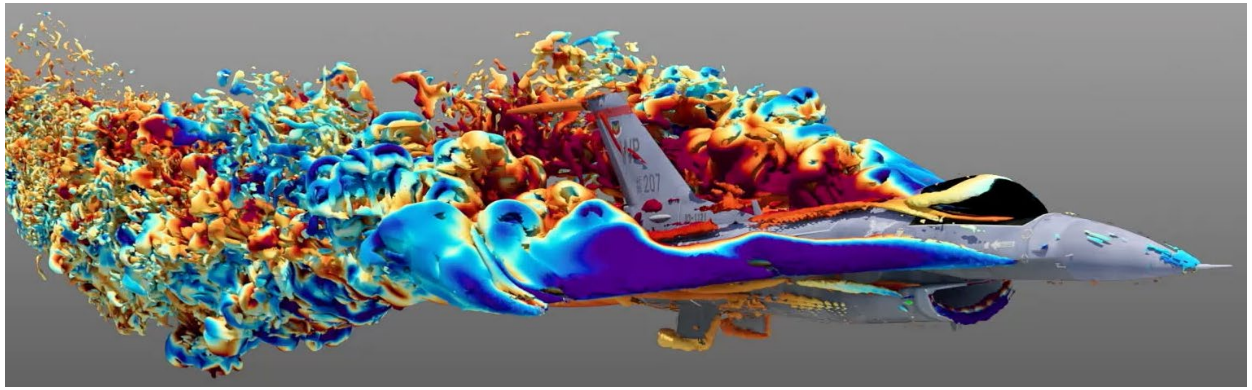

Progress Towards Improving the Models in Model Based Systems Engineering with High Fidelity Physics

Dr. Scott A. Morton, Dr. David McDaniel, and Dr. Jennifer Abras

National Defense Industry Association
Systems and Mission Engineering Conference
1-3 November 2022

DOD HPC MODERNIZATION PROGRAM

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Definition: Digital Engineering vs. MBSE

- **Model-based systems engineering (MBSE) –** a formalized methodology used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems *(Nataliya Shevchenko, “An Introduction to Model-Based Systems Engineering (MBSE),” Software Engineering Institute (SEI), 21 Dec 2020)*

- **Digital engineering (DE)** – an **integrated digital approach** that uses authoritative sources of systems' **data** and **models** as a **continuum across disciplines** to support life cycle activities **from concept through disposal.** *(Defense Acquisition University)*
  - Integrated digital approach → a monolithic solution that suggests there can be no R&E / A&S divide
  - Data → must be regularly managed/updated/curated at each stage of the process
  - Models → both compute and data-intensive; range from basic analysis to high-end computing (HEC)
  - Availability → accessible to anyone in the design, test, evaluation, sustainment, mission planning pipeline
  - Duration → from concept through disposal (and possibly beyond); decades to centuries
  - Extensity → continuum across disciplines; simultaneous accounting of all assets at all lifecycle stages to facilitate projection of current and future forces in a full range of scenarios, to determine gaps, to advise the characteristics of future platforms, and to build preventive maintenance plans for individual assets

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HPC Impacting Digital Engineering

Physics Based Simulation

High Fidelity Physics Simulations Primarily Used for Issue Diagnosis and Resolution or Design Downselect

- Many Single Point Calcs
- Close match with Reality
- Typically Occurs after wind tunnel tests or after flight tests (days/!M's CPU Hrs)
- Fixes can be costly since vehicle is farther in the design process
- Data computed not in a form easily reused for other needed points

Models

System Level Models Useful for Systems Engineering

- Calculations are faster than real time
- Broad applicability of model to vehicle envelope
- Can be available any time in the design cycle
- Only useful if decision level data is accurate enough
- Easily moved through the design cycle
- Continuously updated as system design changes

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Physics Based Surrogates

Physics Based Surrogates

- Based on pre-computed high fidelity simulations
- Broad applicability to vehicle flight envelope
- Faster than real time calc times
- Single or multi-physics applicability depending on pre-computed physics sims
- Can be combined with other surrogates

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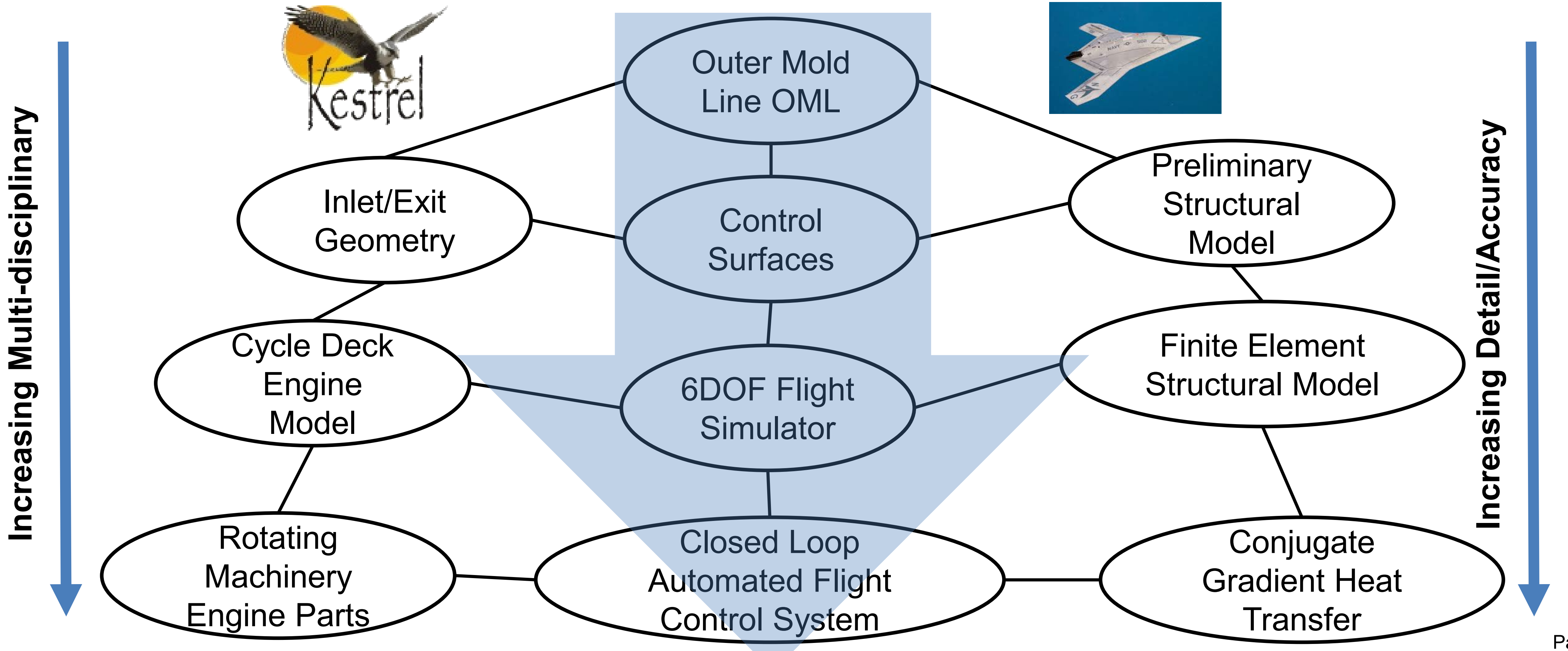
Model Based Systems Engineering

