MULTI-EVENT MODEL UPDATING FOR SHIP STRUCTURES WITH RESOURCE-CONSTRAINED COMPUTING

[1]**Jason Smith**, [2]Hung-Tien Huang, [1,3]Austin Downey, [4]Alysson Mondoro, [4]Benjamin Grisso, [1]Sourav Banerjee

[1] Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA

[2] Department of Computer Science and Engineering, University of South Carolina, Columbia, SC, USA

[3] Department of Civil Engineering, University of South Carolina, Columbia, SC, USA

[4] Naval Surface Warfare Center – Carderock Division, West Bethesda MD, USA

UNIVERSITY OF South Carolina

OVERVIEW

- Importance and Significance
- Methodology
- Results

[Mass Communication Specialist 1st Class James R. Evans, Public domain, via Wikimedia Commons]

WHAT IS A DIGITAL TWIN?

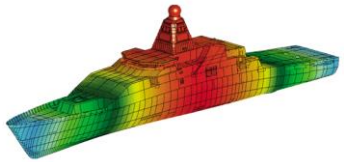
- A Digital Twin continuously forecasts the health of the vehicle or system, the remaining useful life and the probability of mission success.

- 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.

[SumitAwinash, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons]

DIGITAL TWIN VS MODEL

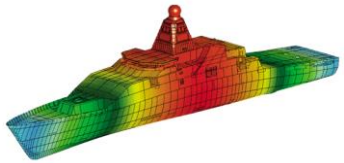
Model



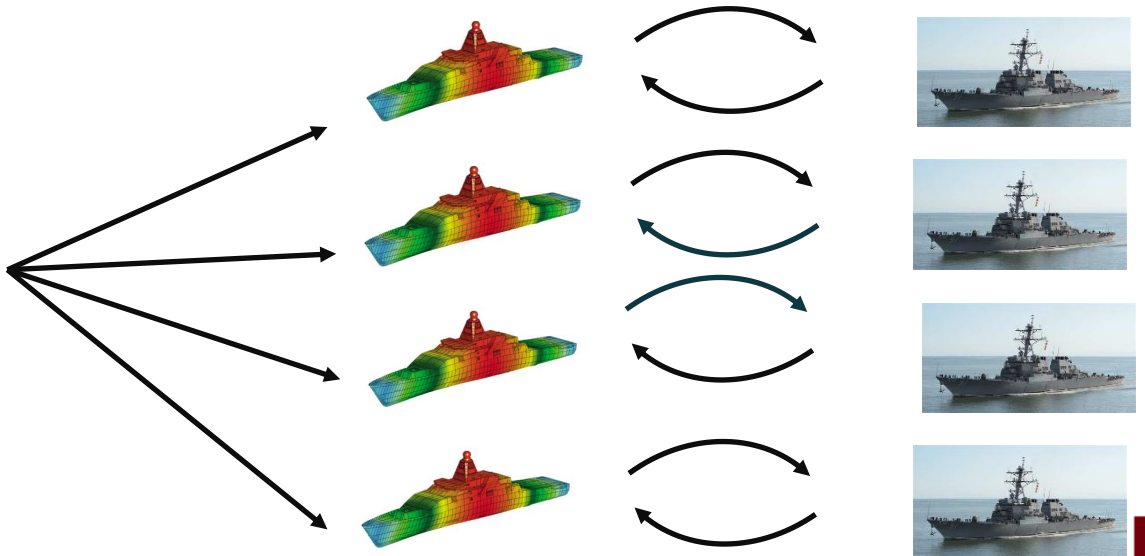
Data don't necessarily update ship model

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

Digital Twin



Class-wide models serve as a starting point

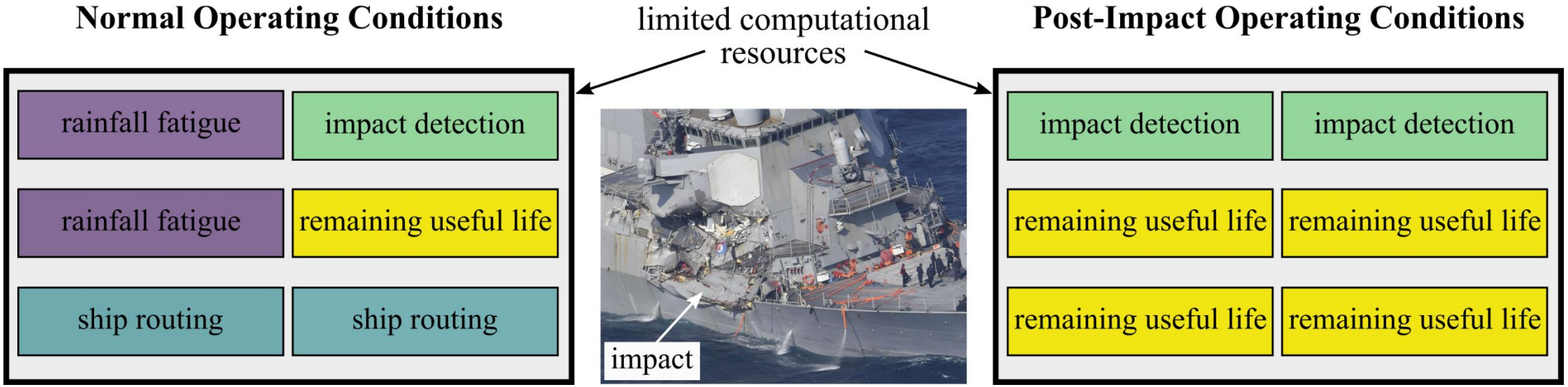


Twin is updated with data from the ships

Twins track condition of *each individual hull*

IMPORTANCE AND IMPLEMENTATION

- Impacts, fatigue and ship life span.
- Increase ship lifespans, maintenance intervals, and survivability.
- Following an impact, computational resources will be used to provide actionable decisions within seconds or minutes.



Reconfiguring limited computational resources to update models of greater importance.

DIGITAL TWIN ENABLING TECHNOLOGIES AND GAPS

Enabling Technologies

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

Engineering Gaps

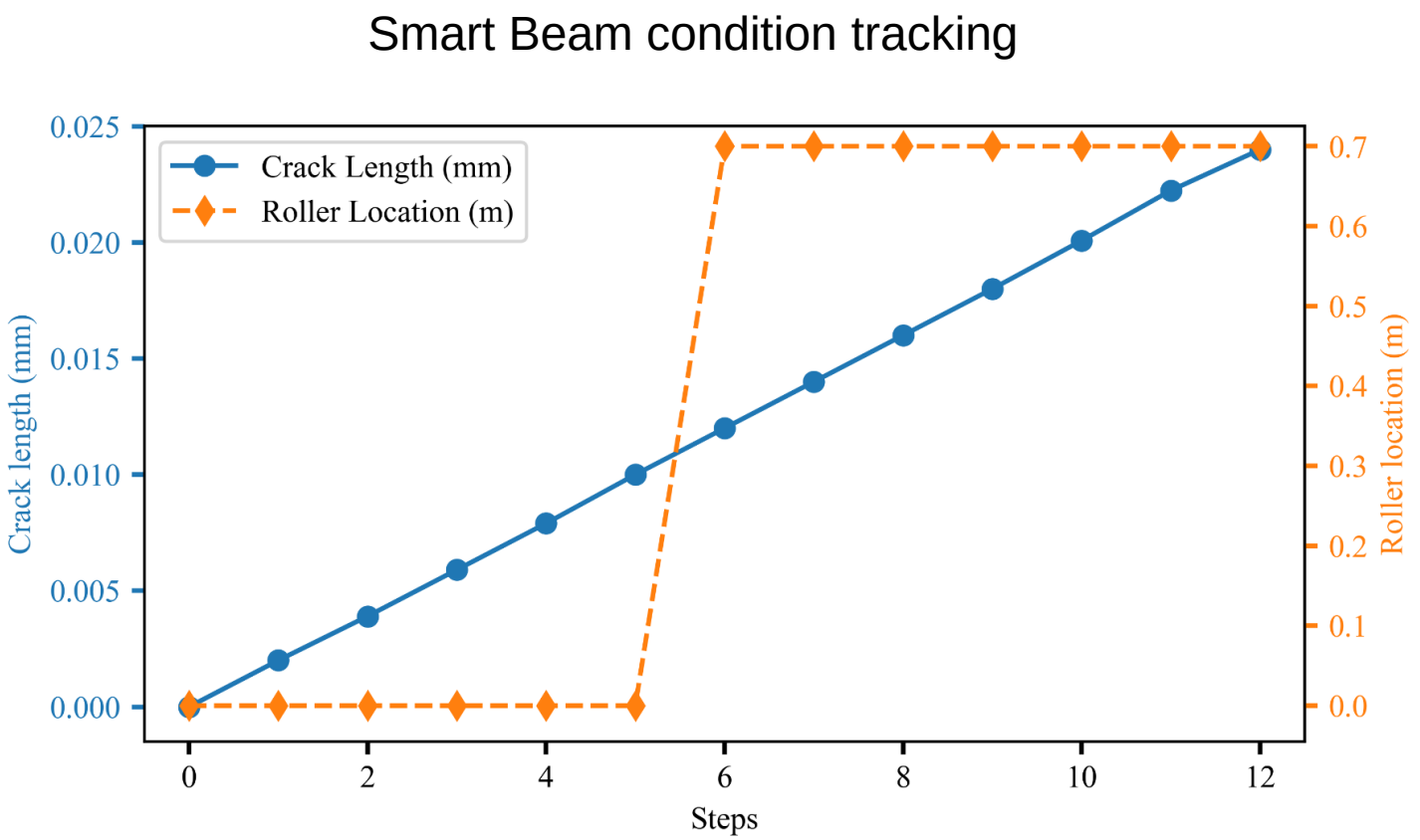
- Integration of ship- and off-board sensor systems that store data
- Multi-level classification communications
- Integrating cloud-based computing
- Distributed (GPU-based) computing high-fidelity
- Cybersecurity
- Workforce expertise with data analytic skill set and tools

