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

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PHM for Human Health and Performance Panel

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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 by 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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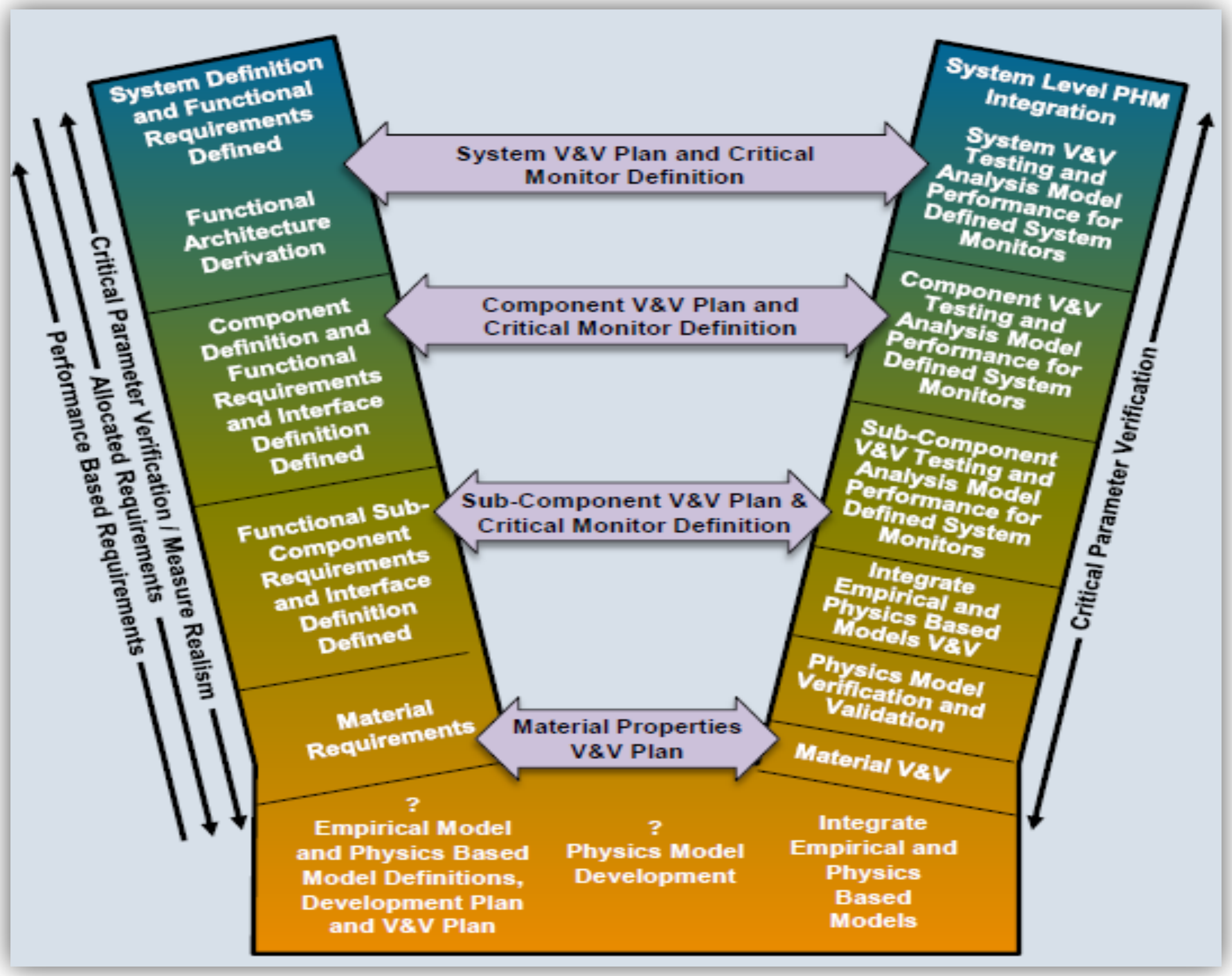
- Yet when we talk about risk, is it always the same thing? Assessment is based upon belief that the likelihood multiplied by consequence is statistically balanced. *"flip a coin expectation is that coin will land on each side 50% of the time"*
- What if the knowledge about the uncertainty is not balanced 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

System Engineering Approach



System engineering V diagram showing requirements capture, allocation and Verification and Validation (V&V) process.[1,2]

1. Derek R. De Vries, Bryan De Hoff, et.al, "Systems Engineering approach to IMLM DAAS goal achievement," JANNAF 61st JPM, Charleston, SC, May 2014.
2. SE Handbook Working Group International Council on Systems Engineering (INCOSE), INCOSE Systems Engineering Handbook v. 3.2.2, Oct 2011.

