Autonomous Wireless Monitoring and Assessment of Railroad Bridges

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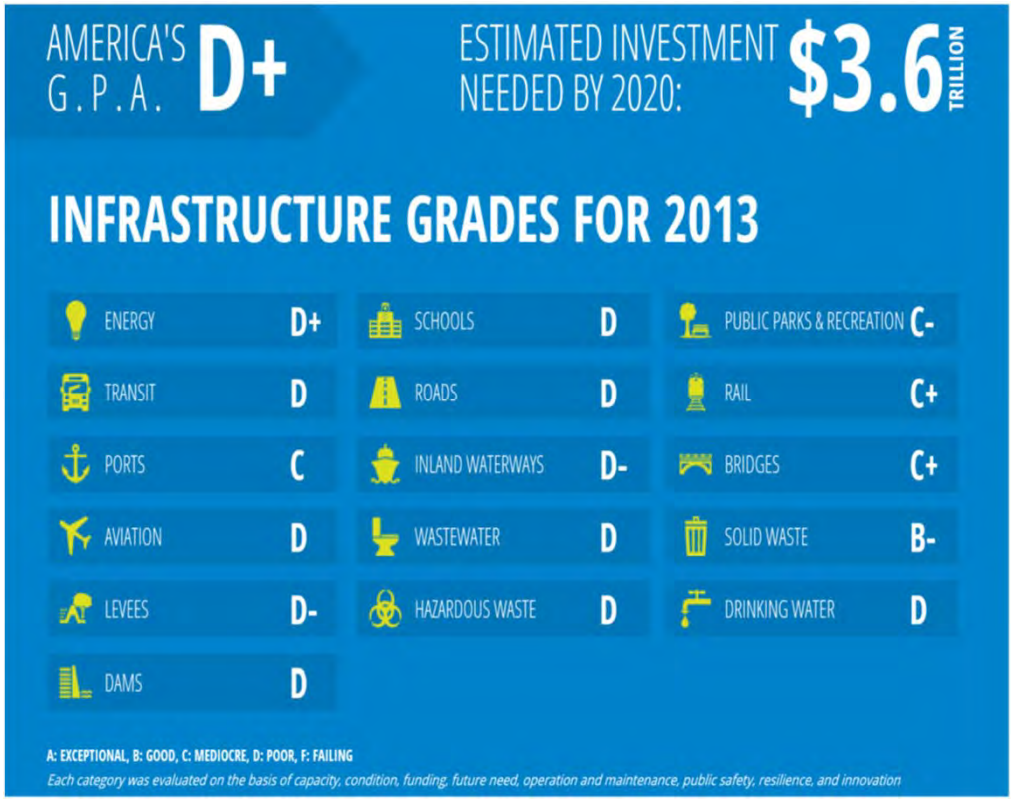
SSTL SMART STRUCTURES TECHNOLOGY LABORATORY

1. Background
2. Technology Background
3. Autonomous Monitoring Framework
4. Data-Driven Inspection Assistant
5. Summary
6. Opportunity to Participate

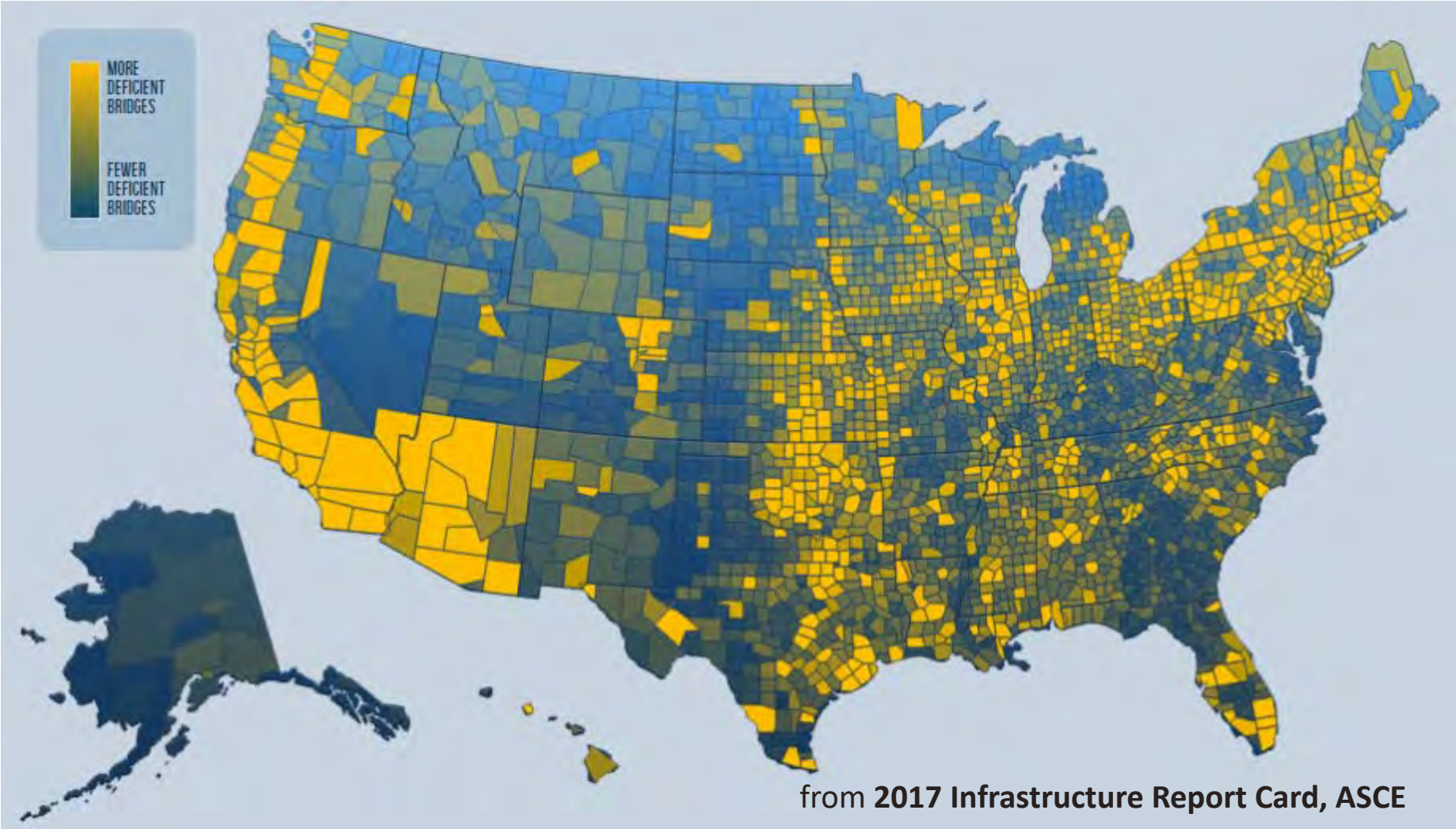
Aging Civil Infrastructure

- **Collapses of Infrastructure**

- **Aging Infrastructure in the US:**
  22.7% of Bridges are structurally deficient or functionally obsolete (ASCE).



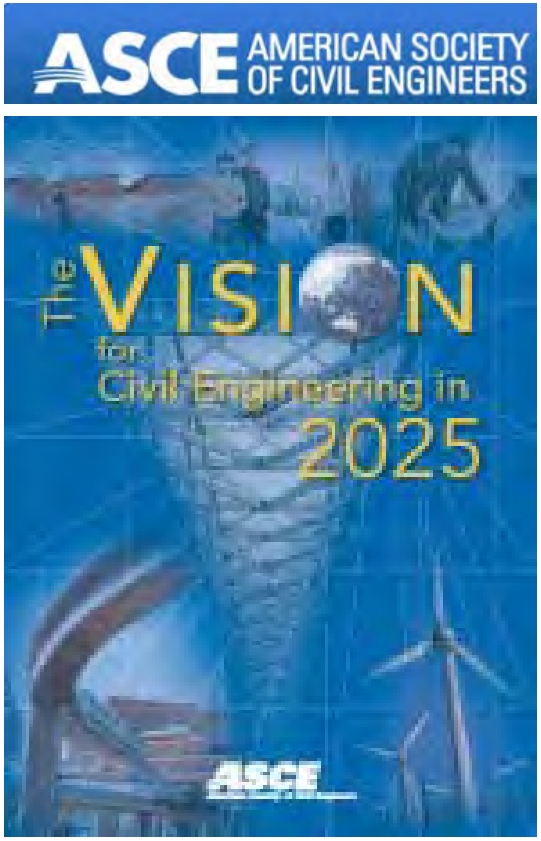
Structurally Deficient America's Bridges



from **2017 Infrastructure Report Card, ASCE**


"Manual visual inspection is still currently the main form of assessing the condition of civil infrastructure in the USA"

Vision of the Future



*"relying on and leveraging real-time access to **living databases**, **sensors**, **diagnostic tools**, and other advanced technologies to ensure **informed decisions** are made"*

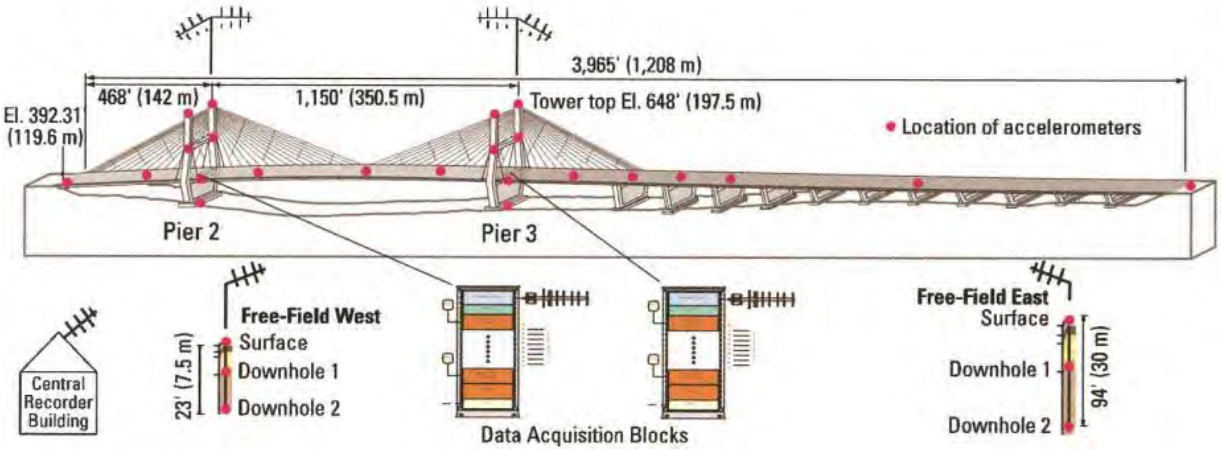
http://www.asce.org/Vision-2025/The-Vision-for-Civil-Engineering-in-2025/

Structural Health Monitoring

❑ Limitation of traditional methods

- Dense arrays of sensor are required to effectively monitor structures
- Wired monitoring systems are expensive, with much of the cost derived from cabling and installation
- Centralized data collection is not challenging for monitoring large civil infrastructure

Cabling & instrumentation for 400 wired strain sensors



Bill Emerson Memorial Bridge SHM system: $1.3M for 86 sensors, ~$15k/sensor (Caicedo et al. 2002; Celebi et al. 2004)

Background

Wireless Smart Sensor

- A wireless sensor as a monitoring system solves the cost problem and offers much more:
  - Intelligence capabilities of the onboard microprocessor
  - Small size
  - Wireless communication
  - Ease of installation

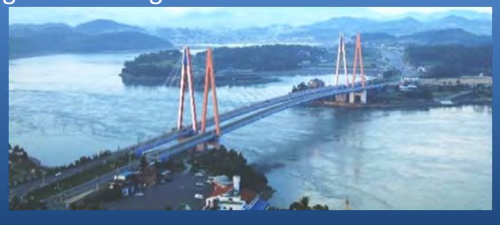
- Since the early 2000s, researchers at Illinois have been actively developing wireless smart sensors (WSS) solutions for SHM

Background

2nd Jindo Bridge Monitoring Deployment

➢ Overview

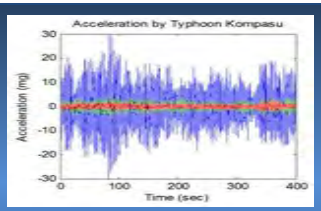
A large scale wireless smart sensor network for structural health monitoring of a cable-stayed bridge, the 2nd Jindo Bridge located in South Korea, was deployed to conduct long-term autonomous monitoring. The monitoring system had 113 wireless sensor nodes providing 669 channels of sensor data, making it the world's largest wireless network for bridge monitoring.

