PHM23 Panel 8: **PHM Education and Professional Development Panel**

Education and professional development in PHM

Welcome and intro: Jeff Bird (PHM Society and TECnos) [10 minutes]
Resource Examples and Provocative Questions by panelists [30 minutes]
Prof. Peter Sandborn, CALCE, University of Maryland
Derek DeVries- Northrup Grumman
Open discussion and Prioritization of Opportunities [50 minutes]
Moderators: Dr. Karl Reichard, Penn State and Jeff Bird, Nancy Madge TECnos

How the PHM Society is trying to help- PHM taxonomy, Professional Development Guidelines, portal, short courses, conference education, …

1. Are curated collections of courses or certificates important for professional development and career growth in the PHM domain?
2. What do you need which might be unique to PHM, and how do we justify it?
3. How could the PHM Society help?

Desired Outcomes

> Summary of resources for curated packages of courses and certificates for PHM
> Your priorities on gaps in technical and professional development resources for integrated learning

PHM Society Education and Professional Development Committee

Jeff Bird, Jamie Coble, Nancy Madge, Karl Reichard and George Vachtsevanos

PHM Society Role?

Society Objectives

1. Free access to PHM knowledge,
2. Interdisciplinary and international collaboration
3. Advance the engineering discipline

Observations

1. Diverse body of PHM knowledge out there: Standards, lessons learned, information, few case studies
2. Multi-disciplinary awareness and engagement is lacking: Many entrants come from single specialities
3. Wide continuing standards participation is difficult: Small companies, long time frame for development
4. To mature knowledge from theory to practice is challenging: Knowing about relevant standards across disciplines, Developing Body Of Knowledge to complement academic training
5. Data and information sharing protocols are essential but problematic: Proprietary and sector specific information

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PHM Taxonomy- what is the scope of PHM?

"A set of capabilities, information and decision-making tools for diagnosis, prognosis and health management of complex systems – Integrating technologies from systems engineering, reliability, analytics"

1. System physical modeling
2. Data Modeling
3. Analytics
4. Test and Experimental (Design and conduct)
5. Software Systems
6. Hardware Systems

7. Life Cycle Analysis
8. Verification and Validation
9. Human Factors
10. System Engineering
11. Cost Benefit Analysis
12. Certification
13. Standards
14. Digital Transformation (new)

PHM Society EPD Activities

Traditional

1. Panels and tutorials at conferences
2. Pre-conference short courses

New initiatives

1. PHM EPD Portal: One stop for docs, resources, forum, taxonomy
2. *EPD Users Group and CPD Guidelines*

PHM Fundamentals and Case Studies Short Course

Introduction to PHM
Deriving Requirements for PHM
PHM Performance Metrics
Methods- Diagnostics, Prognostics, Analytics
Case Studies - Methods
Sensors and Processing
Small Group Workshop 1
CBM+ Technologies
PHM Cost Benefit Analysis
Small Group Workshop 2
Fielded Systems Case Studies CBM, CBA
Way forward (you and us)

Analytics for PHM Short Course with examples

Overview of data-driven PHM
Review- Fundamental statistics, Data Visualization
Machine learning - introduction and concepts
Data transformation & Feature Extraction
Methods- Classification and Regression
Introduction to Neural Networks
Hands-on Lab
Feature Selection and Characterizing Performance
Model Selection and Anomaly Detection
Deep Learning I, II and Applications
Practical matters
Hands-on Lab

2022 Discussions- Priorities

Some key issues from the presentations and discussion ***ranked by audience votes***

22 Better ways to integrate multi-disciplines in PHM
19 Access to PHM case studies ands success stories
12 Orientations to the PHM as a discipline like Body of Knowledge and taxonomy
8 **Access to a resource inventory like the PHM Society portal**
2 Just in time/short presentations on key topics like ROI and management brief
0 Participation in an EPD User Group with diversity features

Sampling of PHM EPD Resources

2022 and 2023

Internal technical programs- Collins Aerospace technical University- Systems College, Communities of Practice, mentoring

Open online courses (audit and credit) Coursera with academic and commercial partners:

course (weeks-months), specialization (3-5), certificate with project, degree (longer term)

Machinery failure analysis (21 10): machine design, survival analysis, materials

Data science (3179 3121): data analysis, machine learning, probability and statistics

Signal processing (45 37): filtering, images/audio/biodata, GPU programming

Systems engineering (1331 857): model-based, requirements, dynamics, fluids, architecture

Technical supervisor (29 37): communications, products, entrepreneur

Certification engineering (398 218?): risk, quality, design, manufacturing

AWS: courses (hours), learning plans by roles or solutions (e.g., 15 courses for 12-26 hours), skill builder

HAI one day courses: Understanding and Implementing an Effective SMS, Maintenance Organization Quality Management, Aviation Maintenance Never Events

