TIMING DETERMINISTIC STRUCTURAL MODEL UPDATING CONSIDERING IMPACT AND FATIGUE DAMAGE

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OVERVIEW

- Importance and significance
- Methodology
- Results
- Next steps

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Importance and significance

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WHAT IS A DIGITAL TWIN?

- A Digital Twin continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success.

- The Digital Twin can also predict system response to safety critical events and uncover previously unknown issues before they become critical by comparing predicted and actual responses.

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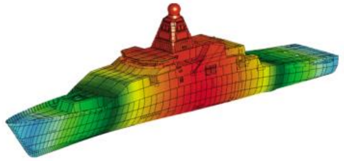
DIGITAL TWIN VS MODEL

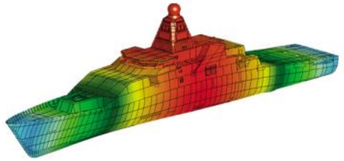
Model

Data don't necessarily update ship model

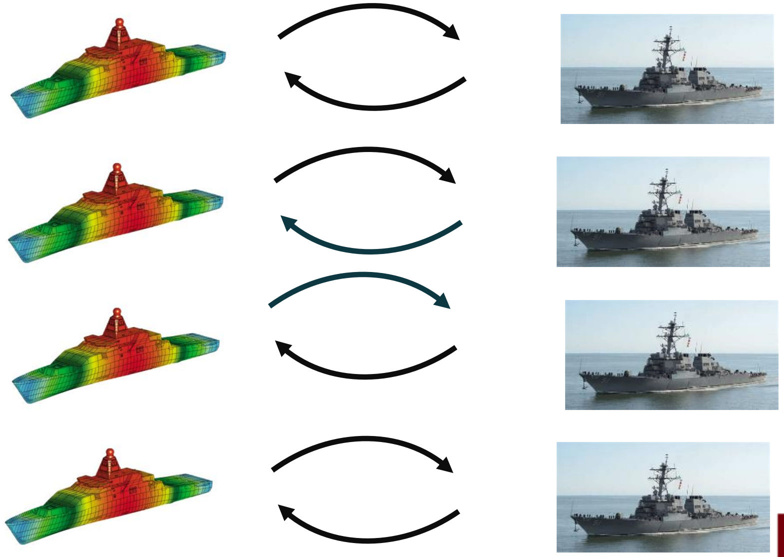


Models inform us of expected ship behavior, based on the whole class

Digital Twin



Class-wide models serve as a starting point



Twin is updated with data from the ships

Twins track condition of *each individual hull*

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DIGITAL TWIN ENABLING TECHNOLOGIES AND GAPS

Enabling Technologies

- Machine Learning
- Distributed Analytics
- Cloud-based Computing
- High-bandwidth Secure Communications

Engineering Gaps

- Integration of ship- and off-board sensor systems that store data
- Multi-level classification communications
- Integrating cloud-based computing
- Distributed (GPU-based) computing high-fidelity
- Cybersecurity
- Workforce expertise with data analytic skill set and tools

Technology Gaps

- “Automatic” fusing of data with models
- Applied machine learning
- Application to sparse data
- Integration of complex environmental data
- Use of data at order-of-magnitude different temporal/spatial scales
- Algorithmic approaches for measured data
- Virtual sensing (sensor inference)
- Extending prognostications
- Uncertainty analysis and propagation
- Cybersecurity
- Optimized control of systems

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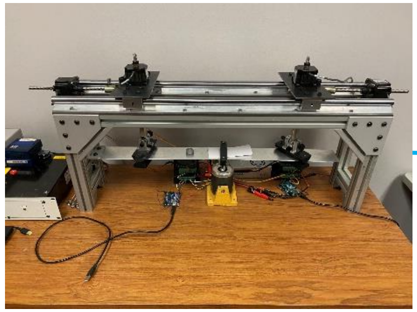
Methodology

ONLINE MODEL UPDATING FRAMEWORK

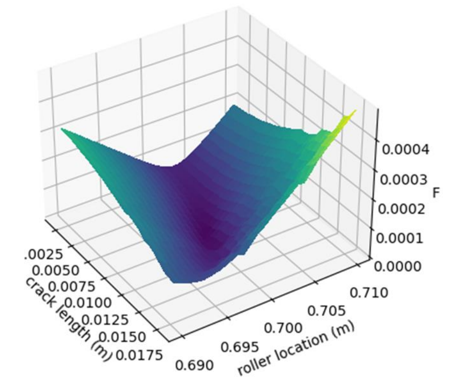


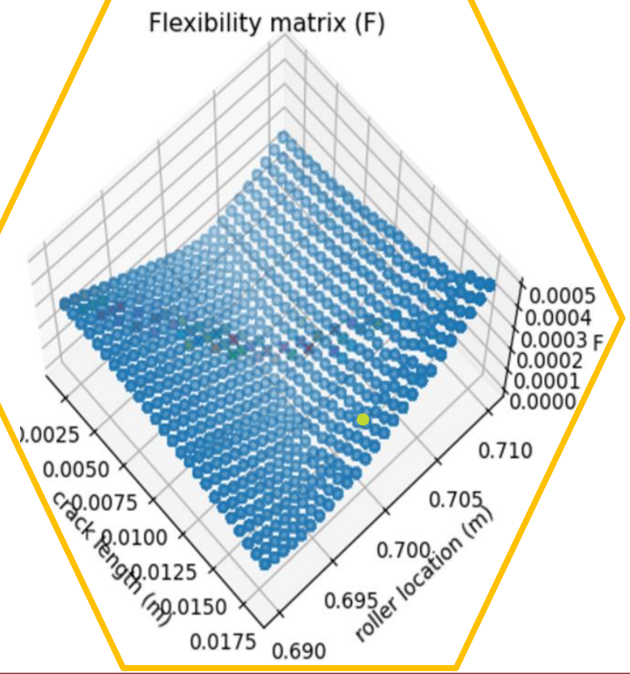
Structure

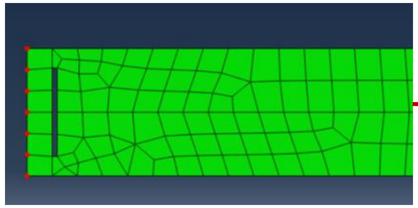
Data

$$F_{trun} = \sum_{i=1}^{n} \left(\frac{d_i}{\omega_i}\right)^2 \bar{\phi}_i \, \bar{\phi}_i^T$$

$$\Delta F_{trun} = F_{trun}^{true} - F_{trun}^{trial}$$







FEA model

Data

$$F_{trun} = \sum_{i=1}^{n} \left(\frac{d_i}{\omega_i}\right)^2 \bar{\phi}_i \, \bar{\phi}_i^T$$

