Welcome everyone to the…

Panel Session 5: Digital Twin

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Before We Start…

Join the Q&A on your mobile device.
Scan the QR code or visit https://sli.do and enter the code below.
#PanelSession5

- Everyone is muted
- **ZOOM** for verbal questions (use raise hand)
- **SLIDO** is being used for written questions & polls
- **CHAT** for ongoing discussion & networking
- In between each panelist presentation, the moderator will select a question to be posed to the panelist. Questions will be fielded for no more than 2-3 minutes between presentations.
- Panelist presentations are expected to be approximately 5 minutes (or less)
- General audience Q&A will be open after the last panel presentation

Image courtesy of Adobe Stock

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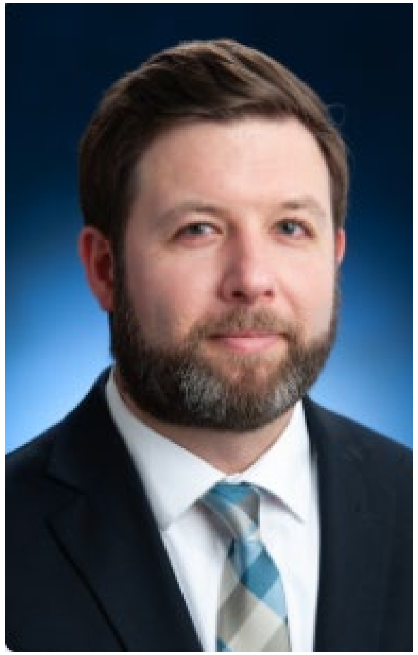
Introducing today's Panelists:

Benjamin Grisso



Naval Surface Warfare Center

Yolanda Mack

Raytheon

Tom Wiegele

Collins Aerospace

Sankaran Mahadevan

Vanderbilt University

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Introducing the Panel's Chair and Moderator:

Antonios Kontsos

Drexel University

Sarah Malik

Drexel University

Panel #5 Agenda:

1. Chair Intro **(8 mins)**

2. Panelist Presentations with time for panelist-specific questions **(32 mins)**

3. General Audience Q&A **(30 mins)**

Panel #5 Specific Points of Discussion

- *efforts to* ***standardize digital twin processes*** *or at least validate parts of them using traceable, repeatable and effective ways;*
- *issues related to creating* ***validated dataset repositories*** *which could assist model and processing approach development, independent of a given application and of case-specific data acquisition, and contributing towards demonstrations of successful alignments of the physical and digital spaces;*
- ***benchmark problems*** *tailored to a PHM-related hierarchy of detection, classification and prediction, similar to other domains e.g. in nondestructive evaluation, material characterization, as well as inspection and maintenance;*
- ***modeling*** *including knowledge-based, deep learning, probabilistic, analytical, physics-based etc., which could be leveraged in digital twin workflows;*
- *efforts to use digital twinning not only in forward flows that involve steps from data to decision but are also* ***creating dynamic adaptations*** *capable of evolving as monitoring occurs, providing feedback to sensors as data is processed and ultimately even creating real autonomy via e.g. data and model-driven adaptive control.*

Section 1: Background on Digital Twin

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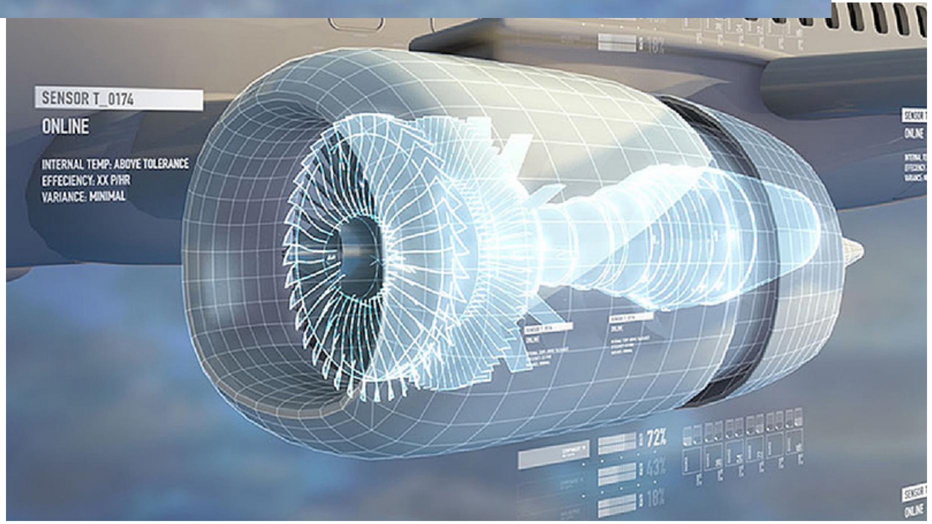
The Digital Twin (DT) Concept

> *"A digital twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding (flying) twin."* – Glaessgen & Stargel 2012

Three essential components

- **Physical Twin**
  - A system or system of systems to which a number of sensors are used for data acquisition
  - Such data could of various types
- **Digital Twin**
  - A model that follows a particular instance of the product
  - The model is updated with data from the physical twin
- **Digital Thread**
  - Ties twin models together
  - It includes both hardware and software



The DT Workflow

Physical Space	• Operational monitoring • Sensors/Gateways/Network
Digital Space	• Virtual Model based on historical data • New model based on Data Space
Data Space	• Real-time data representation • Storage/Pre-processing/Sorting
Knowledge Space	• Self-improving, self-thinking phase • Automatic knowledge navigation and accumulation
Social Space	• Service system for decision making (CRM, ERP) • Bridge between Data-driven DT and Decision Making

Potential for Autonomous Real-time Decision-Making

What is a "Model" in DT?

"***A system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs***." *(Merriam-Webster)*

Conceptual Model: A composition of abstract ideas used to aid the understanding or simulation of a subject.

Mathematical Model: Description of a system using a mathematical description of the relationships between system parameters.

- Governing Equations
- Defining or Constitutive Equations
- Assumptions and constraints

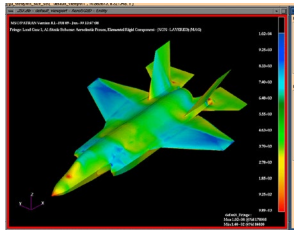
Computational Model: A mathematical model requiring significant computational resources.

Numerical Model: A mathematical model solved with a discretization scheme

ML/AI Model: A numerical or mathematical model which uses data to run

A Representative (Envisioned) Use Case of a DT

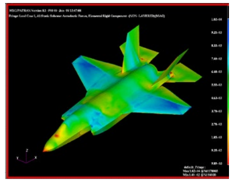
Concurrent delivery of physical **and** digital aircraft



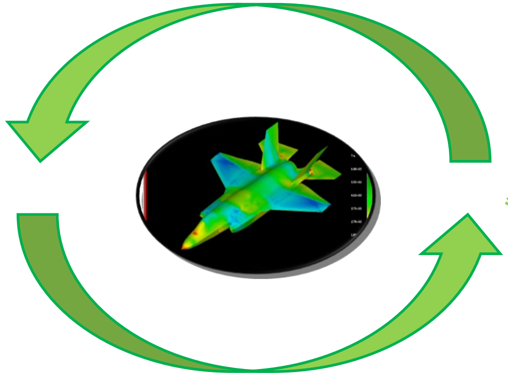
Digital twin is specific to its assigned aircraft and includes all known manufacturing anomalies

Onboard sensors collect load data during flight

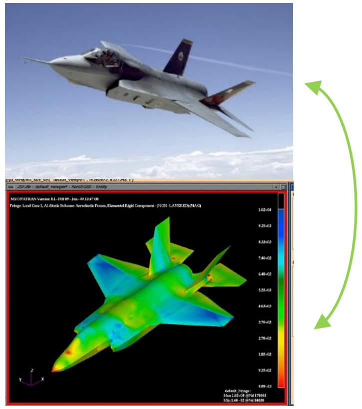
Digital aircraft is updated to include predicted material property changes



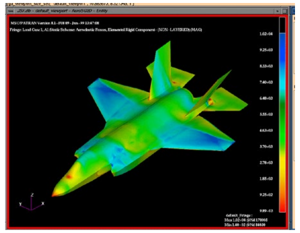
Digital aircraft subjected to simulated lifecycle loading



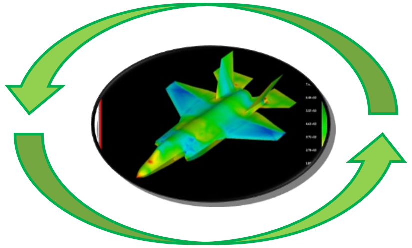
Discrepancies between predicted and observed behavior resolved through statistical techniques



Physical aircraft retrofitted prior to first flight to correct deficiencies



Identical Modifications made to digital aircraft



Lifecycle loading of the updated model can provide RUL and lifetime cost estimates

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Tuegel, Eric J., et al. *"Reengineering aircraft structural life prediction using a digital twin."* International Journal of Aerospace Engineering (2011)

DT-capable (Representative) Commercial Software

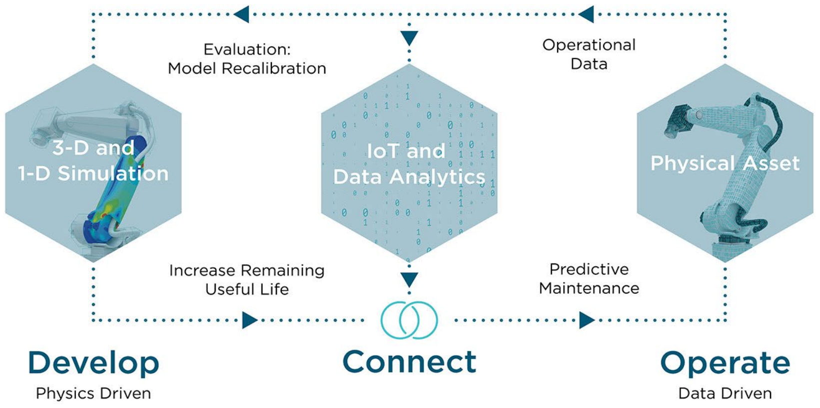


Image courtesy of Altair

1

ALTAIR

The **Altair** digital twin integration platform bl ends physics and data-driven twins to support optimization throughout the products lifecycle.

2

Simio Forward Thinking

Simio Simulation Software can be used for Digital Twin where a virtual copy, or software model, of a physical entity is created. The entity may involve processes, people, places, systems and devices.

3

ANSYS

Ansys Twin Builder is an open solution that allows engineers to create simulation-based digital twins–digital representations of assets with real-world or virtual sensor inputs.

