# Smart Sensors: Safeguarding Everyday Infrastructure in Real Time

Adaptive Real-Time Systems Laboratory (ARTS-Lab)

An Interdisciplinary Controls Lab at USC

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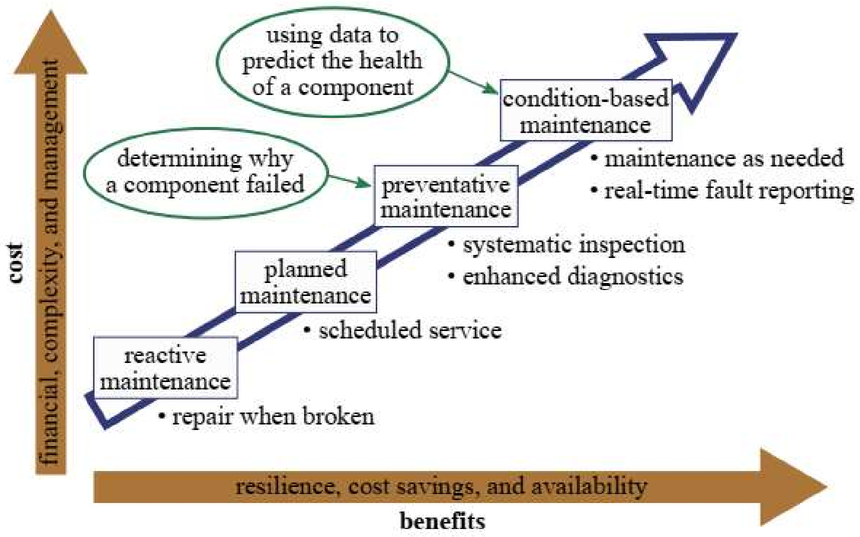
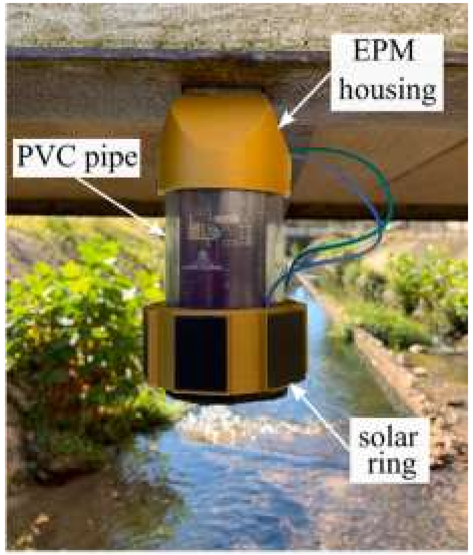
# Introduction

- **Part 1:** Civil Infrastructure
- **Part 2:** Applications and Case Studies




# Civil Infrastructure

# Civil Infrastructure

- Civil infrastructure includes essential public systems and facilities:
  - Roads and highways
  - Bridges and tunnels
  - Water and sewage systems
  - Dams, levees, and flood control structures
  - Electrical grids, transportation networks, and more

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# Infrastructure Maintenance and Upgrade

- Importance of Maintenance and Upgrades:
  - Critical for public safety and economic stability
  - Ensures infrastructure longevity and reliability
  - Necessary to handle increasing demand and urbanization
  - Key to reducing the risk of catastrophic failures, like bridge collapses or dam breaches

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# Infrastructure Challenges

Traditional Challenges:

- Aging infrastructure and limited budgets for repairs
- Manual inspection processes are labor-intensive and time-consuming
- Delayed detection of structural issues leads to reactive maintenance
- Difficulty in predicting failures due to the complexity of infrastructure systems

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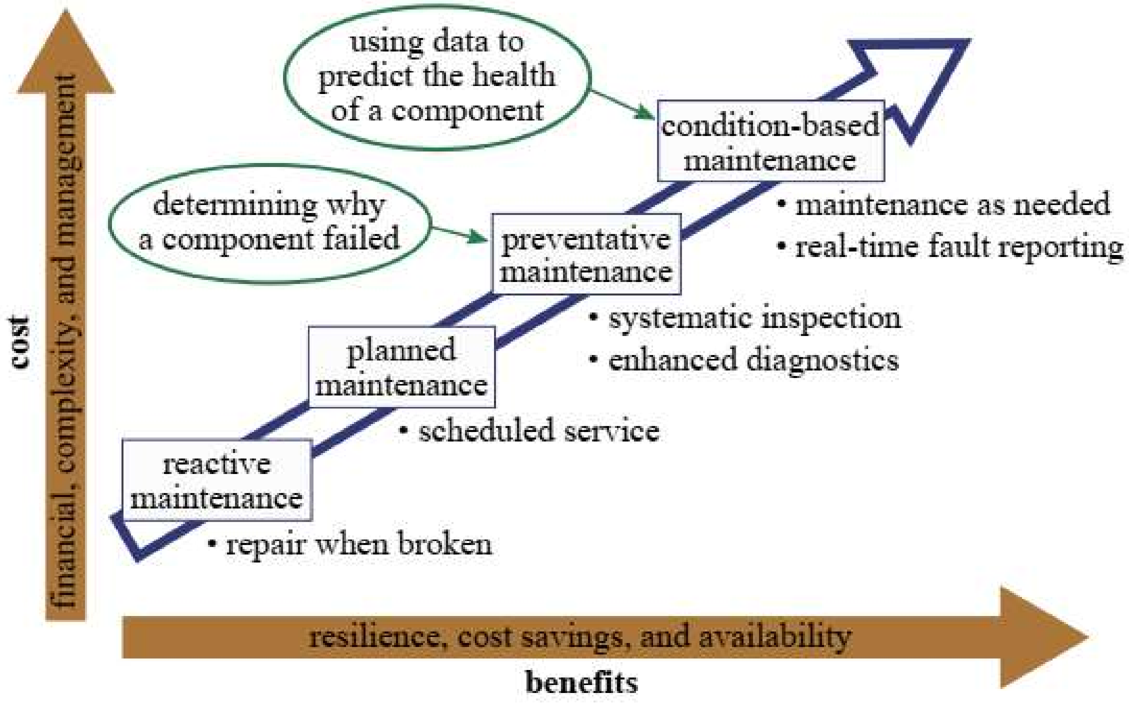
Arlington Memorial Bridge Repair & Reconstruction. National Park Service and Federal Lands Transportation Program. U.S. Department of the Interior. 2013, p. 2., Public domain, via Wikimedia Commons

# Predictive Maintenance

AI Use Cases in Infrastructure:

- **Continuous Sensing:** Real-time strain, vibration, flow, and environmental data
- **On-Edge Analytics:** Automatic anomaly detection and remaining-useful-life (RUL) estimation
- **Optimized Scheduling:** Maintenance only when and where it's needed
- **Improved Resilience:** Fewer unplanned outages, lower lifecycle costs, higher availability




Austin Downey. Sensing skin for the structural health monitoring of mesoscale structures. Iowa State University, 2018, Iowa State University Graduate Theses and Dissertations. 16571

# Goal: Self-Monitoring & Adaptive Infrastructure

Civil Engineering and AI include:

- **Continuous Sensing:** Embedded sensors track stress, strain, water level, vibration, etc., in real time
- **Automated Actuation:** Valves, gates, dampers or cables adjust themselves to changing loads or water pressures
- **Predictive Maintenance:** On-board analytics flag emerging issues—corrosion, fatigue, blockages
- **Enhanced Resilience:** Infrastructure that detects and reacts autonomously to floods, heavy traffic, or seismic events


Photos of the flood gate by Austin Downey in Örebro Sweden, Creative Commons BY-SA 4.0. 3D view taken from Google Maps in October 2024; copyright held by Google.

