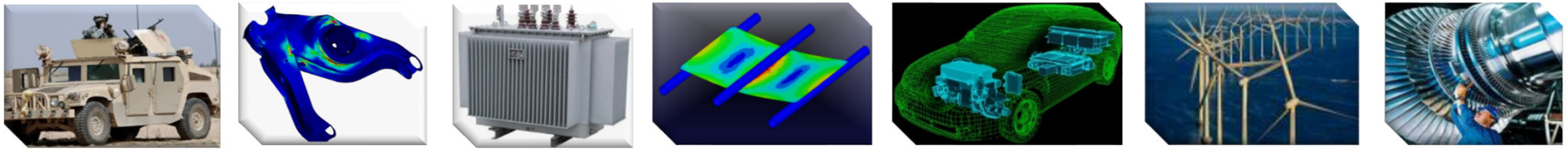


Toward Reliable Engineered System Design:

Reliability-Based Design and Prognostics and Health Management (PHM)

Chao Hu

Assistant Professor

Department of Mechanical Engineering

Iowa State University

Motivation

Boeing 787 Dreamliner fire due to **overheated Li-ion battery**
Japan Airlines (JAL) in Boston, Jan. 2013
Consequence: Over **$1.1 million daily loss** due to groundings

I-35W Bridge collapse due to **faulty design**, Aug. 2007
Consequence: **13 deaths**, 145 injured, **$60 million loss**

Wind turbine collapse due to **faulty maintenance**, Feb. 2008
Consequence: Collapse of **whole wind turbine**

Motivation

Power transformer fire due to **faulty bushing**, Jul. 2002
Consequence: **$5 million** property & business loss

UPS flight fire possibly due to **overheated Li-ion battery**, Feb. 2006
Consequence: 3 injured, loss of **whole airplane**

Research Questions:

Q1. Is it possible to design a system with near-zero failure probability?

Q2. Is it possible to anticipate and prevent failures during system operation?

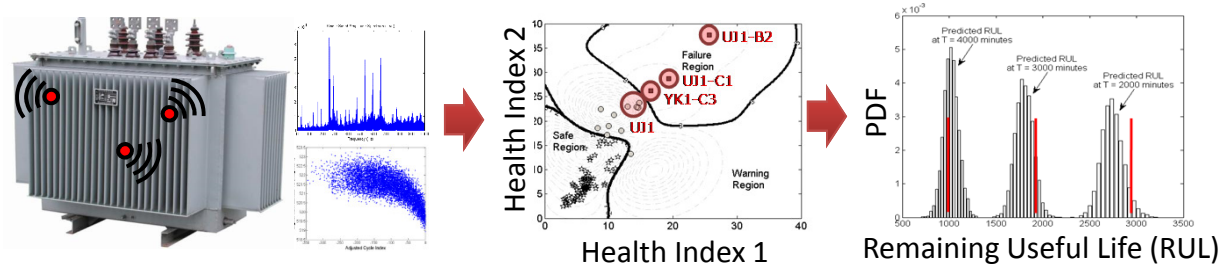
Research Timeline

2007 2009 2011 2013 2015

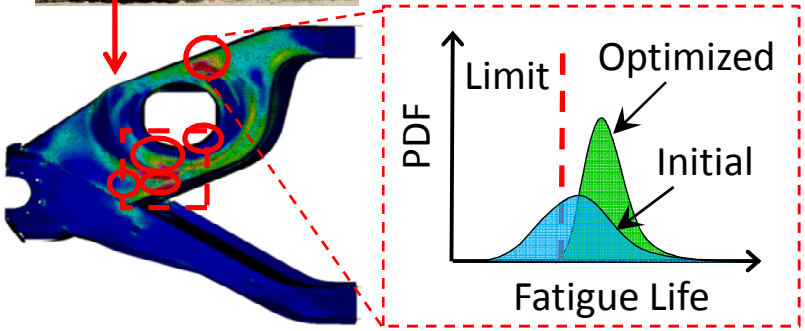
PhD Student @ UMD → Scientist @ MDT / Faculty @ ISU

Prognostics and Health Management (PHM)