Inverse feature scaling

FLEXIBILITY MATRIX

$$\bar{\phi}_i = \phi_i d_i$$

$\bar{\phi}_i$: normalized mode shape

d_i : i^{th} mode mass normalization constant

$$F_{trun} = \sum_{i=1}^{n} \left(\frac{d_i}{\omega_i}\right)^2 \bar{\phi}_i \, \bar{\phi}_i^T$$

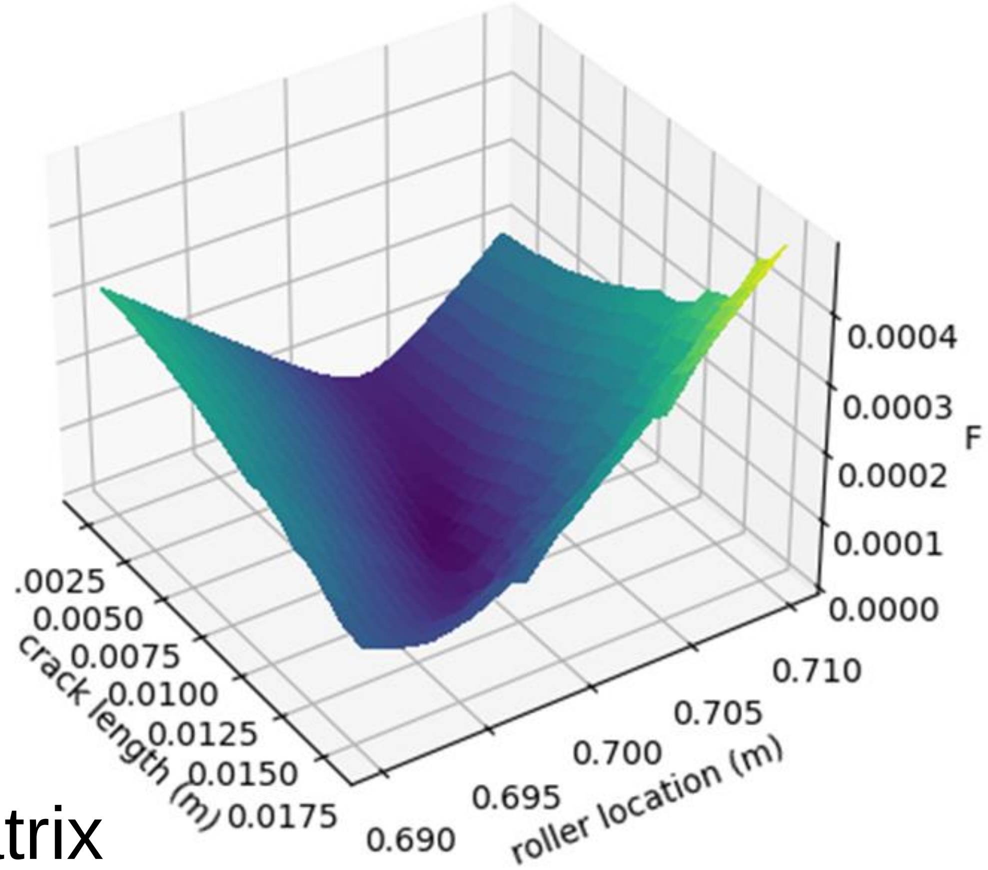
F_{trun} : truncated flexibility matrix

ω_i : modal frequencies matrix

$$\Delta F_{trun} = F_{trun}^{true} - F_{trun}^{trial}$$

F_{trun}^{true}: true (damaged) structure flexibility matrix

F_{trun}^{trial}: trial (FE model) structure flexibility matrix



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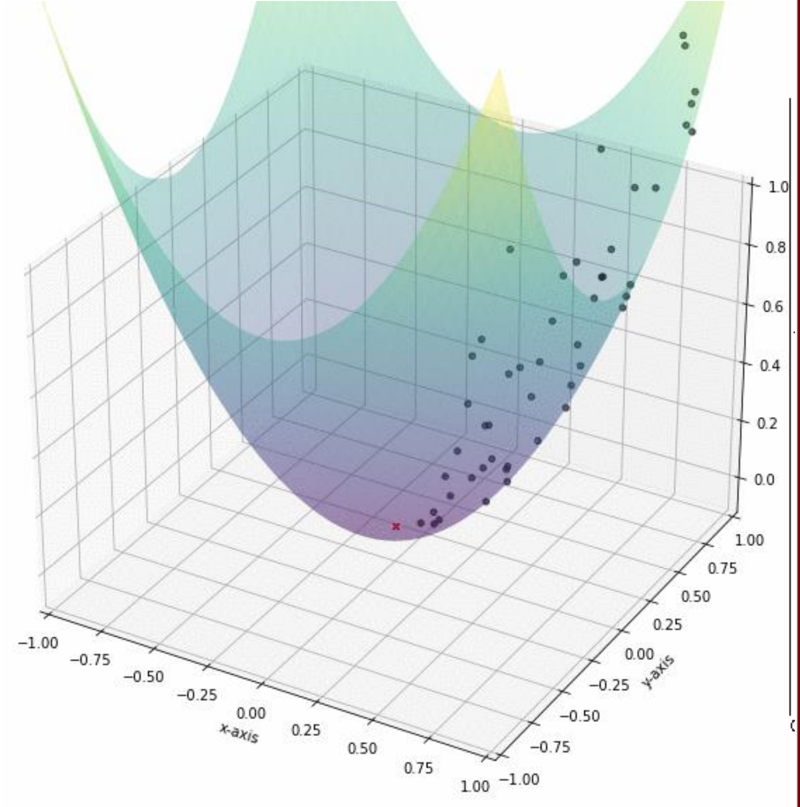
PARTICLE SWARMS

