

Advancements in Structural Health Monitoring through Robotics, Design Principles, and Digital Twin Technologies for Robot-Inspectable Structural Design:

A Roadmap for Comprehensive Structural Health Monitoring

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Research Background

Structural Health Monitoring

- The use of on-structure sensing system to monitor the performance of the structure and evaluate its health state (ANSHM).



SHM Purpose:

- Assess structural conditions (Sarma, Chanda & Reddy 2025)
- Detect damage early (Cha et al. 2024)
- Ensure safety (Zhang et al. 2025)
- Assess performance, and longevity throughout the life cycle while optimizing maintenance plans and support decisions (Plevris & Papazafeiropoulos 2024).

SHM Design Principals

Physical Design	Sensor placement (Sun et al. 2025), robustness, durability (Chin et al. 2024)
Measurement (Mariani, Liu & Cawley 2021)	Sensitivity, calibration, coverage
Data & Information Design (Hassani et al. 2024)	Signal quality, damage detection, decision support
System & Lifecycle Design (Wang et al. 2024)	Maintainability, scalability, cost-efficiency

Research Background

Robotics in Structural Health Monitoring

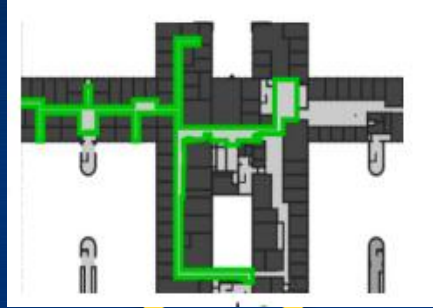
- Highly adaptable collaborative robotics systems that offer:

Customisable Payload



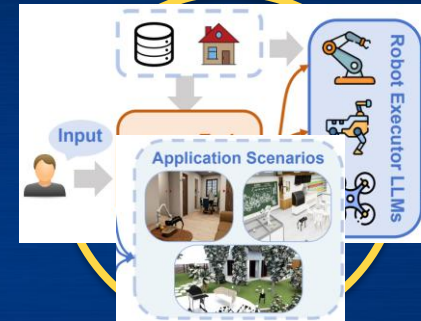
Lindqvist et al. 2022

Mobility and Adaptability



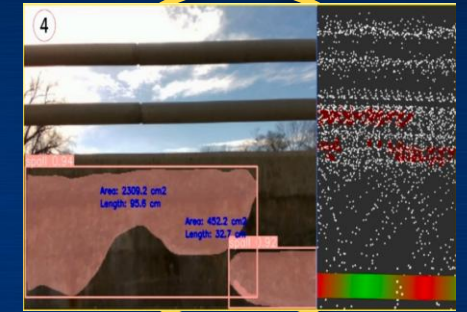
Chen et al. 2025)

Cooperation



Liu et al. 2024

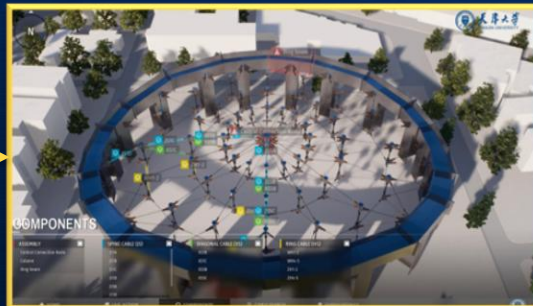
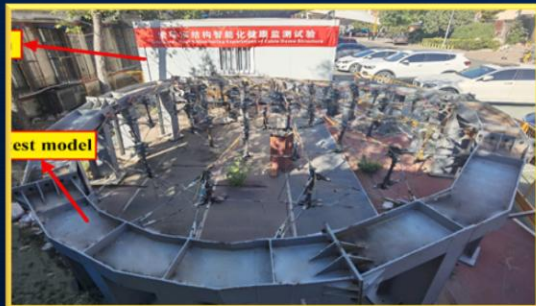
Intelligent Adaption



Ge & Sadhu 2025

Visualisation

- Minimizes manual inspections by integrating multi-source data into an interactive digital twin that enables easy decision-making, simulation, and prediction (Wang et al. 2024; Xu et al. 2026).



Wang et al. 2024



Xu et al. 2026

Problem Statement



Structural Health Monitoring

- Current systems suffer from limited sensor coverage, leaving parts of structures unmonitored (She et al. 2025).
- There are no established standards for optimal sensor placement or SHM systems.
- These limitations reduce accuracy, increase deployment costs, and hinder large-scale adoption of SHM (Shaikh et al. 2025).