# Applications and Case Studies

# Application 1: Structural Health Monitoring

Structural Health Monitoring (SHM)

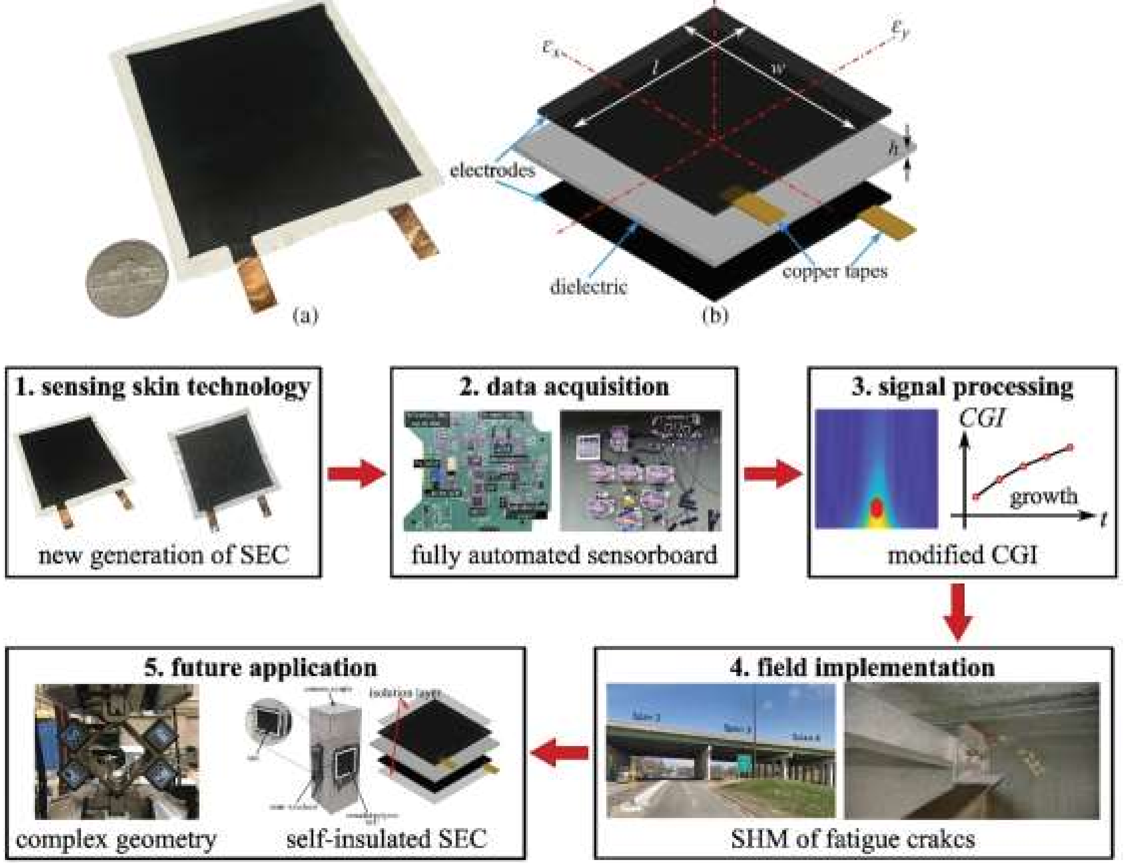
- **Distributed Sensing:** Strain, vibration, tilt and ultrasonic sensors embedded across the structure
- **Continuous Inspection:** Real-time data collection without bucket trucks
- **Damage Detection:** Automated identification of cracks, corrosion, loosened connections
- **Actionable Alerts:** Threshold-based alarms and dashboard reports for timely maintenance

VTrans Rail Bridge Inspection Public Domain

# Case Study 1.1: Bridge Monitoring

Key Benefits of AI in Bridge Monitoring

- **Fatigue Crack Detection:** Sensing skin technology (SEC) detects and monitors fatigue cracks in steel bridges.
- **Large-Area Monitoring:** Soft elastomeric capacitors (SECs) provide coverage over large bridge surfaces for crack detection.
- **Field Validation:** The system was successfully deployed on a highway bridge in Kansas, providing real-world validation for the SEC.

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# Case Study 1.2: UAV Deployed Sensors

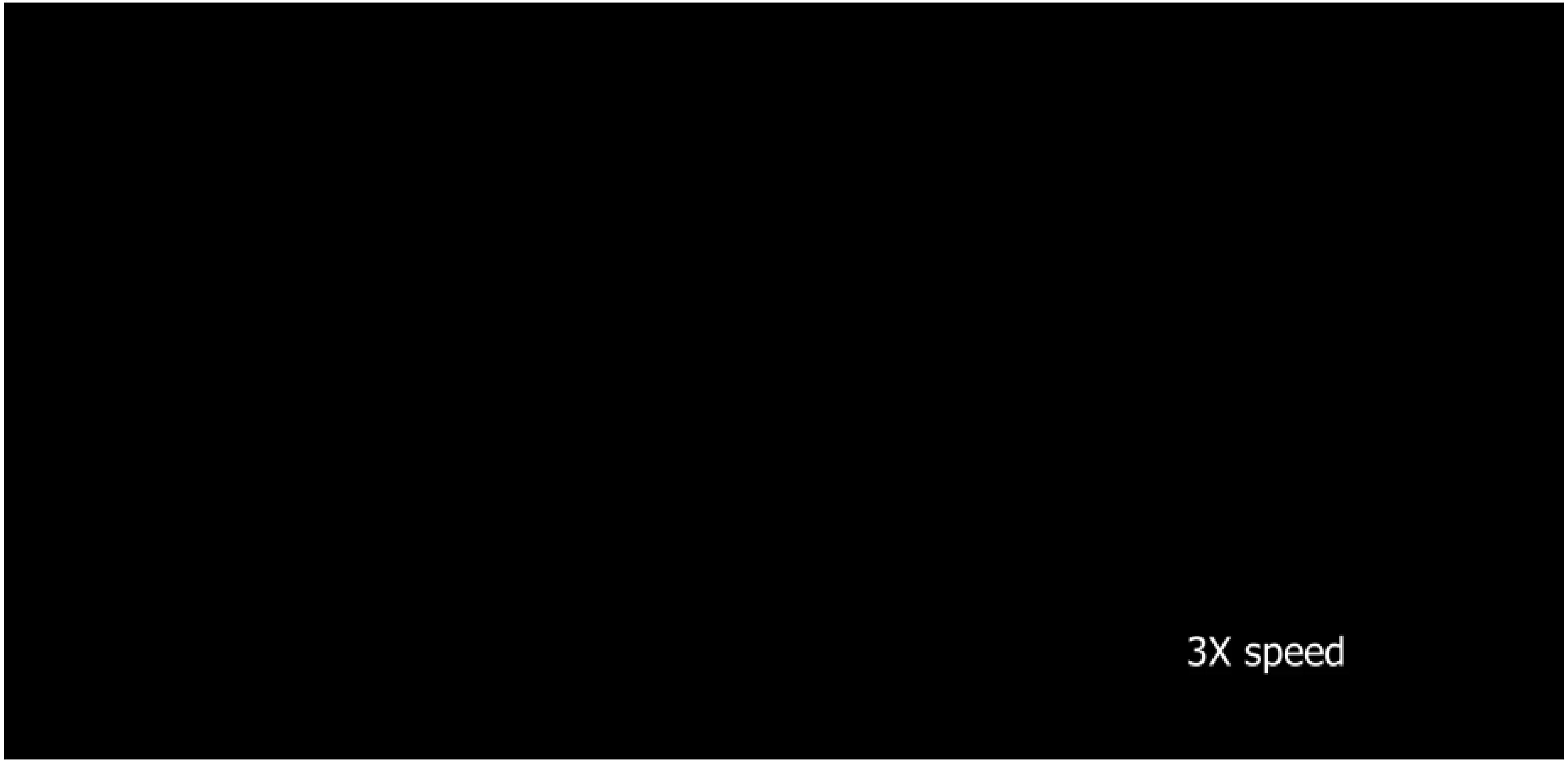
UAV Deployable Sensor Packages

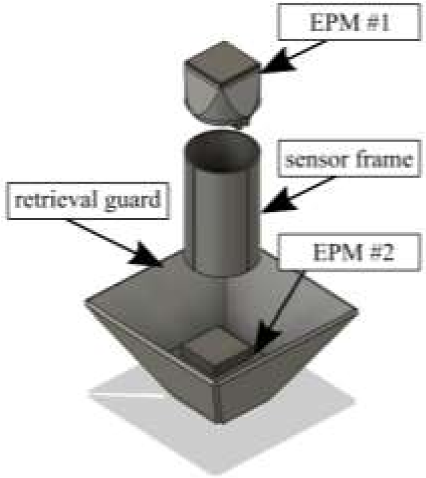
- **Autonomous Deployment:** Fast, precise sensor placement.
- **Real-Time Monitoring:** Continuous data for proactive assessment.
- **Cost & Time Efficient:** Reduces manual inspections.
- **Scalable Solution:** Works for bridges, levees, and more.
- **Enhanced Safety:** Minimizes human exposure.