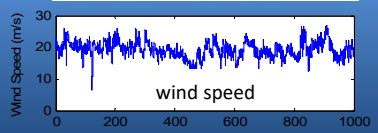


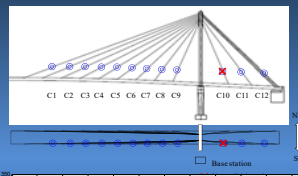
➢ Deployment

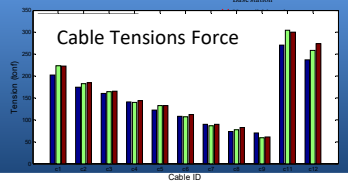
➢ Outcome

The system had been successfully operated autonomously for over 2 years. The effectiveness of autonomous operation was highlighted during typhoon Kompasu (2010), when the measured vibration and wind data was collected in response to excessive vibration.









wind speed

wind speed

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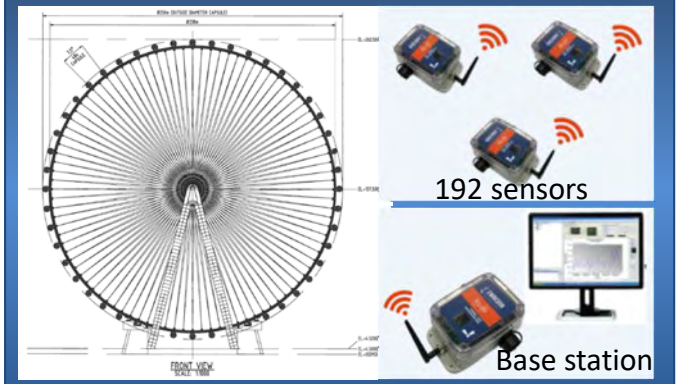
Background

Dubai-I Ferris Wheel Monitoring Deployment

➢ Overview

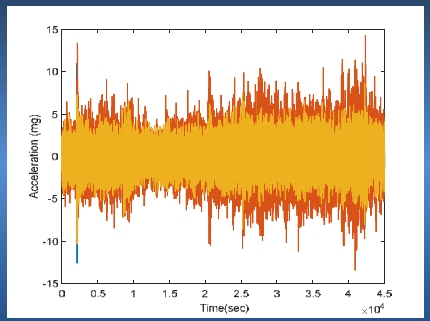
The world's largest Ferris wheel, over 200m in diameter, is currently under construction. The tension of the Ferris wheel's 192 cables needs to be monitored, particularly in the construction phase during tensioning events.

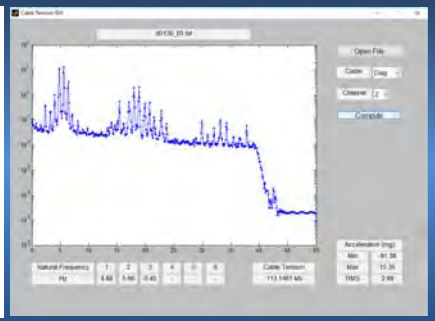
➢ Deployment



➢ Outcome

The monitoring system was installed in stages during the construction, providing daily monitoring information to the engineers on the construction team. The system will continue to operate long-term, once the wheel becomes operational.



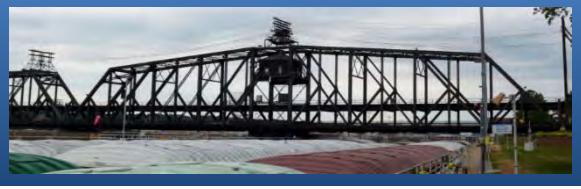


Background

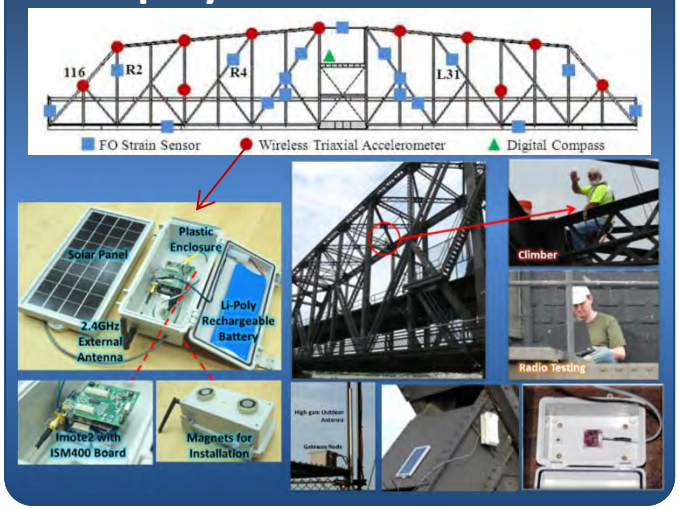
Rock Island Arsenal Government Bridge Monitoring Deployment

➢ Overview

The swing span of the Rock Island Arsenal Government Bridge, built over the Mississippi River in 1896, has the ability to rotate 360° in either direction to pass vehicle, train, and ship traffic. A monitoring system is required to help ensure public safety while also using limited repair and maintenance funds as efficiently as possible. Furthermore, the unique ability of this historic structure to rotate necessitated a multimetric approach to SHM.

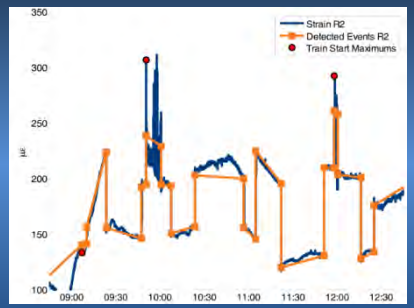


➢ Deployment

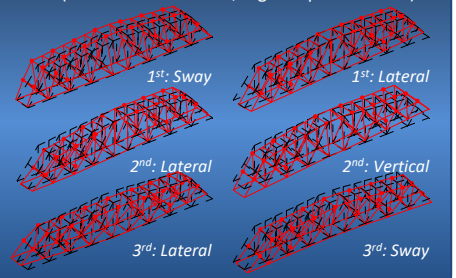


➢ Outcome

The monitoring system was expanded with multimetric observation capability, enabling detection of various events and dramatically reducing the retained data size by only storing detailed information for events classified as significant.



Identified Three Lower Mode Shapes
(Left: Closed Position, Right: Open Position)



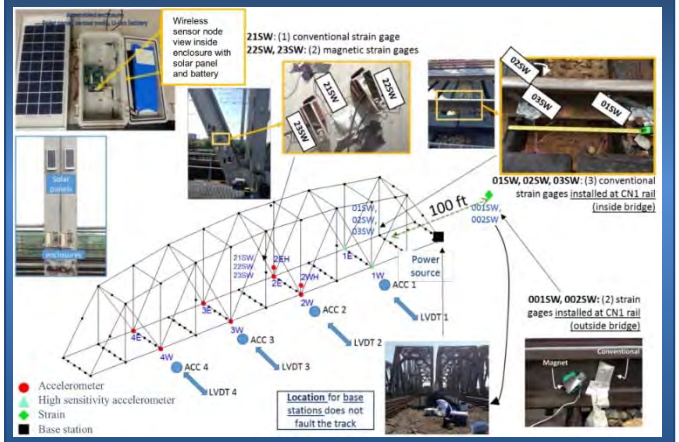
Background

Calumet River Bridge Monitoring Deployment

➢ Overview

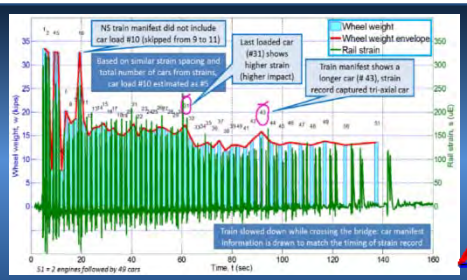
The primary objective of this monitoring deployment was to implement strain and acceleration monitoring for railroad bridge condition assessment in North America. Ultimately, this system will provide railroads with the predicted in-service performance of their bridges under real train loads.

➢ Deployment

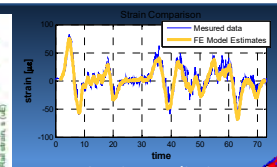


➢ Outcome

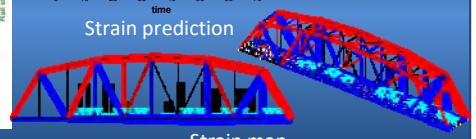
This project enabled trigger sensing to monitor bridge response to train crossings. The collected data forms a basis for a database of expected railroad bridge behavior based on calibrated FE models and measured bridge responses.



Load estimation



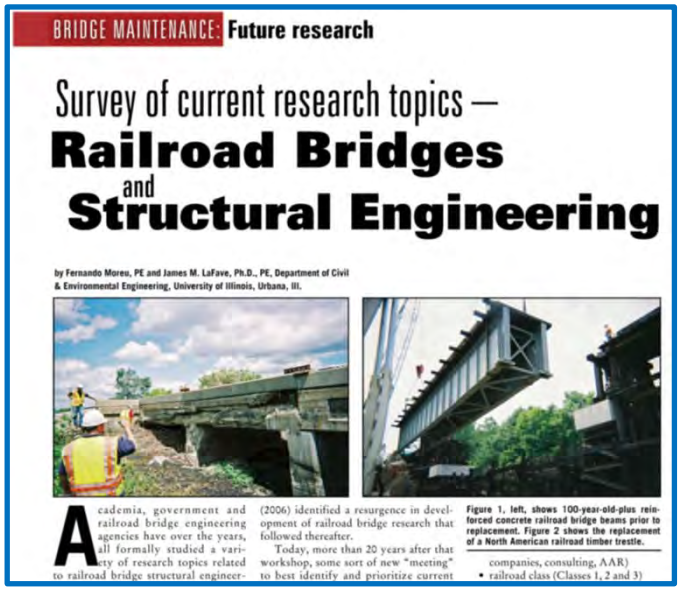
Strain prediction



Strain map

Background

Railroad bridge displacement measurement



BRIDGE MAINTENANCE: Future research

Survey of current research topics —
Railroad Bridges and Structural Engineering

by Fernando Moreu, PE and James M. LaFave, Ph.D., PE, Department of Civil & Environmental Engineering, University of Illinois, Urbana, Ill.

Figure 1, left, shows 100-year-old-plus reinforced concrete railroad bridge beams prior to replacement. Figure 2 shows the replacement of a North American railroad timber trestle.

Academia, government and railroad bridge engineering agencies have over the years, all formally studied a variety of research topics related to railroad bridge structural engineer-

(2006) identified a resurgence in development of railroad bridge research that followed thereafter.

Today, more than 20 years after that workshop, some sort of new "meeting" to best identify and prioritize current

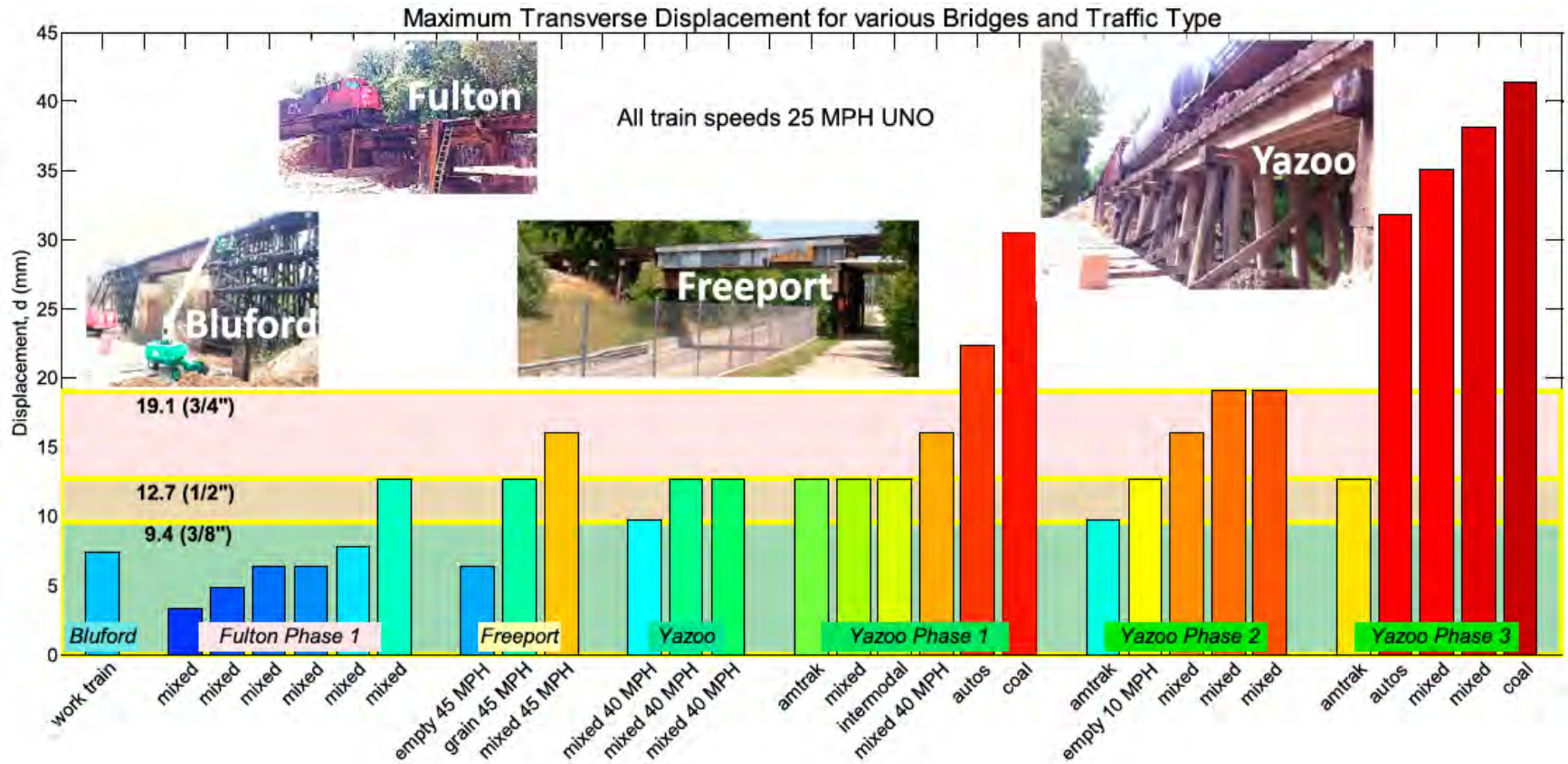
companies, consulting, AAR)
• railroad class (Classes 1, 2 and 3)

The #01 topic of interest is the **assessment of bridge performance** under traffic loading by **measuring displacements.** *(Moreu & Lafave, 2011)*

