metis design

mechanical design
composites engineering
structural health monitoring

Approaches for Data & Power Efficient

Health Monitoring System Architectures

Seth S. Kessler, Ph.D.
skessler@metisdesign.com

222 Third Street • Cambridge, MA 02142 • 617.661.5616 • http://www.metisdesign.com

Overview

- The objective of Health Monitoring is to identify changes in components to reduce life-cycle costs & improve safety
  - inspection & maintenance savings of 30% through improved efficiency
  - must consider capital costs of system implementation & sustainment
  - non-monetary operating costs also play a role: data & power burden

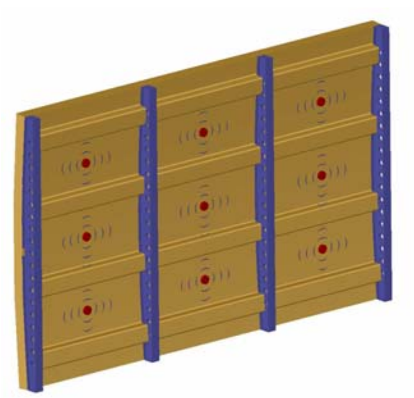
- Applicable to many subsystems
  - structural, engine, electrical, computational (UAV)
  - SHM focus of this talk based on experience, analogous to other systems

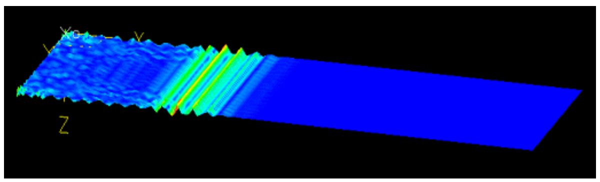
     

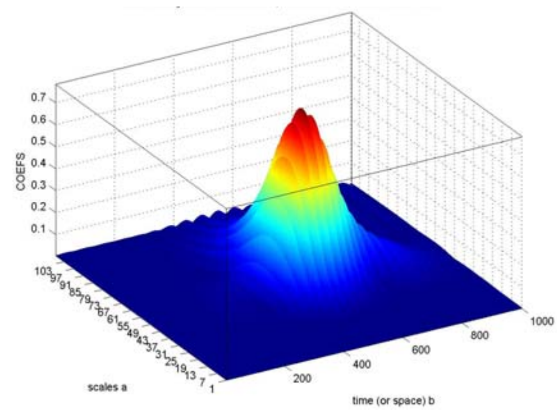
Considerations

- Many variables control the volume of data & required power
  - sensor type, density & overall coverage area
  - active (excitation-based) versus passive (witness layer) detection
  - duty-cycle for monitoring & collection of data
  - infrastructure, particularly wired, wireless & hybrid systems

- Creative architectures & advanced signal processing methods can minimize overall impact data & power have on systems







Application Dependencies

metis design

- Commercial aircraft
  - large coverage area
  - more cost & safety sensitivities
  - FAA requirements, particularly for wireless

- Military aircraft
  - generally smaller coverage area
  - higher performance requirements
  - shorter, less frequent flights

