

Development of a Wind Tunnel Digital Twin with Predictive Aerodynamic Capability

NWTF AI-Enabled Wind Tunnel Experiments Forum Imperial
College London

University of the West of England (UWE), Bristol

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Our Background

Legacy Hardware: Our main subsonic wind tunnel has been a reliable foundation since the 1960s.

High Upkeep: The facility has been very well maintained over the decades to ensure physical testing accuracy.

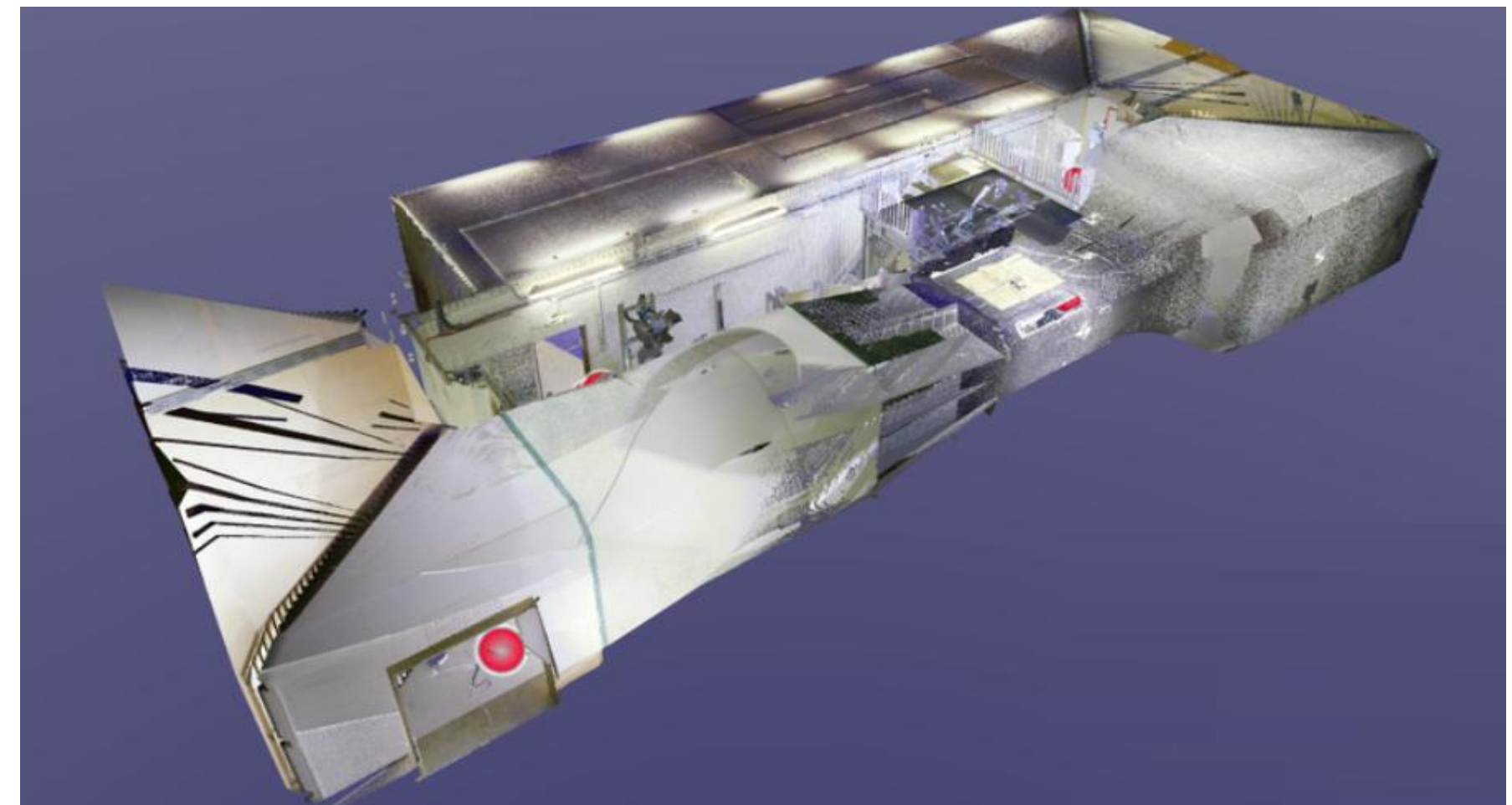
Modern Systems: We have recently implemented upgraded software to handle modern data collection.