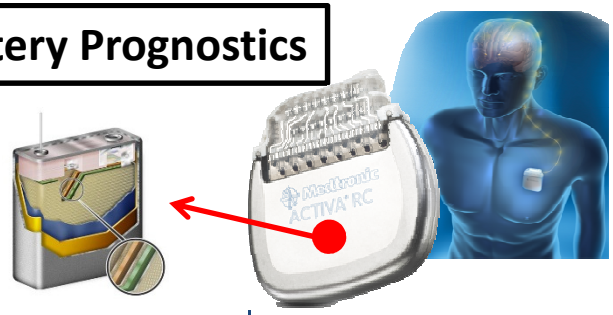
Sensing → Reasoning → Prognostics



Reliability-Based Design



Battery Prognostics



Li-Ion Rechargeable | Deep Brain Stimulators

IOWA STATE UNIVERSITY
College of Engineering

SRSL System Reliability & Safety Laboratory

Research Timeline

2007 2009 2011 2013 2015

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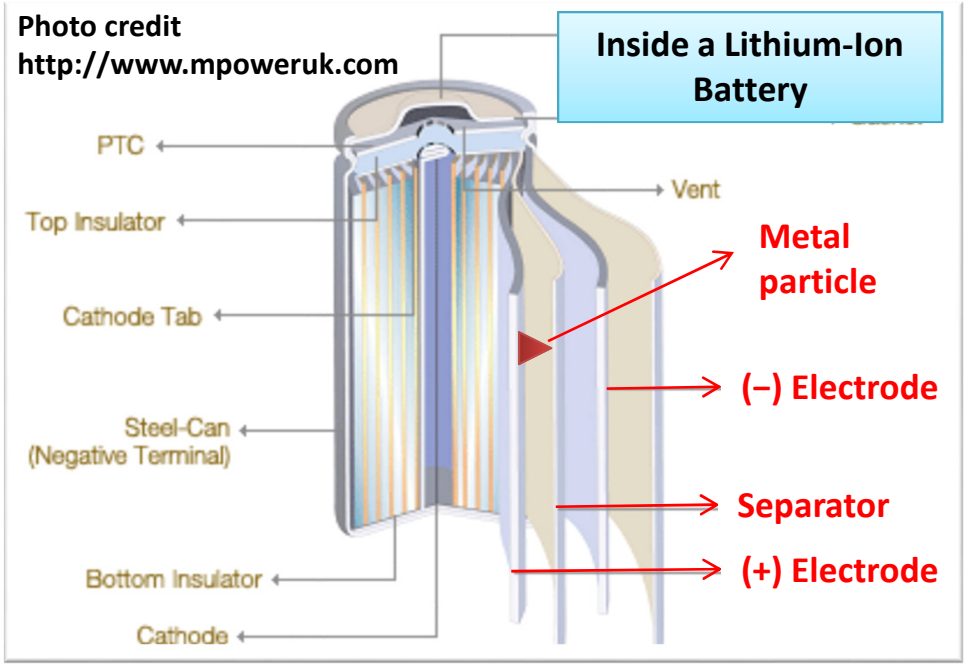
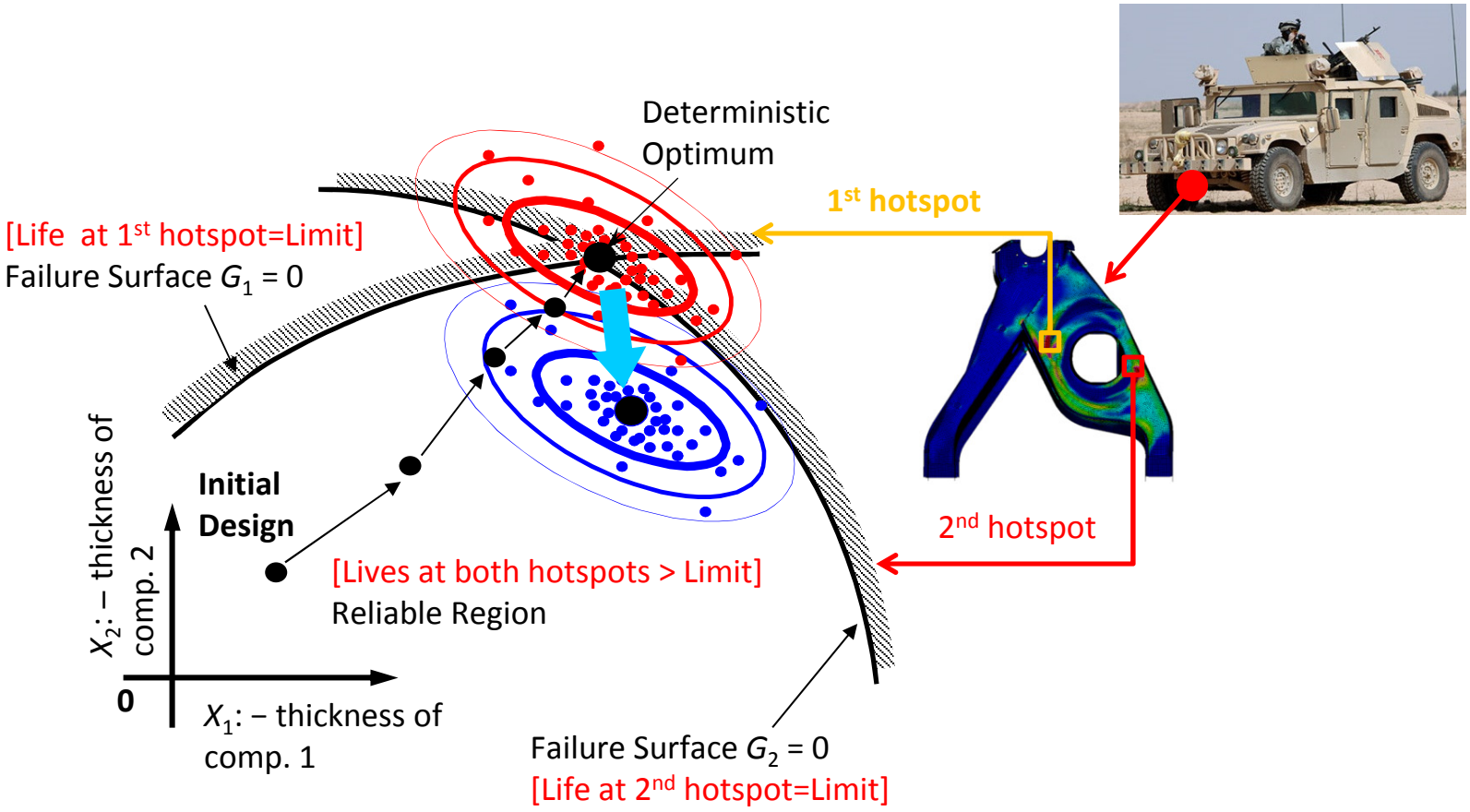


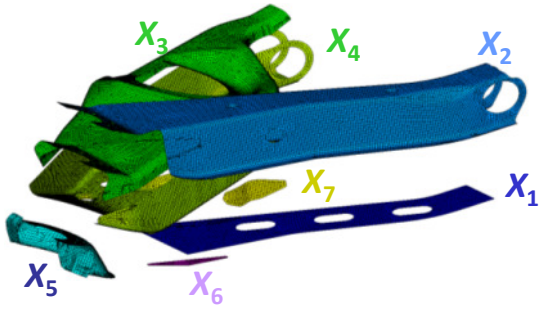
Reliability-Based Design

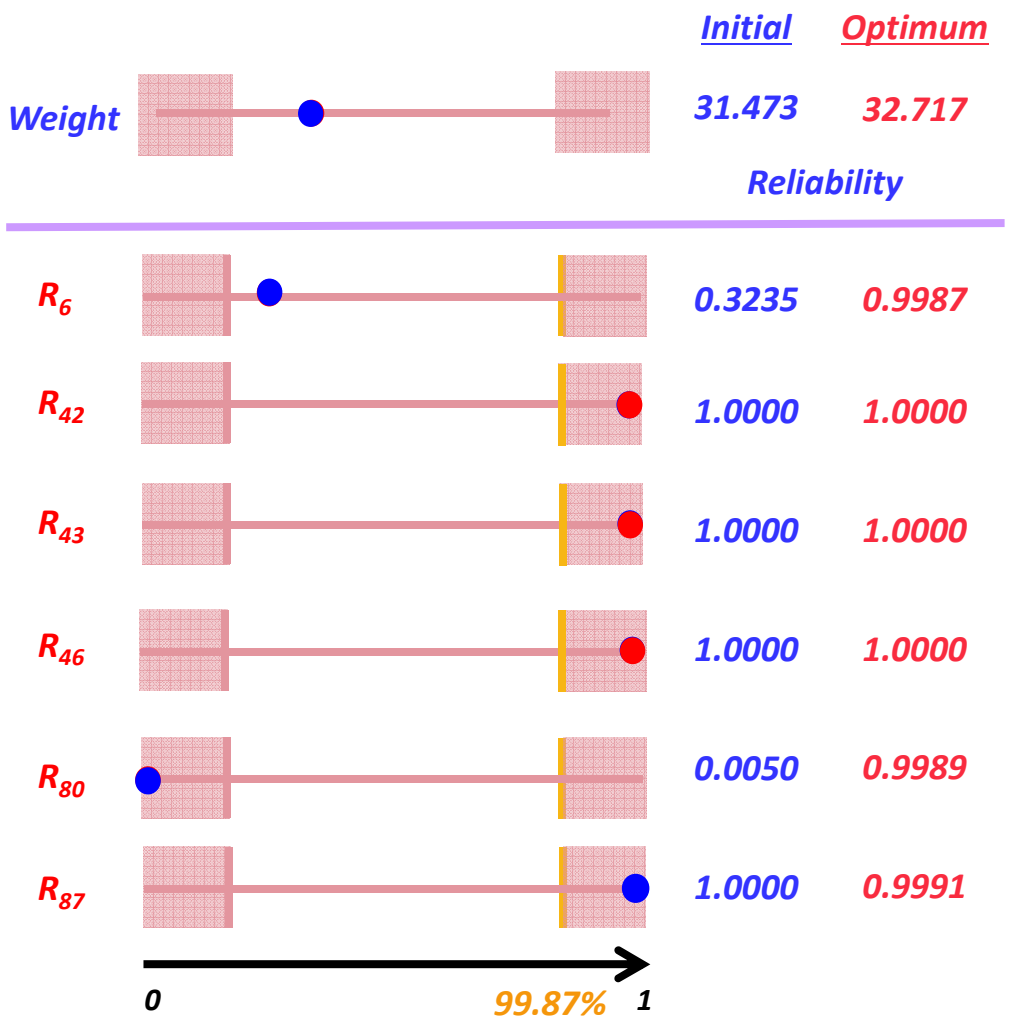
Design of Control Arm (US Army): Methodology