Physics Based Simulations

- **During the design process we can eliminate poor design choices by increasing the fidelity of the PBAs as more information is known (objects and connection notional)**



Physics-Based Simulations

Integrated Rotating Machinery

Integrated Structural Elasticity

Integrated Moving Control Surfaces

Single Point Physics-Based Surrogates

- Many methods of building Surrogates/ROMS
- Aircraft C.G. Loads using System Identification
- Distributed Loads using Proper Orthogonal Decomposition
- Machine Learning using Neural Networks

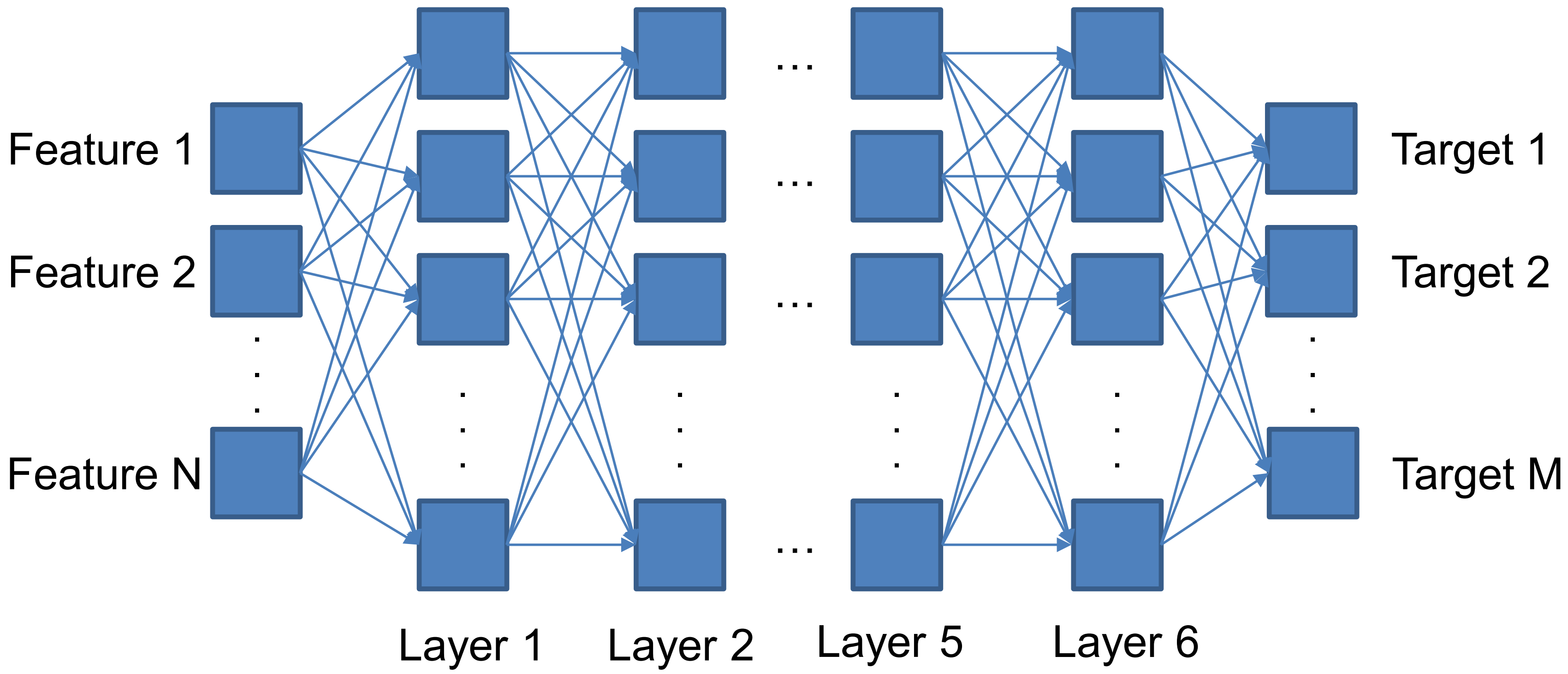
Vehicle Envelope Level Surrogates-AI/ML

Machine Learning Methods

- **A wide variety of machine learning methods exist**
- **For the current effort the Deep Neural Network (DNN) and the Convolutional Neural Network (CNN) are the primary focus**
- **The DNN is a simpler method that learns based on point based information**
  - This is the main ML driver for the effort
- **The CNN is a more complex method that learns based on patterns in distributed information**
  - This is included as an optional feature that allows for the inclusion of more complex physics into the analysis when needed

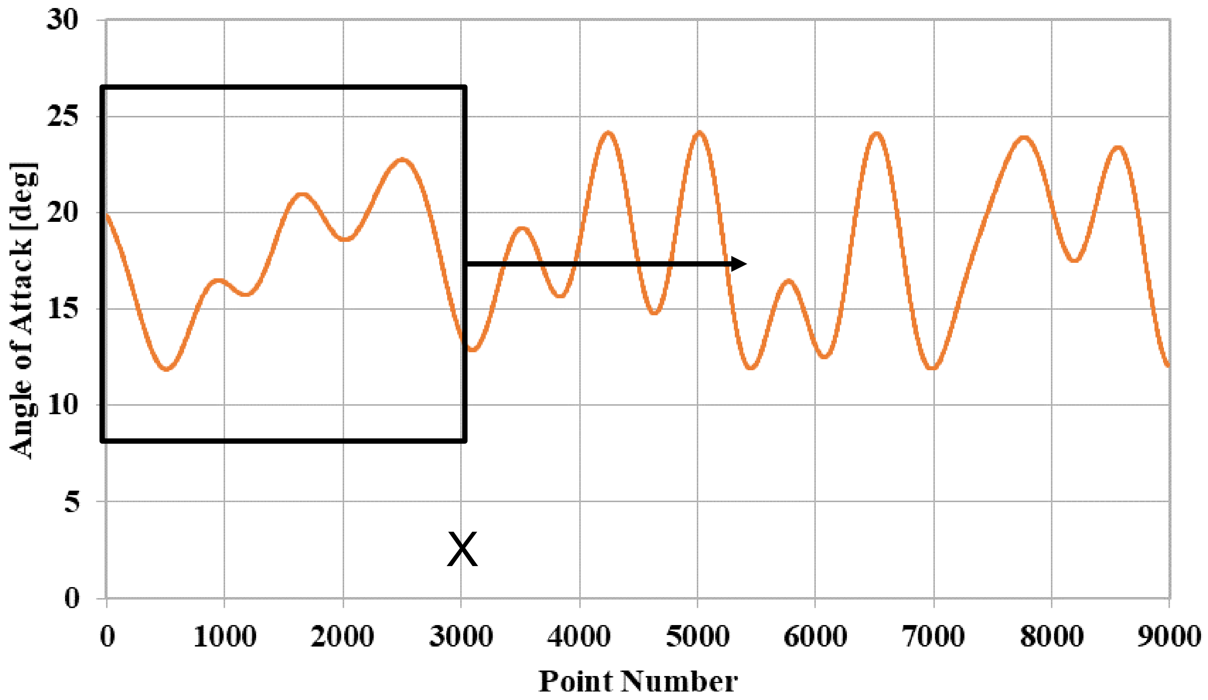
Deep Neural Network (DNN)

