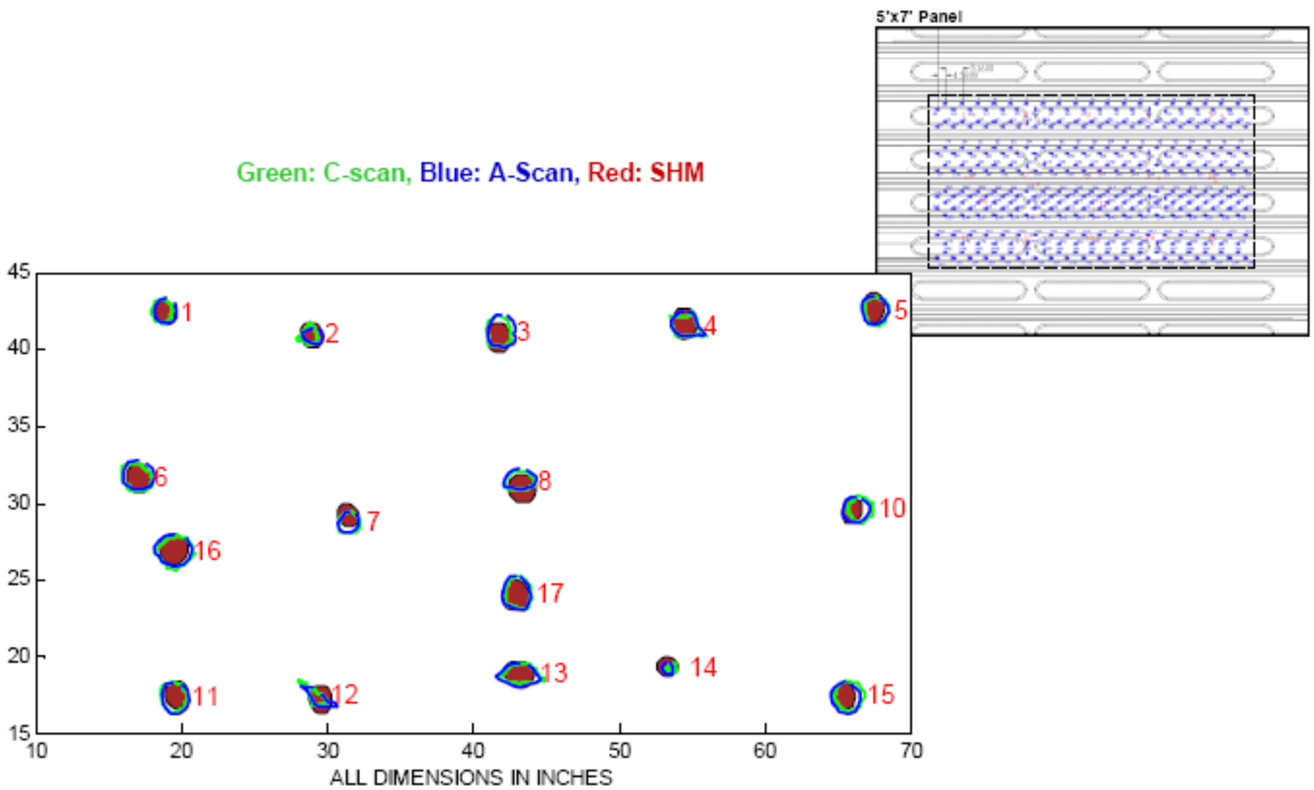
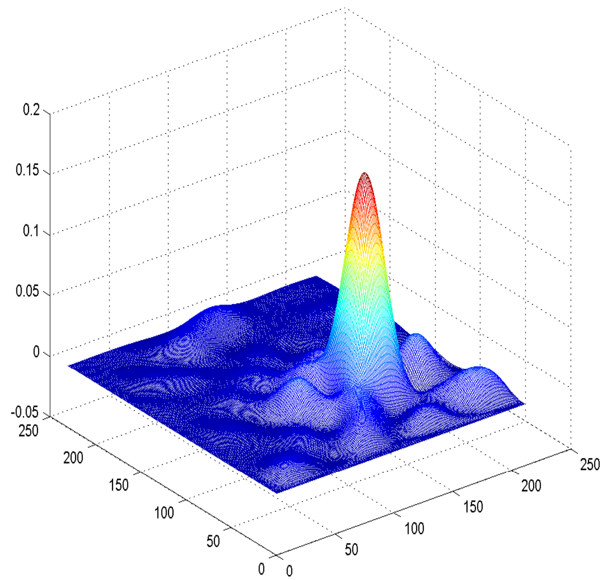
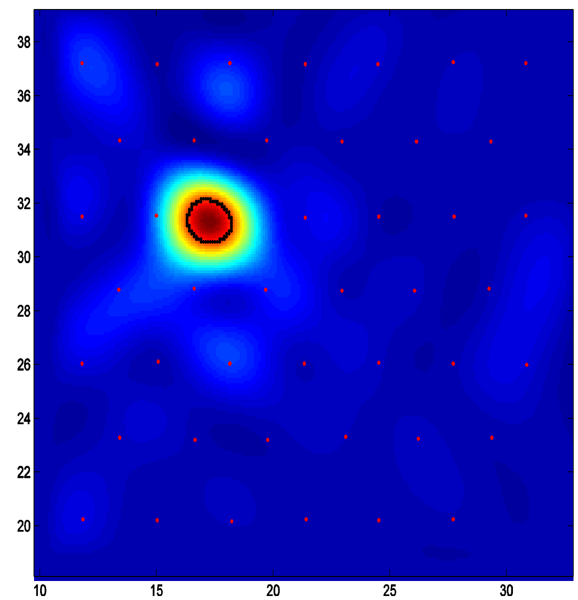


