Challenges for Aircraft Prognostics

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DAMAGE PROGNOSIS TECHNOLOGY

Preventing Catastrophic Failure

Predicting Remaining Life

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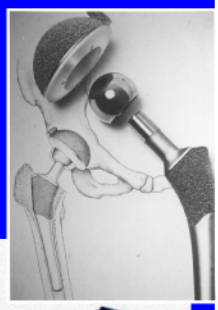
The Need

- Aircraft - power by the hour (airframe and engine)
- Nuclear - life extension of power plants
- Earthquake/terrorism - future use of buildings
- Prosthetics
- Military survivability
- Environment



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Levels of Health Monitoring

- Level 1: *Detect* the existence of damage;
- Level 2: *Detect* and *Locate* damage;
- Level 3: *Detect*, *Locate* and *quantify* damage;
- Level 4: *Estimate* the remaining life and usage; (Prognosis);
- Level 5: Self diagnostics; and
- Level 6: Self healing

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Outcome of Prognosis

- Minor: Continue operating with monitoring
  e.g. high cycle fatigue
- Chronic: continue operating at reduced load
  e.g. loss of control surface
- Acute: immediate action required
  e.g. Fan blade off

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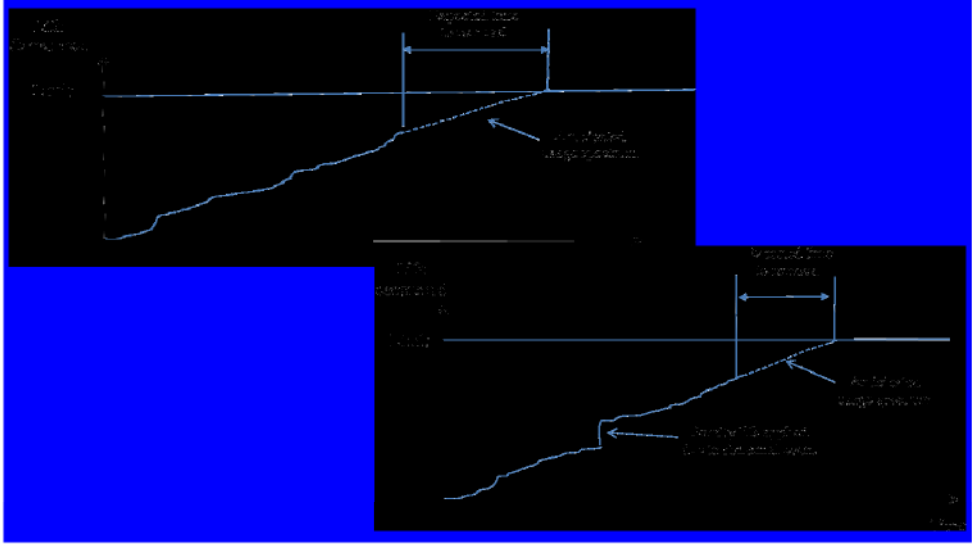
Monotonic damage accrual?



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DAMAGE PROGNOSIS TECHNOLOGY INTEGRATES

Smart Sensing and Computer Simulations
to Diagnose and Forecast System Performance

1. Develop a Computational Model of the System
2. Measure Critical System Parameters and Identify Damage
3. Update the Computational Model of the System
4. Estimate the Future Loading Environments on the System
5. Simulate Updated System Response to Future Environments
6. Predict the Remaining Useful Life of the System

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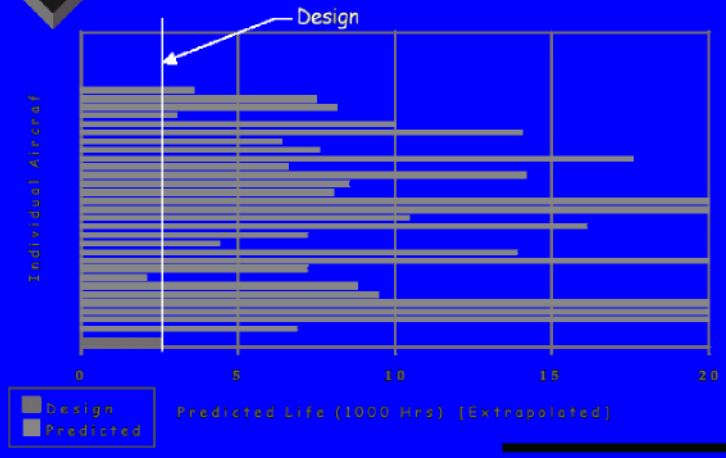
Variability in Component Life

AH-1W Rotor Pitch Link (P/N 214-010-410-119)



[Graham Forsyth – DSTO, HUMS conf, 2003]

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Rotary wing monitoring system – example

[Graham Forsyth – DSTO, HUMS conf, 2003]