A Representative Industrial DT Demo Application

4

Cloud (public or private) based capabilities are closely integrated with an on-premise Predix Machine and **Edge Analytics** Control System, responsible for collecting, formatting and sending **machine data** and for executing **machine level analytics where real-time responses are required on site.**

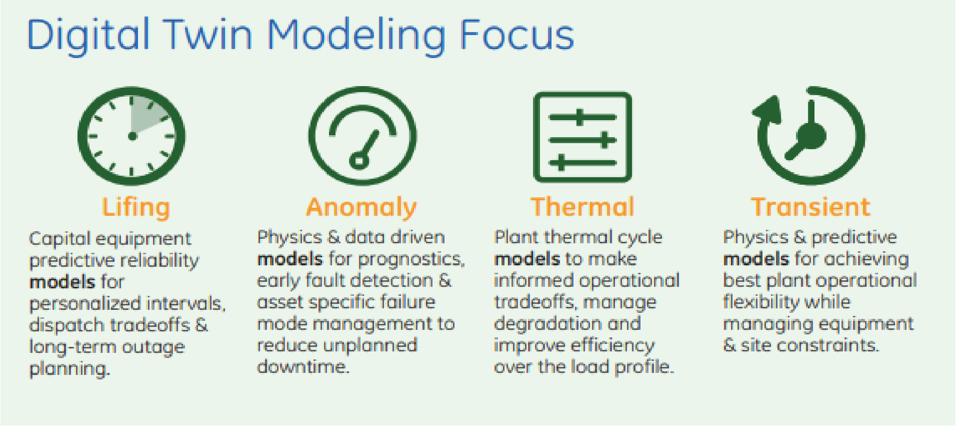


Figure 4: GE Digital Twin Model Categories

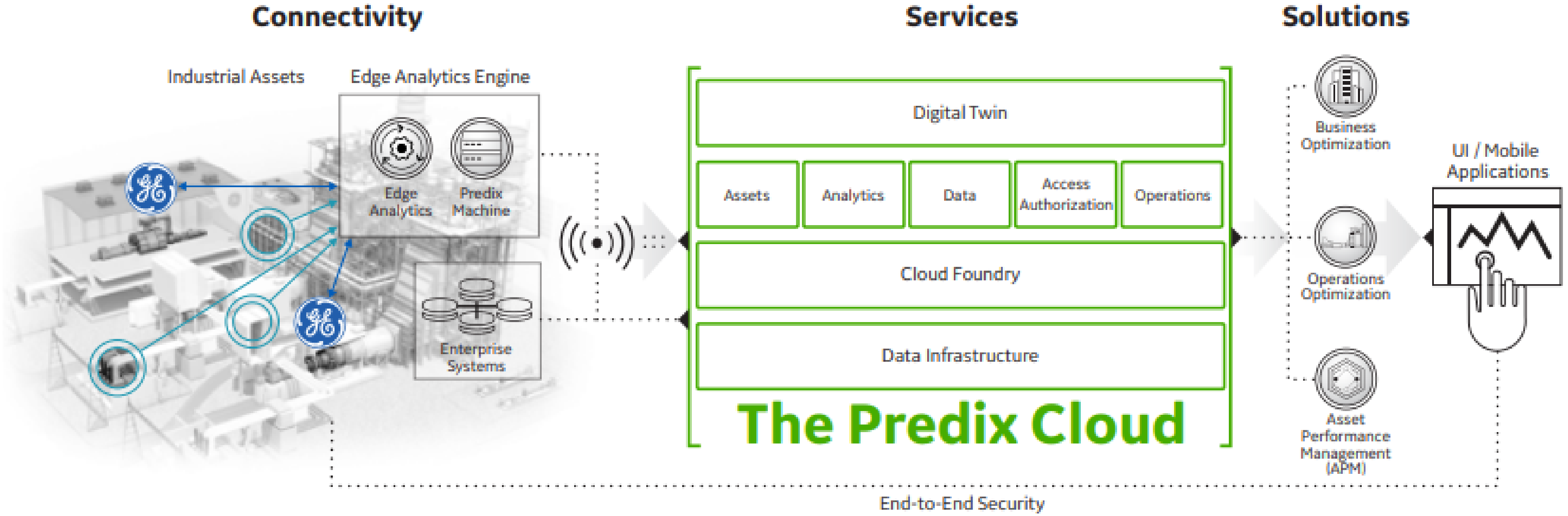
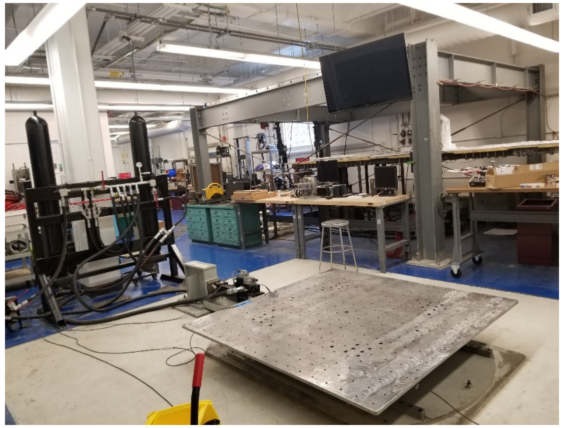


Figure 3: Predix Platform

DT @ Drexel (Overview)

The Physical

Drexel Mechanical & Structural Testing Facility



Drexel-Patented Sensing & Data Acquisition

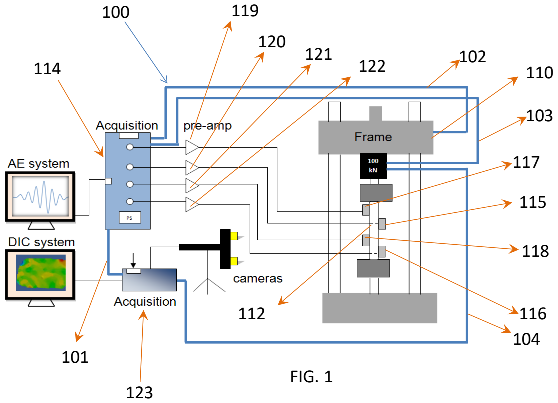
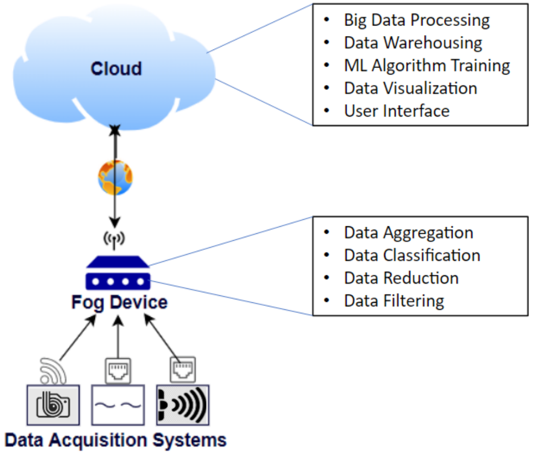


