ANDERS

Merging of Automated and Minimally Invasive Technologies for Bridge Evaluation and Rehabilitation

RUTGERS
Center for Advanced Infrastructure and Transportation

DREXEL UNIVERSITY
College of Engineering

THE UNIVERSITY OF TEXAS AT AUSTIN

MALÅ
Part of the Guideline Geo Group

Pennoni

PD-LD

Georgia Tech

Outline

- Why the project targeted bridges and bridge decks in particular?
- What is the state of practice in bridge and bridge deck evaluation and rehabilitation, and what are the critical needs ?
- What are ANDERS products and how they can change the state of practice and advance knowledge creation?

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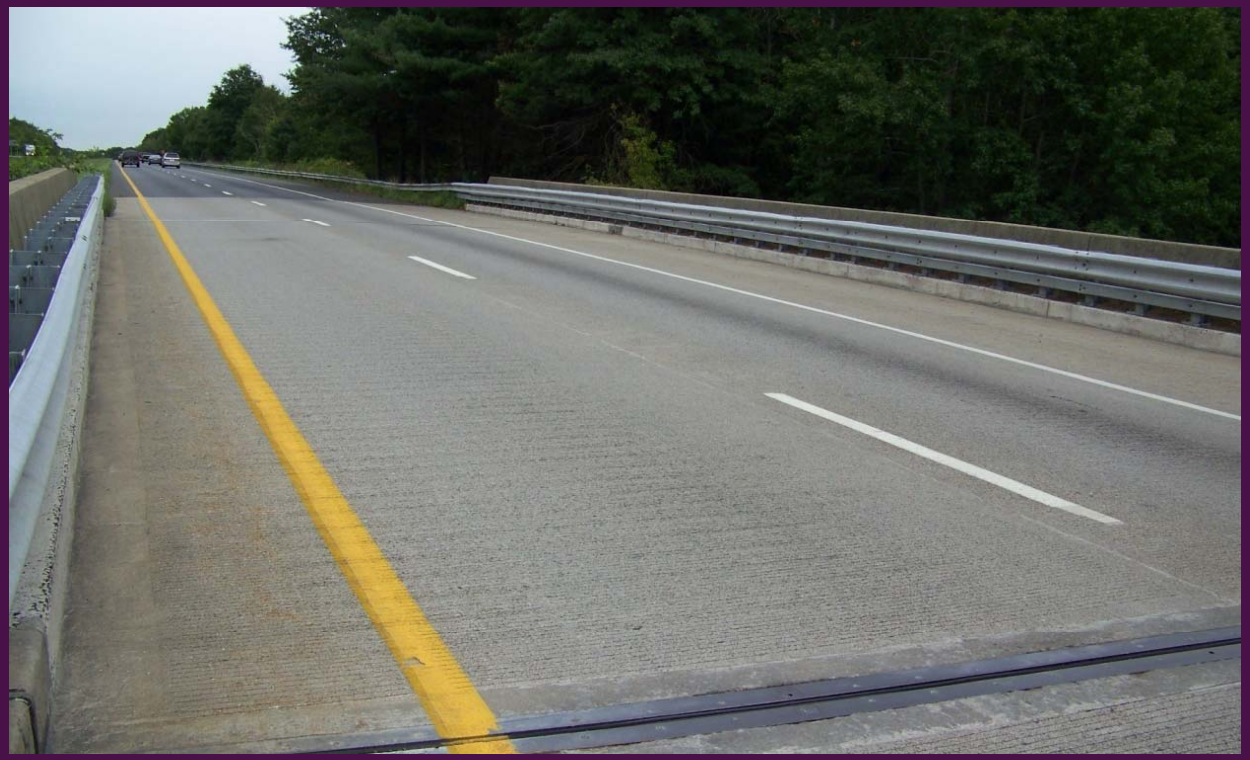
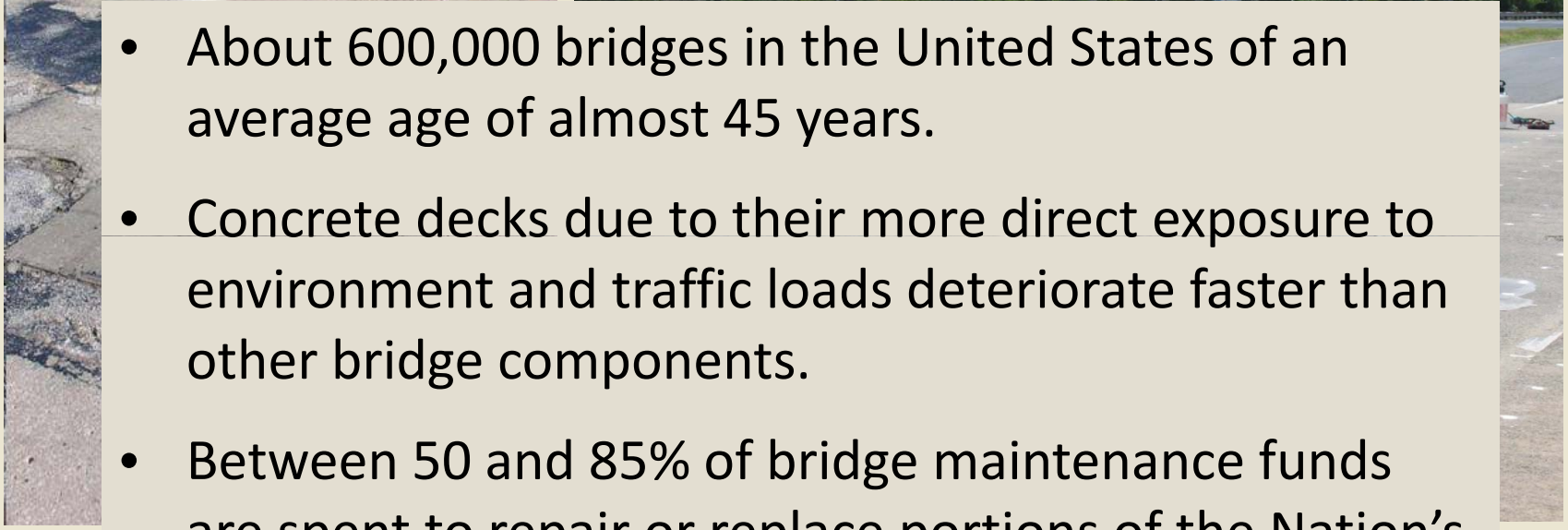
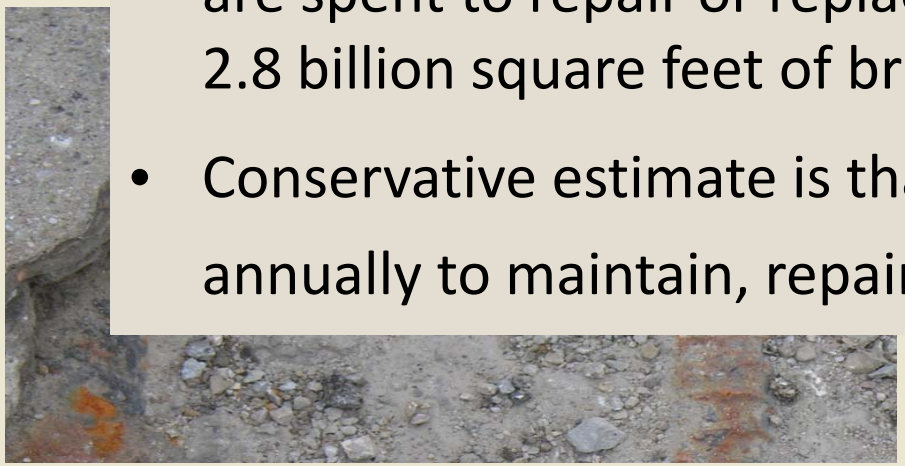
Why bridges and bridge decks in particular?