Examples

REF	PARTS (Per S/S)	COST	Flight Hours DESIGN	Flight Hours PREDICT	PRED/DSN	Δ $/FLT HR
01	Yoke Assembly	$31280	2500	8350	3.3	$10.47
03	Spindle (2)	33400	4400	20000	4.5	5.92
05	Grip Assembly (2)	22960	4400	20000	4.5	4.07
06	Retention Strap (2)	7280	1250	1210	0.97	[0.19]
13	Main Rotor Blade (2)	161860	4400	9200	2.1	19.31
30	M/R Pitch Link Assembly (2)	5880	2500	16700	6.7	2.00
56	90° Gearbox Housing	10750	1400	6640	4.7	6.06
67	Wing, Left	31250	1500	6230	4.1	15.82
68	Wing, Right	31250	1500	20000	13.3	19.27
78	M/R Drag Brace	13690	1210	20000	16.5	10.63
				Total (73 Part No's):		$175.37

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Measurement Strategies

- Acquire everything ("big data")?
- Data integrity/redundancy/false negatives?
- Strain/Acceleration/Displacement/Thermal/Flight parameter……
- Relevancy (sensitivity)
- Wireless?

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Sensor placement – Mode 1 of a Lynx Airframe

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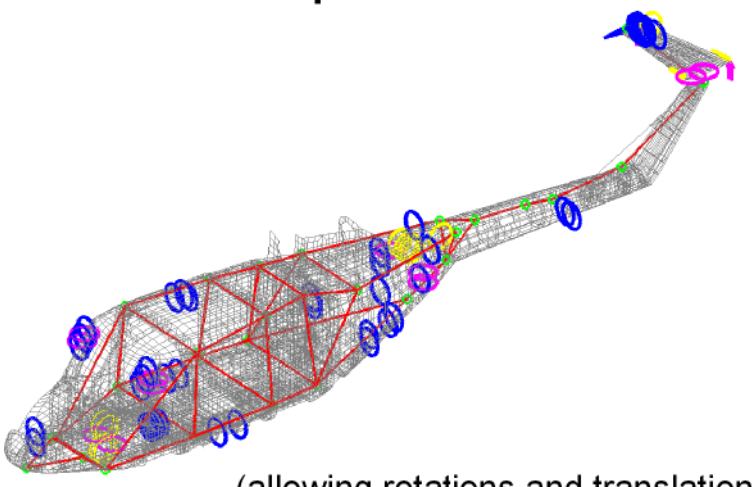
Placement of EfI-optimised sensors



(allowing rotations and translations)

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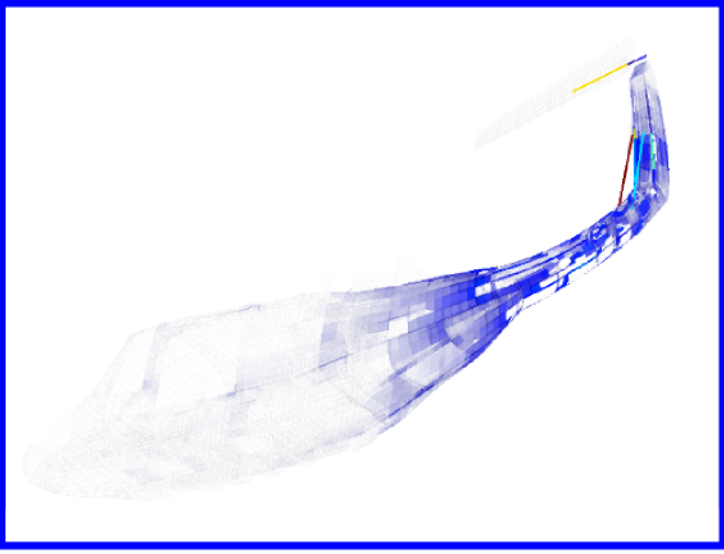
Sensor placement – Strain Energy Distribution



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Wireless sensing - Power Considerations

	Active	Idle	Sleep
CPU	5 mA	2 mA	5 µA
Radio	7 mA (TX)	4.5 mA (RX)	5 µA
EE-Prom	3 mA	0	0
LED's	4 mA	0	0
Photo Diode	200 µA	0	0
Temperature	200 µA	0	0

Panasonic
CR2354
560 mAh

- What does this mean?
  - Lithium cell runs for 35 hrs @ peak load and years at minimum load!
    - » *That's three orders of magnitude difference!*
  - Idleness is not enough, sleep!
  - A 1 byte transmission uses same energy as 11,000 cycles of computation!
    - » *Send decisions not data!*

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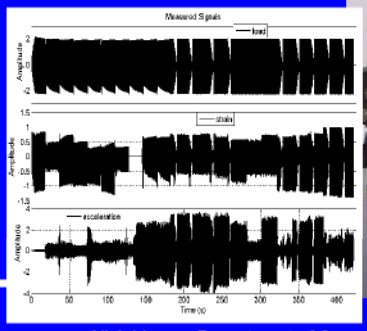
Pitch Link Rig Demonstrator

- Flight Representative Loading
  - Low Cost Replication of Flight Loads on pitch links
  - Controlled and Reproducible Equivalent Flight Profile
  - Generate Corresponding Sensor Signals for known wear conditions



