Advances in Infrastructure Delivery and Stewardship – R&D Perspective

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Outline

- A Research Perspective on Infrastructure:
  - A nervous system for our infrastructure:
    - Why is this needed?
    - Implications for the Measurement Science needs?
- Challenges as per Workshop Baseline Document
- Some relevant project activity related to these challenges
- Summary

A Research Perspective:
Nervous systems for our infrastructure systems?

An Infrastructure Nervous System…

- **Senses** the usage, condition, and contextual environment of each infrastructure component within a system
- Able to **recognize “pain”** within the system, such as excessive stress, damage due to impact or corrosion, loss of support
- Maintains a **memory** over time and space (for future)
- Maintains a **model of its current behavior**
- **Alerts decision makers** about need for early action and **assists them** in exploring effective actions

…Leads to Better Management of Infrastructure

- In Jan 2006, a bridge collapsed onto I-70
- Interstate 70 was closed for several days
- The bridge had been recently inspected and given a rating of 4 out of 10

- Extensive corrosion damage to the pre-stressing cables and reinforcing bars in the concrete beam is believed to have contributed to the failure.
- The extent of this damage was not detected during visual inspection.
- More recently: I-35, I-95, Birmingham Bridge…

And bridges are the best of the infrastructure class….

Subject	2001 Grade	2005 Grade	2009 Grade
Bridges	C	C	C
Dams	D	D	D
Drinking Water	D	D-	D-
National Power Grid	D+	D	D+
Navigable Waterways	D+	D-	D-
Roads	D+	D	D-
Solid Waste	C+	C+	C+
Transit	C-	D+	D
Wastewater	D	D-	D-
5 yr Investment Needs = $2.2 Trillion			

Source = ASCE.ORG website

…Leads to More Sustainable Operations

- “If you can't measure it, you can't manage it”
  - Peter Drucker

- There are many claims being made about energy savings, water conservation practices, emissions reductions, etc.

- How do we know that a LEED Silver building will operate in an environmentally sustainable manner?

- How do we know that a high efficiency furnace continues to operate with high efficiency?

- We must measure the environmental performances over time and space to know how well the building is performing
  - E.g., energy usage, water usage, air quality, temperature, humidity

…Leads to More Informed Future Design Activity

- Each instance of infrastructure will maintain detailed records of:
  - As designed and as-built records
  - Construction challenges associated with the designs
  - usage, performance and deterioration over time
  - Compliance with existing codes

- Collections of data about such instances provides:
  - extensive information useful for future design activity
  - High quality, contextual deterioration models
  - Sections of codes that may need more attention and study

… Leads to More Informed Delivery Process

- Sensing during the construction process provides
  - Detection of deviations between as-designed and as-built info
  - More accurate as-builts
  - Support for commissioning
  - Continuous determination of productivity measures
  - More accurate and more timely cost control information

In Workshop Baseline Document, some needs:

- Cost-effective, field deployable sensing systems:
  - Inspection and monitoring
  - During construction and O&M
- Predictive models of system condition and performance
- Decision support tools that use this information to more economically and reliably deliver and manage infrastructure systems

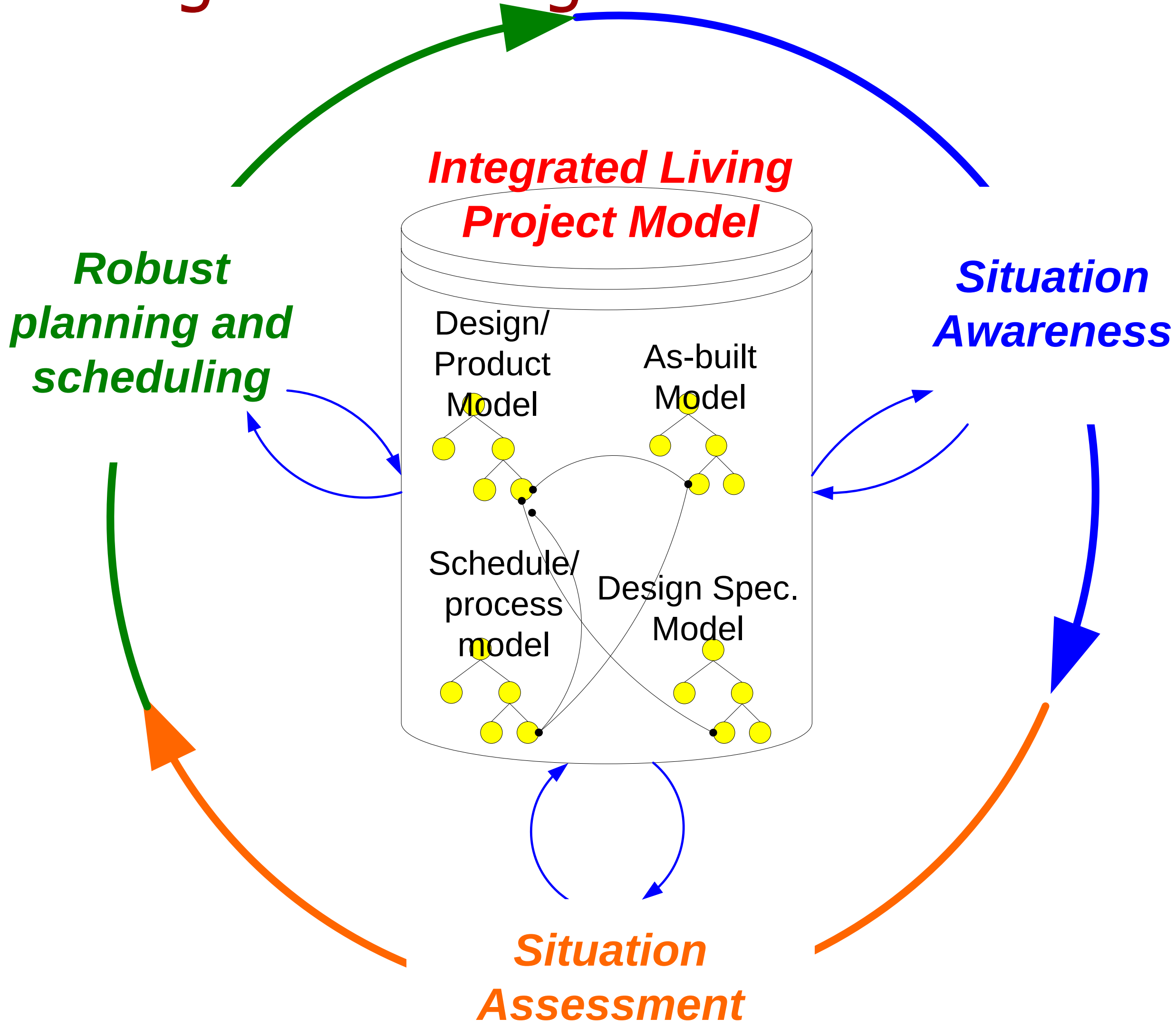
Recent research related to these needs…

- **Cost-effective, field deployable sensing systems:**
  - **Inspection and monitoring**
  - **During construction** and O&M
- Predictive models of system condition and performance
- Decision support tools that use this information to more economically and reliably deliver and manage infrastructure systems

Model-based Sensor-Assisted Construction Engineering and Management

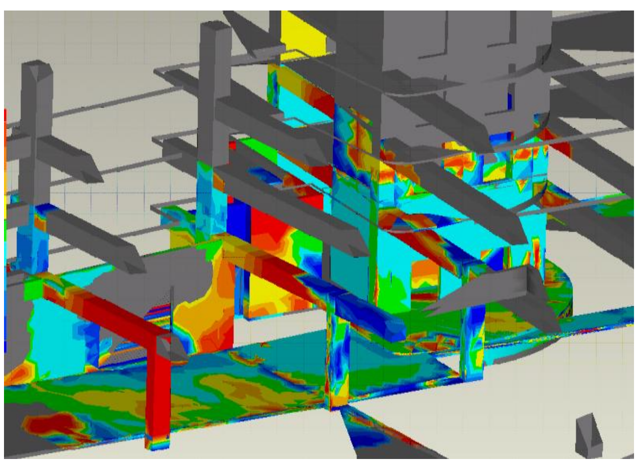
Researchers: Burcu Akinci (CEE)

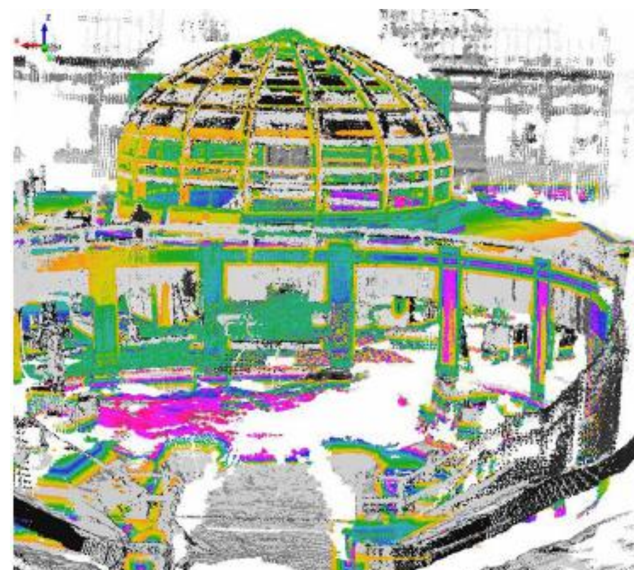
Model-based Sensor-Assisted Construction Engineering and Management



