



Probabilistic Digital Twins for Bridges: From Reactive Repairs to Predictive Resilience

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The Challenge: Our Aging Infrastructure

- A significant portion of global bridge infrastructure is operating near or beyond its original design life
- Traditional management relies on periodic, manual inspections, which are subjective, costly, and inefficient
- Critical damage (e.g., internal corrosion, fatigue cracks) can go undetected in the long intervals between inspections
- This reactive approach leads to higher repair costs, unexpected disruptions, and significant safety risks

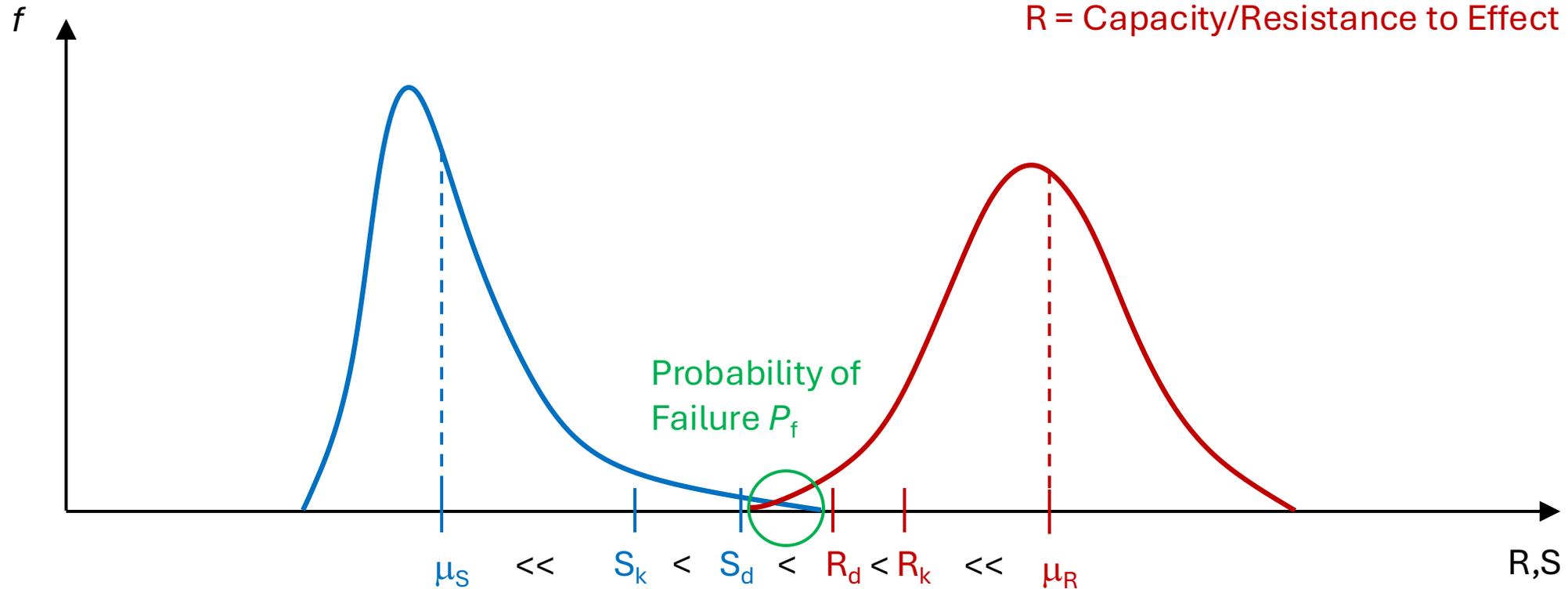




The Probabilistic Way of Thinking

S = Effect (bending, shear, flow, etc.)