Image reproduced with permission from Boeing

A Damage Mapping Example

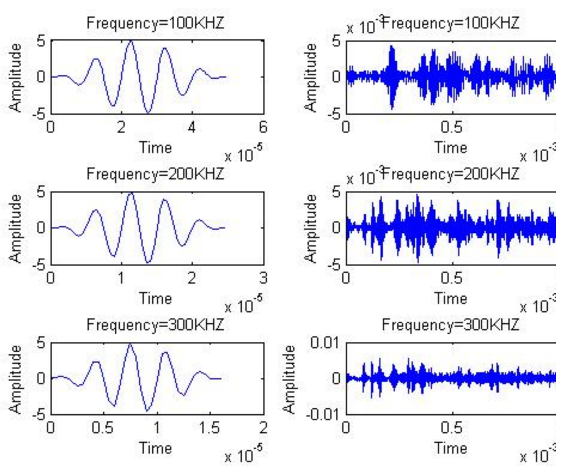


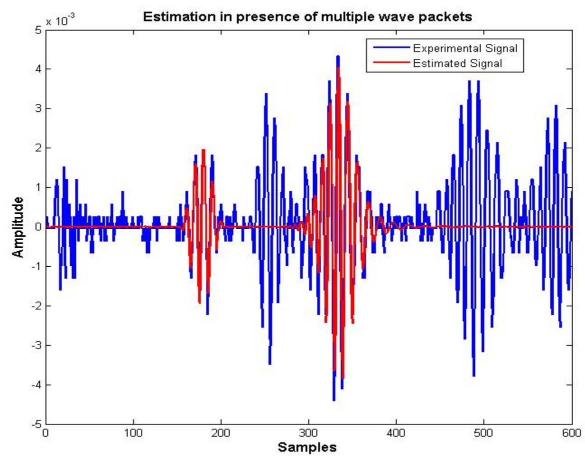


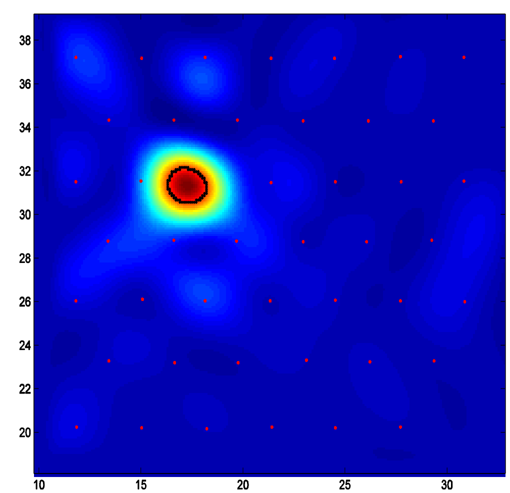
SHM systems can perform as well or better than C-scan-based NDI systems at much lower cost, faster speed, and without expert human supervision

Dynamic Data-Driven Approach for SHM

Data collection using SHMOBOT along all orientations of the structure → Identification of modes from a mixture of modes and reflected wave packets → Separation of overlapped modes (in case they overlap) → Locating damage and its extent using the information extracted from individual modes





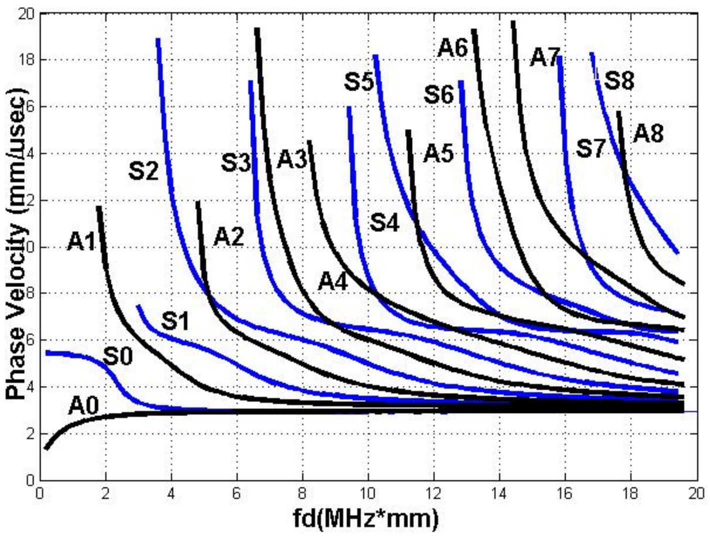


Advantages of DDDAS Approach for Lamb Wave SHM

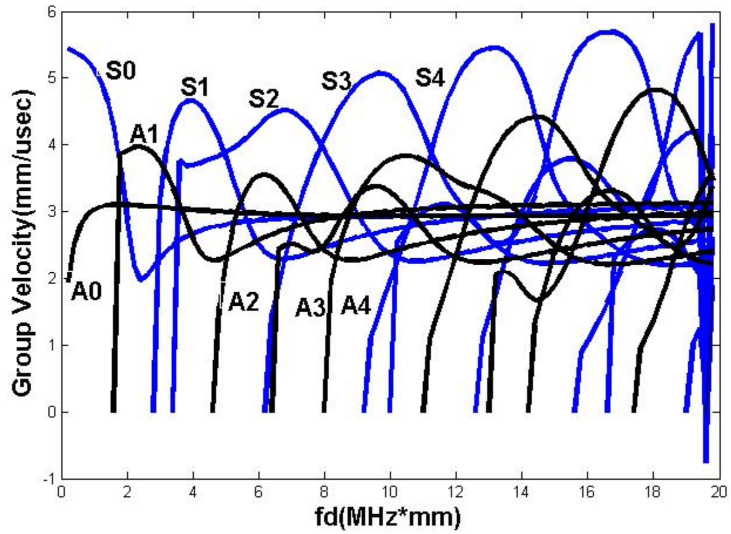
- The multimodal and dispersive characteristics of Lamb waves may change due to changes in environmental conditions and structural properties.
- This may result in failure of models (used to locate and characterize damage) based on previous knowledge of the medium.
- In the data driven approach, the models are developed based on the data collected from the experiments.
- The inference about the location, type and extent of damage is drawn based on these models.