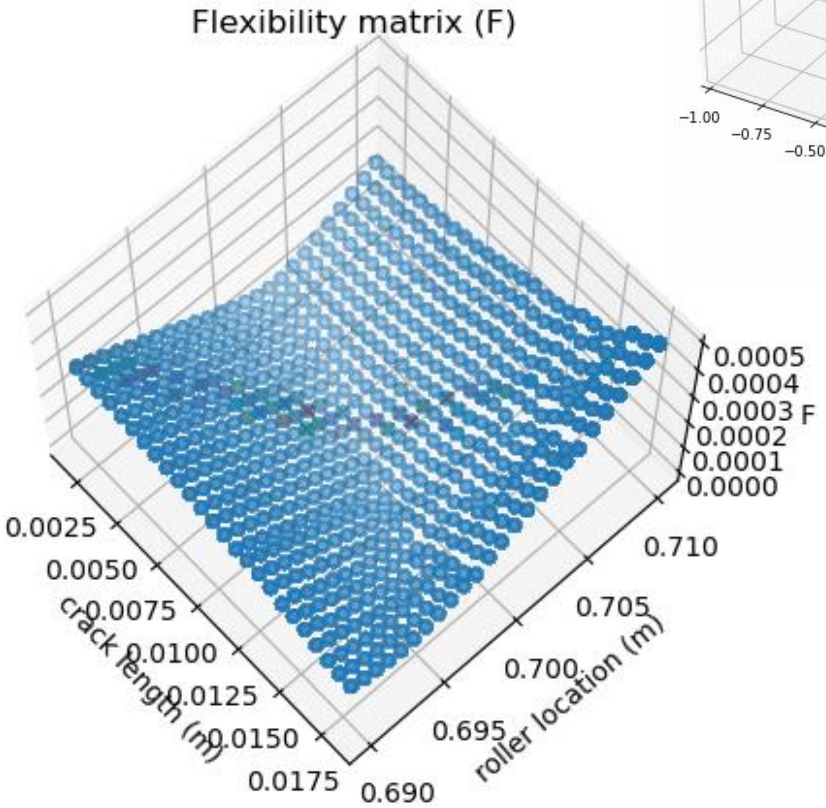
Velocity update:

- $V^i_{(t+1)} = wV^i_{(t)} + c_1u_1(p_{best}{}^i - X^i_{(t)}) + c_2u_2(g_{best} - X^i_{(t)})$
  - w = inertia weight constant (0 - 1)
  - c_1, c_2 = cognitive and social coefficients
  - p_{best}, g_{best} = best position so far

Position update:

- $X^i_{(t+1)} = X^i_{(t)} + V^i_{(t+1)}$
  - $X^i_{(t)}$ = current position
  - $V^i_{(t+1)}$ = updated velocity





Testbed

SHIP STRUCTURE AND FATIGUE ENVIRONMENT (SHIP SAFE) TESTBED

- Designed to allow for changes to the structure's stiffness using the stepper motors.
- Structure's stiffness changes are reversible.
- Produces simple data sets used for validating multi-model data assimilation algorithms.

CAD model of ship safe testbed

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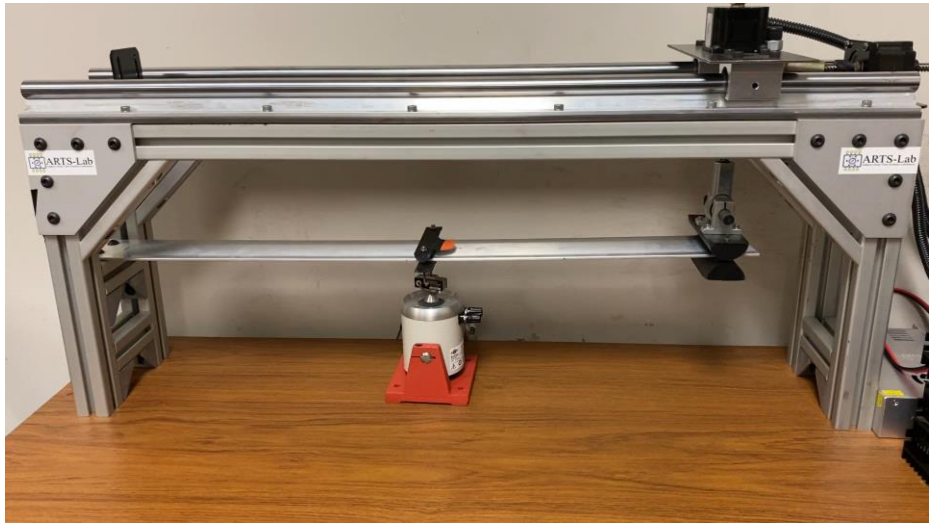
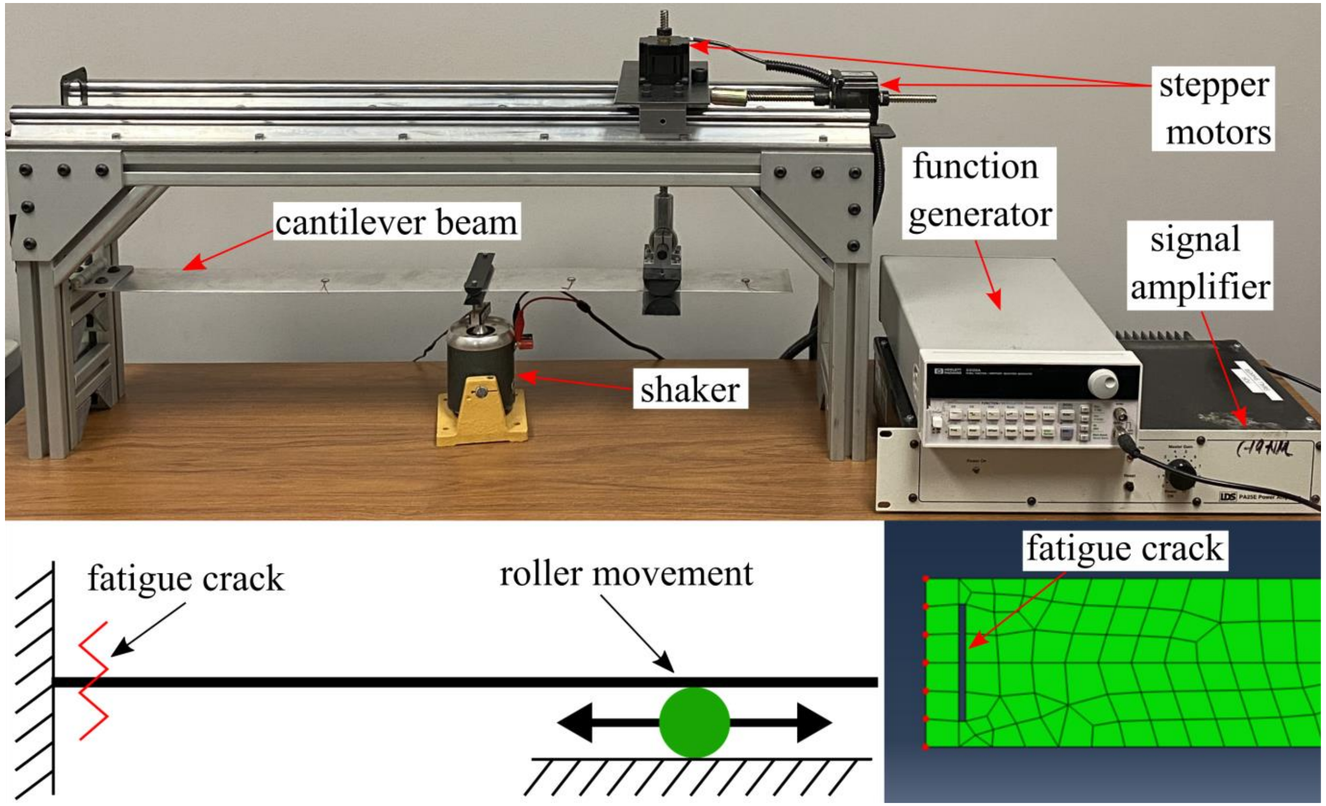
SHIP STRUCTURE AND FATIGUE ENVIRONMENT (SHIP SAFE) TESTBED