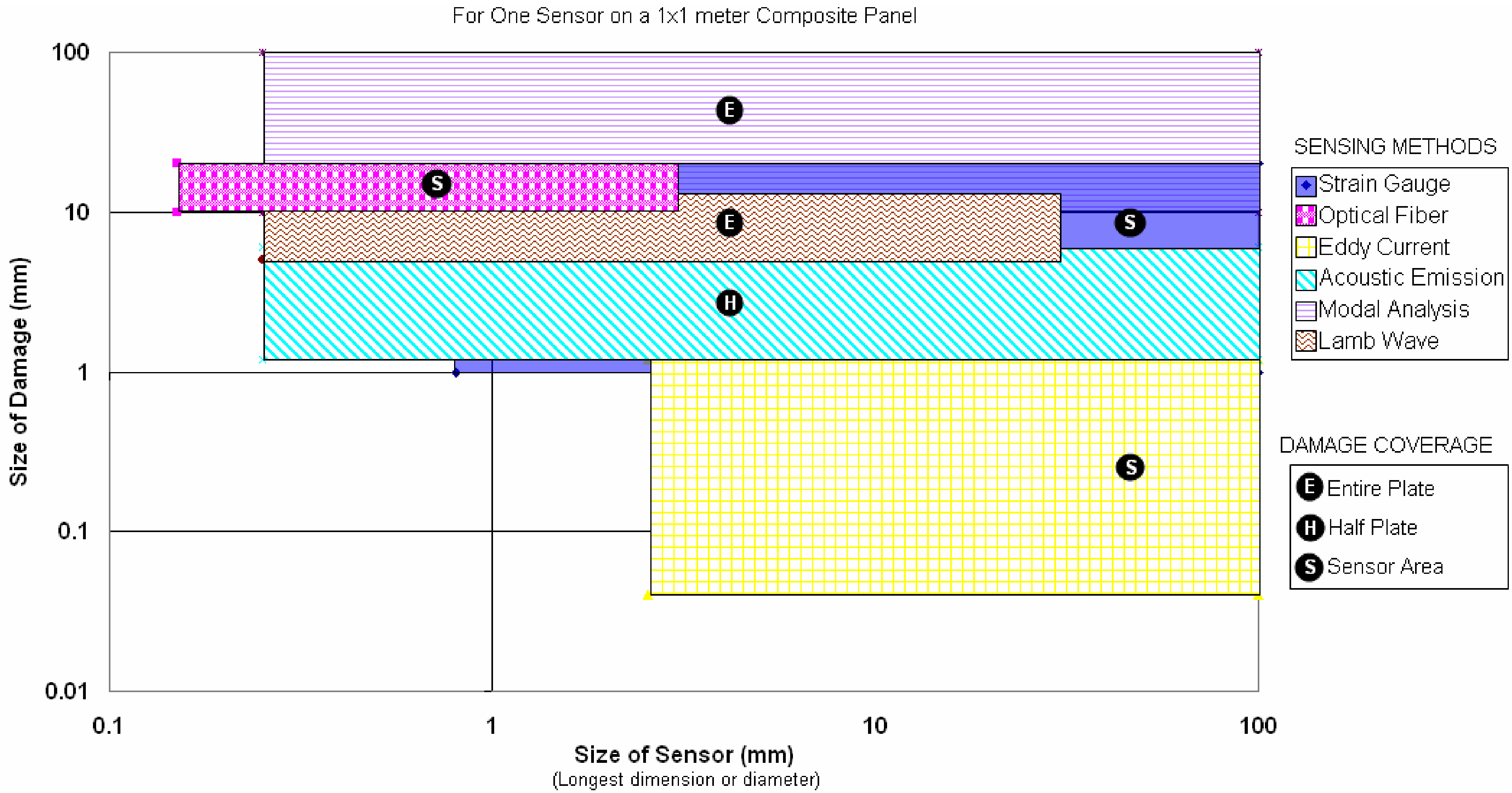
- Other applications
  - rotorcraft – mechanical fatigue & EMI are worse
  - spacecraft – larger weight penalty, environment
  - ground, sea, civil – very long operating time