Analytical Dispersion Curves for Lamb Waves

Phase velocity vs. fd



Group velocity vs. fd



Dispersion curves presented are derived based on Rayleigh-Lamb equations

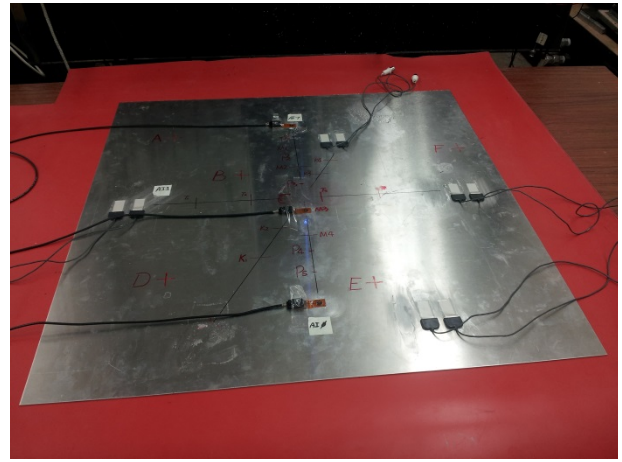
Analytical Model for Sensor Signal

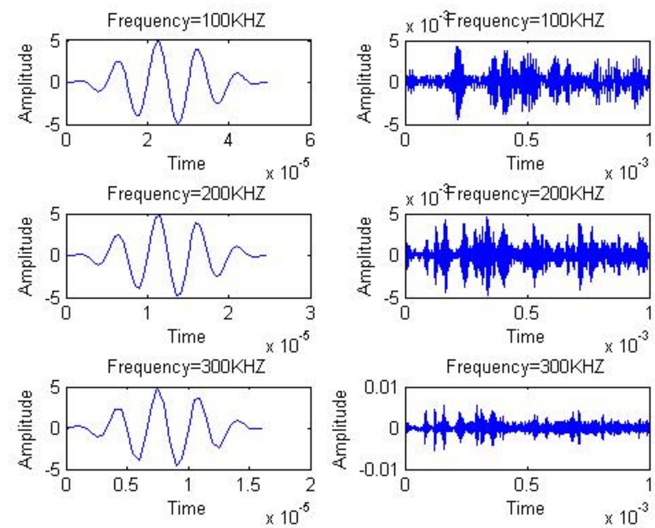
$$y(t) = \mathcal{F}^{-1}\left[\sum_{m=1}^{N} E_m A_m(\omega) X(\omega) H_m(\omega)\right]$$

- Input signal: x(t)
- Output signal : y(t)
- m= Mode number
- E_m =Energy distribution factor
- A_m = Attenuation factor: ($e^{-\alpha * D}$); α=Damping Coefficient; D=Distance between sensors
- X(ω)= $\mathcal{F}$[the windowed signal]
- $H_m(\omega)$= Phase response= $e^{-j\omega\tau}$ (Obtained by using the information from dispersion curves)

Experiments on an Aluminum Plate

- Aluminum panel of thickness 1.6mm
- 2 (0.25 inch Acellent) sensors
- Sensor close to upper boundary - actuator
- Sensor close lower boundary- Receiving sensor
- Excitation signal – 5 cycle, Hanning window

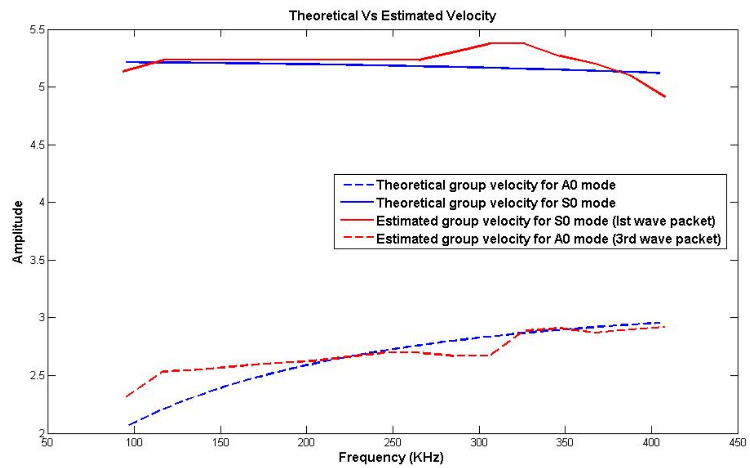




Mode Identification Based on Group Velocity Estimation

Excitation signal (X) and sensed signal(Y) → Band pass filter X and Y → Hilbert transform of the filtered signals to calculate envelope of the signals → Cross correlation between the envelopes to estimate time delay (Δt) → Group velocity= $\Delta D/\Delta t$

- ΔD is the distance separation between actuator and sensor
- Center frequency is shifted by some step and the process is repeated to get a range of velocities.