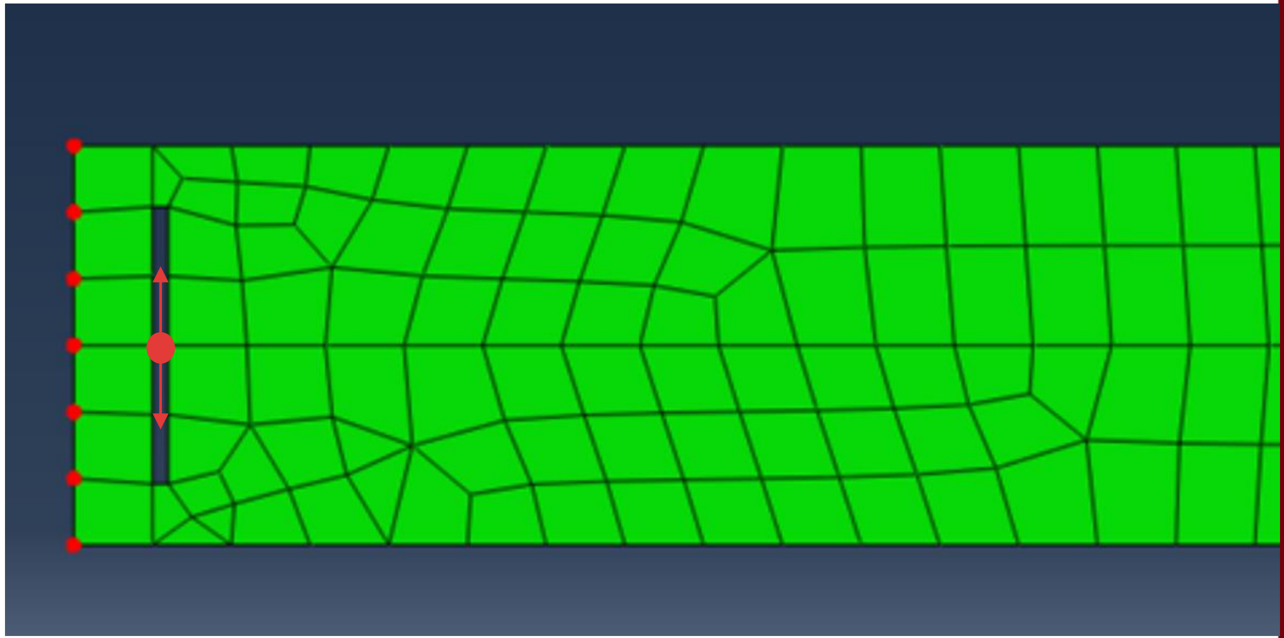




INSERTING A LINEAR CRACK

- Damage cases:
  - Fatigue crack length
  - Roller location along the beam

- Crack starts near the beams left fixity and grows from the beam center outward toward each edge.



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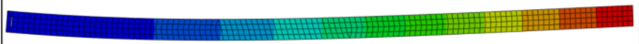
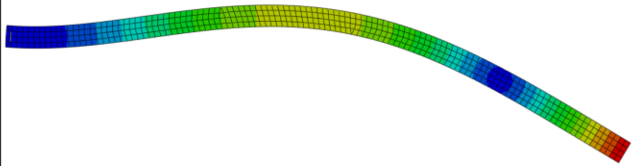
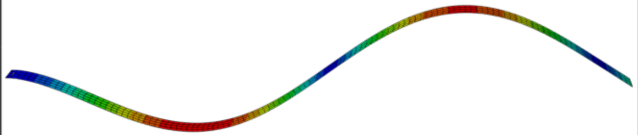
FINITE ELEMENT ANALYSIS MODEL

Modeled in Abaqus:

- Initially built as 3-D model.
  - Most accurate to physical model.
- Finalized as a 2-D model
  - BCs and input forces act in 2-D.
  - Computationally efficient.
  - Produces identical data.