Reliability-Based Design

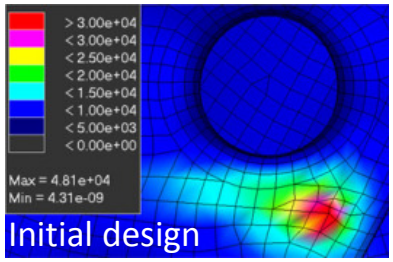
Design of Control Arm (US Army): Optimization Results



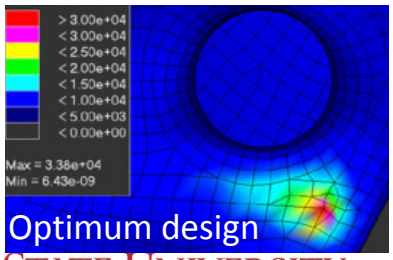


Reliability-Based Design

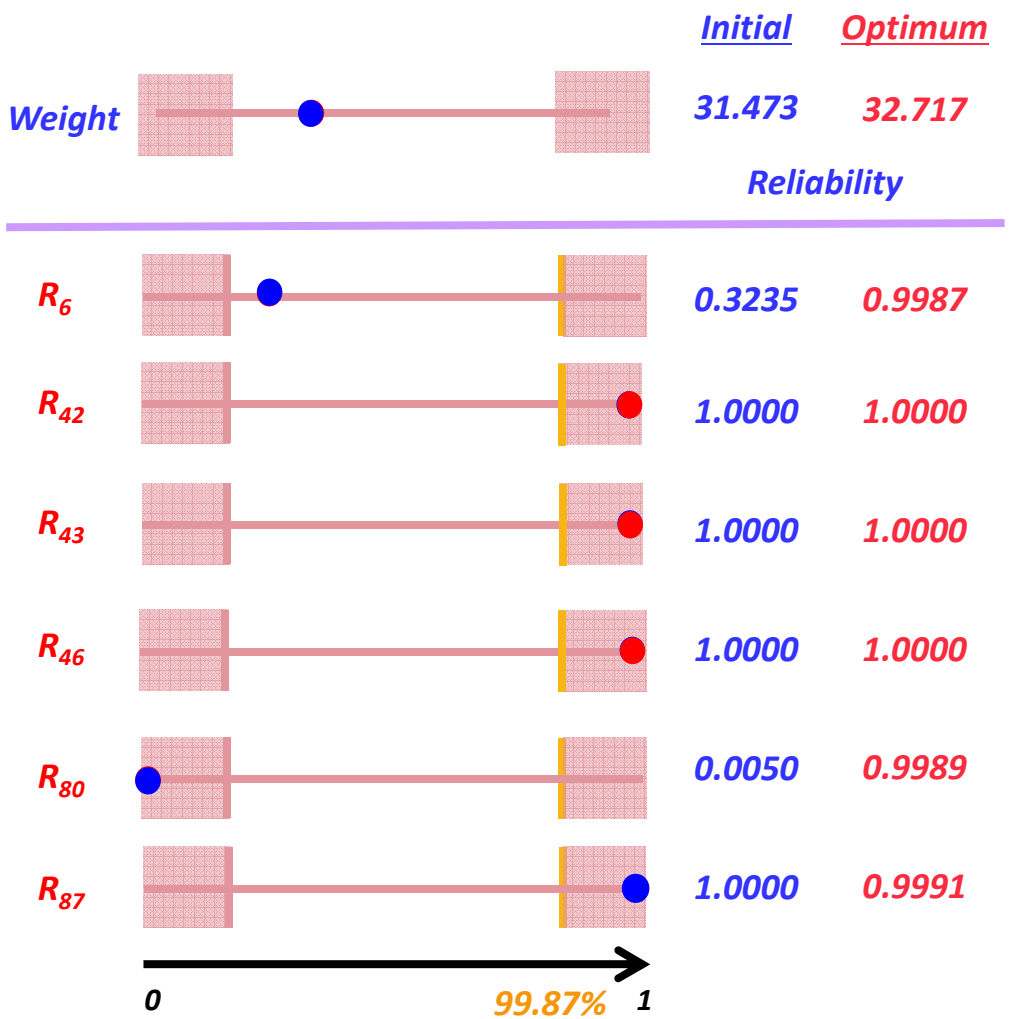
Design of Control Arm (US Army): Optimization Results



Initial Stress Contour



Final Stress Contour



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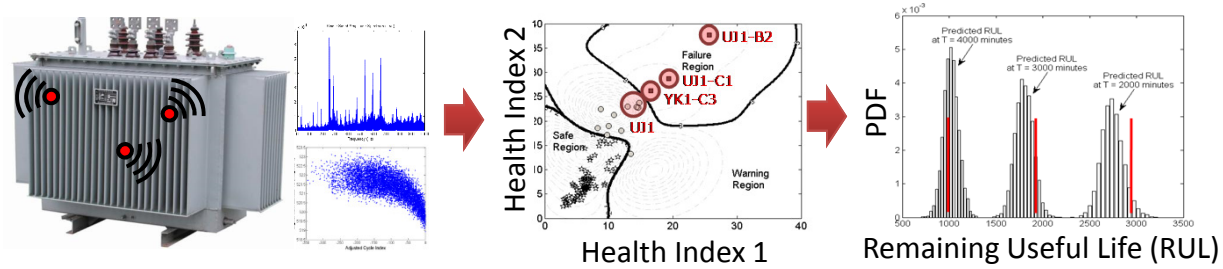
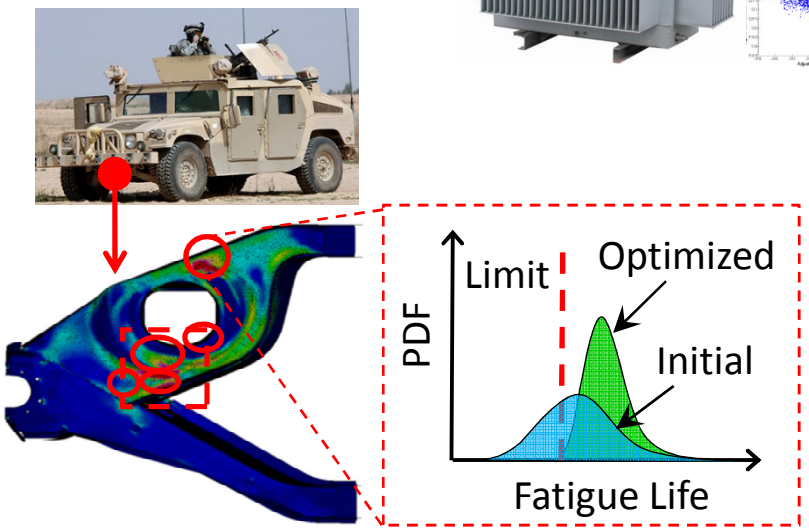
Prognostics and Health Management (PHM)