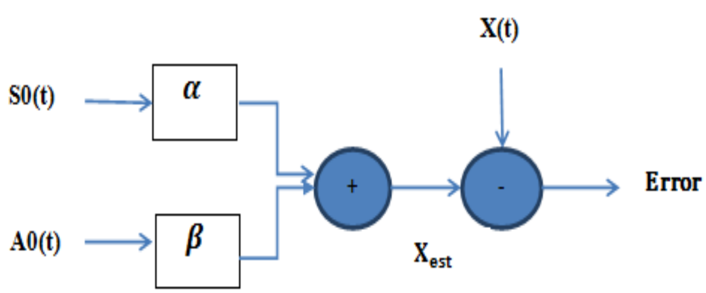
Estimated group velocity for mode identification

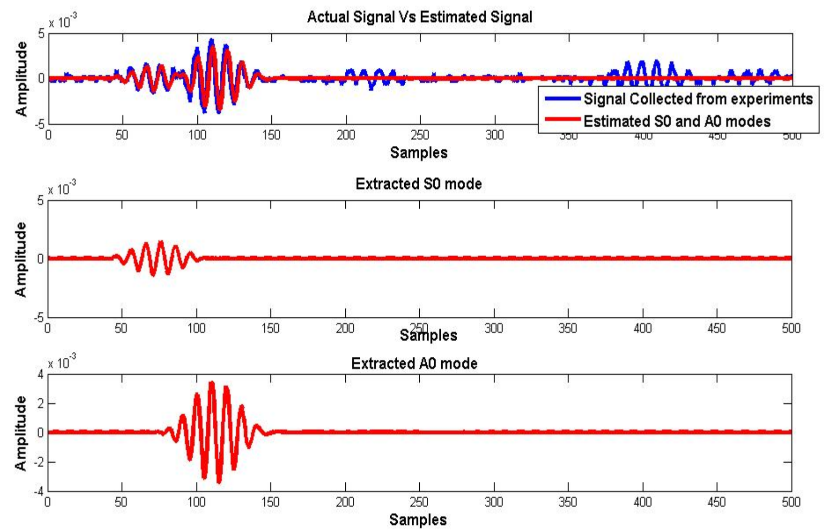
Inference from the plot: First wave packet in the sensed signal is S0 mode. Third wave packet is A0 mode

Separation of Overlapped Modes When Dispersion Characteristics for the Structure is Approximately Known

Method:

- The technique assumes the knowledge of dispersion curves of the material.
- A filter based on the Wiener-Hopf criterion is used.
- Input to the filter: Modes generated using analytical model.
- Desired signal : Result of the experiments at the receiver sensor.
- The estimated output: Combination of individual estimated modes.