Mode	Frequency	Mode Type	Shape
1	36.036 Hz	Bending - Y	
2	69.790 Hz	Bending - Z	
3	224.81 Hz	Bending - Y	
4	225.92 Hz	Bending - Z	
5	470.05 Hz	Bending - Z	

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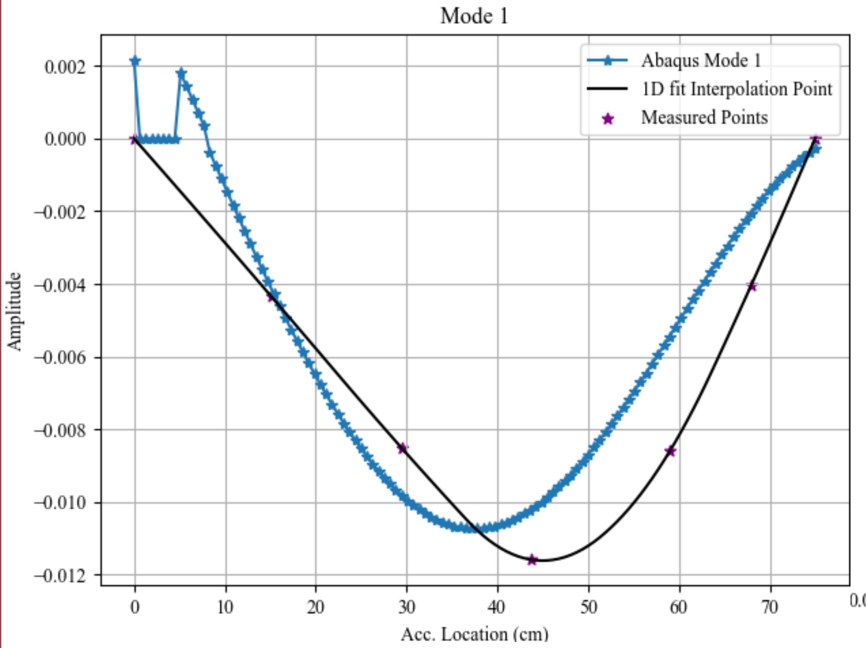
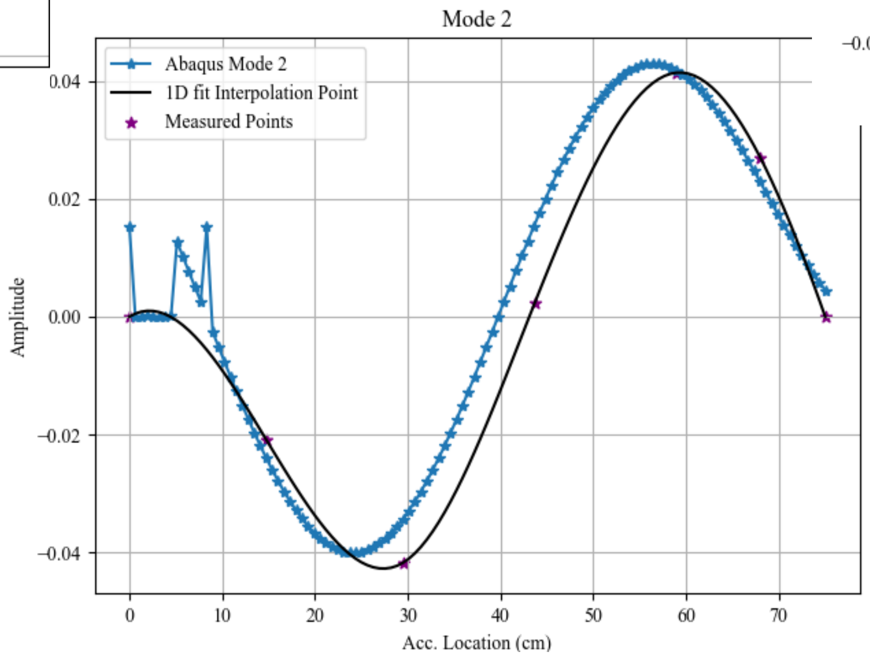
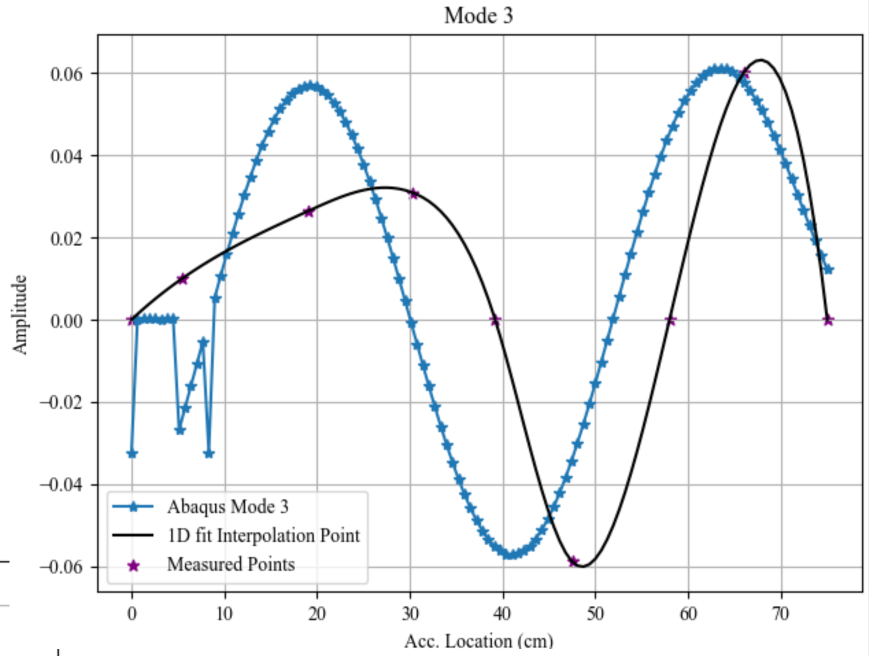
MODAL ASSIMILATION