Joud N. Satme, Daniel Coble, Hung-Tien Huang, Austin R. J. Downey, and Jason D. Bakos. Non-linear vibration signal compensation technique for UAV-deployable sensor packages with edge computing. In Zhongqing Su, Maria Pina Limongelli, and Branko Glisic, editors, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023. SPIE, apr 2023. doi:10.1117/12.2658563

# Case Study 1.2: UAV Deployed Sensors



# Application 2: Water Quality Monitoring

Water Quality Monitoring

- **Real-Time Monitoring:** Continuous, real-time tracking of water quality parameters (e.g., pH, turbidity, contaminants).
- **Early Detection of Contaminants:** Machine learning models identify harmful substances in water early, improving response times.
- **Predictive Analysis:** AI predicts potential water quality issues based on environmental and historical data trends.
- **Cost Efficiency:** Reduces the need for manual sampling and testing, optimizing resource use and operational costs.

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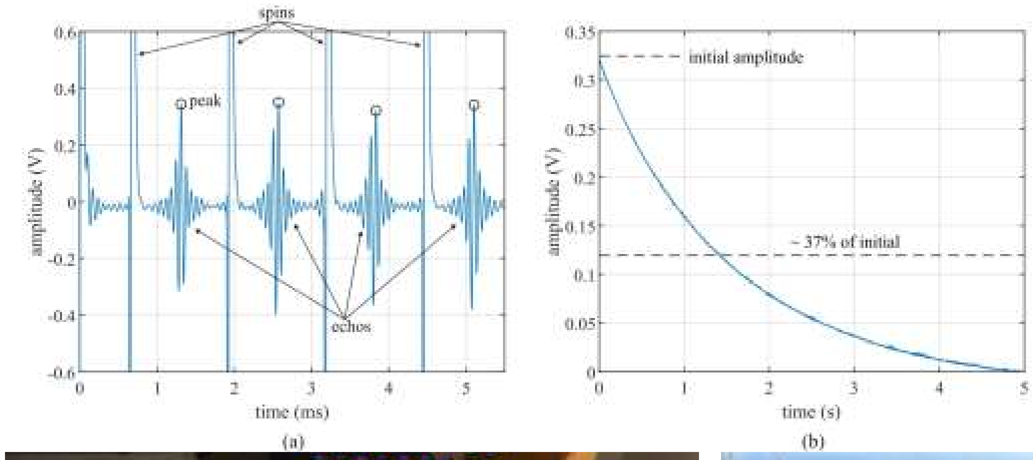
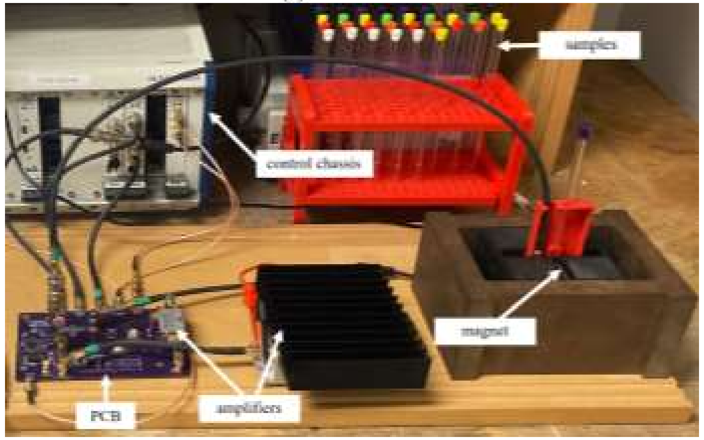
# Case Study 2.1: NMR-based Water Quality Monitoring




NMR-Based Water Quality Monitoring

- **How NMR Works:** Magnetic pulses align tiny “magnets” in water molecules, then we listen for their echo signals
- **Echo Signals:** The pattern and strength of those echoes tell us about what’s in the water
- **Portable Design:** A small permanent magnet and custom electronics let us bring the lab to the field