R = Capacity/Resistance to Effect



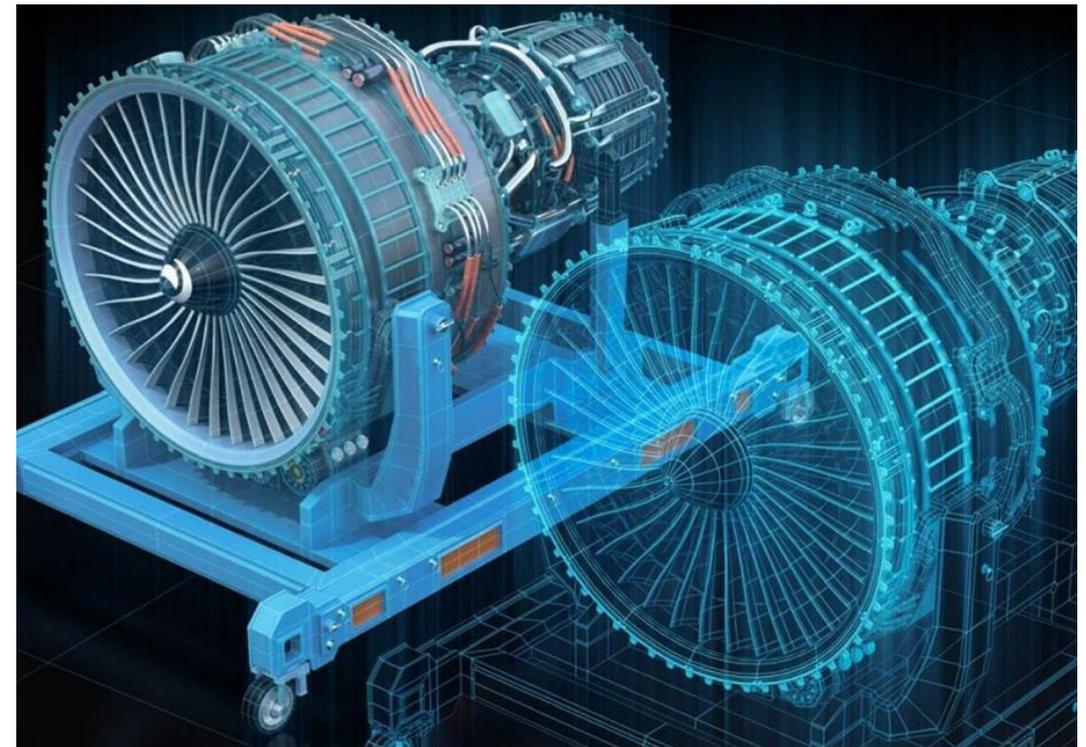
Getting the Data: Structural Health Monitoring (SHM)

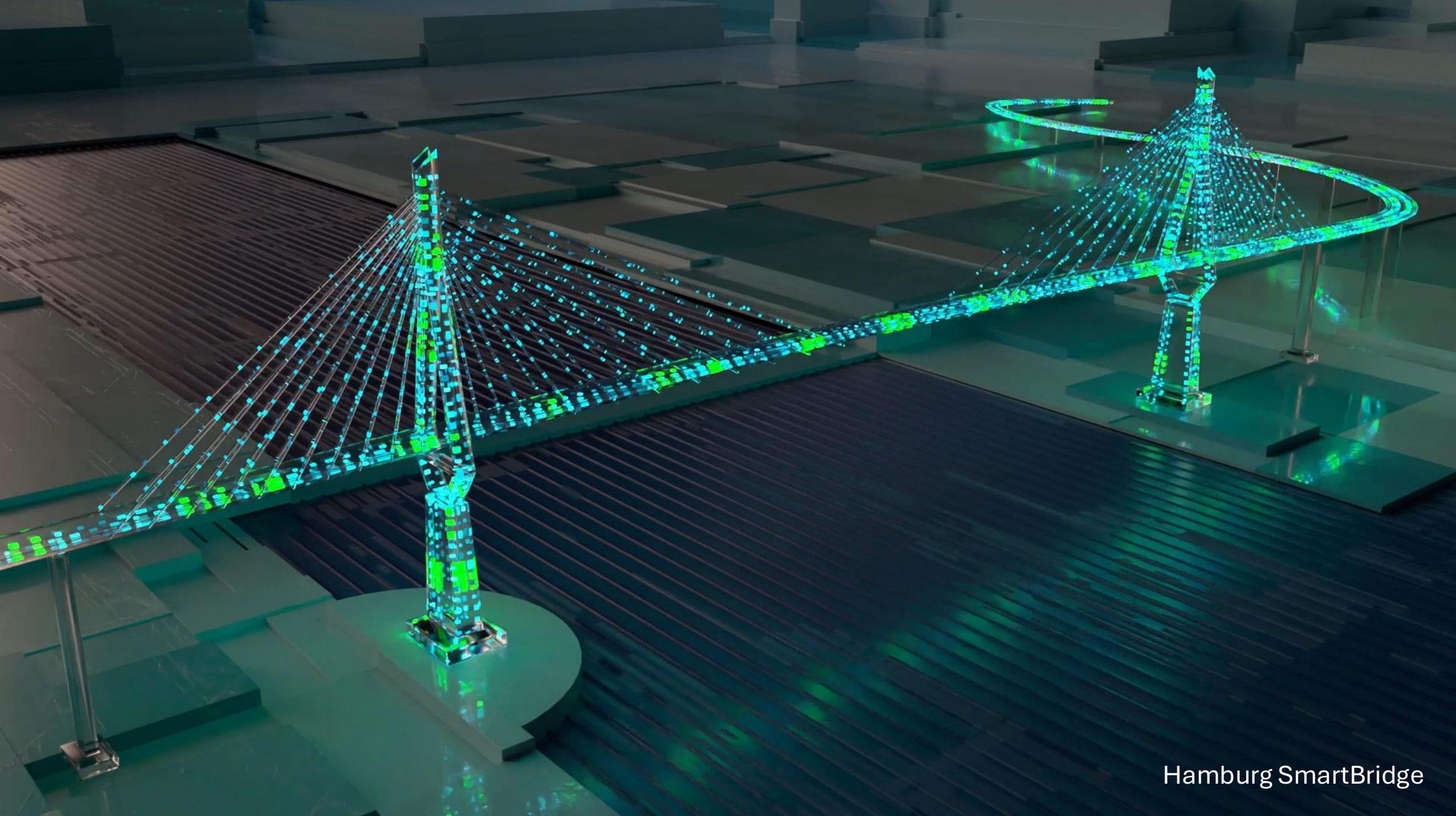
- **What is it?** SHM is the process of instrumenting a bridge with sensors to continuously monitor its performance and condition in near real-time
- **What does it measure?** Key parameters like strain, vibration, displacement, temperature, and corrosion
- **The Key Benefit:** It enables a fundamental shift from inefficient, schedule-based maintenance to highly cost-effective, condition-based maintenance
- **The Result:** Enhanced safety, optimized maintenance spending, and extended asset service life