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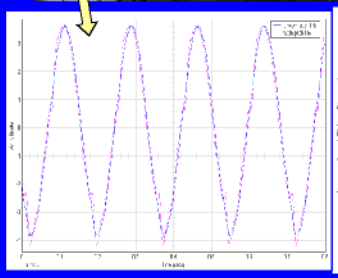
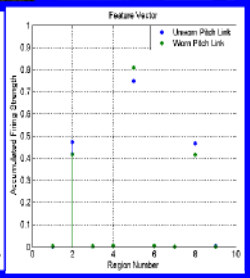
Pitch link tests





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Feature Extraction Algorithm Demonstrators

- Feature Extraction Algorithms
  - Significant reduction in transmission requirement
    - Power savings make battery/energy harvesting practical
  - Algorithms
    - Rain Flow Algorithm, fatigue cycle counting
    - Analogue Filtering
    - Wavelength Packet Transform

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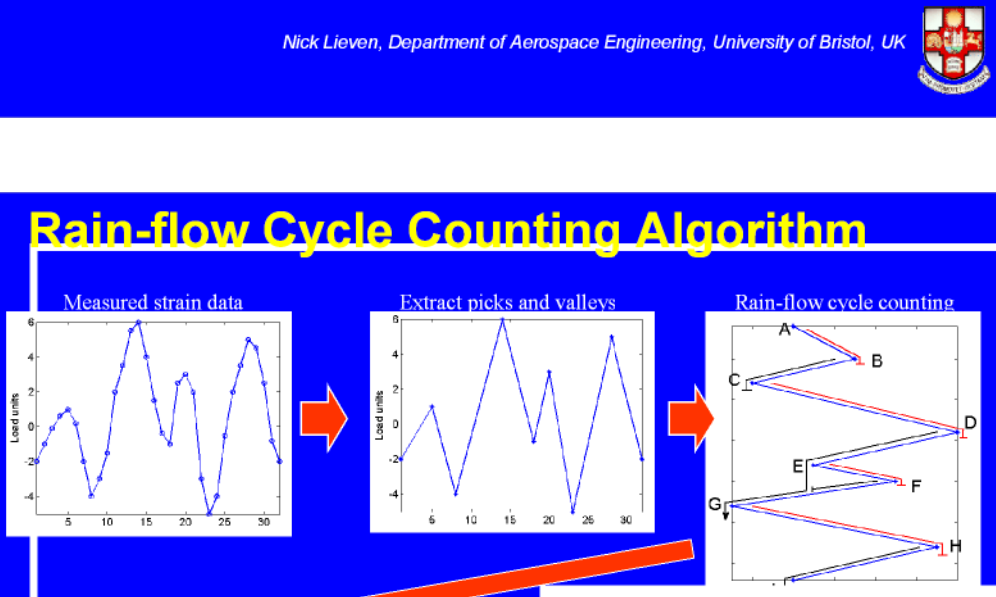
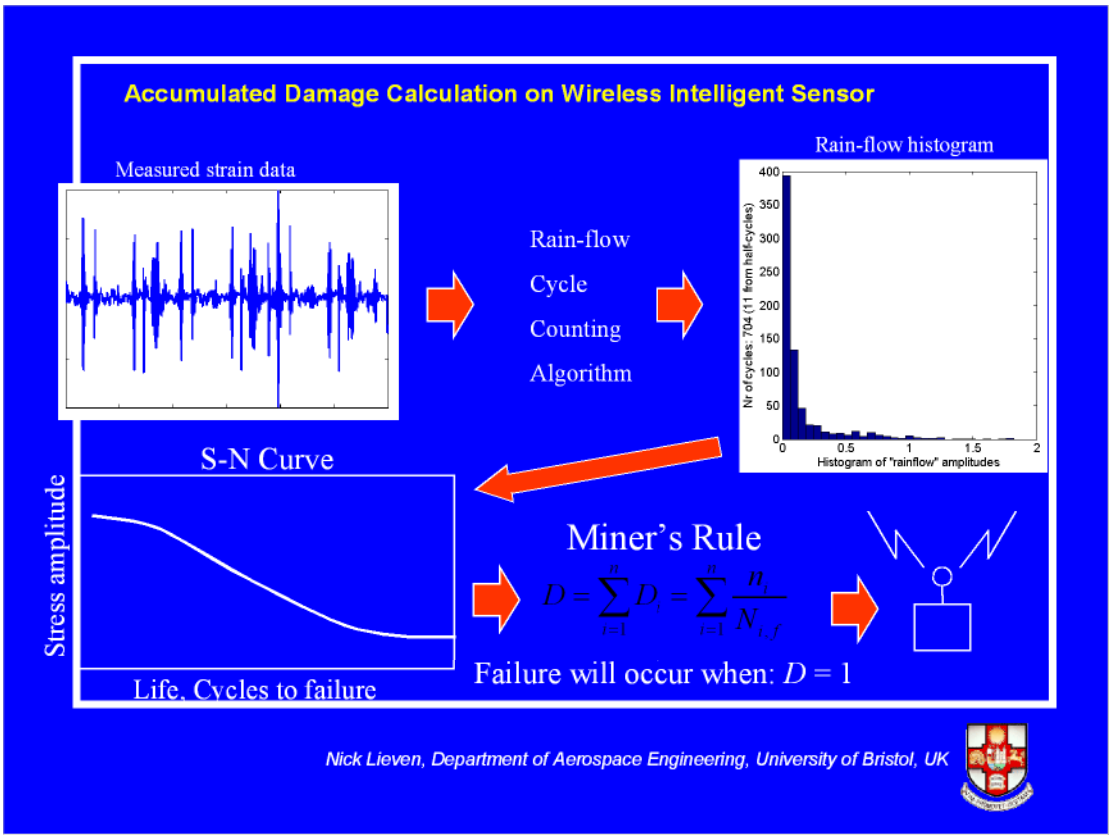