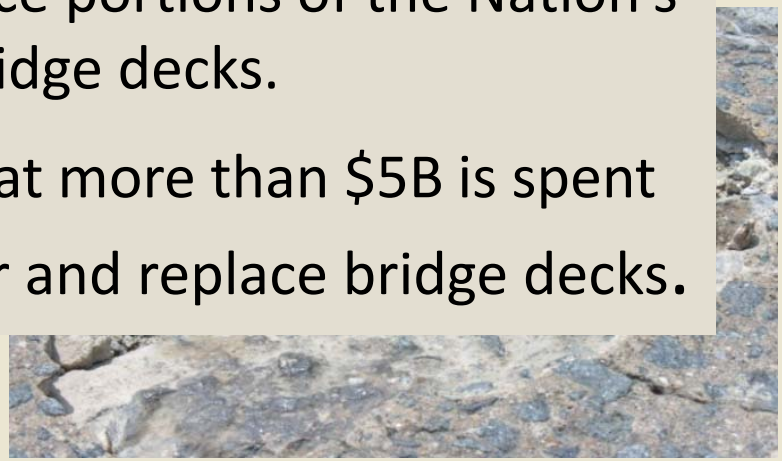


Bridge Deck Deterioration



- About 600,000 bridges in the United States of an average age of almost 45 years.
- Concrete decks due to their more direct exposure to environment and traffic loads deteriorate faster than other bridge components.
- Between 50 and 85% of bridge maintenance funds are spent to repair or replace portions of the Nation's 2.8 billion square feet of bridge decks.
- Conservative estimate is that more than $5B is spent annually to maintain, repair and replace bridge decks.





Reinforced Concrete Deterioration/Defects

Vertical Cracking

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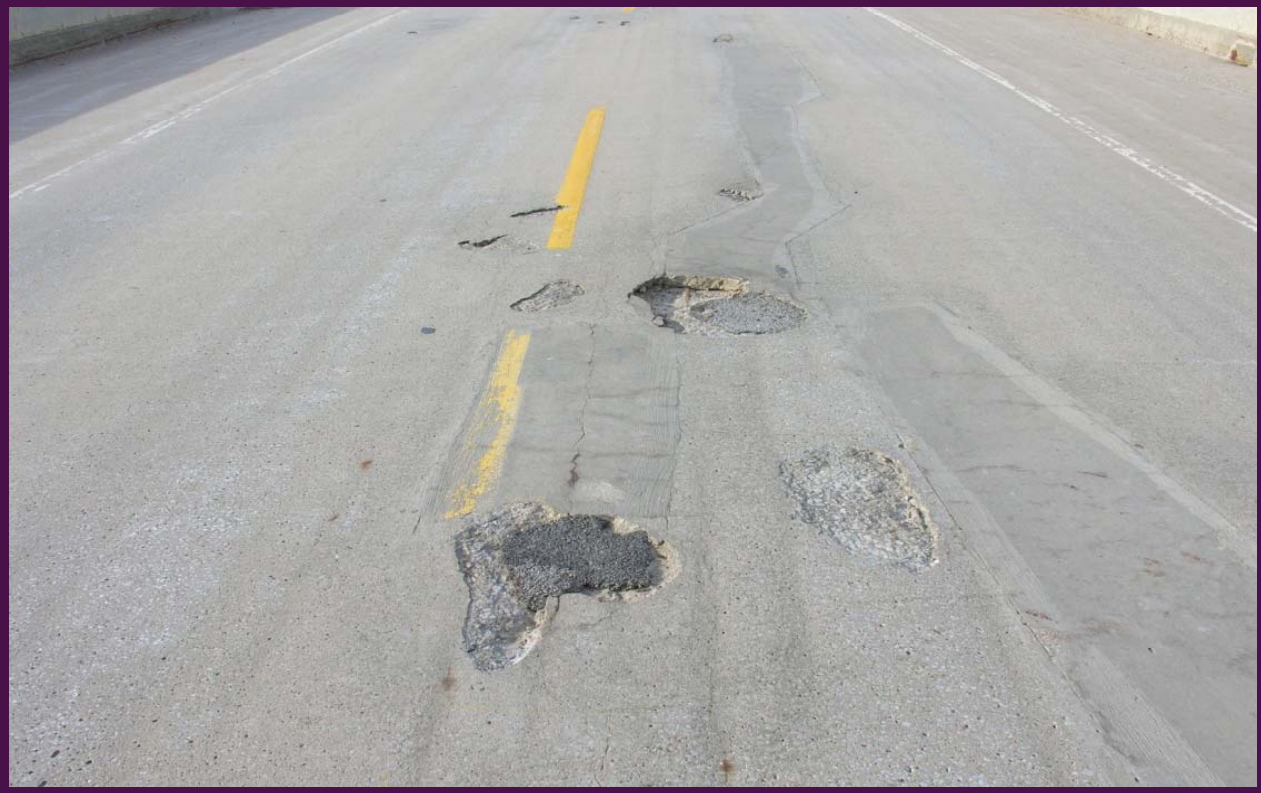
What is the state of practice and where are the critical needs?