Sampling of Certificates for PHM

1. Academic
   a. Graduate Certificates:
      i. Illinois- Value Chain management (4-12 months, $4K)
      ii. Colorado- IOT (10 courses on-line, 6-12 months, $6K)
      iii. Penn Sate- Additive Manufacturing (3 grad courses, $12K), EE, Engineering Leadership
      iv. Purdue- Systems (3 grad courses, $13K)
   b. Masters track certificates
      i. U Chile- Certificate in Analytical Models for Business Decision Making (6 m @11-22hrs/week)
   c. Certificate in Prognostics and Health Management at Gautam Buddha University , Greater Noida (3 months)

2. Commercial https://www.coursera.org/certificates/
   a. Google Adv Data analytics professional certificate (6m@10 hours/week)
   b. MS Azure Data Scientist Associate (6.5m@4hrs/week)
   c. Deep Learning.AI tensor Flow Dev. Pro (4 course, 4m@5hrs/week)
   d. IBM Machine Learning (3m@5hrs/week)
   e. Udemy- Certified Quality Engineer exam prep (39 hours on-demand video)

Workshop Panelists

Prof. Peter Sandborn, CALCE, University of Maryland

Derek DeVries- Northrup Grumman

Questions to be addressed:

1. **Are curated collections of courses or certificates important for professional development and career growth in the PHM domain?**
2. **What do you need which might be unique to PHM, and how do we justify it?**
3. **How could the PHM Society help?**
4. **Other short courses for conferences: Advanced Diagnostics, Technical Language Processing Ready for PHM, …**

PHM Education Panel

Peter Sandborn
sandborn@calce.umd.edu

November 2023

The Current State of Academic Training

Undergraduate:

- Math (and programming)
- Some introduction to machine learning and maybe data analytics

Graduate (Masters and PhD):

- Data science programs
- Systems engineering programs
- Reliability engineering programs
- Maintenance engineering programs (more prevalent outside the US)
- Various university research groups offer miscellaneous courses specific to PHM and system health management as part of more general degrees

In general, universities are good at preparing students to design shiny new things, but most students are never introduced to the problems of maintaining and sustaining systems

Level Setting (What Universities Offer)

- Non-Degree Seeking Students ("Advanced Special Student")
  - Take selected courses (for credit), students are not admitted to a degree program
- Certificate
  - 12 credits (4 classes)
  - Part-time students, nominally 1 year
  - In-person, on-line, or hybrid (not available in-person to non-domestic students)
- Professional Masters (MEng)
  - 30 credits (10 classes)
  - Part-time students, nominally 2 years
  - No thesis
  - Can be 100% on-line
- Masters of Science (MS)
  - 30 credits (8 classes + 6 thesis credits)
  - Full-time students, nominally 2 years
  - Thesis
  - In-person, on-line, or hybrid
- Doctorate (PhD)
  - 48 credits (12 classes + 12 research credits)
  - Dissertation
  - In-person, on-line, or hybrid

Suggested path for PHM-related education at the University of Maryland

+ Industry Short Courses

Example: Suggested University of Maryland MEng in PHM

Jay Lee, UMD

Suggested Core Courses:

- Fundamental Physical-Based PHM
- Fundamental Data-Centric PHM
- Introductions to Machine Learning and AI in Engineering
- Data Quality Engineering and Evaluation in PHM
- Design of PHM for Product Life Cycle and Asset Management

Suggested Elective Courses:

- Introduction to Digital Twin Systems
- Introduction to Reliability Systems (many existing graduate courses)
- Introduction to Non-Traditional Machine Learning (transfer learning, domain adaption, federated learning, etc.)
- Sensory Systems for PHM
- Introduction to System Sustainment
- Course Project Based on PHM Data Challenges

… Hard Realities

- To offer a focused degree (like the one suggested on the previous slide), a business case has to be made
  - The program must financially breakeven within a couple of years
  - It must have a consistent enough flow of new students to sustain itself
  - Narrowly defined technical areas are more difficulty to justify
  - Degrees and certificates are highly scrutinized and controlled, i.e., the process is arduous

- Case Study: Masters of Engineering in Additive Manufacturing
  - Additive manufacturing courses have been and still are in high demand, they fill up fast
  - A Masters of Engineering program in Additive Manufacturing was formed in 2017
  - The program never broke even and was canceled in spring 2023 – everyone wants the additive manufacturing courses, but nobody wants a whole degree in it

Currently Available University of Maryland Industry Short Courses

- 1-3 days
- You don't have to be a student at the University of Maryland
- Taught at customer sites (or via Zoom)

- Failure Analysis of Electronics
- Root-Cause Failure Analysis of Electronic Products
- Reliability Science (Physics of Failure)
- Accelerated Product Qualification
- Virtual Qualification and Reliability Assessment
- Prognostics and Health Management
- Reliability of Electrical Contacts and Connectors
- Capacitor Technology and Reliability
- Light Emitting Diode (LED) Reliability