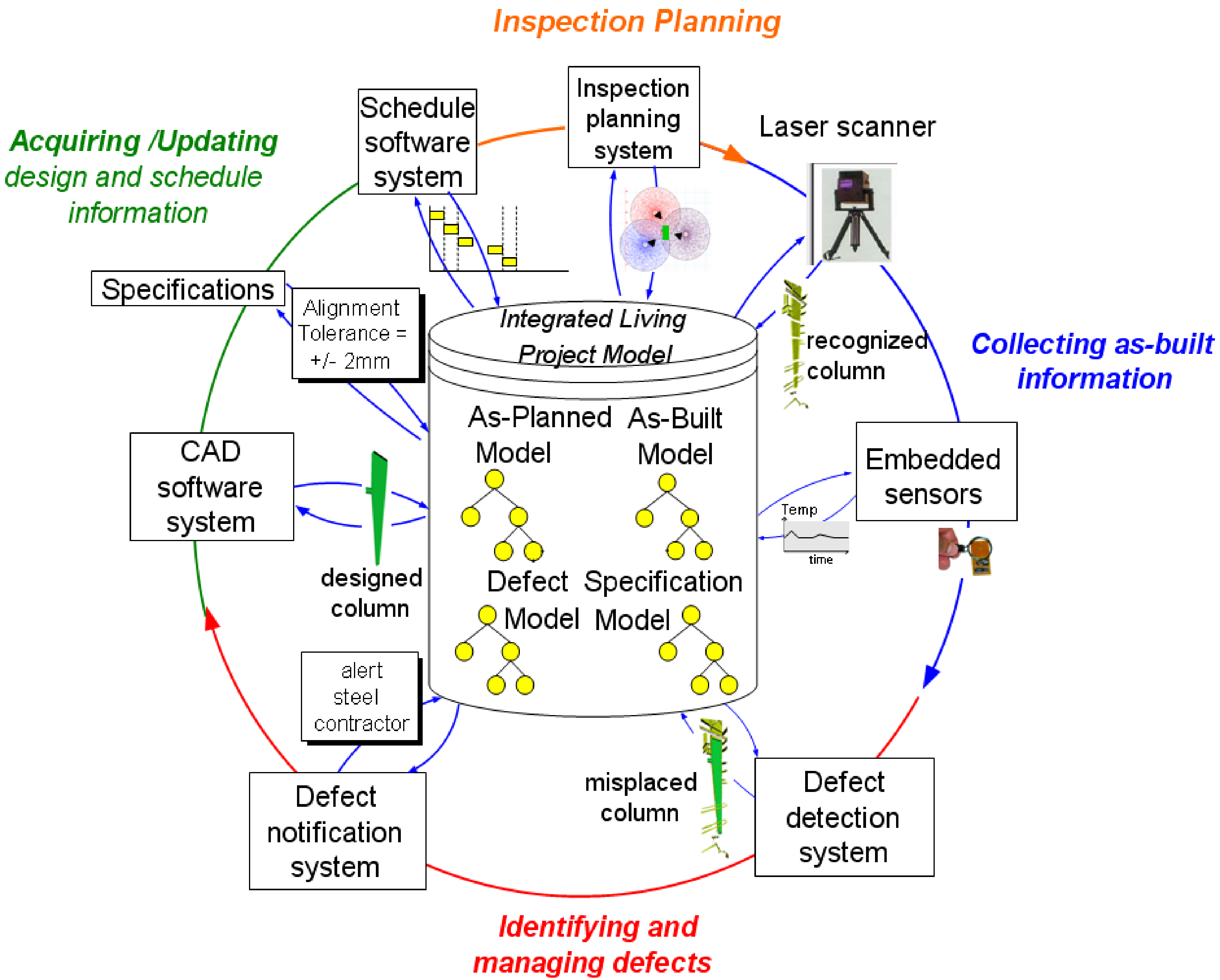
Advanced Sensor-Based Deviation Detection

- Construction deviations and defects occur frequently
  - Constitutes 8-12% of construction cost, when detected late (Burati and Farrington 1987; Josephson and Hammerlund 1998).
  - Defects detected in maintenance constitute 8% of construction cost. (Burati and Farrington 1987; Josephson and Hammerlund 1998).
  - 54% of the construction defects, attributed to human factors like unskilled workers or insufficient supervision of construction work (Opfer 1999)
- Current site inspection approaches need to be improved
  - in increasing the situation awareness
  - in identifying deviations and defects





Advanced Sensor-based Defect Detection and Management on Construction Sites



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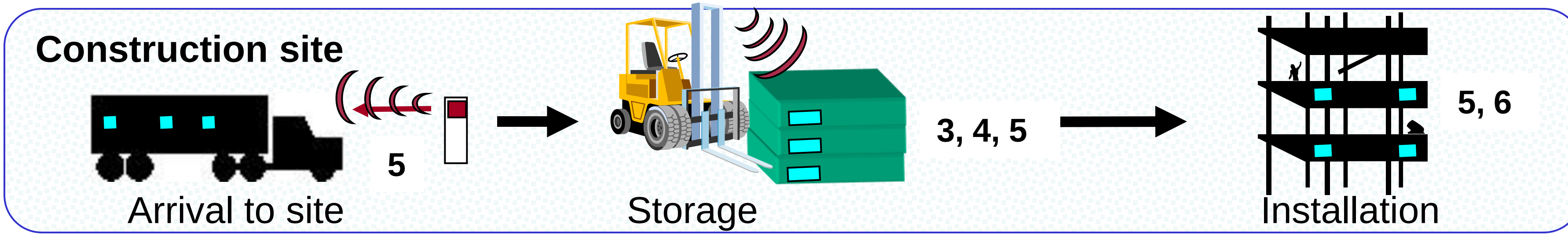
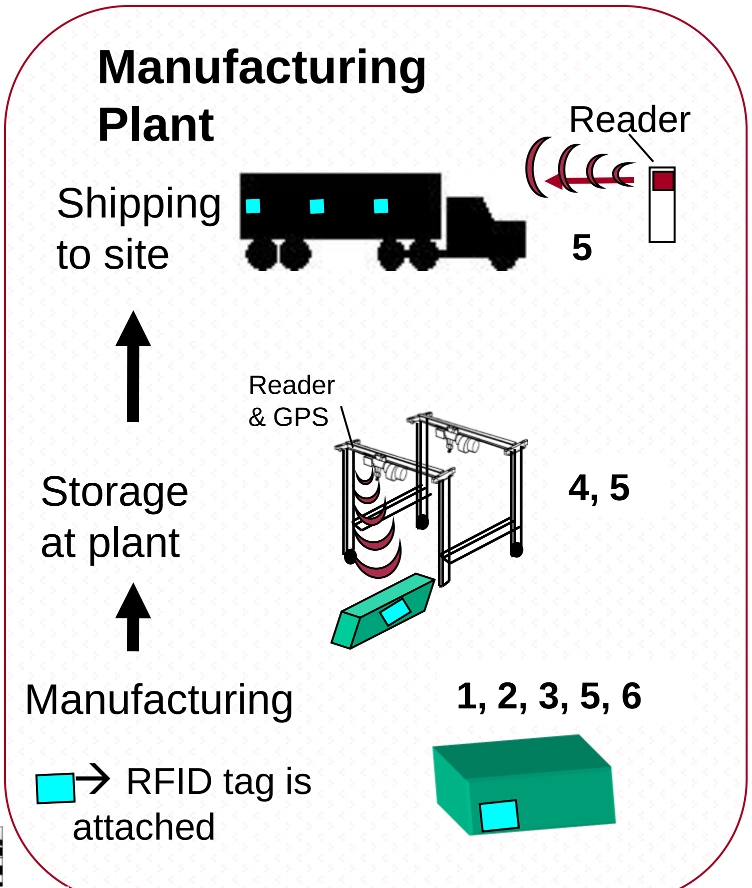
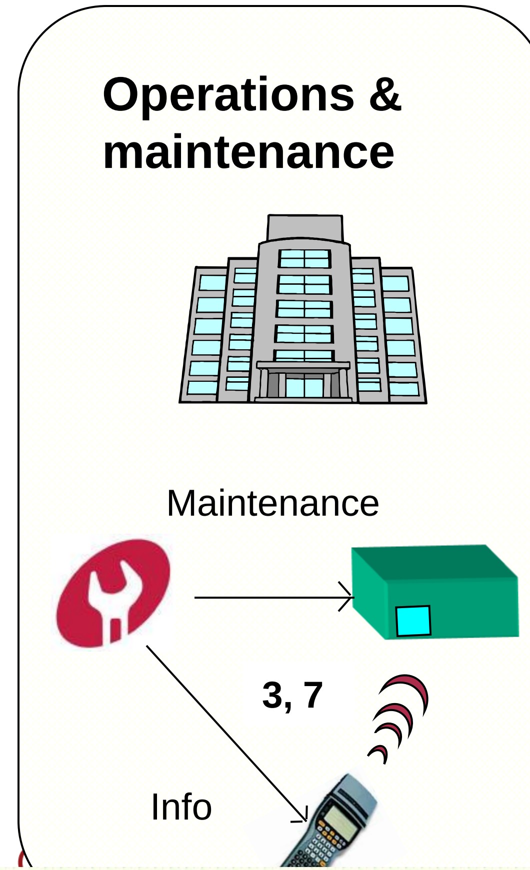
Automated material tracking and capturing product history





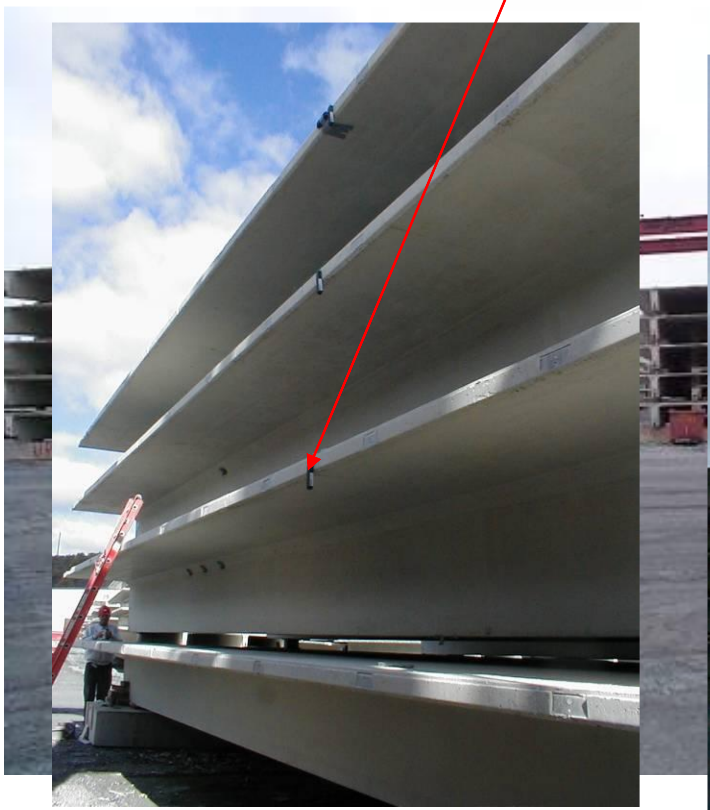
Information Items that are transferred

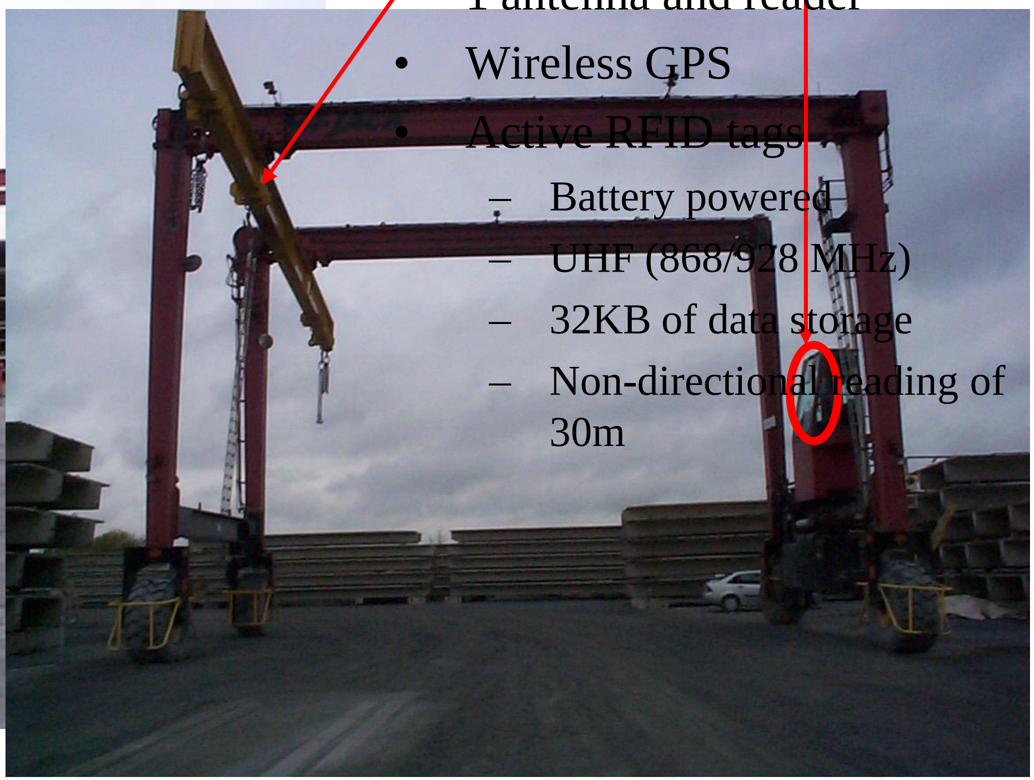
1. Manufacturing info
2. Storage & handling manual
3. Inspection info
4. Storage & location info
5. Status info
6. Final location at the structure
7. Maintenance info