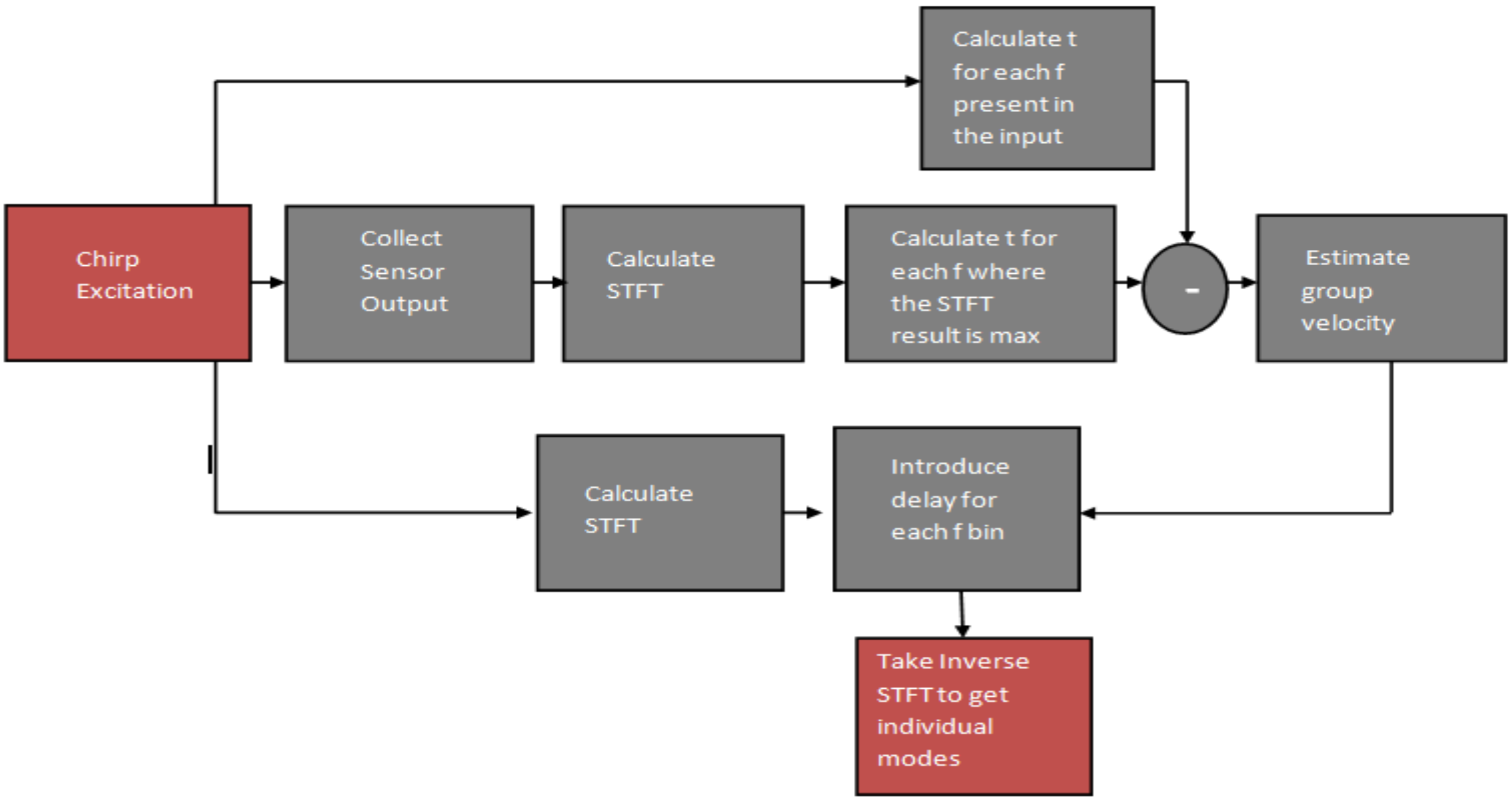




Here S0(t) and A0(t) are the modes calculated using analytical model and X(t) is the experimental result.

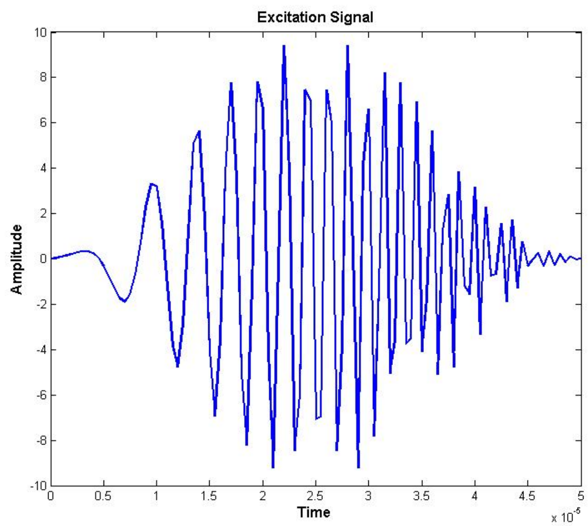
Separation of Overlapped Modes When the Dispersion Curves of the Structure are Unknown

Method (shown in block diagram)

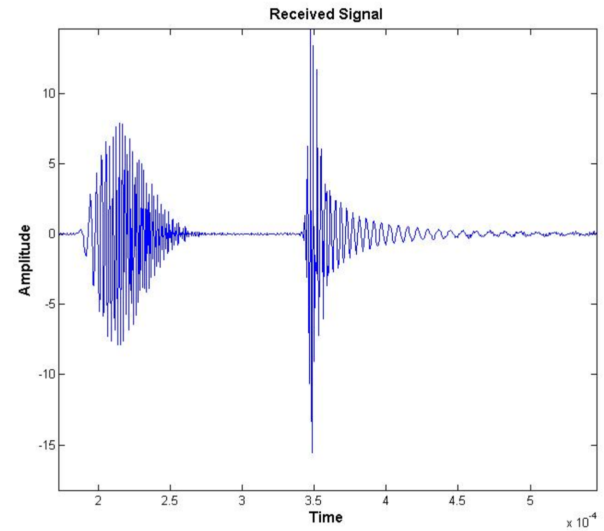


t represents time and f represents frequency

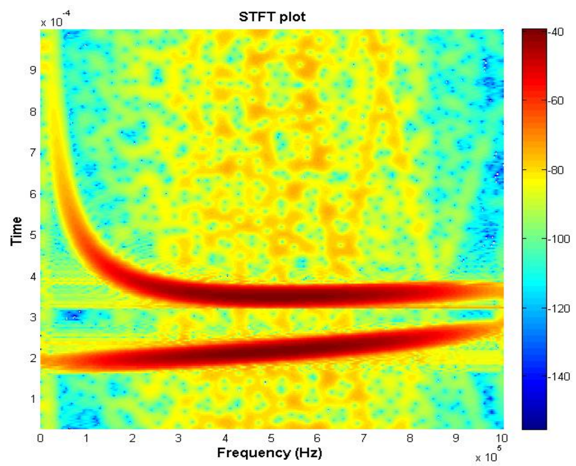
Simulation Results



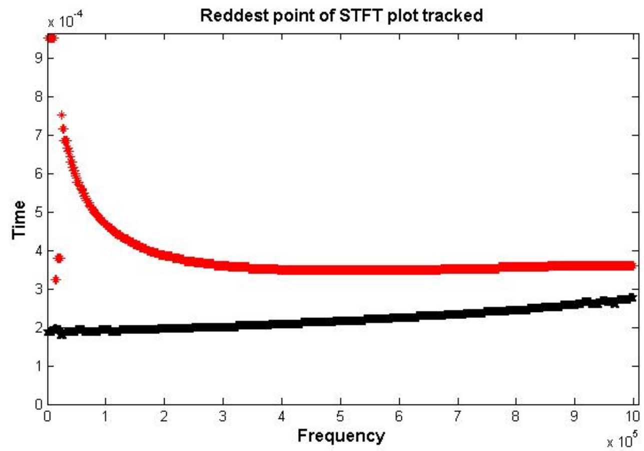
Excitation signal (chirp; frequency 20 KHz to 900 KHz)