Digital Mapping: We are using METENG's CAD scans to capture the exact physical dimensions of the tunnel.

The Next Step: We are now actively implementing a Digital Twin and AI to bring this classic facility to the cutting edge.

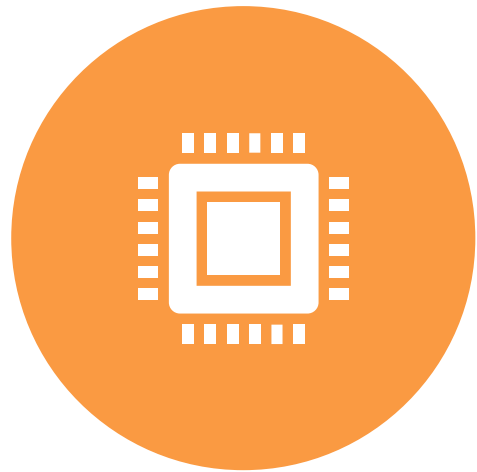


Lecturers at UWE Subsonic Wind Tunnel



METENG'S 3D CAD Scan of the whole Wind Tunnel

The Digital Twin: Architecture and Flexibility



Core Purpose: Augments physical wind tunnel testing with real-time predictive AI and statistical uncertainty estimation.



Operating Mode 1 (Real-Time Predictive Database): Predicts real-time aerodynamic loads using an internal wind tunnel database and active test-model telemetry.



Operating Mode 2 (Shape Optimisation): Predicts and guides physical shape modifications on the test model to mitigate turbulence.



Integrated Data Pipeline: Ingests live and historical data across both Computational Fluid Dynamics (CFD) and experimental wind tunnel runs via LabVIEW linked directly into MATLAB.

Pre-Processing, Denoising, and Force Coefficients

01

Noise and Anomaly Filtering: Custom pre-processing scripts in MATLAB eliminate raw sensor jitter, drift, and anomalous telemetry spikes.

02

Dynamic Pressure Normalisation: Computes real-time dynamic pressure across fluctuating freestream velocities.

03

Dimensionless Normalisation: Converts raw load cell forces into lift and drag coefficients.

04

Operational Agility: Enables predictions to generalise dynamically across a continuous envelope of Reynolds numbers, rather than memorising fixed test points.

Probabilistic Aerodynamic Modeling via GPR

01

Algorithm Formulation:
Employs Gaussian Process Regression (GPR) to model both linear and non-linear aerodynamic regimes.

02

Explicit Uncertainty Quantification: Simultaneously outputs the mean prediction and a continuous confidence interval.

03

Dynamic Stall Prediction:
Explicitly maps nonlinear separation boundaries, alerting operators to impending stall regimes based on expanding variance bounds.

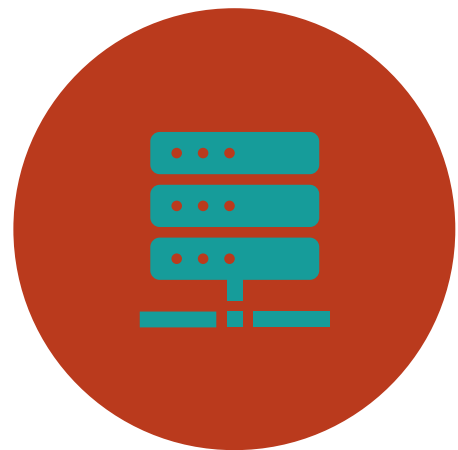
MATLAB Kinematic Renderer and Control Interlocks



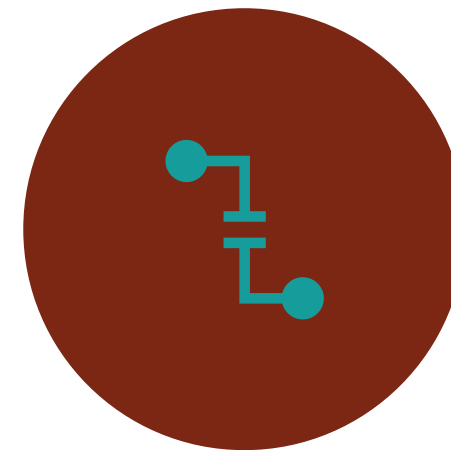
Live Kinematics: Powered by MATLAB's live kinematic rendering tools to project real-time aerofoil attitude and aerodynamic envelopes.