Implementation at a material supplier

Tag





- 1 antenna and reader
- Wireless GPS
- Active RFID tags
  - Battery powered
  - UHF (868/928 MHz)
  - 32KB of data storage
  - Non-directional reading of 30m

Recent research related to these needs…

- **Cost-effective, field deployable sensing systems:**
  - **Inspection and monitoring**
  - **During construction** and **O&M**

- Predictive models of system condition and performance

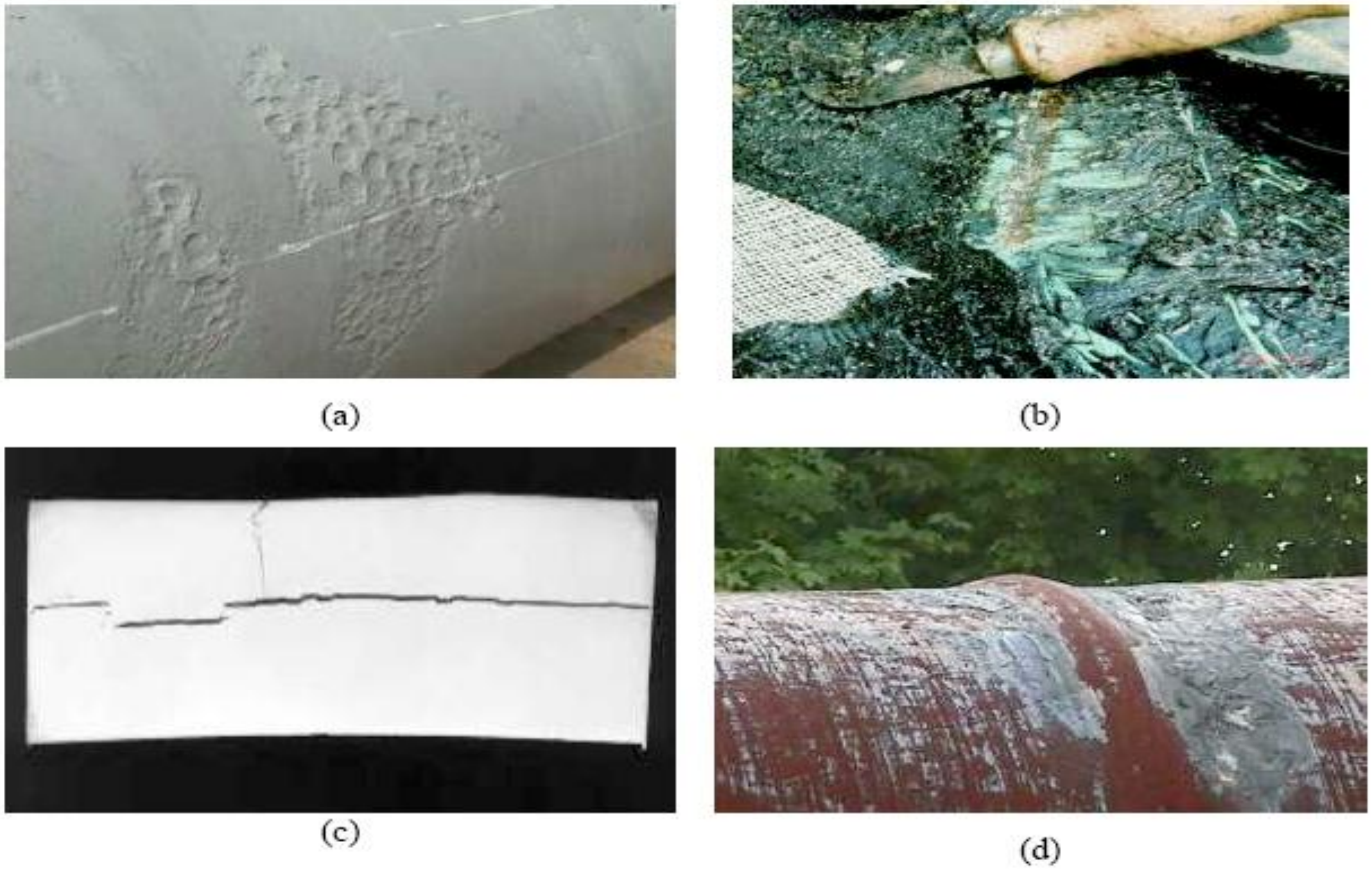
- Decision support tools that use this information to more economically and reliably deliver and manage infrastructure systems

Piezoelectric Sensing and Time Reversal Signal Analysis for Monitoring Condition of Natural Gas Pipelines

Researchers: Moura (ECE), Oppenheim (CEE), Soibelman (CEE), Garrett (CEE), Sohn (CEE- KAIST)

Sponsored by DOE NETL

Types of Damage in Gas Pipelines



(a) Metal Loss; (b) Gouging; (c) Metal anomalies; (d) Buckling

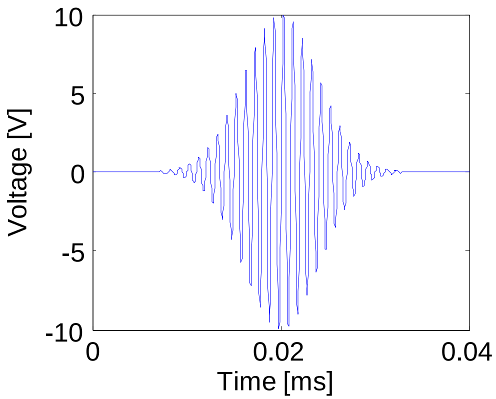
Source: www.battelle.org/pipetechnology/MFL/Links/DefectTypes.htm

Objectives

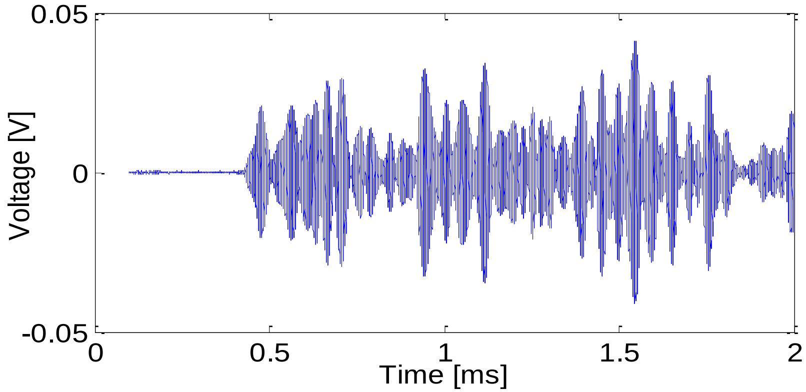
- Demonstrate that a combination of piezoelectric sensors and time reversal signal processing can:
  - interrogate the steel walls of a natural gas pipeline
  - identify the existence of, location and extent of damage in the walls of that pipe

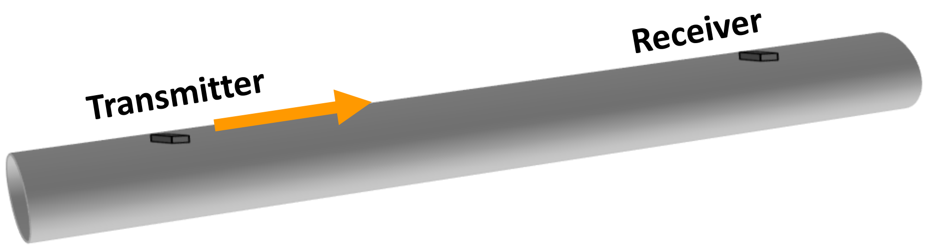
Guided Waves in Pipes

Excitation



Response



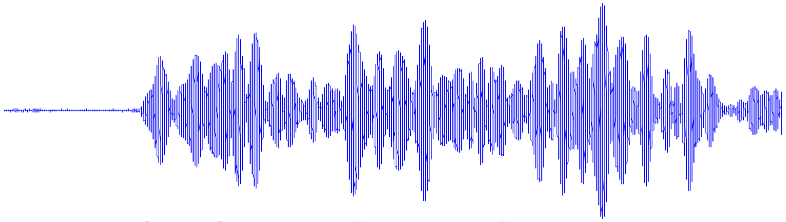


Multi-modal

Dispersive

Multi-path

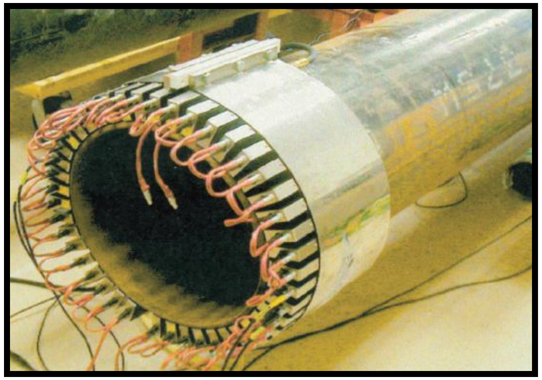
Potential Solutions



Multiple modes and Dispersion

Adverse effects

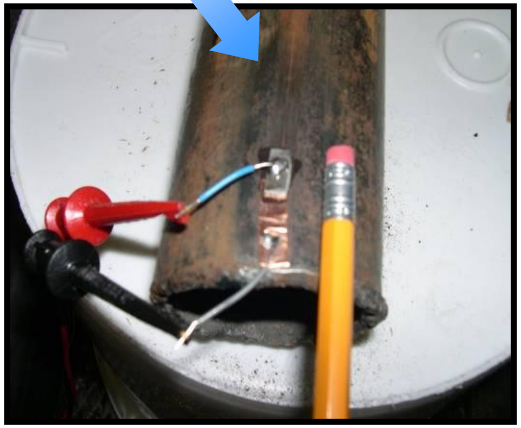
Advantages



Collar sensing device

Teletest system from Plant Integrity Ltd.