- The DNN is the core ML method employed for this effort
- The DNN implemented is a multi-layer perceptron regressor
- The current setup uses 6 hidden layers of 100 neurons

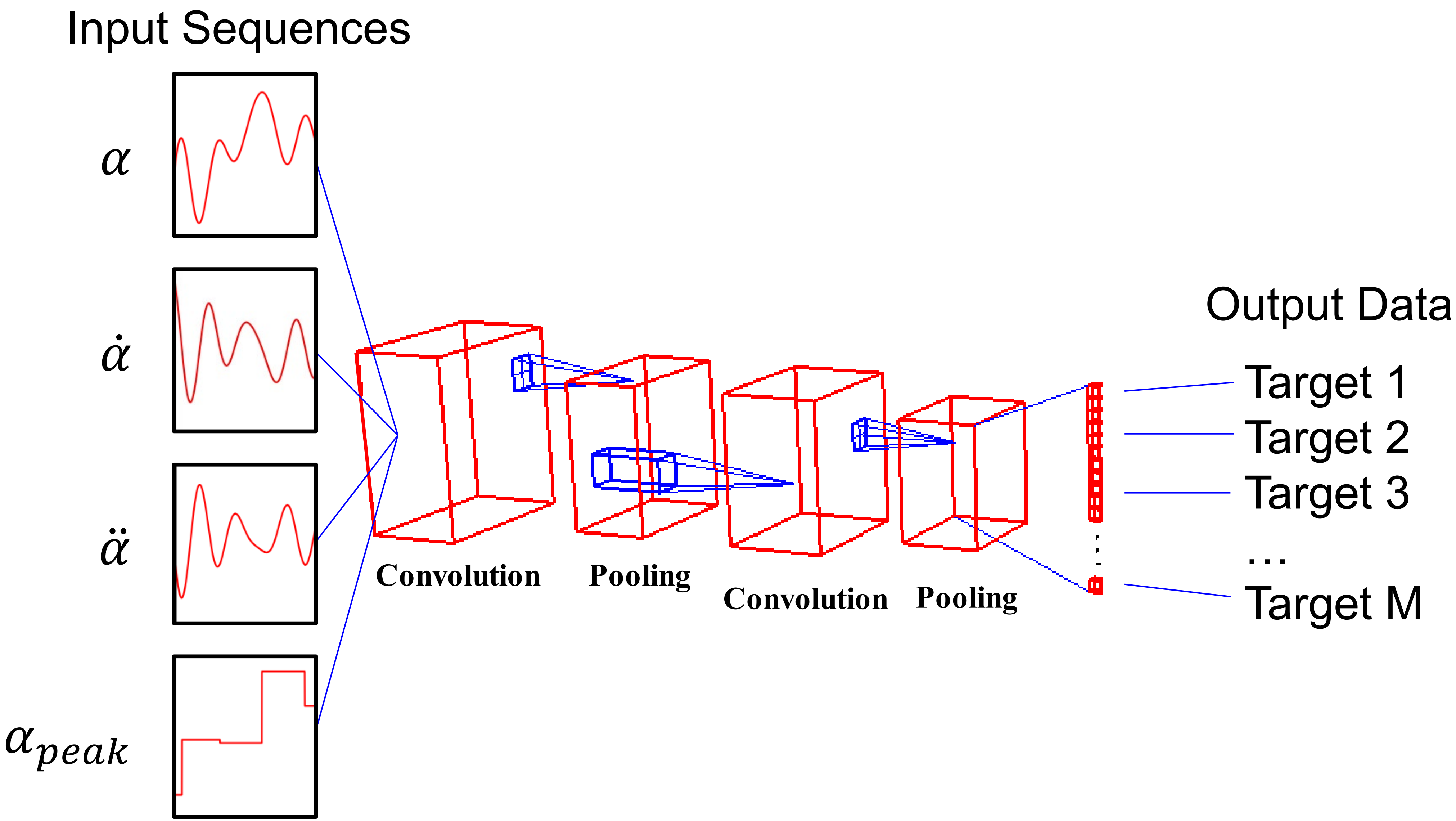


Convolutional Neural Network (CNN)

- A one-dimensional form of the CNN is employed in this effort
- The input time-history data are divided into sequences to train the model
- The target data are extracted at the next point in the sequence