Electronics Reliability

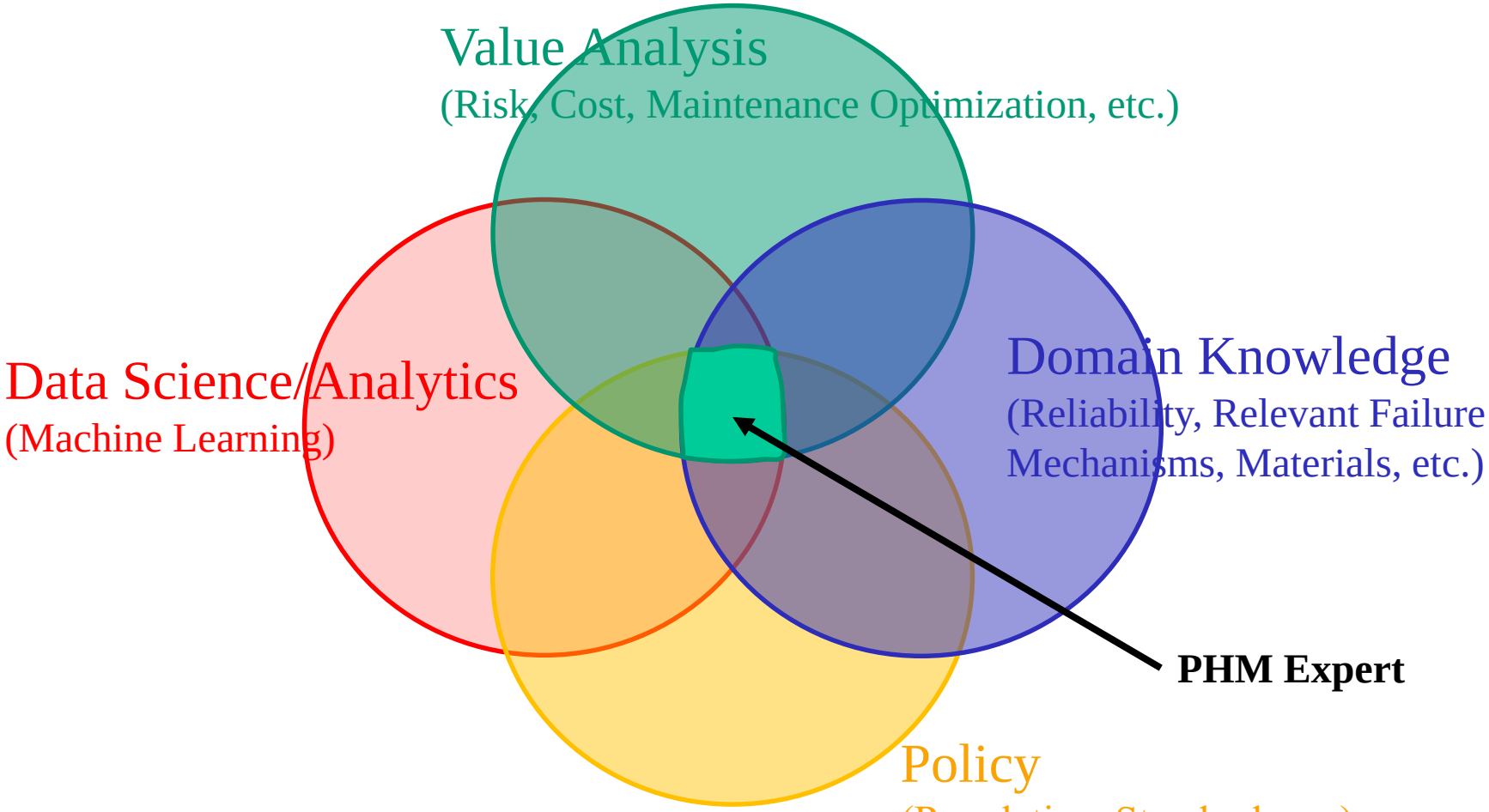
- Uprating
- Electronic Part Obsolescence Forecasting, Mitigation, and Management
- Counterfeit Part Detection and Management
- Understanding Electronic Packaging Materials
- High-Temperature Electronics
- Lead-Free Readiness
- Plastic Materials for Microelectronics

Electronic Parts Management

- Electronic Product and System Cost Analysis
- Critical Systems Sustainment

Electronic Systems Management

What Portion of This Should Universities Provide?