Sensed signal

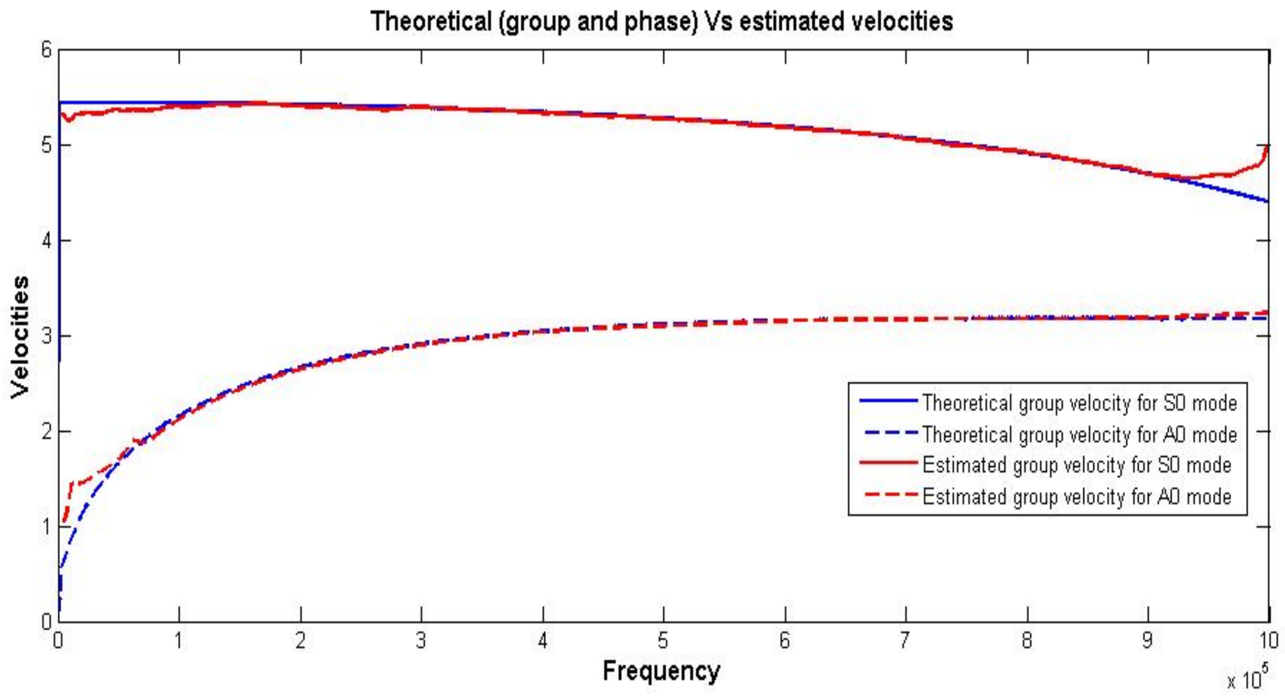


STFT plot of the received signal



Points with maximum amplitude of the STFT plot tracked

Theoretical Vs Estimated Velocity



Final Signal reconstruction is in the stage of implementation. Once individual modes are identified and extracted, damage mapping can be done.

Current Issues

- Uncertainty Quantification
  - Developing Polynomial Chaos system for the Cp function
  - Compare to Monte Carlo methods
- Mobile robot for optimal data acquisition for parameter estimation
  - Sensor placement
  - Sensor trajectories
  - Sensor selection
- Symmetry Analysis (Data, PDE's, etc.)

Uncertainty Quantification

- Determine parameters, **x**, of Cp function as centered, normalized, mutually orthogonal Gaussian variables
- Space of Hermite polynomials in **x**
  - If Cp(**x**) is a Gaussian random variable, then the Hermite basis is optimal
- Cp(**x**): see following slides

UQ: Cp Function

- Solving for constants lead to Rayleigh-Lamb Frequency Equation:

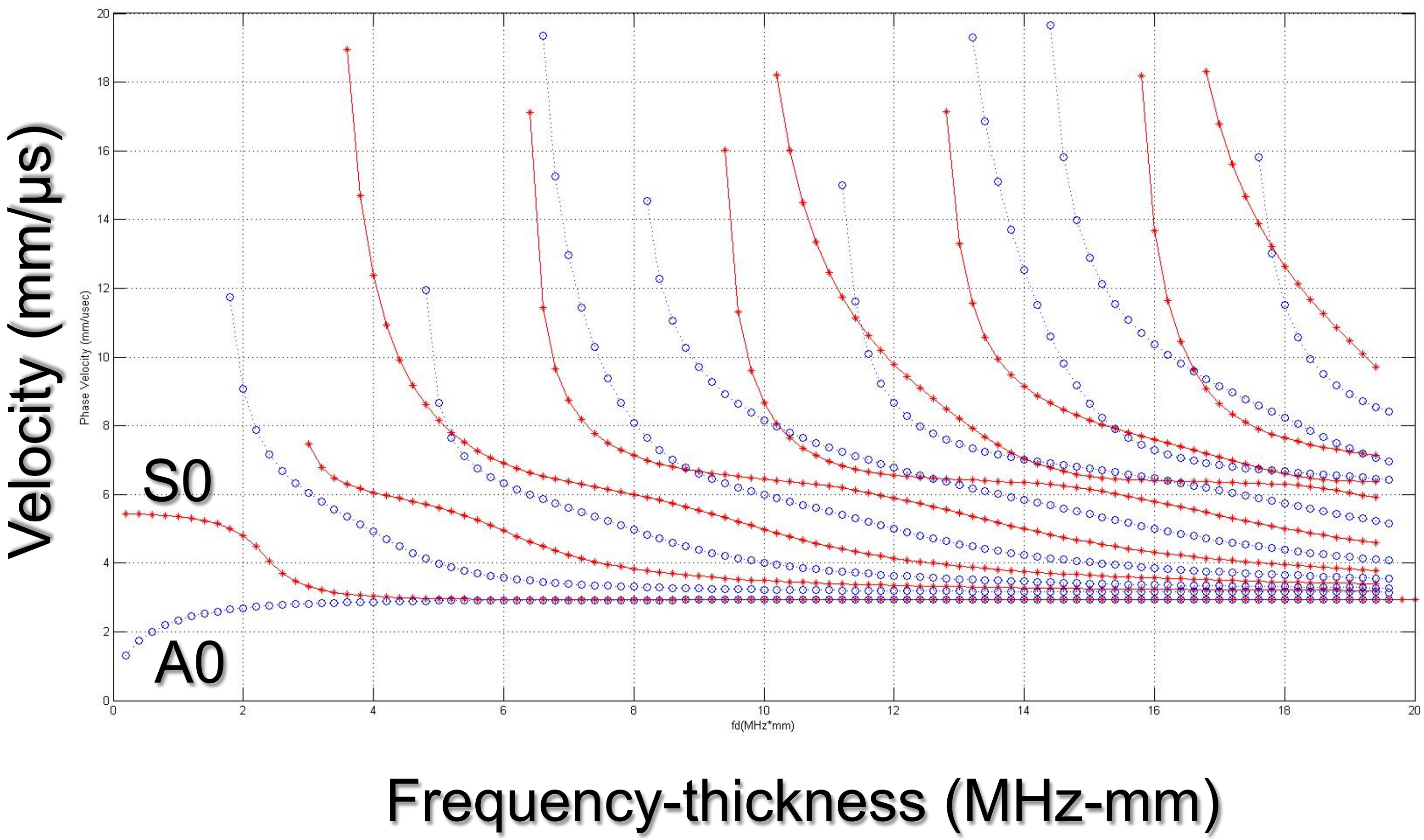
$$\tan(qh)/\tan(ph) = -4k^2 pq/(q^2 - k^2)^2$$

Symmetric Modes

$$\tan(qh)/\tan(ph) = -(q^2 - k^2)^2/4k^2 pq$$

Antisymmetric Modes

UQ: Dispersion Curves



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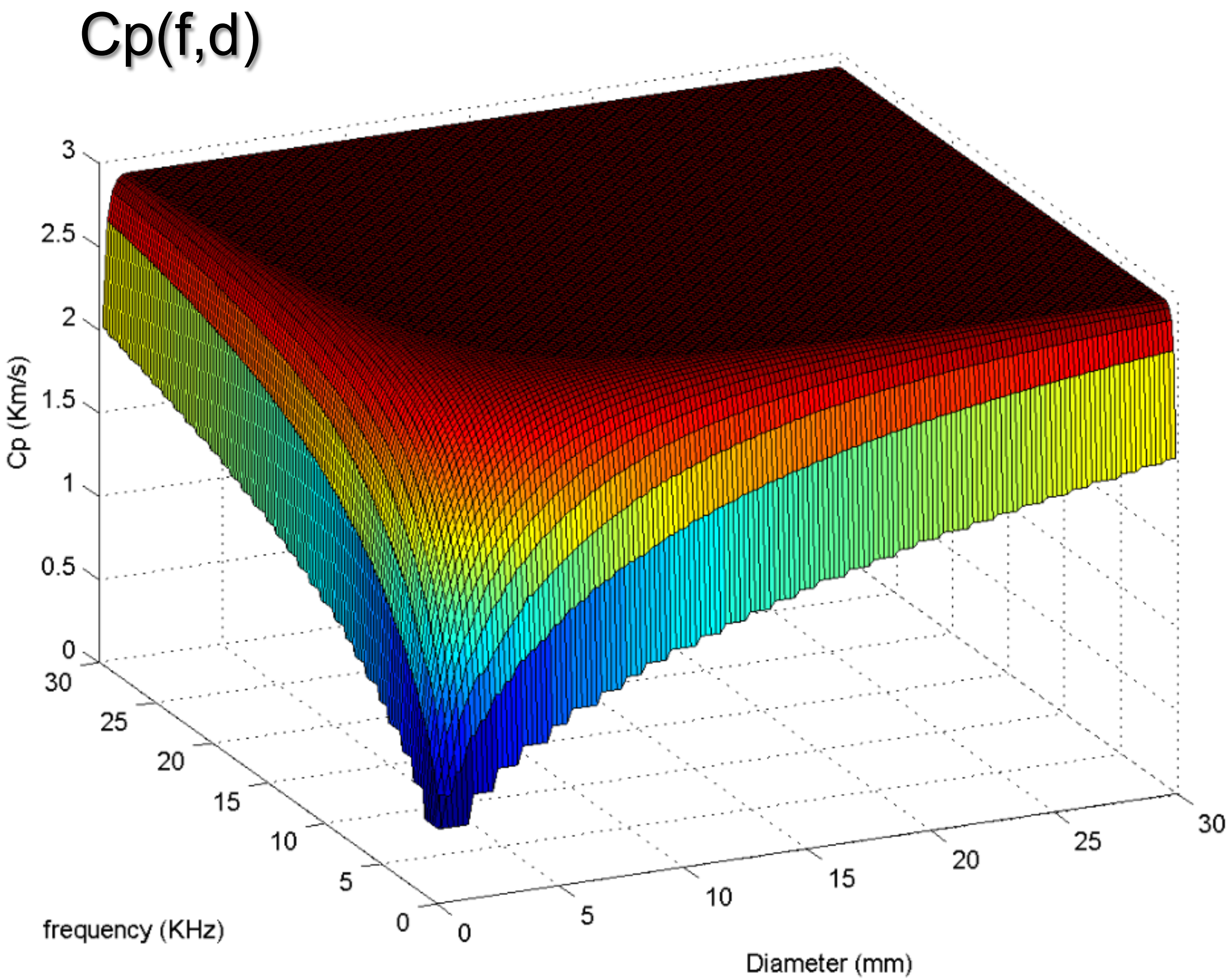