Dynamic Telemetry: Visualises real-time load changes and uncertainty bounds directly over the experimental data curves.



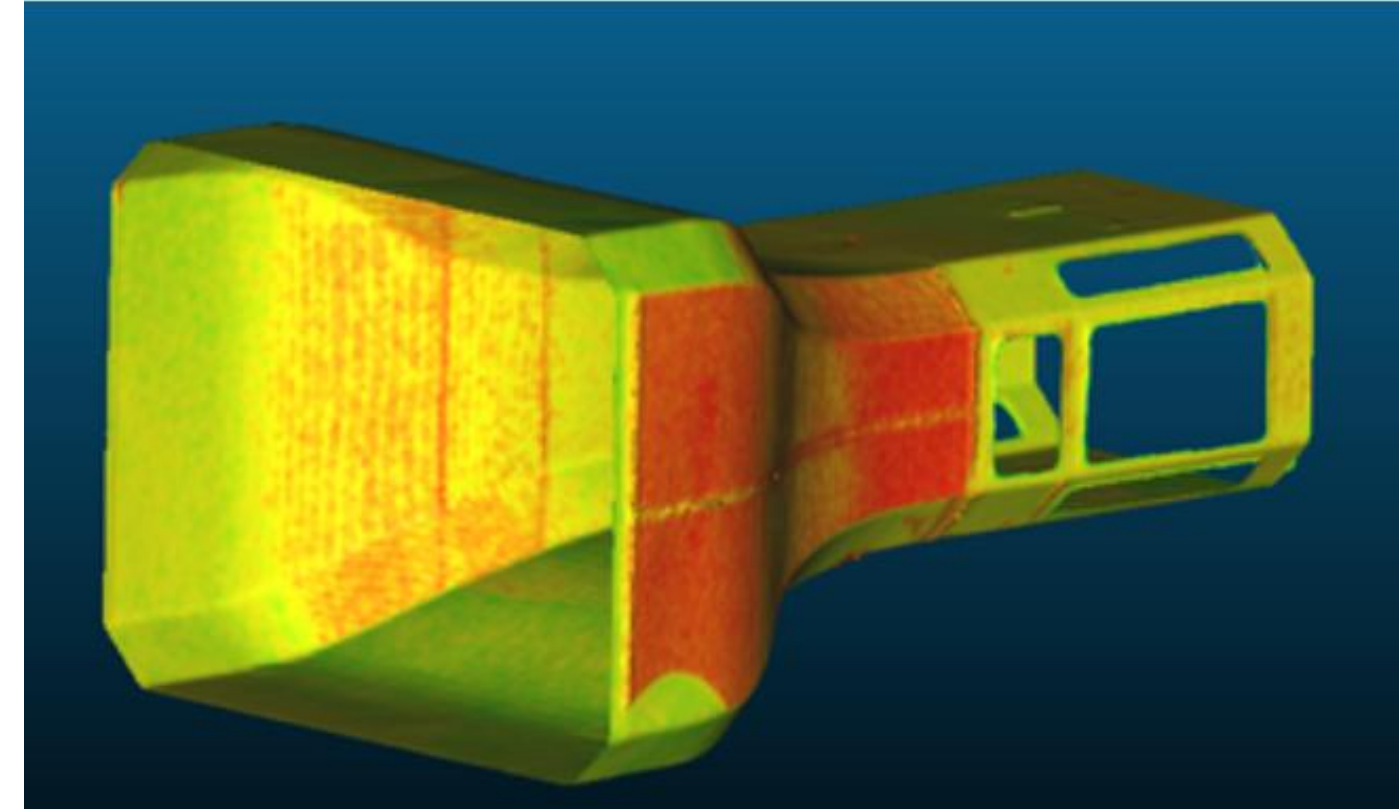
Automated Testing Suite: Implements an automated sweep across 60+ angle-of-attack increments, automatically logging validated CSV records.