Your BIM Model Enhanced: The Digital Twin

- Your teams are (likely) already proficient in BIM/BrIM – a rich, but typically static, 3D model with associated data
- A **Digital Twin** is the next evolution: a “living” virtual replica of the physical bridge
- **The Critical Difference:** A Digital Twin is **frequently and automatically updated** with the real-time data streamed from the SHM system
- This creates a continuous, two-way data connection—a "digital thread"—between the physical asset and its virtual model

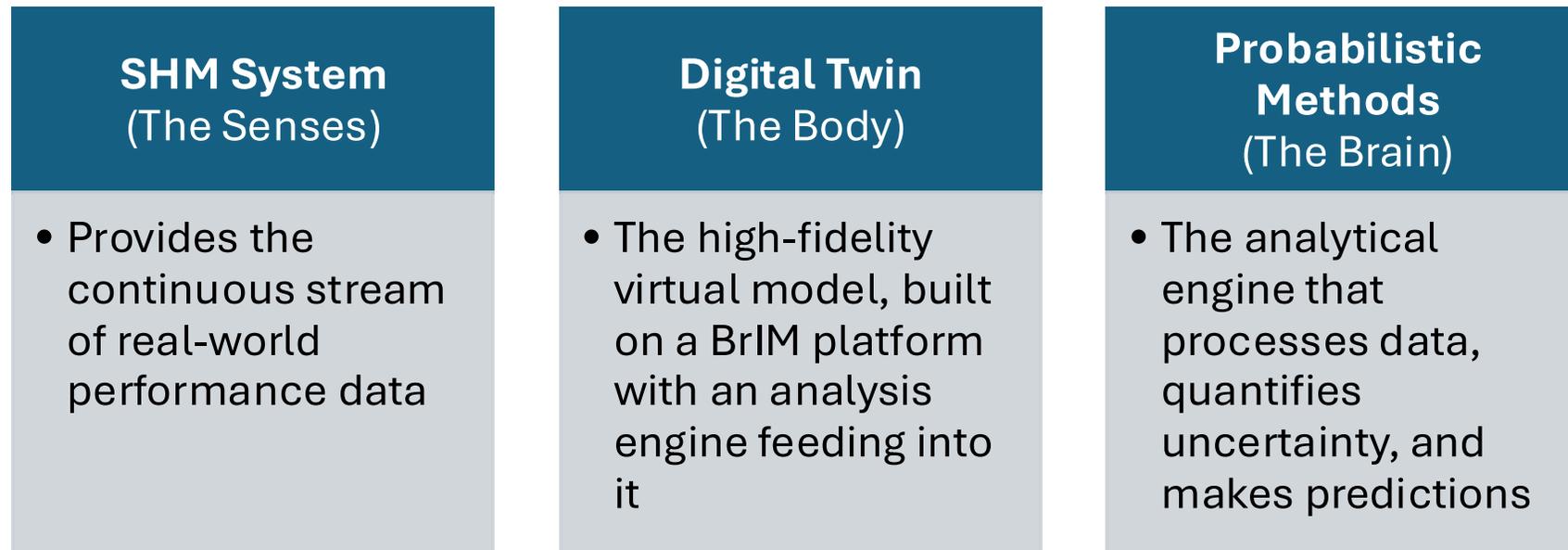




Hamburg SmartBridge

What is a Probabilistic Digital Twin (PDT)?

The fusion of three powerful concepts



It doesn't just show the current state; it answers the crucial question: **"What is the likelihood of a future problem?"**

How It Works: The Continuous Learning Loop

Forecast: This refined, highly calibrated model is used to run thousands of future scenarios and predict the probability of future issues.

Physical Asset

Start: An initial physics-based model (FEM) is created with prior uncertainties about its properties

Decision & Action

Sensor Data

Measure: The SHM system streams real-world performance data from the bridge

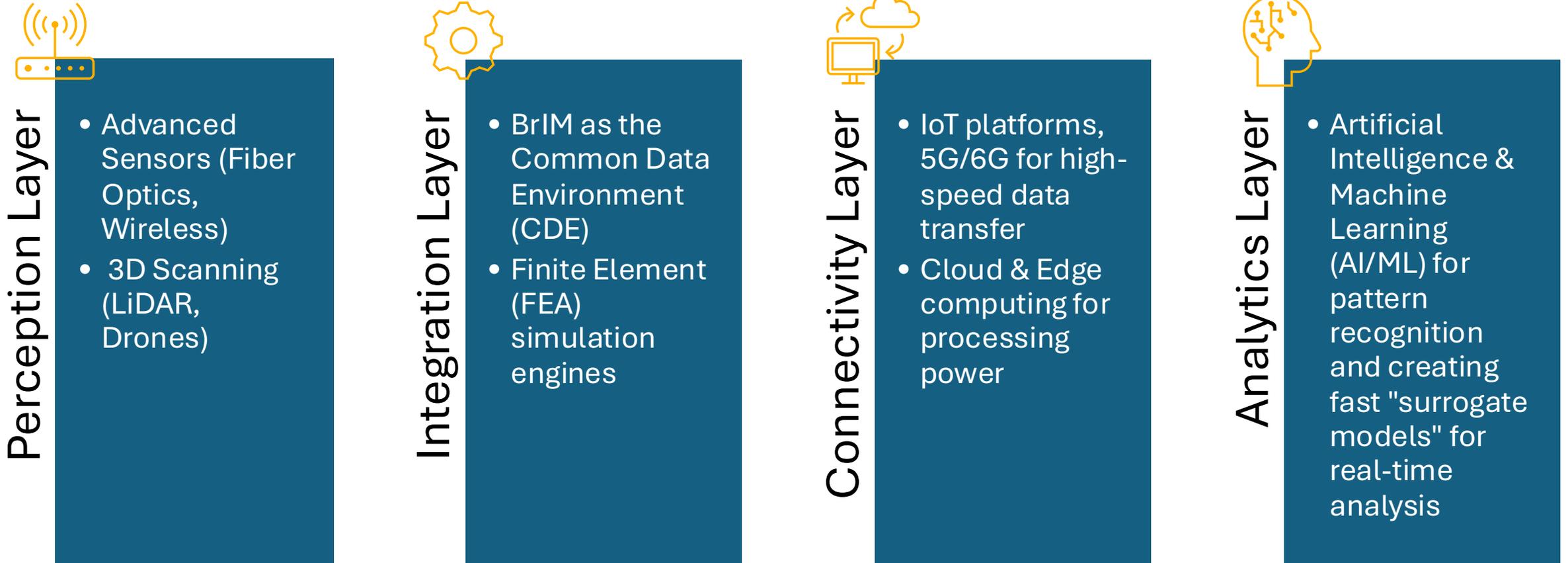
Update (Bayesian Inference): The model's parameters are probabilistically updated to better match reality. The model's uncertainty is reduced.