Rain-flow Cycle Counting Algorithm

Range (Units)	Cycle Counts	Events
12	0	
11	0.5	D-G
10	1	C-D, G-H
9	0	
8	0	
7	0.5	H-I
6	0	
5	0.5	B-C
4	1	E-F
3	0.5	A-B
2	0	
1	0	


Accumulated Damage Calculation on Wireless Intelligent Sensor
Measured strain data
Rain-flow
Cycle
Counting
Algorithm
Rain-flow histogram
Nr of cycles: 704 (11 from half-cycles)
Histogram of "rainflow" amplitudes
S-N Curve
Stress amplitude
Life, Cycles to failure
Miner's Rule
$D = \sum_{i=1}^{n} D_i = \sum_{i=1}^{n} \frac{n_i}{N_{i,f}}$
Failure will occur when: $D = 1$
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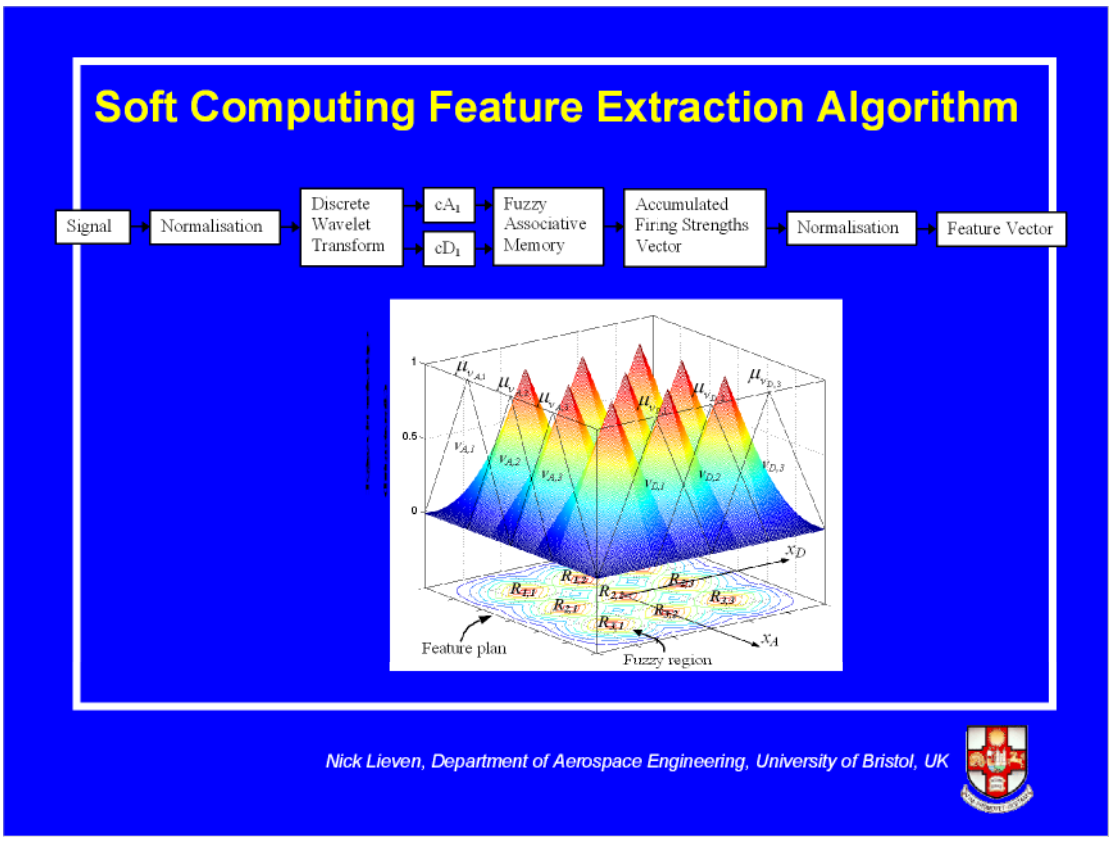
Soft Computing Feature Extraction Algorithm
Signal
Normalisation
Discrete Wavelet Transform
cA_1
cD_1
Fuzzy Associative Memory
Accumulated Firing Strengths Vector
Normalisation
Feature Vector
Feature plan
Fuzzy region
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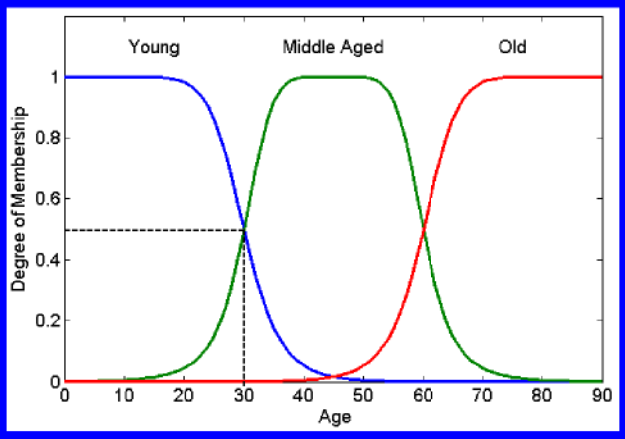
Fuzzy Associative Logic – an example