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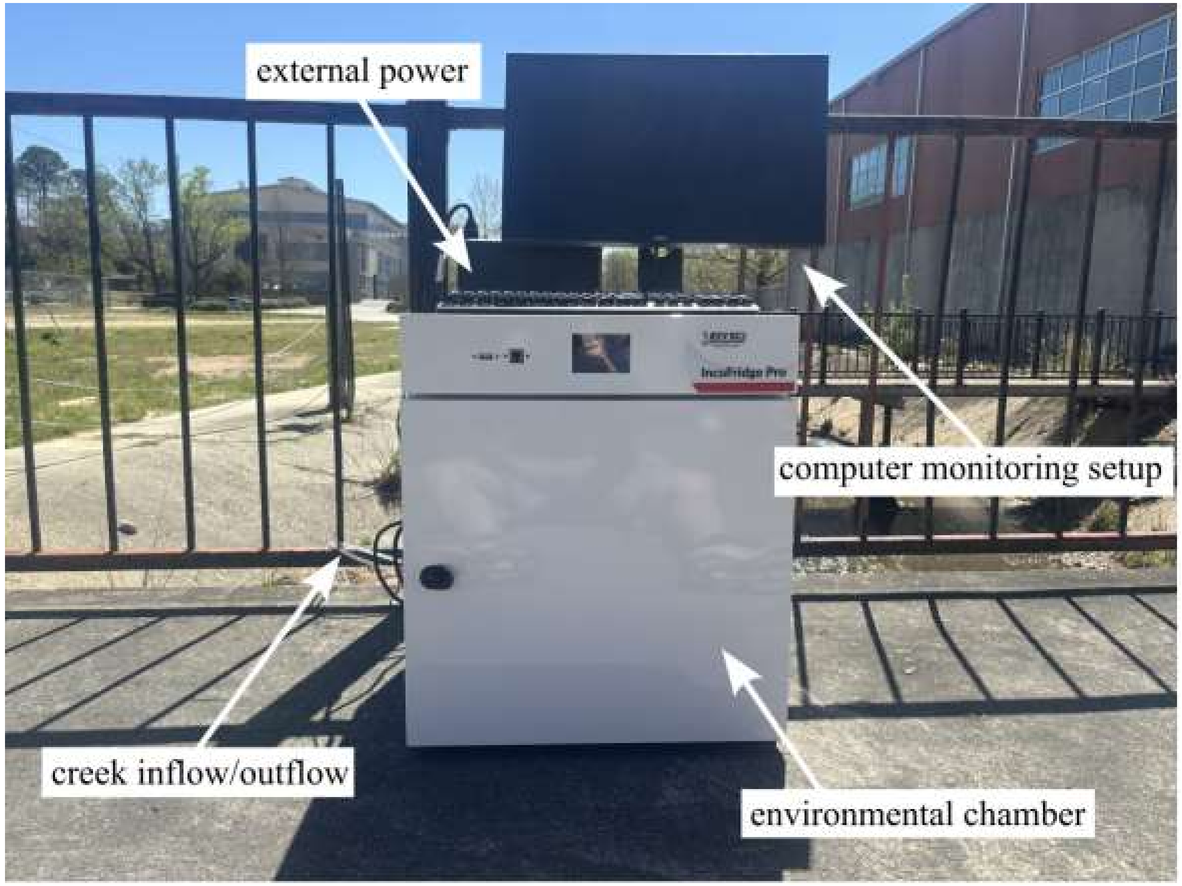
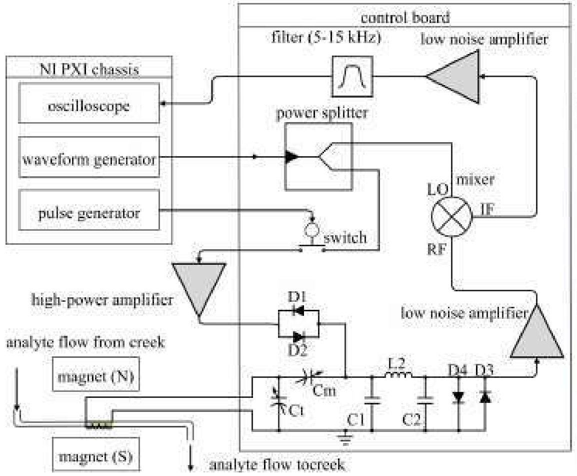
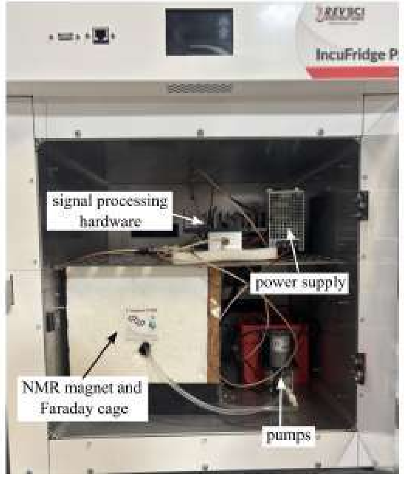
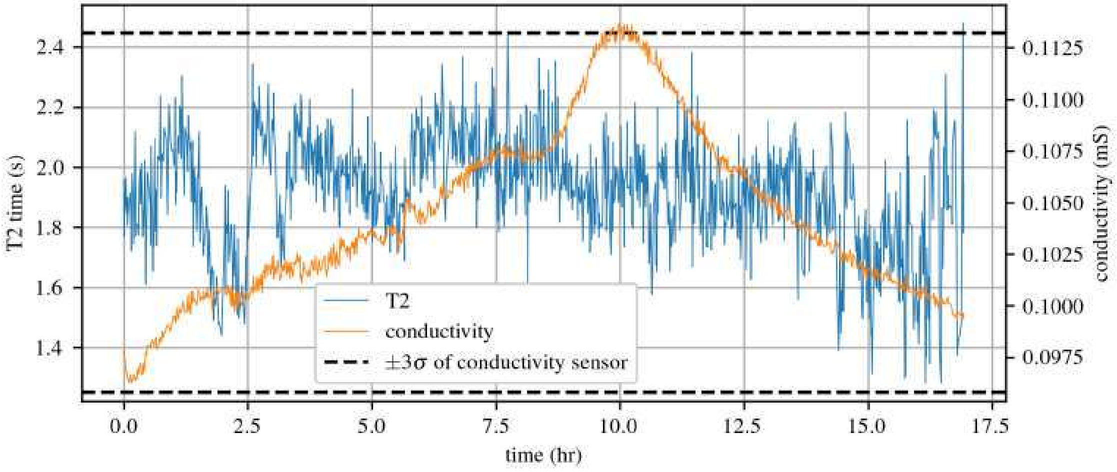
# Case Study 2.1: NMR-based Water Quality Monitoring



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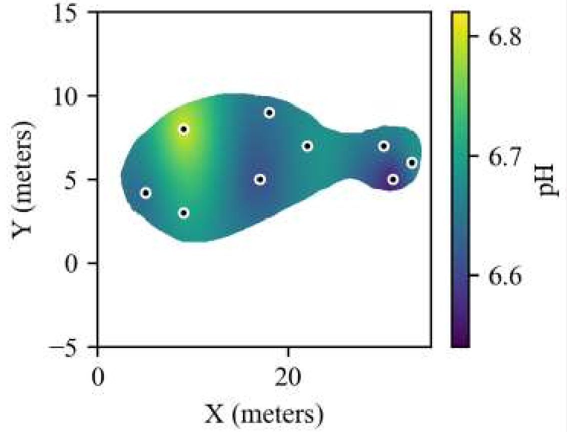
# Case Study 2.2: UAV-deployable in situ Water Quality Sensors




Key Benefits of in situ Sensors

- **Real-Time Monitoring:** UAVs deploy water quality sensors to provide continuous, real-time data.
- **Rapid Deployment:** UAVs allow fast, efficient sensor deployment in remote or hazardous locations.
- **Spatial and Temporal Analysis:** Interpolation techniques map water quality over space time.
- **Cost-Effective Solution:** Affordable, open-source sensors provide reliable water quality data.



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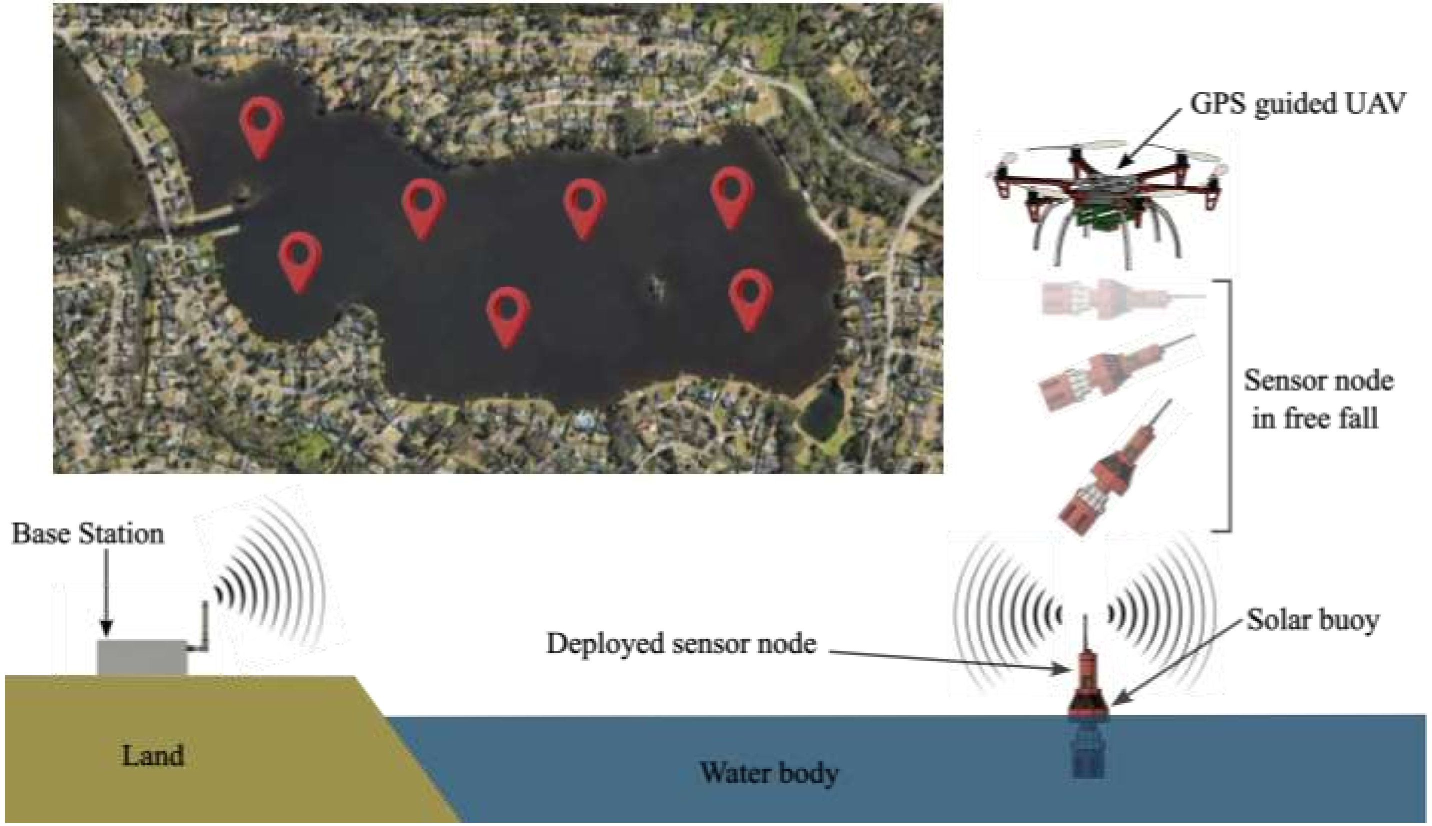
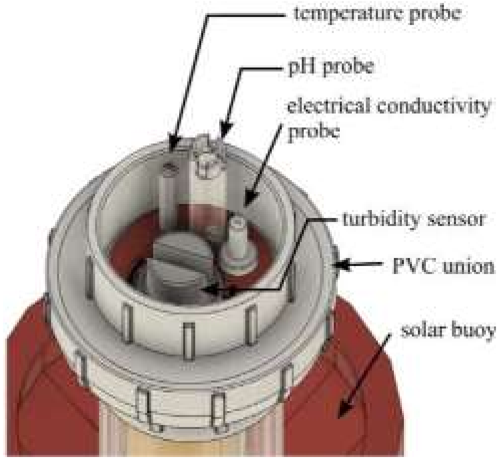
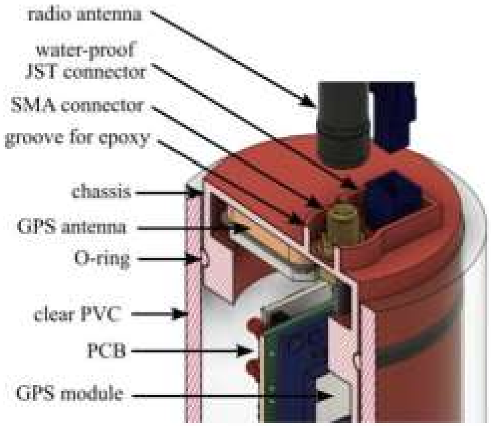
# Case Study 2.2: UAV-deployable in situ Water Quality Sensors