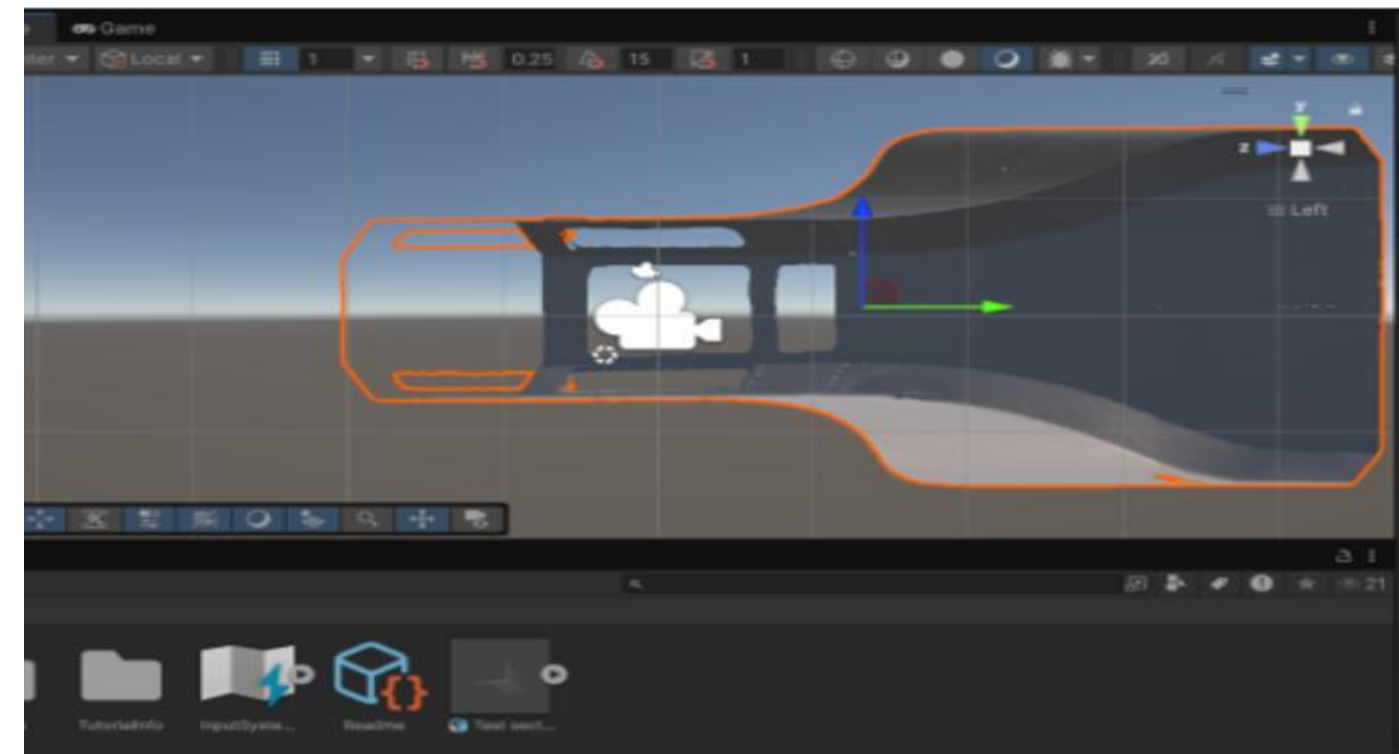
Interface Interlock: A hardware-level software interlock prevents the manual slider and the auto-sweep algorithm from commanding the system simultaneously, preventing data corruption during automated testing.