+ Systems Engineering

PHM Society Curated Certificates

Another approach …

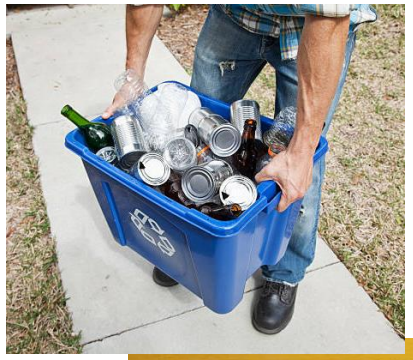
Rather than universities forming new degree programs maybe it is more practical to:

- Identify a list of applicable courses at *participating* universities (this could also include industry short courses and MOOCs)
- Students take “approved” courses (or course streams)
- Students submit transcripts showing the courses taken to the PHM Society
- The PHM Society issues a letter of approval (a “certificate”) to the student
- The student can, of course, apply the courses taken to existing MEng, MS or PhD programs at the universities if they wish (maybe transfer course credits between universities in some cases)

PHM Cultural Education

- Besides training students for the PHM workforce, we also need to “socialize” everyone
- Even socializing the students that will not enter the PHM/sustainment workforce is important because they will become customers or stakeholders (tax payers, decision makers, voters)

We want the public to automatically think/ask: “how is the system’s health going to be managed?” “who is going to manage it?” and “how are we going to resource its management?”



An example of really successful socialization …

THE VALUE OF PERFORMANCE.

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Innovation Through Understanding of Design Uncertainty and Its Effect on Probability of Failure

IEEE PHM Panel – From a Practitioners Point of View

6 March 2019

Derek R. DeVries, P.E.
Senior Fellow, Avionics and Control Systems
Northrop Grumman Innovation Systems

Culture of Innovation

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*"The biggest threat to innovation is internal politics and an organization culture, which doesn't accept failure and/or doesn't accept ideas from outside and/or cannot change" **

*"Innovation requires cultural change and acceptance of manageable risk. Failure Enables Innovation." ***

Source: *Gartner Financial Services Innovation Survey, July 2016
** Derek R. DeVries P.E., Senior Fellow Northrop Grumman Propulsion Systems, Linked In Dec 2016

Why PHM?

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- Prognostic Health Management (PHM) systems are required when:
  1) A system or component is known to change behavior with time
  2) The risk of an inaccurate prediction of future behavior is not acceptable
- System behavior changes are generally caused by one of the following types of conditions:
  1) **Cumulative physical damage** caused by induced loads
  2) **Material changes** due to chemical aging mechanisms or exposure to environments
  3) **State or condition changes** caused material interaction or exposure to environments
- PHM is an enabling requirement for implementing systems with robust Condition-based Maintenance Plus (CBM+) capability
- PHM technologies can provide invaluable insight into the performance of a material or product

PHM systems enable CBM+, which has been proven to reduce life cycle cost while ensuring reliable operation for the life of the systems

Uncertainty Quantification → Risk Management

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- **There are known knowns** – These are things we know that we know.* *"Aleatory risks"*
- **There are known unknowns** – That is to say, there are things we know we don't know.* *"Epistemic risks"*
- **There are also unknown unknowns** – There are things we don't known we don't know.* *"Ontological risks"* ***

- What is Risk? How are risks addressed and managed?
- Risk management allows us to make decisions in an uncertain world where we do not know everything about a system, component, or material and cannot perfectly predict future capabilities or performance outcomes.**

* Donald Rumsfeld - 2002
** Matthew Squair, https://criticaluncertainties.com/2009/10/11/epistemic-and-aleatory-risk/
https://criticaluncertainties.com/2013/02/26/the-don-rumsfeld-ignorance-management-framework/
*** Where used, NGIS PSD combines these with epistemic risks / uncertainties and not attempt to separate them out

Uncertainty Quantification → Risk Management

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- Yet when we talk about risk, is it always the same thing? Assessment is based upon belief that the likelihood multiplied by consequence is statistically balanced. *"flip a coin expectation is that coin will land on each side 50% of the time"*
- What if the knowledge about the uncertainty is not balanced or is unknown. *"coin is biased or thrown where it cannot be seen"*
- Quantification of risk must be an active process and include as much knowledge of the uncertainty contained in the risk identification as is available
- This includes quantification of Aleatory and Epistemic risks
- Risk mitigation is the process of reducing the uncertainty by systematically gaining knowledge and managing the identified risks. This process must assume Epistemic and Ontological risks in uncertainty.