Architecture of a Physics-based PHM System

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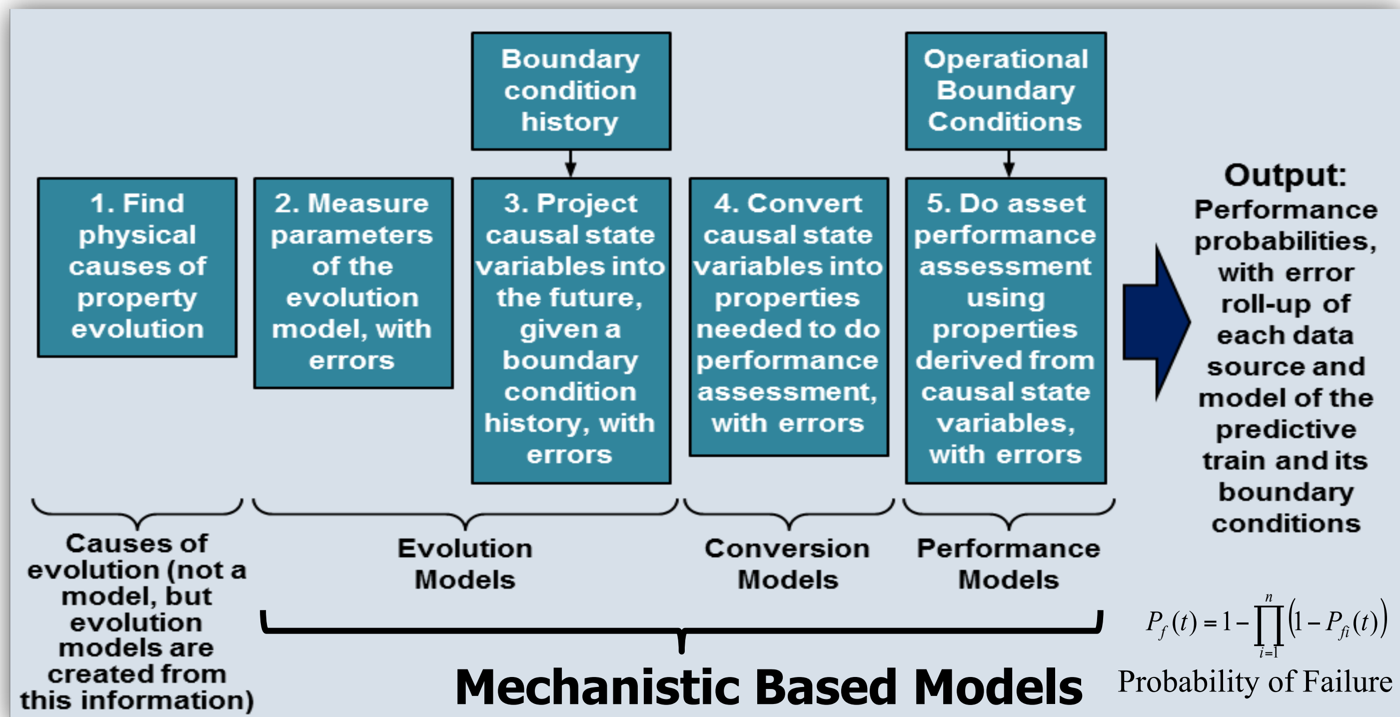
Predictive Train

A sequence of models and data sources that start with the causal state variables on the left and end with predicted asset performance on the right



Error Rollup Quantifies Uncertainty of P_f (t) → $\sigma(P_{fi}(t)) = \sqrt{\left(\frac{\partial P_{fi}(t)}{\partial a_1}\sigma(a_1)\right)^2 + \ldots + \left(\frac{\partial P_{fi}(t)}{\partial a_j}\sigma(a_j)\right)^2 + \ldots + \left(\frac{\partial P_{fi}(t)}{\partial a_m}\sigma(a_m)\right)^2}$