Structural Monitoring Methods

metis design

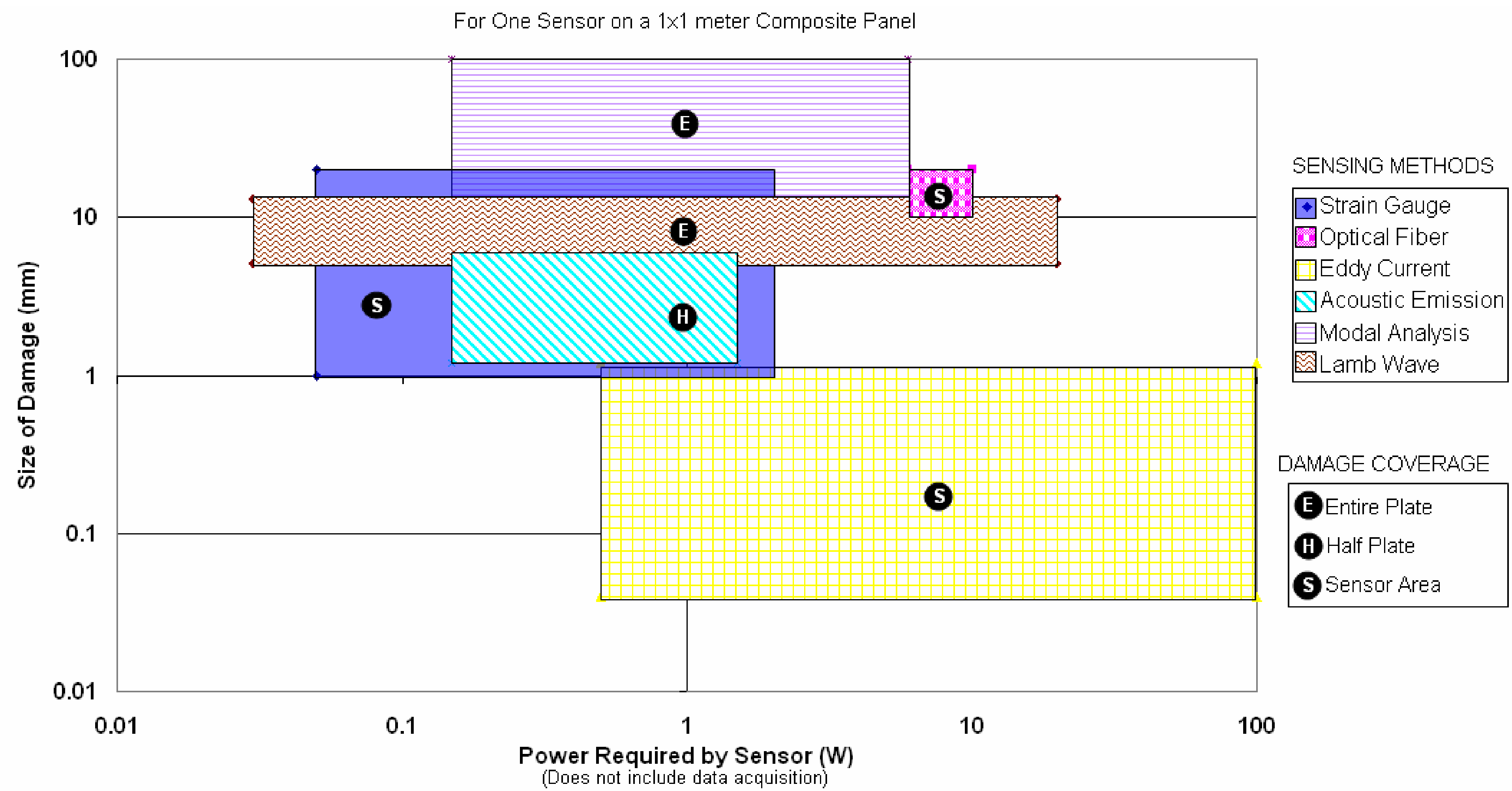
Methods	Description	Strength	Limitation
Strain Gauge	Use of foil gauges to measure local strain	Thin, low-power, light, inexpensive	Limited local info obtained, static
Fiber Optics	Use of light to measure local strain along fibers	Small, large linear coverage	Limited transverse into, high-power
Eddy Current	Electric & magnetic fields affected by permittivity	Highest sensitivity, thin & light sensors	Limited coverage, power, complex
Acoustic Emission	Collects broadband wave responses to damage events and propagation	Large coverage, flexible placement, event discretization	High acquisition rates, blind to ageing changes
Modal Analysis	Compares modal responses over time	Large coverage, flexible placement	Large databases, only global results
Lamb Wave	Elastic perturbation slows & reflects from stiffness or density changes	Large coverage, detailed results, surface penetrating	Complex setup, complex results, can be high power

Detectable Damage vs Sensor Size



Methods with best damage/sensor size ratio typically have low coverage, only Lamb wave and FR methods cover entire area, AE covers most

Detectable Damage vs Sensor Power



Methods with lowest power requirement typically have lowest coverage; for Lamb wave and FR methods sensitivity scales with power level

Method Comparison

metis design

Methods	Data	Power	Active/Passive
Strain Gauge	2 bytes/s – 2kB/s (1Hz – 1kHz)	~70mW @5V 350 Ω ($P \propto V^2$)	Passive
Fiber Optics	2GB/s 1GHz	~10W mostly for laser (not grading dependant)	Passive
Eddy Current	2kB/s – 200MB/s (1kHz – 100MHz)	~800mW @5V 30mm² ($P \propto A^*V^2$)	Active
Acoustic Emission	2MB/s – 20MB/s (1MHz – 10MHz)	~100mW @5V ($P \propto V^2$)	Passive
Modal Analysis	200kB/s (100kHz)	~175mW @5V 25kHz ($P \propto f^*A^*V^2$)	Either
Lamb Wave	2MB/s (1MHz)	~300mW @5V 100kHz ($P \propto f^*A^*V^2$)	Active