CNN Architecture Illustration



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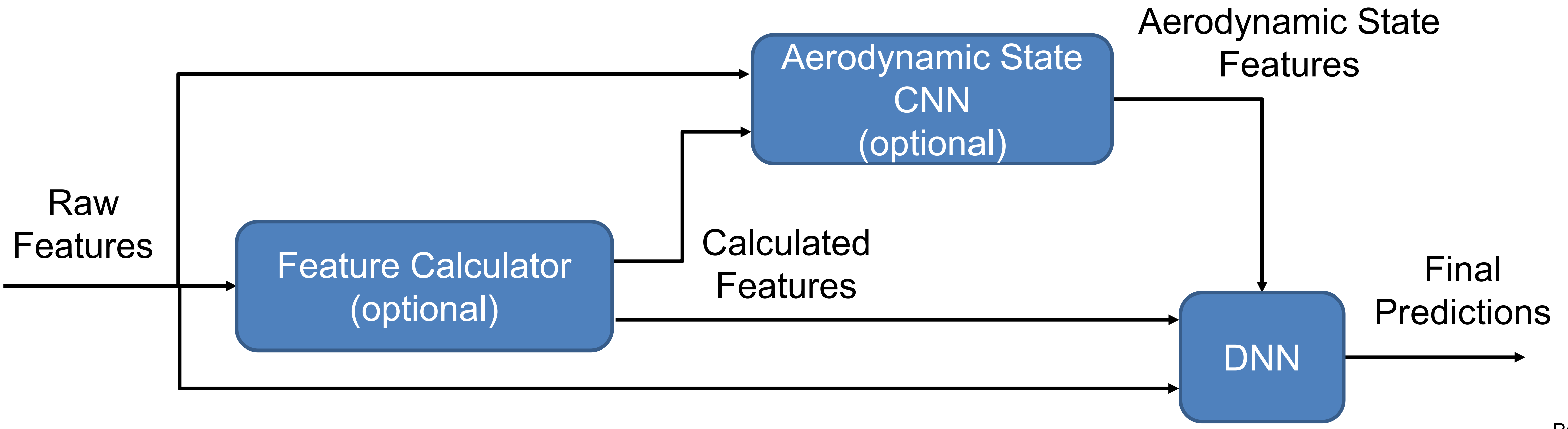
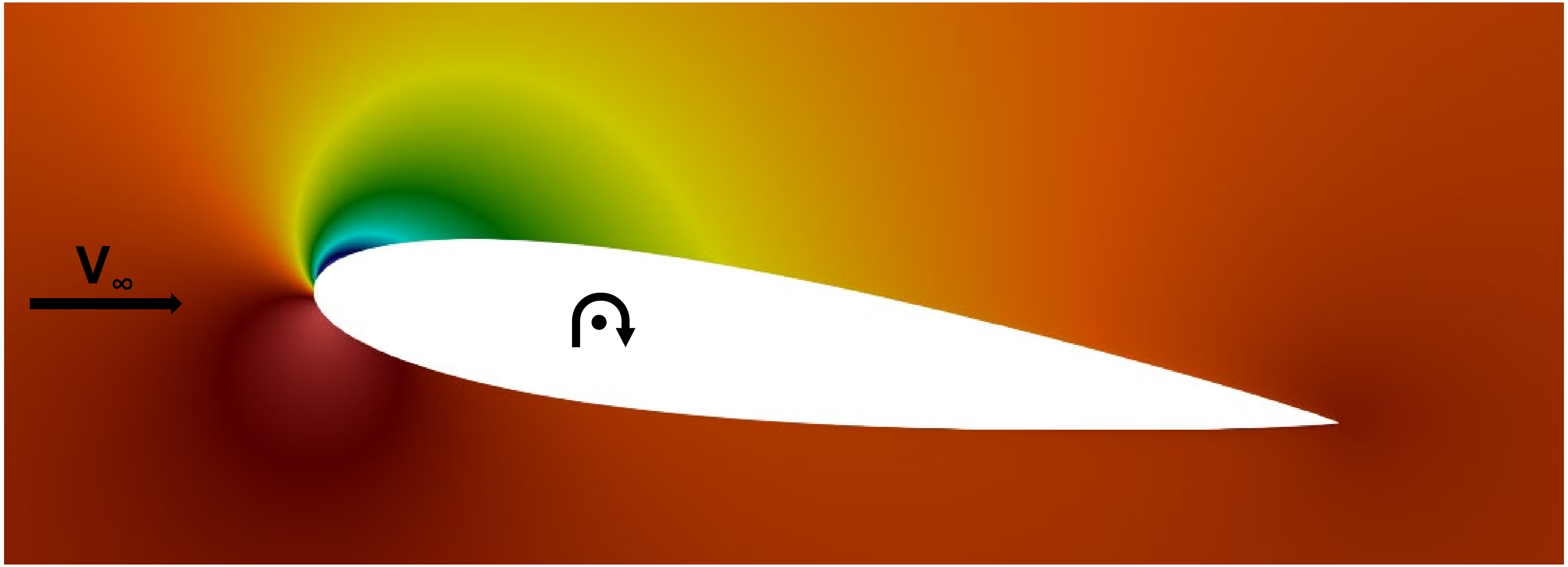
Dual Machine Learning Framework

- **The DNN and CNN are combined into a dual ML framework**
- **Inclusion of the aerodynamic state is beneficial for the prediction of loads where the contribution of more complex physics is a non-trivial factor**
  - The CNN is used to include the more complex physics behavior where needed
  - Use of the CNN is optional because for a majority of the use cases targeted the contribution of complex physics isn't a major factor in predicting sufficiently accurate integrated loads