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

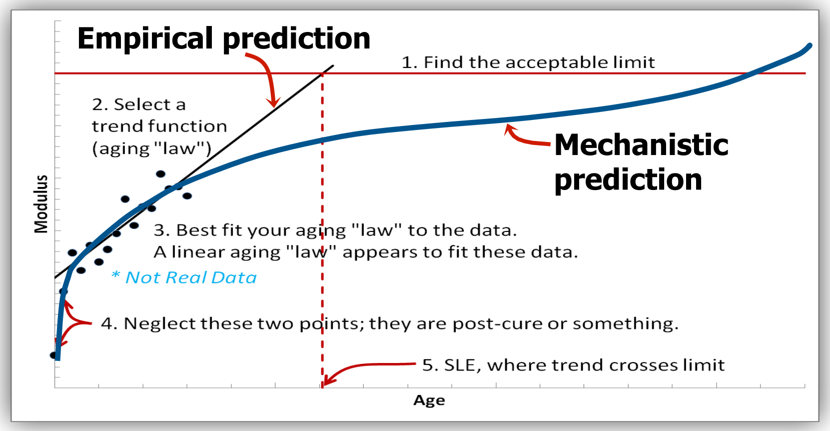
PHM Analysis System Basis

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

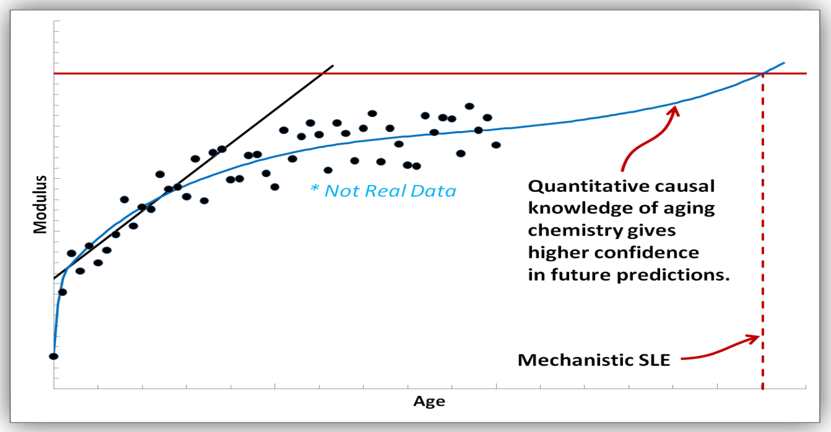
    or
  - b) Knowing the fundamental causes of the changes in system behavior
    - ➢ Defined as “**Mechanistic Analysis**” approach

    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

Prognostic Health Management (PHM)[3]