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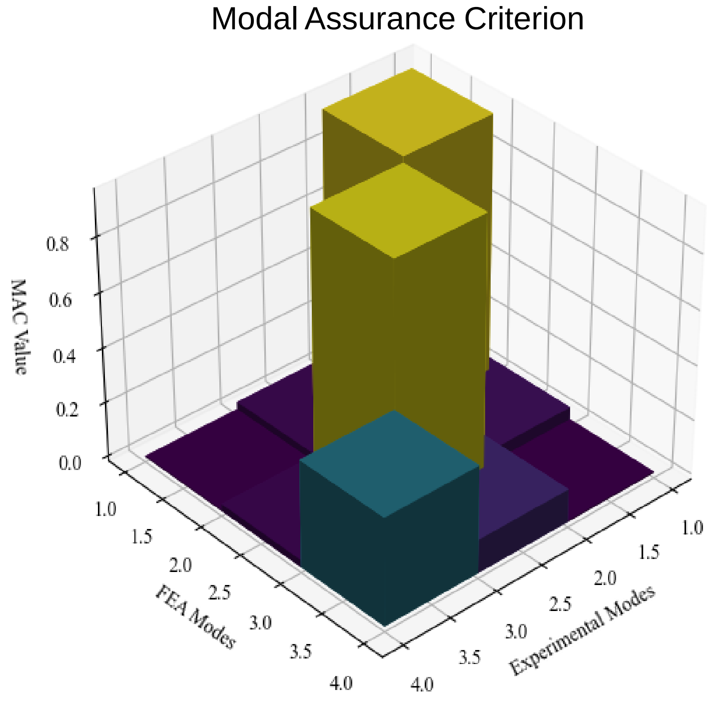
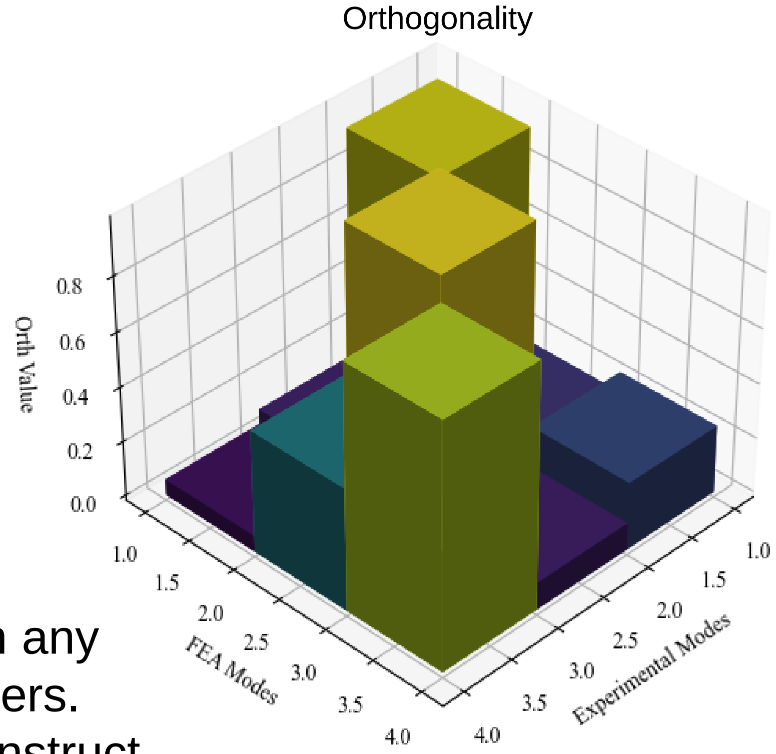
MAC AND ORTHOGONALITY METRICS



$$MAC_{ij}=\frac{[\{a_i\}^T\{b_j\}]^2}{[\{a_i\}^T\{a_i\}][\{b_j\}^T\{b_j\}]}$$

Mode shape statistical indicator which is most sensitive to large differences and relatively insensitive to small differences. Provides a good statistic indicator and a degree of consistency between mode shapes.

Orthogonal modes cannot construct any one mode with any linear combination of the others. Moreover, you can't even construct part of one mode through any linear combination of the others.



$$ORT_{ij}=\{u_i\}^T[M]\{j_j\}^T$$

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Results
(Simulation Only)

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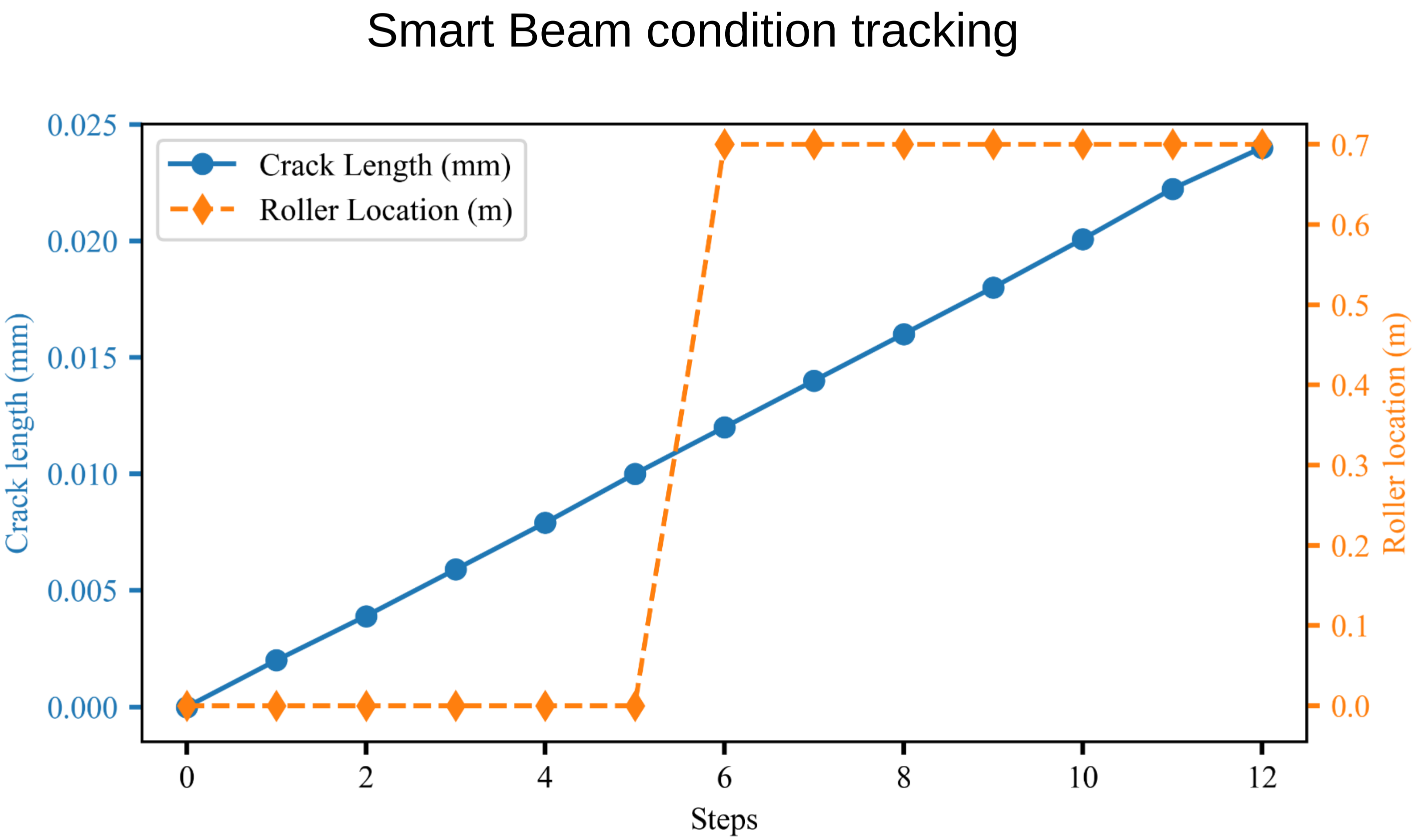
CONDITION TRACKING