Background

Railroad bridge displacement measurement

29 train crossing events and different levels of displacements/ concerns



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Background

Railroad bridge displacement measurement

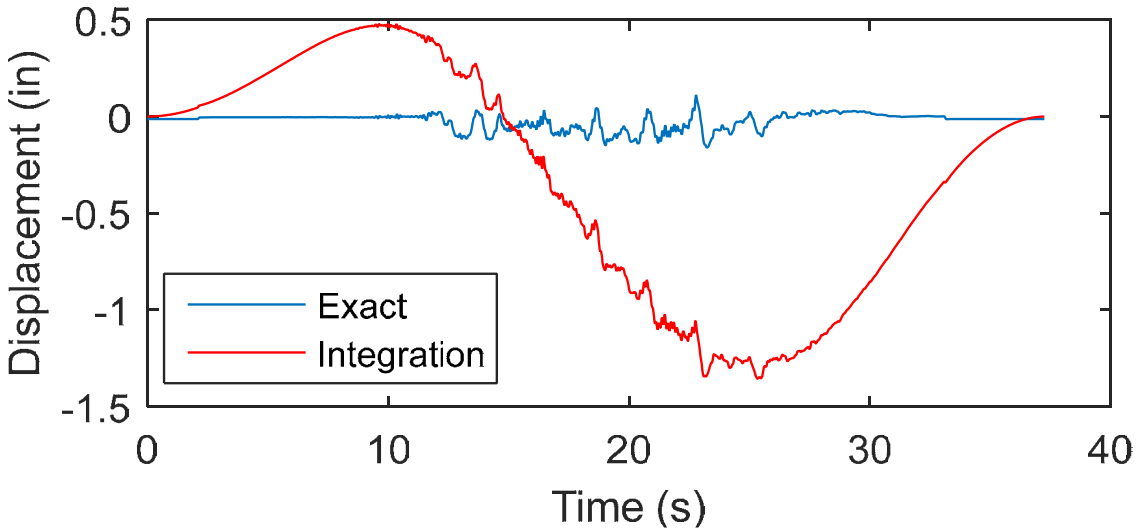
Displacements of bridges under in-service trainloads provide a good measure of the performance of a bridge. However,

- Measuring displacements directly is difficult and expensive
- Acceptable in-service displacement limits have yet to be determined

Background

Railroad bridge displacement measurement

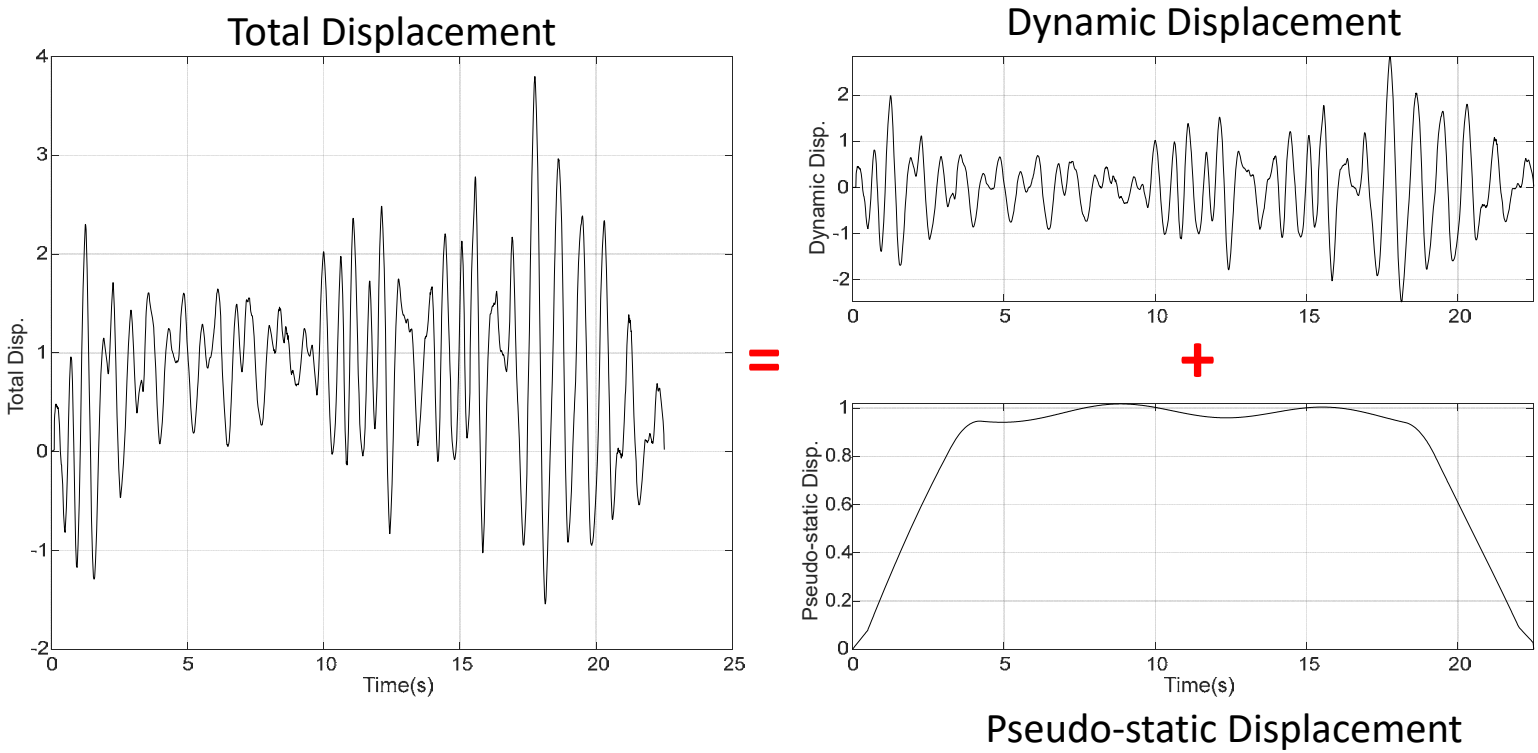
A simple double-integration of the acceleration gives an inaccurate estimation of the displacement due to the low-frequency noise



Background

Railroad bridge displacement measurement

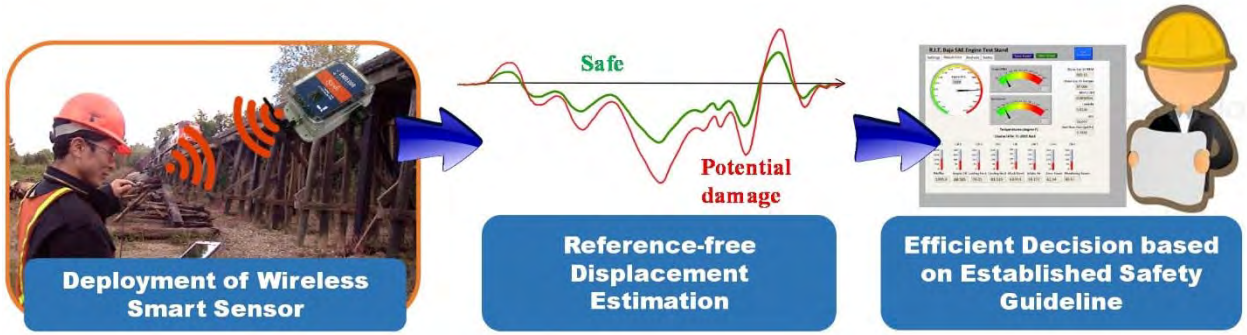
- Dynamic displacement extracted from total displacement by applying a 0.5 Hz high-pass filter



Background

Objectives

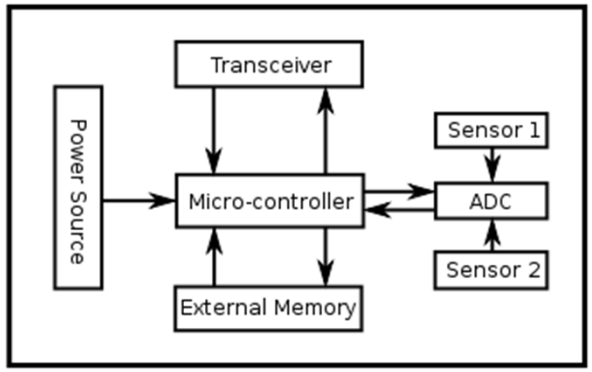
- Employ reference-free estimates of bridge displacement under revenue-service train loads with WSSs
- Subsequently, determine bridge performance and safety guidelines (green, yellow, red) to assist railroads in managing/maintaining bridge assets and prioritizing repairs
- Focus on railroad bridges of higher interest/need for condition assessment, such as timber trestles and steel trusses
- The final result is an inexpensive, effective, quickly deployable, and smart tool to estimate railroad bridge condition

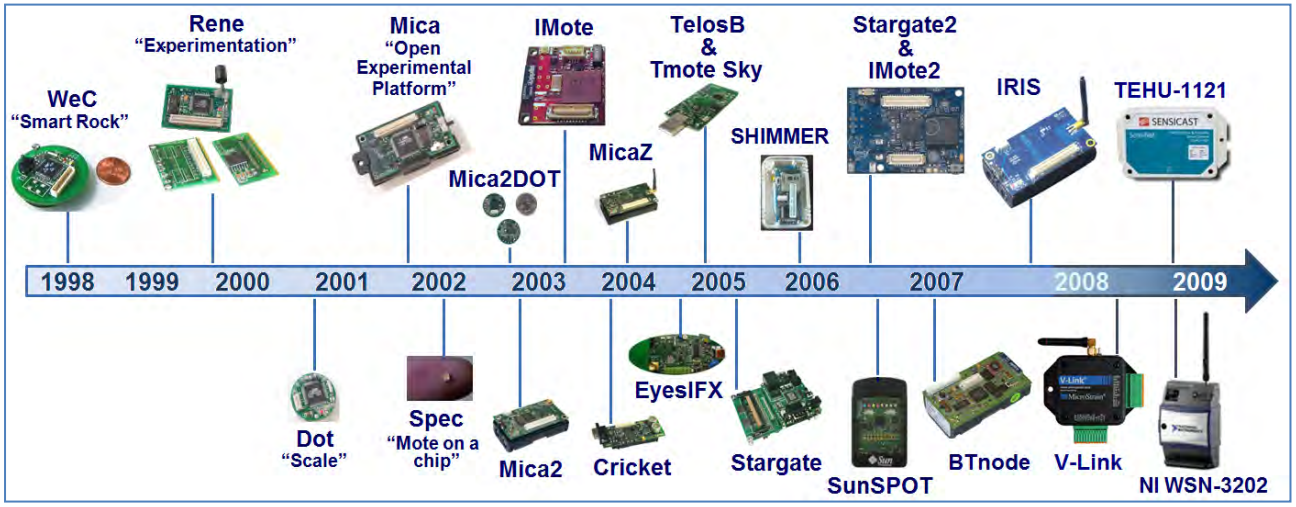


Technology Background

Background

Wireless Smart Sensor

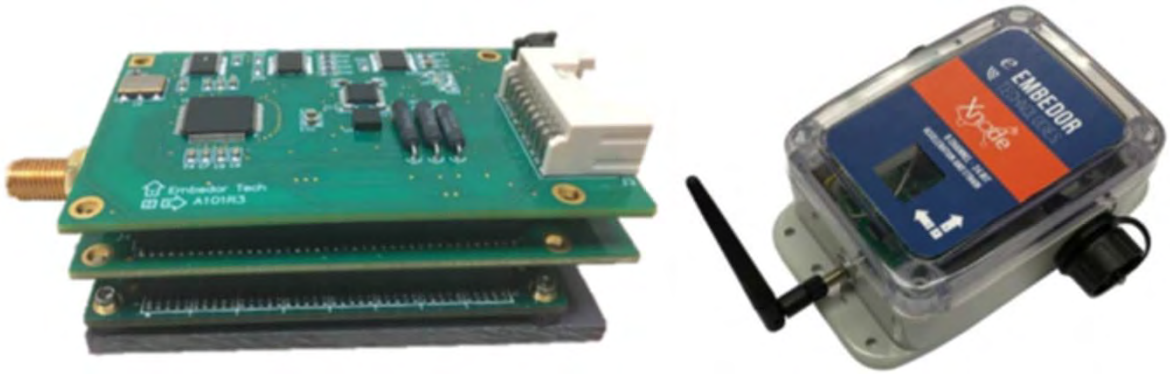




Technology Background

Xnode Wireless Smart Sensor

- Wireless Smart Sensor – Xnode feature overview:
  - High fidelity: 24-bit sensing (acceleration and optional external sensors)
  - Full autonomy: solar powered and end-to-end wireless
  - Online monitoring: near-real-time remote data retrieval and reporting
  - Robust: validated on multiple railroad bridge monitoring campaigns



Technology Background

Wireless smart sensors for dynamic displacement estimation

Measure accelerations with WSS

↓

Time convolution with filter

- Formulated as a minimization problem with regularization to suppress the noise effect
- Optimized for filter coefficients and window length