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

CONDITION TRACKING

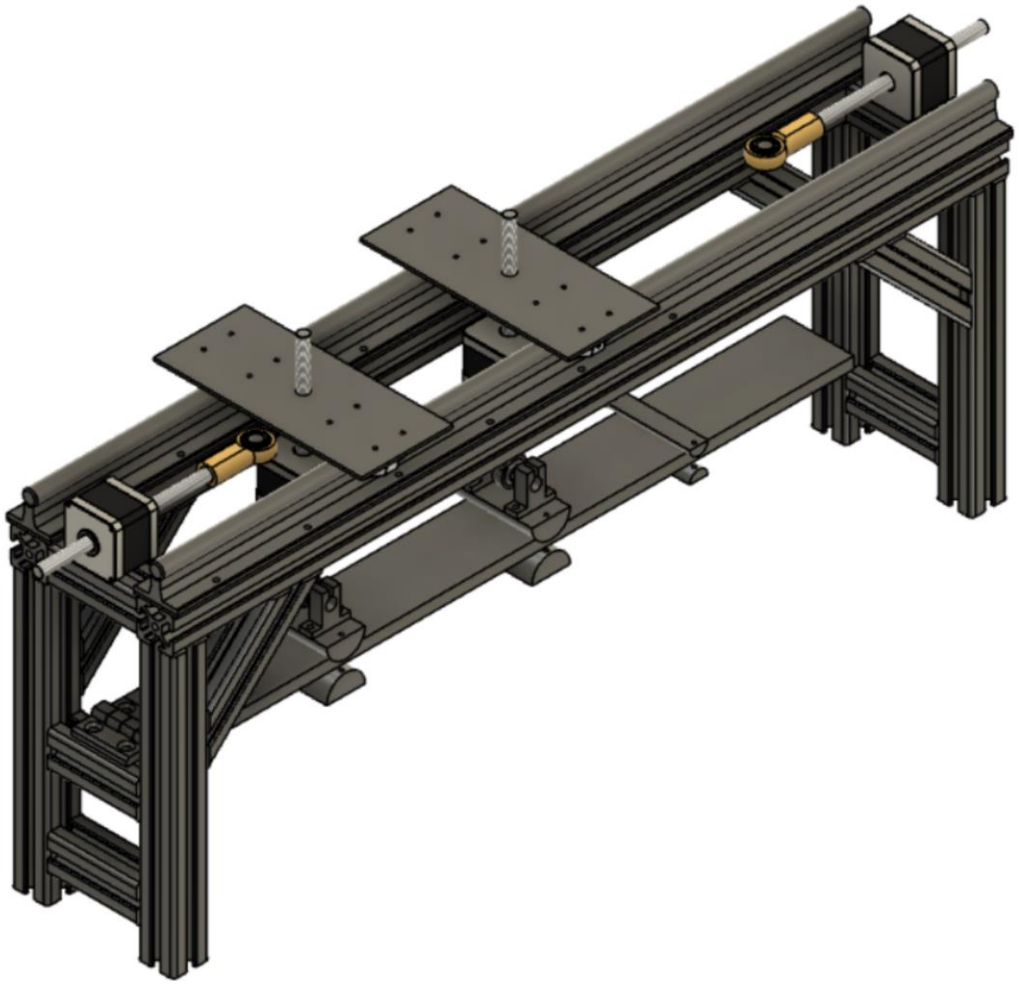
- Build a “Smart Beam”
  - Connection inside ship structure.
  - Tracks foreground and background changes.
  - Damage to supports and fatigue cracks.



South Carolina

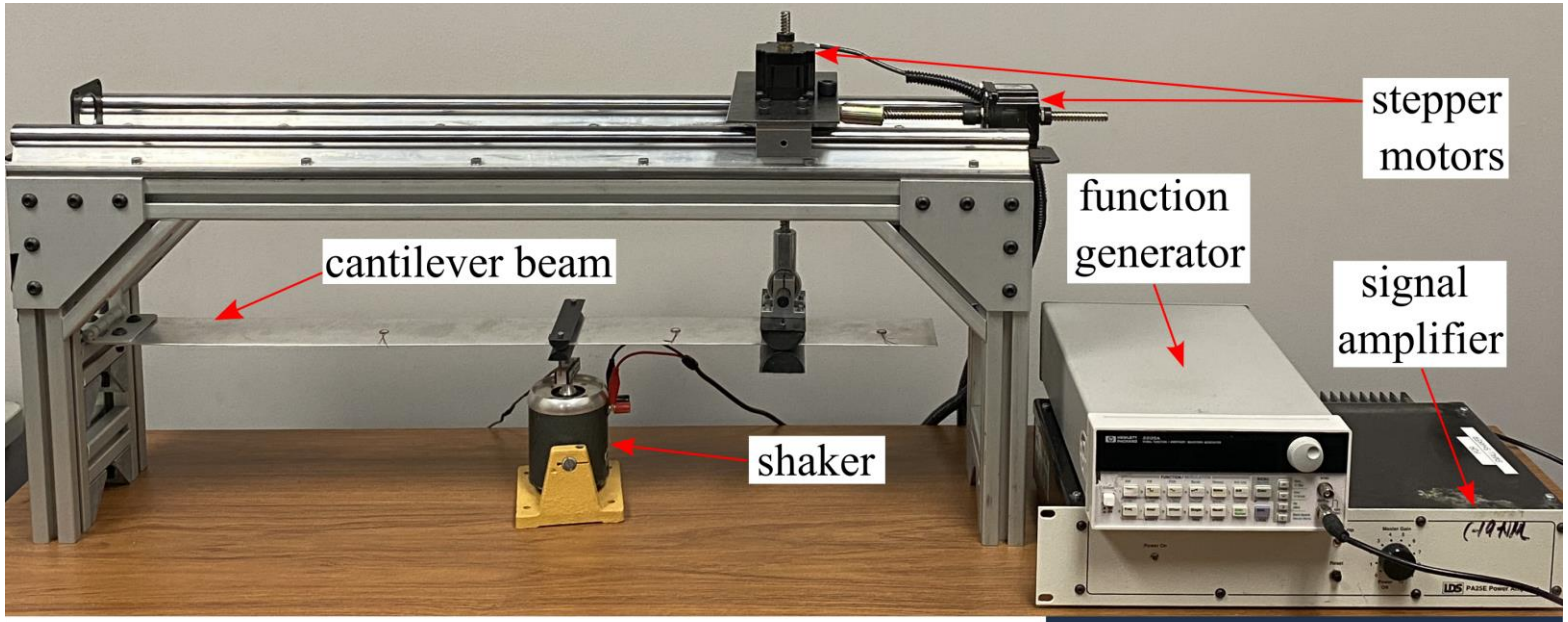
SHIP STRUCTURE AND FATIGUE ENVIRONMENT (SHIP SAFE) TESTBED

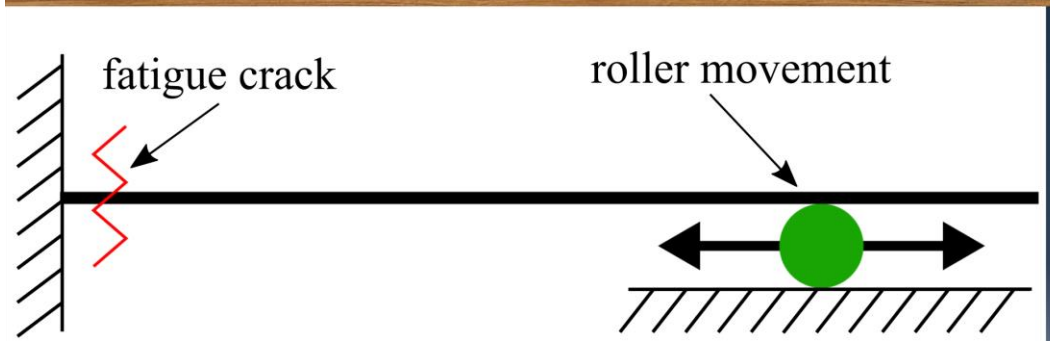
- Designed to allow for changes to the structure's stiffness using the stepper motors.
- The changing of the structure's stiffness is reversible.
- Will produce simple data sets that will be used for validating multi-model data assimilation algorithms.