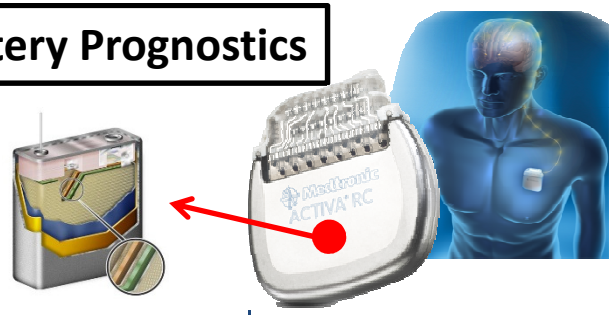
Sensing → Reasoning → Prognostics



Reliability-Based Design



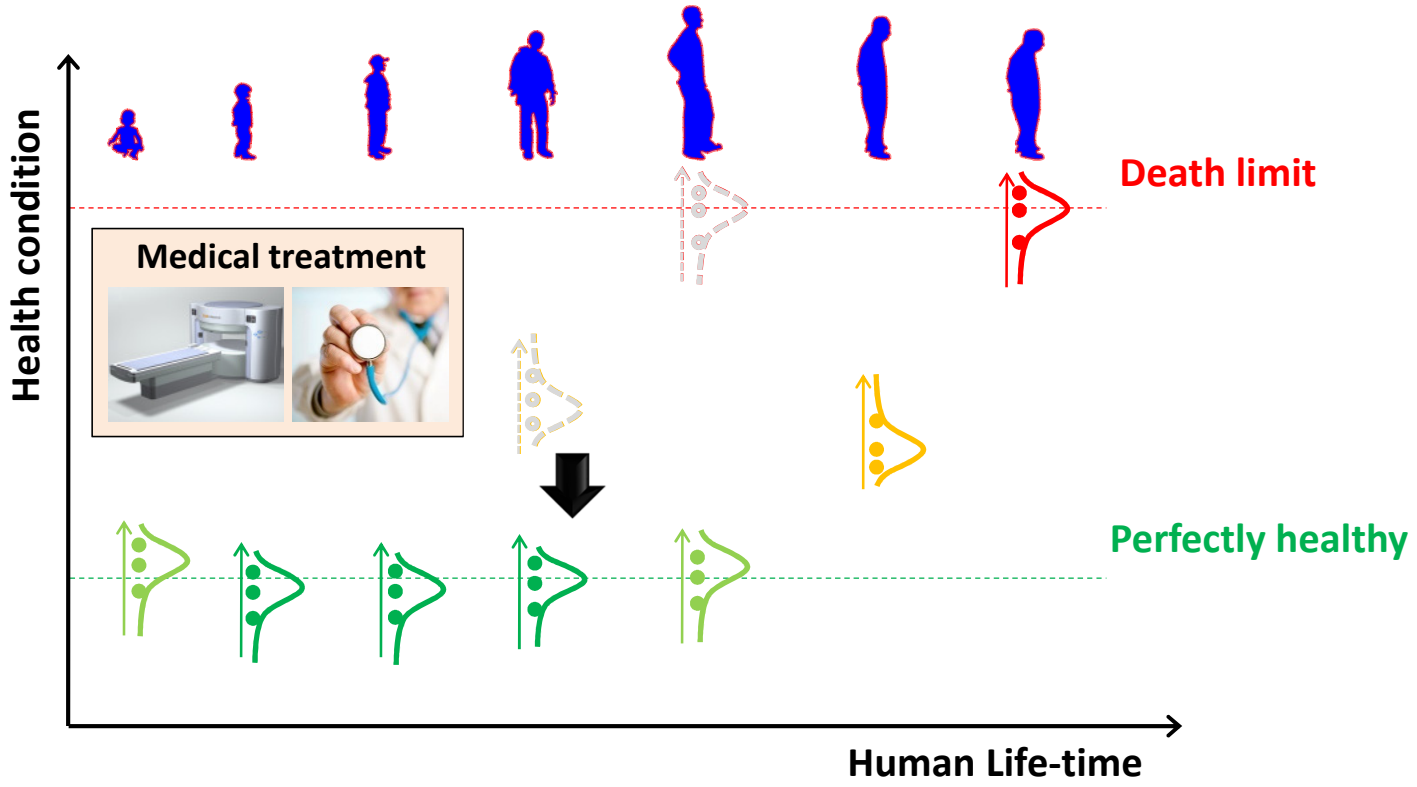
Battery Prognostics



Li-Ion Rechargeable | Deep Brain Stimulators

Prognostics and Health Management (PHM)

Human PHM Process

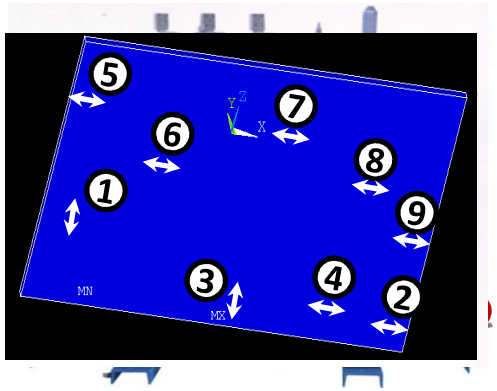


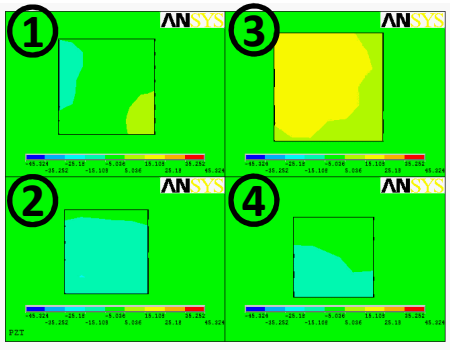
Prognostics and Health Management (PHM)

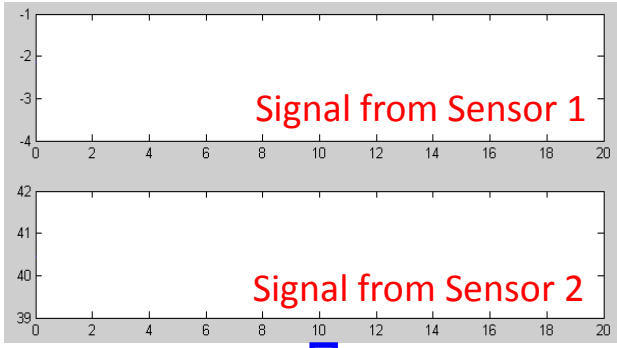
An engineered system cannot manage itself. It must be managed.