State of Practice in Bridge Deck Evaluation

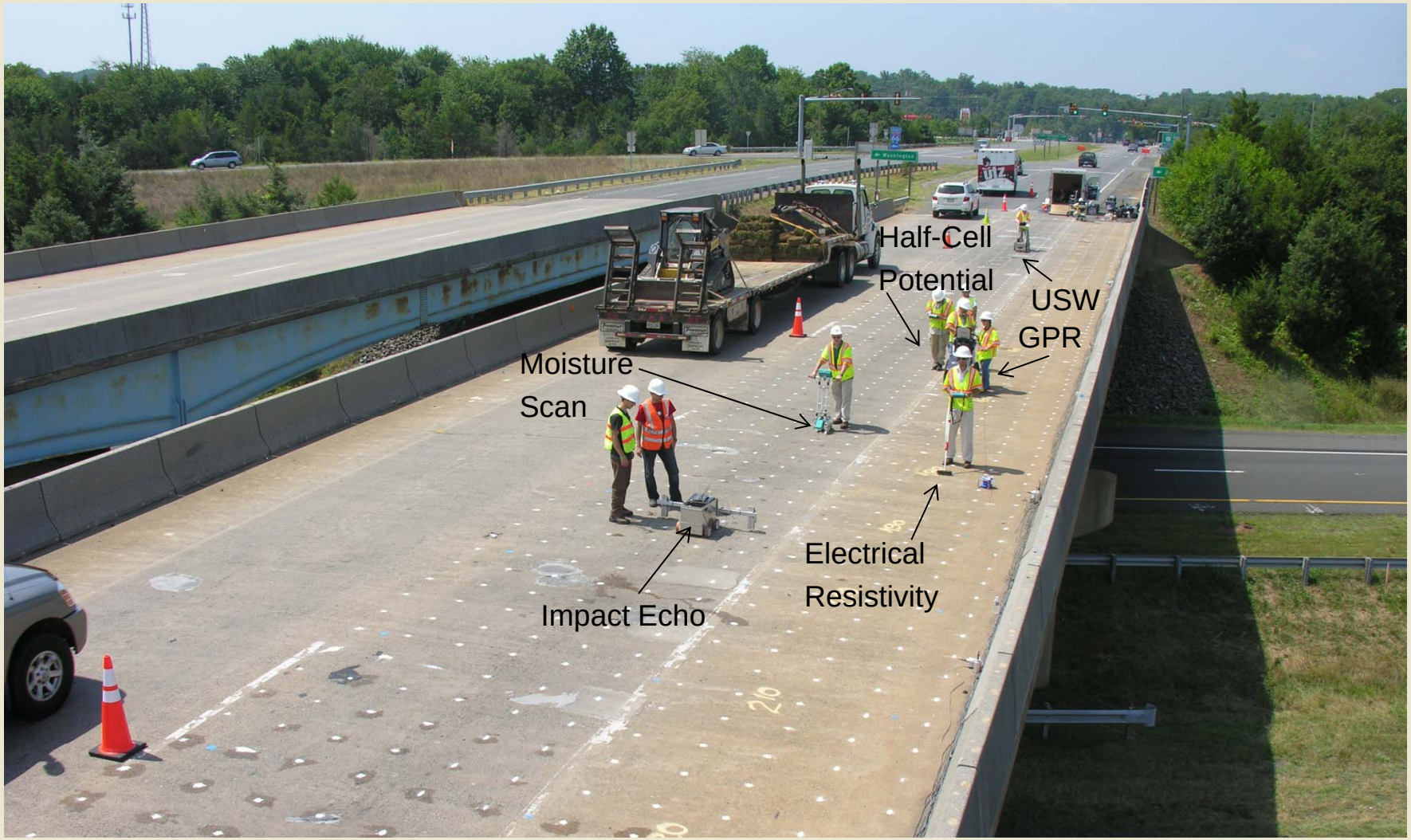
NDE of Bridge Decks

Impact Echo Testing

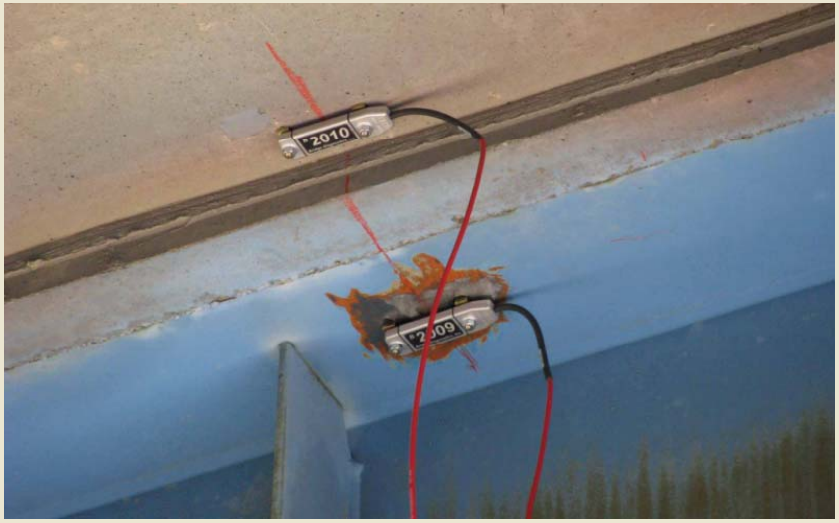
ResistivityTesting

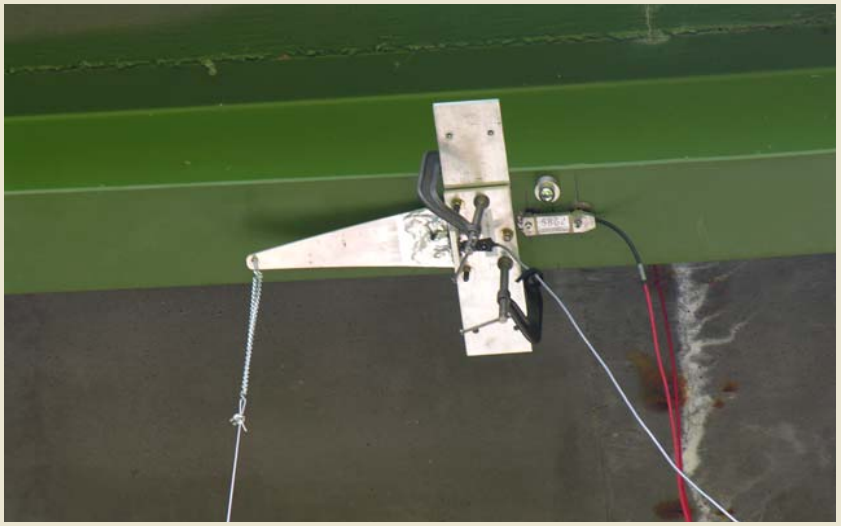
Surface Wave Testing

NDE Bridge Deck Data Collection



Global Response - Live Load Testing





State of Practice in Bridge Deck Rehabilitation

State of Practice in Bridge Deck Rehabilitation

Health Monitoring and Prevention

- Prevention
- Diagnostics/monitoring
- Early intervention
- Overall health

- Better lives
- Longer lives
- Financially sounder lives

Critical Needs in Evaluation, Monitoring and Rehabilitation to be Addressed

1. Improved **speed** of condition surveys,
2. Concentration on **early problem detection and rehabilitation,**
3. **Multimodal/complementary** approach with **data integration and fusion,**
4. Monitoring of both **global and local** performance.

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How can we change the state of practice and advance knowledge?

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- **A**utomated **N**on-**D**estructive **E**valuation and **R**ehabilitation **S**ystem
- Composed of **three physical components** that merge NDE with innovative intervention approaches to arrest deterioration processes:
  - Multi-Modal NDE (MM-NDE) System
  - Global Structural Assessment (GSA) System
  - Nondestructive Rehabilitation (NDR) System
- **Joint venture**: Rutgers University, Drexel University, MALA Geoscience USA, PD-LD, Pennoni Associates
- **Subawardees**: University of Texas at Austin and Georgia Tech

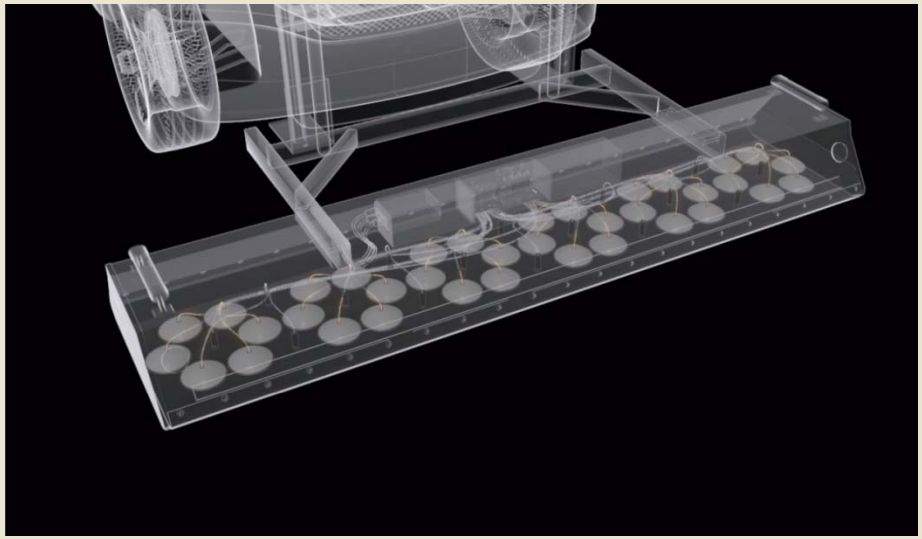
ANDERS Product Aims

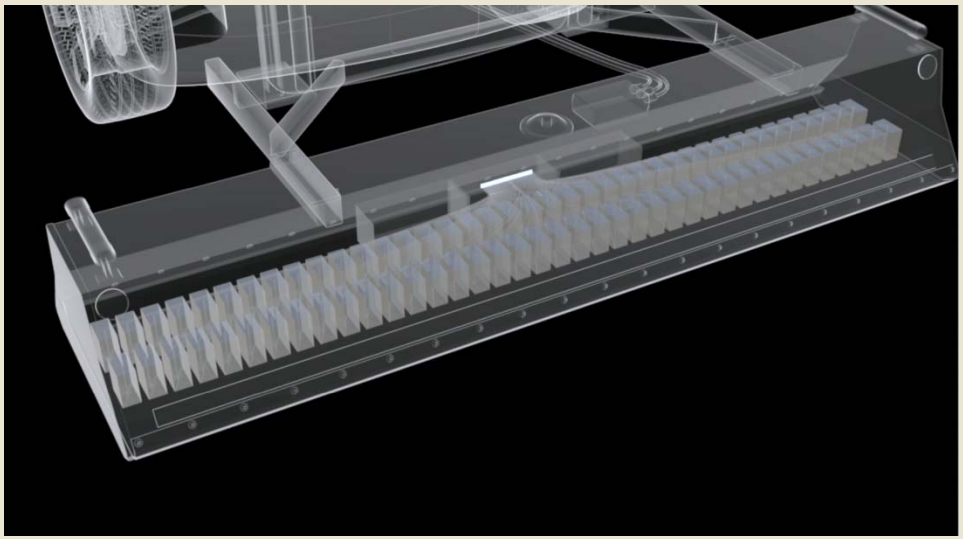
- A much higher evaluation detail and comprehensiveness of **detection of early stage deterioration** at lower cost and less time than traditional approaches,
- Comprehensive **global structural assessment** (including the **understanding of effects of local deterioration on global performance**), and
- **Integrated assessment and rehabilitation** that is nondestructive, rapid, cost effective and **implementable at all stages of deterioration.**

Multi Modal NDE (MM-NDE) System Goals

To be able to detect and characterize deterioration and map the zones of the deck to be repaired. Deterioration of the highest interest:

- Delamination
- Concrete degradation
- Vertical cracking
- Corrosion (corrosive environment)