↓

Dynamic displacements

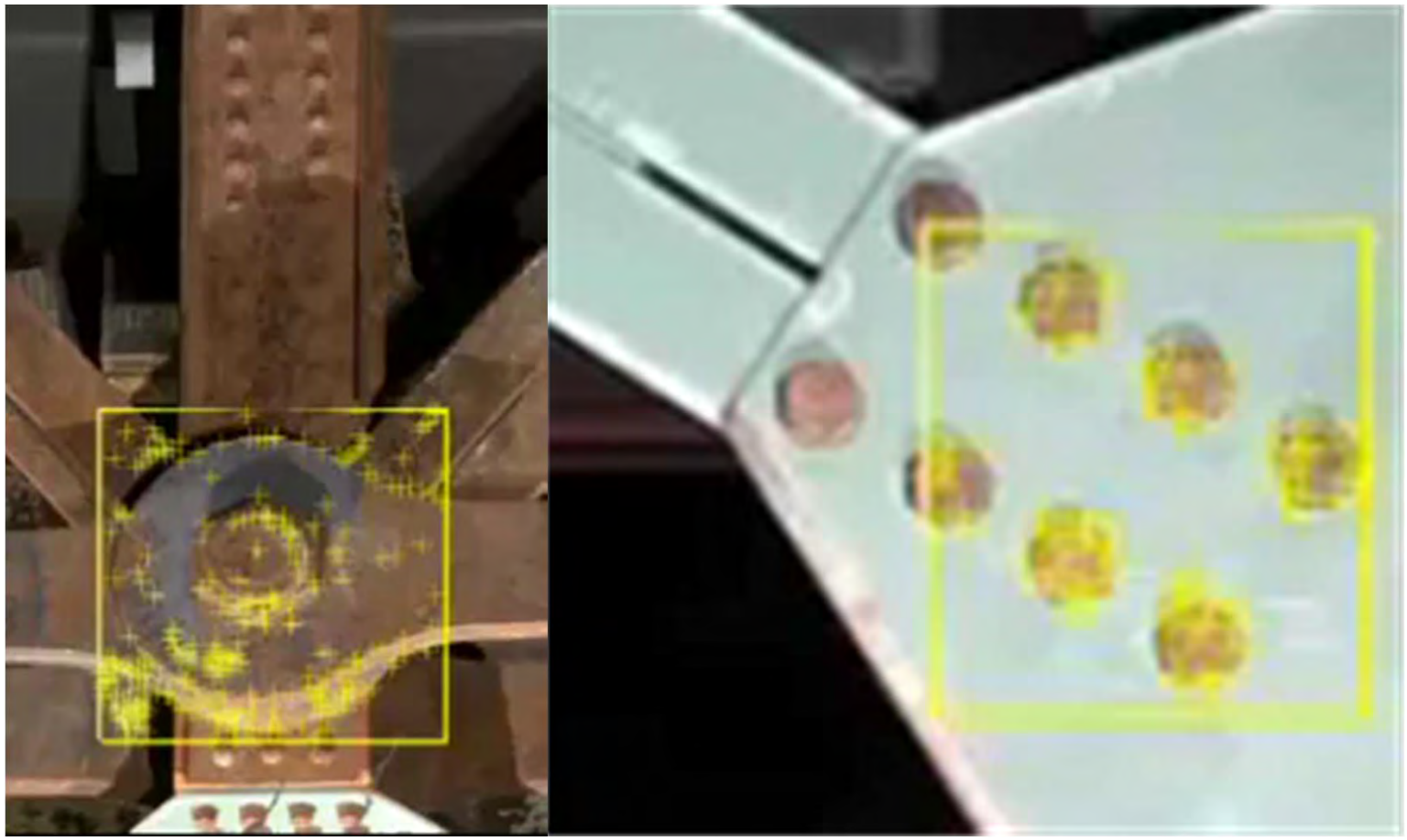
- Hardware-accelerated computation can be performed concurrently with sensing

Technology Background

Wireless smart sensors for dynamic displacement estimation

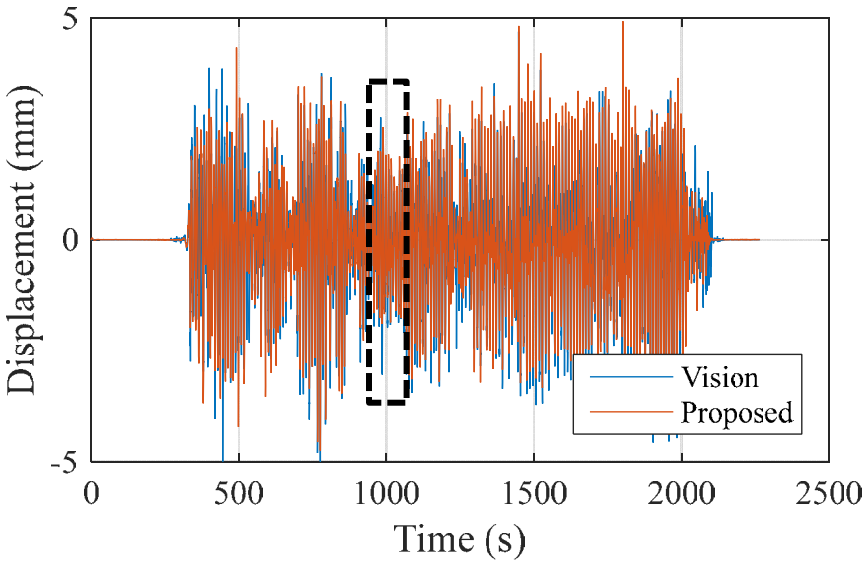
Technology Background

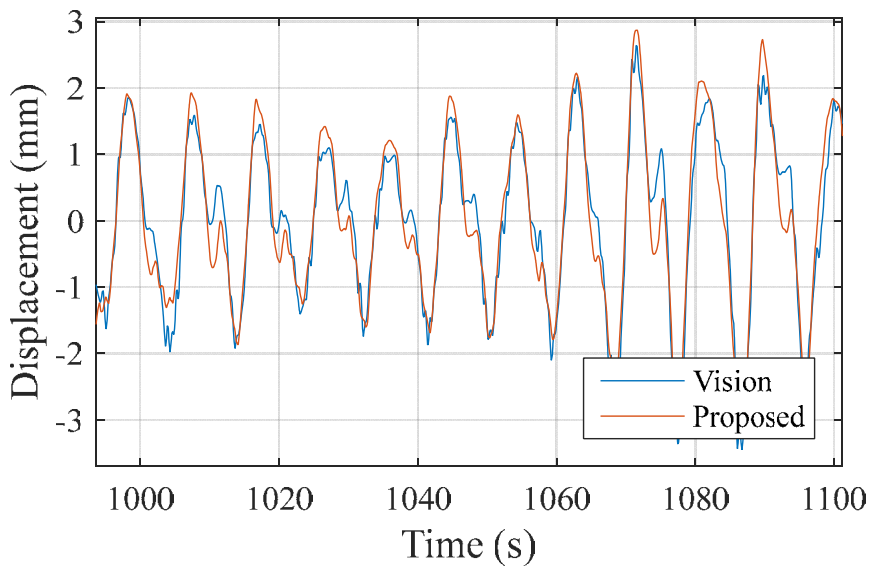
Wireless smart sensors for dynamic displacement estimation



Technology Background

Wireless smart sensors for dynamic displacement estimation





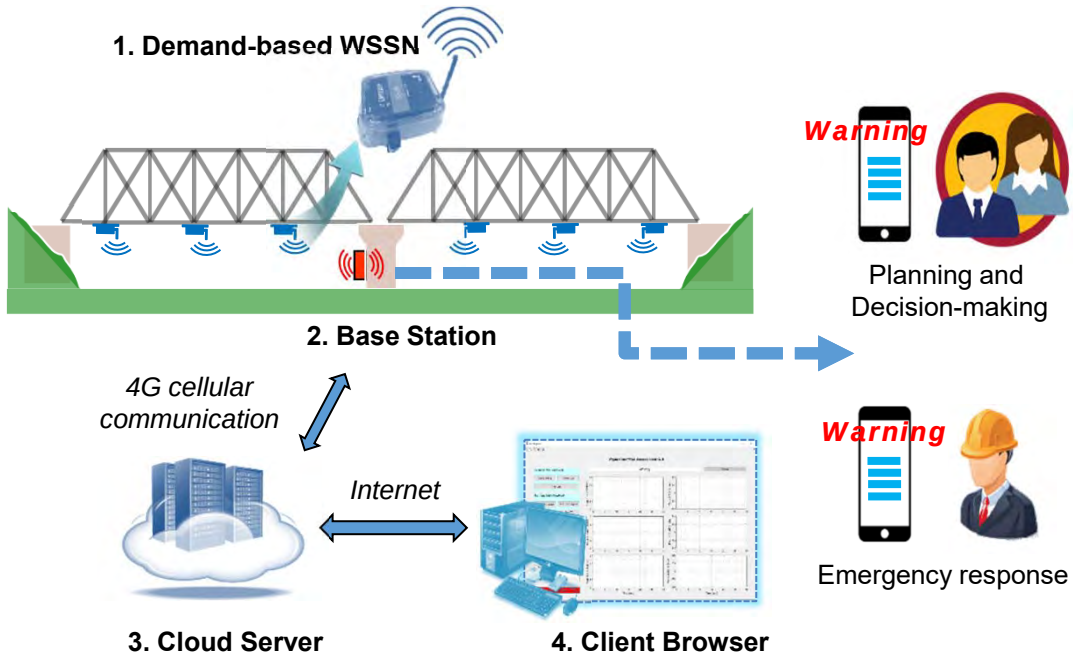
Lateral displacement: Peak-to-peak error = 1%. RMS error =1.6%.

Autonomous Monitoring Framework

Autonomous Monitoring Framework

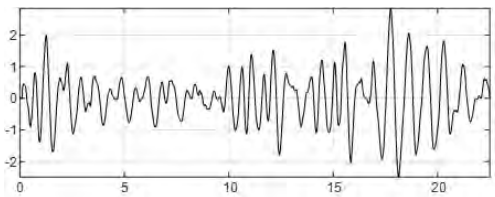
Overview

1. Ultra-low power always-on train detection
2. Real-time onboard displacement estimation
3. 4G-LTE technology
4. Cloud-based data management

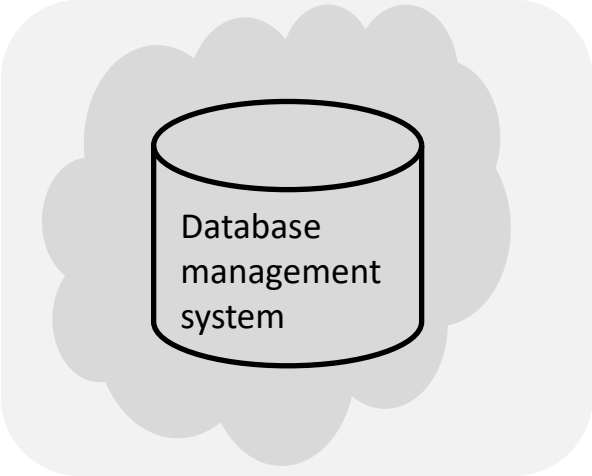


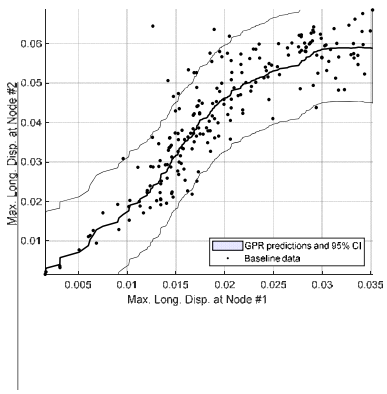
Autonomous Monitoring Framework

Overview - From sensor data to actionable information

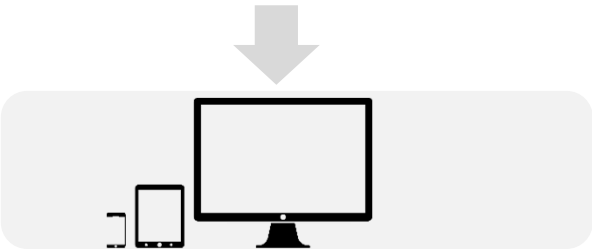


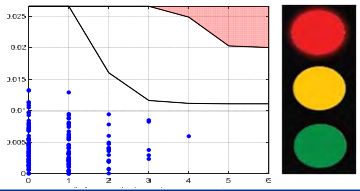
- Synchronized sensing
- Orientation estimation and adjustment
- Displacement estimation





- Short- and long-term change detection
- Raw and processed data stored in relational databases for optimal storage and query



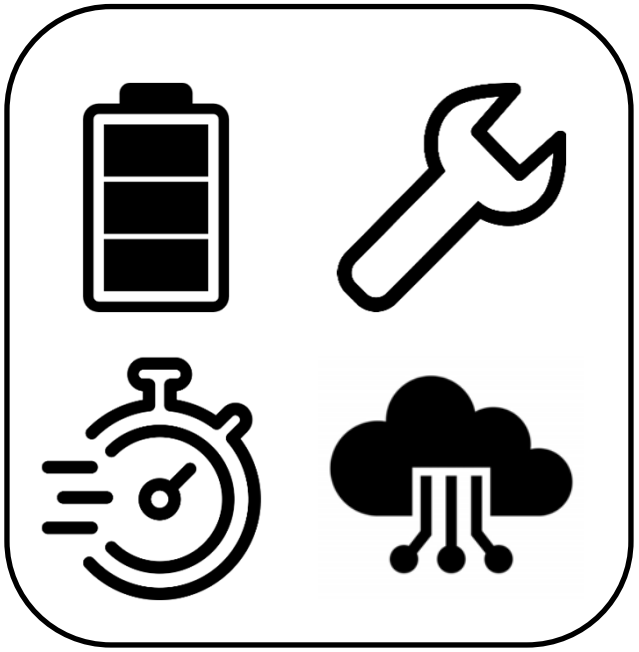


- Rapid preliminary assessment

Autonomous Monitoring Framework

Overview - Sensor-in-a-box

- **Sensor-in-a-box**: No extra installation steps, only turn on, and instrument
- **Ultra-low power consumption**: can stay in sleep-mode for >2 years
- **Intelligent reconstruction**: multi-sensors data fusion provides entire event records
- **Low-delay data retrieval**: end-user can receive detailed event report in 2-3 minutes
- **Quick assessment**: Edge-computing and cloud-computing are harnessed for rapid assessment