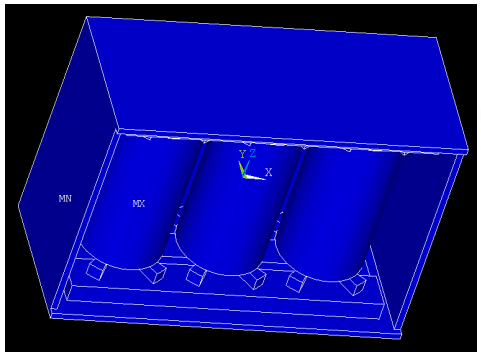
Prognostics and Health Management (PHM)

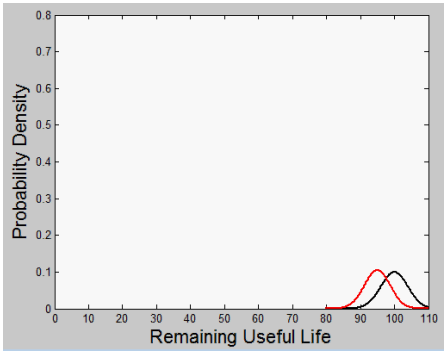
Health Management of Power Transformer

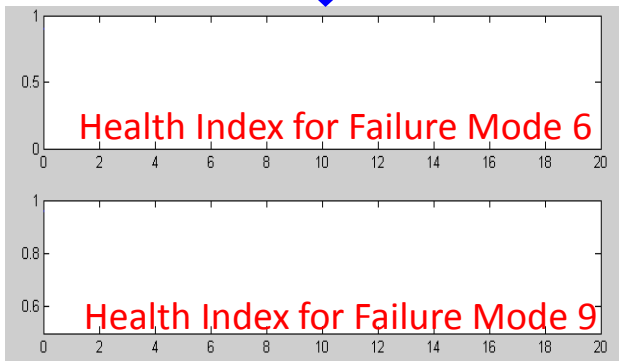








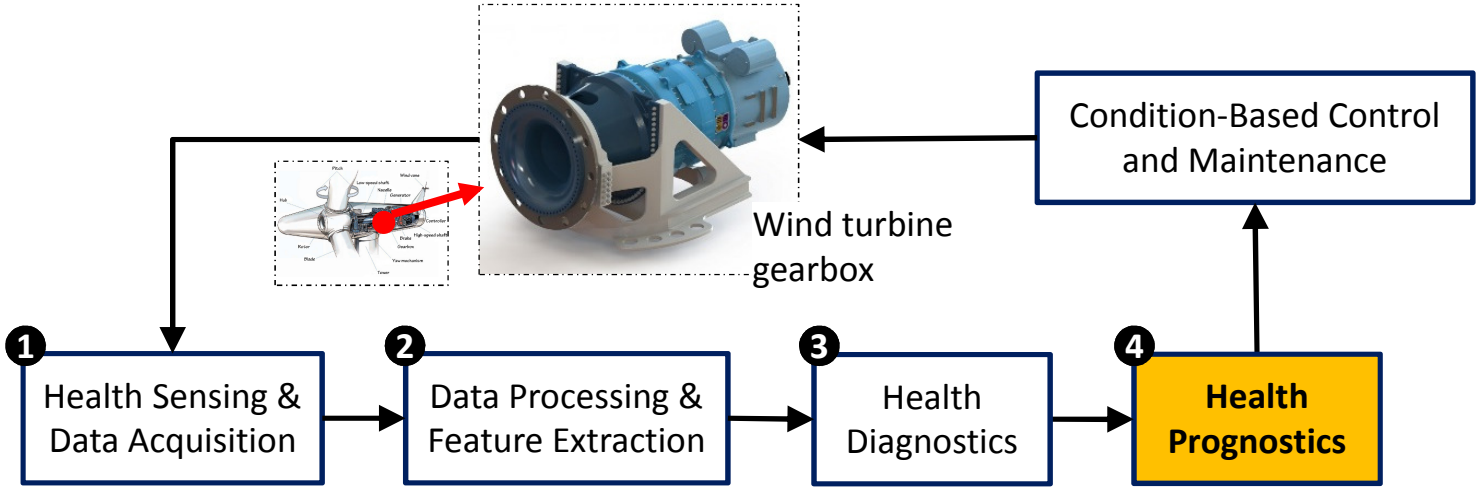


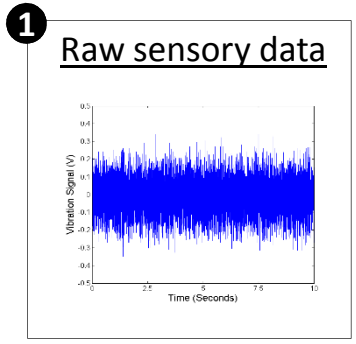


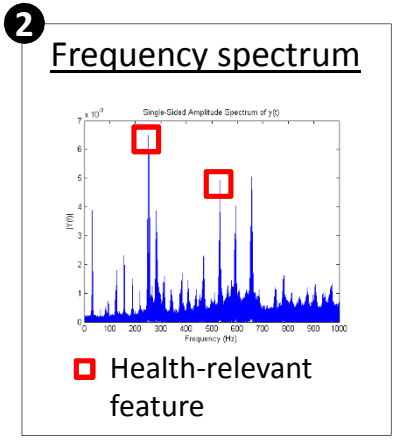
PHM Functions

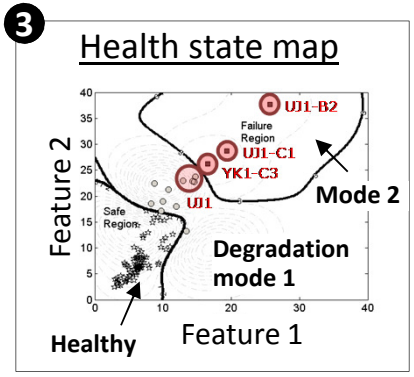
Prognostics and Health Management (PHM)

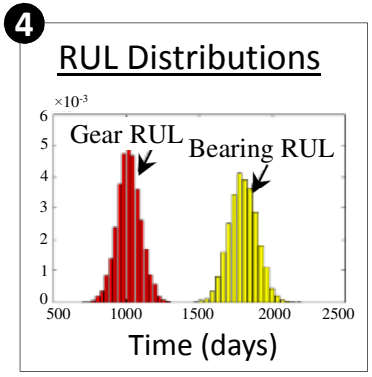
Intelligent Prognostics Platform for Wind Turbine Gearbox