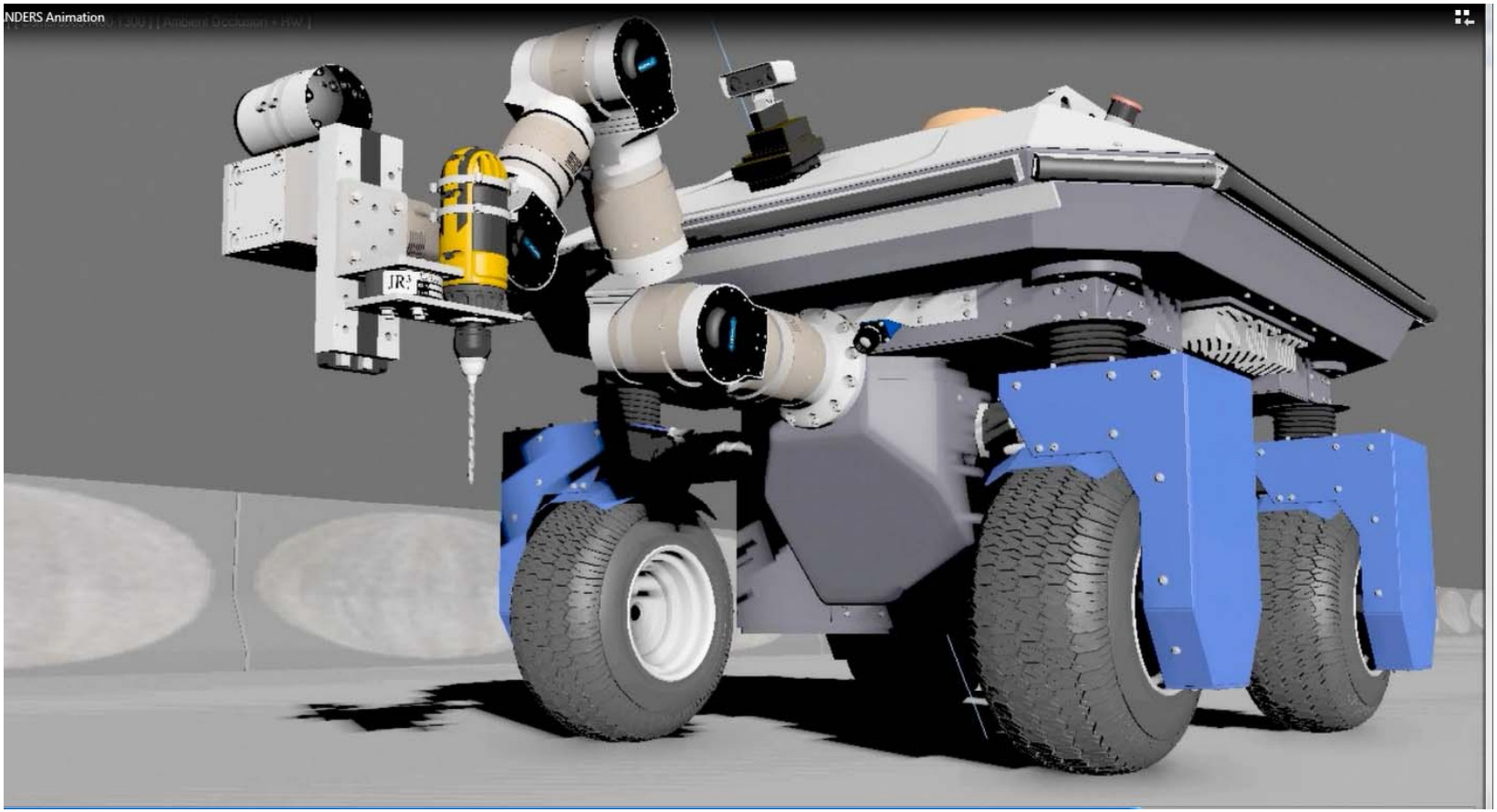


Global Structural Assessment (GSA) System

- GSA System aims to capture **global structural characteristics** and any appreciable effects of deterioration on a bridge.
- Auto St-Id assesses overall **structural vulnerability and capacity**.

Nondestructive Rehabilitation (NDR) System

NDR System leverages robotics for the precision and **rapid delivery of novel materials** capable of **halting an early-stage deterioration**.



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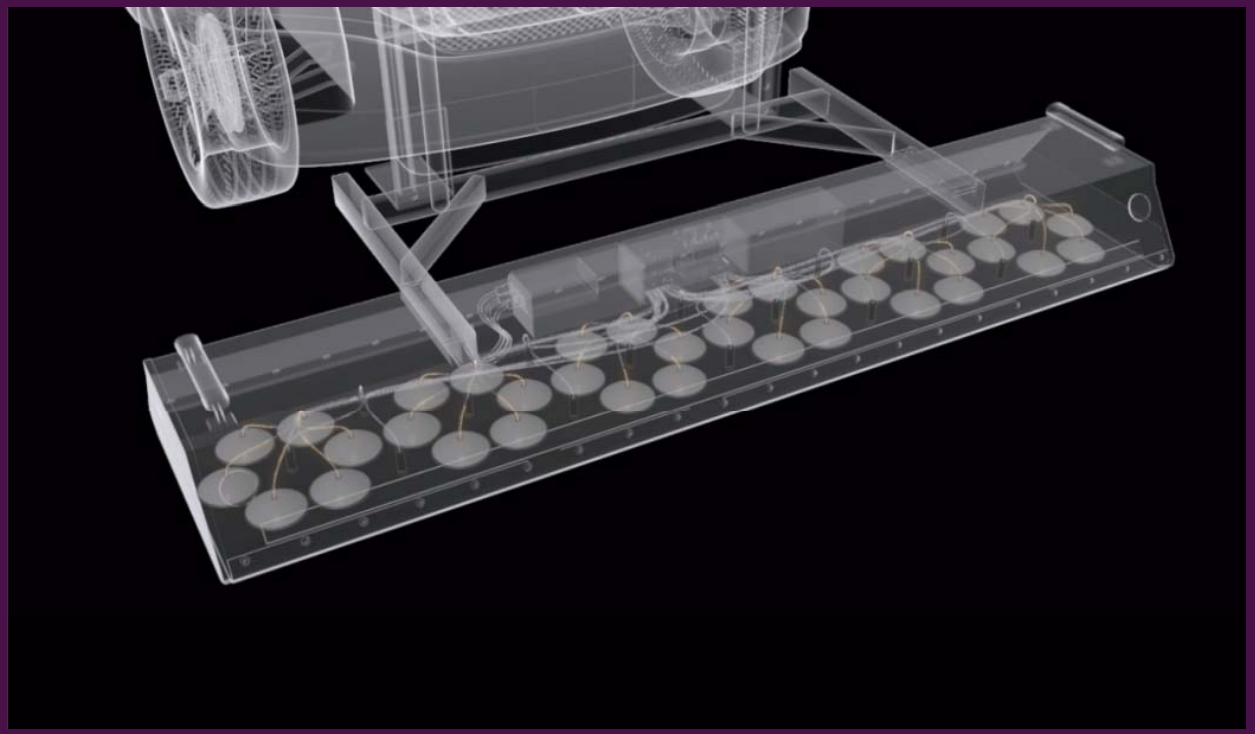
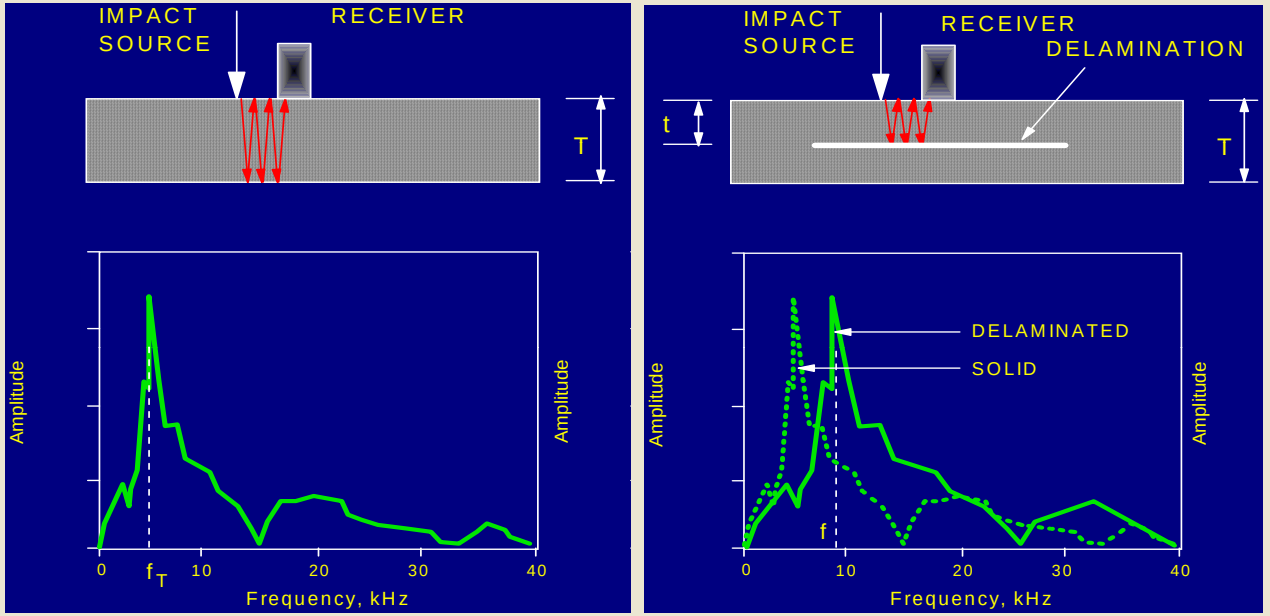
Air-Coupled Ultrasonic System (ACUS)