http://www.plantintegrity.co.uk/



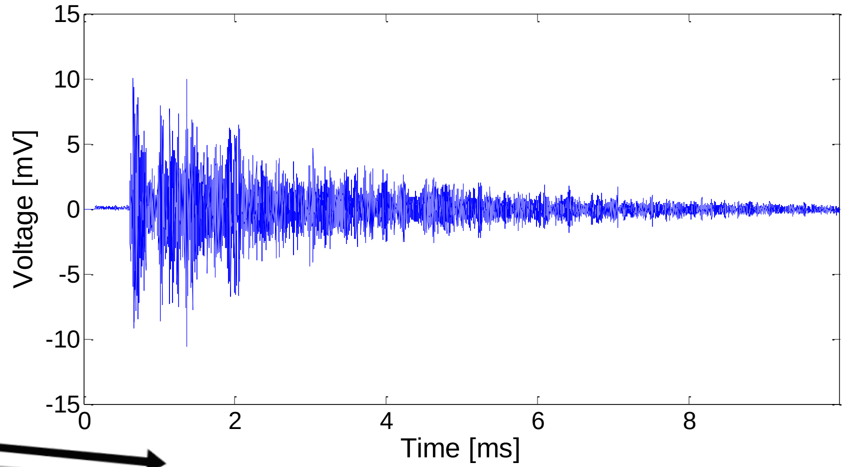
Time Reversal techniques

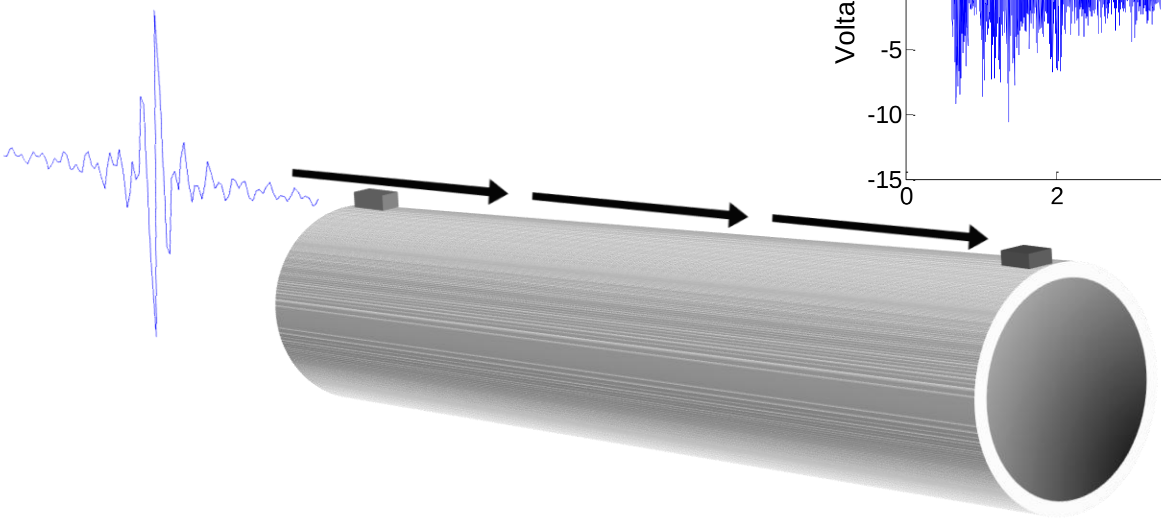
PZT wafer (Lead Zirconate Titanate)

Time Reversal Change Focusing

Transmit excitation, receive baseline signal

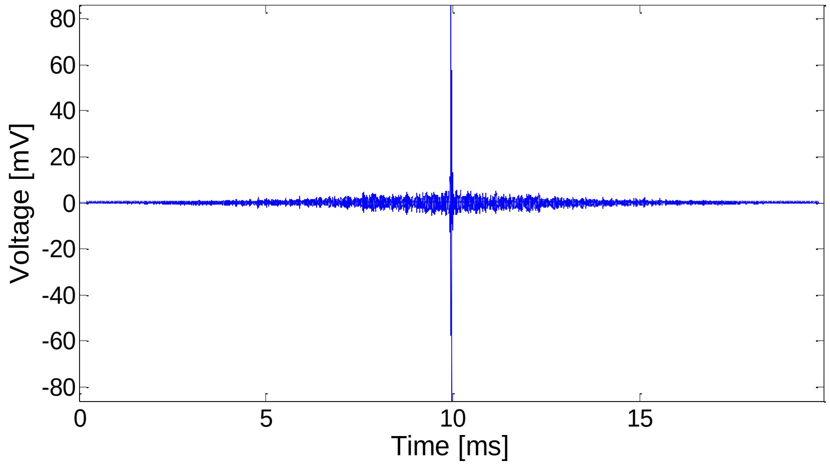
Baseline response



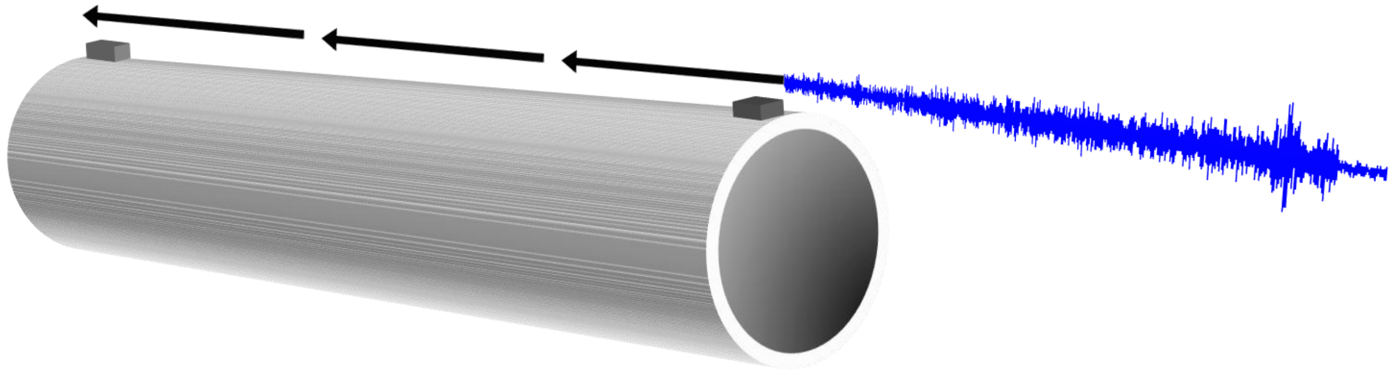


Time Reversal Change Focusing

Back-transmit difference between baseline and signal received



Time reversal of difference signal for undamaged pipe



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Time Reversal Change Focusing

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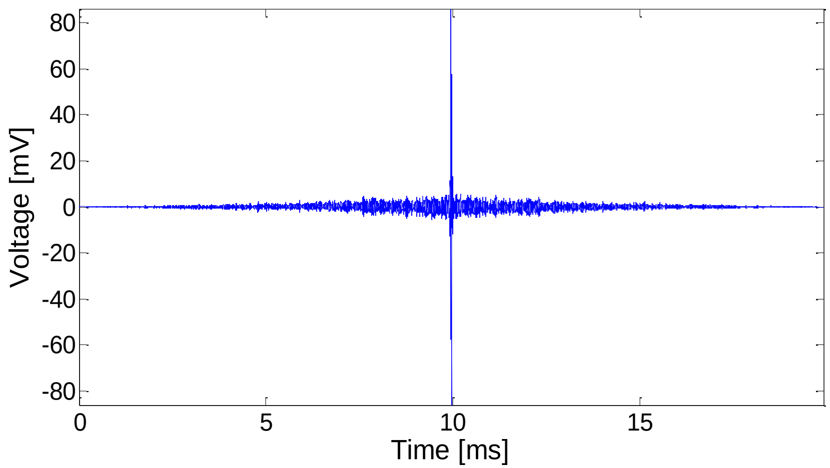
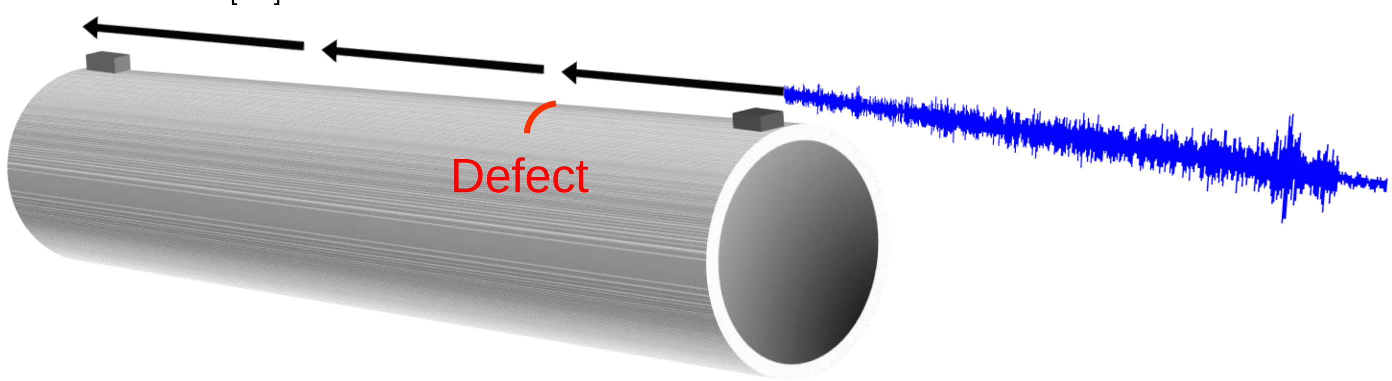


Time reversal of difference signal for damaged pipe



LIDAR Support for Bridge Inspection

Researchers: Akinci (CEE), Huber (CMU Robotics), Earls (PITT)