* Matthew Squair, https://criticaluncertainties.com/2013/02/26/the-don-rumsfeld-ignorance-management-framework/

An advanced aerospace PHM system must account for uncertainty and quantify known error sources and knowledge of those sources

The Aerospace PHM Challenge

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- Physics of failure – **understanding casual effects** of a system change
- Trend extrapolations hopes past and current propulsion system behavior will predict future propulsion system behavior
  - Often this is not the case "Epistemic Effect"
- The fundamental challenge of a propulsion system PHM is to identify bad assets in the inventory and remove or repair them before they can be used or cause harm
  - The current state of motor viability prediction is based on using data from motor sets with significant motor-to-motor variability
    - Often the representative data are obtained by a sample of the fielded motor set and/or separate accelerated aging samples of representative motor constituents
  - Perform an empirical extrapolation of key motor properties associated with a sampled motor and apply that prediction to the full set of motors "Aleatory Effect"
  - This variability results in large standard deviations, making accurate individual motor prediction difficult and results in conservative service life estimates, which retire systems early "Epistemic and Ontological Effects"

An advanced aerospace PHM system must monitor individual assets and their environments to improve; service life predictions and confidence in the fleet's reliability assessments

PHM Analysis System Basis

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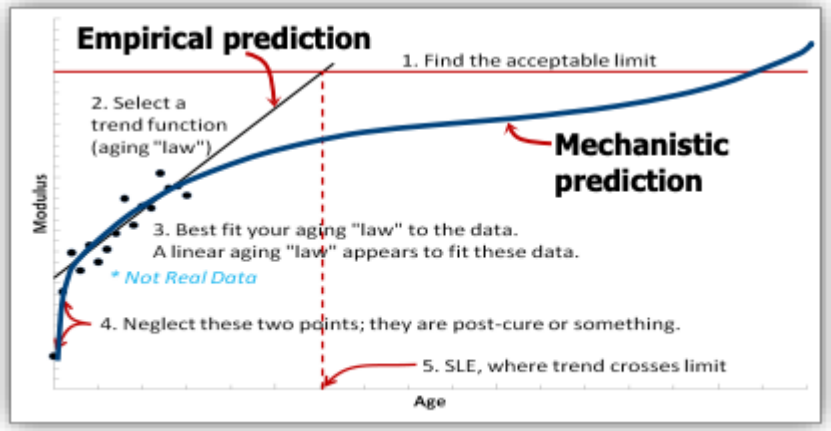
- PHM analysis systems are typically based on either:
  - a) Trend extrapolation
    - ➢ Defined as "**Empirical Analysis**" approach

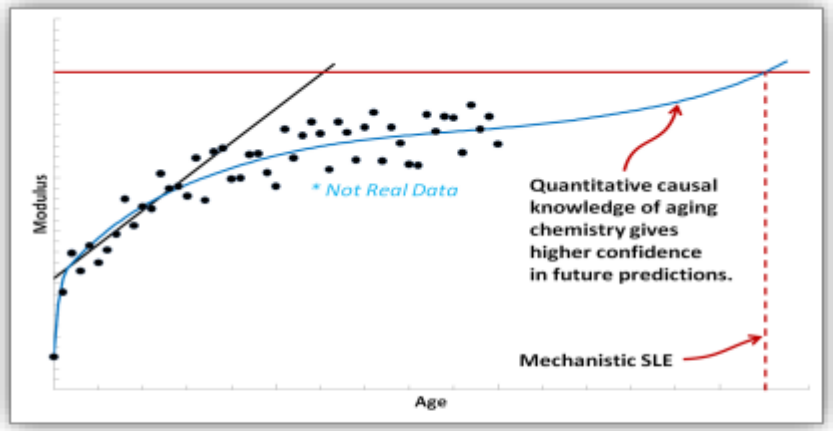
    or
  - b) Knowing the fundamental causes of the changes in system behavior
    - ➢ Defined as "**Mechanistic Analysis**" approach

    or
  - c) Elements of both

Empirical Approach



Mechanistic Approach



Mechanistic approaches are necessary when a system's / component's reliability predictions are needed beyond existing empirical data