Probabilistic Analysis

Digital Twin

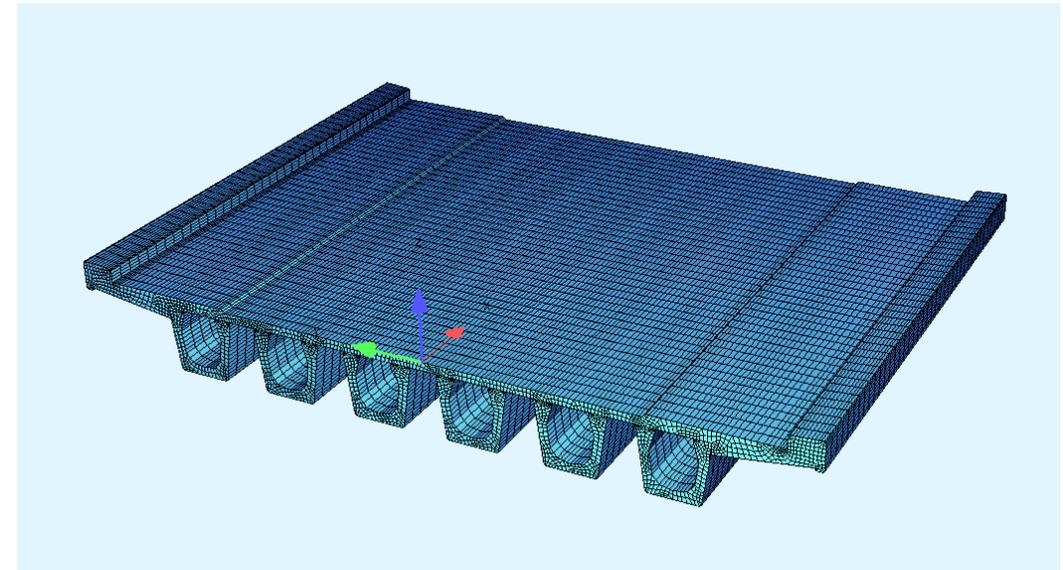
Compare & Learn: The model's predictions are compared to the real data

The Technology Ecosystem



Real-World Application: The PRODIGI Project

- **Project:** PRODIGI (Probabilistic Digital Twins for Bridges) in Ireland
- **Goal:** To enhance bridge maintenance by developing a PDT for a major piece of national infrastructure
- **Test Case:** N7 Road Overbridge
- **Aim:** To demonstrate the practical benefits of using probabilistic models for the routine care of critical infrastructure, moving this technology from academic theory to real-world practice



Key Implementation Challenges

- **Computational Cost:** Running complex probabilistic simulations in near real-time is computationally demanding and can be a bottleneck
- **Data Interoperability:** The “digital thread” is often broken
 - Getting BIM, FEA, and various IoT platforms to communicate seamlessly remains a major industry challenge
- **Model Validation:** How do you prove the twin's predictions are accurate? This requires rigorous, ongoing validation against physical reality

All models are wrong, but some are useful...

...and some are more useful than others.

- **Skills Gap:** This new paradigm requires a blend of expertise across civil engineering, data science, and IT

The Future Trajectory: Towards Intelligent Infrastructure

- The PDT is a step on a path to increasingly autonomous asset management
- **Predictive Twin (Today):** “What is the likelihood of a problem?”
- **Prescriptive Twin (Near Future):** “What is the best action to take to mitigate it?”
- **Cognitive Twin (Long-term Vision):** An autonomous system that can “sense-analyse-act” with human engineers shifting to a role of oversight and management-by-exception
- This will scale from single assets to **Network-Level Digital Twins** for system-wide optimization and resilience.

Summary & Key Takeaways

- The old “inspect and react” model for bridge management is broken...not working as well as it could; we need a **proactive, data-driven approach**
- A Probabilistic Digital Twin (PDT) is the synthesis of SHM (data), Digital Twins (platform), and Probabilistic Analysis (intelligence)
- It moves beyond simple digitalization (like BIM) to create a “**living**” **prognostic engine** that learns and improves over time
- The ultimate benefit is enabling **risk-informed decision-making** to enhance safety, optimize maintenance spending, and extend the life of our critical infrastructure



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