FIG. 1

The Data

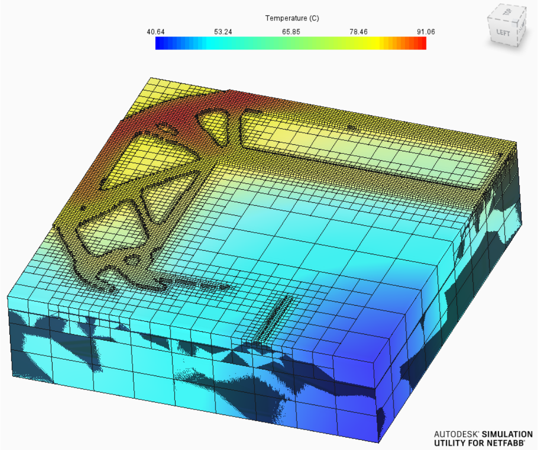
Edge-Fog-Cloud



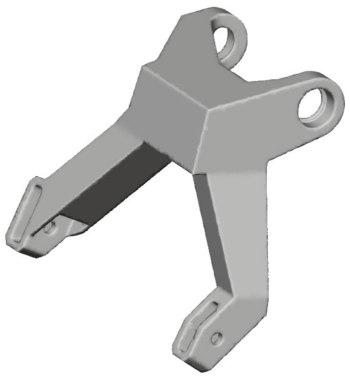
High Performance Computing

The Digital

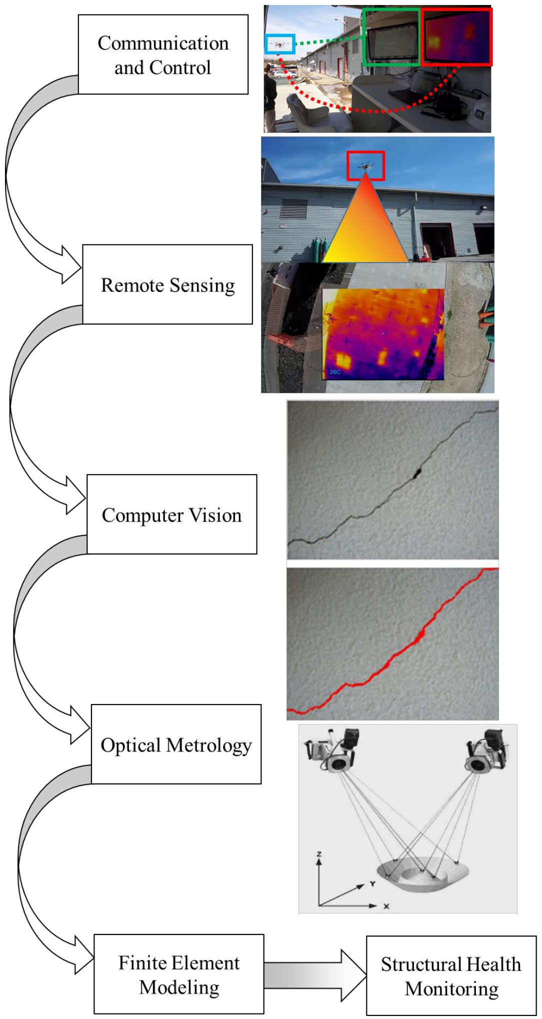
Predictive Manufacturing



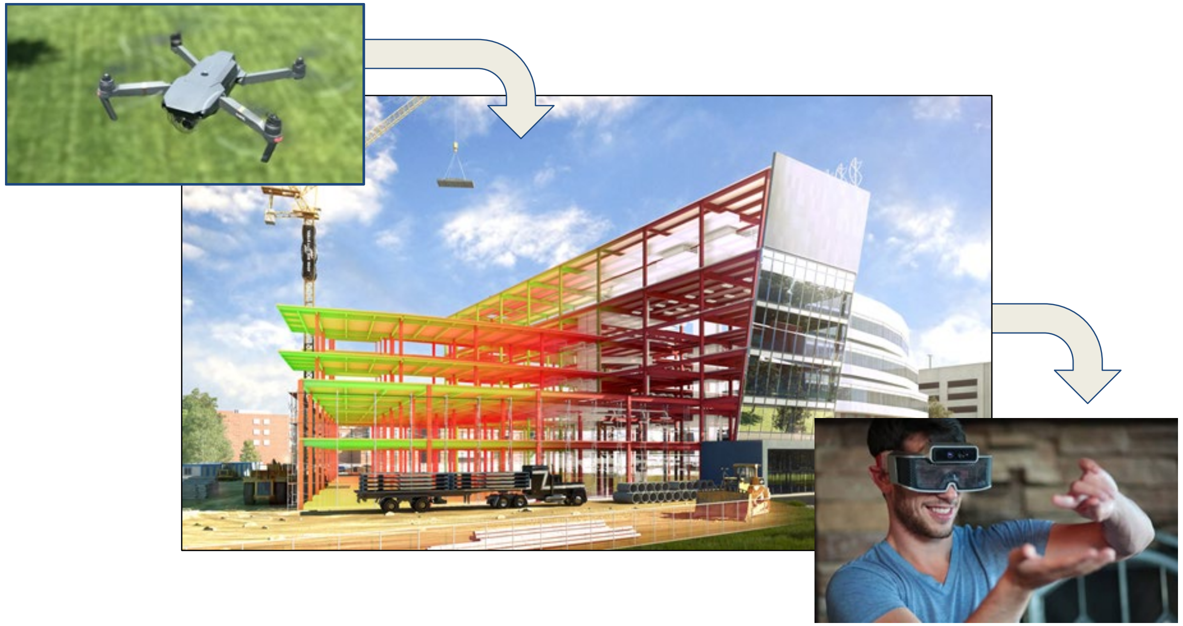
Design Optimization

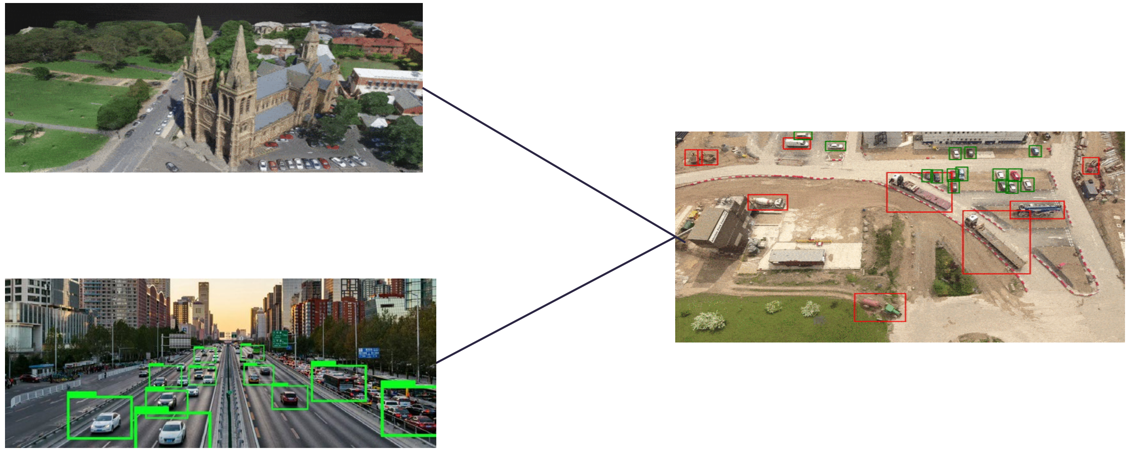


DT @ Drexel Application (Remote Monitoring with AR/VR)



(2018) A. Ellenberg, **A. Kontsos**, I, Bartoli, "*On the Use of Unmanned Aerial Vehicles in Nondestructive Evaluation of Civil Infrastructure*", Materials Evaluation, Vol. 76(5), pp. 629-642





(2016) Ellenberg, **Kontsos, et al.**, "*Bridge Deck Delamination Identification from Unmanned Aerial Vehicle Infrared Imagery*", Automation in Construction, Vol. 72, pp. 155-165

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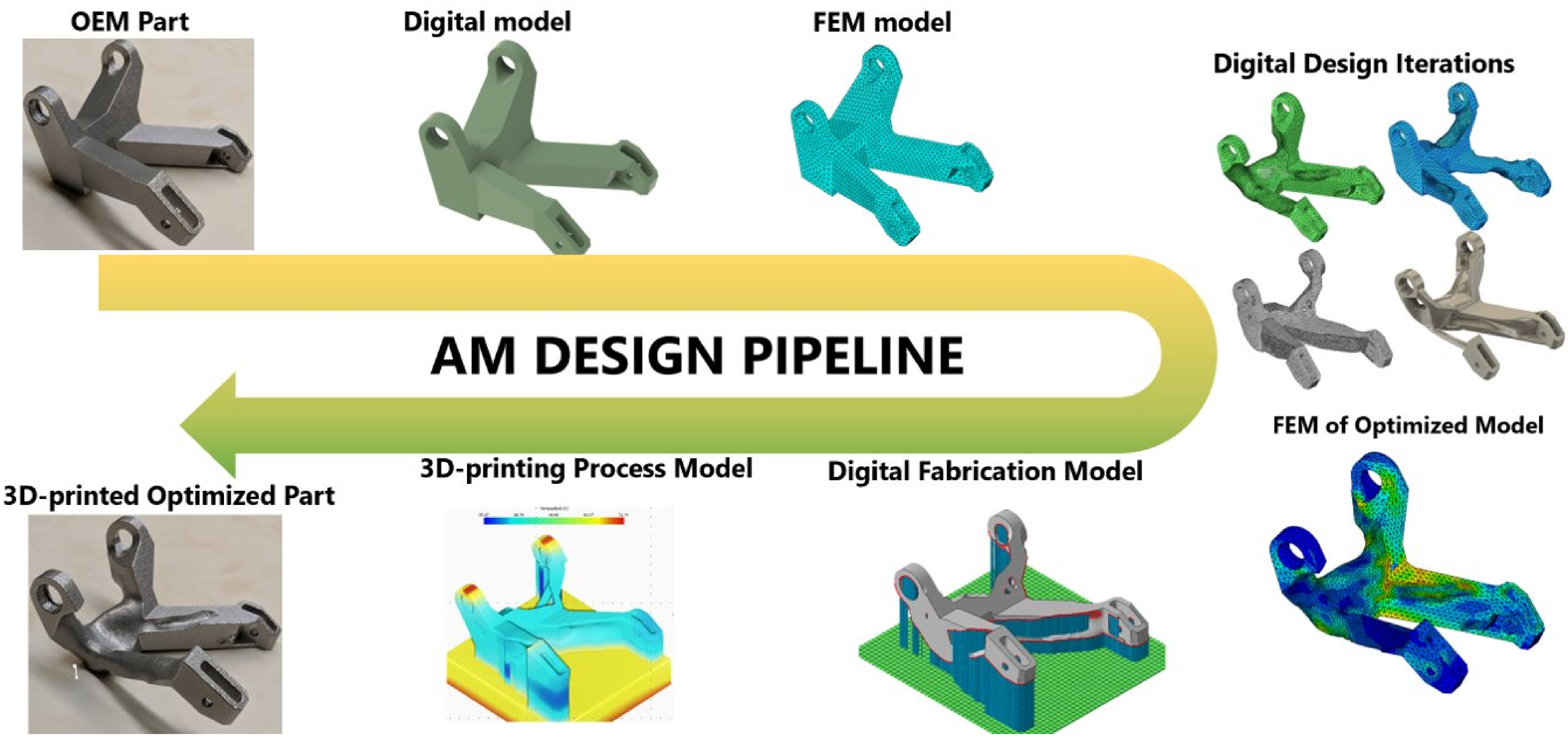
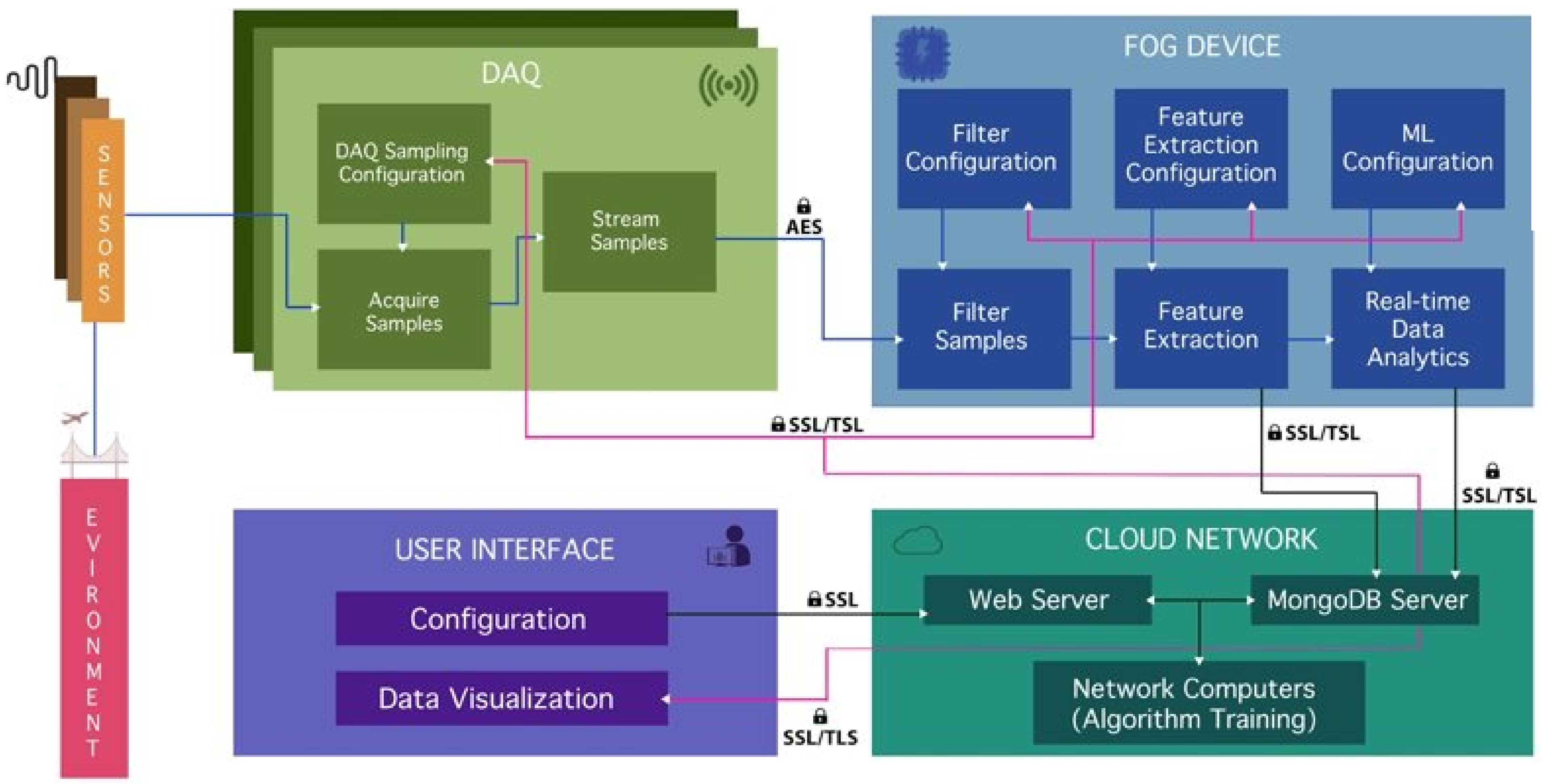
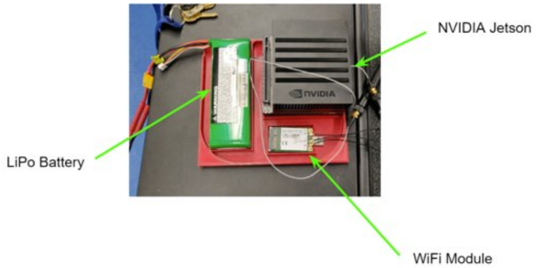
DT @ Drexel Application (Predictive Metal Additive Manufacturing)



(2020) V.I. Perumal, A. Najafi and **A. Kontsos***, "*A Novel Digital Design Approach for Metal Additive Manufacturing to Address Local Thermal Effects*", Designs, Vol. 4, pp. 41