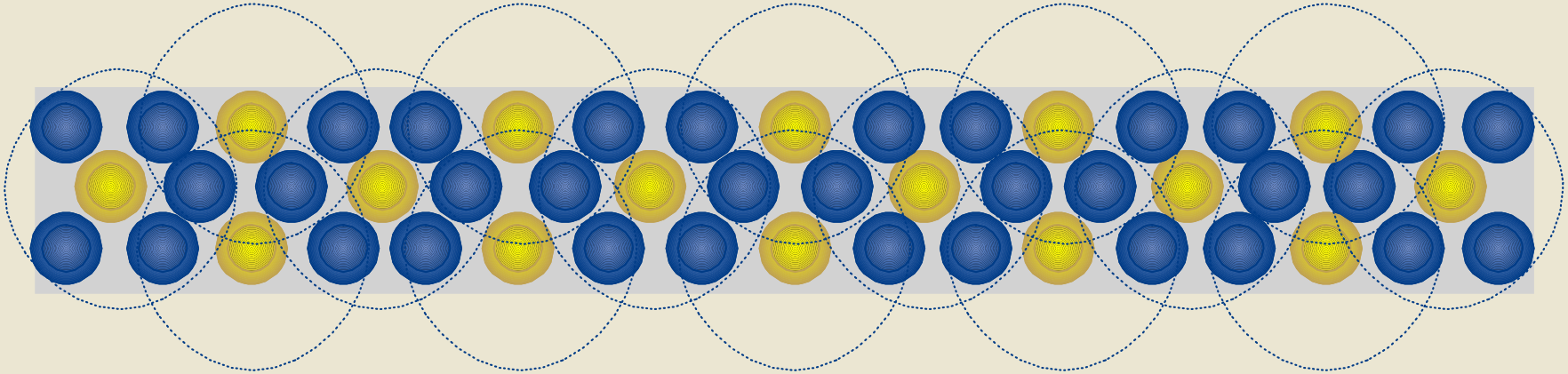
ACUS Configuration and Applications

- Consisting of multiple **hexagonal arrays** (modules).
- **Basic hexagonal array** has six **microphones** and a solenoid type impact source. Additional impact sources between hexagonal modules.
- The next generation will have **air-coupled sources**.
- **Applications** include:
  - **Delamination** detection and characterization,
  - **Concrete quality** assessment, and
  - **Vertical cracks** characterization.