Active vs Passive Sensing

metis design

- Active damage detection methods
  - actively seek out damage sites
  - requires an excitation source; major power driver
  - can be stress, vibration, electric, magnetic or light-induced
  - typically yields more detailed damage state information
- Passive damage detection methods
  - passively witness operating environment
  - distinguishing feature is no structural excitation necessary
  - record maximum strain, displacement, impact energy, etc; reduced data
  - some methods can also constantly record
  - overall these methods are used to infer damage, often model-based

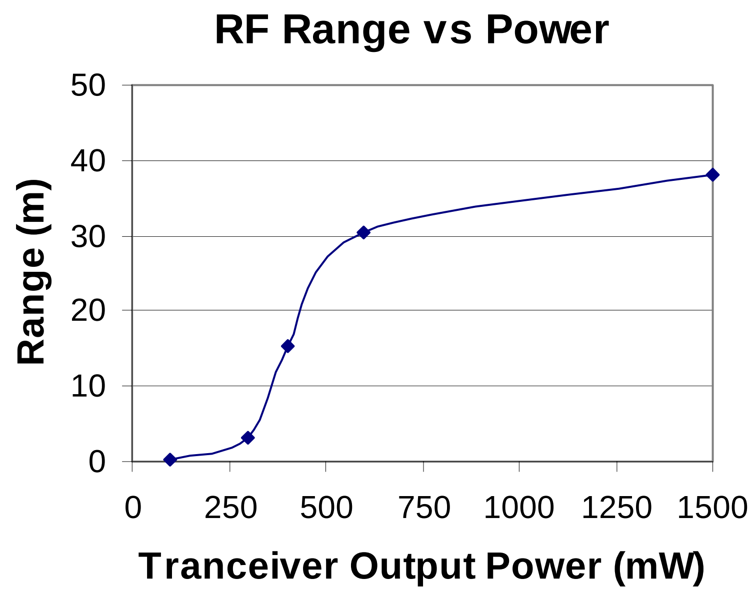
System Infrastructure Components

- **Connectors & cables: attach to sensors (semi)permanently**
- **Amplifiers: improve outgoing actuation or incoming signal**
- **Data acquisition: set rate and bit-resolution for digitization**
- **Computation: control and coordinate other components**
- **Memory: storage of collected data**
- **Communication: accept external commands, pass data**
- **Power: provide excitation source, supply for electronics**

Wired vs Wireless Systems

metis design

- Need for wireless SHM
  - Cables & connector, are fault prone
  - Corrode & crack in harsh environment
  - add weight, cost, integration time
  - established communication protocol



- Downsides to wireless
  - heavily regulated in several applications (FAA for EMI, DOD for security)
  - places large constraints on sensor power consumption
  - requires batteries, which carry own longevity issues, including recharging
  - transmission range is power dependant

- Hybrid system can take advantage of many of the upsides
  - use wireless communication powered from a common bus
  - more reliable to monitor health of power lines compared to data lines

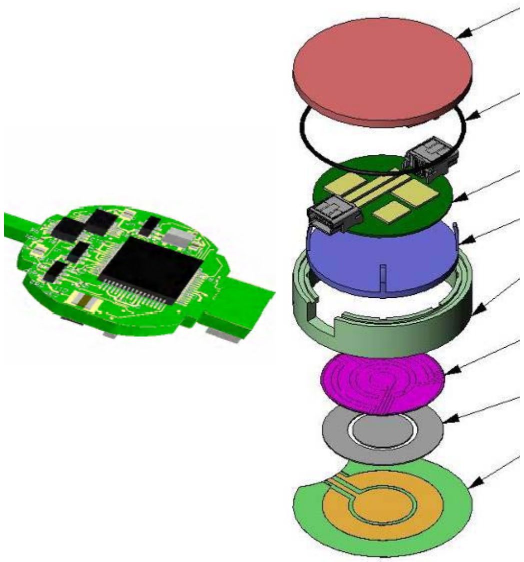
Duty-Cycle

- Duty-cycle defines how often data is collected
  - scheduled: such as pre or post-flight, particular altitude or speed
  - time intervals: sample every second, minute, hour, day, etc
  - continuous: always on and collecting
- Strategic states can be used to reduce composite power draw
  - *Off*: all chips in low power mode, analog disabled, ~1mW
  - *Listening*: transceiver waiting for commands, analog disabled, ~80mW
  - *Transmission*: sending data, analog disabled, ~220mW
  - *Testing*: all chips & sensors operating, ~3mW + 0.1W to 10W for sensor