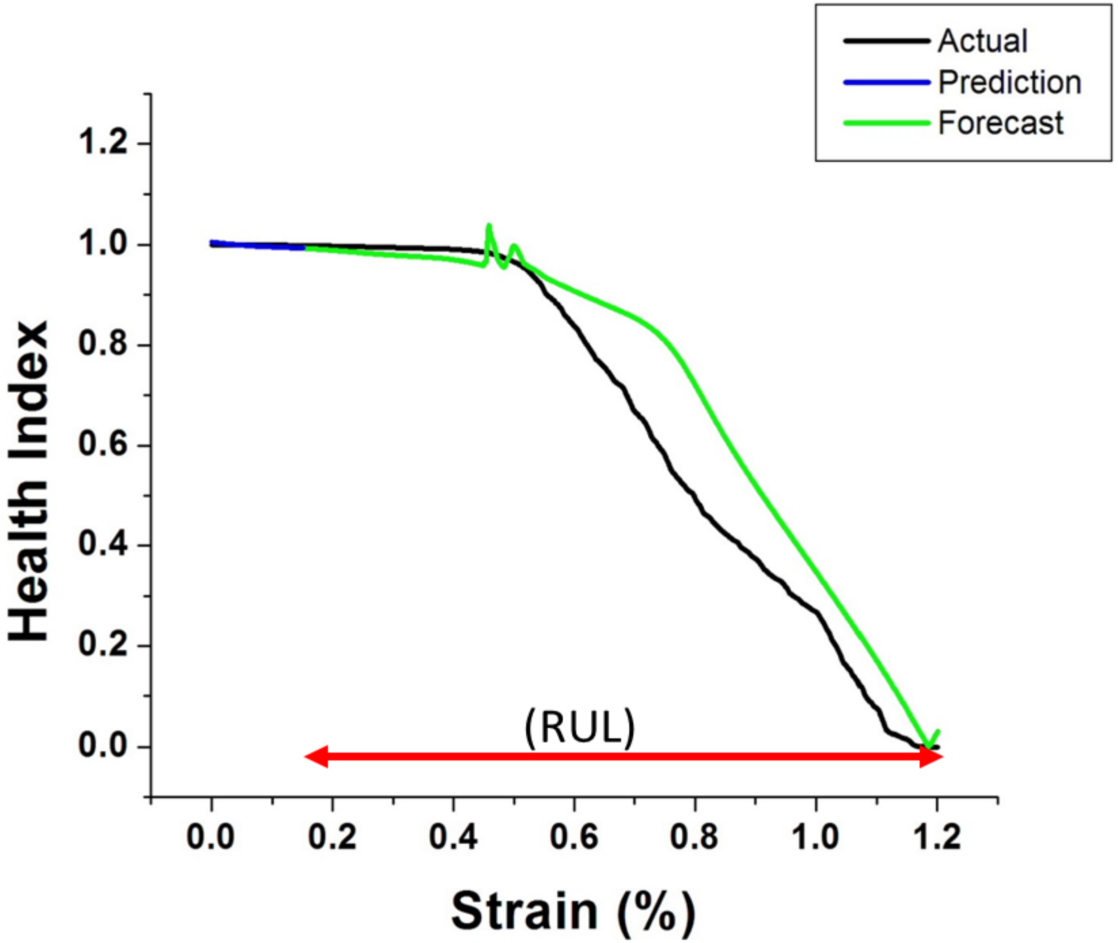
DT @ Drexel Application (IoT for Digital Threading)





(2020) S. Malik, R. Rouf, K. Mazur and **A. Kontsos***, *"The Industry Internet of Things (IIoT) as a Methodology for Autonomous Diagnostics in Aerospace Structural Health Monitoring"*, Aerospace, Vol. 7, 64

DT @ Drexel Application (Composite Material RUL prediction)



- Step 1: Post-Process NDE data to define a Health Index **(HI)**
- Step 2: Train a Hidden-Markov Model **(HMM)**
- Step 3: Train an Adaptive Neuro-Fuzzy Inference System **(ANFIS)**
- Step 4: Implement Steps 3 & 4 in the IoT system **(real time RUL)**

(2019) K.Mazur, S.Malik, R.Rouf, M.Bahadori, M.Shehu, M.Mathew, E.Tekerek, B. Wisner, and **A.Kontsos***, "*Composite Material Remaining Useful Life Estimation Using an IoT-Compatible Probabilistic Framework*", 11th International Workshop on Structural Health Monitoring, Stanford University, California, September 2019

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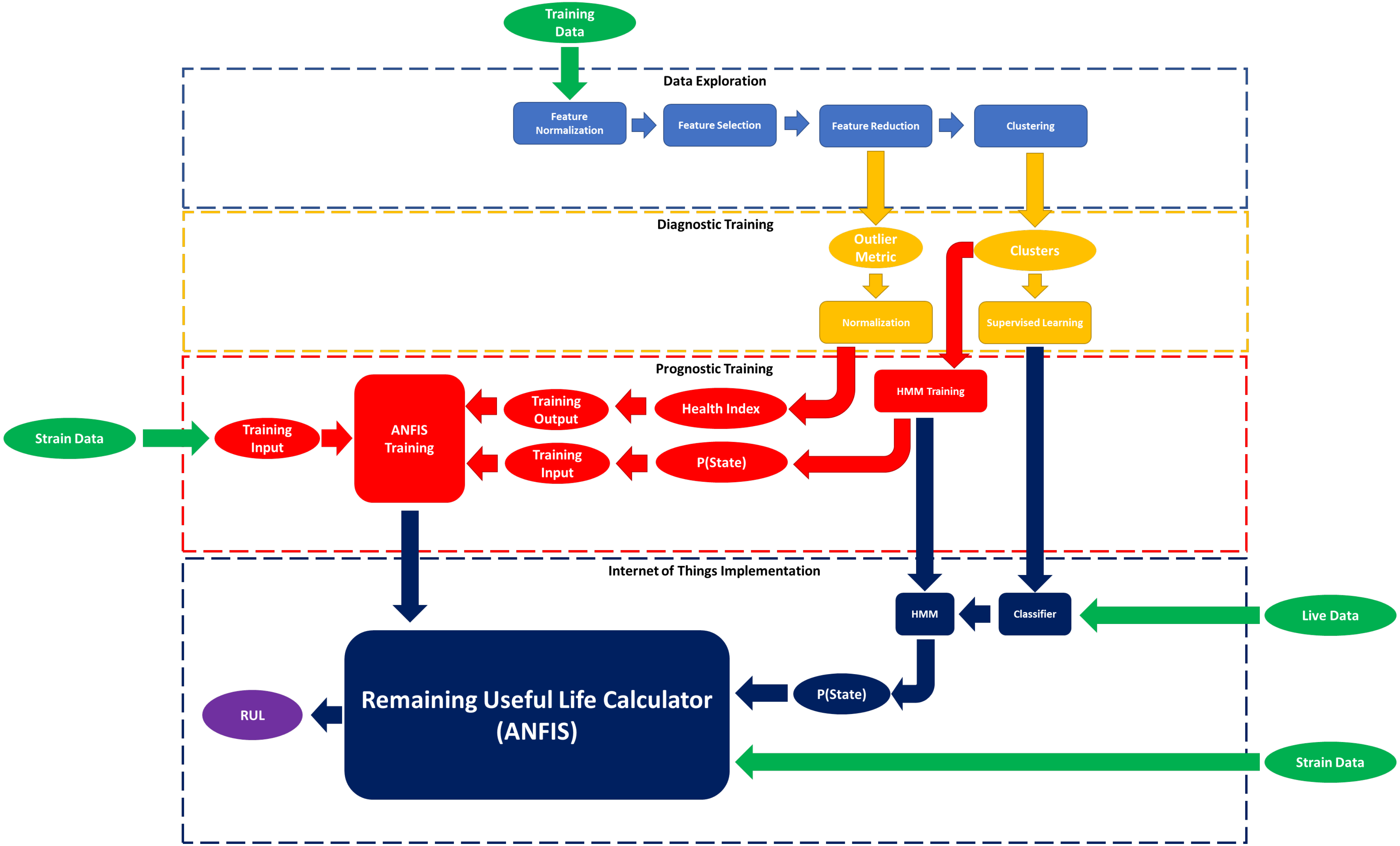

(2019) K.Mazur, S.Malik, R.Rouf, M.Bahadori, M.Shehu, M.Mathew, E.Tekerek, B. Wisner, and **A.Kontsos***, "*Composite Material Remaining Useful Life Estimation Using an IoT-Compatible Probabilistic Framework*", 11th International Workshop on Structural Health Monitoring, Stanford University, California, September 2019

Section 2: Panelists' Presentations

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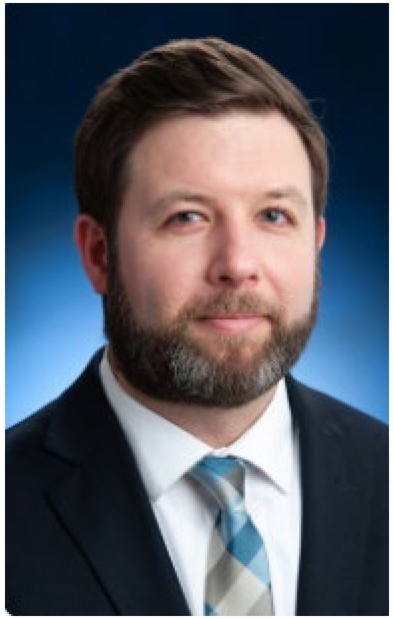
Introducing today's Panelists:

Benjamin Grisso



Naval Surface Warfare Center

Yolanda Mack

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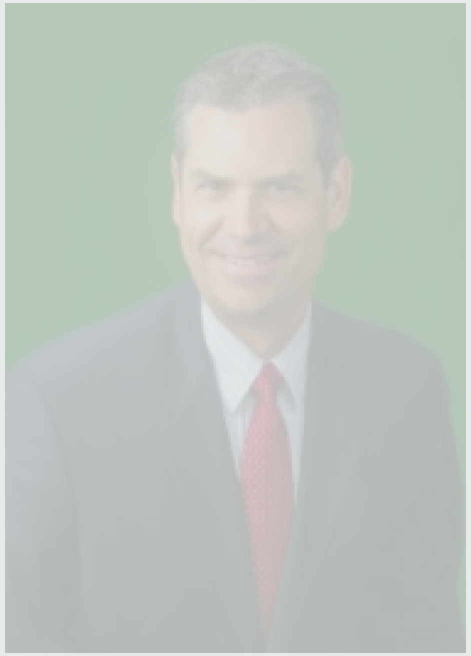


Collins Aerospace

Sankaran Mahadevan

Vanderbilt University

Naval Surface Warfare Center, Carderock Division

AMERICA'S FLEET STARTS HERE

NAVSEA WARFARE CENTERS Carderock

Digital Twin for Navy Ship Structures

1 December 2021

CAPT Todd Hutchison
Commanding Officer, NSWCCD

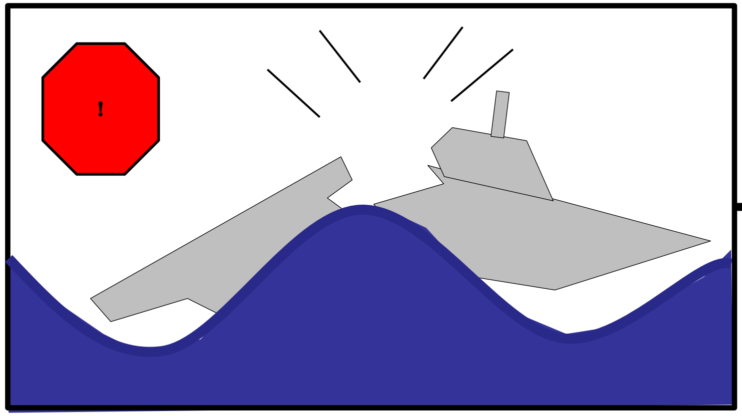
Presented by:
Benjamin Grisso, *Ph.D.*, Code 654

Lawrence Tarasek, SES
Technical Director, NSWCCD

Distribution Statement A: Approved for public release; distribution is unlimited.