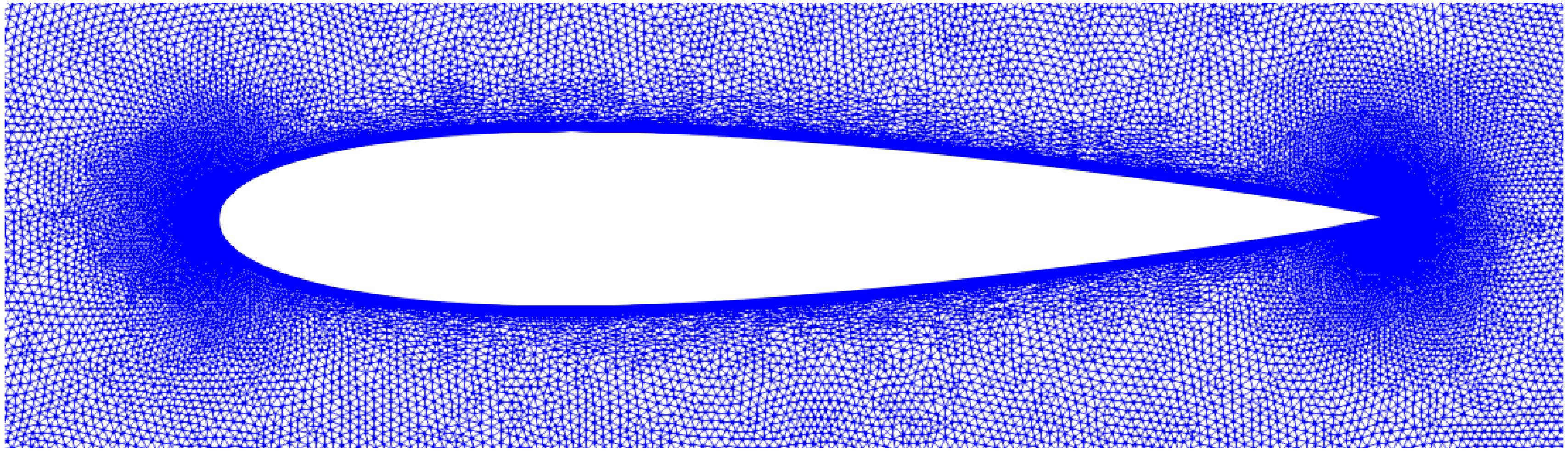
NACA0015: Problem Description

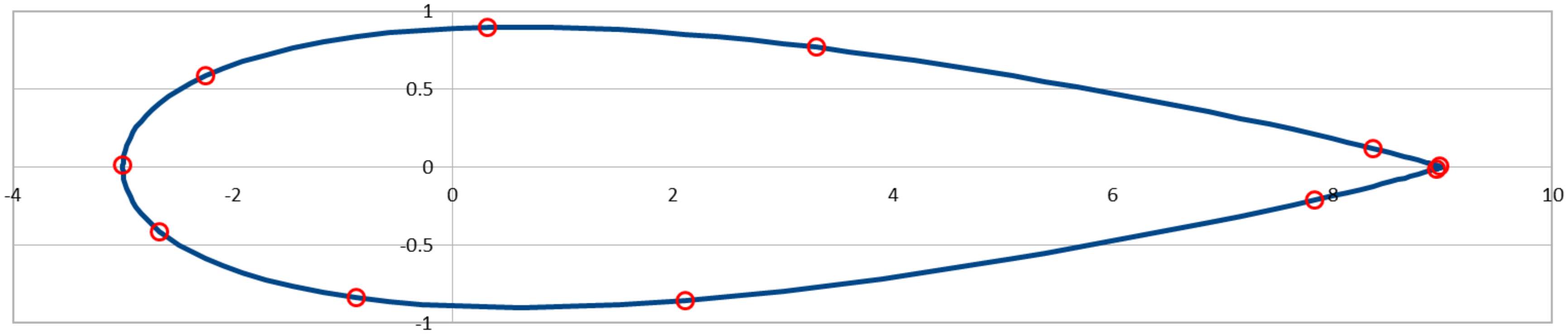
- **NACA0015 pitching airfoil about the quarter chord**
  - R. A. Piziali, “2D and 3D Oscillating Wing Aerodynamics for a Range of Angles of Attack Including Stall,” NASA-TM-4632, 1994
- **Case setup to match this report as well as to define parameter bounds for angle and frequency**
  - No comparisons to experimental data are intended



NACA0015: CFD Setup Description

- **Kestrel v12.1, 44 Procs (Onyx)**
- **2D Airfoil, 200 surface taps, 11 taps used for the ML study**





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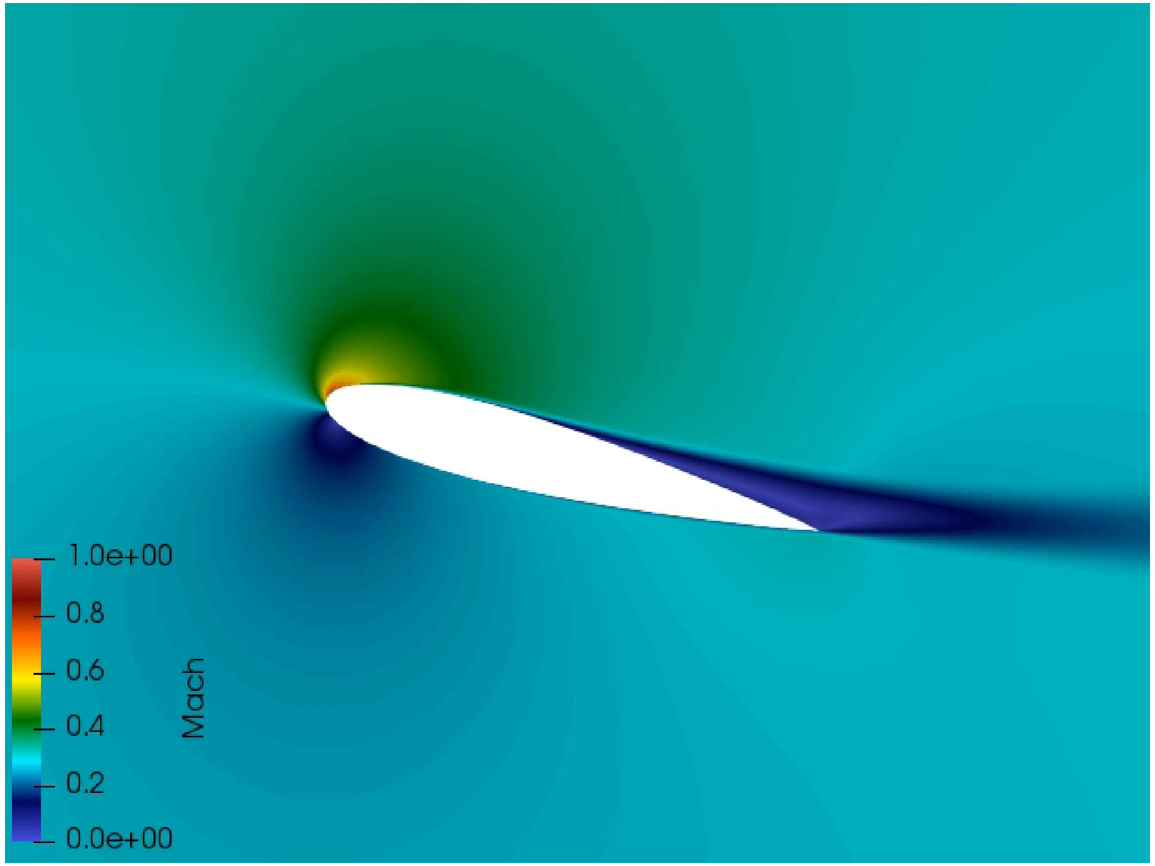
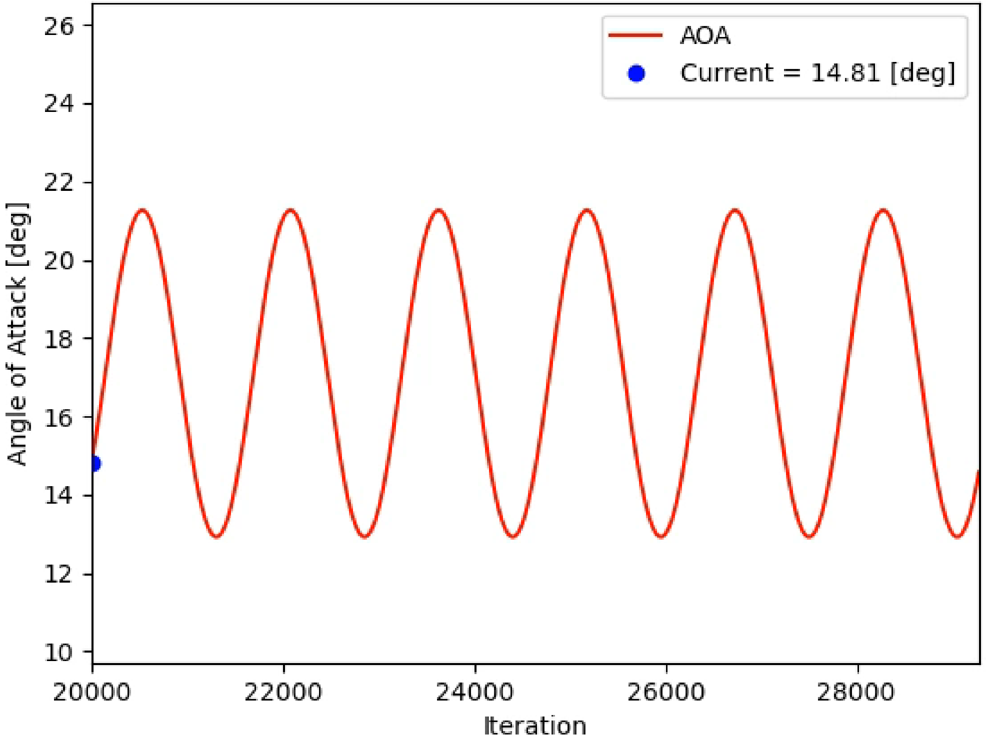
NACA0015: Simulation Illustration