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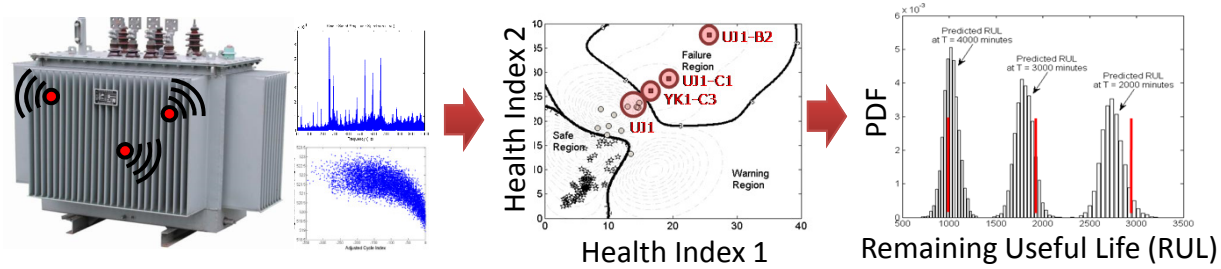
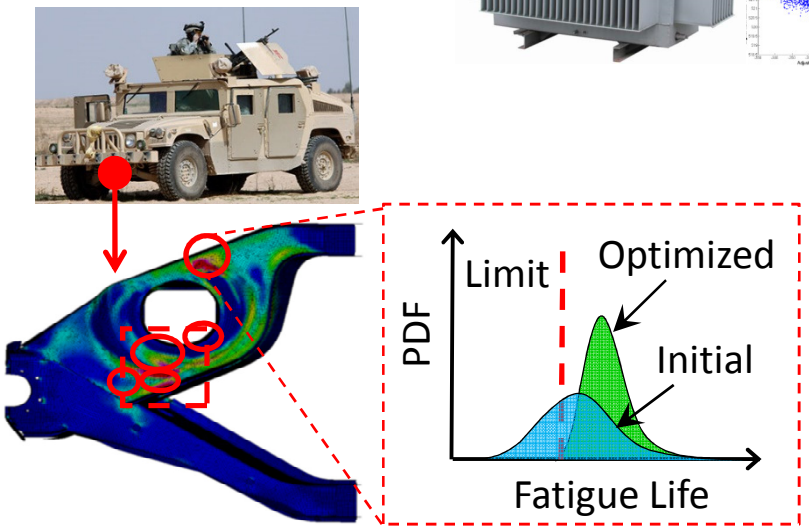
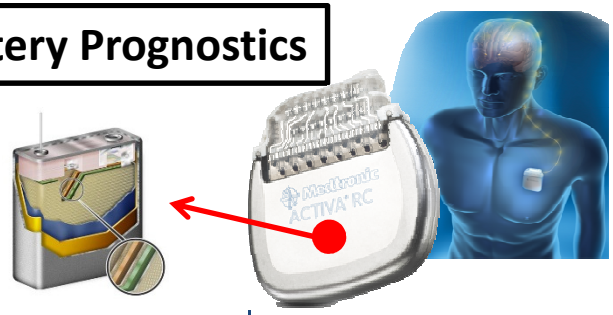


Reliability-Based Design



Battery Prognostics



Li-Ion Rechargeable | Deep Brain Stimulators

Li-Ion Battery in Implantable Medical Devices

Since 2004

Spinal Cord Stimulators
Mild electrical stimulation in the spinal cord to alleviate chronic pain.

Since 2010

Deep Brain Stimulators
Targeted electrical stimulation to part of brain for mitigating movement disorder.

Targeted longevity of 9 years, and 1000+ cycles
Inductively coupled recharge

Battery Prognostics

Do Patients/Physicians Need to Know More?

Patients/physicians are informed of battery charge level

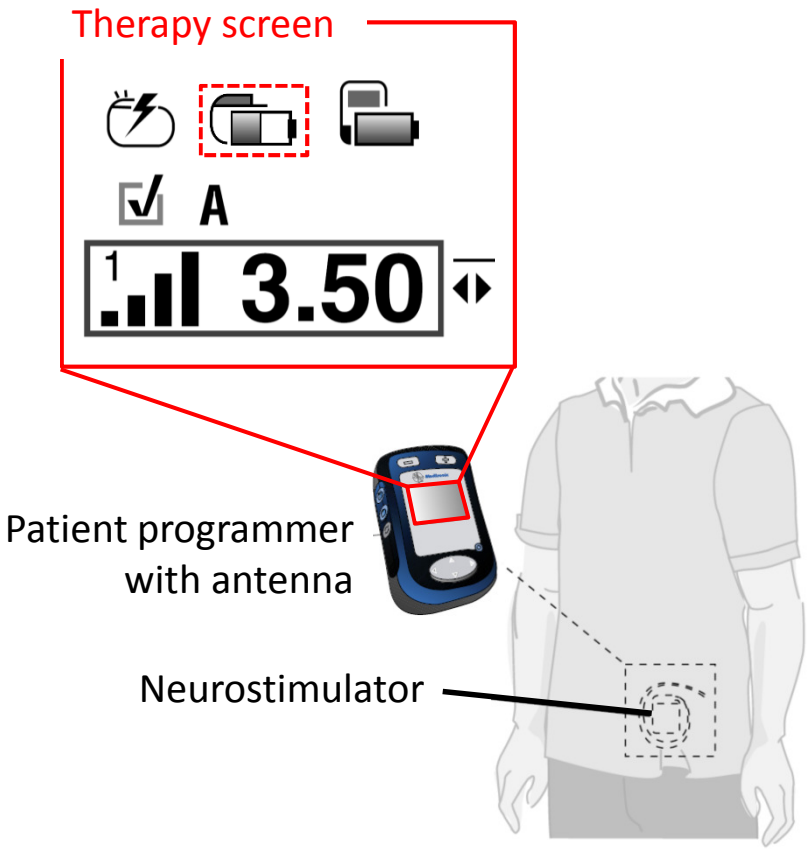
Need to know more:

- Capacity every recharge cycle

Remaining capacity 80% BOL capacity

- Remaining use life during annual check-up

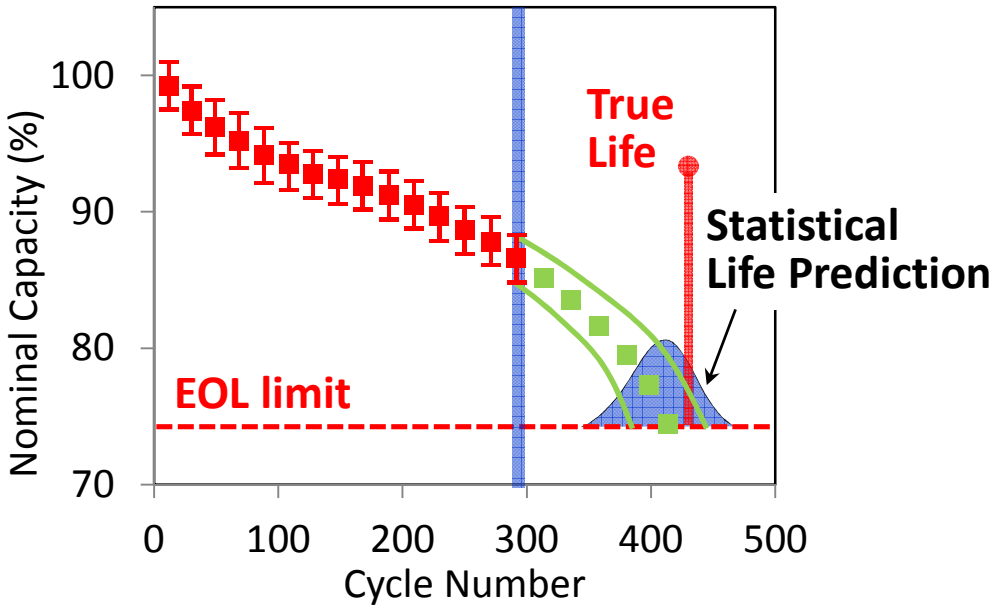
Remaining useful life 6 years 8 months



Battery Prognostics

Schematic of Prognostics

- Estimated capacity based on voltage and current measurements
- Projected capacity
- Predicted end of life (EOL)



Particle filter used to consider two sources of uncertainty:

- Capacity estimation
- Model projection

Hu C., Jain G., Tamirisa P., and Gorka T., "Method for Estimating Capacity and Predicting Remaining Useful Life of Lithium-Ion Battery," *Applied Energy*, v126, p182–189, 2014.