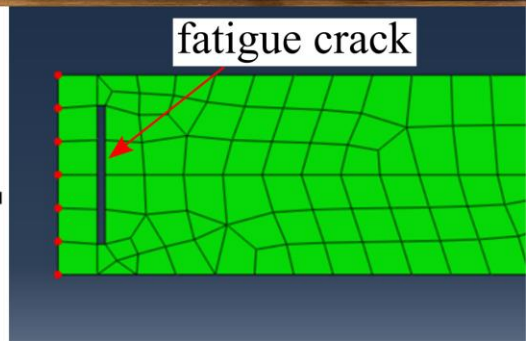


CAD model of ship hull

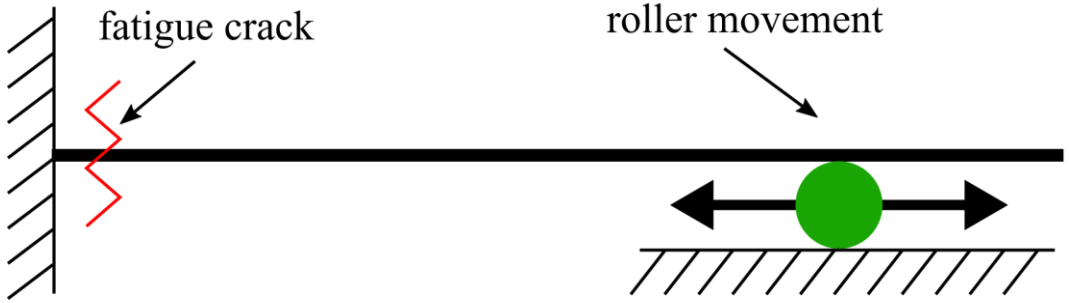
SHIP STRUCTURE AND FATIGUE ENVIRONMENT (SHIP SAFE) TESTBED

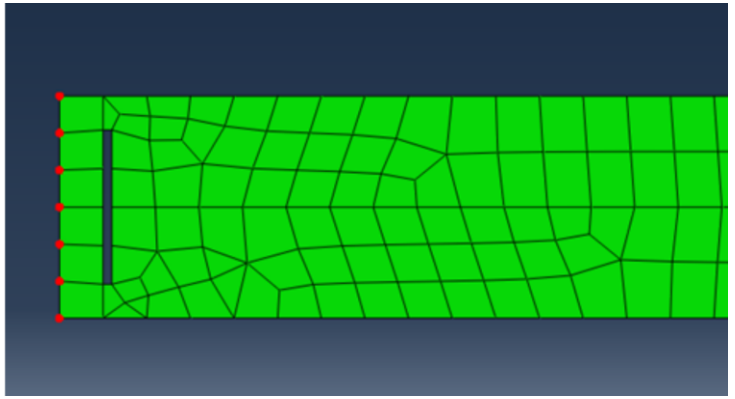






FEA AND POST PROCESSING



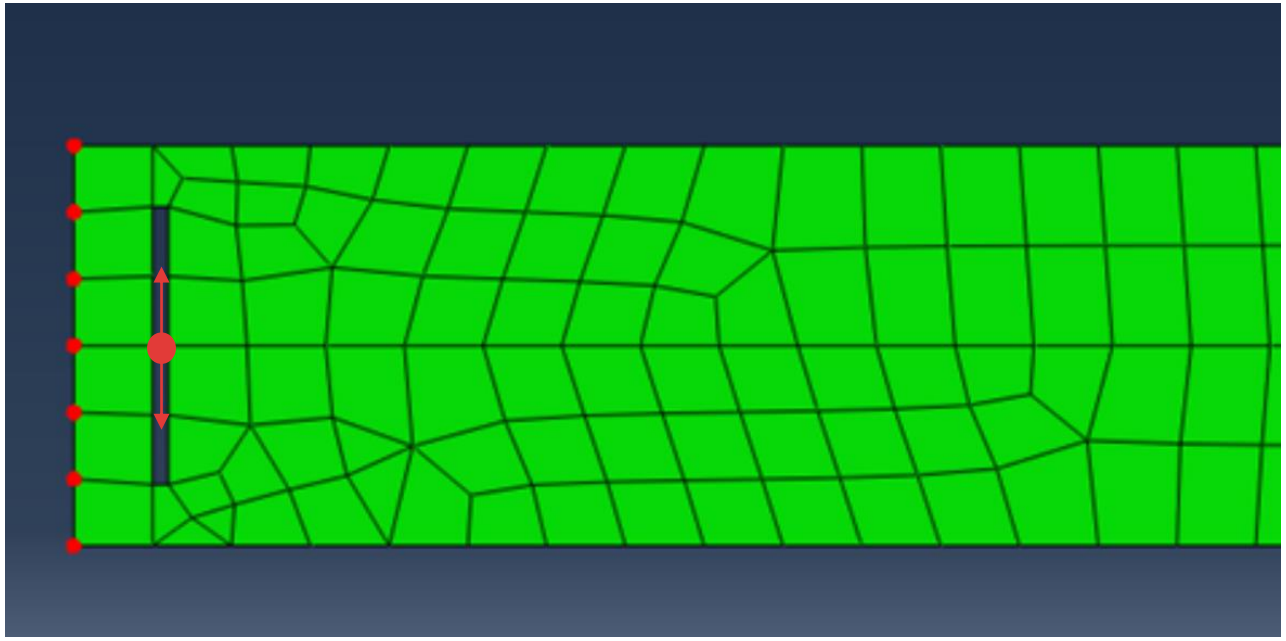


FEA model of smart beam

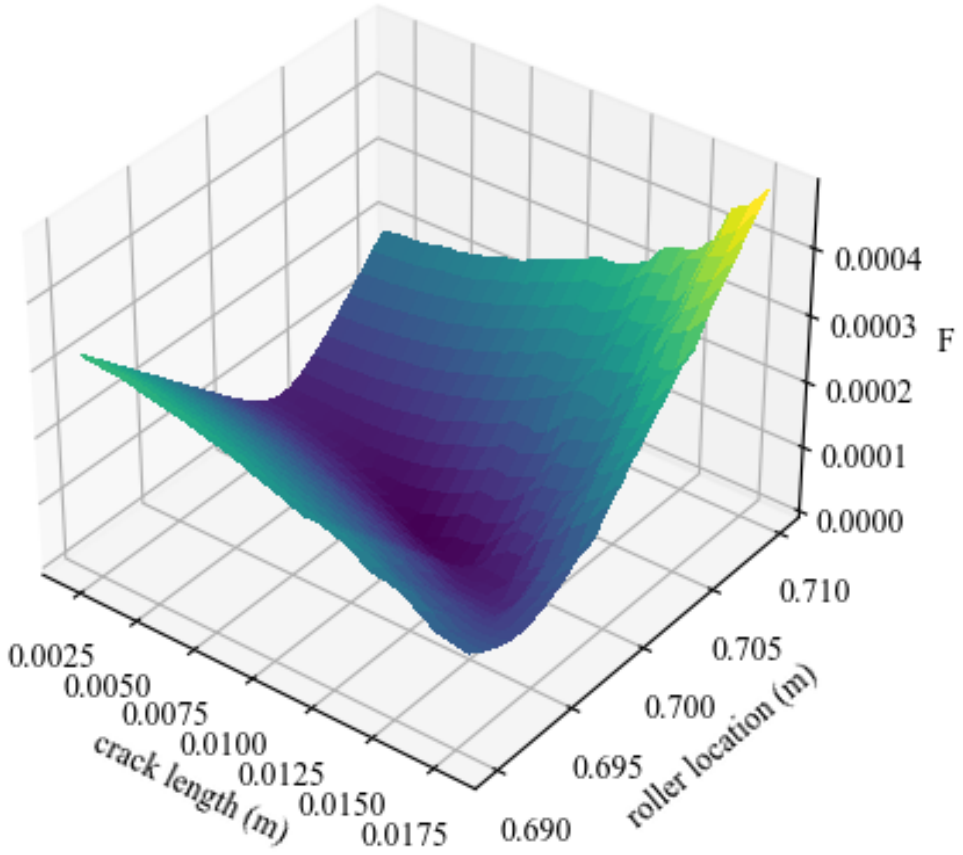
- Damage cases:
  - Fatigue crack length
  - Roller location along the beam