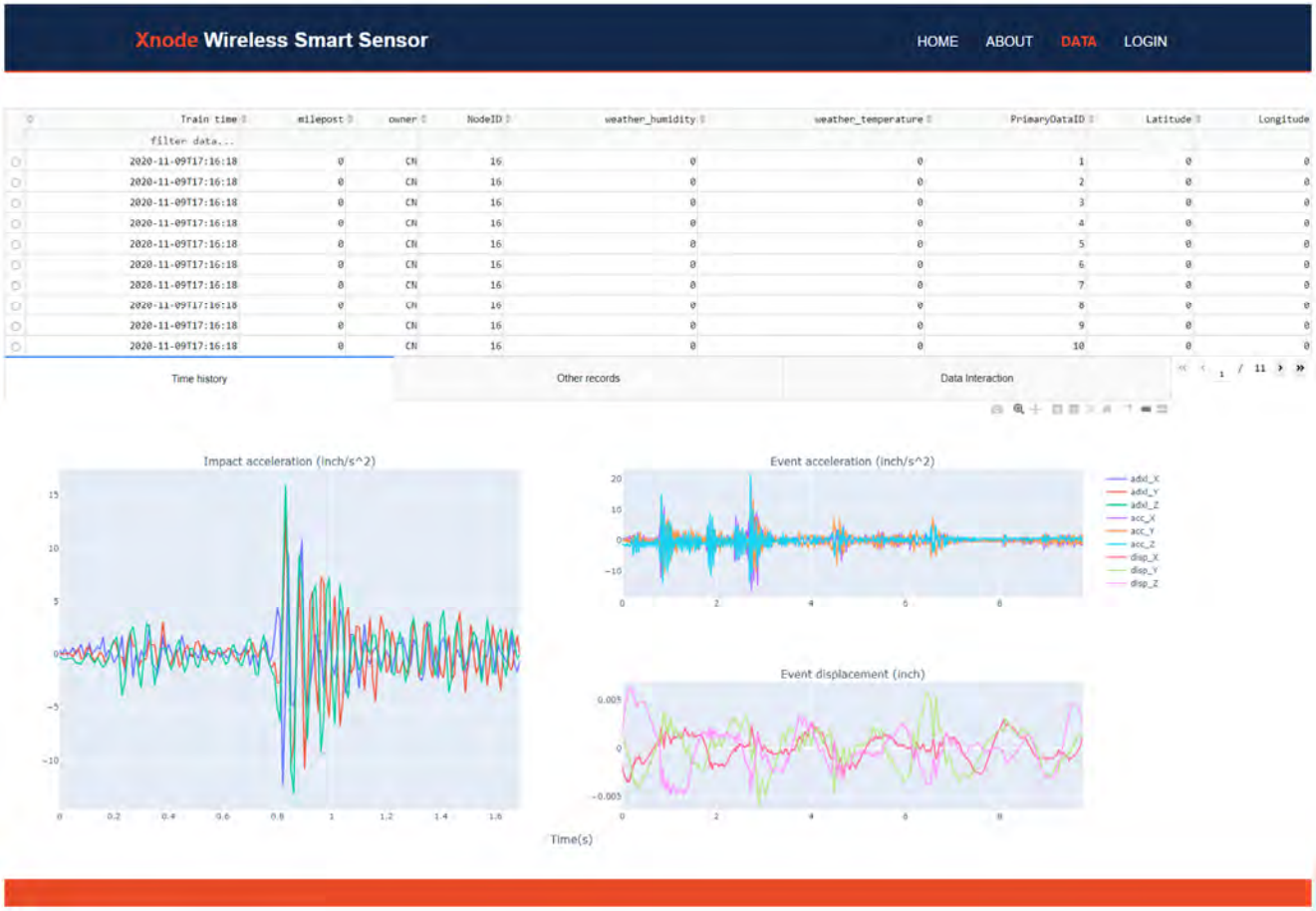
Autonomous Monitoring Framework

Interactive web interface

Autonomous Monitoring Framework

Interactive web interface

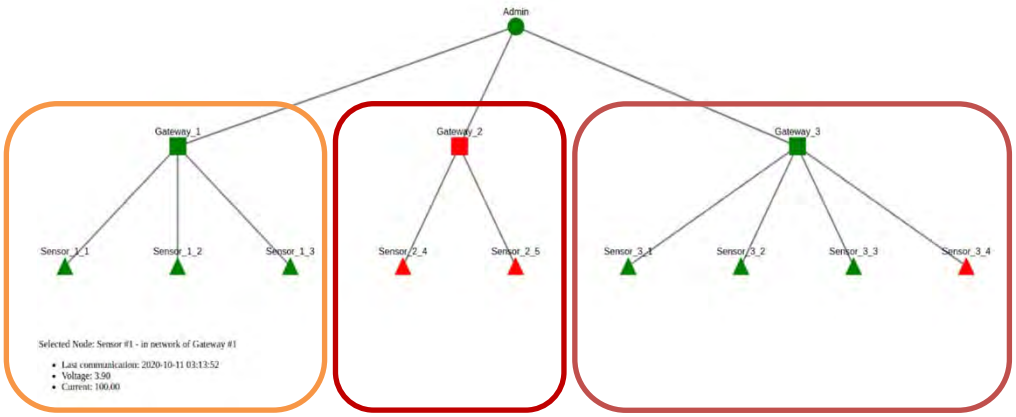
- Near-real time remote data access

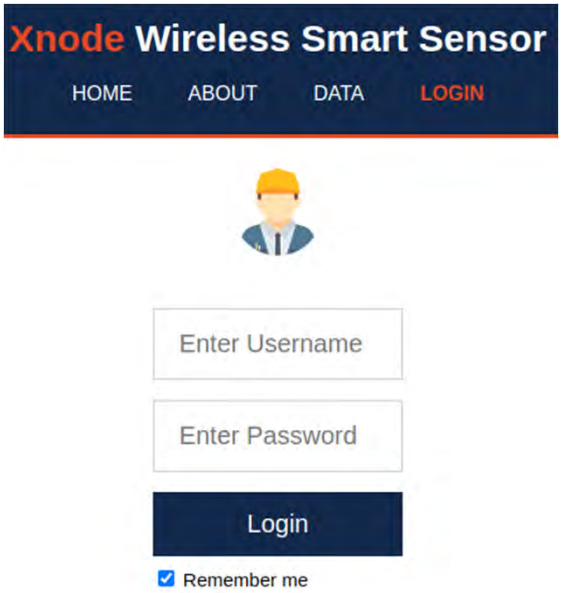


Autonomous Monitoring Framework

Interactive web interface

- Secure user authentication for data access
- Real-time network condition reporting
- Raw and processed data exporting support





A	B	C	D	E	F	G	H	I
	Time (s)	Acc. X (inch/s^2)	Acc. Y (inch/s^2)	Acc. Z (inch/s^2)	Disp. X (inch)	Disp. Y (inch)	Disp. Z (inch)	
0	0	392.4229899	29.79484404	50.15598565	-0.00661761	0.02106506	-0.010000579	
1	0.01	443.9429576	12.99388147	50.28793774	-0.013213538	0.024683172	-0.008032038	
2	0.02	425.1874039	-13.92645807	66.08128546	-0.018031779	0.028930917	-0.004582592	
3	0.03	431.9106804	24.85837019	88.30103215	-0.022412414	0.031563208	0.001788357	
4	0.04	434.7210395	-46.80959986	42.20191929	-0.02581126	0.033382767	0.012377461	
5	0.05	446.8680782	39.28610981	50.34711529	-0.027683117	0.03170983	0.023816705	
6	0.06	416.222674	43.33276425	8.805586802	-0.027596557	0.031669913	0.03578574	
7	0.07	391.8585615	-33.95544692	-11.64714599	-0.027749714	0.033987233	0.045271297	
8	0.08	416.769947	-18.28076801	18.98546097	-0.030280849	0.034042437	0.050305025	
9	0.09	417.1642362	13.2063109	12.80562971	-0.033562647	0.030724523	0.052963553	
10	0.1	396.8361816	62.67534508	7.09704644	0.027723925	0.02726991	0.053007601	

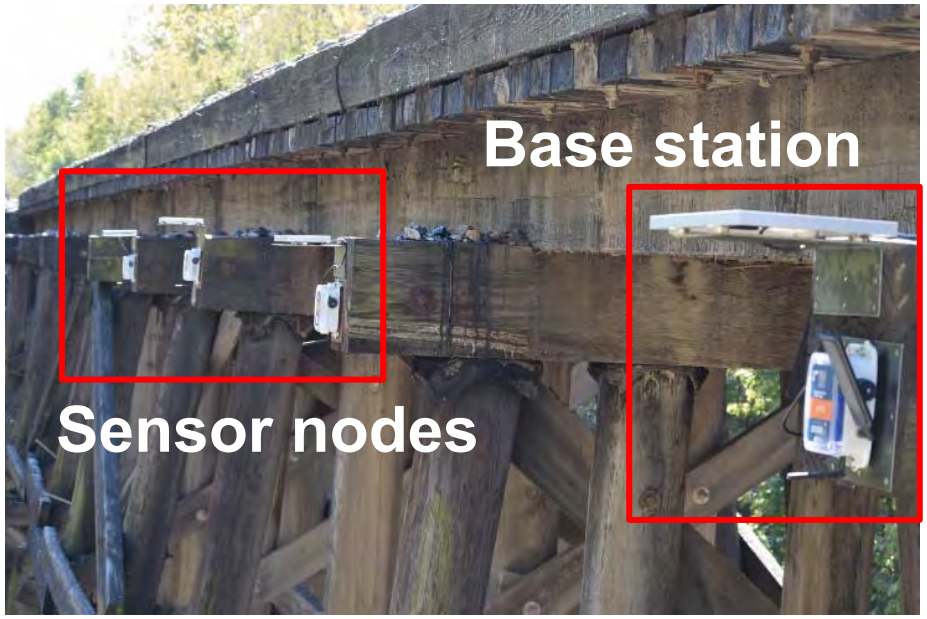
2019-01-07 08-12-45 | 2019-01-07 14-25-50 | 2019-01-07 14-58-31 | 2019-01-07 22-25-52 | 2019-01-07 22-

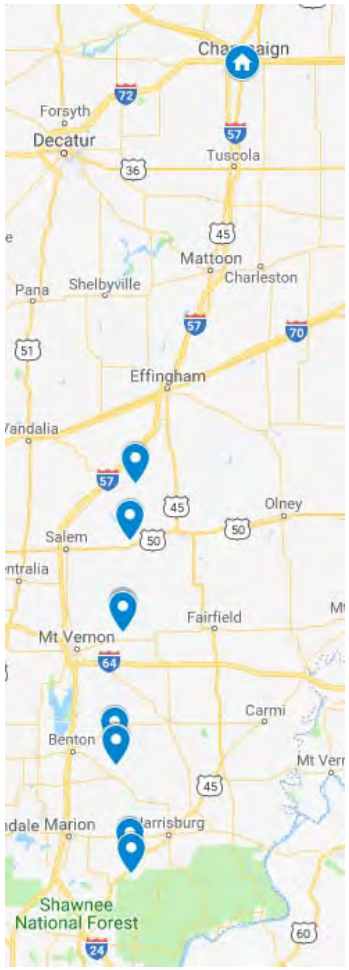
Data driven inspection analysis

Data driven inspection analysis

Timber trestle bridges long-term monitoring – Overview

- Two campaign-style deployments, one year apart
- 1-2 months deployment duration