- Build a “Smart Beam”
  - Connection inside ship structure.
  - Tracks foreground and background changes.
  - Damage to supports and fatigue cracks.



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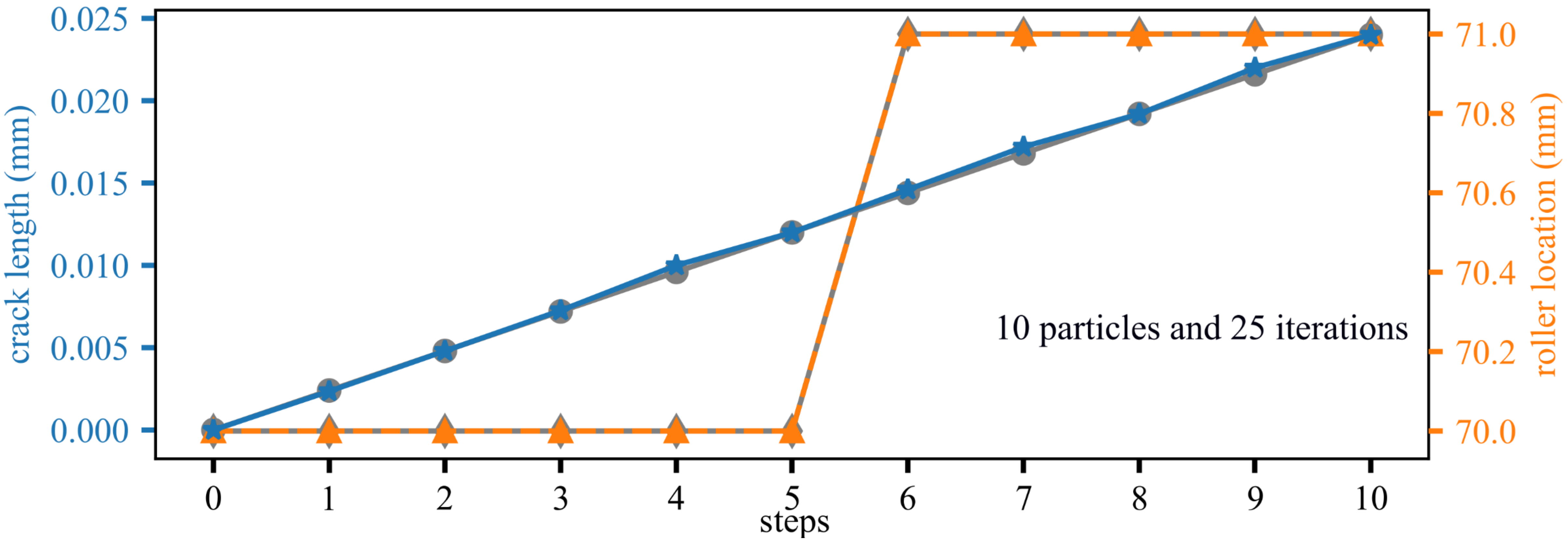
PARTICLE SWARM



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Next steps

NEXT STEPS

1. Experimental validation
2. Demonstration for a system under continuous loading
3. Online real-time model updating demonstration

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QUESTIONS?

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WHAT IS DIGITAL TWIN?

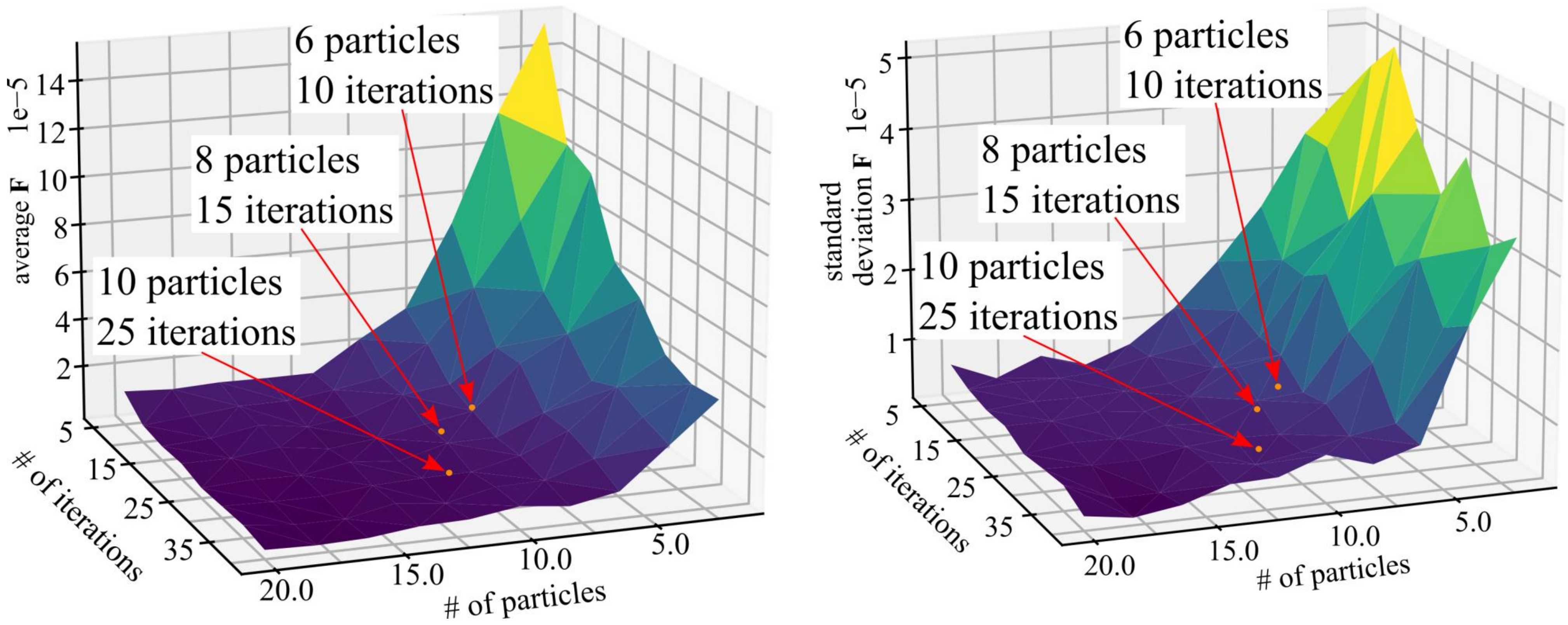
Cyber-physical systems are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components