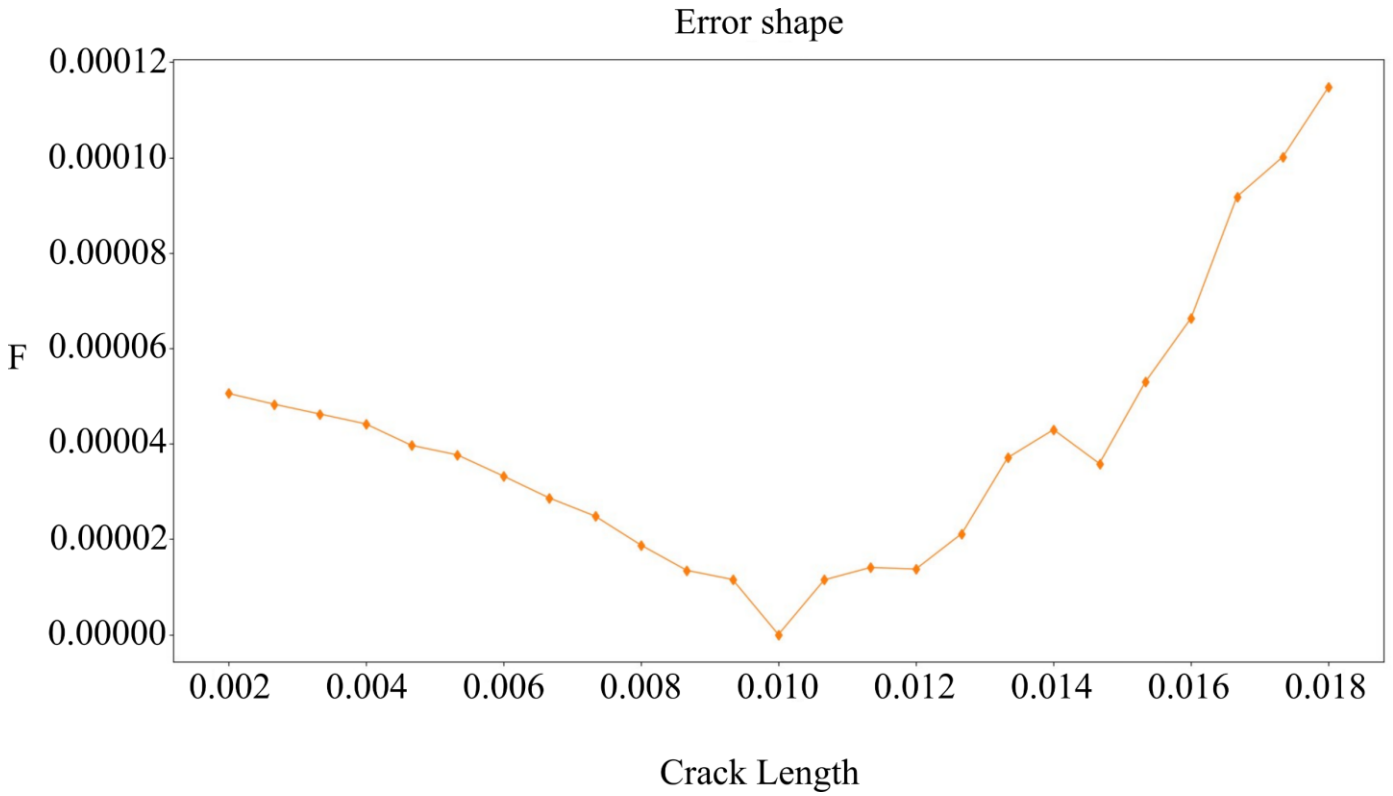
INSERTING A LINEAR CRACK

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



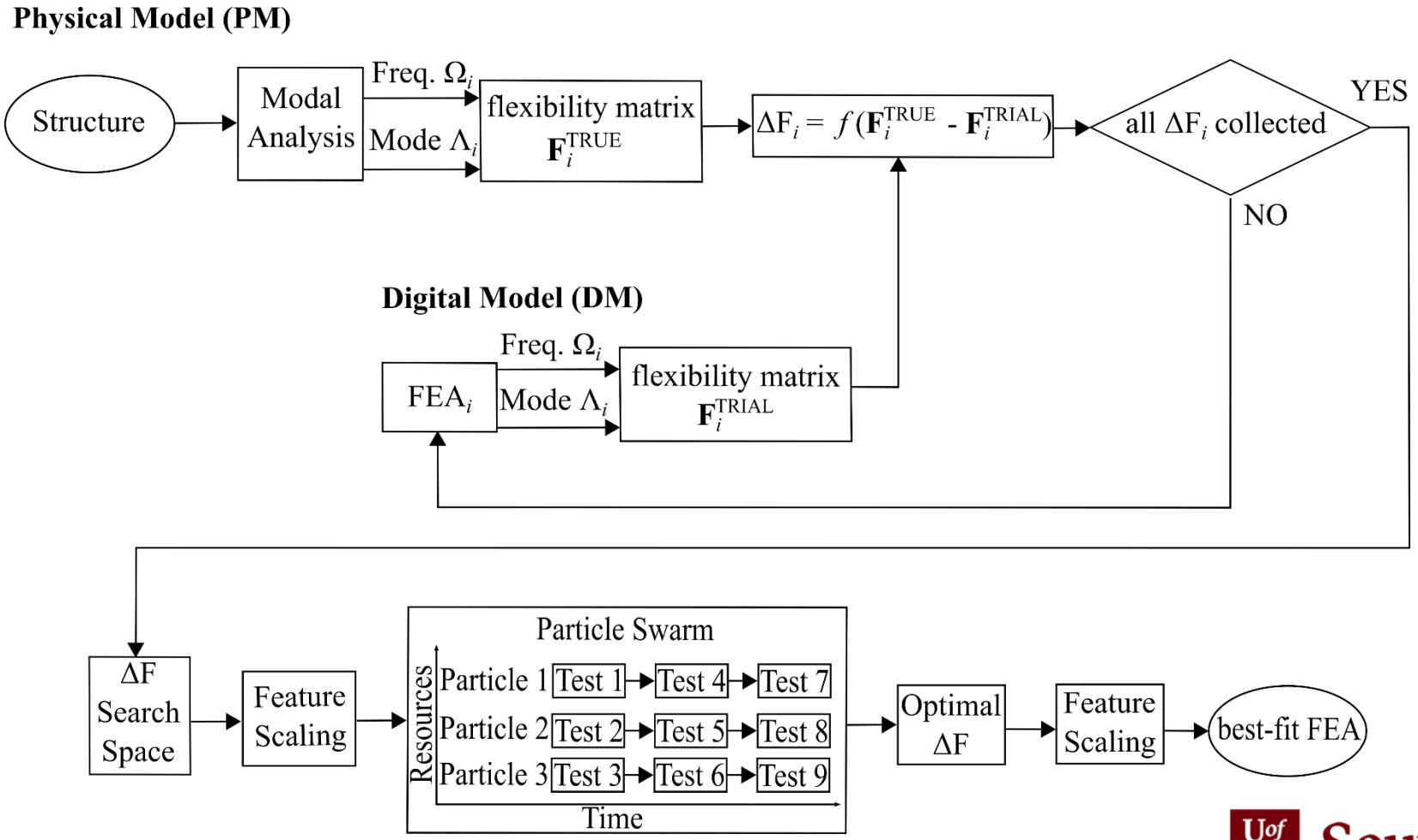
VALIDATING CONVEX ERROR SHAPE





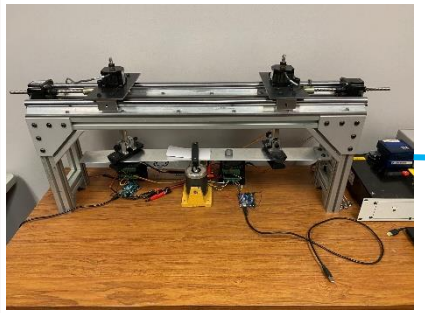
PROJECT FLOWCHART

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



FEA updating process

PROJECT FLOWCHART

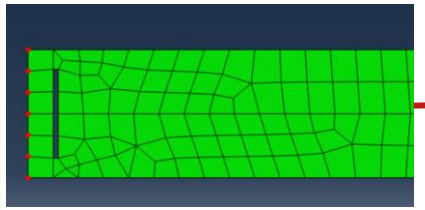


Structure

Data

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

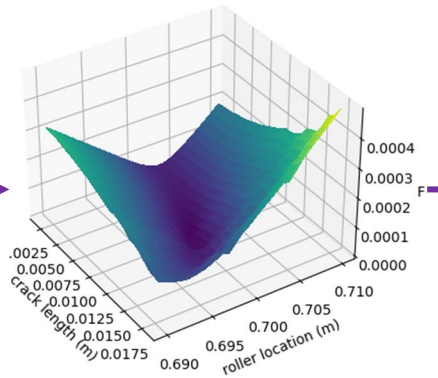
$$\Delta F_{trun} = F_{trun}^{true} - F_{trun}^{trial}$$