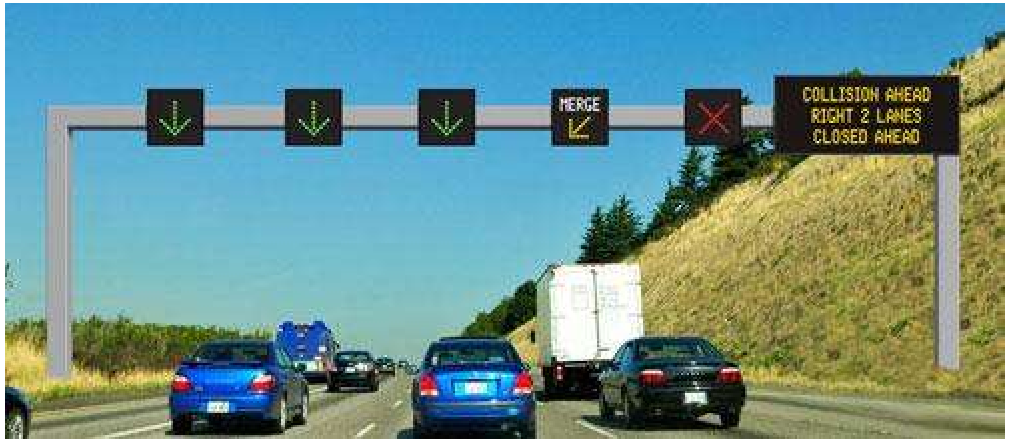



Md Asifuzzaman Khan, Matthew Burnett, Austin R. J. Downey, Joud N. Satme, and Jasim Imran. UAV deployable buoy-style sensor for in situ water quality monitoring. In Defense and Commercial Sensing. SPIE, May 2025

# Application 3: Traffic and Transportation

Key Benefits of AI in Transportation

- **Traffic Flow Optimization:** Manage and optimize traffic flow in real-time, reducing congestion.
- **Predictive Traffic Management:** Forecast traffic patterns, allowing cities to adjust signals and infrastructure accordingly.
- **Autonomous Vehicle Integration:** AI plays a crucial role in the development and management of autonomous vehicles, enhancing safety and efficiency.
- **Smart Public Transportation:** AI enables efficient routing, scheduling, and capacity management for public transport systems.



Washington State Department of Transportation: Public Domain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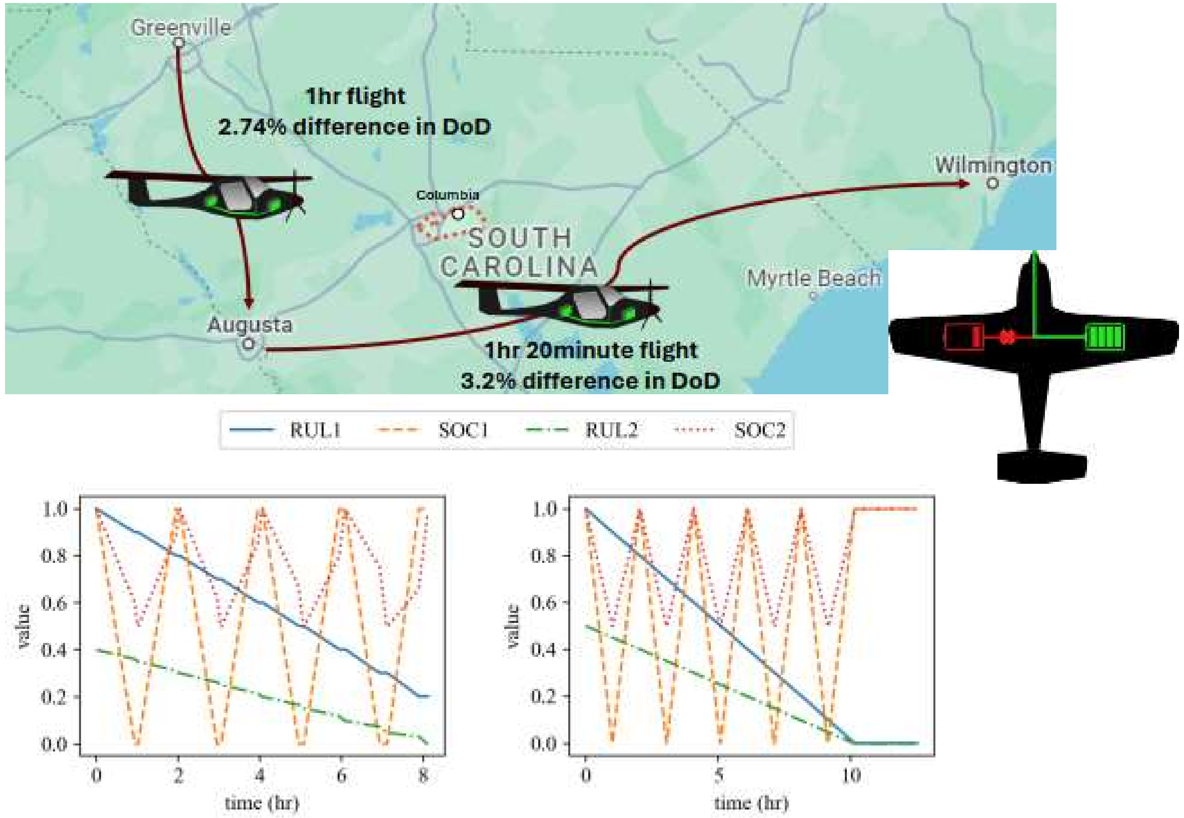
# Case Study 3.1: Electric Aircraft Optimization

Electric Aircraft Traffic Routing

- **Route-Based Maintenance Scheduling:** Use flight paths and traffic density data to predict optimal maintenance windows, minimizing unscheduled downtime.
- **Battery Life Forecasting:** Forecast remaining useful life (RUL) by accounting for route profiles.
- **Traffic Corridor Optimization:** Design and update airspace corridors to reduce delays and idle loitering—lowering overall energy.