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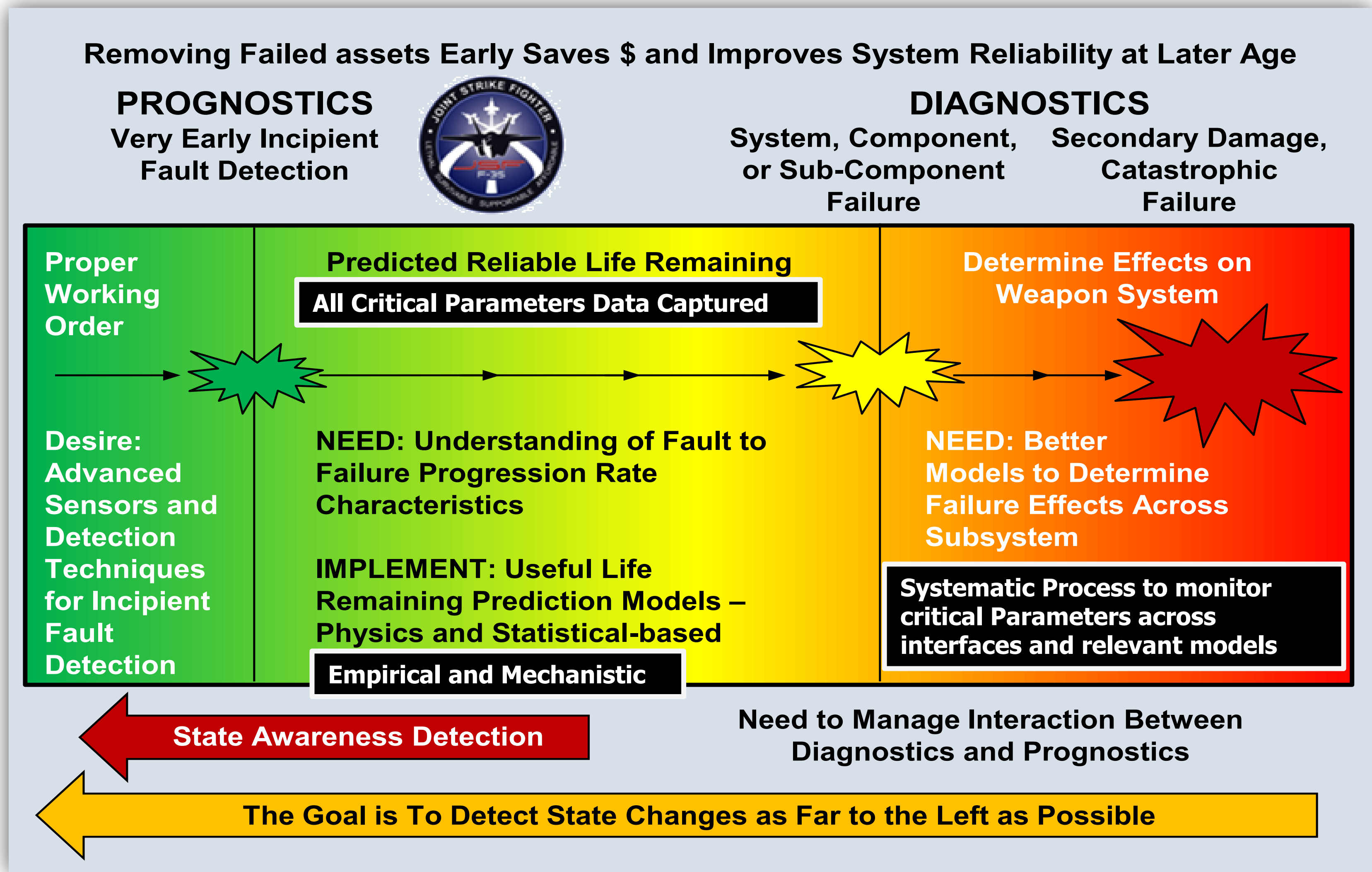

3. A. Hess, T Dabney, "Joint Strike Fighter PHM Vision," IEEE Aerospace Conference, Big Sky MT, Mar 2004.

Conclusion

- Northrop Grumman's System Engineering approach has led to successful implementation of a prognostic health management system, which captures critical performance information and provides a mechanistic approach to accurately predict the reliability of an individual asset and associated system service life
- An accurate service life assessment with quantifiable confidence intervals requires a thorough understanding of the uncertainty in the performance predictions for the system's critical parameters
- The V&V approach is critical to validation of the data collection and modeling processes and verifying the quantified uncertainty in the performance assessment for each critical parameter of the system
- Northrop Grumman's PHM approach enables CBM+ for the solid propulsion industry
- Understanding the mechanisms that lead to the failure for each component provides the ability for innovative solutions
- Understanding the P_f of our products is the method that allows us to provide higher performance in operational environments at a reduced cost

A systematic approach is necessary to achieve a functional PHM capability that provides the necessary balance between the system's driving requirements
- programmatic and technical -

Risk Type Identification

- **Perception risks.** We don't know we know it. We have the information, but for whatever reason it fails to get to the people who actually need it or fails to be perceived as salient by those persons, and is discounted.

- **Aleatory risks.** We know it and we know we know it. Where randomness exists it is understood and fully characterized. The question is whether the loss rate associated with the risk is acceptable.

- **Epistemic risks.** Uncertainty about a known parameter, e.g., a known unknown, for example uncertainty about a failure rate or potential severity. We may understand there is a risk but still be uncertain about how much there is.

- **Ontological risks.** Unidentified holes and flaws in our understanding, the unknown unknowns. We don't know how many risks there are in our portfolio and may even be uncertain about the types of risks that we may be running.

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

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