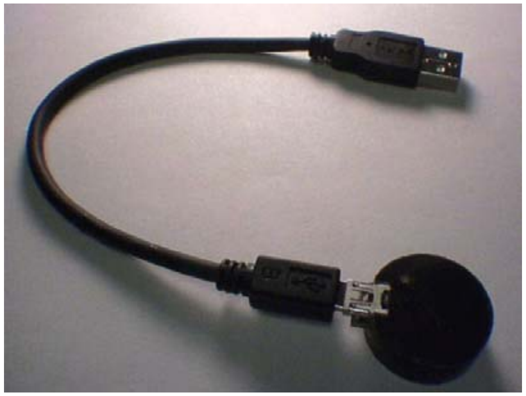
Duty-Cycle (1ms test)	Acquisition Rate for Lamb wave	Time to Fill 1GB File	Time to Drain 1Ah Battery
Continuous	1MHz	9 minutes	6.5 hours
1 sample/min	1MHz	1 year	0.5 year

Point of Measurement Electronics

- Point-of-Measurement (POM) is an MDC patent-pending concept for integration of SHM infrastructure components locally
  - digitizing at POM minimizes EMI introduction
  - digital bus requires less cabling then analog
  - POM amplification eliminates stray capacitance
  - achievable for nearly any detection method
  - enables several other data & power strategies



- M.E.T.I.-Disk 3 Digital SHM Node
  - Lamb wave, modal analysis, AE capable
  - 1MHz 16-bit ADC & 1MS/s 8-bit DAC
  - self-diagnostics for electronics & sensor
  - daisy-chain compatible using CAN bus
  - no external hardware required



Hybrid System Data Fusion

metis design

- Enabled by POM
- Active/passive hybrid system
  - use of local logic to adaptively set duty-cycles
  - passive methods used to trigger active methods
  - reduce data & power requirements without sacrificing state detail
- Multi-sensor hybrid system
  - shared infrastructure for multiple SHM methods reduces cabling
  - allows redundancy, better state understanding
- Multi-disciplinary hybrid system
  - shared infrastructure for monitoring multiple subsystems reduces cabling
  - potential can monitor structure & electrical system locally, for example

Distributed Computing

metis design

- Enabled by POM
- Nodal collaboration
  - nodes can communicate with each other as well as share data
  - facilitates Lamb wave pitch-catch or transfer function for modal analysis
  - can be used for efficient damage triangulation
- Traditional distributed computing
  - central processor would choreograph all microprocessors
  - using grid of nodes, central computation time is greatly reduced