- Illustrates the degrees of freedom for the setup
- Also provides an example of why predicting the aerodynamic state is sometimes needed



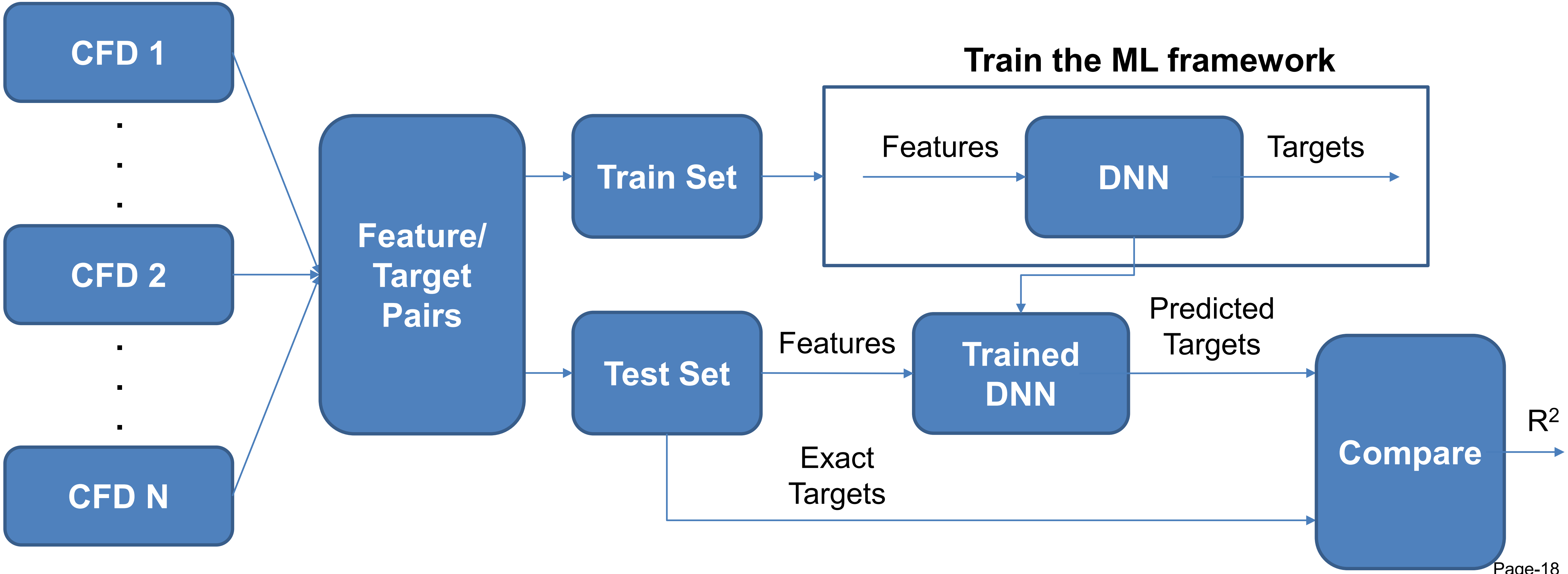


NACA0015: ML Model Setup

- **Input Features**
  - Case 0: α
  - Case 5: $\alpha, \dot{\alpha}, \ddot{\alpha}, \alpha_{Peak}$
- **Output Targets**
  - CNORMAL, CAXIAL, CPITCH
- **Case 0 is trained using steady CFD data**
- **Case 5 is trained using unsteady CFD data**

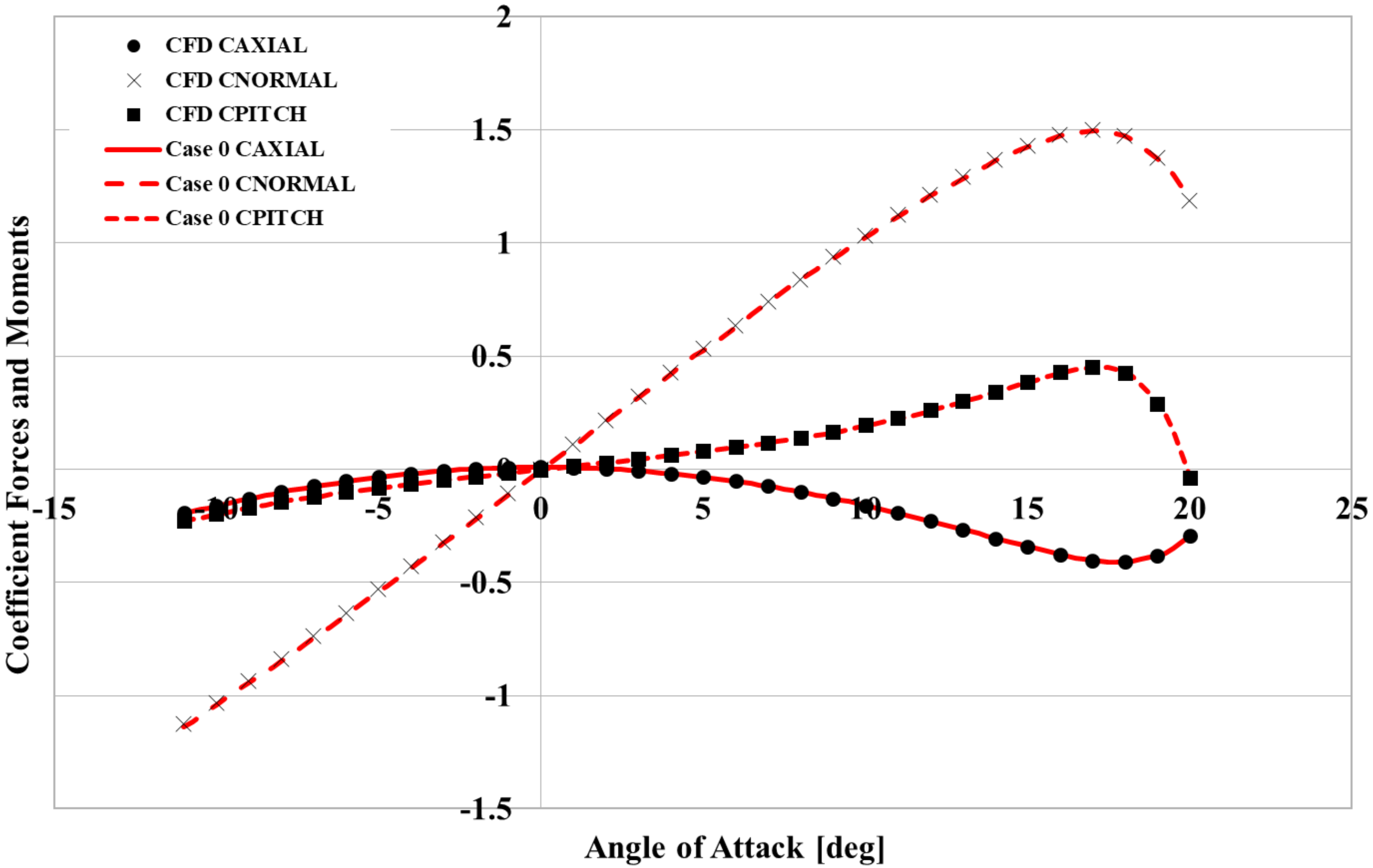
NACA0015: Training Workflow

- **Time-history data sourced from multiple CFD simulations**
- **Each iteration of each simulation is treated as an individual example**