Empirical Performance Analysis Example

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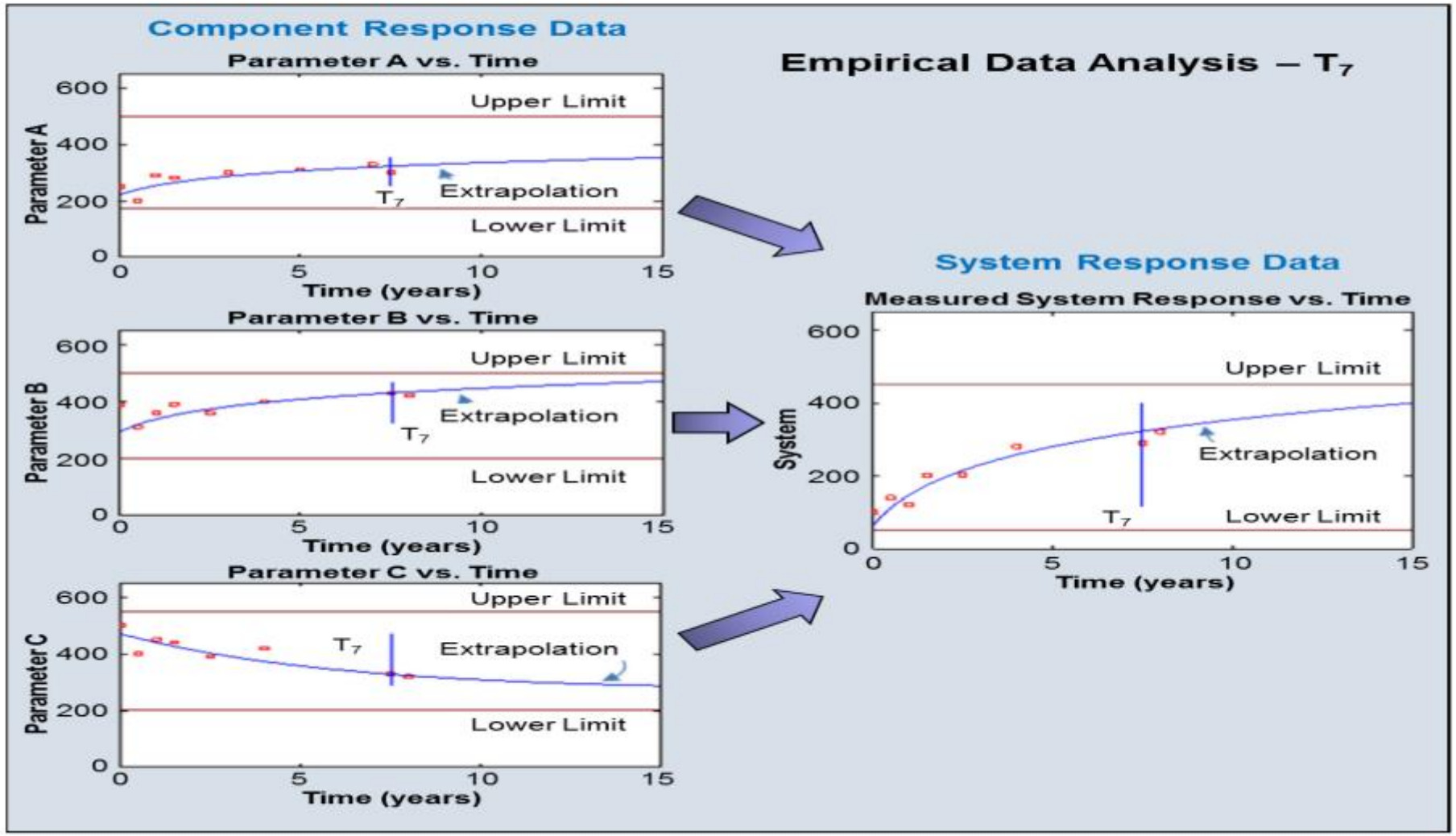
Representation of data from time T0-T7 and an extrapolation of the data out to time T15



Embedded RFID Passive Sensor Application Example

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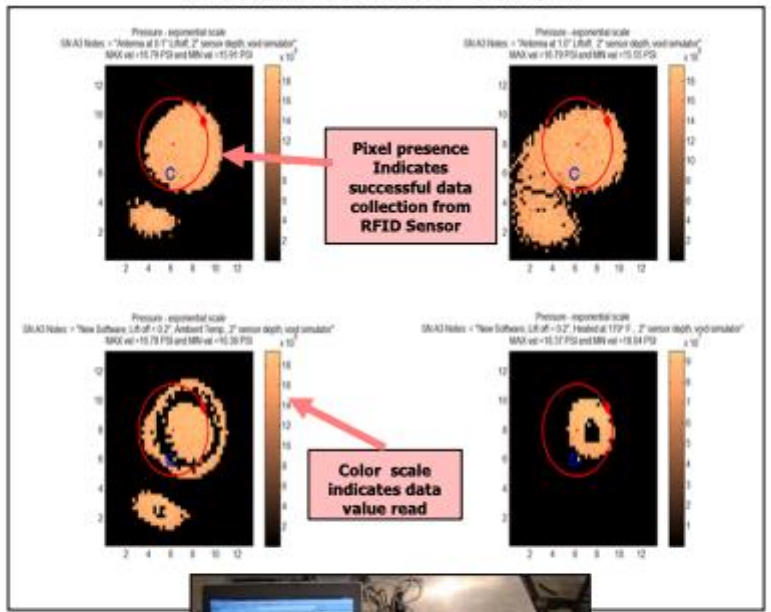
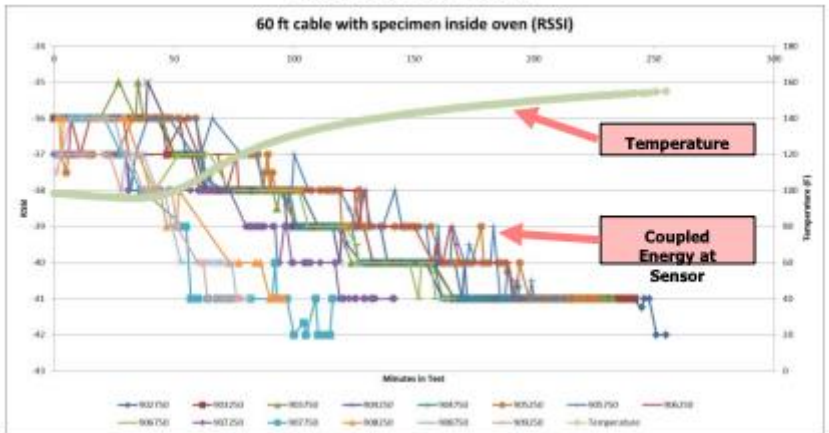
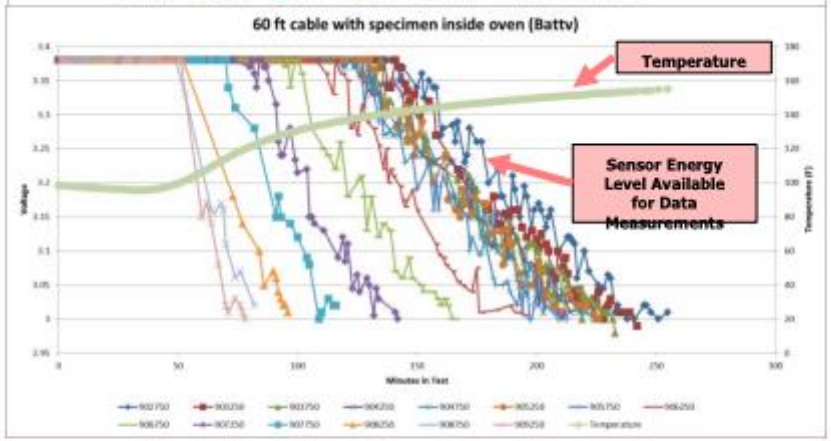
Signal Loss as a Function of Temperature, Location, Distance From Read Antenna to Sensor