Robotics in SHM Context

- Most current approaches are **reactive** not **proactive**.
- Rarely integrated into the design phase (Zargar et al. 2025), limiting efficiency and seamless implementation.
- Existing methods often target either built or operational structures, with little integration of structure's lifecycle (Halder & Afsari 2023).



Visualisation

- Limited combination of design, robotics, and SHM with no common data standards (Li et al. 2026).
- High computational demands and poor scalability for large structures (Wang et al. 2024).
- Challenges in synchronising live data and ensuring quality/fused information (Xu et al. 2026)



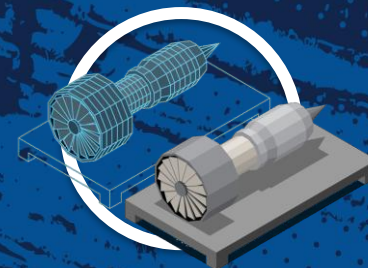
Research Question 1: **Design Principals for Robot Integration**

How we can we leverage design principals in SHM and structural design techniques for the integration of robotics in the early design stage?



Research Question 2 **Lifecycle: Proactive Monitoring & Maintenance**

How can robotic systems be integrated into the lifecycle of a structure to enable proactive continuous monitoring and maintenance?



Research Question 3 **Digital Twin as SHM Visualiser**

How can we justify using digital twin to visualise complete structural monitoring systems?



Research Objectives

Multi-Objective Optimization

- Formulate a balanced optimization framework that simultaneously considers mechanical performance (stiffness, weight minimization, stability) and inspection efficiency (coverage, accessibility, visibility), producing robust and practical designs.
- Develop topology optimization methods that embed visibility metrics (isovists, ray-casting, coverage analysis, etc) into the design loop, ensuring that structural forms are not only efficient but also fully inspectable by mobile robots and drones.

Robot-Integrated Structural Health Monitoring (SHM)

- Using structural geometries that inherently facilitate robotic inspection, enabling seamless integration of autonomous ground and aerial robots for continuous health monitoring, defect detection, and digital twin updating.
- Support the long-term deployment of robotic SHM systems by creating designs that inherently allow efficient scanning, monitoring, and data capture.

Computational Load Reduction

- Manage large data streams from sensors and inspection robots efficiently.
- Apply simplified representation models (surrogate models, reduced order models) to approximate visibility and structural responses.
- Use machine learning for rapid prediction of inspection and performance metrics for digital twin updating.

Towards Sustainable Infrastructure of Complete Systems

- Reduce lifecycle inspection costs by designing structures that are easier to maintain and monitor.
- Enable the integration of digital twins and AI-driven SHM into civil infrastructure from the earliest design stages.

PROPOSED METHODOLOGY



Design

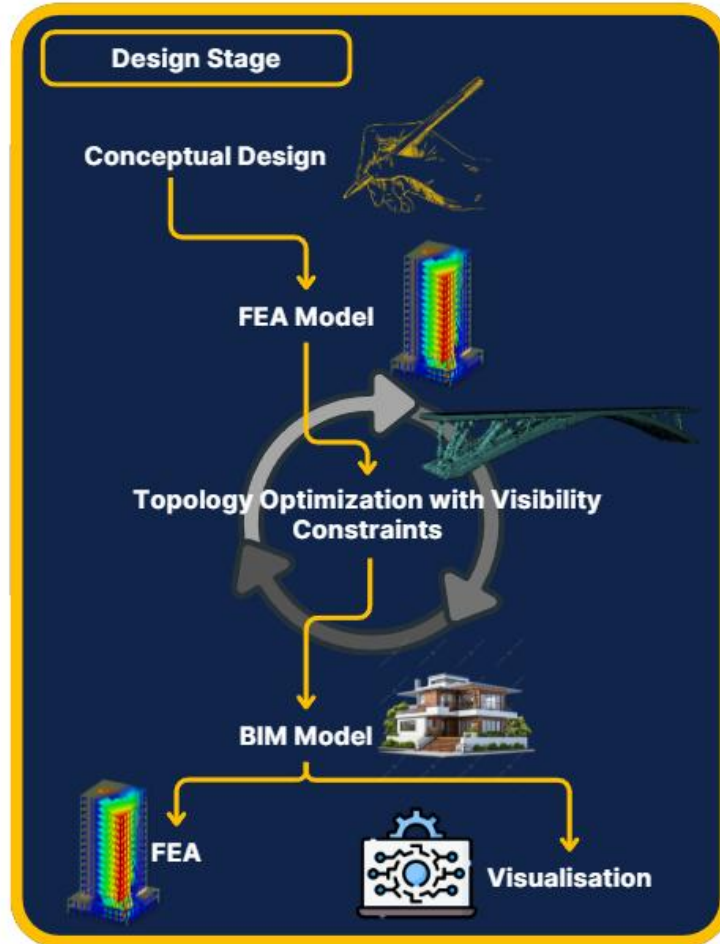
SHM Data Management

Robotics

Visualisation

- Create structural designs optimized for robotic inspection
- Produce a SHM plan that can be optimized for performance, and digitally integrated for sustainable, cost-effective continuous infrastructure monitoring of that said structure.
- These stages aim to deliver technical, operational, and sustainable outcomes by addressing gaps.