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# Application 4: Flood Modeling and Forecasting

Flood Modeling and Forecasting

- **Real-Time Data Analysis:** Process real-time sensor and weather data to predict flood risks.
- **Improved Forecast Accuracy:** Machine learning models enhance the accuracy of flood forecasts.
- **Early Warning Systems:** AI-driven models provide early flood warnings, improving disaster preparedness.
- **Risk Mapping:** Flood risk maps to identify vulnerable areas and inform urban planning.
- **Emergency Response:** Optimize resource allocation during flood events for efficient response.

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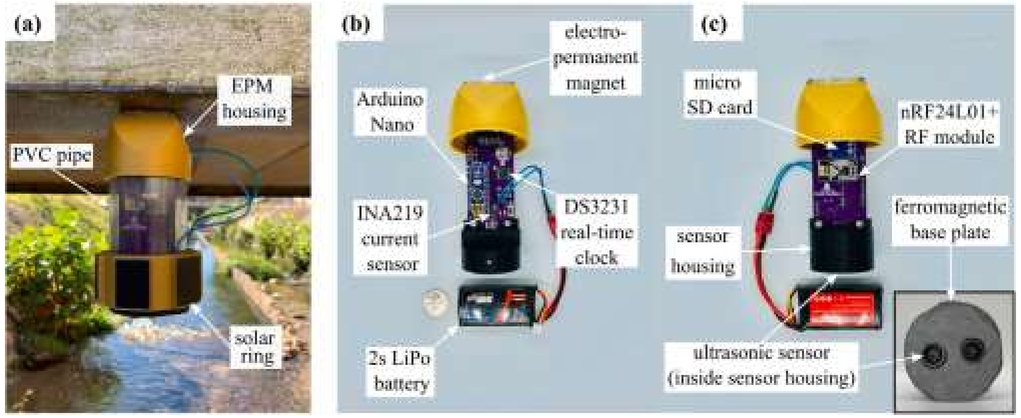
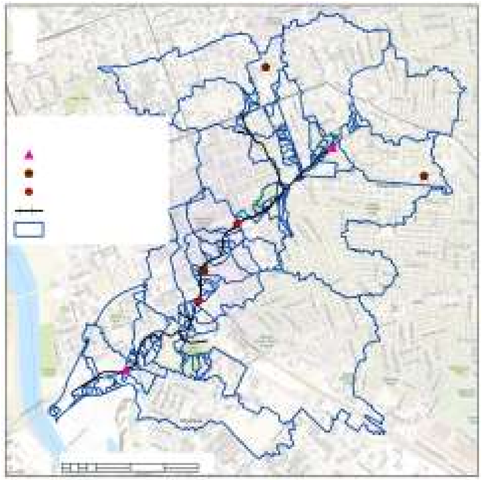
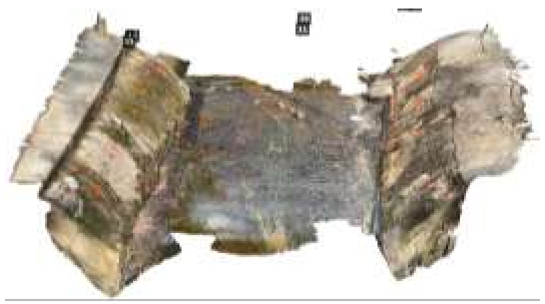
# Case Study 4.1: Low-cost Height Sensors

Flood Modeling and Forecasting

- **Real-Time Monitoring:** Sensors deployed by UAVs collect real-time water height data, providing real-time information during floods.
- **Optimization:** Optimize flood model parameters in real-time.
- **IoT Integration:** IoT-enabled sensors for seamless data transmission and faster model updates, improving flood response times.
- **Predictive Forecasting:** Enhance flood prediction by processing large data sets and optimizing forecasts for urban watersheds.







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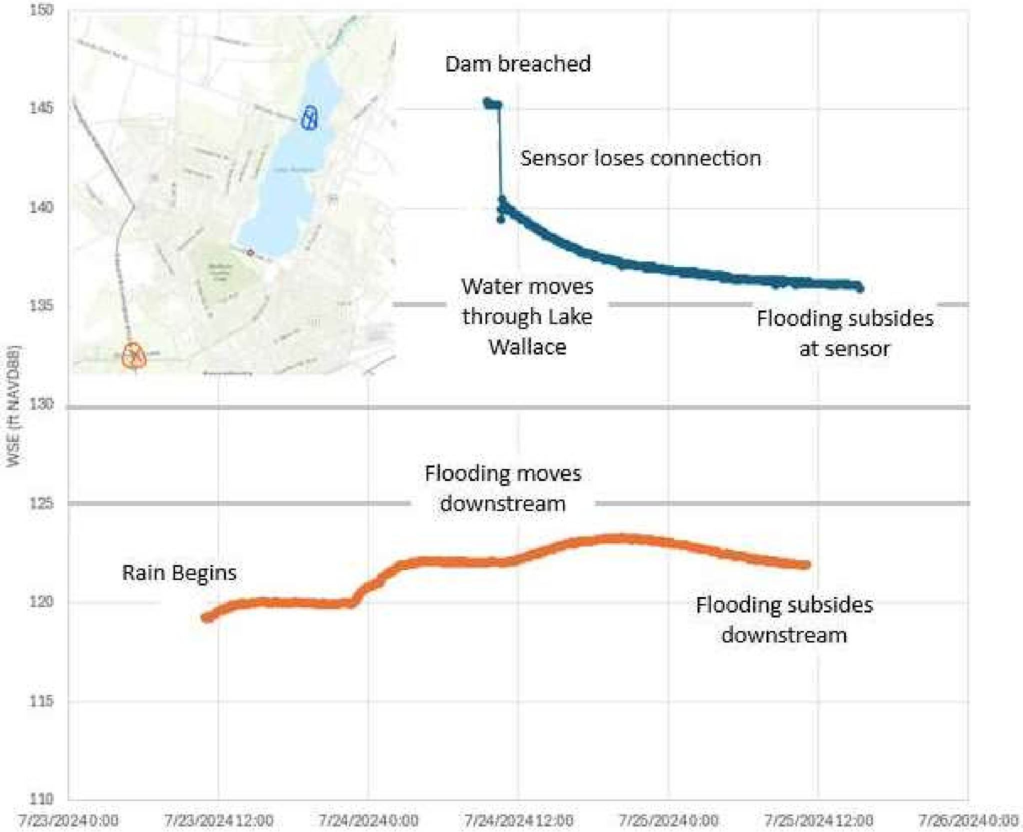
# Case Study 4.1: Low-cost Height Sensors


WBTW

**Bennettsville dam failure blamed on internal erosion, state regulators say**

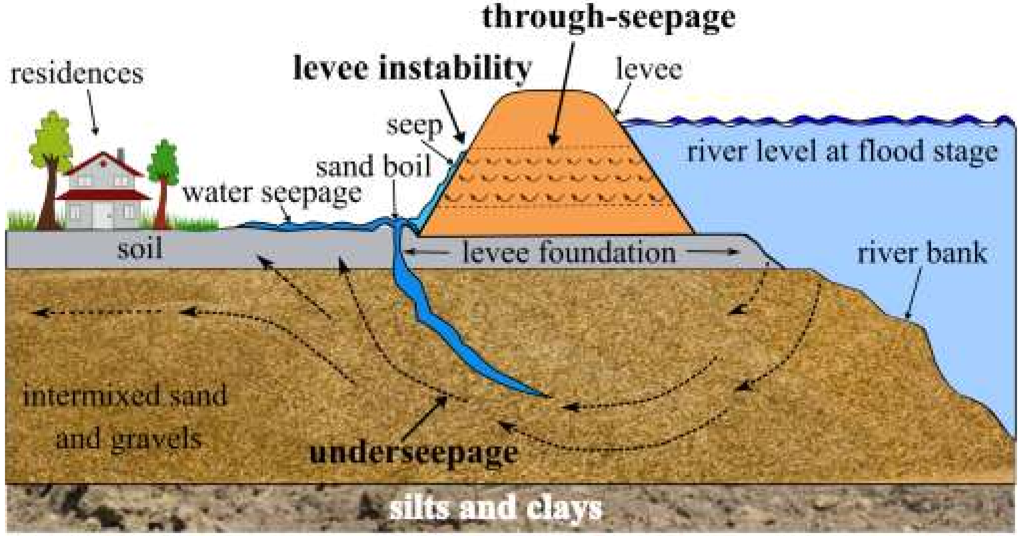
Internal erosion is to blame for a May 6 breach of the Lake Paul Wallace Dam in Marlboro's largest city — and the structure remains in need of...