Signal Loss as a Function of Temperature and Frequency





Understanding how the sensor is affected by the system and how the system responds to the sensor is critical to an accurate PHM system prediction

Linear-Elastic Modeling Using Empirically Derived Material Properties

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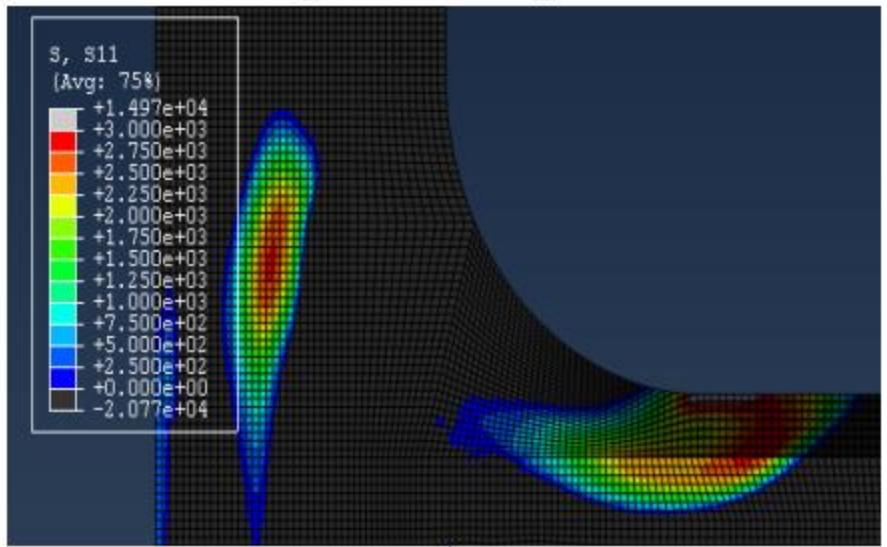
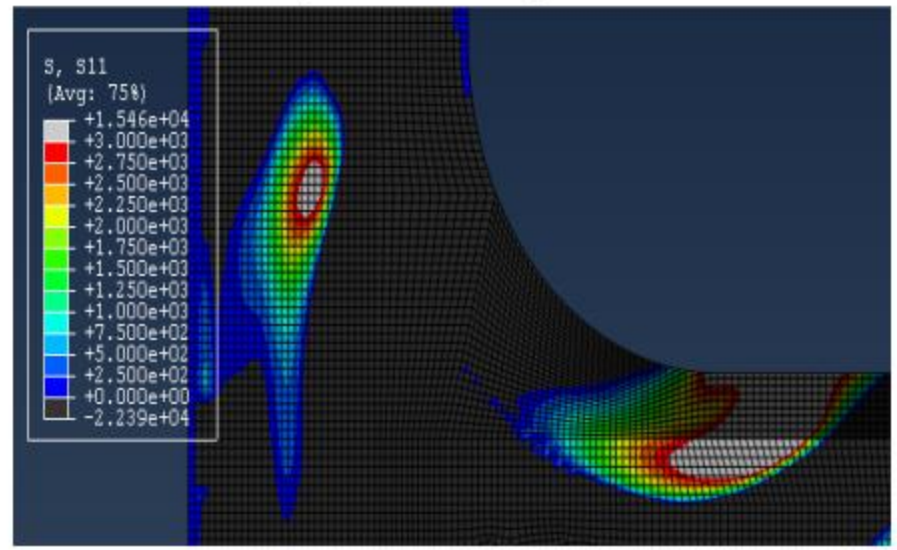
Comparison of Empirically Derived Statistically Nominal vs. Point Derived Material Properties Model Effects