NACA0015: Steady Train and Prediction Results

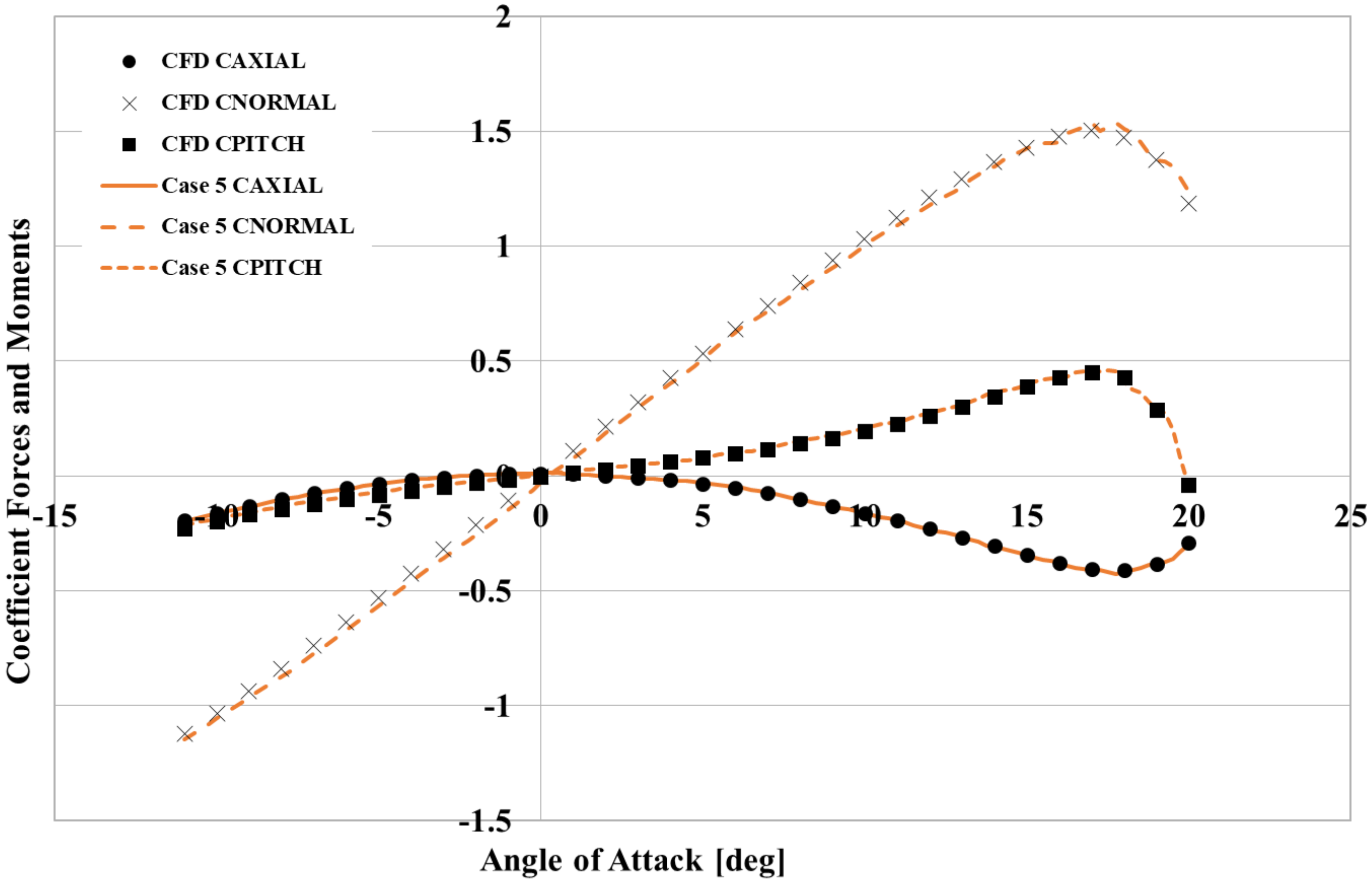
- **For the airfoil case the results are a good fit for Case 0 where only steady-state data are used to train the model**
- **In this database lookup type use case having only angle of attack as input is acceptable/preferable**



NACA0015	Case 0 (α)
Test Data Score	0.9998

NACA0015: Results using Unsteady Train Data

- **Steady predictions are still possible using the unsteady dataset**
- **Increasing the feature space to include rate and prior peak data is able to capture the steady angle of attack sweep**