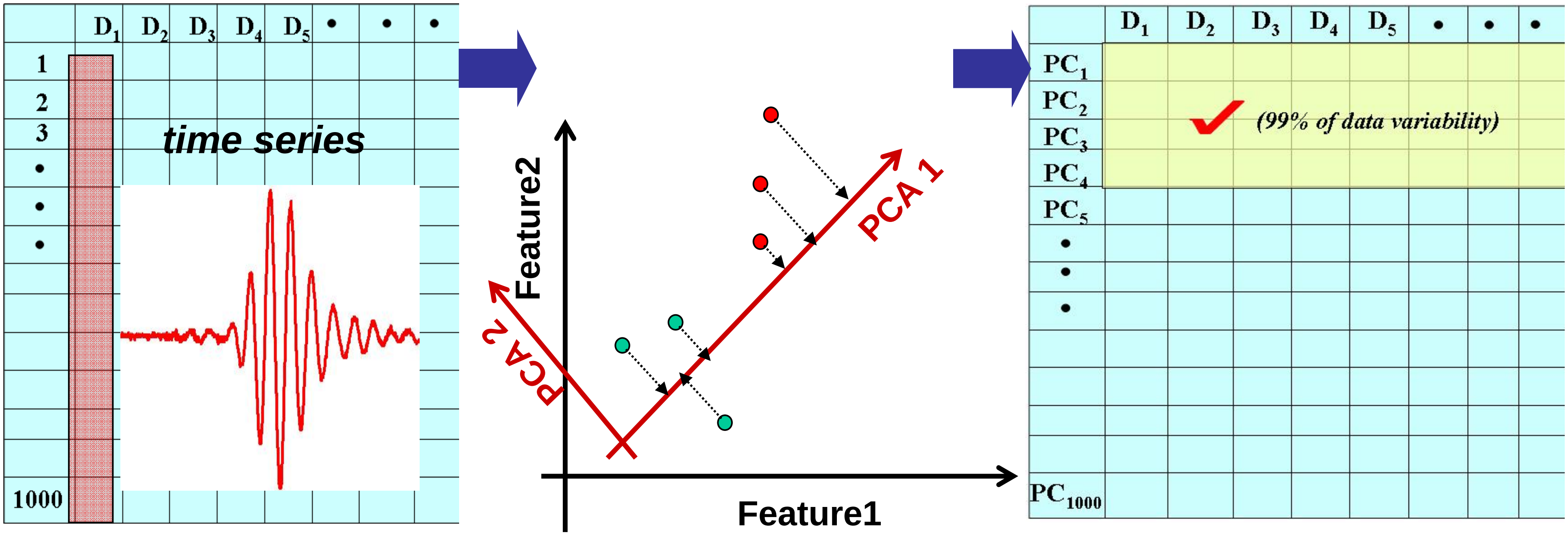
Local/Global Architecture

metis design

- Enabled by POM
- Local computation on microprocessor & FPGA
  - signal processing (filtering, denoising, etc)
  - data reduction (averaging, PCA)
  - logic or more complex algorithms
  - limit and/or compress data that is communicated to central processor
- Selectively sending data to central processor reduces volume
  - data only transmitted when damage state is determined
  - more elaborate or computationally intensive analysis can be performed
  - can corroborate results by commanding test at adjacent sensor nodes
  - simple OK signal can be used as a fail-safe

Principal Components Analysis (PCA)

metis design



- Technique for reducing dimensionality of dataset
  - minimizes data to be transmitted or stored without loss of accuracy
  - traditionally implemented by reducing the quantity of features selected
  - data sets are mapped to a multi-dimensional feature space
  - data sets are then projected to find axes yielding maximum variance
  - data sets are transformed into Principal Components (PC1,PC2,PC3…)
  - a 1000 time-series signal can be effectively reduced to a 4-level PCA

Pattern Recognition

Methods	Description	Strength	Limitation
Nearest Neighbor	Category of new data point determined by nearest neighbor point category	Intuitive, simple, highly adaptable	Sensitive to noise, large storage space
K-Nearest Neighbor	Category of new data point determined by average of k-nearest neighbors categories	Intuitive, simple, highly adaptable	Computationally intensive recall, large storage
Decision Tree	Series of branched questions leading to category leaves, weighting implicit in structure	Easiest to train, accommodates missing features	Rules may be complex, can be unstable
Neural Network	Machine-learning technique uses training data sets to weight input/output links	Robust to noise, multivariate & non-linear OK	Needs most training data, “black box”

Pattern recognition methods efficiently use collected training data to extract key features within multiple domains to classify “state” of health from new sensor data, including presence of damage, type and severity

Pattern Recognition Results

Methods	Damage Presence	4-Category Classify	Training (ms)	Testing (ms)	Memory (kB)
Nearest Neighbor	100%	100%	0	4	3.5
K-Nearest Neighbor	100%	80%	0	5	3.5
Decision Tree	97%	90%	16	4	6.25
Neural Net	100%	86%	950	8	26.75

- Example results from 8-ply quasi-isotropic composite laminates: undamaged, delaminated, 2-delaminations, matrix-cracking
- 18 training data sets used for each class, 1000 points each
- PCA used to reduce data to 4 principal components
- Very good presence results, categories improve with more data
- Presently working on implementation of damage severity state

Summary

metis design

- Data volume and power consumption play a major role in designing viable architectures for health monitoring systems
- Creative architectures & signal processing can minimize impact
  - sensor selection (active vs passive detection)
  - duty-cycle for monitoring & collection of data
  - wired, wireless & hybrid systems
  - principal component analysis (PCA) for data reduction
  - pattern recognition for state classification with minimal data collection
- Point of Measurement (POM) infrastructure
  - hybrid system data fusion
  - distributed computing
  - local/global architectures
- Not all of these architectures will work for every application, provides concepts & benchmarks to assist in design of system