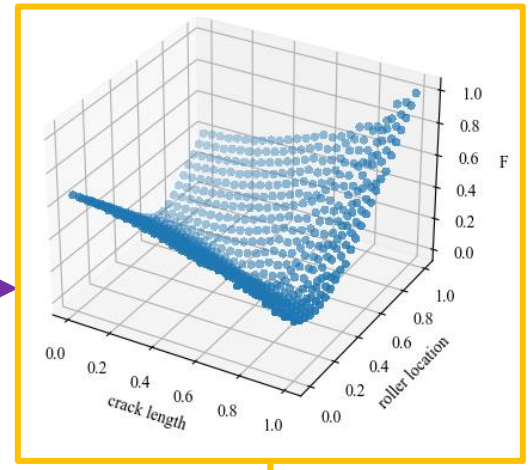


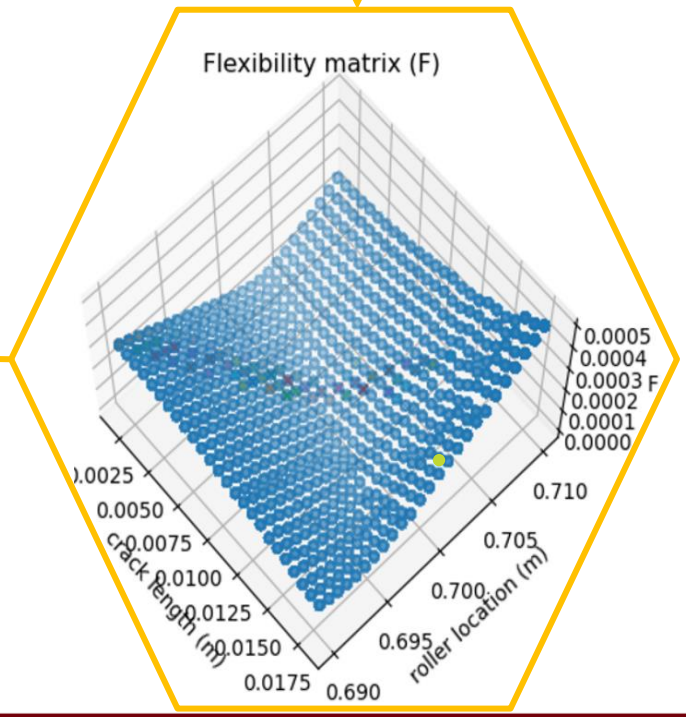
FEA Model

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

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

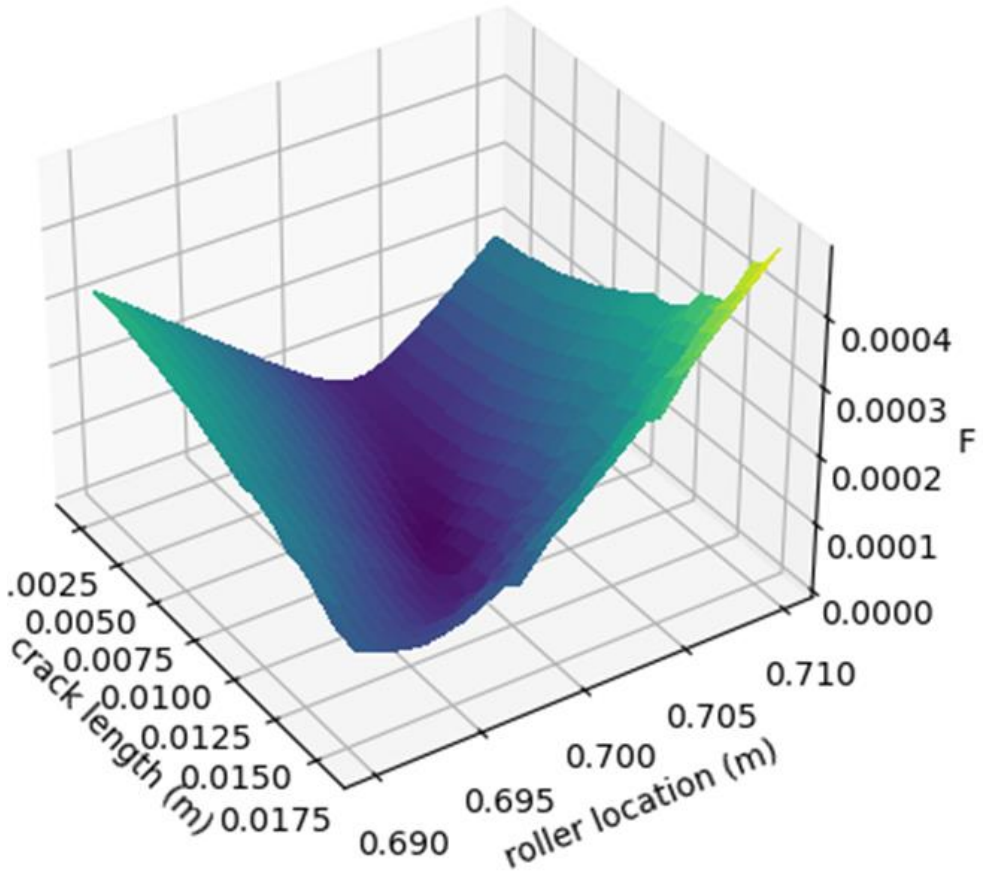
$\bar{\phi}_i$: normalized mode shape

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

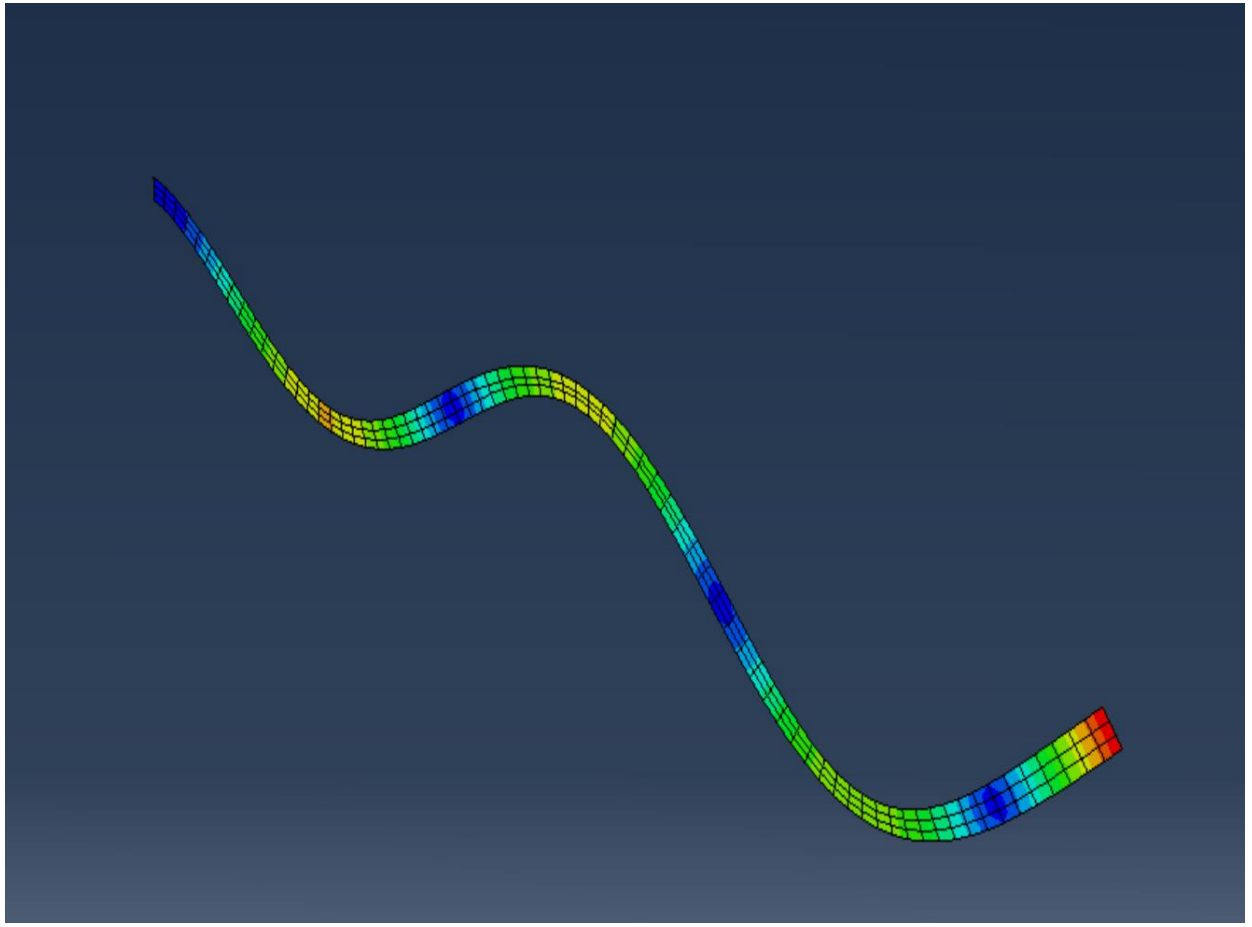