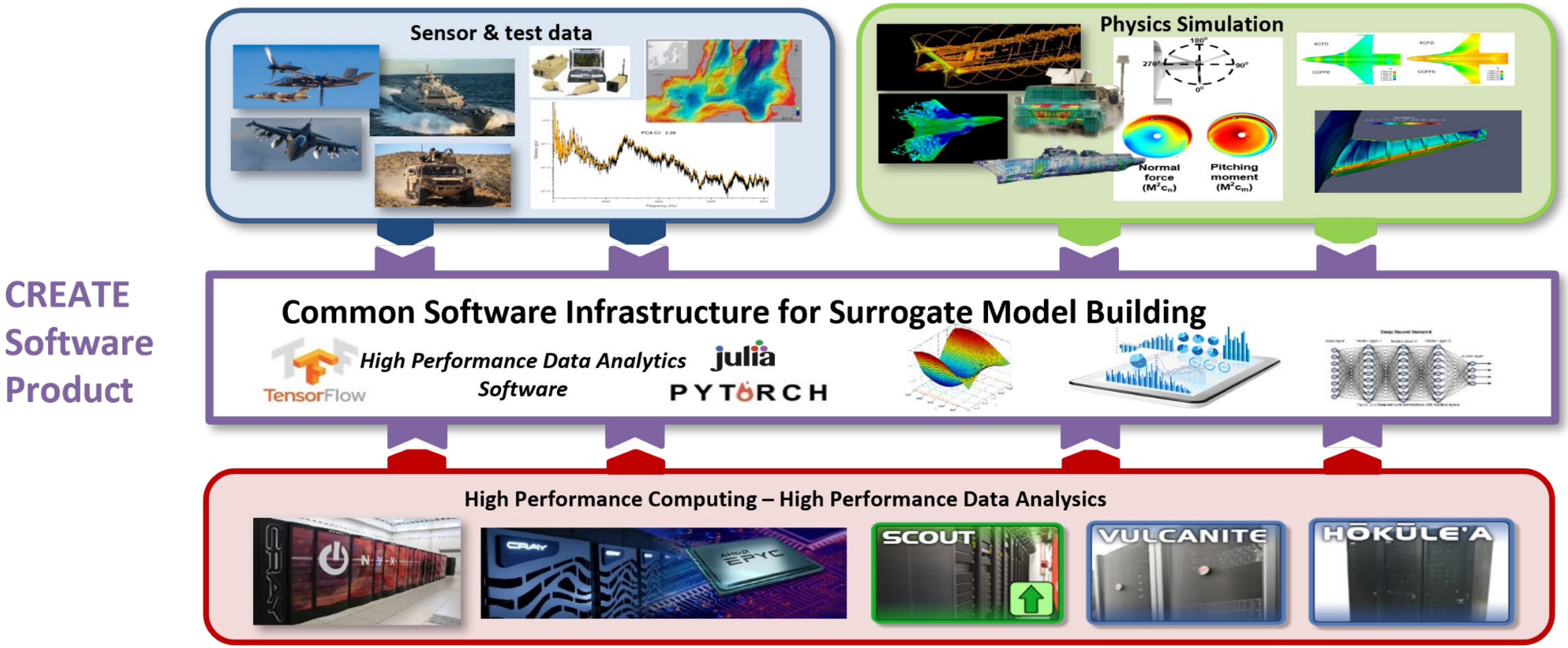


NACA0015	Case 5 $(\alpha, \dot{\alpha}, \ddot{\alpha}, \alpha_{Peak})$
Test Data Score	0.9452

Surrogate Building Infrastructure

Software infrastructure to enable *surrogate model generation from data-driven analytics and physics-based analytics for DoD Air, Land, and Sea Vehicles

*Surrogate = approximate model used when a full-physics computational model is intractable



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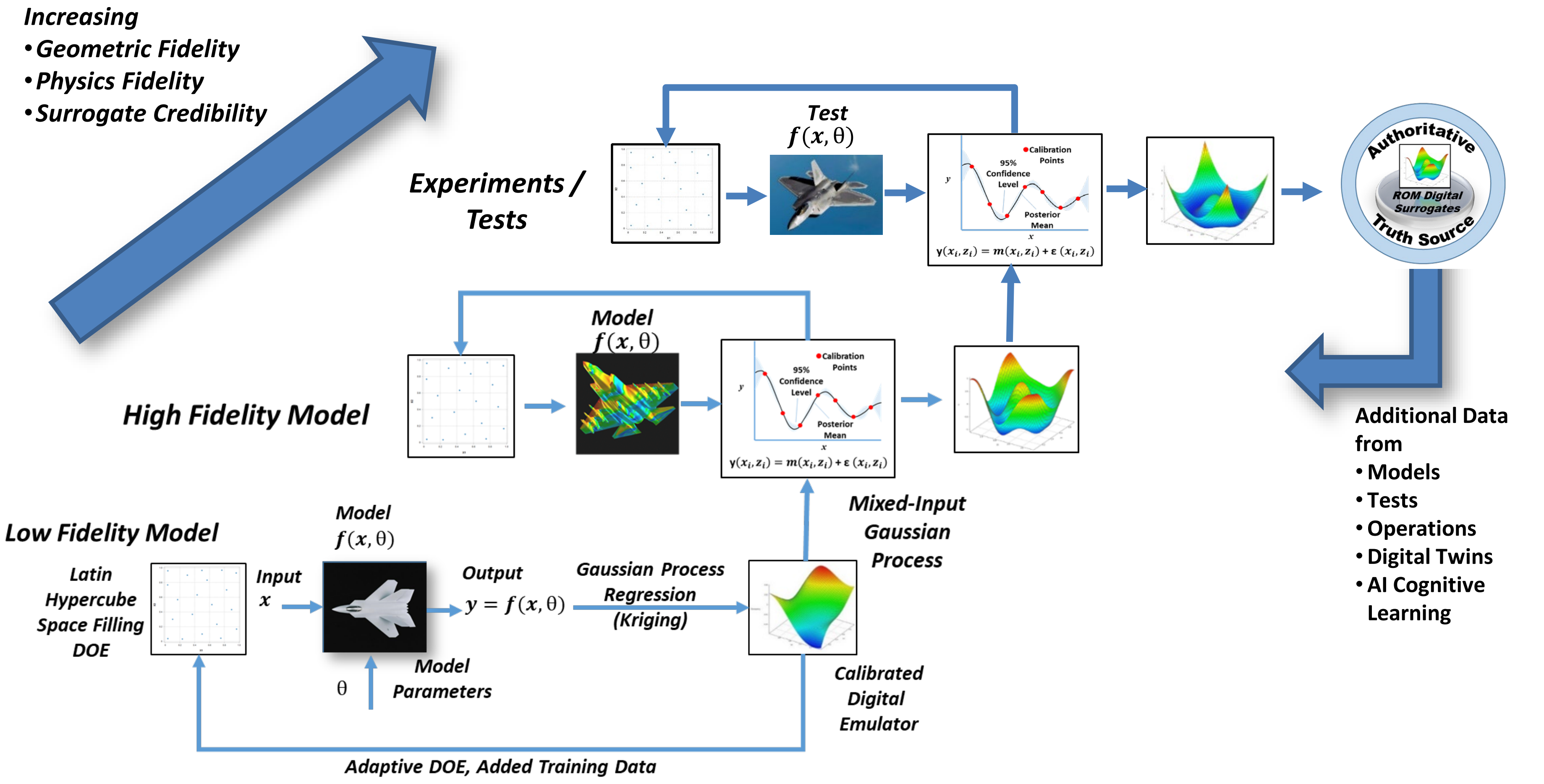
Developing an Authoritative Digital Surrogate Reduced Order Model for Aerodynamics



Edward M. Kraft, "Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source," AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

Concluding Remarks and Discussion

- The Connection between Physics Based Simulation and Useful Models for Model Based Systems Engineering have been described
- The union of Machine Learning and Digital Surrogate Training via Physics-Based virtual test is what will deliver decision support data at the speed of relevance
- A ML based surrogate model has been developed using a combination of Deep Neural Network based Machine Learning techniques
- A generalized framework that incorporates the novel ideas of aerodynamic state prediction can capture complex temporal variations
- The model has been validated for a number of 2D and 3D steady-state and unsteady cases
- Broader applicability to the aircraft system are underway to include more than just aerodynamics and across the vehicle envelope

Acknowledgements

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Questions?