Sponsored by PENNDOT and PITA

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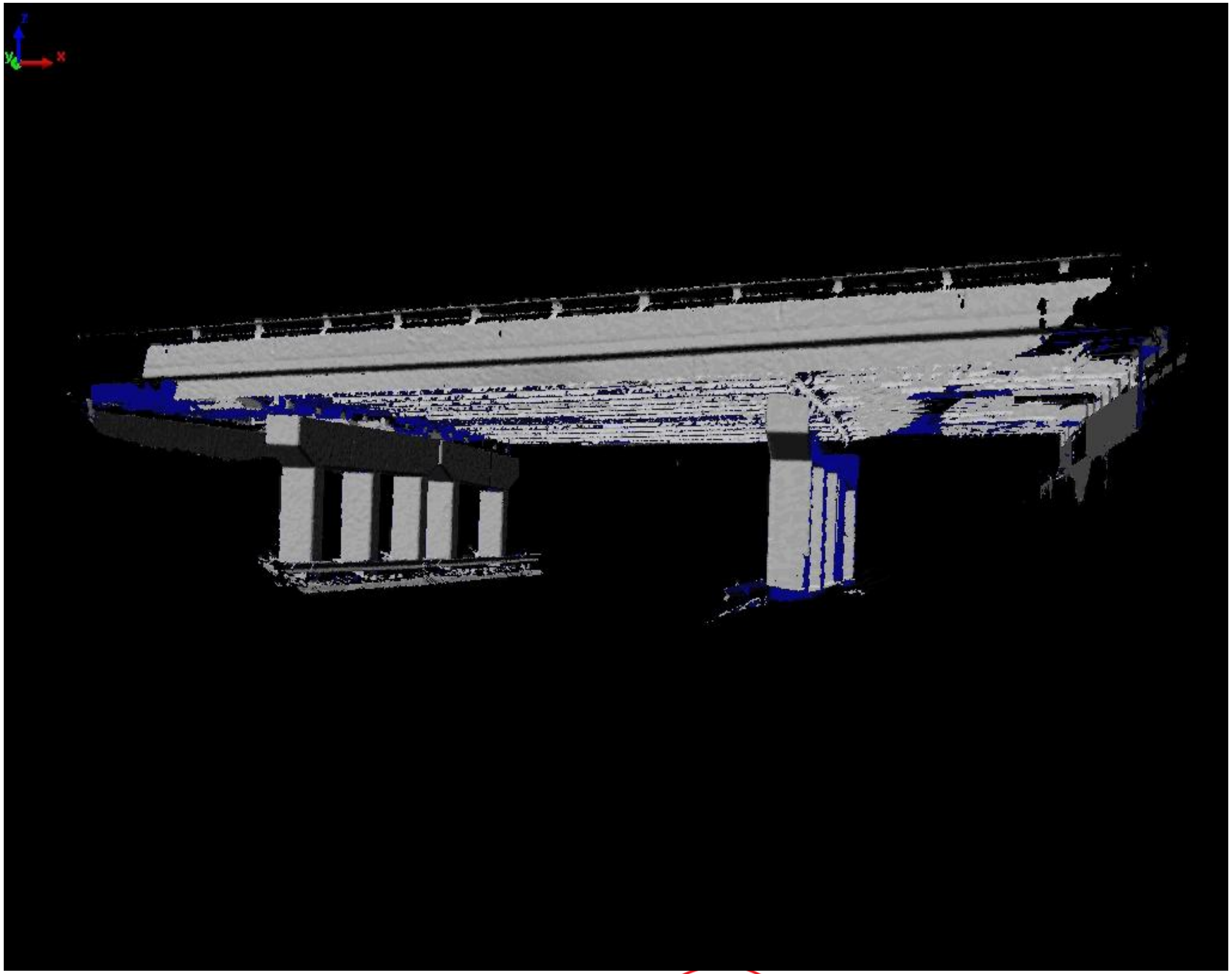
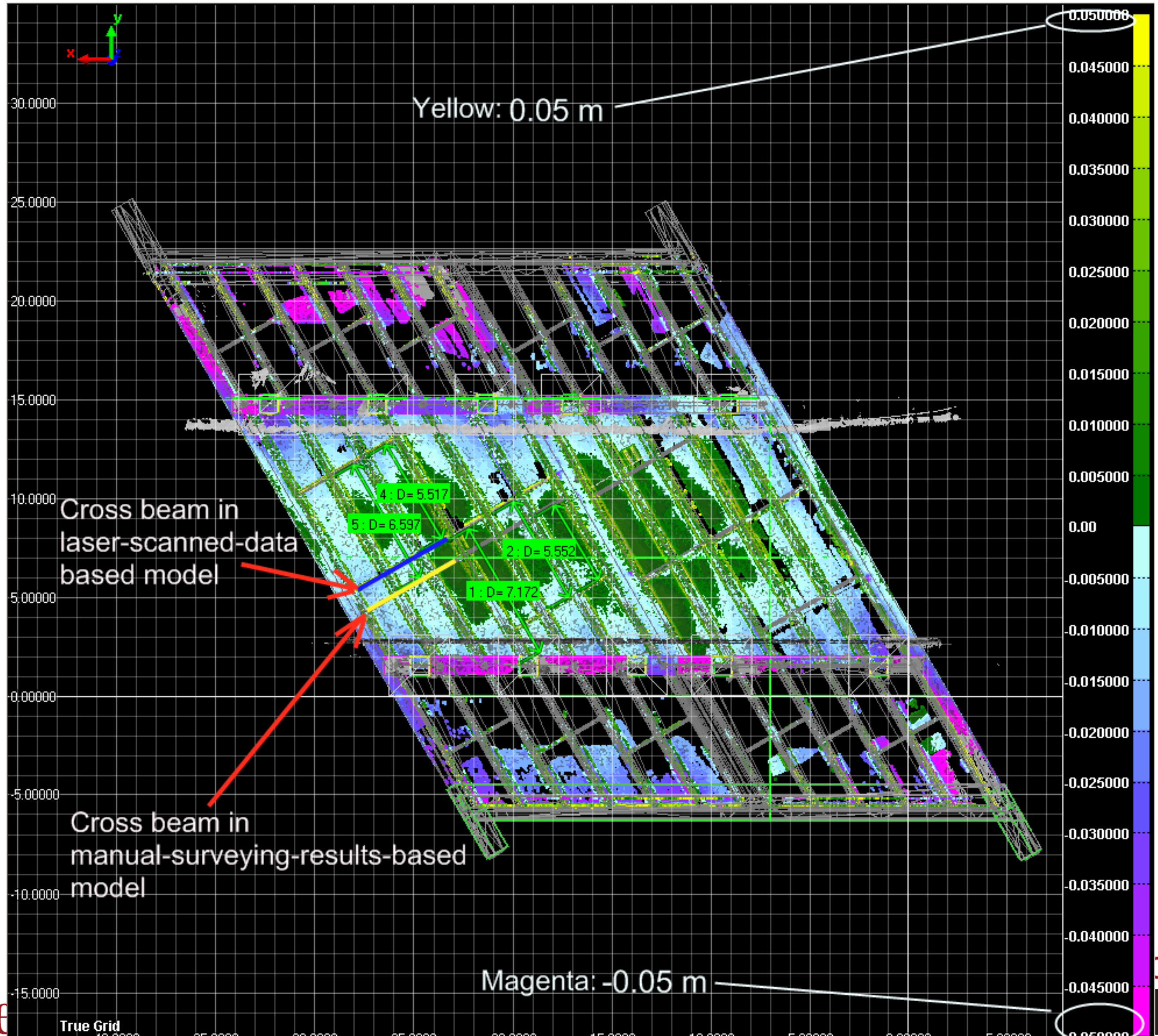
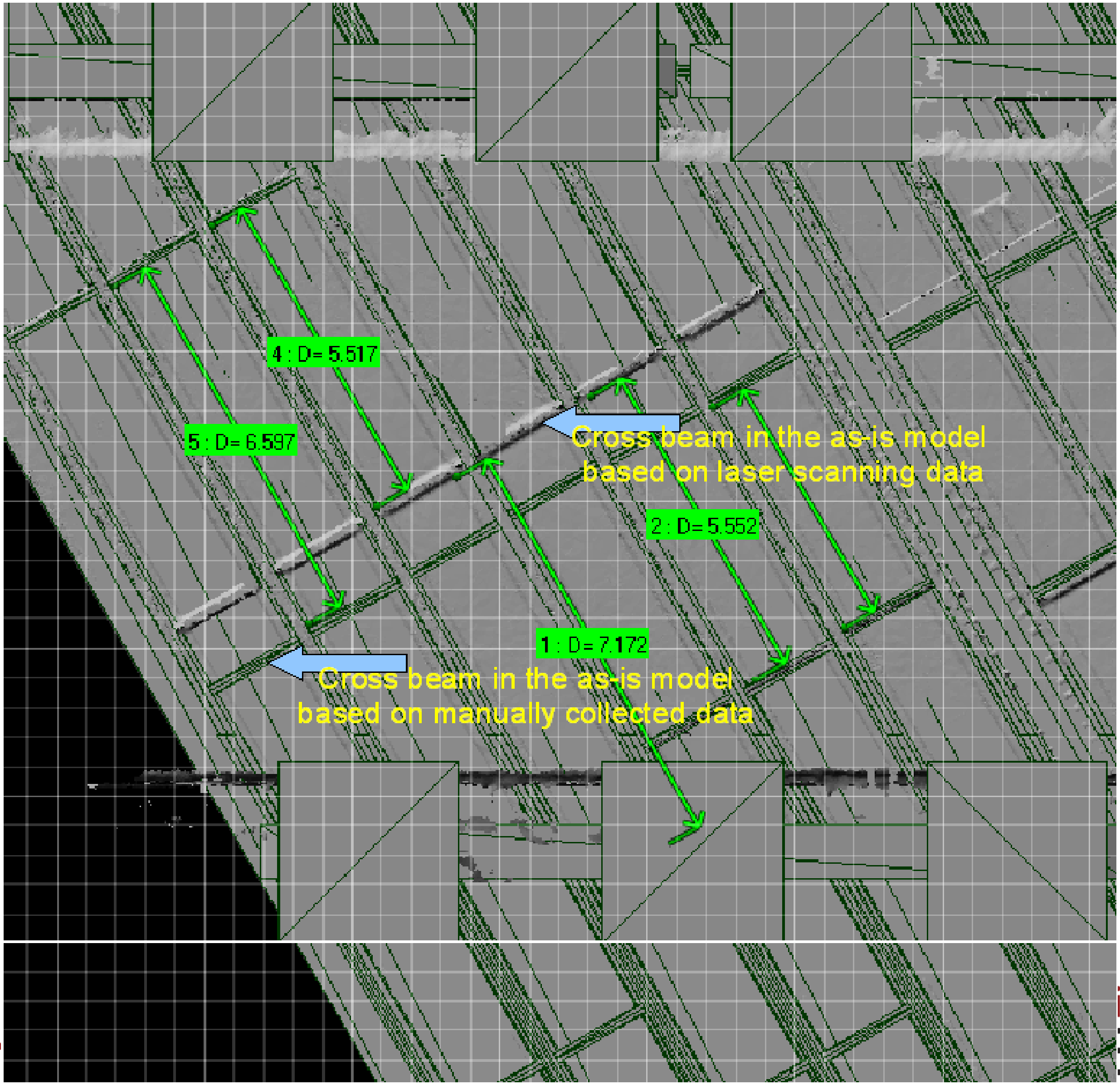
Bridge Inspection Using Lidar Sensing