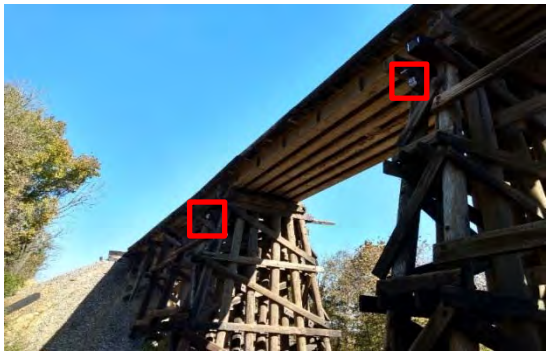
Bluford Subdivision, Illinois

Data driven inspection analysis

Timber trestle bridges long-term monitoring – Overview

- ~5 minutes installation time per sensor

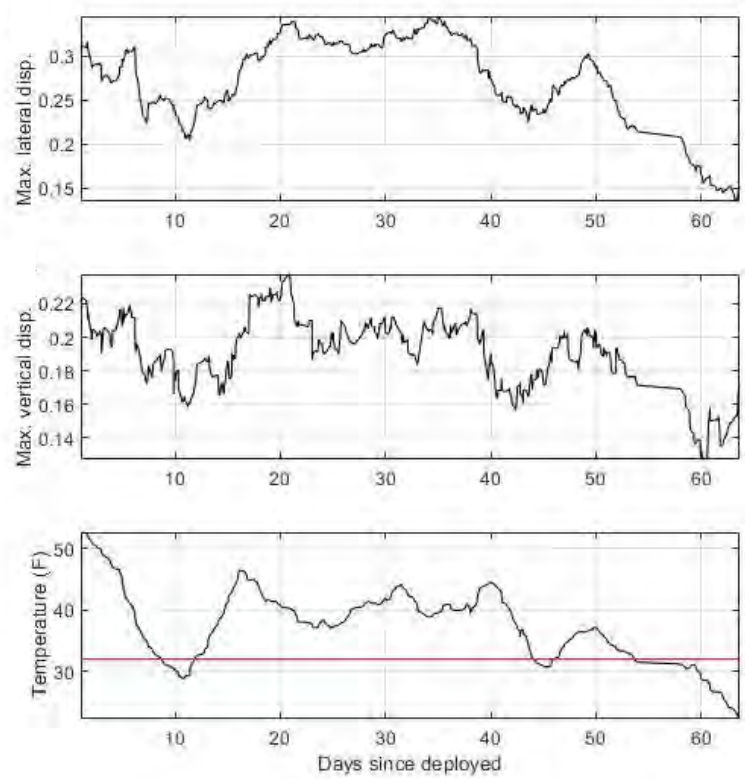


Data driven inspection analysis

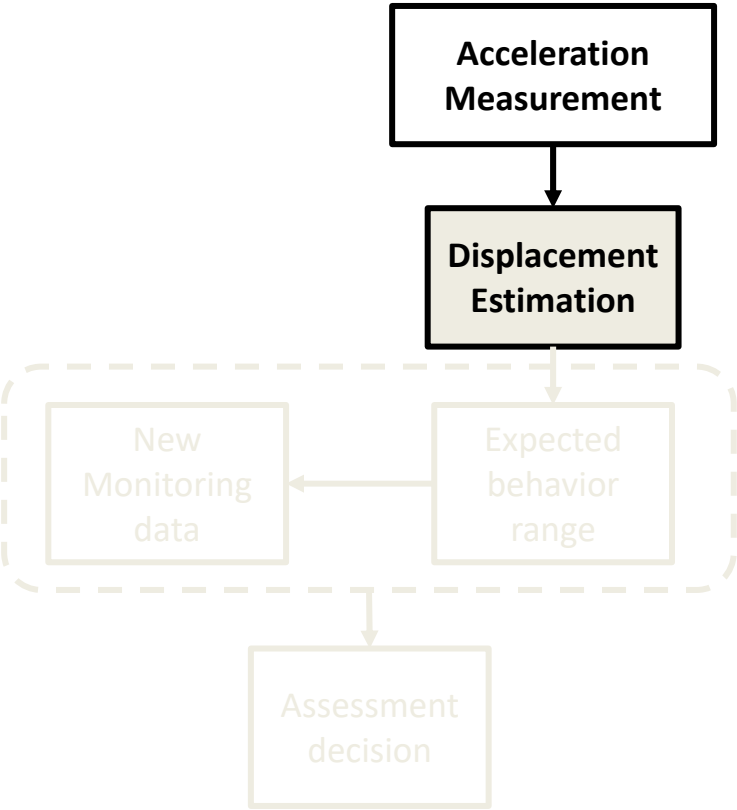
Timber trestle bridges long-term monitoring – Overview

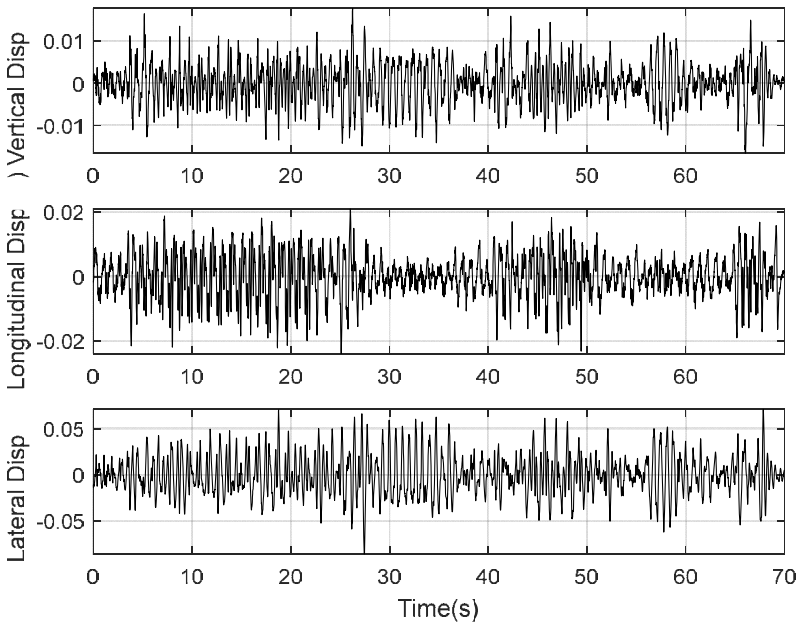
- Structural behavior is highly correlated with operational and environmental conditions
- Gaussian Process Regression is used to standardize the measurements with respect to those factors
- Statistical Process Control is then used for automatic change detection