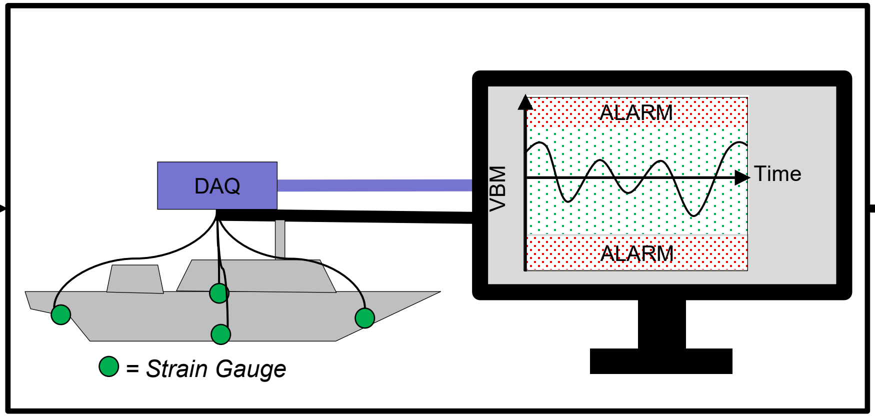
Ship Structural Monitoring and Prognostics

Root Problem



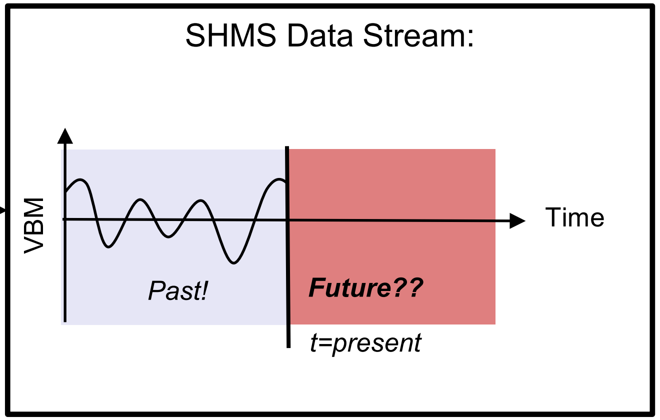
Avoid structural damage during operations

Existing Solution



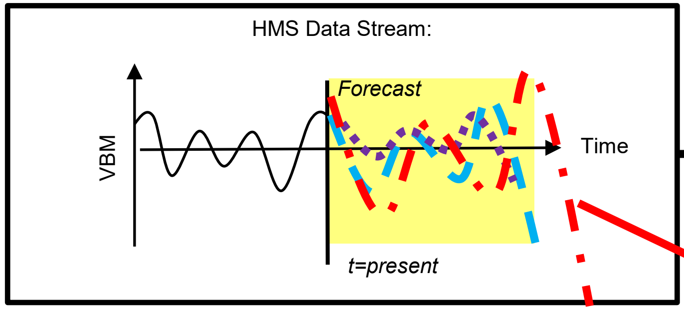
Structural Health/Hull Monitoring System (SHMS)

Gap



SHMS is backward-looking (reactive)

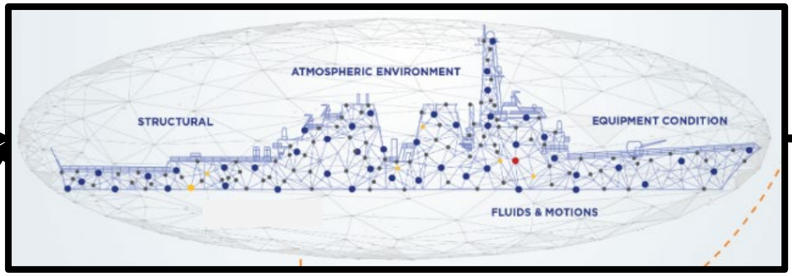
Improvement Opportunity: Prognostics



Forecast future platform condition based on historical data, current condition, and future mission parameters (proactive)

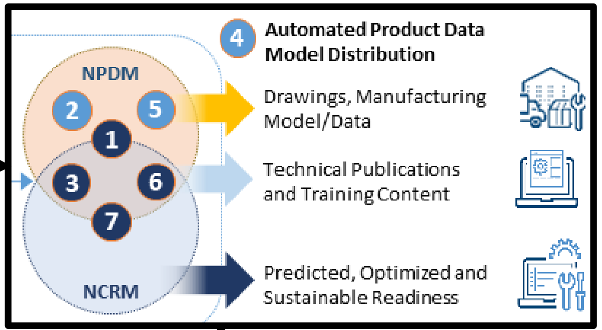
Damage Event

Digital Twin Used to Predict Future State



Provide current and future condition to NAVSEA Digital Thread

MBPS: Common Readiness



Material Ordering and Availability Planning for repairs

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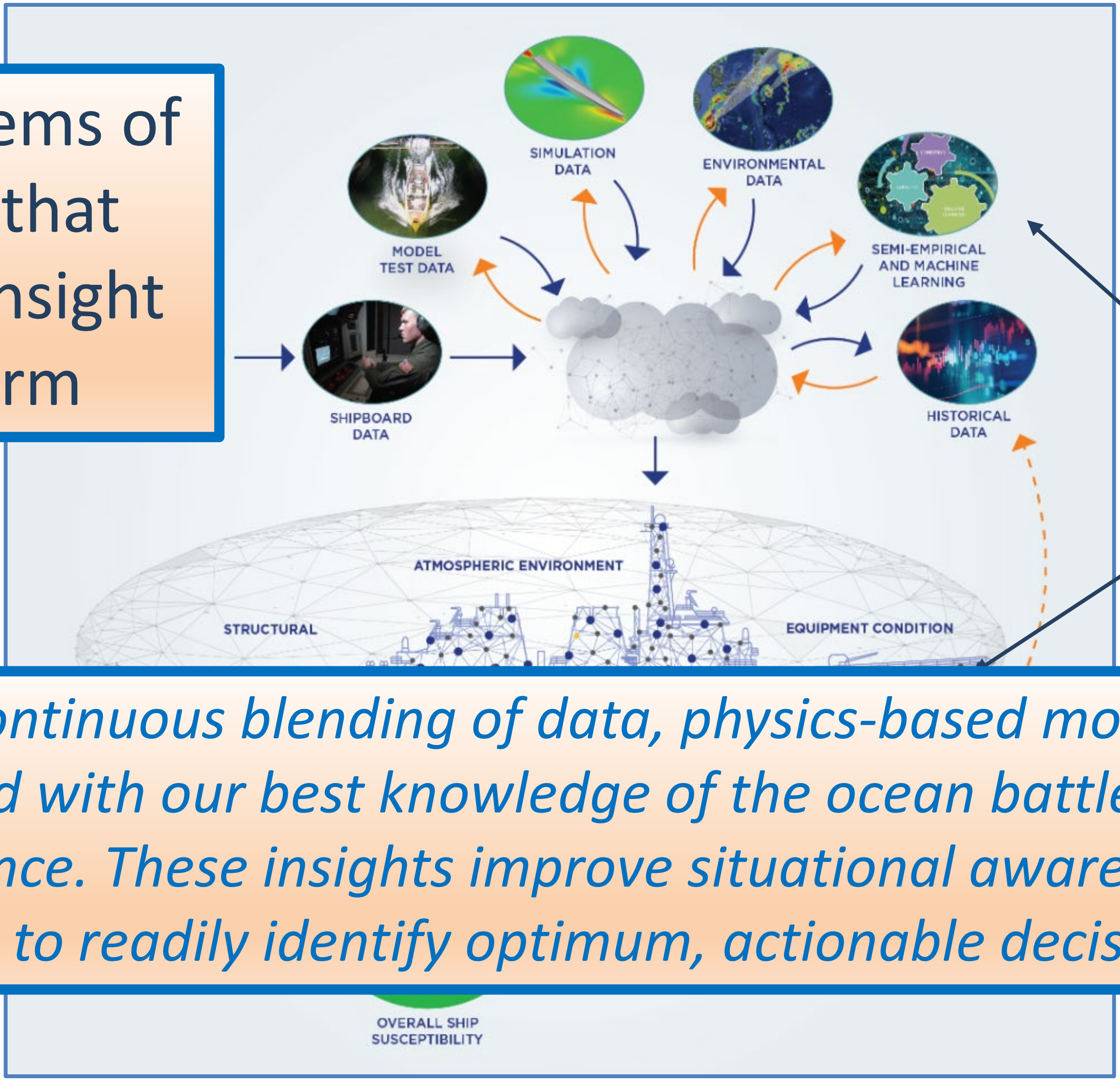
How do we define digital twin?

Ultimately, a Systems of Systems model that enables greater insight into the platform



Integrates data from on and off the platform

Provides actionable

Digital Twin is a continuous blending of data, physics-based models, and machine learning combined with our best knowledge of the ocean battlespace to forecast platform performance. These insights improve situational awareness and enables a user to readily identify optimum, actionable decisions

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Navy Cyber-Physical Digital Twin: The basis for a digital fleet

Starting with design, and progressing through model testing, fabrication, fitting out, and into service, the "Digital Twin" is "built" alongside the real world vessel. Shipboard sensors and data with model test data (when needed) allows the "Digital Twin" and furnishes a virtual fleet for enhanced performance and readiness for emerging and future threats

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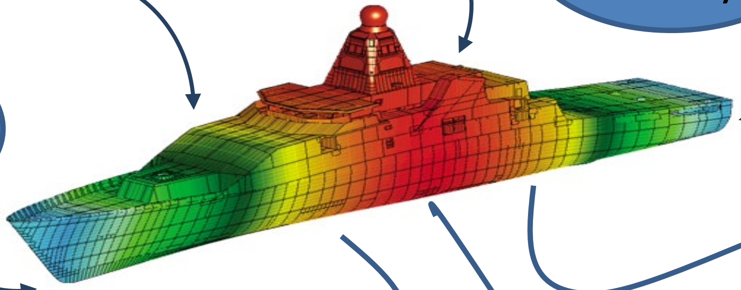
What can twins provide?