Bridging Computation and 3D Virtual Environments

- **Unity 3D Test Section:** Complete virtual geometry of the UWE subsonic contraction cone, working test section, and internal aerofoil mounts. (Unity is a real time 3D development software platform from Unity Technologies)
- **UDP Networking Bridge:** High-throughput UDP protocol continuously synchronises MATLAB's analytical calculations with the 3D Unity engine in real-time.
- **Bidirectional Interactivity:** Bridges the critical gap between raw computational data and the interactive virtual environment, enabling information exchange in real time.
- **Immersive Visualisation:** Renders interactive flow fields, dynamic mesh deformations, and spatial aerodynamic phenomena inside an authentic 3D environment.



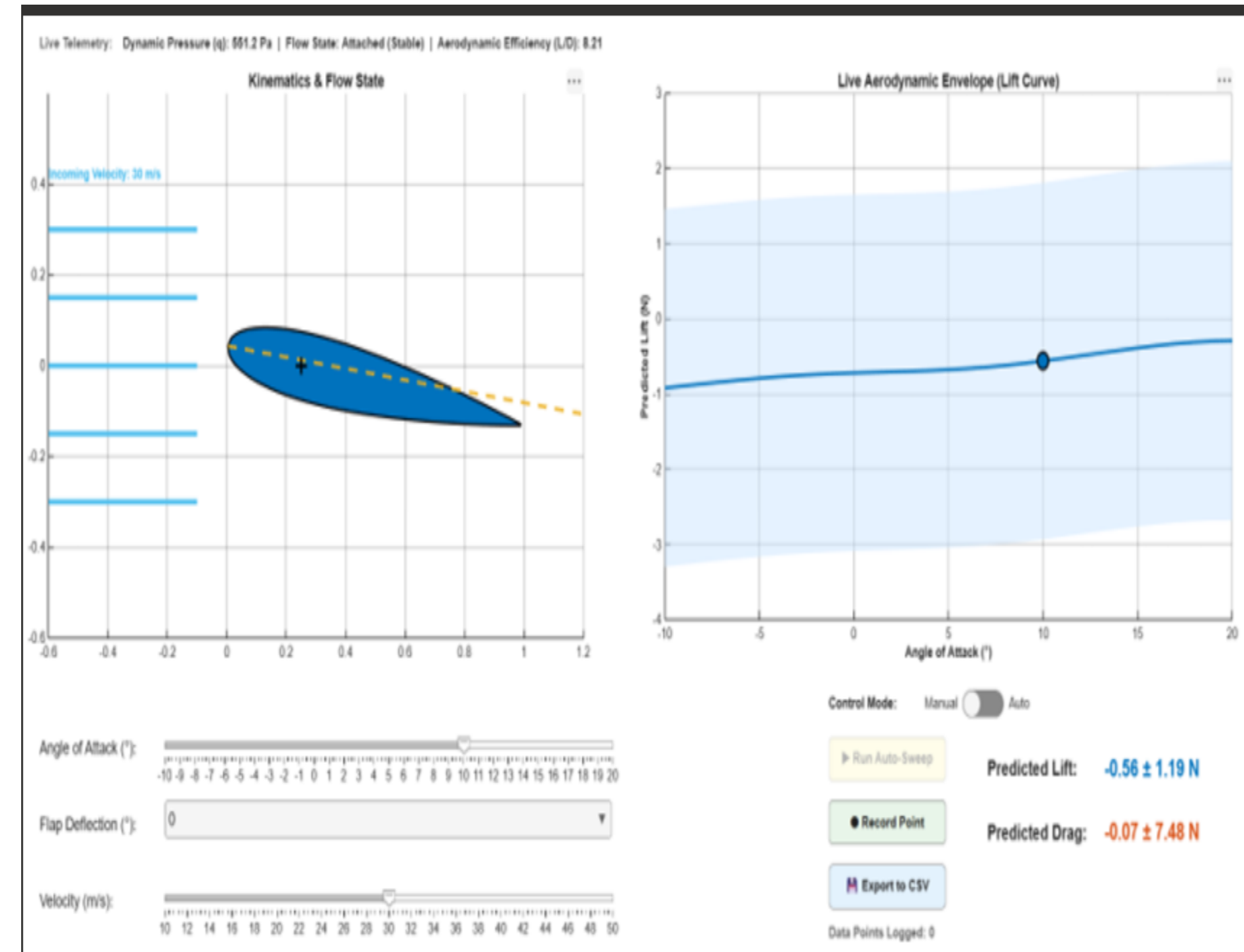
Optimised CAD and CFD of the Test Section