Data driven inspection analysis

Timber trestle bridges long-term monitoring – Framework

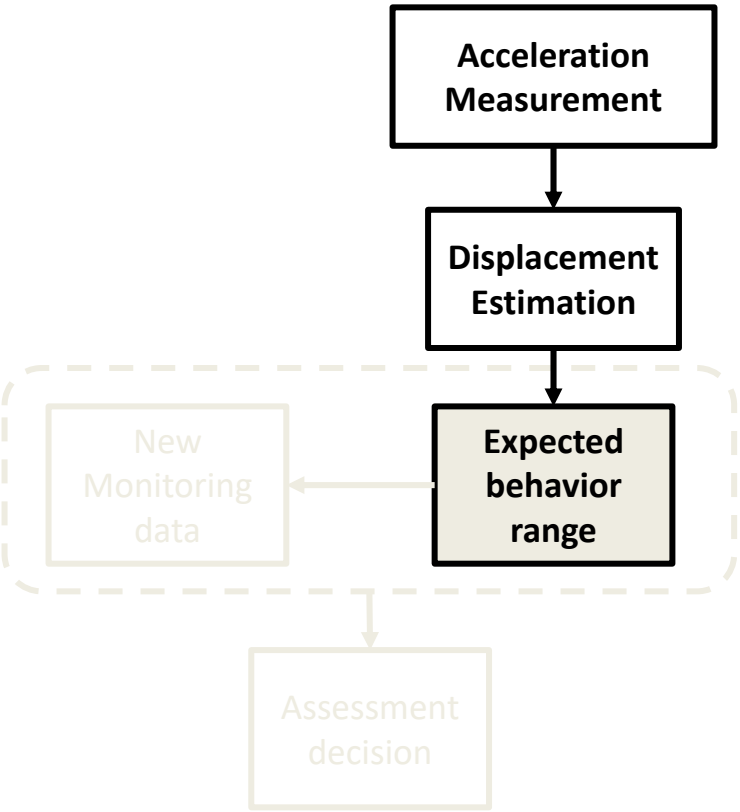


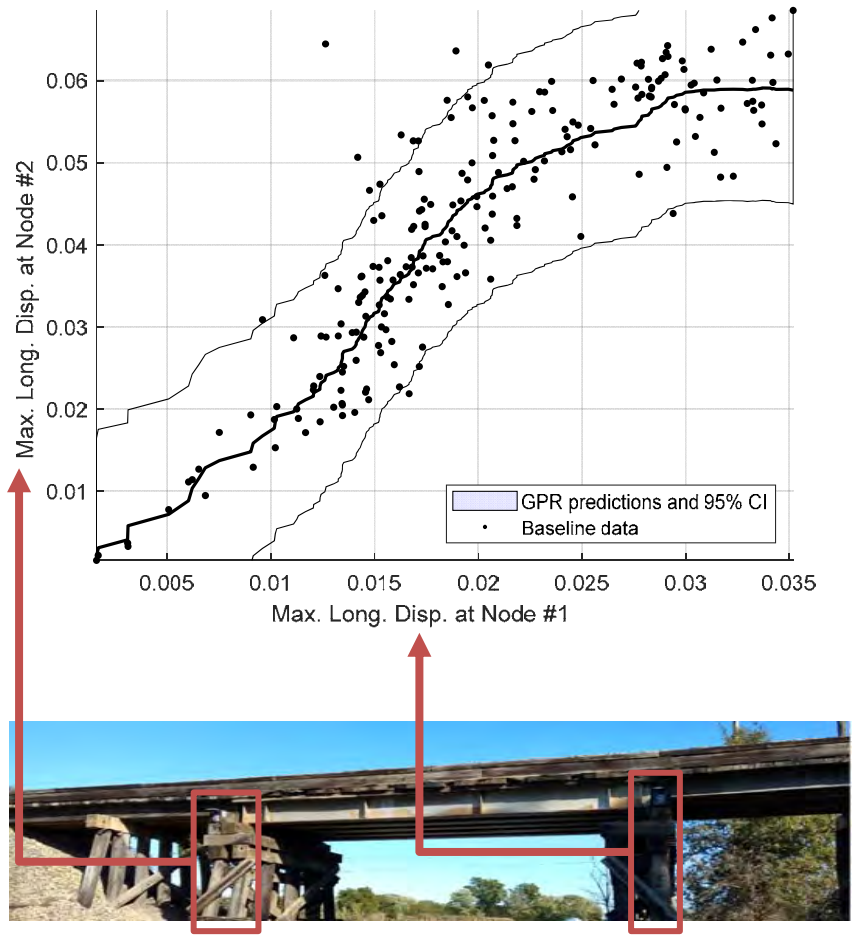


Displacement is computed and orientation-adjusted onboard

Data driven inspection analysis

Timber trestle bridges long-term monitoring – Framework

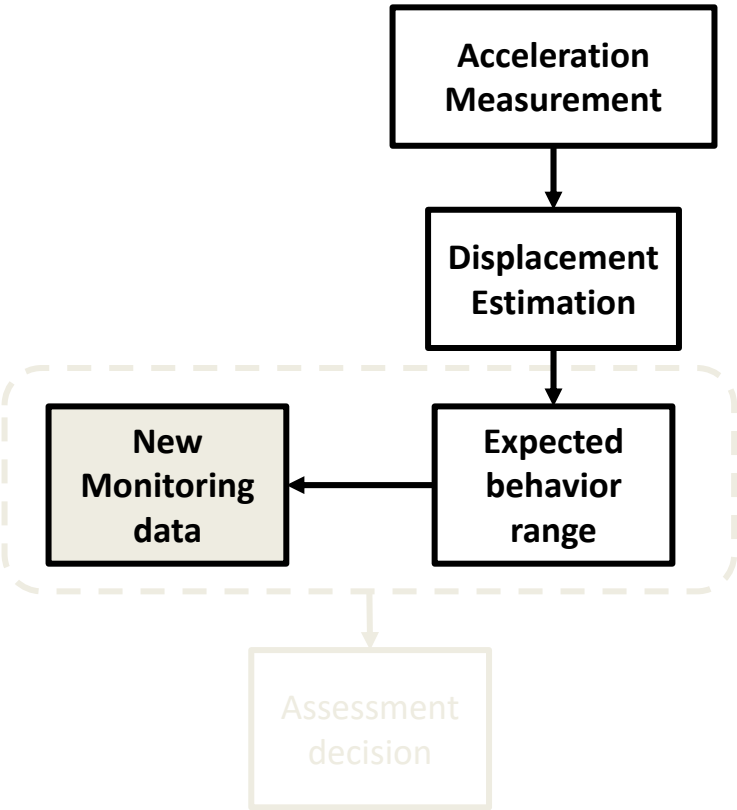


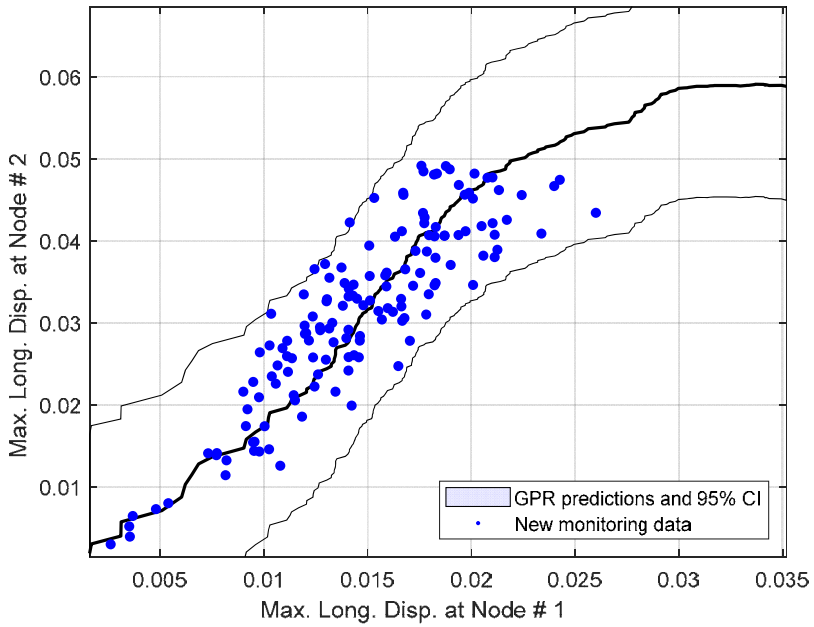


Features of maximum displacement at multiple piers are correlated

Data driven inspection analysis

Timber trestle bridges long-term monitoring – Framework

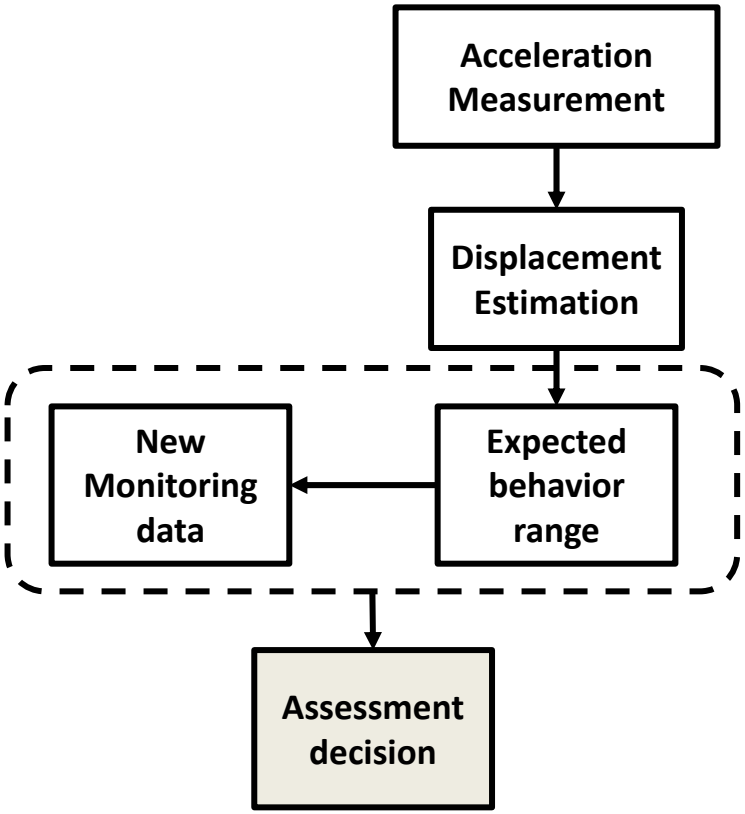




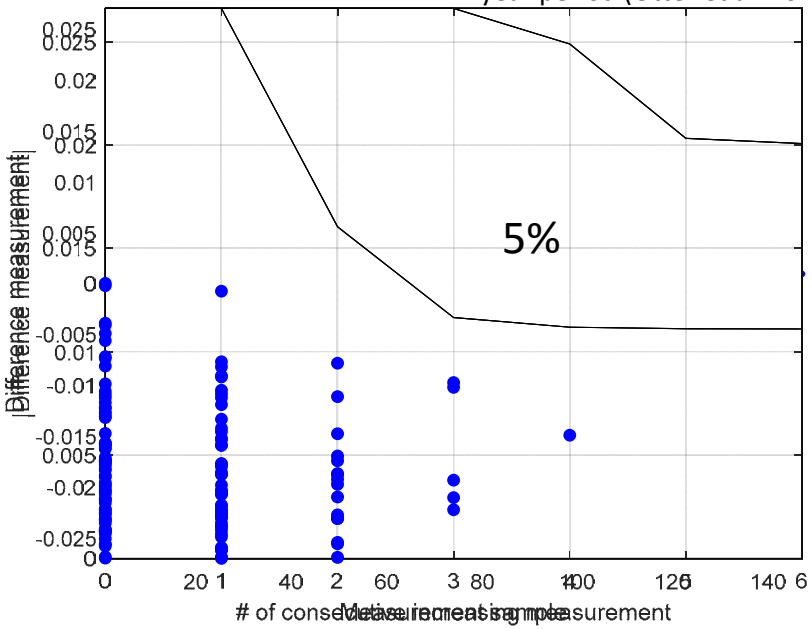
New measurements are compared against the model

Data driven inspection analysis

Timber trestle bridges long-term monitoring – Framework



0.15% - 8563 incidents over 10 year period (Otter et al. 2012)



Classification based on the abnormally high displacement as well as gradually drifting away from expected behavior range

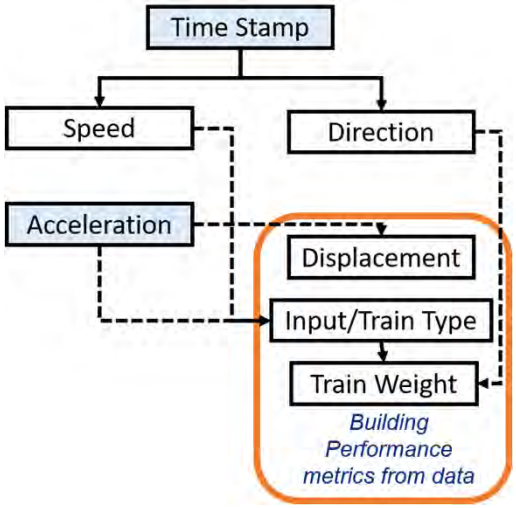
Otter, D., Joy, R., Jones, M. and Maal, L. (2012). Need for Bridge Monitoring Systems to Counter Railroad Bridge Service Interruptions. *Transportation Research Record: Journal of the Transportation Research Board*, 2313(1), pp.134-143.

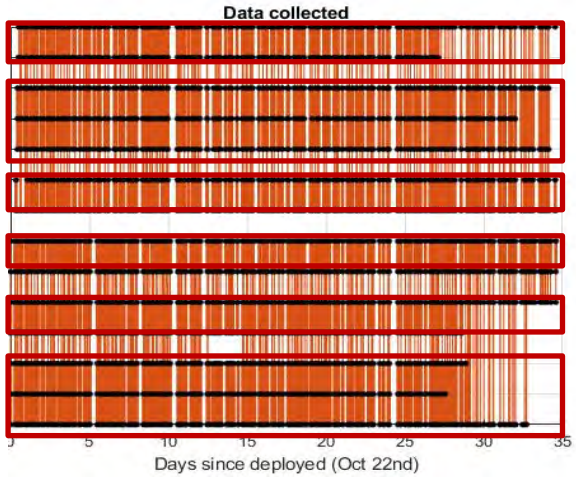
Data driven inspection analysis

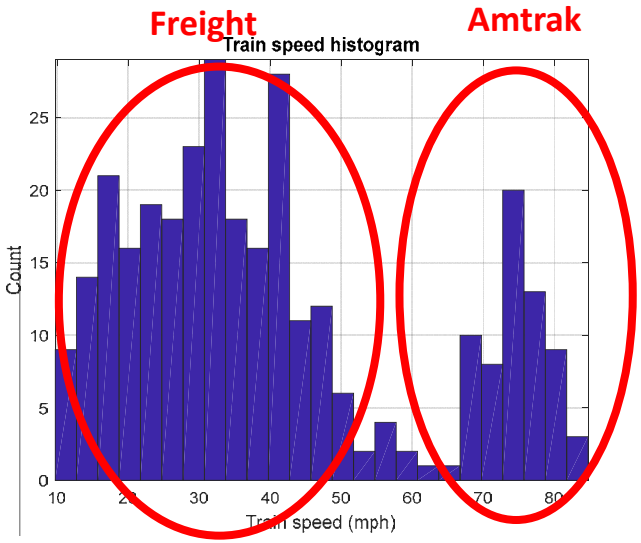
Timber trestle bridges long-term monitoring – Framework

Detected train crossings:

- 3,200 data sets collected
- 260 distinct trains tracked across multiple bridges
- Trains classified by speed, length, and weight



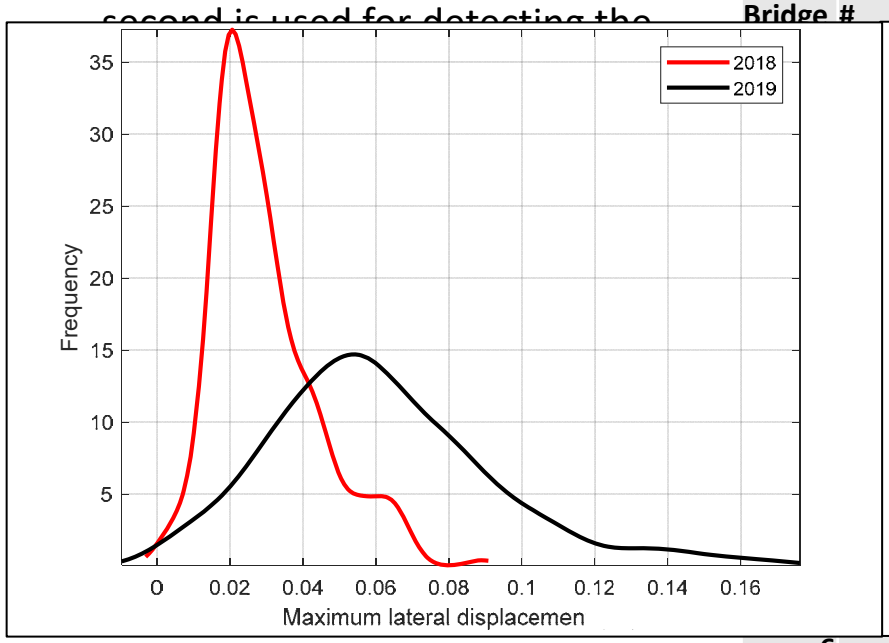


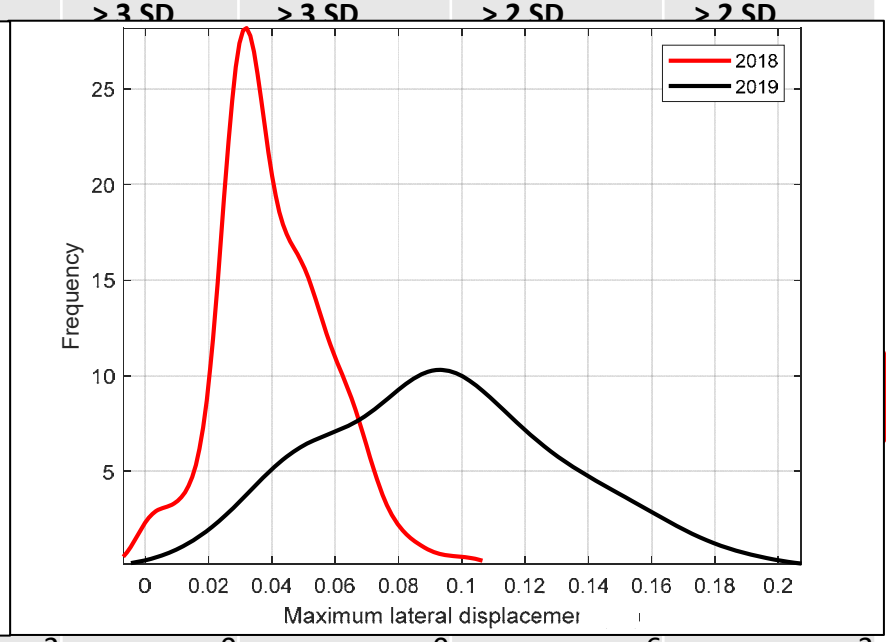


Data driven inspection analysis

Timber trestle bridges long-term monitoring - Results

- Data from first deployment is used for training, while data from the second is used for detecting the

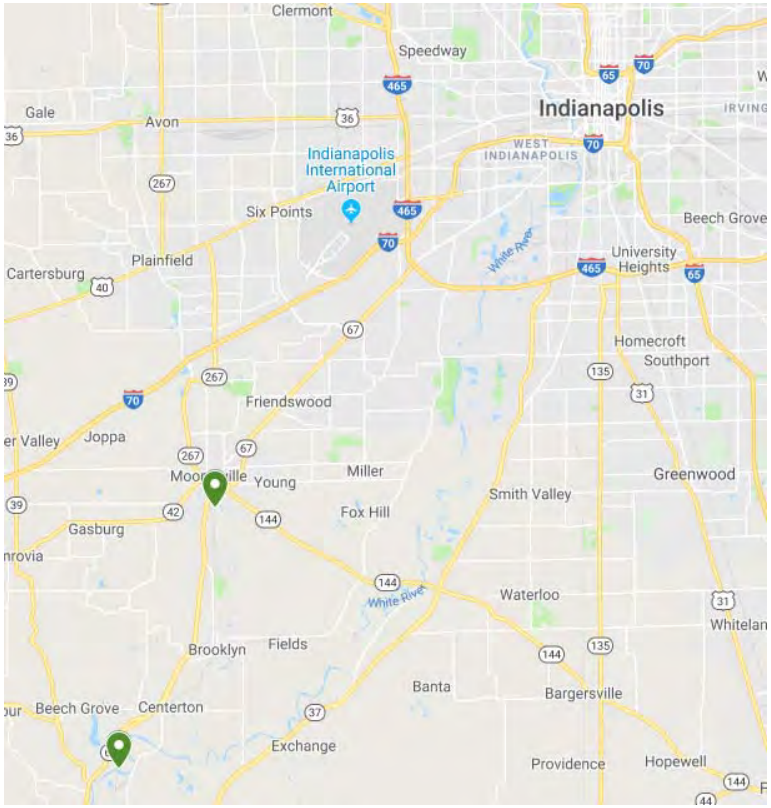




Bridge #	Node	# data points > 3 SD	More than 3 cons. points > 3 SD	# data points > 2 SD	More than 3 cons. points > 2 SD
6	2	0	0	6	3
6	3	0	0	3	0

Data driven inspection analysis

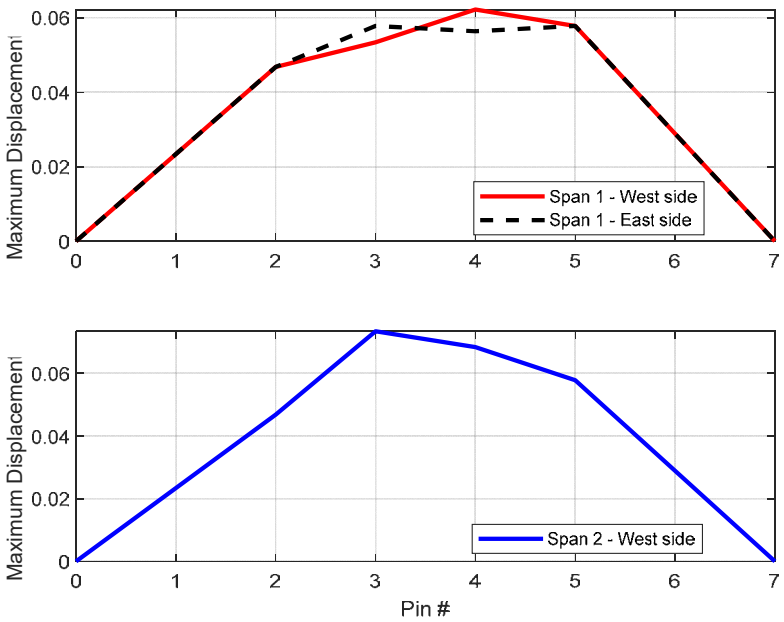
Steel truss bridges short-term monitoring