Statistically Nominal
Compressive Properties



Point Derived
Compressive Properties



This model is more representative of the actual part's performance

THE VALUE OF PERFORMANCE.

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Discussion

AUDIENCE

Prof. Peter Sandborn, CALCE, University of Maryland

Derek DeVries- Northrup Grumman

Some questions to guide our discernment:

1. **Is there a gap between formal training and what industry needs?**
2. **Are curated collections of courses or certificates important for professional development and career growth in the PHM domain?**
3. **What do you need which might be unique to PHM, and how do we justify it?**
4. **How could the PHM Society help?**
5. **How do we socialize PHM in our community and in general?**
6. **Other short courses for conferences: Advanced Diagnostics, Technical Language Processing Ready for PHM, …**

Priorities ?

Discussion

1. We need to keep pace with innovations and do skill development throughout our careers
2. We might be good at preparing students to design ‘shiny new things’ but without much integration of maintenance and sustainment
3. Innovation requires multiple disciplines and cultural change while incorporating risk
4. Large company approach is to hire engineering expertise and teach them PHM through assignments on PHM projects (alternative approach finds that data scientists never get enough engineering expertise)
5. Options might be an undergrad in engineering or SW with a minor in PHM or a masters in the domain and a certificate in PHM accessible across many domains
6. Difficult for any one university to be all things in PHM- could the society identify a suite of courses across PHM domains around the world and then ‘certify’ completion of the package with a certificate of ours associated with the official transcripts
7. Certificate could include current and new Society short courses
8. Society could also help develop courses and identify content with universities
9. Integration into career progression, in-house industry employee development/continuing professional development are key targets but not much input yet- need industry participation in certificate development process
10. Interest in other short courses?: Natural language processing for the world of the possible (not R&D)

Conclusion by show of hands: We should develop the concept of a PHM Society certificate

Way Forward- Get Involved!

- IJPHM papers and communications
  Indexed in the Emerging Sources Citation Index
  - Submit an abstract for a paper or a communications
  - Propose a Special Issue
- Updates on EPD in progress
  - *PHM EPD Portal* - PHM Education and Professional Development Portal - PHM Society as part of the Society community
  - EPD Users Group - join
  - Forum discussions – participate in the EPD forum: PHM Education - PHM Society
- **Volunteer to help develop the PHM Society Certificate**
- What else would be useful?

Please visit and participate in the PHM23 discussion group on WHOVA

Thank you

See you in Prague in July 2024 for PHME24 and Nashville in November for PHM24 with short courses like Short Courses - PHM Conference 2023 (phmsociety.org)

2022 Discussions Among 40+ attendees

- Need to identify the core competencies needed by industry and academia for PHM professionals: can we crowd source ideas in the particular fields to identify common themes to drive new courses, webinars, resources compilations, …
- Universities are working to provide bridges to industry needs for new workers- engineering informed statistics, internships, capstone projects, 1 year M. Eng. and full collaborative projects
- Industry pull is encouraged, e.g., 'soldier-sponsored'; Disconnects exist between what universities teach and what professionals need. PHM Society could promote more interactions.
- NIST has some best practice resources https://www.nist.gov/programs-projects/prognostics-and-health-management-reliable-operations-smart-manufacturing-phm4sm; SAE on cost benefit analysis
- "YouTube" model for learning- short, specific sources of information but need for integration and experience
- Need to distinguish/highlight PHM augmentations to conventional systems engineering- PHM is seen as an activity (not always necessary) but not a discipline
- Collins uses an internal Community of Practice to share and mentor in addition to their Technical University's System Engineering School
- Need product orientations and best practice guides for new workers to complement their technical knowledge and enable nimbleness and adaptability
- Challenges are the development time and skills for focused short courses fitting people's busy lives, and PHM integrated into system requirements by informed clients
- Create a short presentation (45 minutes) for executives about PHM and ROI: introduce into leadership and MBA programs, build discussion and acceptance of PHM contributions
- Use opportunity to bring hands-on experience by recruiting veterans into project teams