May 14, 2024

# Application 5: Geotechnical Monitoring

Geotechnical Monitoring

- **Real-Time Monitoring:** AI processes sensor data to monitor soil movement and stability in real time.
- **Early Detection of Failures:** Detects early signs of slope instability, landslides, and foundation settlement.
- **Predictive Maintenance:** Forecast potential geotechnical issues, allowing for timely interventions.
- **Cost Reduction:** Monitoring reduces the need for frequent manual inspections and prevents costly failures.

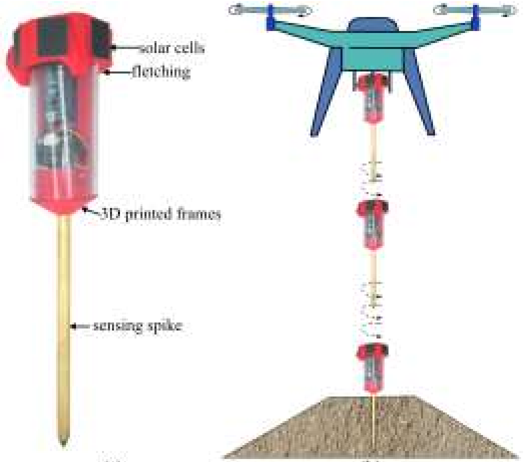





# Case Study 5.1: UAV-Deployable Soil Saturation Sensors

Soil Saturation Monitoring

- **Real-Time Monitoring:** UAV-deployed smart sensing spikes provide continuous soil moisture monitoring across levees.
- **Data Expansion:** Gaussian process regression (kriging) to generate continuous moisture maps from discrete sensor data.
- **Automated Classification:** Categorize soil conditions into dry, partially saturated, and saturated zones using k-means clustering.
- **Early Detection:** The system predicts areas at risk of levee failure by monitoring soil saturation and detecting seepage.

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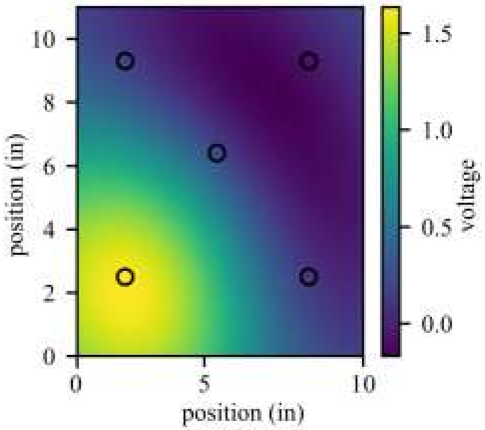


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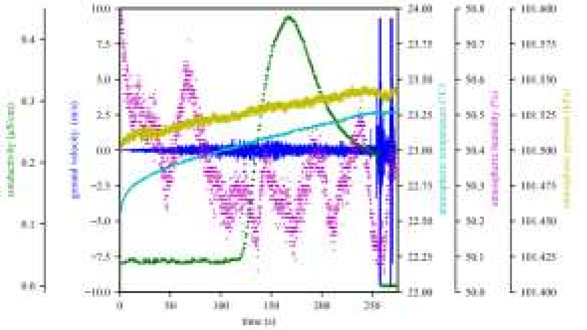
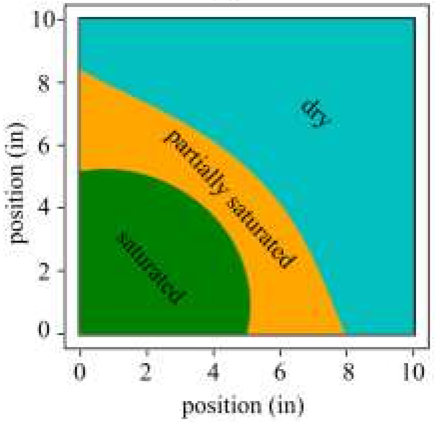
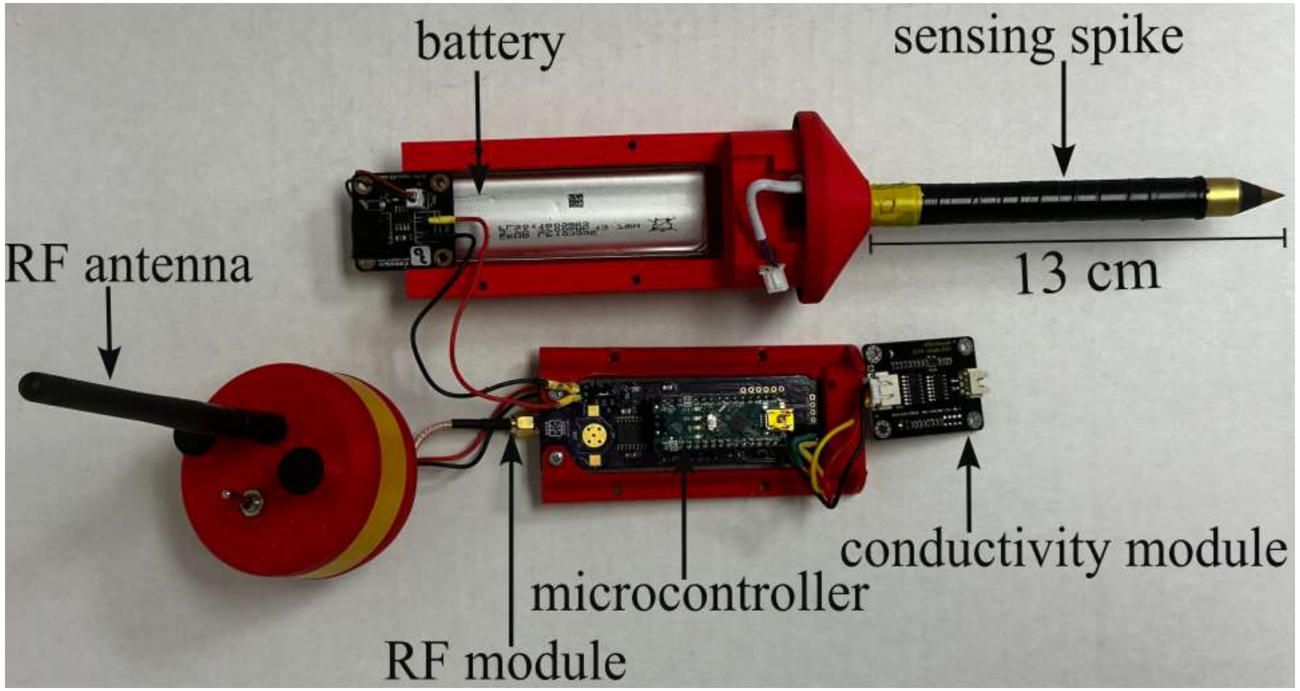