Spencer Subdivision, Indiana

Data driven inspection analysis

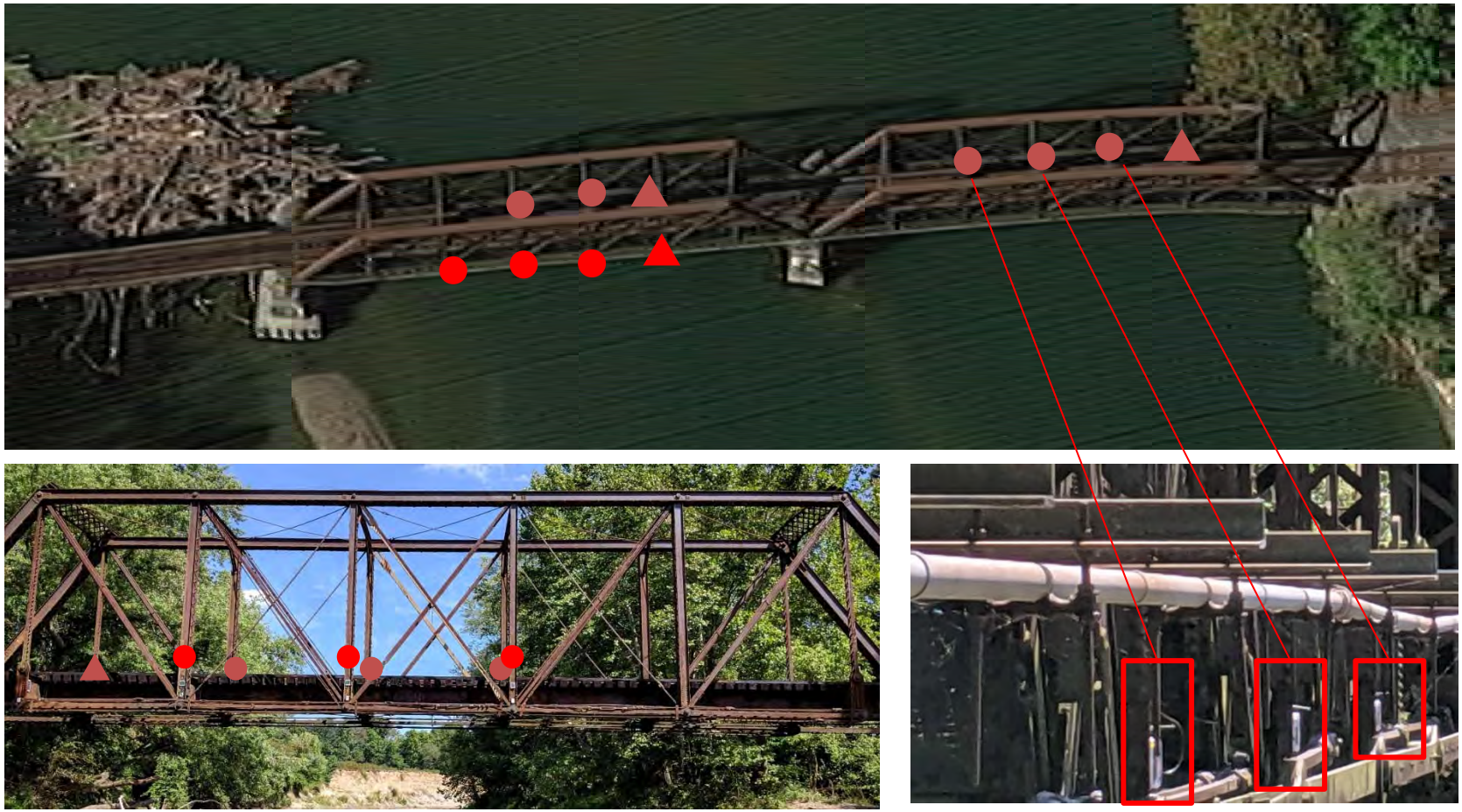
Steel truss bridges short-term monitoring – Bridge 1



*Inspection Report (Oct 2018) showed no section loss in the trusses

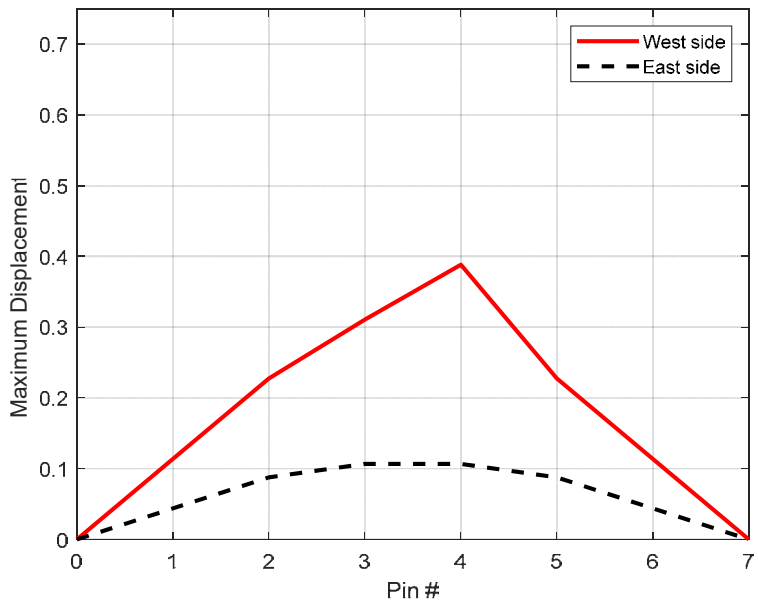
Data driven inspection analysis

Steel truss bridges short-term monitoring – Bridge 2



Data driven inspection analysis

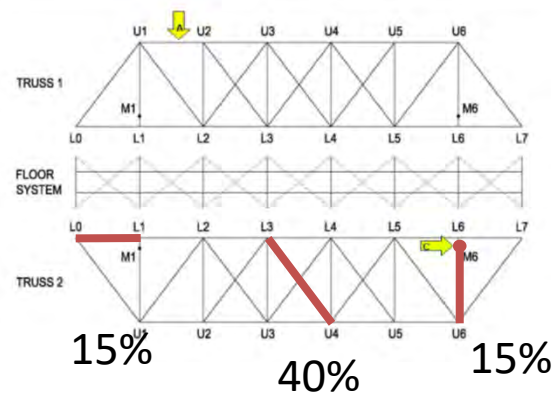
Steel truss bridges short-term monitoring – Bridge 2



*Inspection Report (Oct 2018) showed the truss on the West side had multiple members with section loss, while the East side had no section loss

West

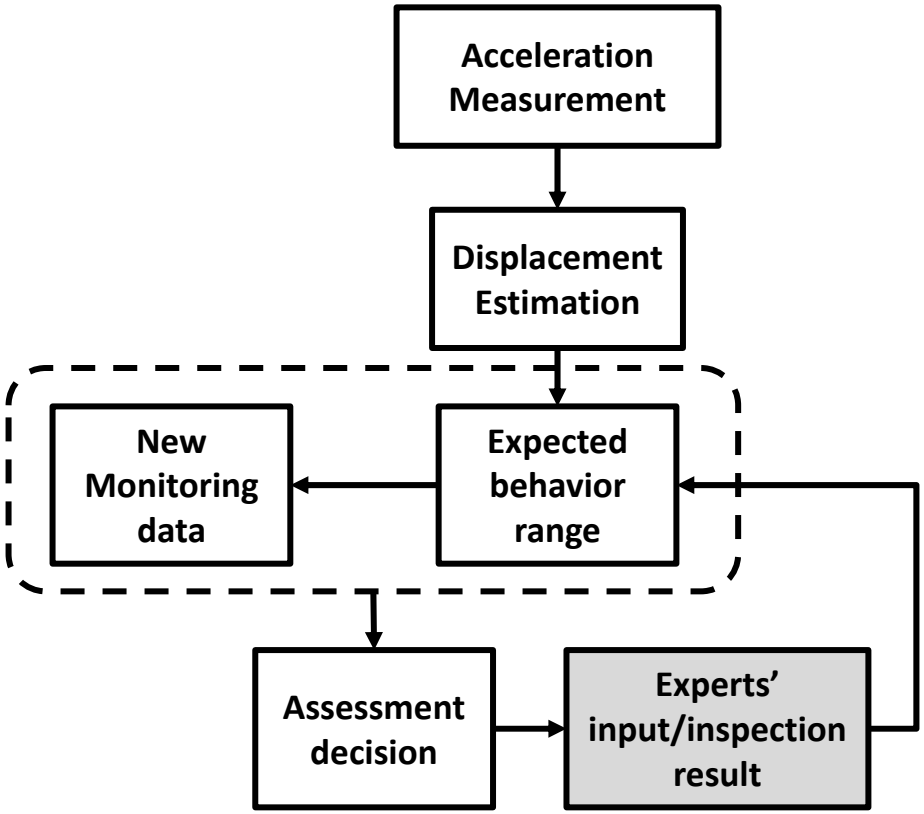
East



Data driven inspection analysis

Future outlook

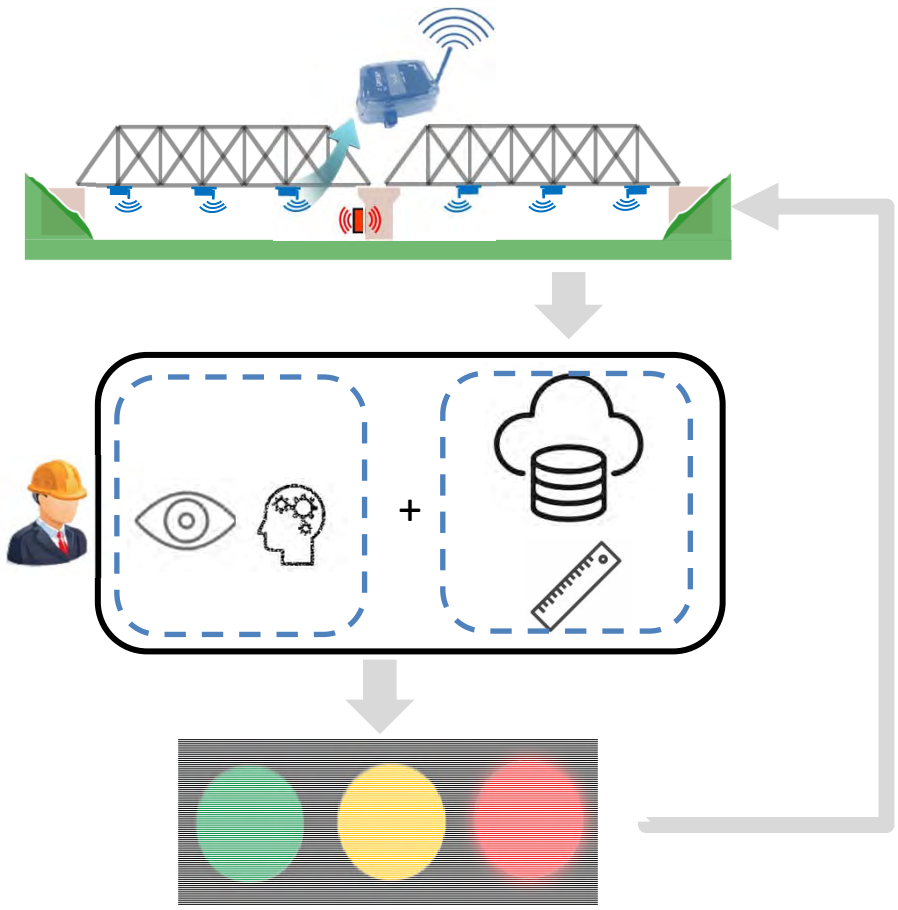
- Baseline framework is fully autonomous, with no human in the loop required
- Optionally, can incorporate experts' input to refine the subsequent classification outputs



Data driven inspection analysis

Future outlook

- Initial target structures for monitoring are ones with known structural concerns and/or scheduled for major maintenance or replacement.
- Inspection results are incorporated into the monitoring system and database for re-calibration of future monitoring campaigns.



Conclusions

- A fully autonomous tool assisting railroad bridge inspections under service load was developed and validated with full-scale deployments
- Provides an inexpensive, quickly-deployable means of obtaining bridge displacements under train loads
- This smart sensor technology is used to overcome limitations of existing wired and wireless monitoring systems
- Additional capabilities to meet the needs of the rail industry are being implemented for this platform, e.g., impact detection

Opportunity to Participate

- We are seeking industry partners to conduct additional field testing and validation (i.e., beta testers)
- Opportunity to instrument and monitor structures that are of interest to you
- In particular, seeking deployments on bridges with known or suspected structural issues
- Thanks to FRA support, monitoring system can be provided at no cost for these deployments

Acknowledgement

We want to thank CN and G&W for their strong support of our monitoring campaigns on their bridges. The support of the FRA is also gratefully acknowledged.

Sponsors

Cameron Stuart (FRA Manager)

Industry Partners

Questions?

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