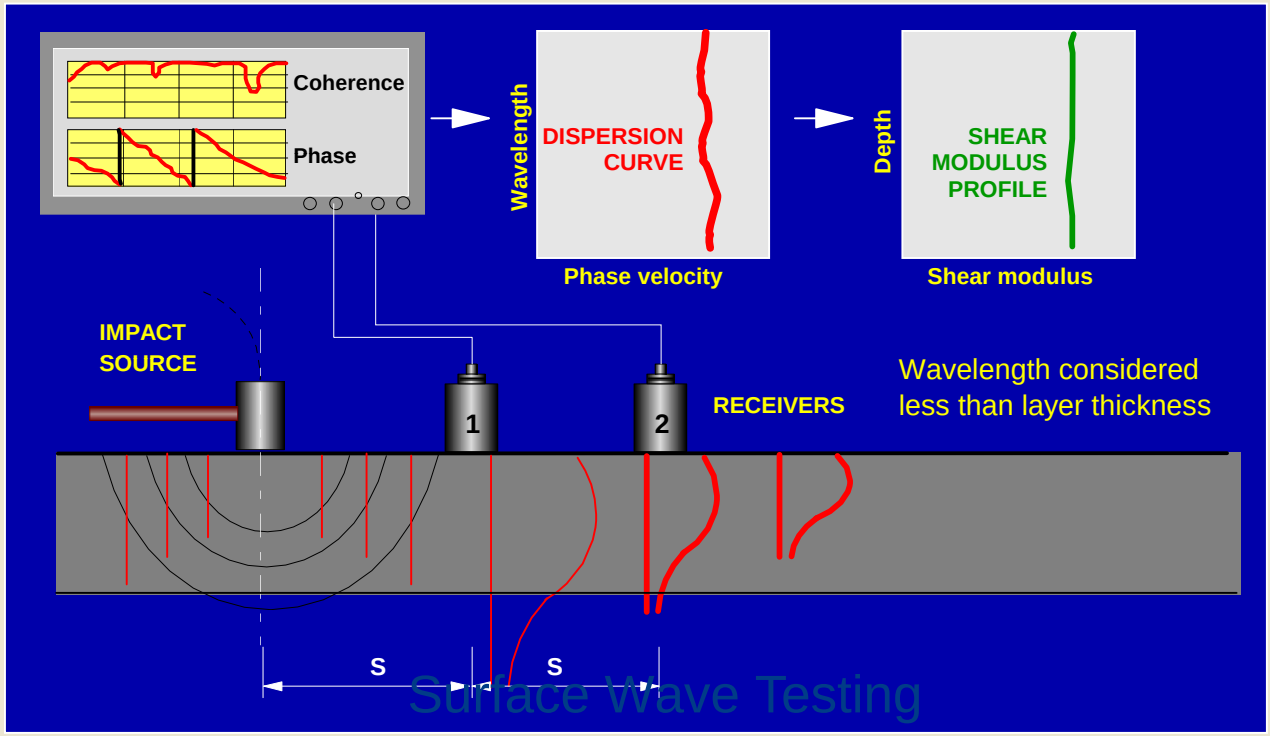
ACUS Optimization – Impact Echo Testing

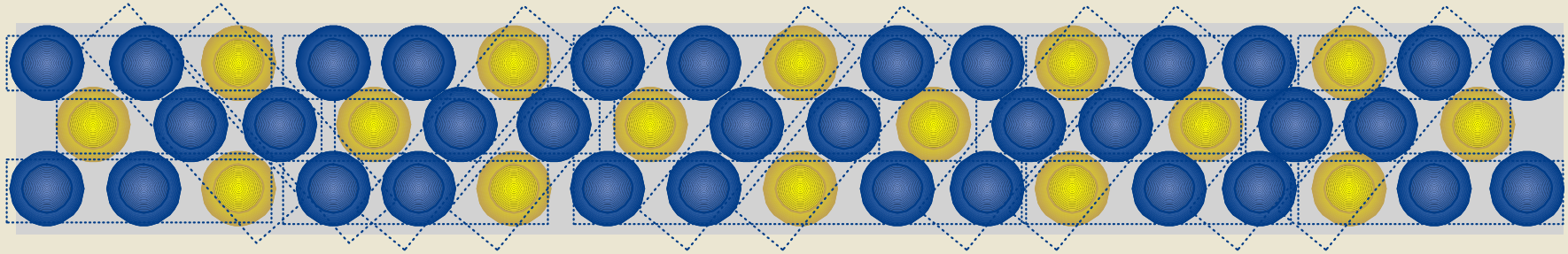


Impact Echo Testing



ACUS Optimization – Surface Wave Testing

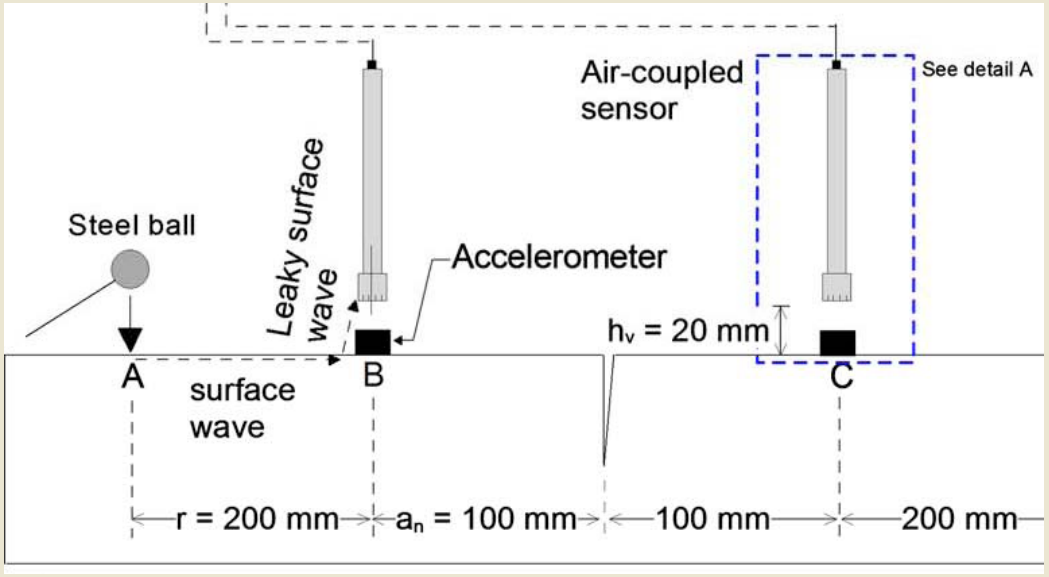


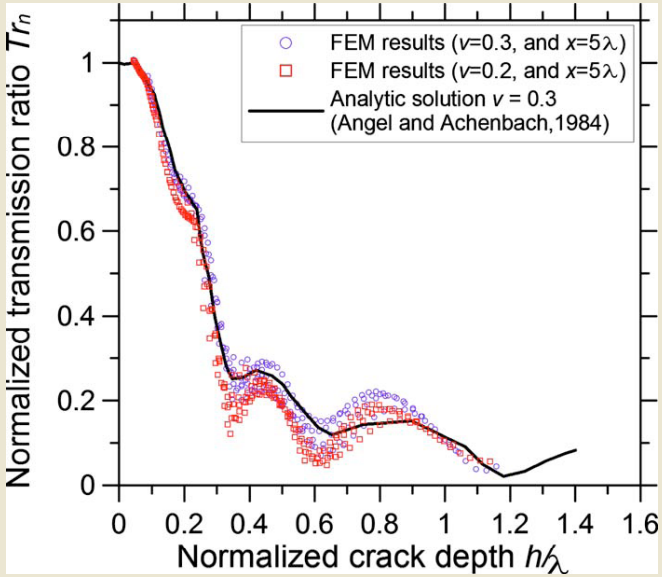


Source

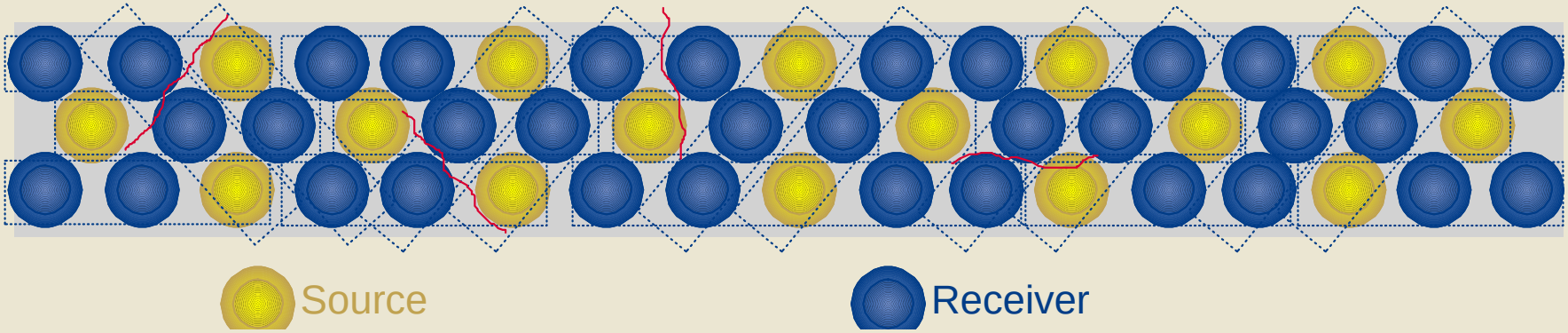
Receiver

ACUS Optimization – Crack Characterization

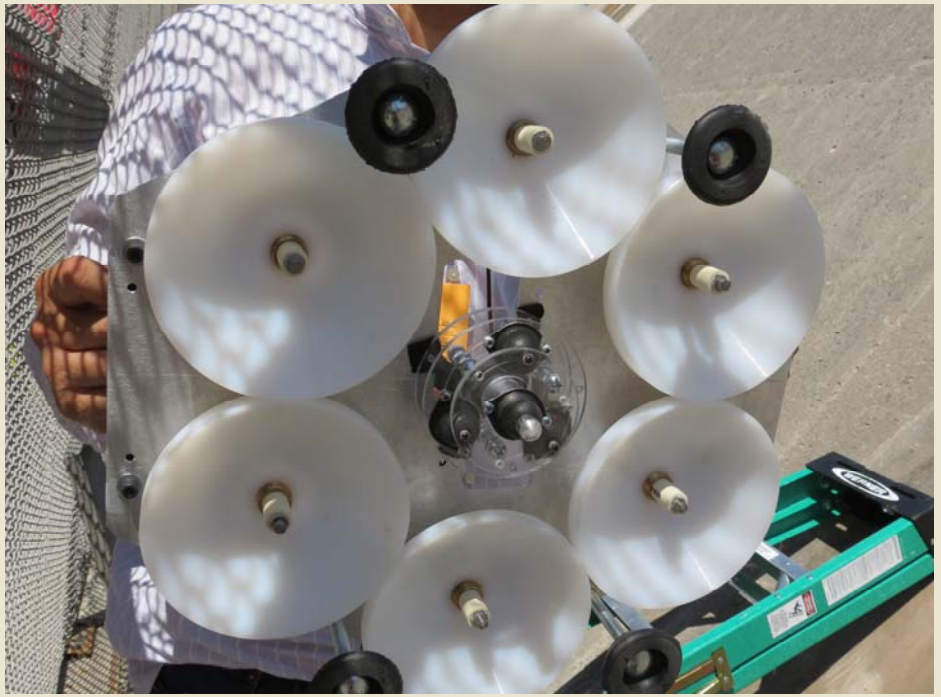