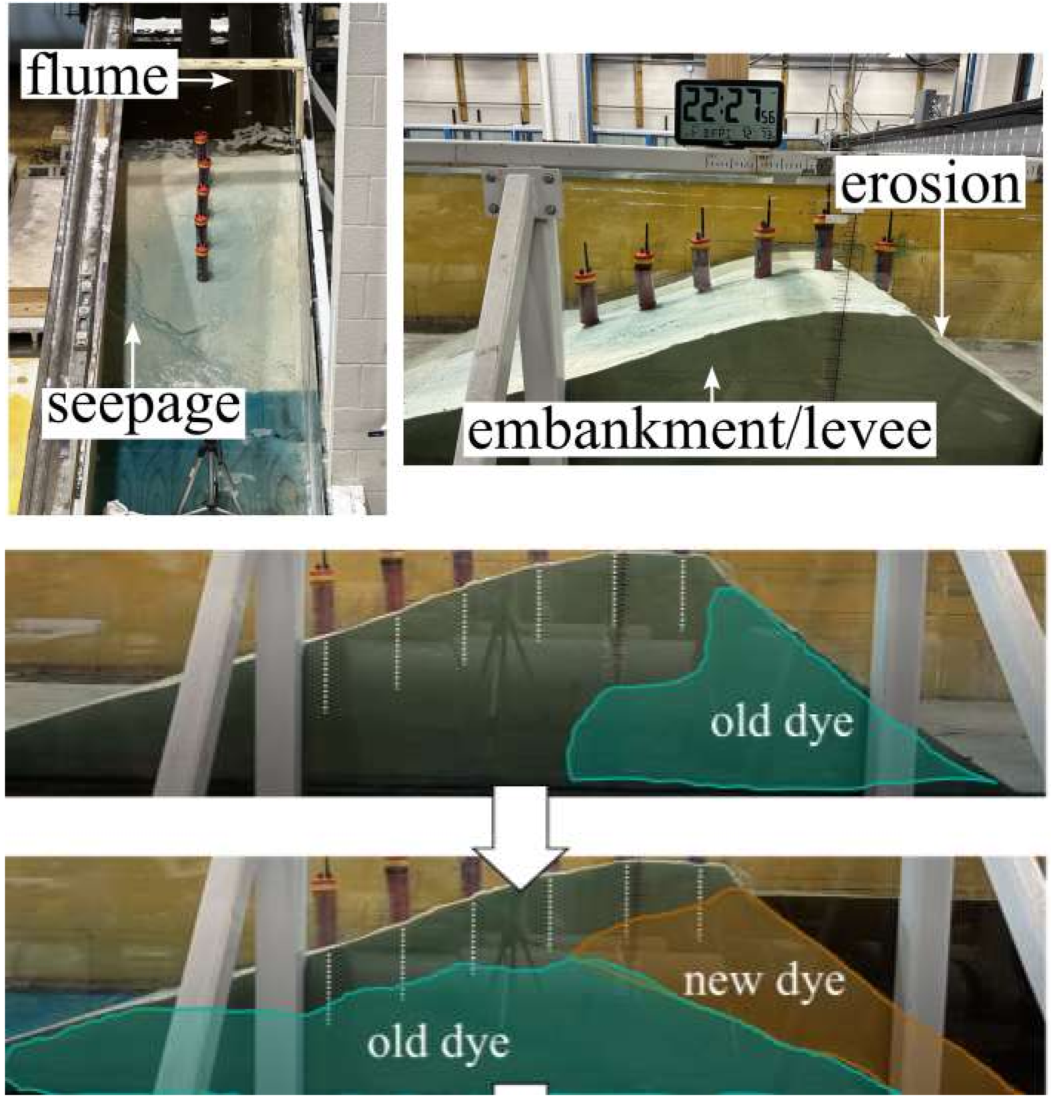



(b)

Puja Chowdhury, Joud N. Satme, Ryan Yount, Austin R. J. Downey, Sadik Khan, Jasim Imran, and Laura Micheli. Classifying soil saturation levels using a network of UAV-deployed smart penetrometers. In ASME 2023 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS2023. American Society of Mechanical Engineers, September 2023. doi:10.1115/smasis2023-111009

# Case Study 5.1: UAV-Deployable Soil Saturation Sensors

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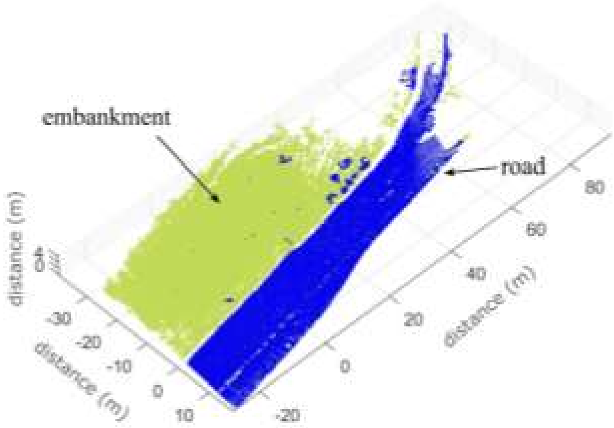
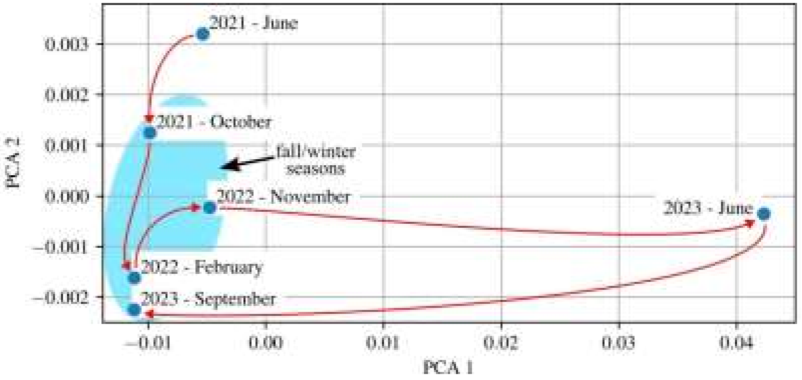
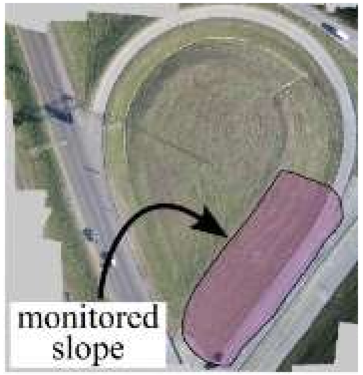
# Case Study 5.2: LIDAR-based Monitoring

LIDAR-Based Monitoring for Slope Stability

- **High-Resolution Data:** LiDAR captures 3D topography for precise monitoring of slopes.
- **Seasonal Monitoring:** Track moisture variations and their impact on soils.
- **Risk Assessment:** LiDAR scans identify potential failures, offering early warnings for slope instability.
- **Efficient Processing:** Advanced algorithms speed up data analysis for real-time monitoring.

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# Challenges for Active & Smart Infrastructure

Challenges:

- **Aging Assets:** Many bridges, tunnels, and water-control structures exceed their design life, increasing collapse risk
- **Private Autonomous Systems:** Self-driving cars, delivery drones, and other on-demand vehicles introduce new, unpredictable loads and traffic patterns
- **Delayed Maintenance:** Scheduled service can lead to under- or over-maintenance, wasting resources

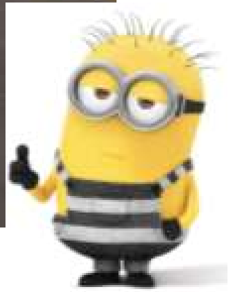

Volvo Cars Data Collection Video, Austin Downey CC BY-SA 2.0

# Conclusion

**No researchers were harmed during this endeavor!**

Final Thoughts:

- **Active Infrastructure:** Sensors and actuators enable real-time self-monitoring.
- **Predictive Maintenance Pays Off:** Early fault detection cuts downtime.
- **Interdisciplinary Teams Win:** Collaboration drives resilient designs.
- **Field-Proven Technologies:** Case studies show practical impact.
- **Your Turn to Build the Future:** Pursue careers that protect and sustain.



# Questions and Discussion



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