Assessment of bridge conditions over time



Assessment of bridge as-builts



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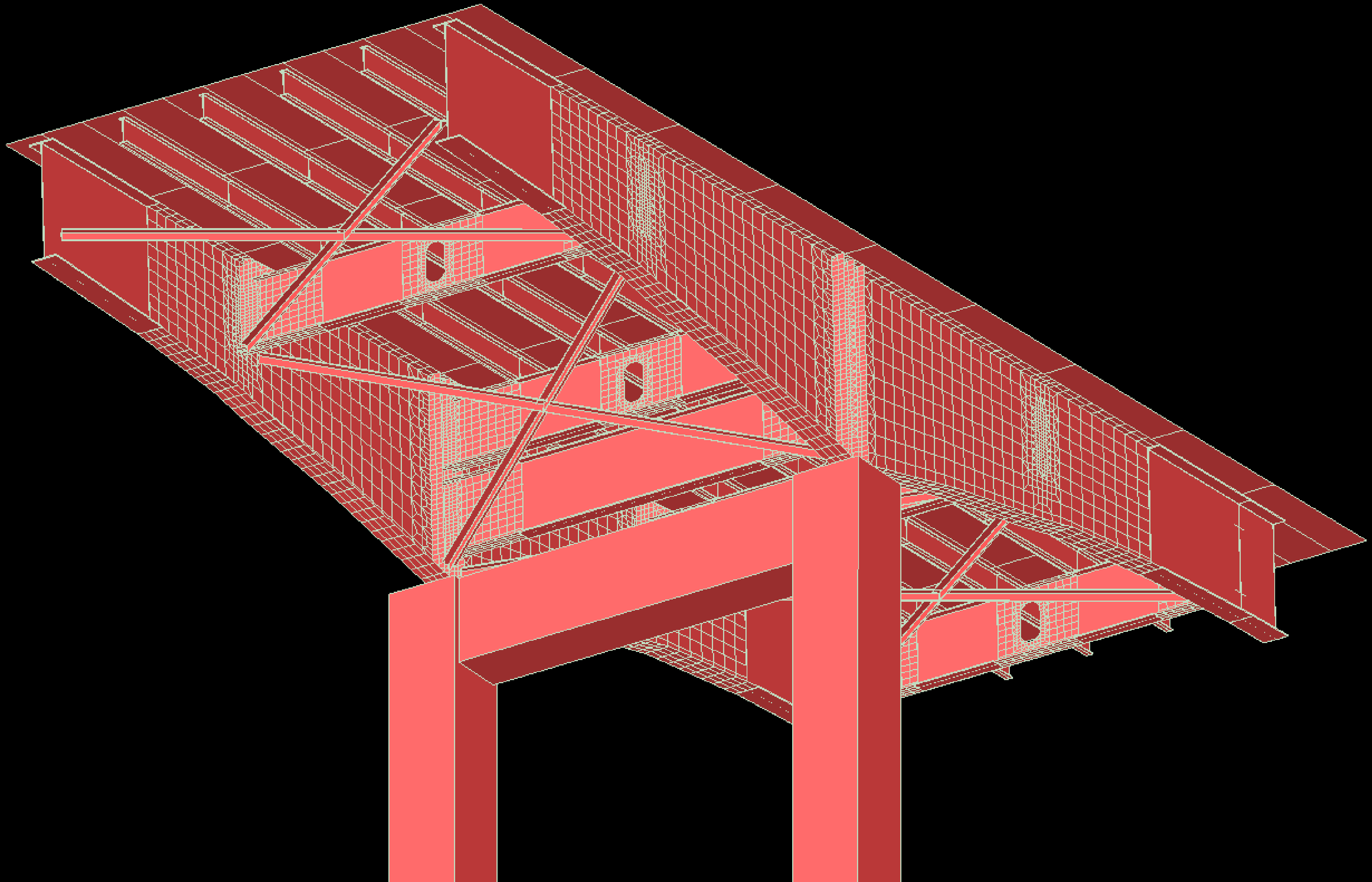
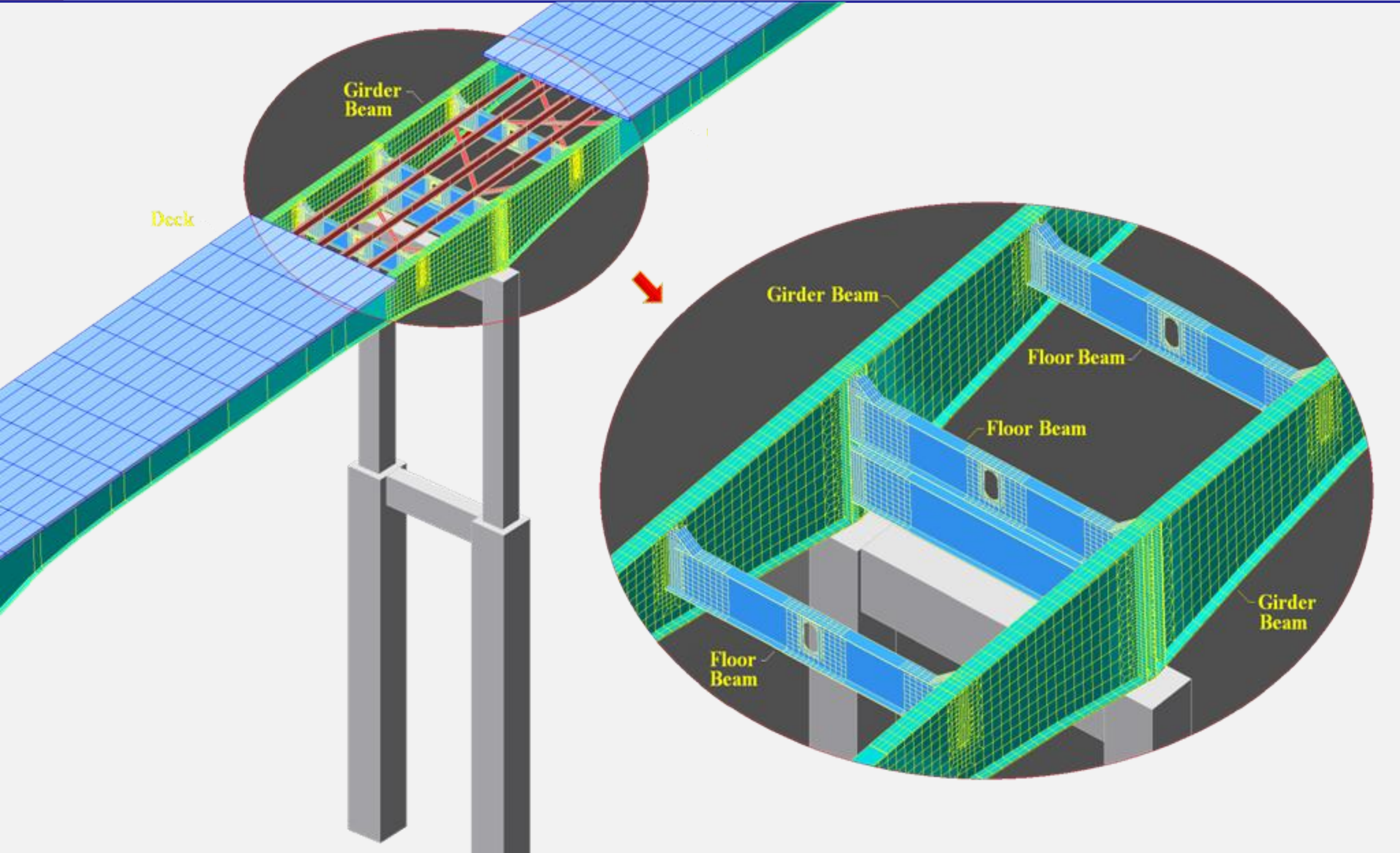
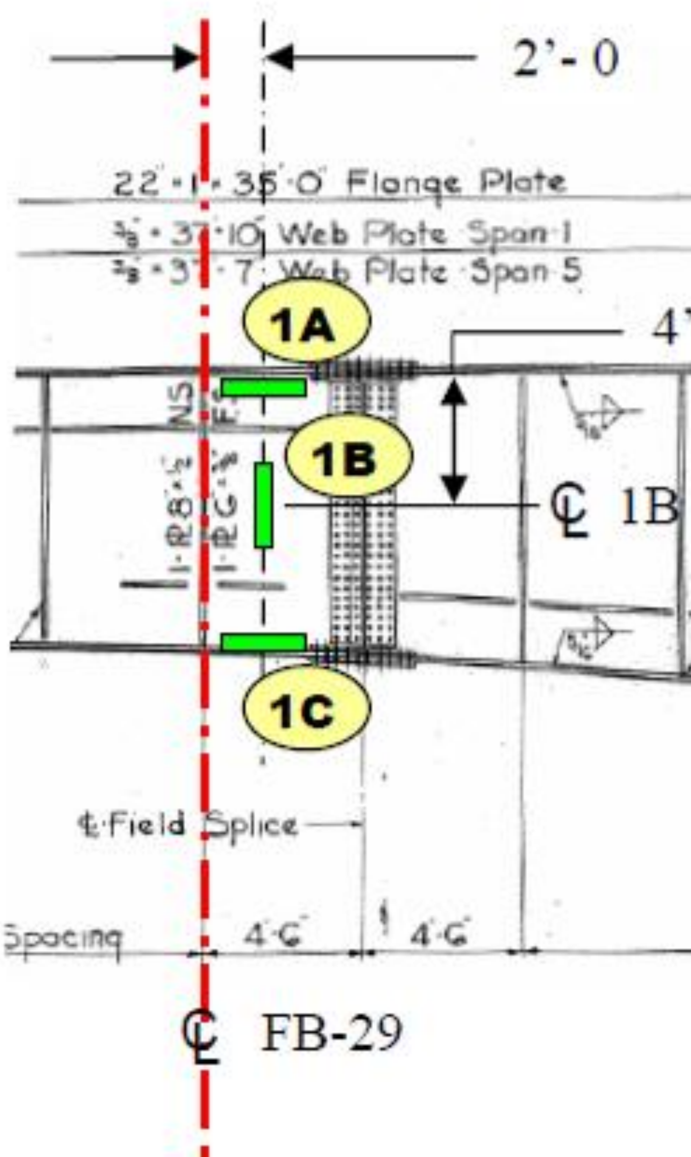
Precise Global Modeling