F_{trun}^{trial}: trial (FE model) structure flexibility matrix

FINITE ELEMENT ANALYSIS MODEL

Modeled in Abaqus:

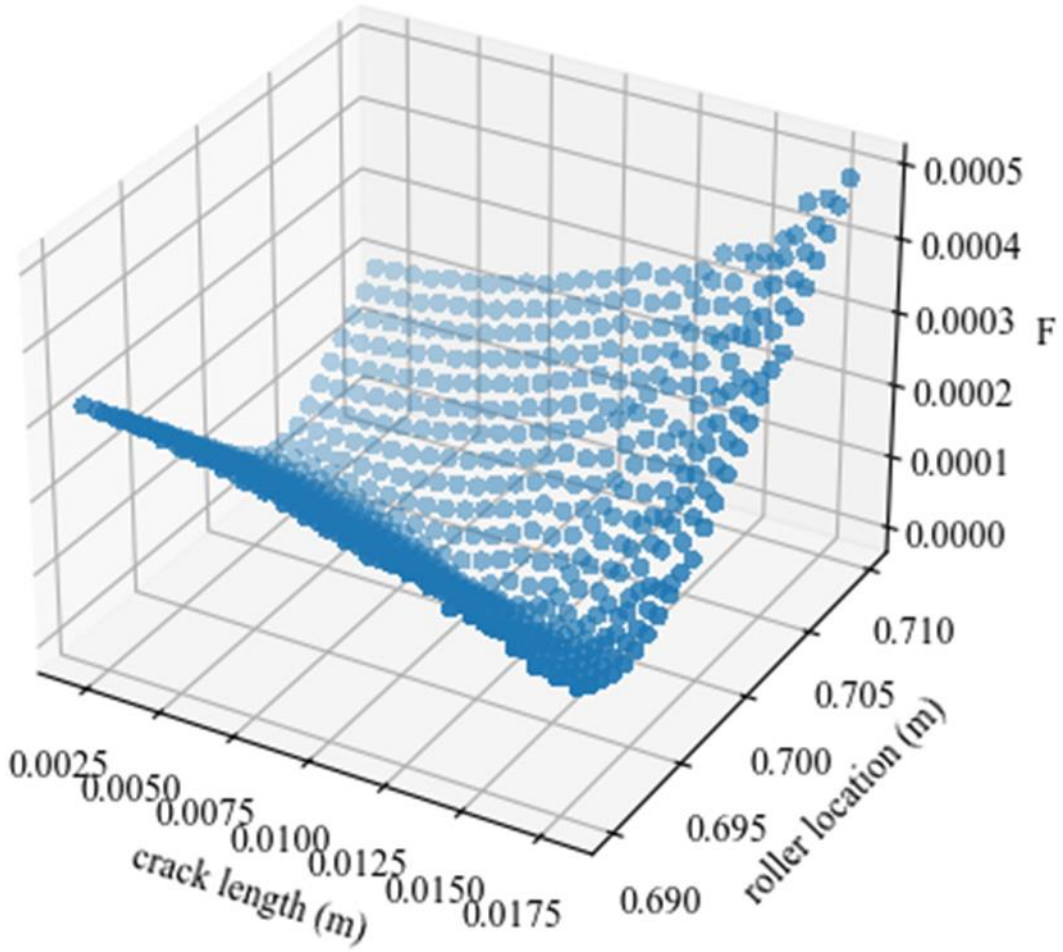
- Initially built as 3-D model.
  - Most accurate to Physical Model.

- Finalized as a 2-D model
  - BCs and Input forces act in 2-D.
  - Computationally efficient.
  - Produces identical data.