$\mu_{Young}(30) = 0.5 \quad \mu_{Middle\ Aged}(30) = 0.5 \quad \mu_{Old}(30) = 0$

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Wear classification - Fuzzy associative logic

Unworn

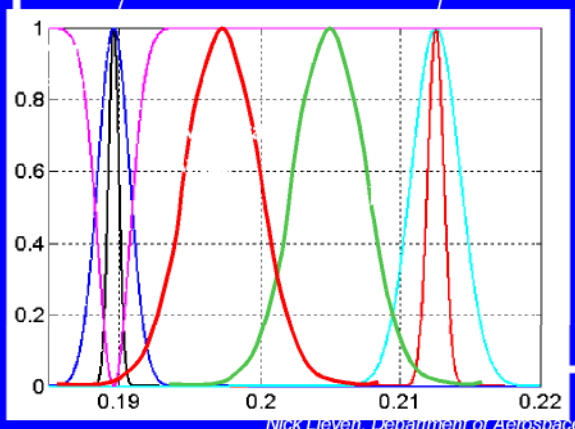
$\sigma_{\overline{FV}} = 0.0003743$

$\overline{FV} = 0.1896$

Worn

$\sigma_{\overline{FV}} = 0.000571$

$\overline{FV} = 0.2125$



Values calculated by averaging the feature vectors over 10 cycles of the signal

$$\overline{FV} = \frac{1}{n}\sum_{i=1}^{n}\overline{FV_i}$$

$$\sigma_{\overline{FV}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{FV_i} - \overline{FV}\right)^2}{n-1}}$$

$$\mu(x;\sigma_{\overline{FV}},\overline{FV}) = e^{\frac{-(x-\overline{FV})^2}{2(\sigma_{\overline{FV}})^2}}$$

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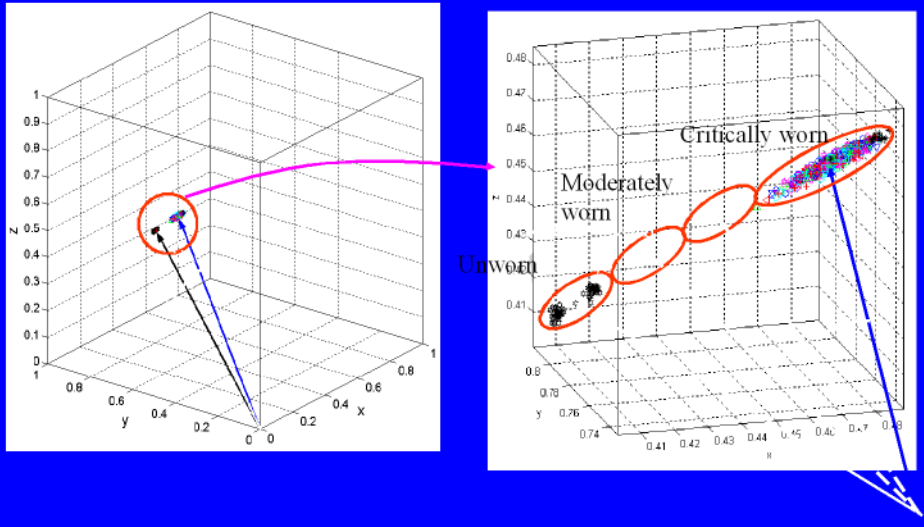
Feature classification



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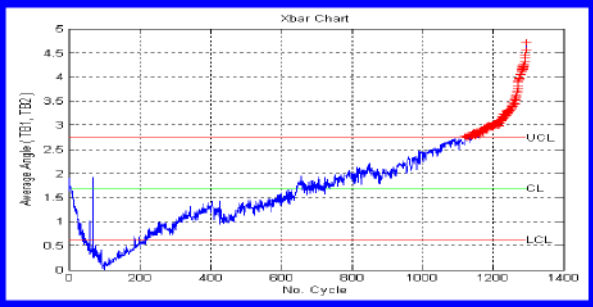
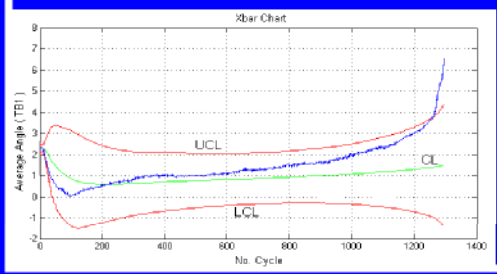
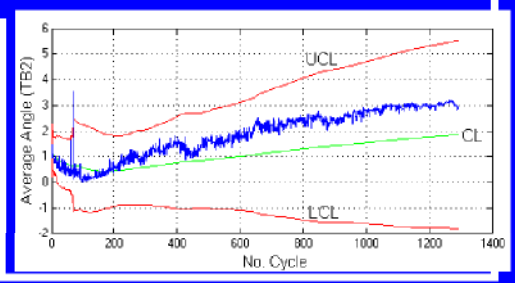
Statistical Process Control