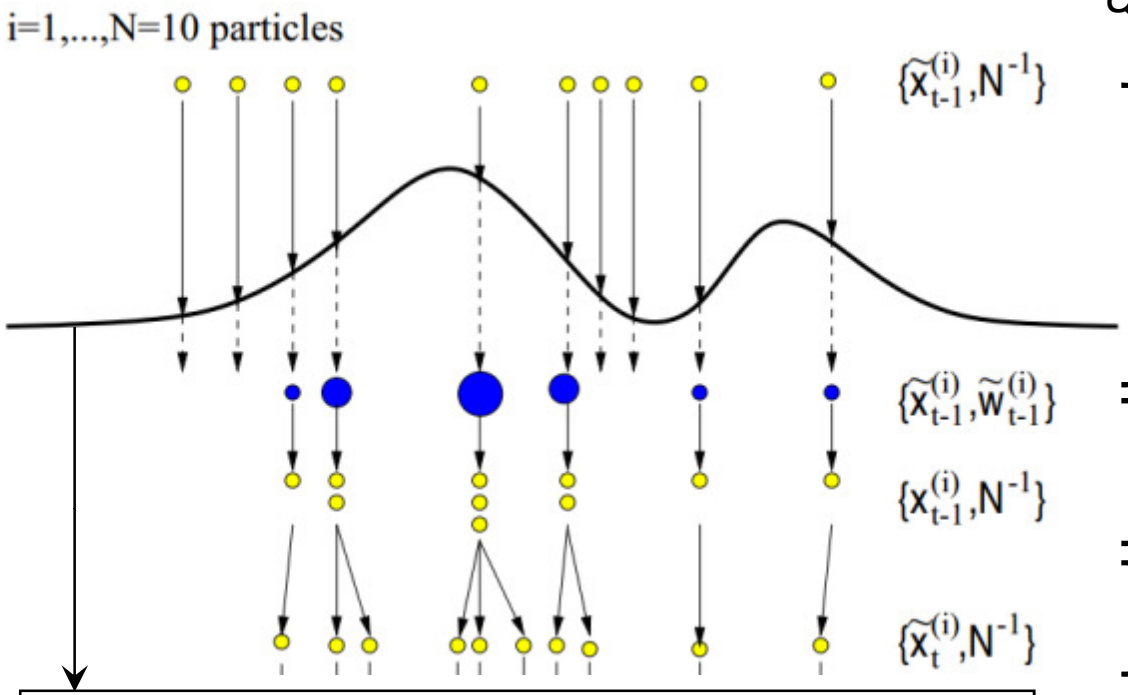
Battery Prognostics

Particle Filter for Estimating Joint Distribution of Model Parameters

[Pitt and Shephard, 1999, Journal of the American Statistical Association]

$$Q(t,C) = k_1(1-e^{-t/to}) + k_2 t + m_c C$$

$$\mathbf{X} = \{k_1, k_2, t_0, m_c\}$$



Step 1: Evaluate Importance Weights

Step 2: Selection

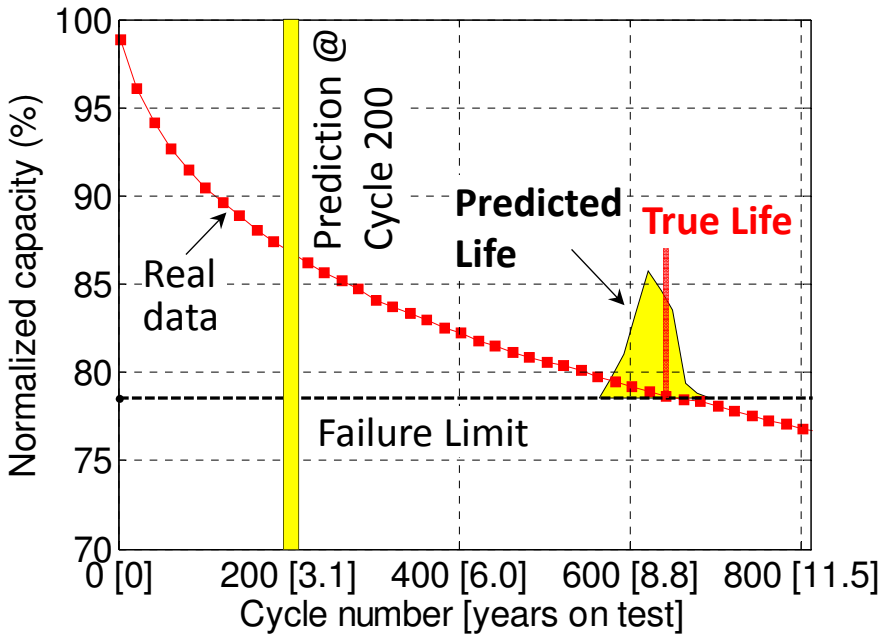
Step 3: Sampling

Likelihood function based on capacity estimates

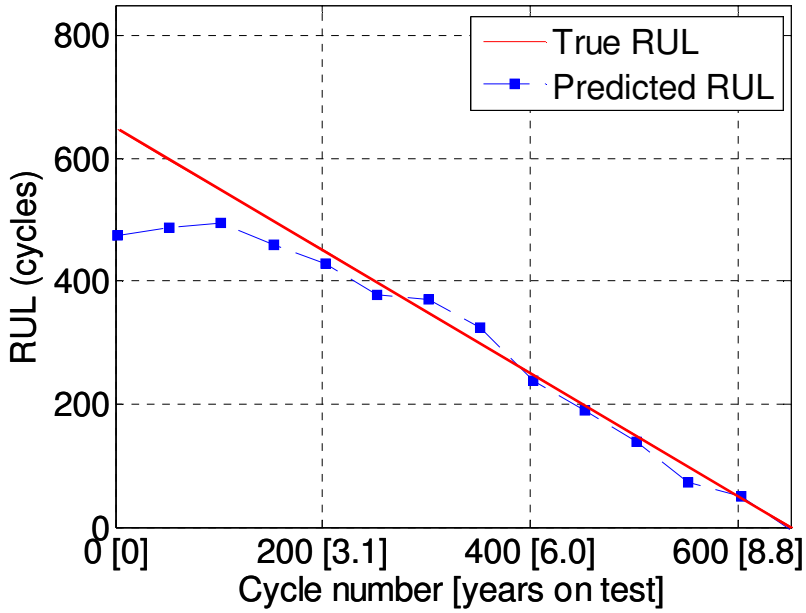
Hu C., Jain G., Tamirisa P., and Gorka T., "Method for Estimating Capacity and Predicting Remaining Useful Life of Lithium-Ion Battery," *Applied Energy*, v126, p182–189, 2014.

Battery Prognostics

Life Prediction @ Cycle 200



Life Predictions @ Multiple Cycles



Hu C., Jain G., Tamirisa P., and Gorka T., "Method for Estimating Capacity and Predicting Remaining Useful Life of Lithium-Ion Battery," *Applied Energy*, v126, p182–189, 2014.