Machinery data

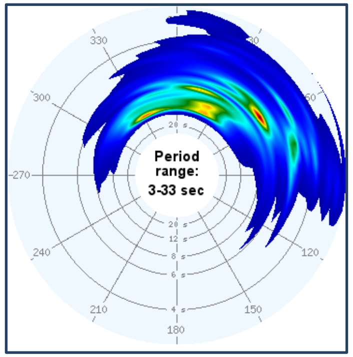
Maintenance Records

Wind/Wave History

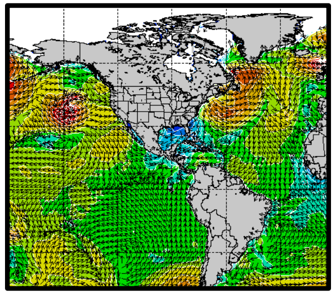
Structural data



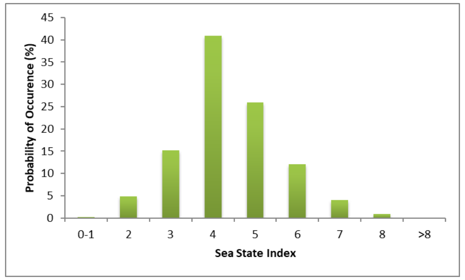
Insights are provided across a range of timescales



Course and Speed Adjustments



Ship Routing Decisions



Expected loads during deployment

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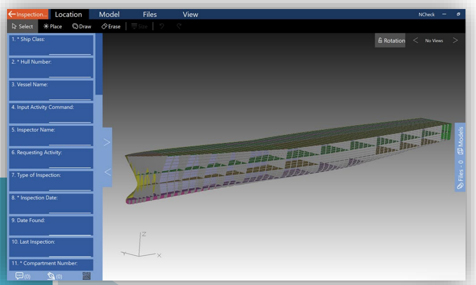
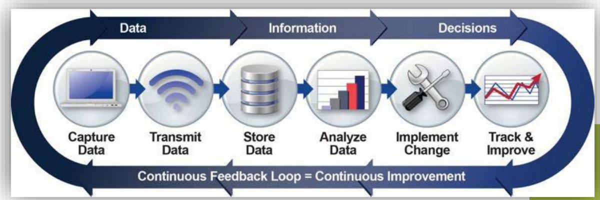
Digital Transformation of Ship Structural Condition



Fully digital ship inspections capturing images, NDE, and visual findings & continuous SHM

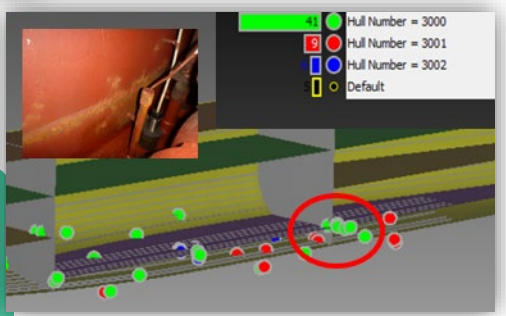
Create and update predictive maintenance models



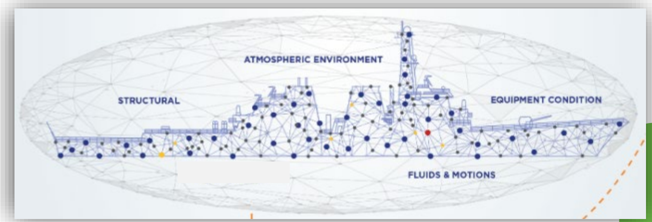
Digital Ship Inspections & SHM

CBM+ for Ship Structures

3D Structural Condition Tracking



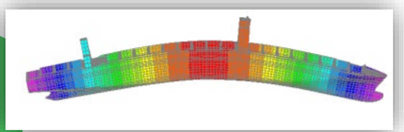
3D data capture, visualization, and analysis of structural condition (corrosion, cracking, deformation), etc.



Digital Twin for Prognostics

Continuous analytical fusion of data, physics-based models, and machine learning to prescribe multiple future predictions of the ship and its environment

Update Physics-Based Models



Modify ship FEM to reflect current condition

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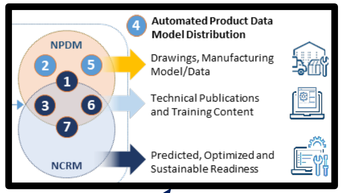
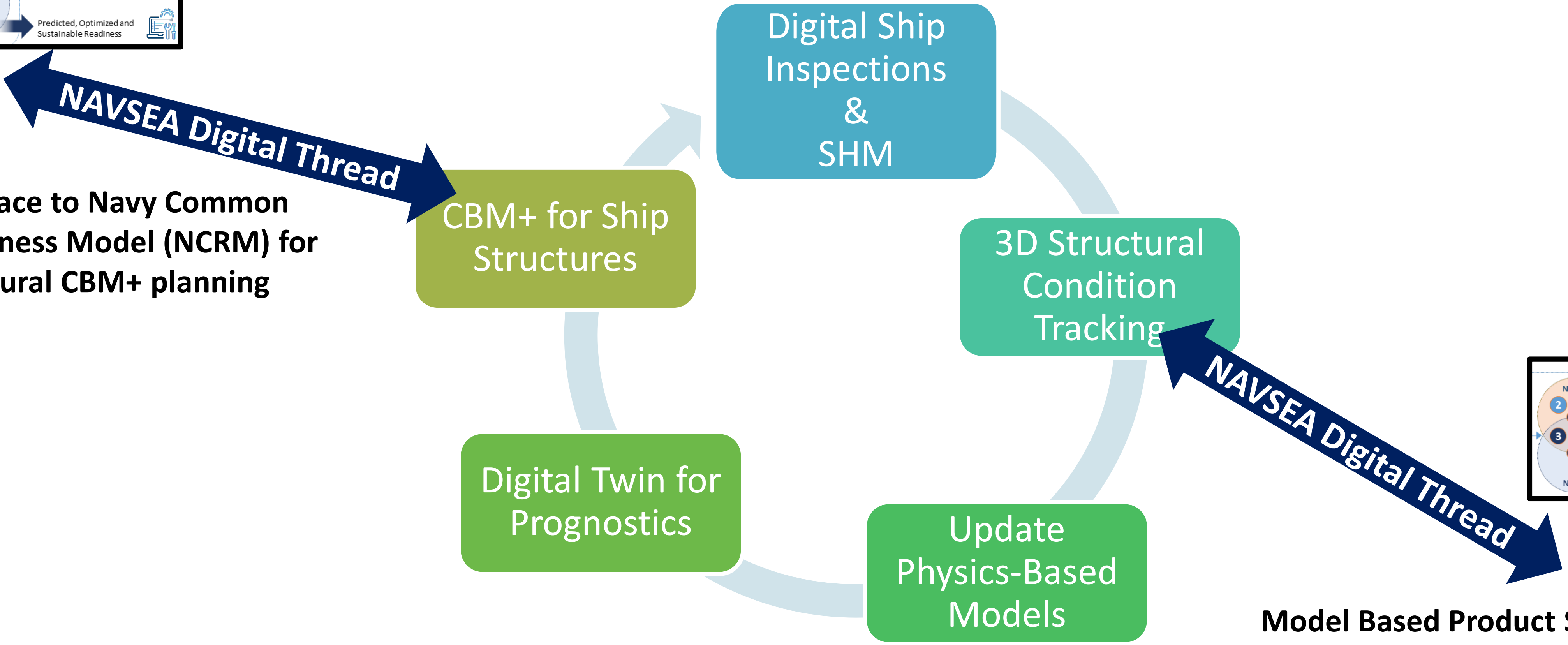
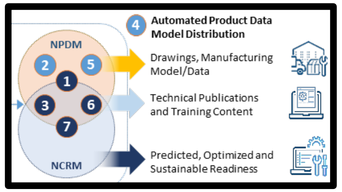
Connection to NAVSEA Digital Thread





Interface to Navy Common Readiness Model (NCRM) for structural CBM+ planning



Model Based Product Support (MBPS) interface for structural condition "Authoritative Source of Truth"

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Questions for Panelist #1

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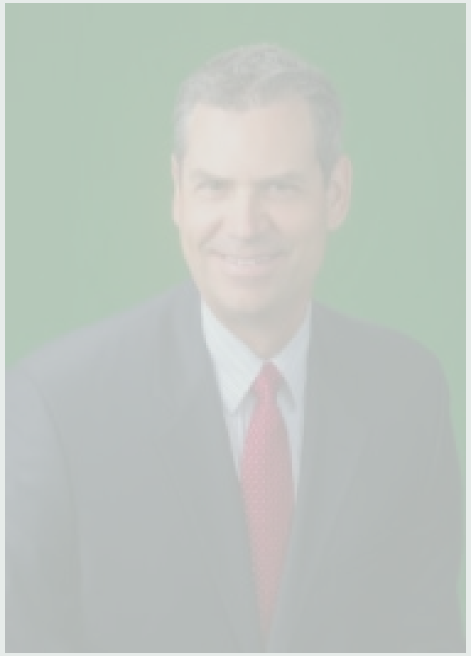

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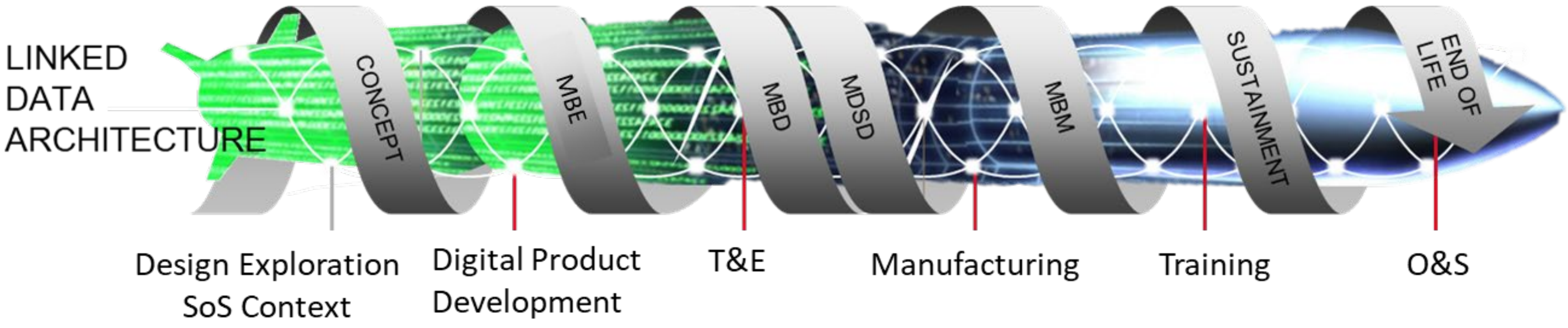
Missiles & Defense

Digital Transformation Executive Summary

Yolanda Mack, PhD

- November 2021

RMD Digital Transformation (DTx) Objectives



Cycle Time Reduction

- Responsive (even predicative) to new threats
- New capabilities and features into the hands of the warfighter quicker

Improved Productivity and Quality

- Efficiency (and effectiveness) through automation
- Rapid design iterations using integrated Digital Thread ecosystem
- New technologies (e.g., AIML) to more thoroughly interrogate design space

Respond to DoD Need

- New RFPs require digital product development

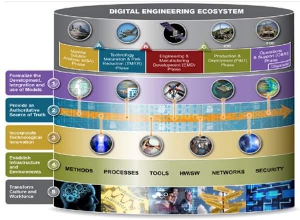
Partnering with the government to jointly address DTx needs to help more rapidly respond to emerging threats

Raytheon Technologies - Approved for Public Release

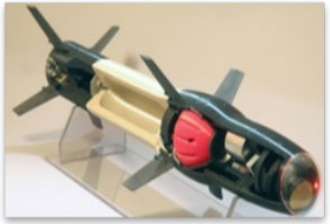
Digital Transformation spans the Product Life Cycle