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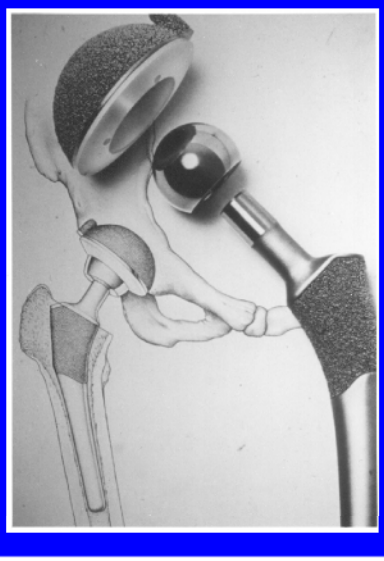
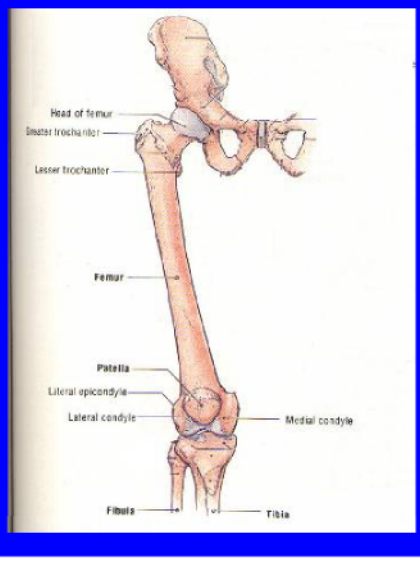
Example





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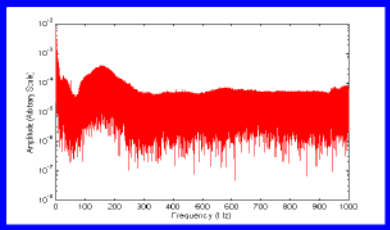
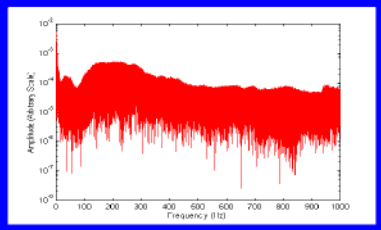
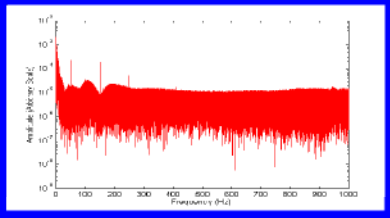
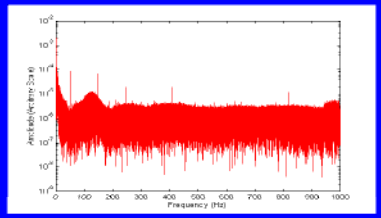
FFT of Loose and Fixed Prostheses









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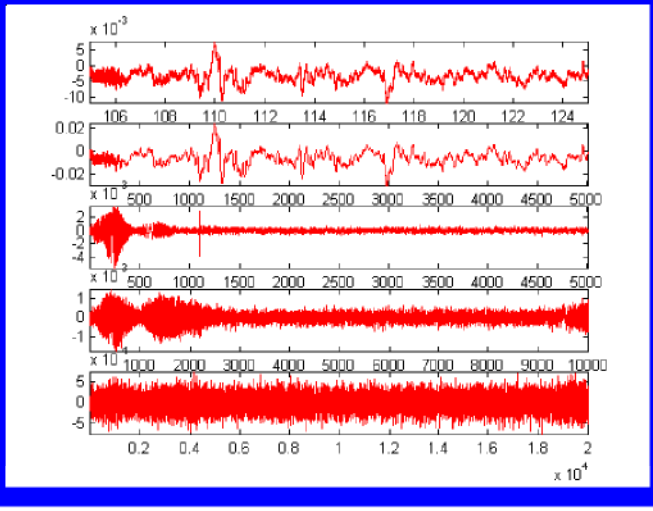
Level 3 DWT decomposition of output signal



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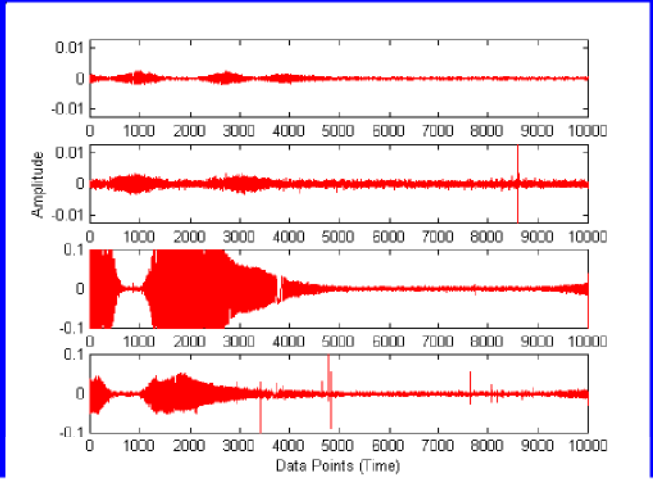
DWT level 1 decompositions for 4 patients