Test Section integration into Unity

System Validation and NWTF Scalability

- **Validation Benchmarks:** System testing on aerofoil data proves high accuracy, ranging from a few percent upwards depending on model confidence of nonlinear dynamic predictions.
- **Nonlinear Flow Tracking:** Accurately isolates dynamic stall behavior, tracking experimental bounds as confidence variance expands.
- **VR/XR Integration:** Future integration includes immersive virtual reality testing headsets and physical-to-digital hardware controller links.
- **Facility Impact:** Scales seamlessly across the National Wind Tunnel Facility network, lowering testing hours and optimising aerodynamic profiling through digital twins.



Digital Twin User Interface and Dashboard

UWE's Digital Twin Future: AI in our Wind Tunnel



The Vision: Growing our early digital twin into a smart, fully connected wind tunnel system.

Improving Airflow: Using METENG's CAD scans for CFD simulations. Using AI to help change the tunnel's inner shape to give us better flow quality.

Smart Hardware: Upgrading the facility with moving blades that adjust themselves in real time based on AI predictions.

Connecting New Equipment: Planning how to link our new physical tools, specifically the integration of a new traverse system and balance system, straight into the digital twin.

We have created a video that walks you through our development journey and showcases exactly where we currently are with the operational status of the digital twin.

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Questions and Answers

How much of the digital twin currently relies on AI?

The predictive core of the digital twin relies heavily on AI. We use Gaussian Process Regression (GPR) to actively predict aerodynamic loads and dynamic stall, filling the gaps between physical sensor readings in real-time. AI is used to drive the optimisation of the tunnel sections, by utilising METENG's CAD scans alongside CFD simulations, the AI predicts geometric shape changes to the tunnel's inner walls to actively reduce turbulence and improve overall flow quality.

Is AI going to be used more in the future?

Yes, significantly. Our plan transitions AI from a purely predictive tool to an active control system. We are planning to use AI for shape optimisation to dynamically alter the tunnel's inner geometry and to drive adaptive hardware to improve quality.

What sort of accuracy have you found with GPR?

Within the linear, attached flow regime, we are seeing high accuracy, typically within a few percent. When entering the nonlinear dynamic stall regime, the system accurately tracks experimental bounds, using its expanding confidence variance to reliably map where the flow becomes chaotic.

Why GPR?

Unlike standard neural networks that provide a single

How far across the Mach number and angle of attack range has this been tested? Testing covers the full operational envelope of our subsonic tunnel, up to approximately Mach 0.15. Within this regime, we ran automated sweeps across 60+ angle-of-attack increments, pushing the aerofoil from clean, attached linear flow into deep stall.

How much of an advantage has shape optimisation been?

Shape optimisation is central to our second operational mode. By combining METENG's CAD scans with CFD, the AI predicts how to alter the tunnel's inner shape to actively reduce turbulence. This improves baseline flow quality, allowing for much cleaner physical data collection. In the contraction cone area, optimisation reduced both vorticity and swirl by 10% for fixed Mach number.

How can this system improve current testing with complex geometries in real-time?

Testing complex models is highly siloed: physical data is logged slowly, and CFD is run separately offline. This digital twin bridges that gap via our UDP network. By having MATLAB handle the GPR and streaming it to Unity, engineers can interact with complex geometries, view dynamic mesh deformations, and see real-time flow fields instantly, drastically reducing overall testing hours.

Do we know the turbulence level of the tunnel?

0.7%

Have you tried other AI methods?

Yes, we have tested several standard machine learning methods across a variety of studies for our subsonic wind tunnel and CFD data. While GPR is fantastic for uncertainty quantification, we found that the Random Forest method consistently produced the lowest overall error, both within defined aerodynamic regimes and when scaling across multiple regimes.

When do you think this will be completed by?

This is an ever-evolving project, and hopefully it will be integrated modularly so it can be used whilst being expanded upon. Ideally built and integrated fully within the next 2-3 years.