METHODOLOGY - Design



Design Aspect: Incorporate Robotics' awareness into optimization framework for greater visual inspections and coverage.

Aim: Quantify visibility into Topology Optimization Framework, to create structures that maximise functionality (visibility, strength) and minimise material usage.

Proposed Methodology:

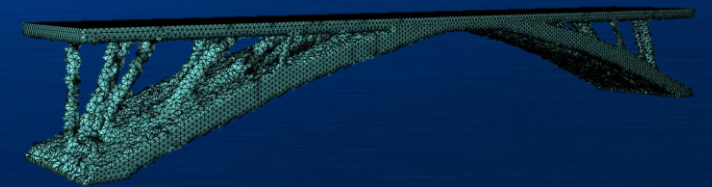
- Modifying the constraints/objectives in a multi-objective topology optimization framework

How to quantify visibility?

- Isovist: visible area from a single point
- Ray-casting: detects visible surfaces
- Visibility graph analysis: grid-based sightline network
- Viewshed: terrain-based visible zones
- Line of sight analysis: visibility between 2 points

Why Topology Optimization

- Purely Structural
- Complex shapes
- Allows to test capabilities of robotics



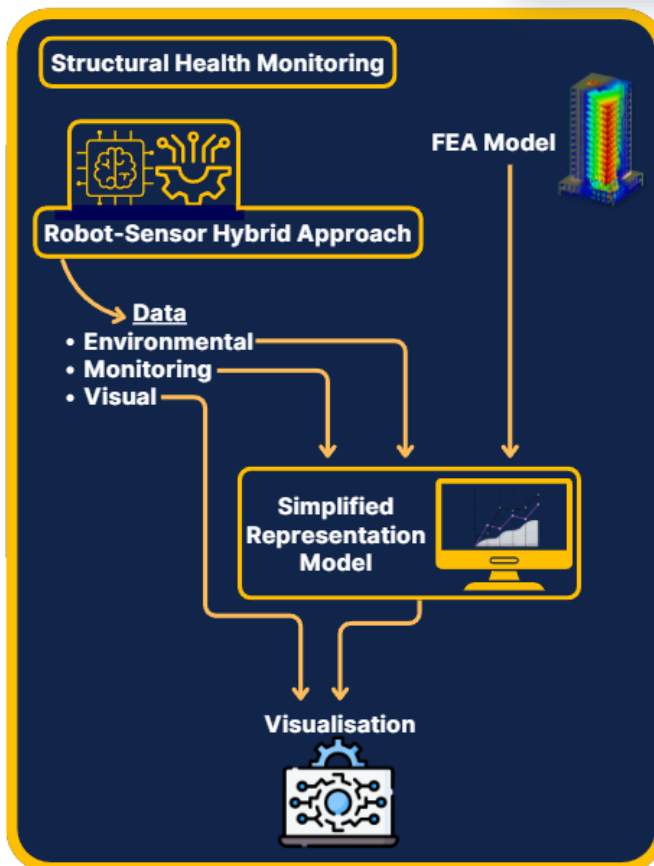
METHODOLOGY - SHM Data



Data Management:

Transmission and Storage

Processing



SHM Data Management Aspect: Improve the Data Management process for SHM

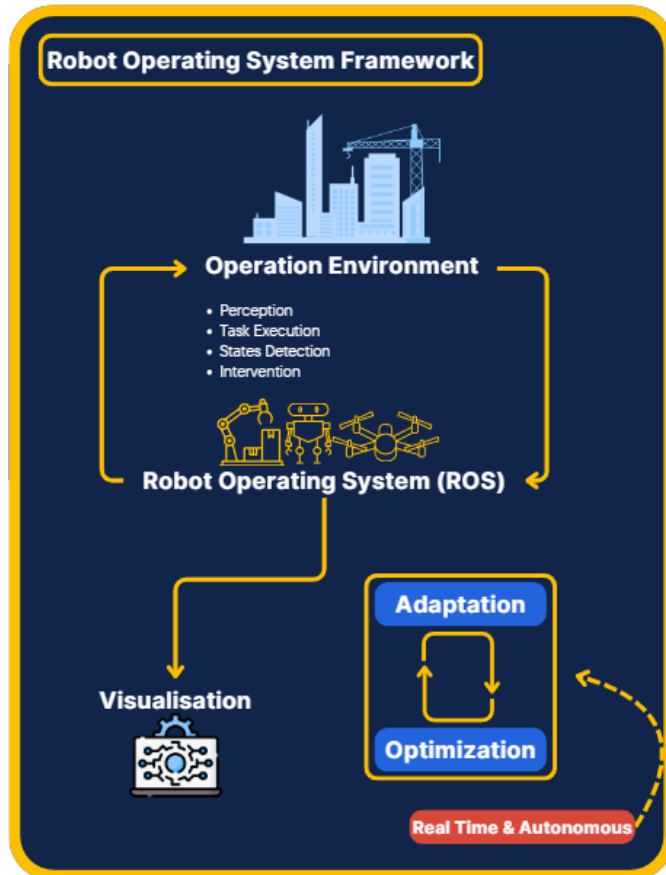
Aim: Simplify Structural Model and Condense SHM data to reduce computational load to enable easier visualisation and further SHM capabilities (predictions, real-time) through Digital Twin Updating

Proposed Methodology

- FE-based structural models as foundation
- Filter data from hybrid approaches
- Use numerical models (surrogate models, ROM, etc.) to discretise the monitoring data and match it to related building component
- Visual data directly managed in the visualisation process.

METHODOLOGY - Robotics

Data Collection

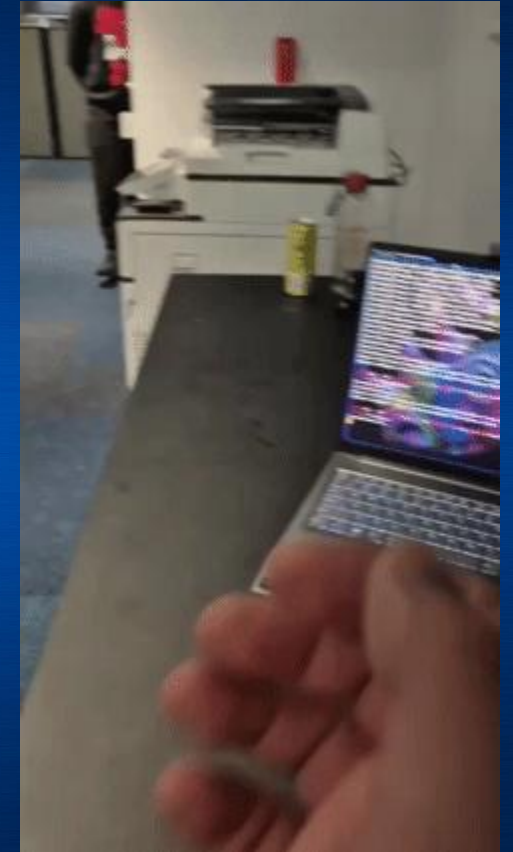


Robotic Aspect: Move towards autonomous robotics and seamless integration

Aim: Develop a Real Time and autonomous robot operating framework that adapts and optimises by itself to its surroundings.

Proposed Method:

- Leverage ROS extensive capabilities as the central processing system.



Boston Dynamics Spot®

METHODOLOGY - Visualisation



Interpretation

Visualisation of Complete Systems

BIM Model



Simplified Representation Model



Robot Operating System (ROS)

Visual Data



Visualisation



Visualisation Aspect: Be able to combine multiple formats of SHM components and apply it on a scalable model for Digital Twin

Aim:

- Create a scalable topology model as physical asset
- Develop an interactive and real-time digital twin model that incorporates robotics and Machine Learning capabilities for constant updating, monitoring and predictions

Proposed Methodology

- Use a game engine for the combination of all inputs like Unity or Unreal Engine.
- Using 3D printed technology and/or prefab for model creation

Expected Outcomes



Technical Outcomes

- Novel topology optimization method/s that incorporate visibility metrics
- Demonstrating multi-objective design for mobile robot inspections



Operational Outcomes

- Proactive structural health monitoring through the integration of robotics
- Computationally efficient workflows for predictions and data management
- Enhanced inspection reliability and speed, reducing manual intervention



Sustainability Outcomes

- Reduce lifecycle costs for easier inspection, maintenance, and monitoring
- Facilitation of digital twin integration and Machine Learning from the design stage
- Contribute to long-term resilience of infrastructure systems

Moving Forward

- Literature Review

- Advancements in Structural Health Monitoring through Robotics, design principals and digital twin technologies for Robot-Inspectable Structural Design: A literature review

Thank You for Listening
Any Questions?

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Problem Statement Reference

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