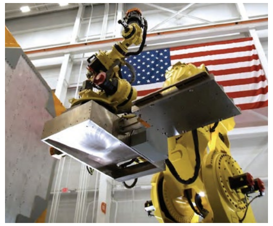
Use Cases

Engineering & Design Chain

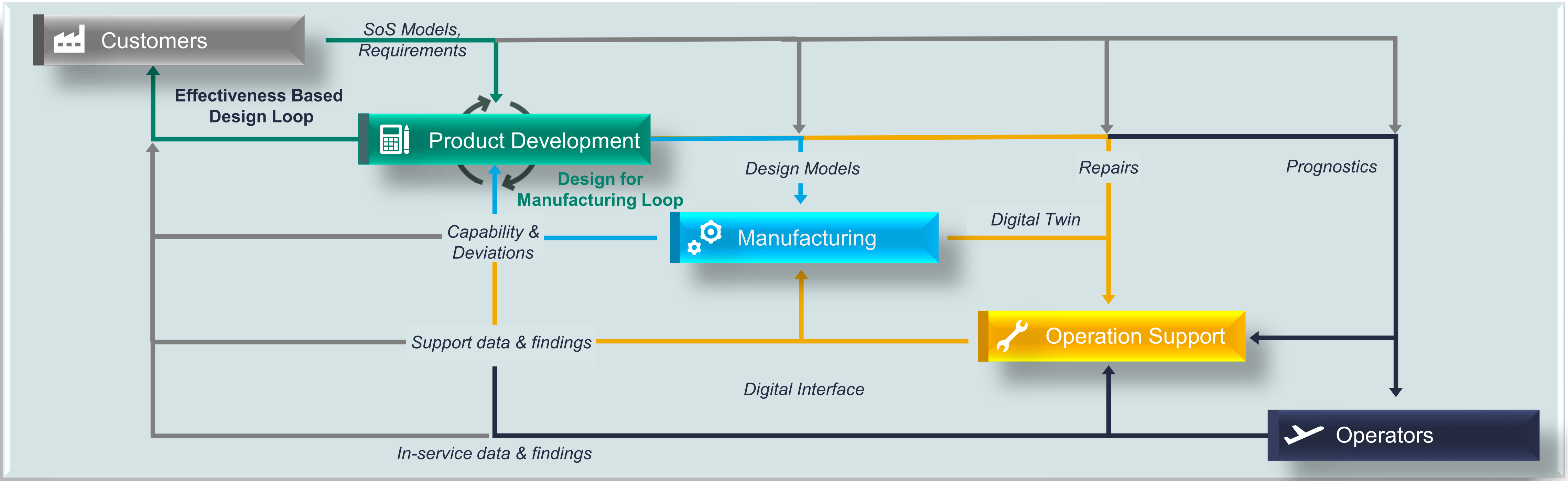


Manufacturing Development/Production





Product Operation & Support



Shared data and models, rapid flow, and feedback loops characterize our future product life cycle

Questions for Panelist #2

phmsociety

Introducing today's Panelists:

Benjamin Grisso

Naval Surface Warfare Center

Yolanda Mack

Raytheon

Tom Wiegele

Collins Aerospace

Sankaran Mahadevan

Vanderbilt University

phmsociety

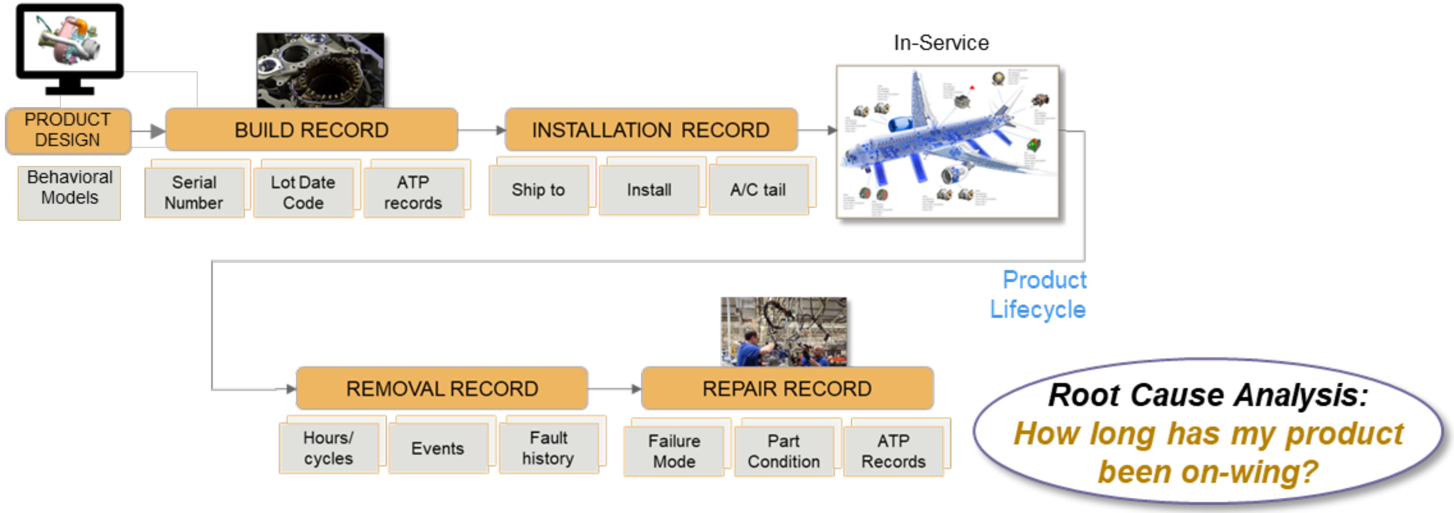
THE COLLINS DIGITAL THREAD

Raytheon Technologies
Collins Aerospace
Power & Controls

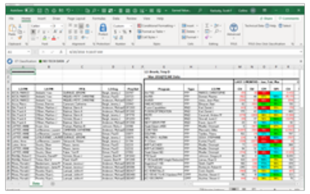
Tom Wiegele, Ph.D.
Senior Technical Fellow

DIGITAL THREAD OVERVIEW

A PROACTIVE APPROACH TO PRODUCT LIFECYCLE MANAGEMENT



Traditional Approach



Excel Spreadsheets

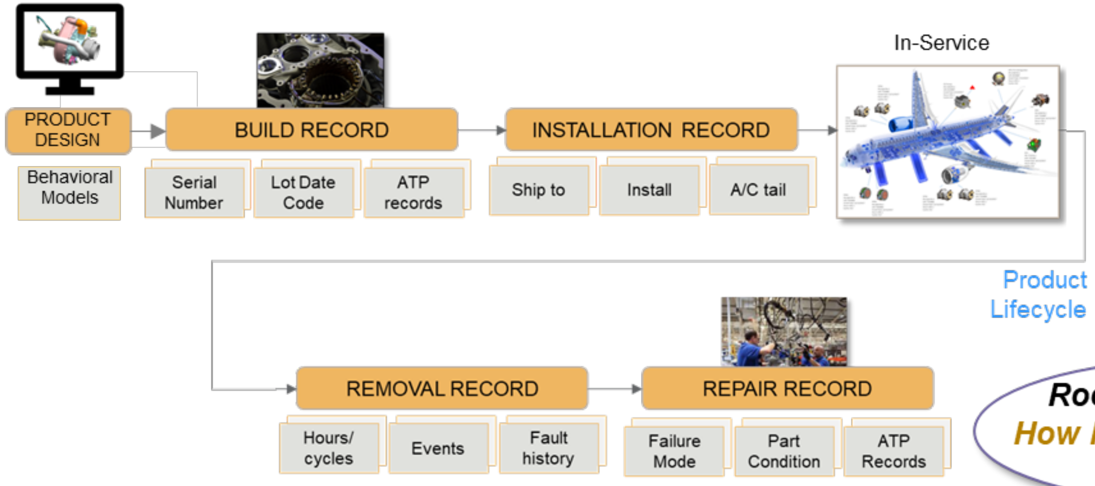
Manual compilation of data

Weeks to collect dozens of part histories

Incomplete RCCA, repeat fixes to field

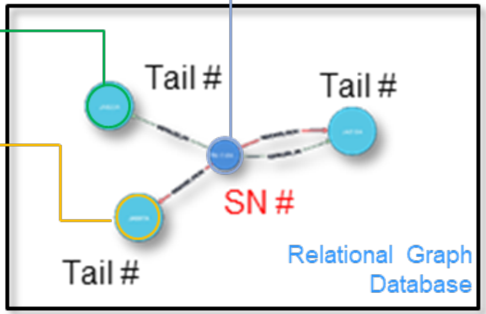
DIGITAL THREAD OVERVIEW

A PROACTIVE APPROACH TO PRODUCT LIFECYCLE MANAGEMENT



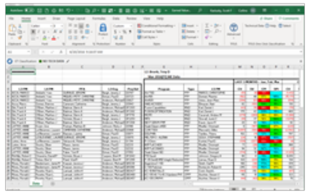
Events	Repository				Cloud
SN creation, ATP, teardown/rebuild	Repository A	->		->	Serial #
Build/test records	Repository B	->	*Extraction*	->	
Install on wing	Repository C	->	*API Call*	->	Install Date
Flight routing	Repository D	->	*Query*	->	
Sys reports, maint msgs	Repository E	->	*Transfer*	->	
On-wing analytics	Repository F	->	*Etc.*	->	
Sched/unsched removal	Repository G	->		->	Remove Date

Discrete Data Repositories



Root Cause Analysis:
How long has my product been on-wing?