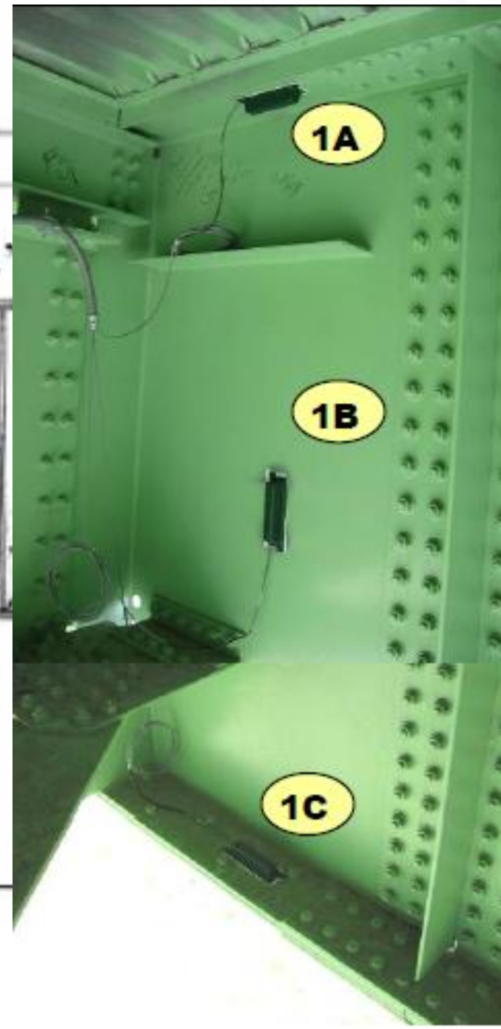


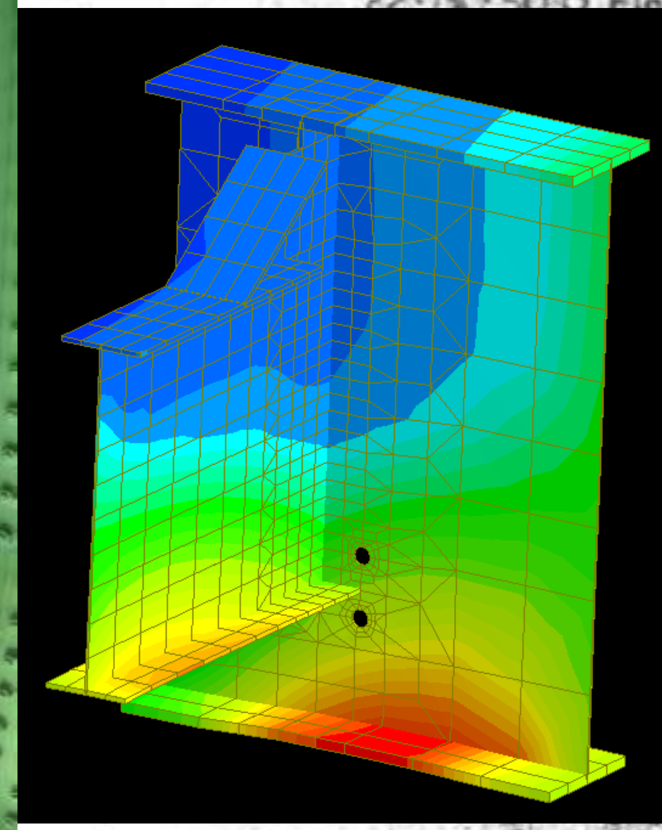
Focus on Points of Interest

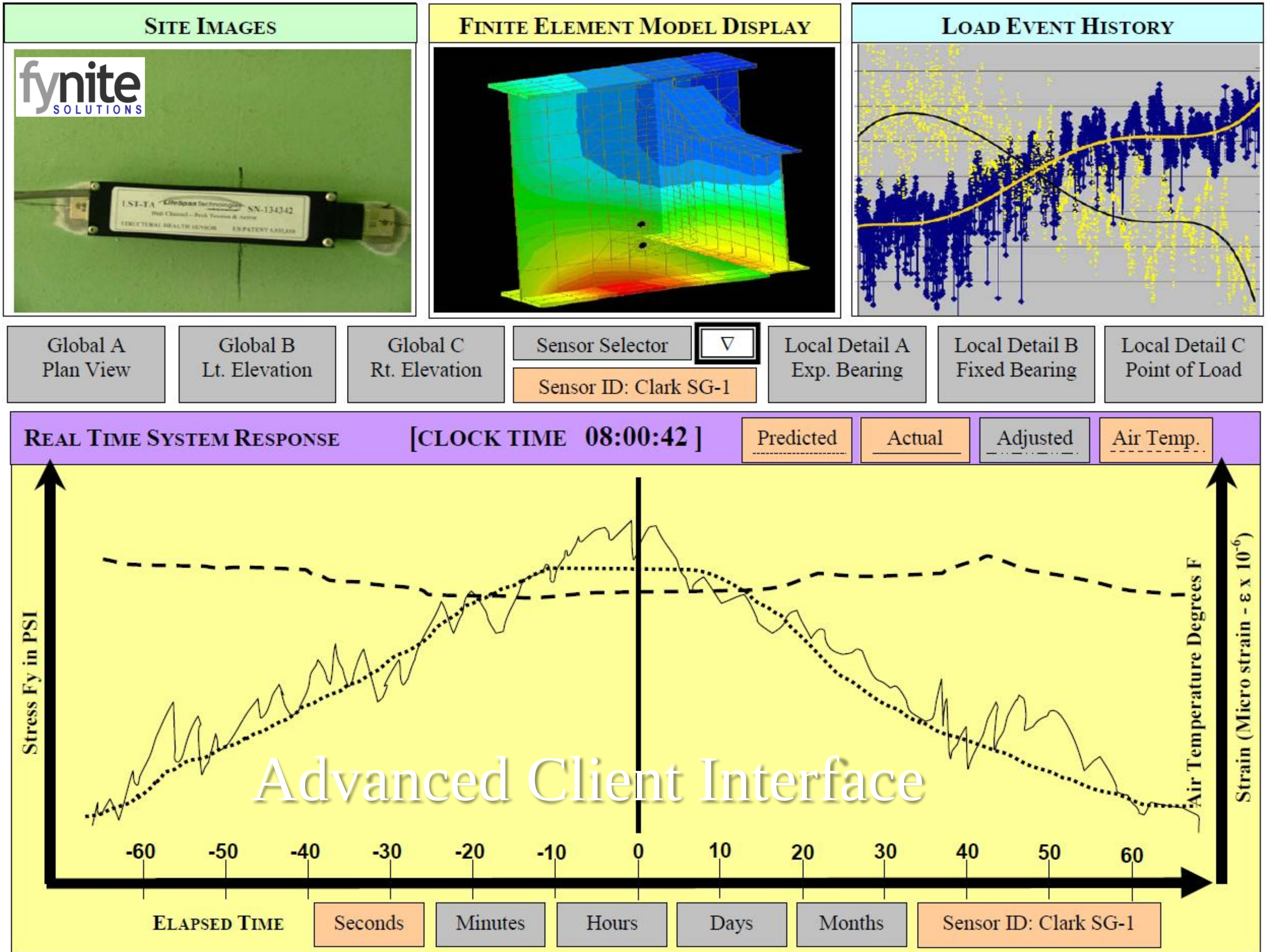


Precise Sensor Locations








SITE IMAGES
fynite
SOLUTIONS
LST-TA
SN-134342
FINITE ELEMENT MODEL DISPLAY
LOAD EVENT HISTORY
Global A
Plan View
Global B
Lt. Elevation
Global C
Rt. Elevation
Sensor Selector
∇
Sensor ID: Clark SG-1
Local Detail A
Exp. Bearing
Local Detail B
Fixed Bearing
Local Detail C
Point of Load
REAL TIME SYSTEM RESPONSE
[CLOCK TIME 08:00:42]
Predicted
Actual
Adjusted
Air Temp.
Stress Fy in PSI
Air Temperature Degrees F
Strain (Micro strain - ε x 10⁻⁶)
Advanced Client Interface
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
ELAPSED TIME
Seconds
Minutes
Hours
Days
Months
Sensor ID: Clark SG-1

Recent research related to these needs…

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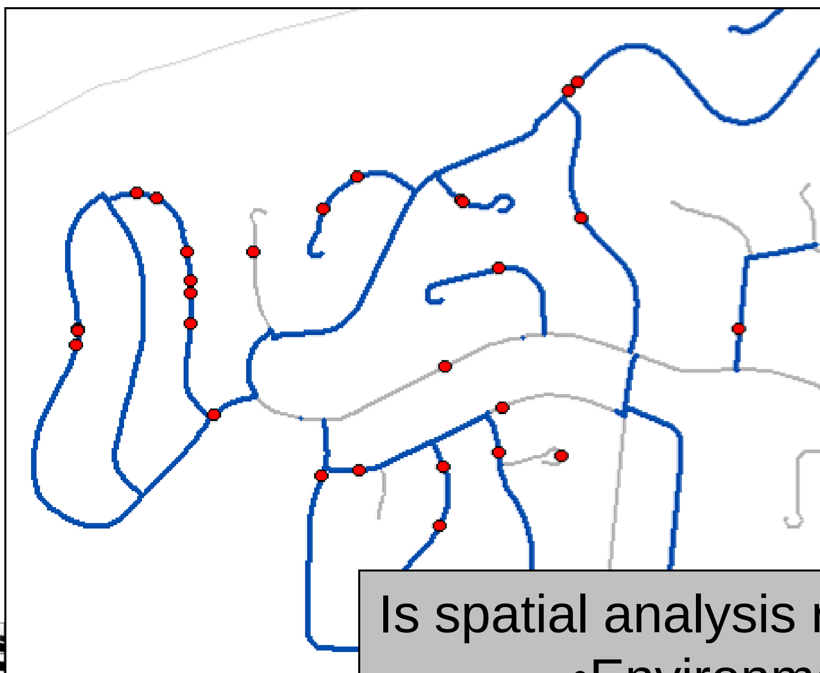
Spatial Data Mining To Improve Understanding and Management of Water Main Breaks

Researchers: Soibelman (CEE), Garrett (CEE)
Oliviera (CEE) and Rajagopolan (CEE)

Sponsored by NSF and PITA

Motivating context

- Consider two similar groups:
  - cast iron pipe, 6” diameter, installed before 1967
- Same pipe characteristics, but different behavior



Is spatial analysis relevant? Consider two factors:

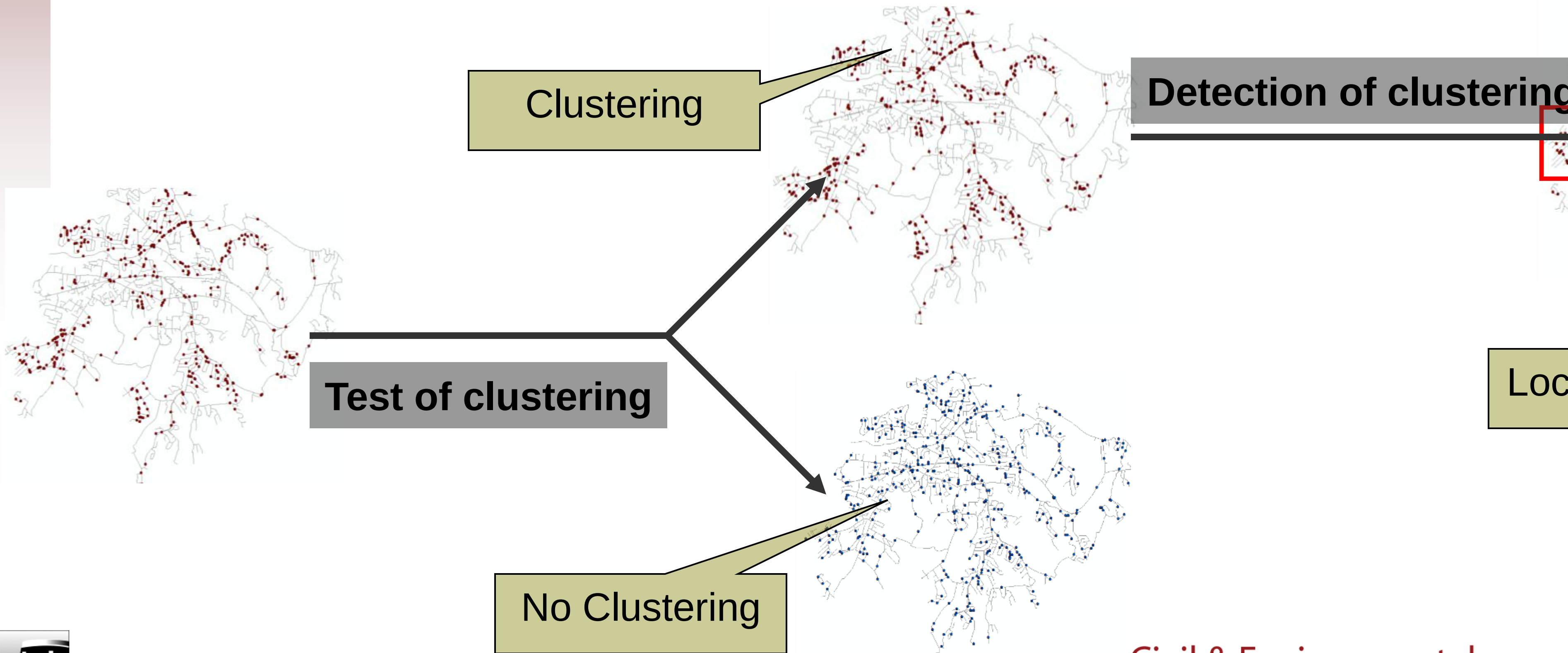
- Environmental factors vary over space
- Interaction between breaks/leaks

Spatial analysis of water main breaks

- The sort of questions that can be asked about spatial analysis of pipe break events:
  - Are breaks clustered?
  - Where?
  - What factors may cause clusters?
- How to perform exploratory spatial data analysis (ESDA) in order to identify significant spatial factors and interdependencies that explain deterioration?

Exploratory spatial data analysis (ESDA) example

Is there any clustering tendency?
Where are the clusters?
How large are the clusters?
What causes the clusters?