Dynamic Data Acquisition

- **S**tructural **H**ealth **M**onitoring R**obot**: **SHMOBOT**
  - Demonstration Prototype
  - Simple Tracked Robot
  - Reusable Sensors (Not Bonded)

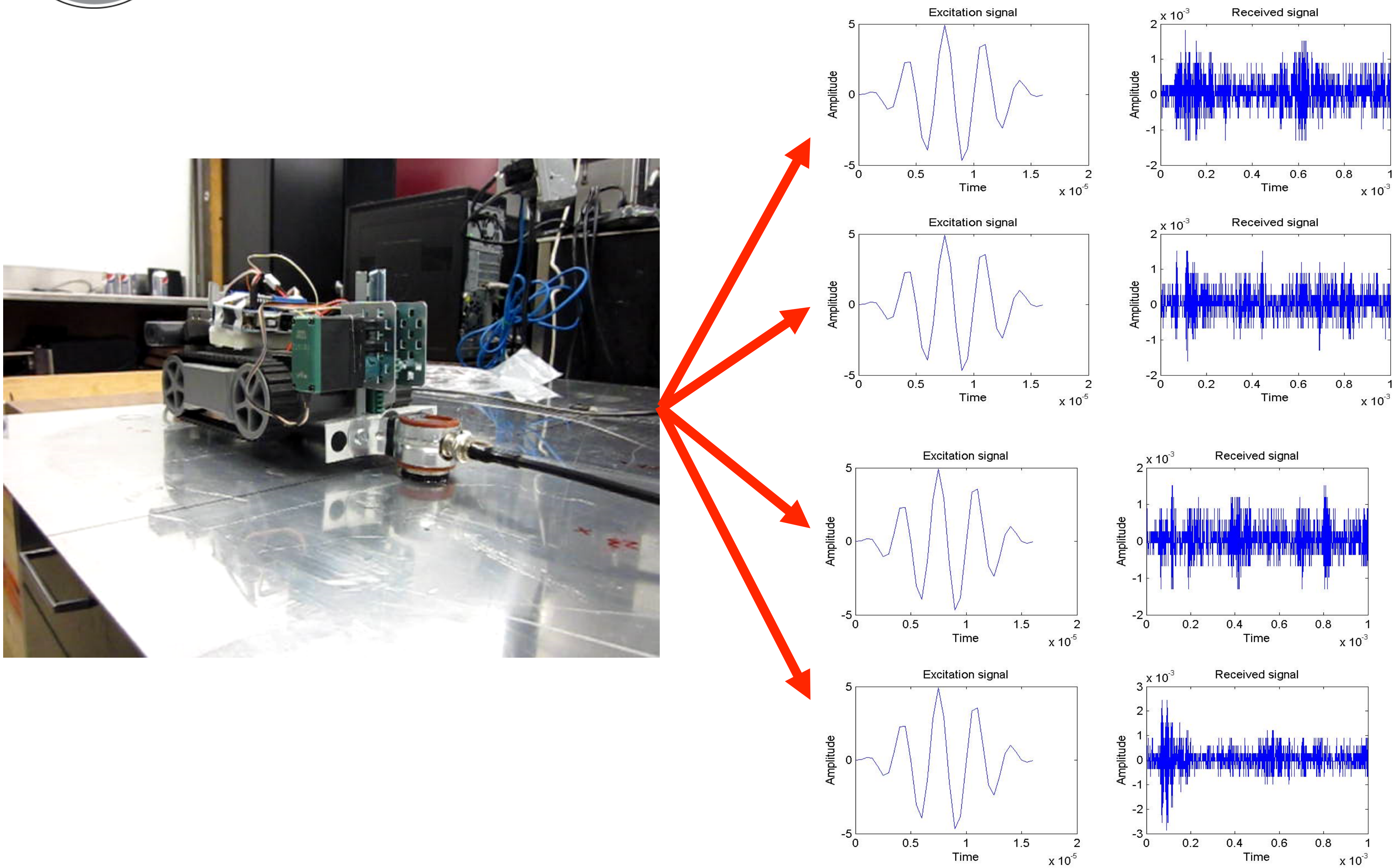
  - Optimal sensor placement
  - Baseline Measurements
  - Parameter identification in distributed parameter systems
  - Robot Localization (inverse problem)
  - Multi-robot (sensor) coordination

Sensor

Acoustic Technology Group, Inc

- **VS900-RIC Sensor: 100-900 kHz, ceramic face, integrated preamplifier (34 dB gain)**

Shmobot: First Cut



Recent Related Patent (Eddie Grant)

US008510061B2

(12) **United States Patent**
Grant et al.

(10) **Patent No.:** **US 8,510,061 B2**
(45) **Date of Patent:** **Aug. 13, 2013**

(54) **METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR WIRELESS CRACK DETECTION AND MONITORING**

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(73) Assignees: **North Carolina State University**, Raleigh, NC (US); **DRS C3 & Aviation Company**, Herndon, VA (US)

(58) **Field of Classification Search**
USPC 702/38–49, 104, 116–124, 182–189
See application file for complete search history.

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(Continued)

Questions?