Crack Characterization from Surface Wave Testing

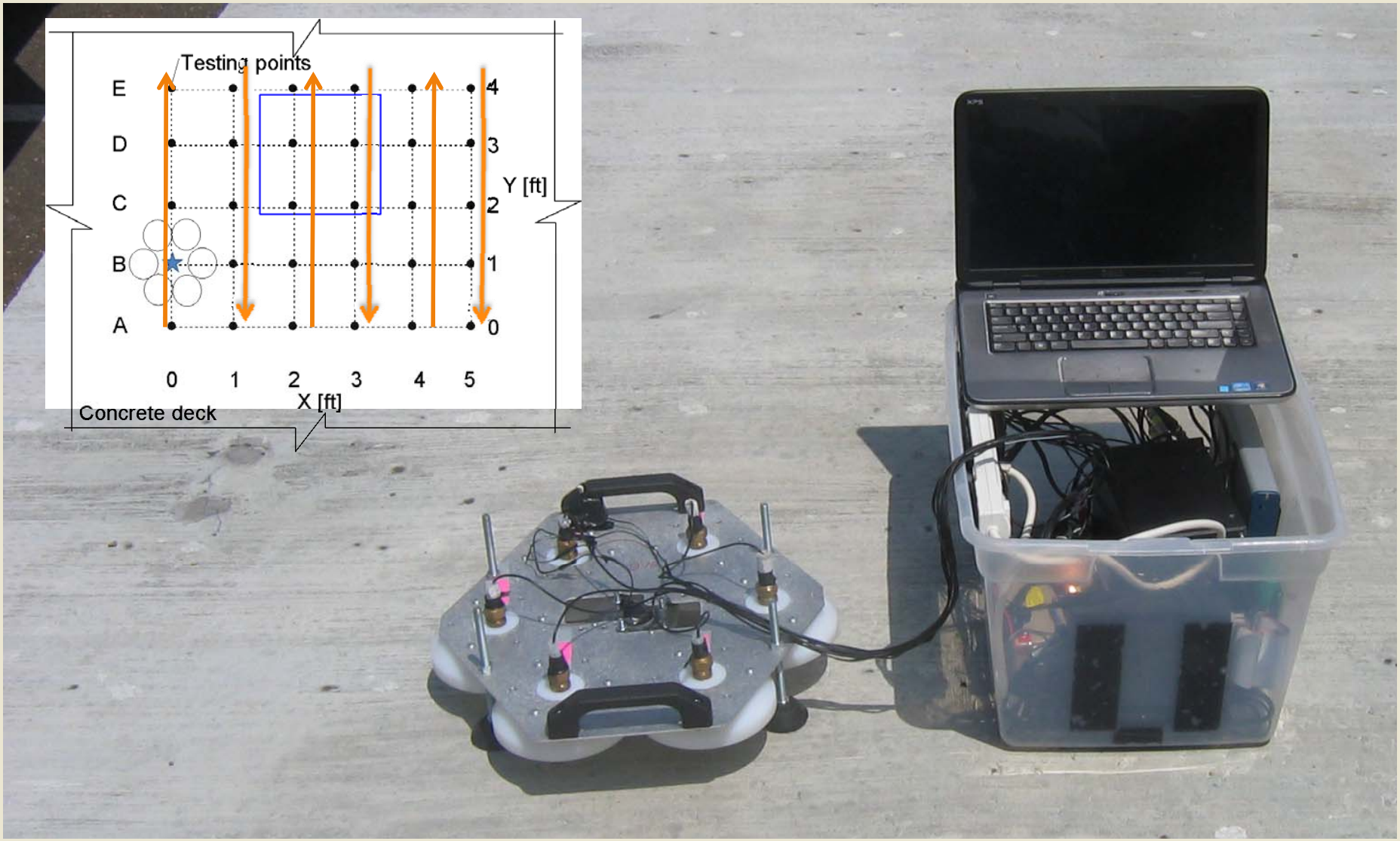


Hexagonal Air-Coupled Sensor Array

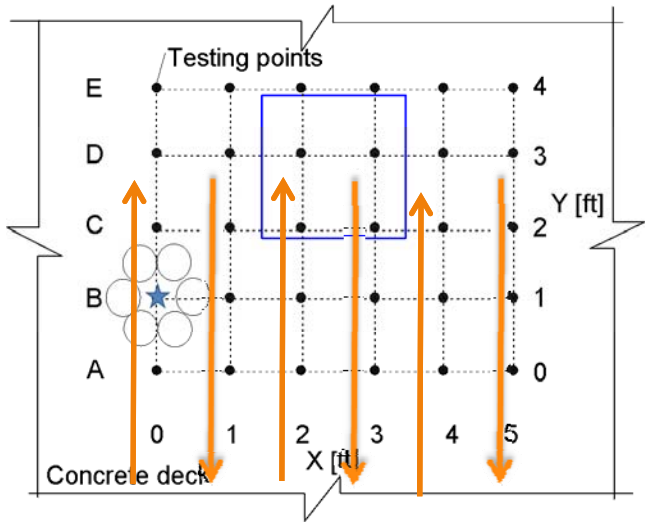


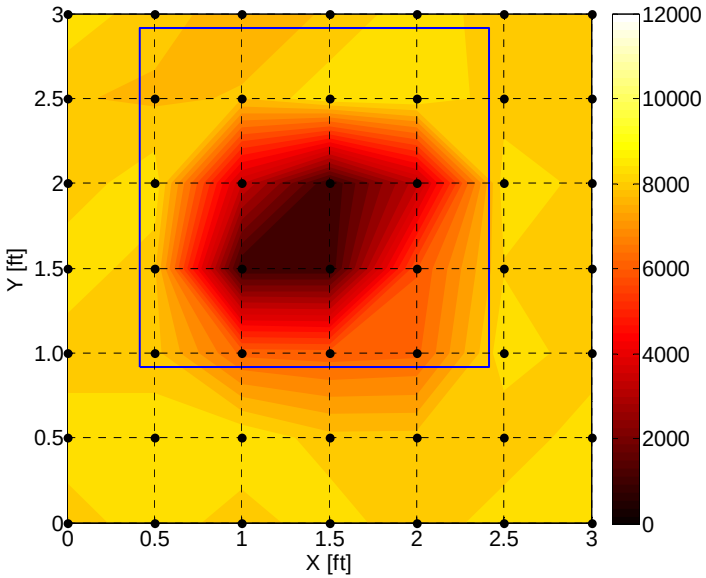
- Six air-coupled sensors at each vertex of a hexagon.
- Solenoid-driven Impact source at the center.
- Fully portable, battery-powered system.
- For IE and surface wave measurements.