*Navy Digital Twin is a continuous analytical fusion of data, physics-based models, and machine learning to prescribe **multiple future instantiations** of the ship and its environment, which enables the user to readily identify the optimum choices*

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. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, including airframe, propulsion and energy storage, life support, avionics, thermal protection, etc. The extreme requirements of the Digital Twin motivate the integration of design of materials and revolutionary approaches for material processing. Manufacturing anomalies that may affect the vehicle are also explicitly considered, evaluated and monitored. In addition to the backbone of high-fidelity physical models of the as-built structure, the Digital Twin integrates sensor data from the vehicle's on-board integrated vehicle health management (IVHM) system, maintenance history and all available historical and fleet data obtained using data mining and text mining.

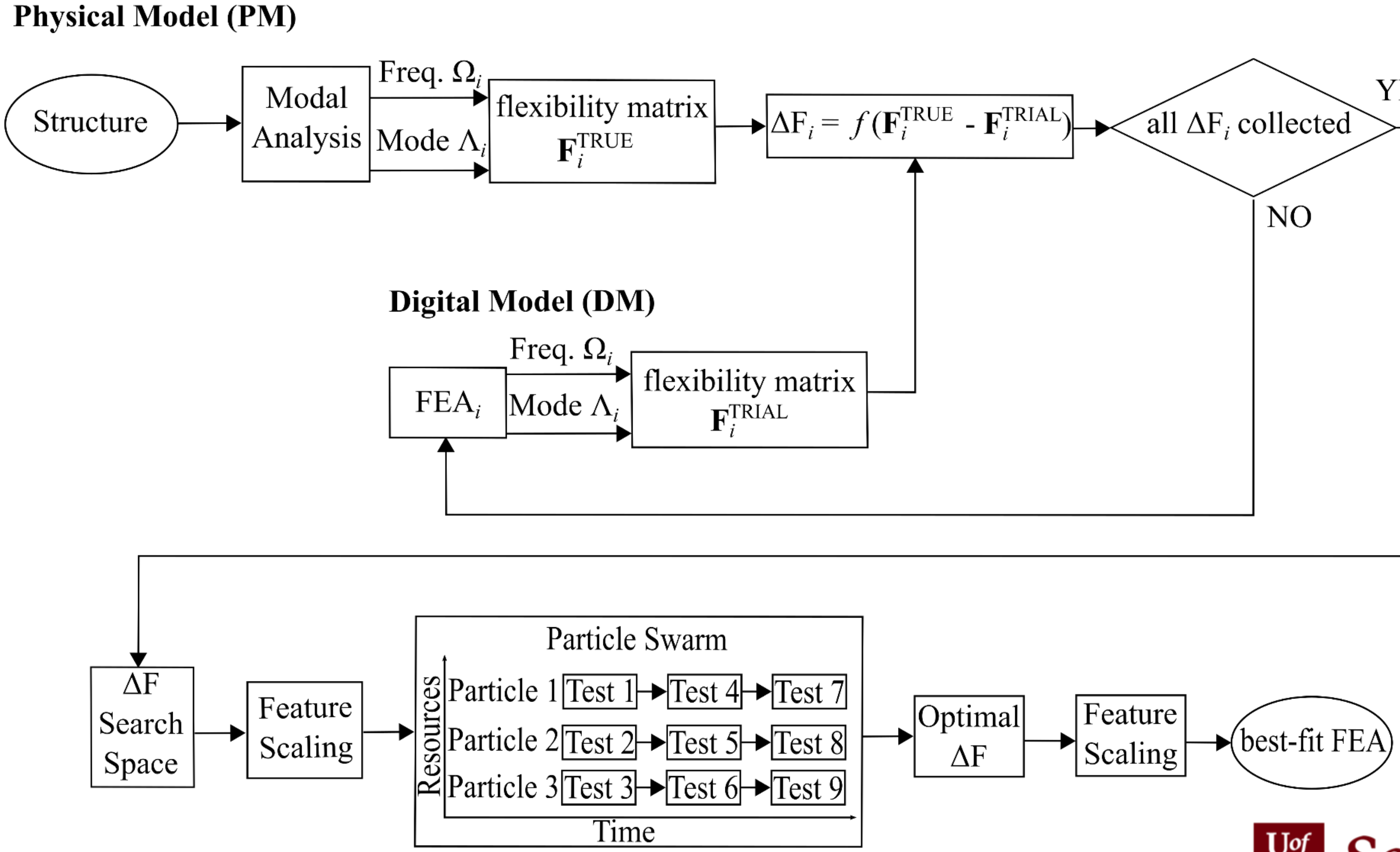
By combining all this information, **the Digital Twin continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success.** The Digital Twin can also predict system response to safety critical events and uncover previously unknown issues before they become critical by comparing predicted and actual responses. Finally, the systems on board the Digital Twin are capable of mitigating damage or degradation by activating self-healing mechanisms or by recommending changes in mission profile to decrease loadings thereby increasing both the life span and the probability of mission success.

DETERMINING BEST PS PARAMETERS



PROJECT FLOWCHART

- Update an FEA model of the "Smart Beam" in real-time.



FEA updating process

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