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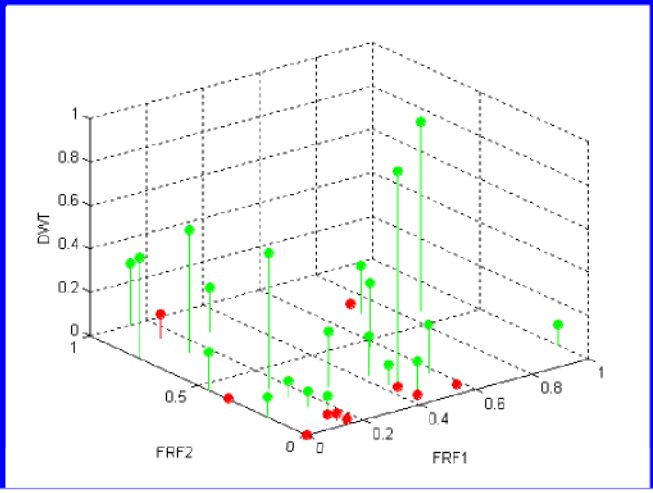
Visualisation of NN input data sets



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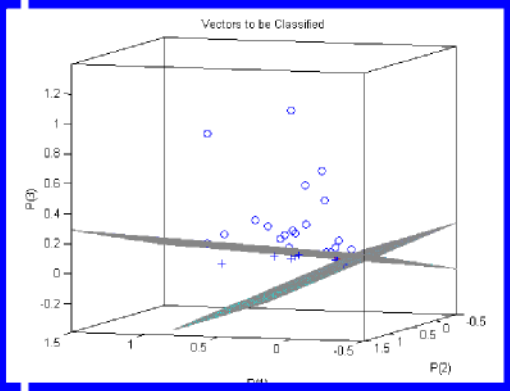
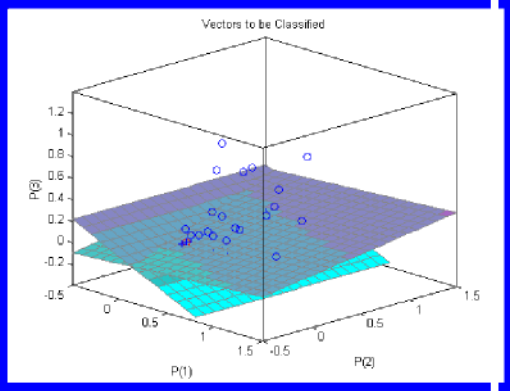
Neural Network Hyperplanes





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Inspiration's Link to Touch: The Machinist's "Sense of Touch"

THE MACHINIST'S SENSE OF TOUCH

DESPITE the high development of automatic-machine construction, the sense of touch remains an essential factor in a large part of the operations performed in manufacturing. This is due, we are told by *The American Machinist* (New York, October 5) to the wide utilization of semi-automatic and hand-operated machinery even in the most scientifically organized plants. In the majority of shop operations are still carried on upon a scale which warrants only a limited amount of automatic machinery. So, in spite of the general departure from the earlier hand-processes, the sense of touch remains of considerable importance. We read, for instance, that

"The faculty known as the sense of touch that enables the operator of a hand-screw machine to follow, by the 'feel' of his lever, the cutting action of stock of the tools as it is in here run over the rotating stock, and to finish the cut with a definite pressure against the tool-fitts stop, also serves as an accurate medium by which the operator of the hand-screw may gage the action of the cutter-under which he feeds his work. In these cases, as with certain other machines of the hand-operated type, the practised work-

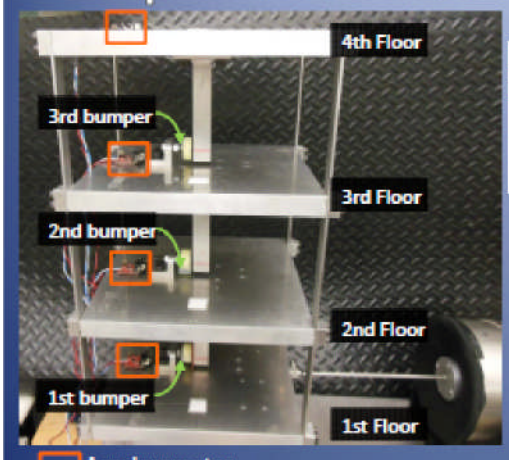
A Tidewater screw machine under the hand of the man who runs it.

In *The Literary Digest*; Oct. 28, 1911; p. 733
http://www.unz.org/Pub/LiteraryDigest-1911oct28-00733

"The faculty known as the sense of touch that enables the operator of a hand-screw machine to follow, by the 'feel' of his lever .... serves as an accurate medium by which the operator .... may gage the action of the cutter which he feeds his work."