Future Research Plan

Design for Functional Reliability

Design for Failure Prevention

Design for Resilience

Energy Storage

Student to be identified

- Reliability evaluation and failure prognostics of new materials

Wind Energy

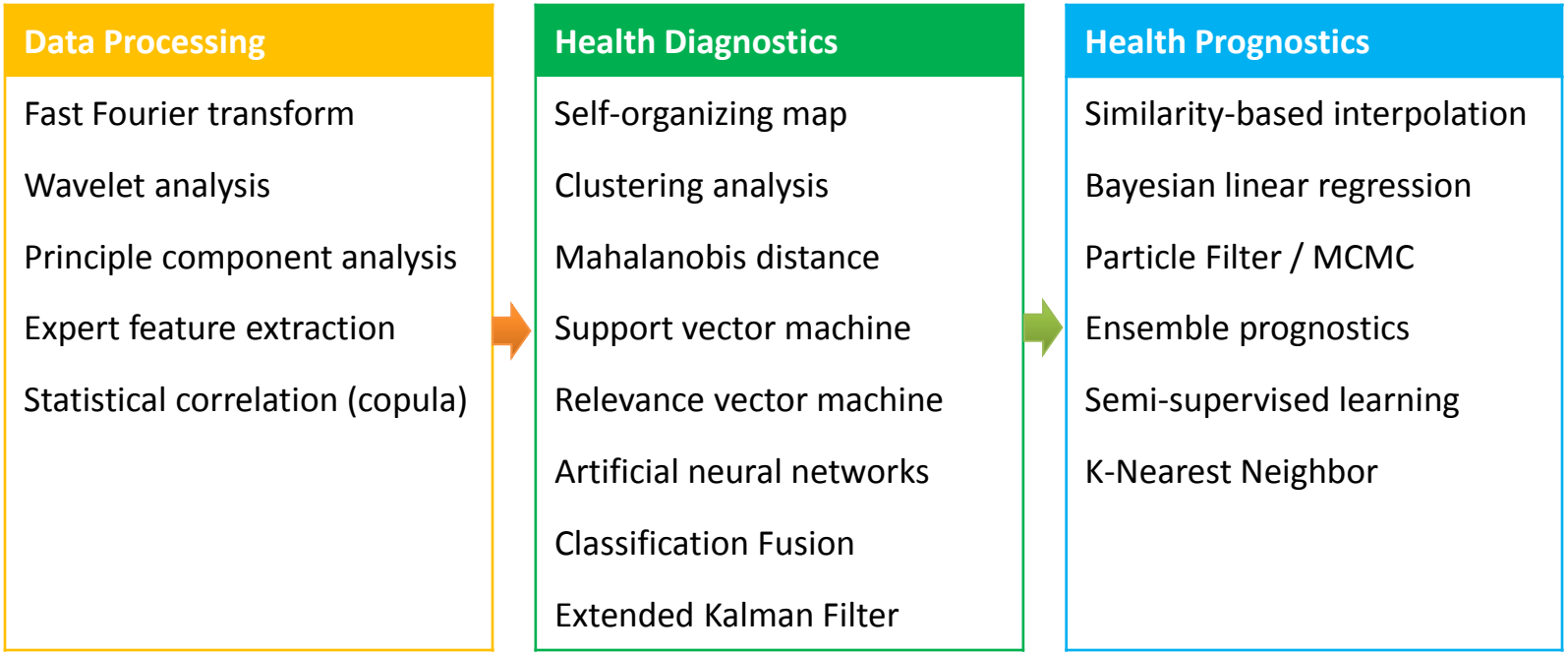
Ms. Kayla Johnson (PhD Student)

- Intelligent prognostics of wind turbine gearbox

Thank You!

Q/A

PHM Toolbox being Developed at Hu's Lab



Journal Publications on PHM

1. Wang P., Youn B.D., and **Hu C.,** "A Probabilistic Detectability-Based Sensor Network Design Method for System Health Monitoring and Prognostics," *Journal of Intelligent Material Systems and Structures*, DOI: 10.1177/1045389X14541496, 2014. [DOI]
2. **Hu C.,** Wang P., Youn B.D., and Lee W.R., "Copula-Based Statistical Health Grade System against Mechanical Faults of Power Transformers," *IEEE Transactions on Power Delivery*, v27, n4, p1809–1819, 2012. [DOI]

Health Sensing & Data Processing

3. Youn B.D., Park K.M., **Hu C.,** Yoon, J.T., and Bae Y.C., "Statistical Health Reasoning of Water-Cooled Power Generator Stator Bars Against Moisture Absorption," *IEEE Transactions on Energy Conversion,* vPP, p1–10, 2015. [DOI]
4. **Hu C.**, Jain G., Schmidt C., Strief C., and Sullivan M., "Online Estimation of Lithium-Ion Battery Capacity Using Sparse Bayesian Learning," *Journal of Power Sources*, v289, p105–113, 2015. [DOI]
5. Bai G., Wang P., and **Hu C.**, "A Self-Cognizant Dynamic System Approach for Prognostics and Health Management," *Journal of Power Sources*, v278, p163–174, 2015. [DOI]
6. Bai G., Wang, P., **Hu C.**, and Pecht M., "A Generic Model-Free Approach for Lithium-ion Battery Health Management," *Applied Energy*, v135, p247–260, 2014. [DOI]
7. **Hu C.,** Jain G., Zhang P., Schmidt C., Gomadam P., and Gorka T., "Data-Driven Approach Based on Particle Swarm Optimization and K-Nearest Neighbor Regression for Estimating Capacity of Lithium-Ion Battery," *Applied Energy*, v129, p49–55, 2014. [DOI]
8. Tamilselvan P., Wang P., and **Hu C.**, "Health Diagnostics Using Multi-Attribute Classification Fusion," *Engineering Applications of Artificial Intelligence*, v32, p192–202, 2014. [DOI]
9. **Hu C.,** Youn B.D., and Chung J., "A Multiscale Framework with Extended Kalman Filter for Lithium-Ion Battery SOC and Capacity Estimation," *Applied Energy,* v92, p694–704, 2012. [DOI]

Health Diagnostics

10. **Hu C.,** Youn B.D., Kim T.J., and Wang P., "Semi-Supervised Learning with Co-Training for Data-Driven Prognostics," *Mechanical Systems and Signal Processing*, v62–63, p75–90, 2015. [DOI]
11. **Hu C.,** Jain G., Tamirisa P., and Gorka T., "Method for Estimating Capacity and Predicting Remaining Useful Life of Lithium-Ion Battery," *Applied Energy*, v126, p182–189, 2014. [DOI]
12. Xi Z., Wang P., Rong Jing, and **Hu C.,** "A Copula-Based Sampling Method for Data-Driven Prognostics," *Reliability Engineering and System Safety*, DOI: 10.1016/j.ress.2014.06.014, 2014. [DOI]
13. **Hu C.,** Youn B.D., and Wang P., "Ensemble of Data-Driven Prognostic Algorithms for Robust Prediction of Remaining Useful Life," *Reliability Engineering and System Safety,* v103, p120–135, 2012. [DOI]
14. Wang P., Youn B.D., and **Hu C.,** "A Generic Probabilistic Framework for Structural Health Prognostic and Uncertainty Management," *Mechanical Systems and Signal Processing*, v28, p622–637, 2012. [DOI]

Health Prognostics