Traditional Approach



Excel Spreadsheets

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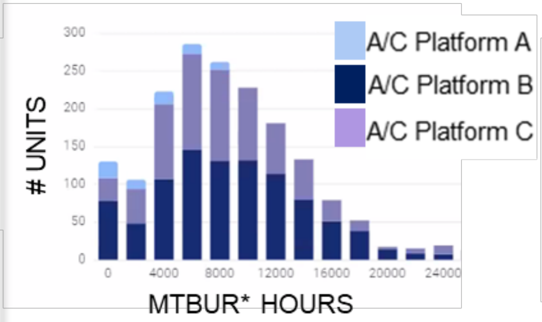
Digital Thread Approach



Data standards that enable integration of sources

Full fleet data compiled in seconds (100's of parts)

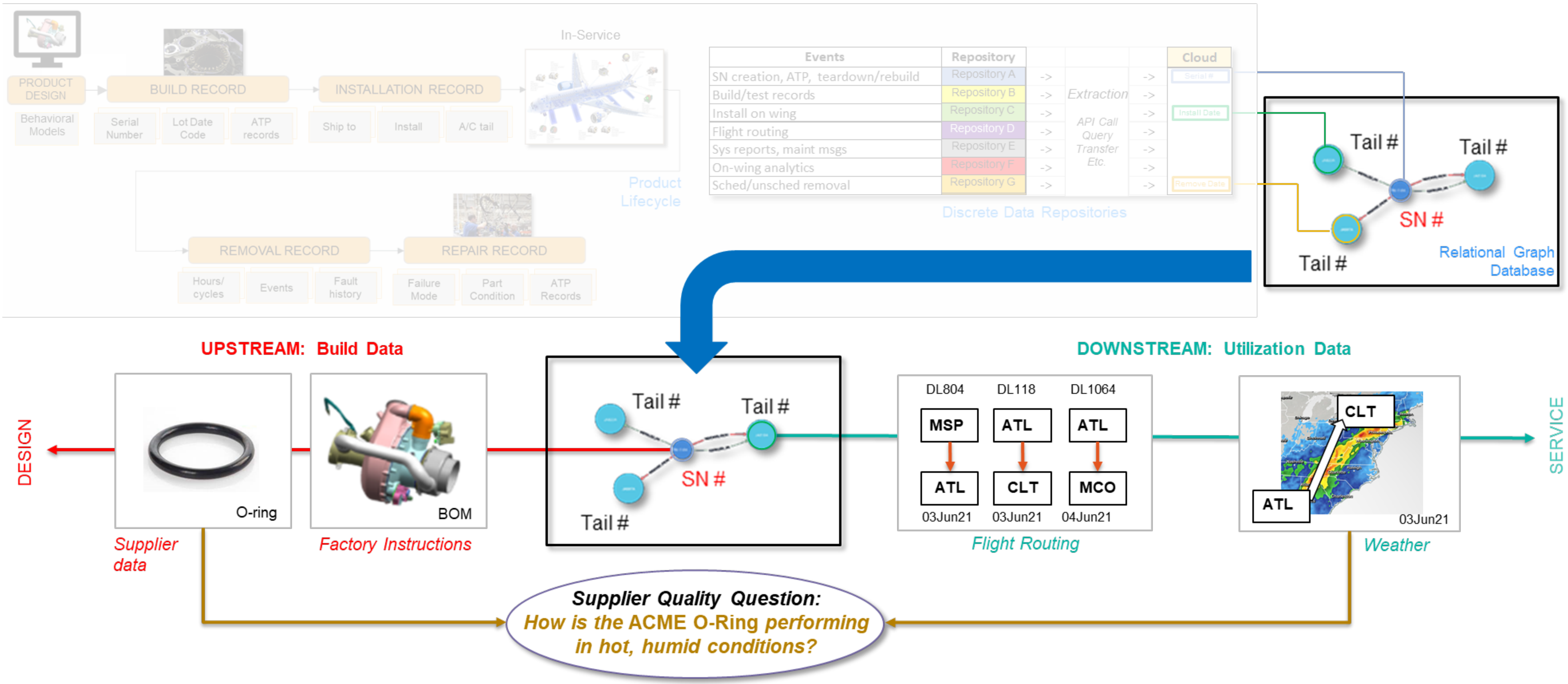
Accelerated RCA, Improved reliability predictions

Fixes fully validated

**Mean Time Between Unscheduled Removals*

DIGITAL THREAD OVERVIEW

A PROACTIVE APPROACH TO PRODUCT LIFECYCLE MANAGEMENT



DIGITAL TWIN CAPABILITIES

Questions for Panelist #3

Introducing today's Panelists:

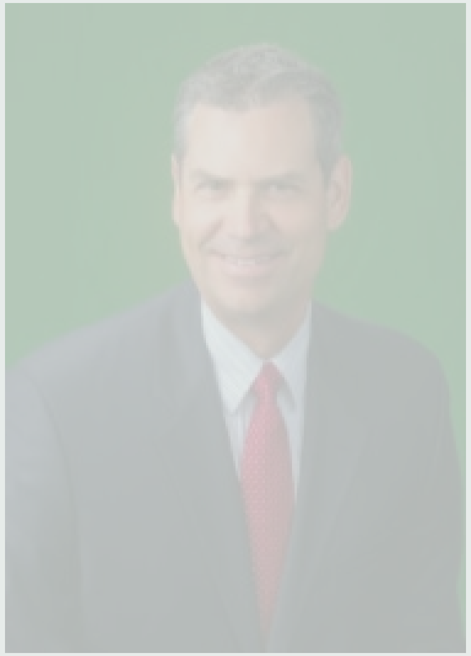
Benjamin Grisso

Naval Surface Warfare Center

Yolanda Mack

Raytheon

Tom Wiegele



Collins Aerospace

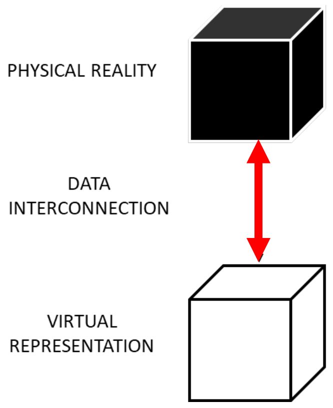
Sankaran Mahadevan

Vanderbilt University

Probabilistic Digital Twin for Individual Asset Risk Management (Sankaran Mahadevan, VU)

Digital Twin

- Virtual representation of the physical system
  - ➢ Design, manufacturing, properties, operational history, health history
- Updated with new data about the physical system
  - ➢ Individualized risk management for each asset
  - ➢ Decision-making with up-to-date information



Vanderhorn & Mahadevan, DSS, 2021

Probabilistic digital twin methodology

- Information fusion (multiple, heterogeneous data sources and computational models)
  - Dynamic Bayesian Network
- Uncertainty quantification, aggregation and reduction → Decision support
  - Both forward and inverse problems → Model calibration, V&V, Asset diagnosis and prognosis
- Computational effort reduction strategies
  - Efficient stochastic sampling (e.g., importance sampling)
  - Surrogate modeling, machine learning
  - Sensitivity analysis, dimension reduction, reduced-order modeling, multi-fidelity modeling
  - Efficient Bayesian network computation

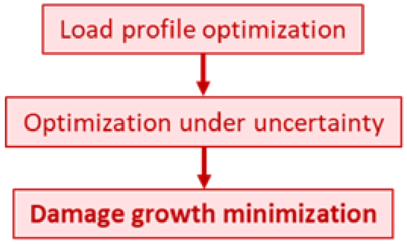
10 hours → 1 sec

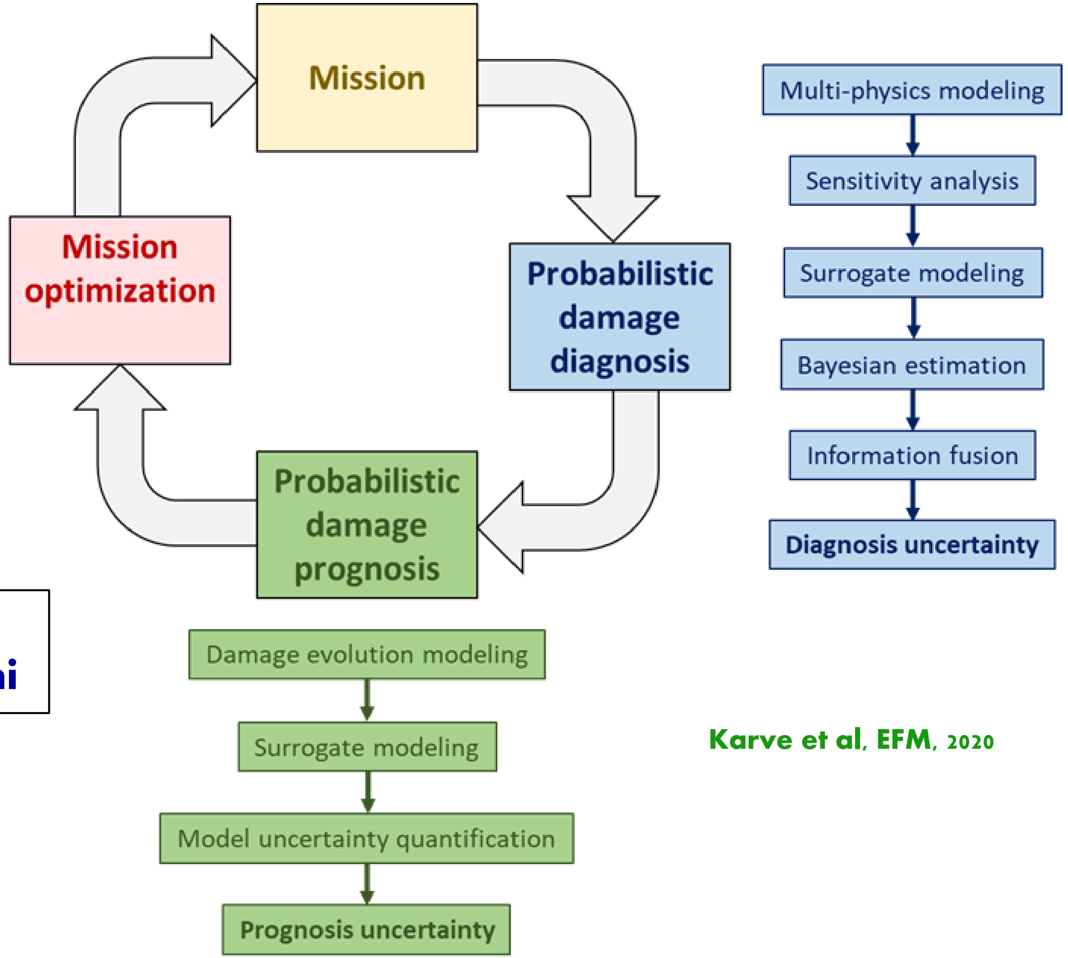
Li & Mahadevan, RESS, 2021

Decision Support with Probabilistic Digital Twin

Applications

- Marine vessel fatigue monitoring **Vanderhorn et al, RESS, 2022**
- Aircraft wing sustainment **Li & Mahadevan, RESS, 2021**
- Rotorcraft operations **Sisson et al, AIAA J, 2022**
- Additive manufacturing process control **Nath & Mahadevan, AM, 2021**





Karve et al, EFM, 2020

Decision Support

- Prognosis
- Sensor placement
- Sustainment: Inspection, repair, maintenance
- Mission planning
  - Flight parameters, AM process parameters
- Operational maneuvers
  - Flight maneuvers, AM process control

Funding: FAA, NASA, US Air Force, US Army, ABS, Mitsubishi

Complexity of models in digital twin depends on decision turnaround time!

Questions for Panelist #4

Audience Q&A

phmsociety

Panel #5 Specific Points of Discussion

- *efforts to* ***standardize digital twin processes*** *or at least validate parts of them using traceable, repeatable and effective ways;*
- *issues related to creating* ***validated dataset repositories*** *which could assist model and processing approach development, independent of a given application and of case-specific data acquisition, and contributing towards demonstrations of successful alignments of the physical and digital spaces;*
- ***benchmark problems*** *tailored to a PHM-related hierarchy of detection, classification and prediction, similar to other domains e.g. in nondestructive evaluation, material characterization, as well as inspection and maintenance;*
- ***modeling*** *including knowledge-based, deep learning, probabilistic, analytical, physics-based etc., which could be leveraged in digital twin workflows;*
- *efforts to use digital twinning not only in forward flows that involve steps from data to decision but are also* ***creating dynamic adaptations*** *capable of evolving as monitoring occurs, providing feedback to sensors as data is processed and ultimately even creating real autonomy via e.g. data and model-driven adaptive control.*

Thank you!

Thank you to all of you who attended today's panel on PHM for Digital Twins. And thanks to our panelists for their time and perspective.

If you would like to continue these discussions and network with the other conference attendees, please use Chat

Enjoy the rest of the conference!