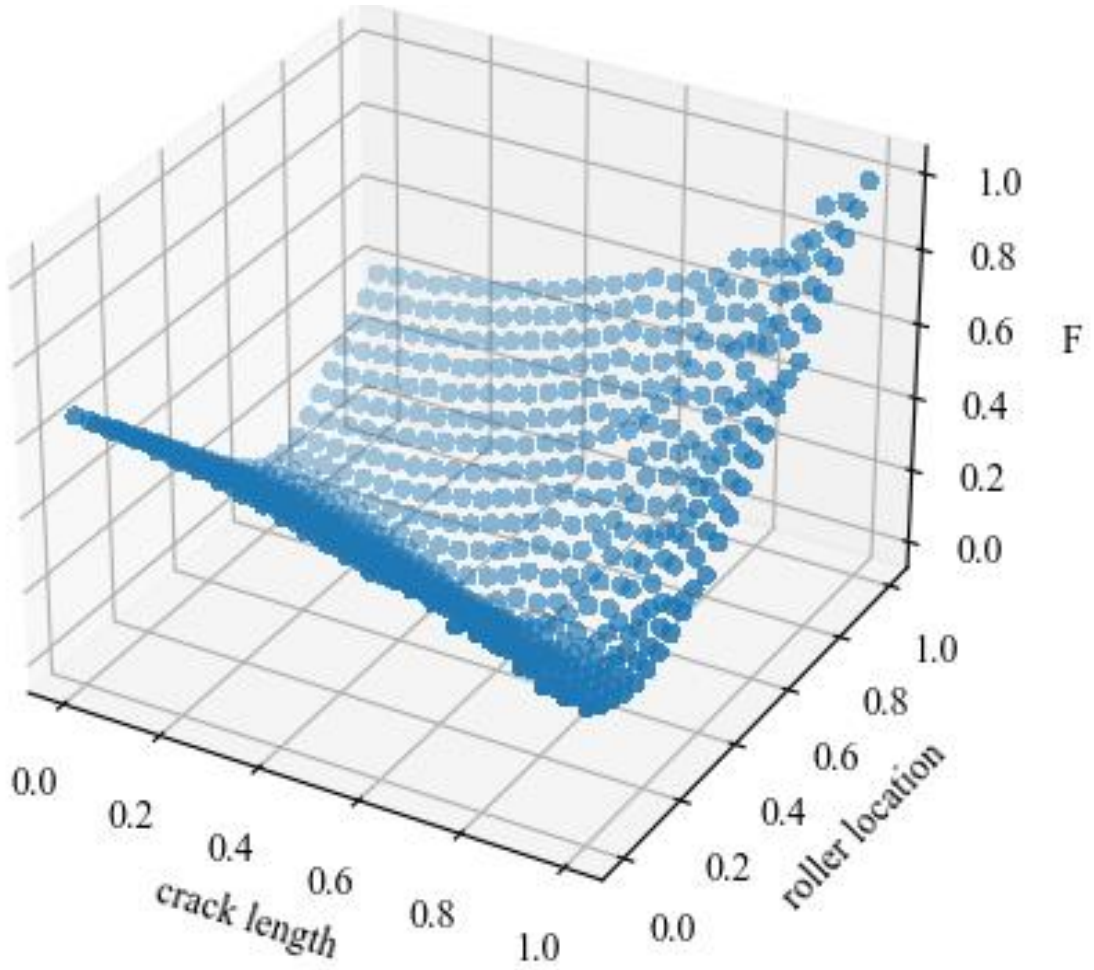


MIN-MAX NORMALIZATION

Unscaled data

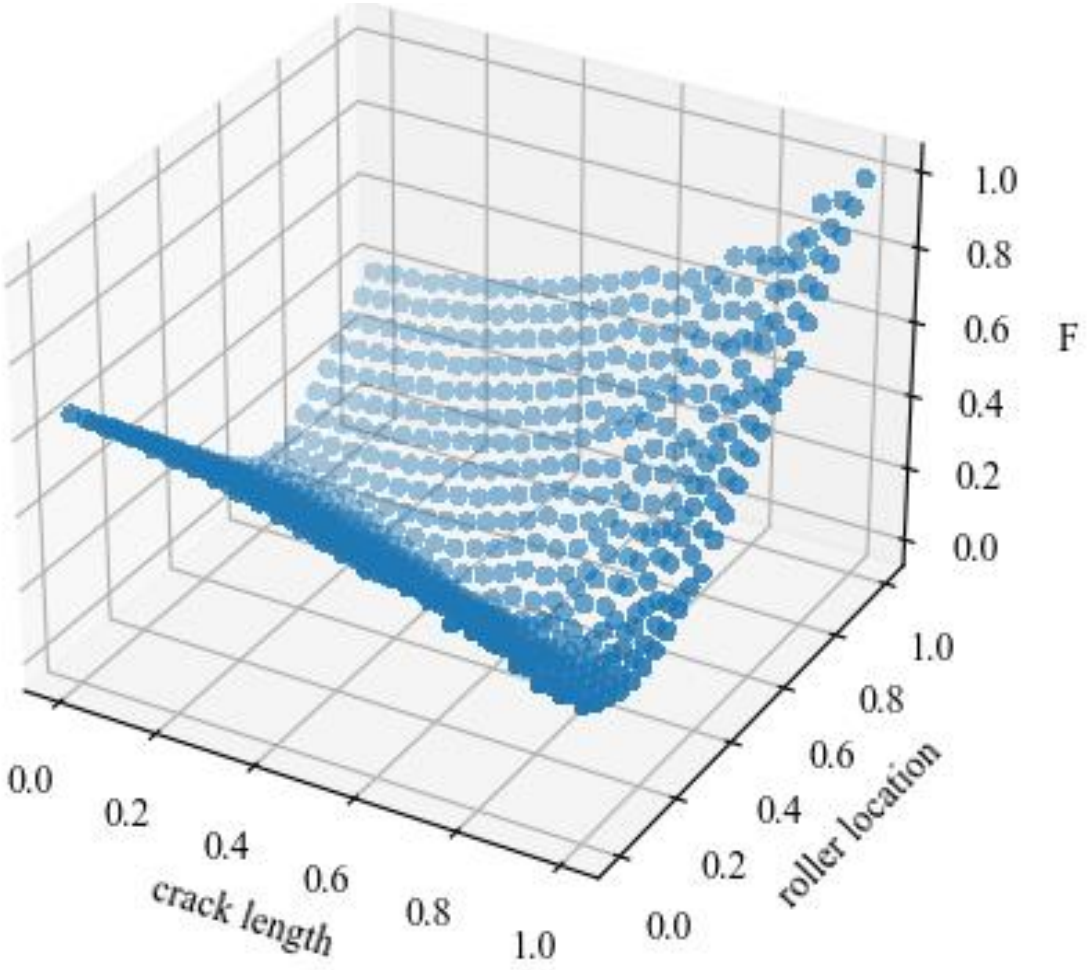


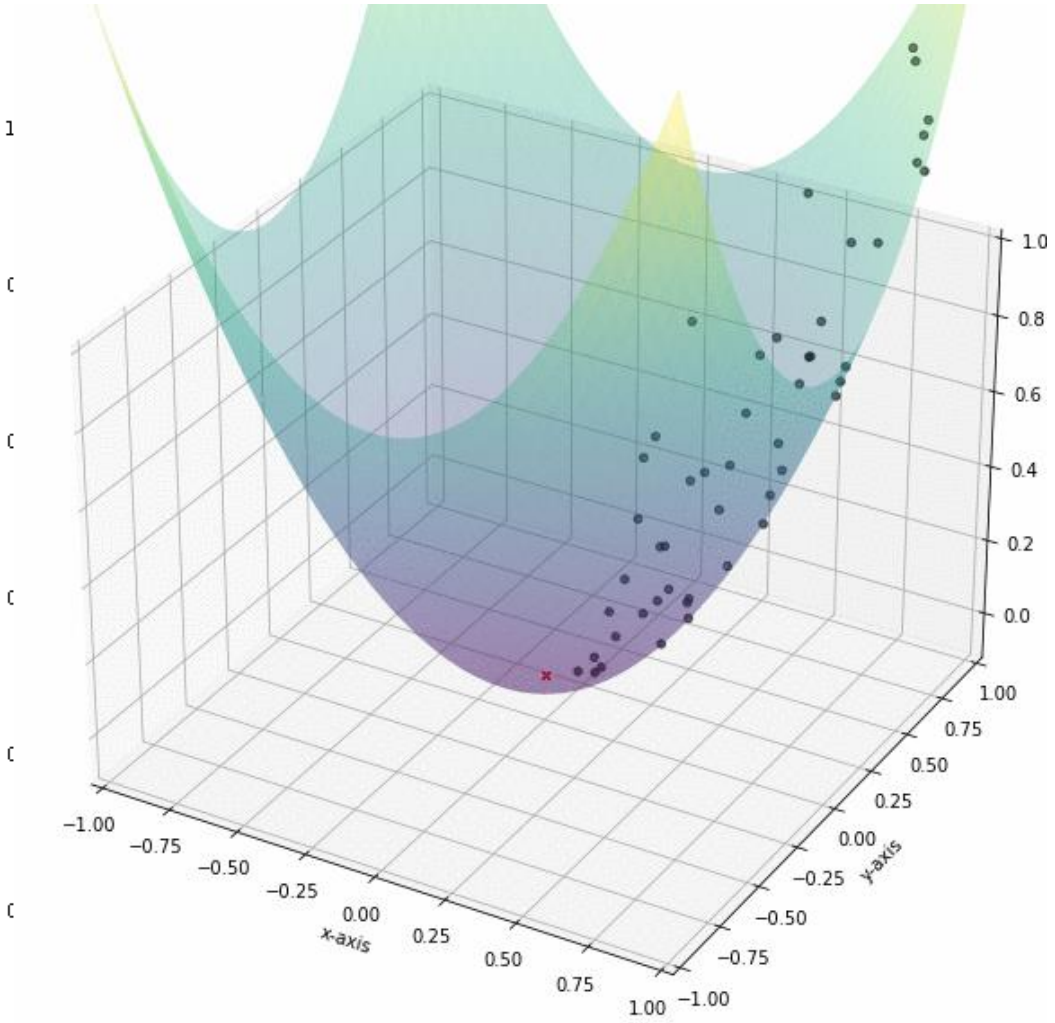
Scaled data



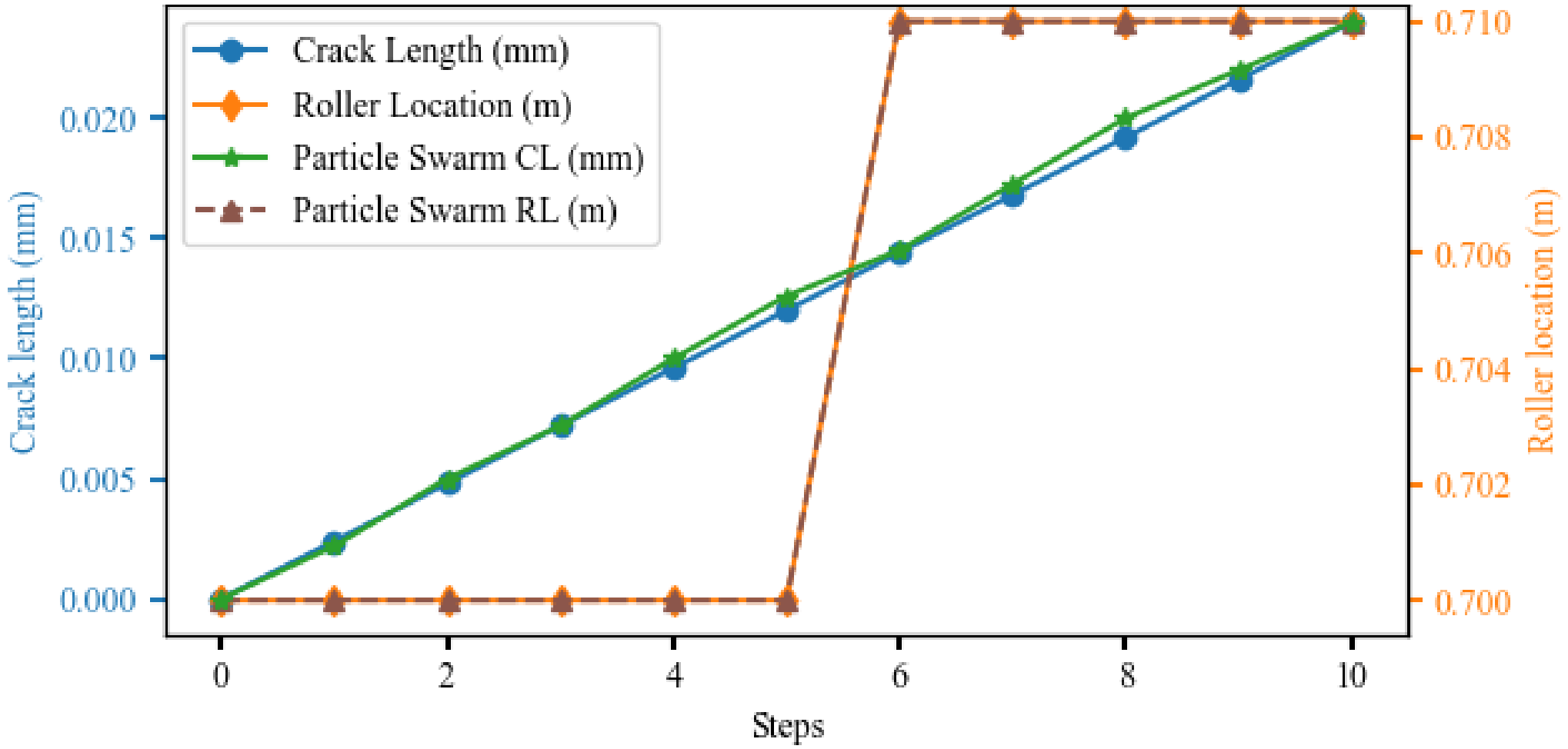
PARTICLE SWARM

Scaled data



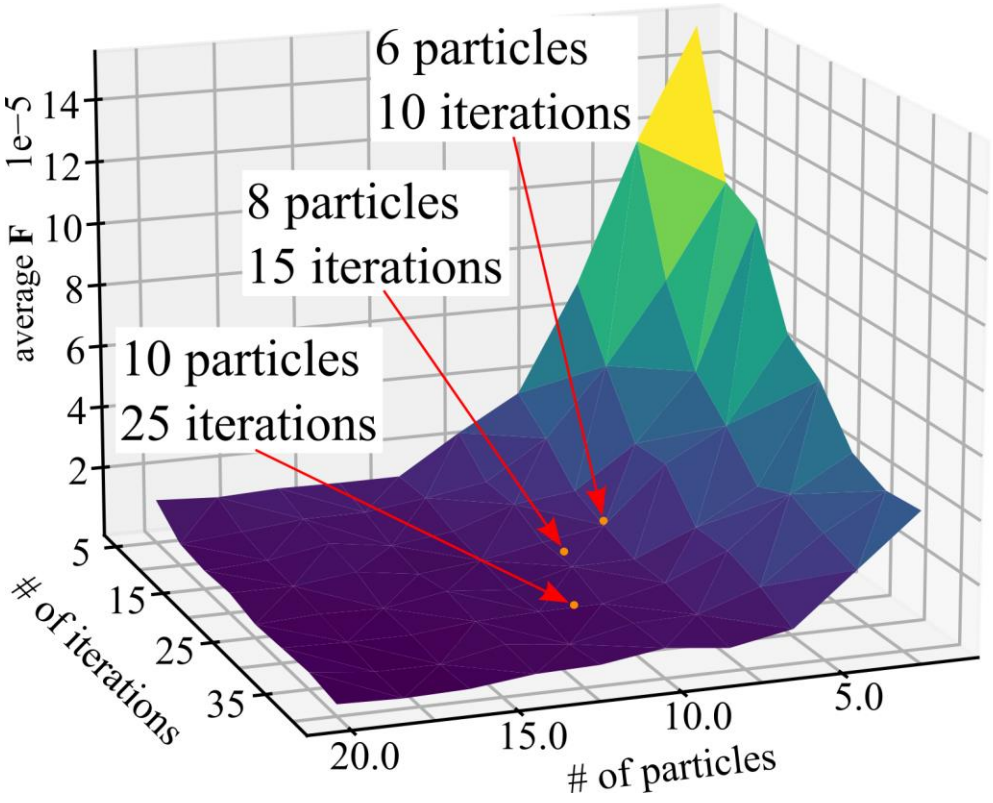


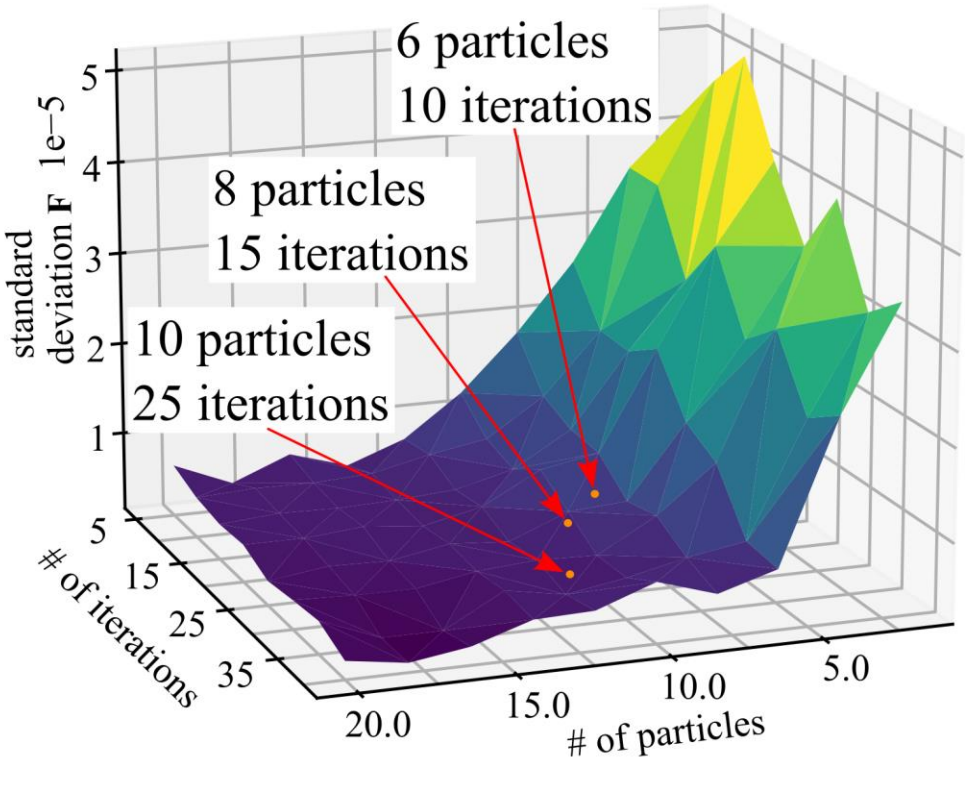
PARTICLE SWARM



South Carolina

DETERMINING BEST PS PARAMETERS





ACKNOWLEDGEMENTS

This material is based upon work partly supported by the Air Force Office of Scientific Research (AFOSR) through award no. FA9550-21-1-0083. This work is also partly supported by the National Science Foundation Grant number 1850012. The support of these agencies is gratefully acknowledged. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the United States Air Force.

QUESTIONS?

Jason Smith

Mechanical Engineering, M.S.M.E May 2023

Jms32@email.sc.edu

South Carolina