- Speedy, regular, and subconscious movements
- Able to feel actions of machine
- Accurate feeding rate

Experimental Setup



Bumper	Case							
	0	1	2	3	4	5	6	7
3rd	-	-	-	O	-	O	O	O
2nd	-	-	O	-	O	-	O	O
1st	-	O	-	-	O	O	-	O

O : Damaged

- 4 accelerometers
- 10k sampling points
- 100kSa/sec sampling rate
- 70.7 Hz harmonic excitation
- 8 times measurements for each cases
- Rubber pads between the bumper and columns for stability

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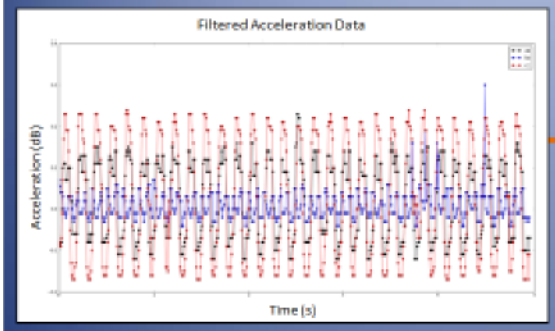
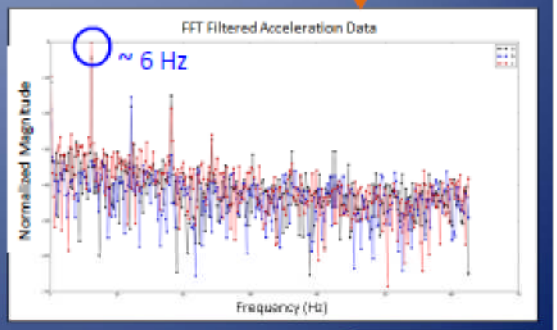
Results



Fast Fourier Transform (FFT)



- FFT
  - Undamaged – Single resonance
  - Damaged – Harmonics

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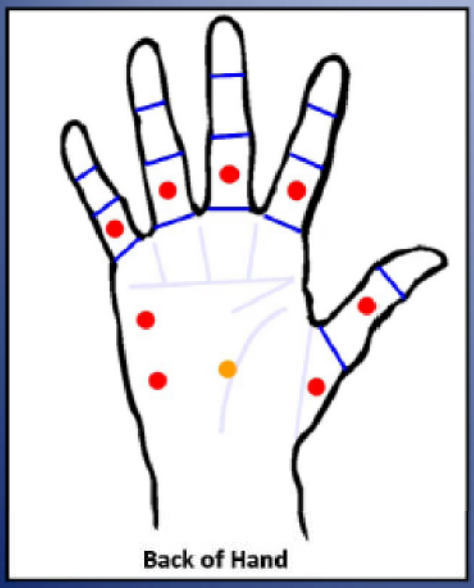
Glove Design

Finished Product



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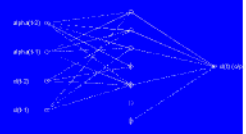
Significant Challenges

- Sensing: What to measure, how to measure it
  - Densely distributed fault-tolerant micro-sensor technology
  - Reconfigurable and adaptable sensing system
- Information Technology: Data interrogation and fusion
  - Distributed and adaptive on-board micro-processing
  - Model compression and updating
  - Large-scale data management



- Predictive Modeling: Damage evolution
  - Evolution of micro-scale damage initiation to system level failure
  - Near-real-time predictive capability capturing relevant mechanics
- System Integration & Deployment on Real-World Hardware
- Communicating the right outcomes

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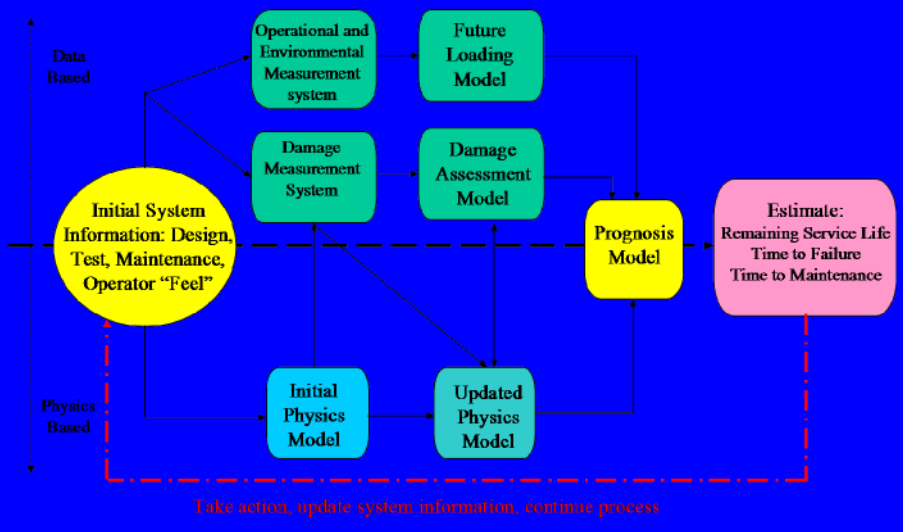
A Schematic for Prognostics



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Concluding Remarks

- Acquiring data is the easy part (do not underestimate certification requirements)
- Never forget the physics of the problem.
- Interpretation of outcomes needs to anticipate future environments

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