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Using Clusters to Decide to Repair or Replace

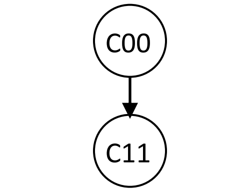
- Deterioration model includes not only temporal aspect, but also the spatial dimension of failure

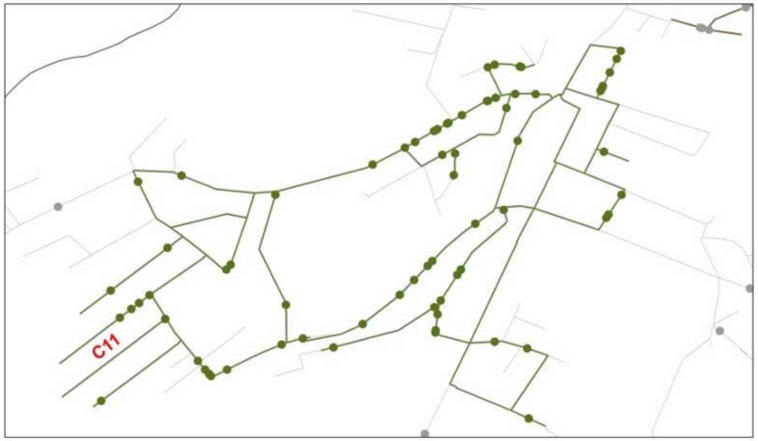
- Cluster analysis can provide insight to
  - Decision making process for repair and replacement of pipe segments
  - Long term rehabilitation planning

- Using spatially referenced data (such as soil, traffic, businesses affected) to assess impact of failure locally
  - Availability of spatially referenced data from sources like Census, DOT
  - GIS used as a platform for data integration
  - Locality specific cost that includes both Utility and User cost (sum of which is total social cost)

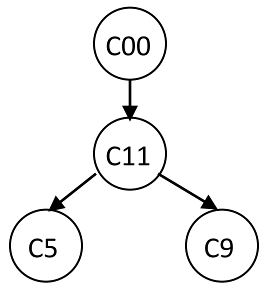
Spatial Analysis

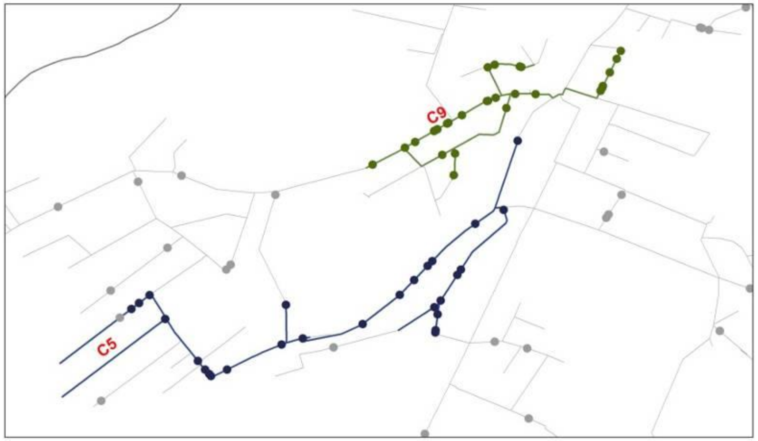
Identify areas with higher breakage than surrounding areas



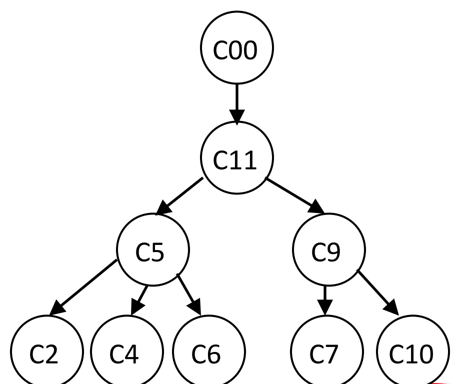


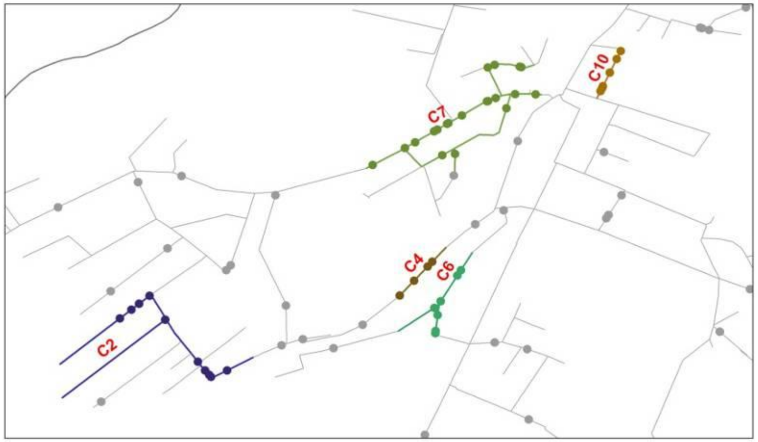
Spatial Clusters defined by local density of breakage





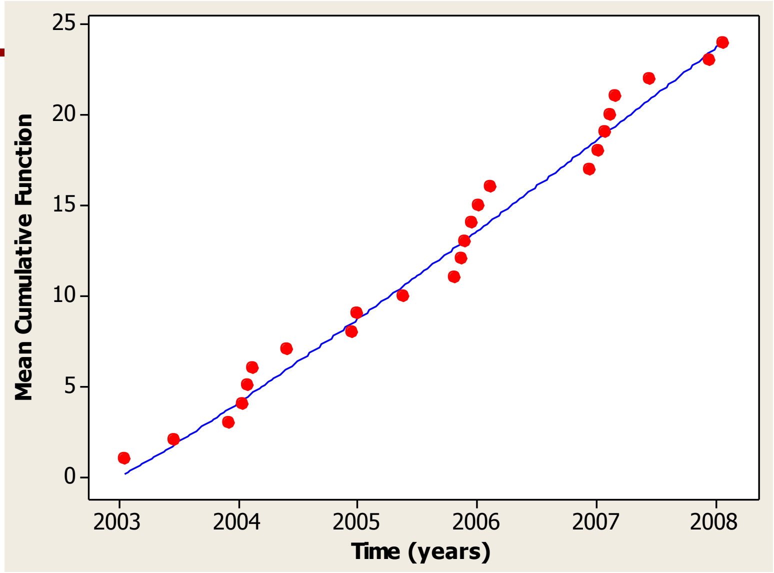
Hierarchy of clusters with higher breakage rate at subsequent levels of hierarchy



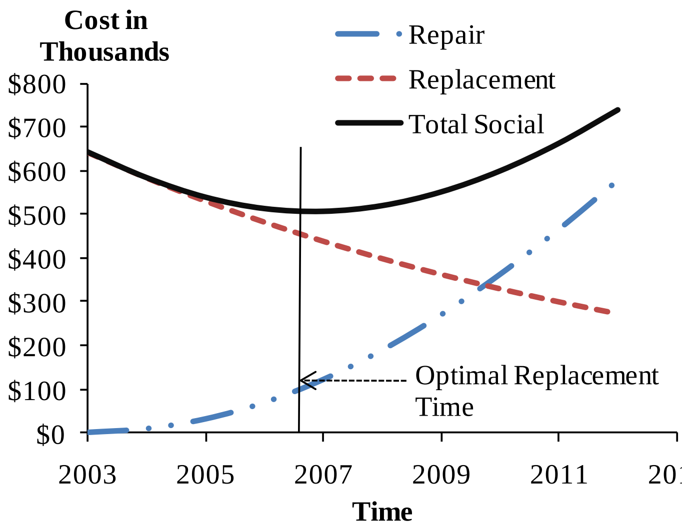


Temporal Analysis

- Calculate the rate of failure for each cluster (group of pipe segments) using data about failure rates for each cluster

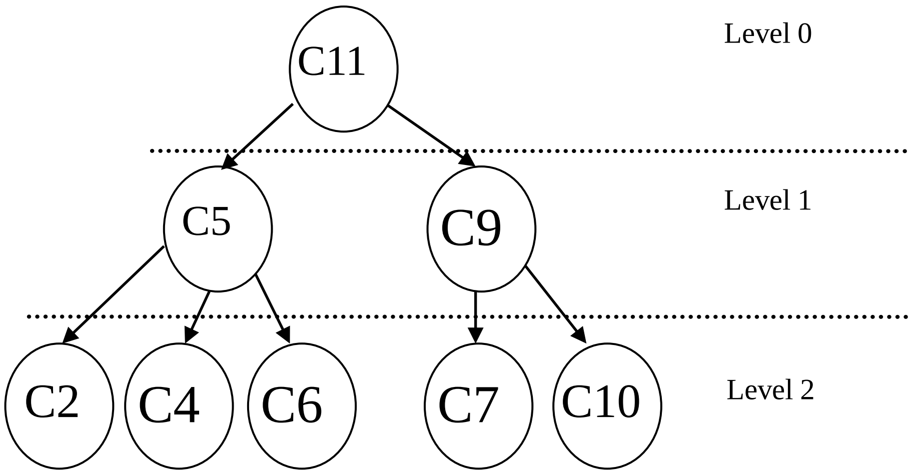


- Calculate the optimal replacement time for each cluster, where optimal replacement time defined as time at which lowest total social cost was achieved



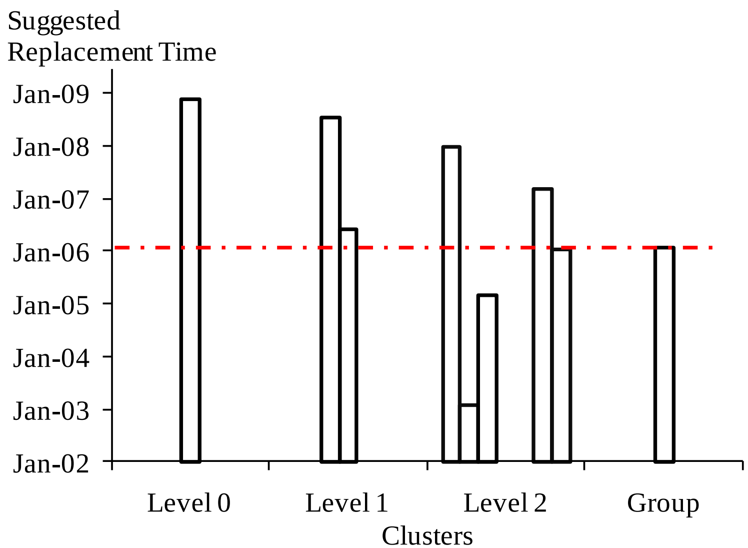
Cluster analysis vs conventional approach

	Total Length	Total (Social) Replacement Cost	Clusters
Group	34,498	$1,601,425	
Level 0	39,810	$1,770,825	C11
Level 1	17,316	$1,003,560	C5
			C9
Level 2	11,645	$1,170,416	C2
			C4
			C6
			C7
			C10



The chart on the right compares the replacement time for clustering with conventional approach for grouping pipes

Delayed suggested replacement time indicates avoidance of unnecessary pipe segment replacements



Summary

- The future delivery, maintenance and operation of our facilities and infrastructure must include "nervous systems" consisting of:
  - Cost-effective, field-deployable sensor networks
  - Distributed data repositories and automated mining techniques
  - Intelligent decision support applications that make use of this data to build usable models for diagnosis and prediction
- We need much more and better information about the use, state and condition of our infrastructure so as to better deliver, operate and manage them

Thank you! Questions?

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