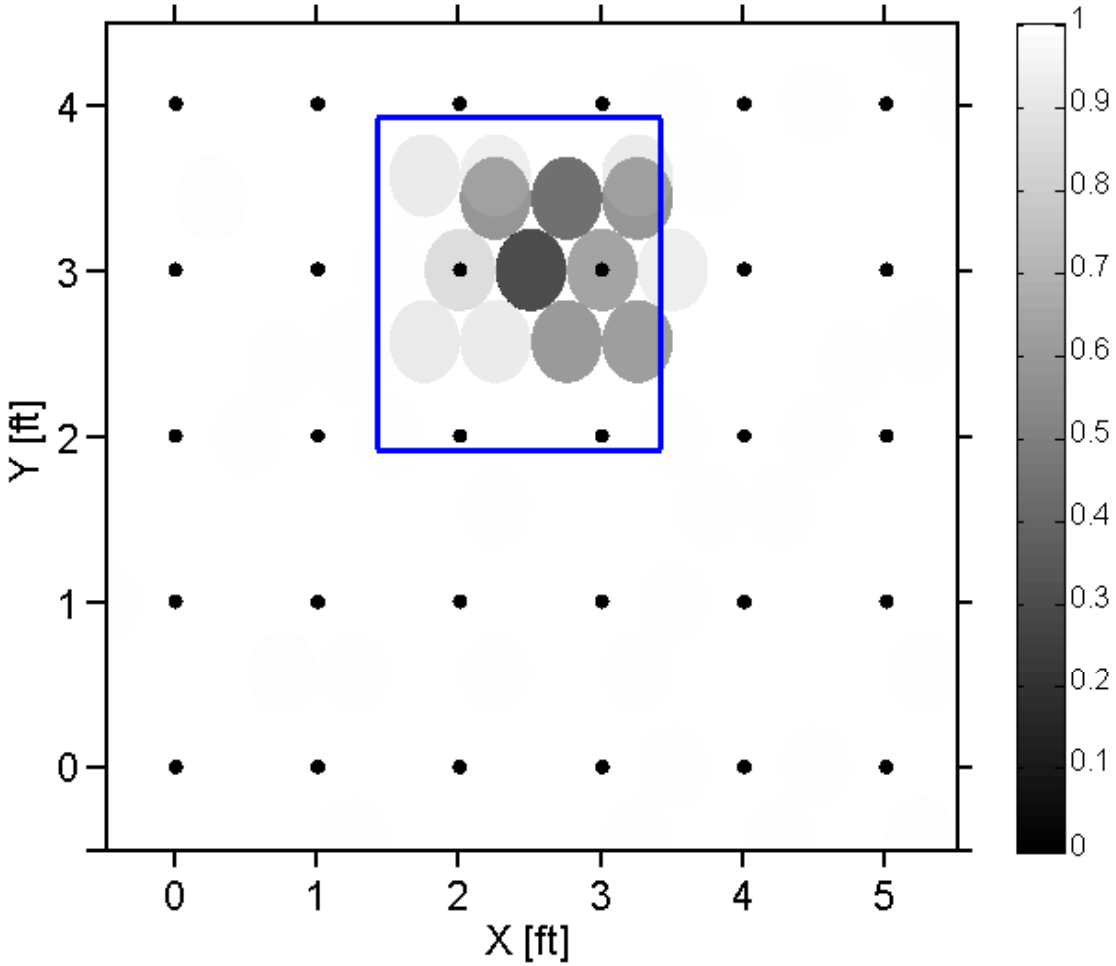
IE Testing on ANDERS Validation Slab



Frequency Map From Hexagonal Array IE Test

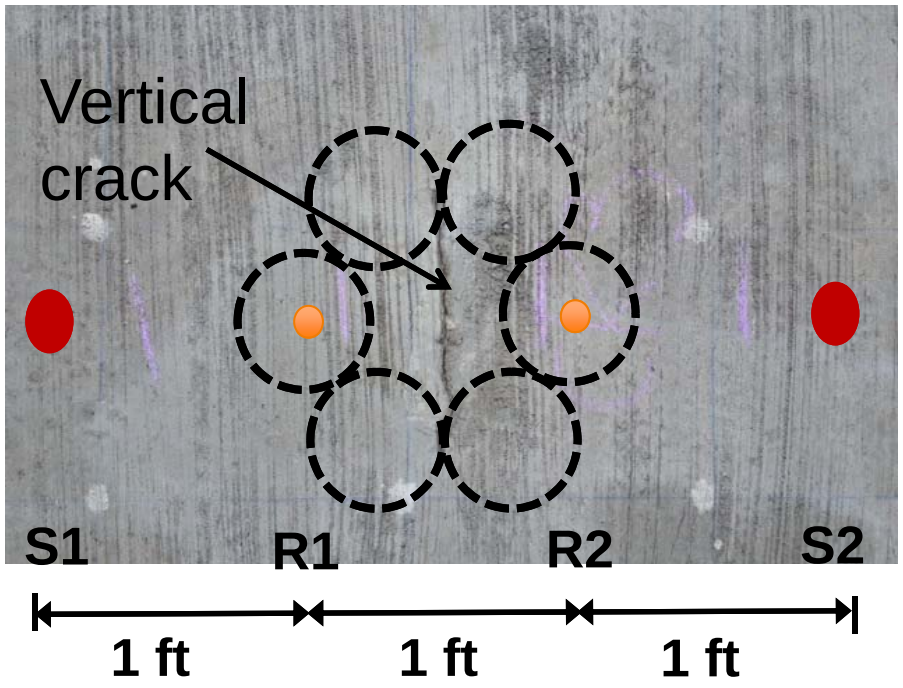


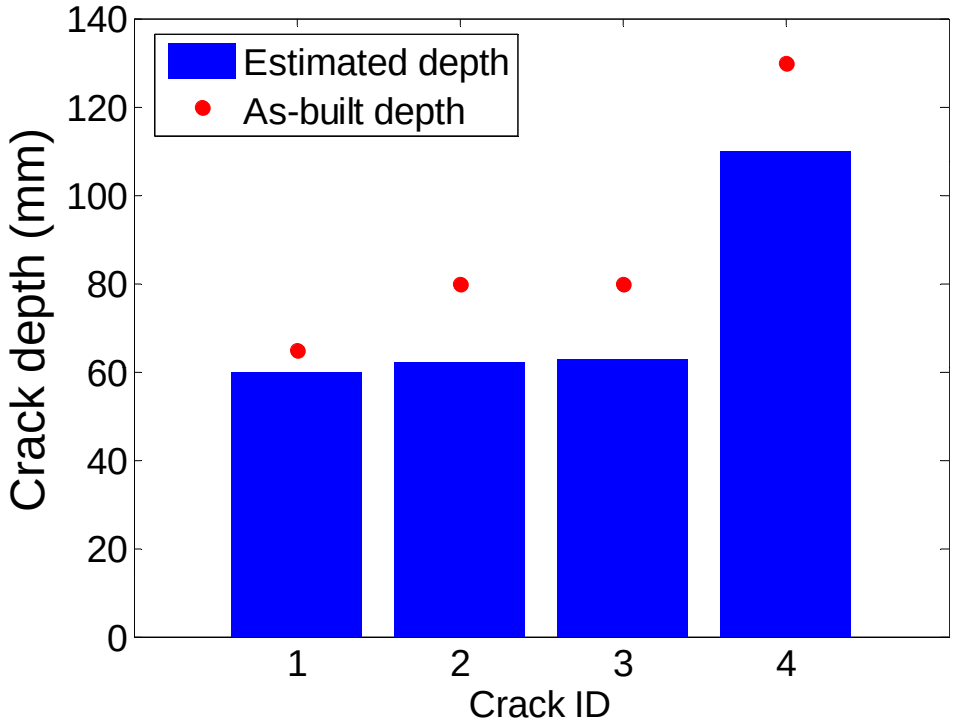




Crack Characterization Using Surface Waves

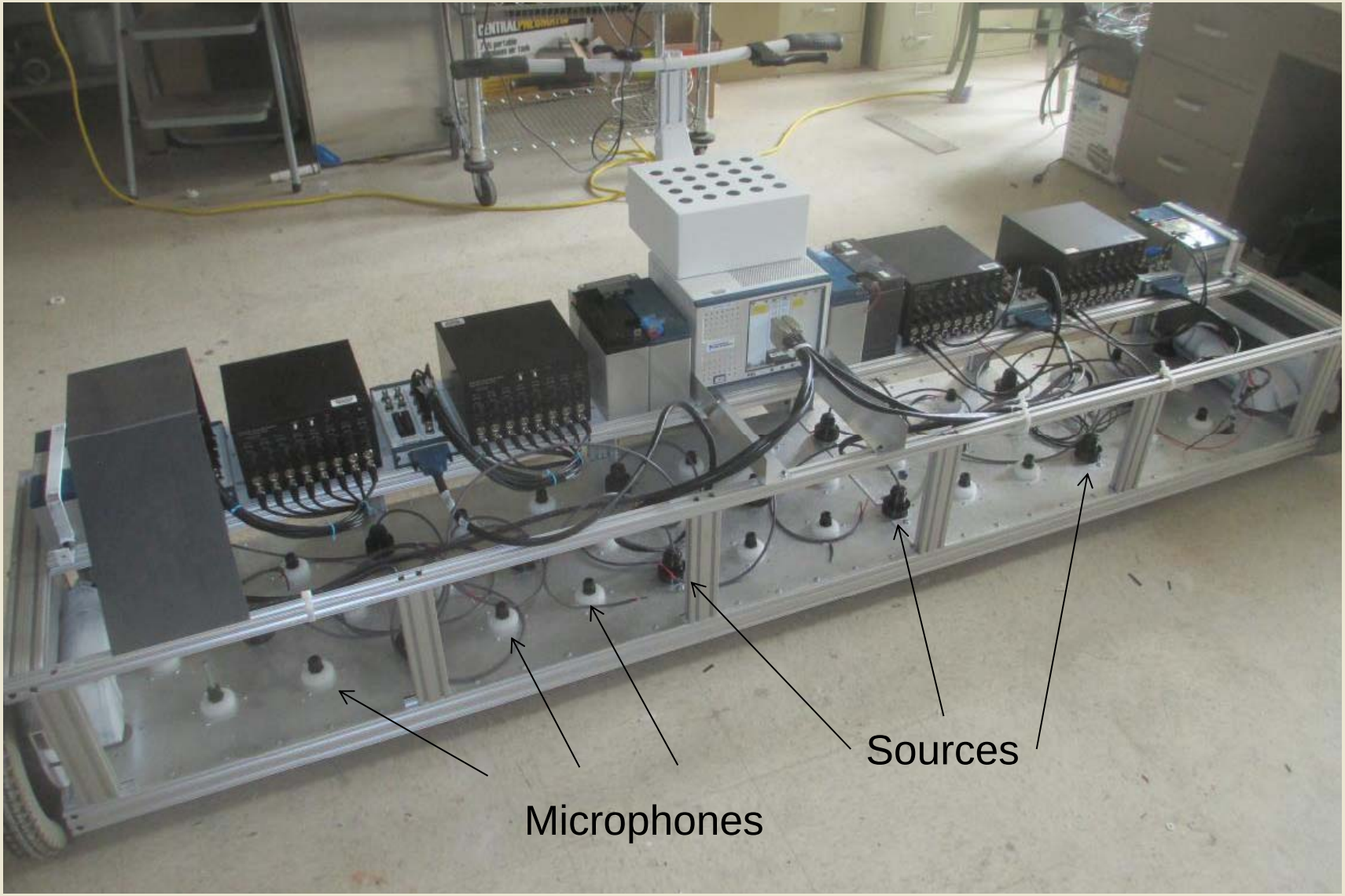
ANDERS validation slab





ACUS Hexagonal Modules

Air-Coupled Ultrasonic System (ACUS)

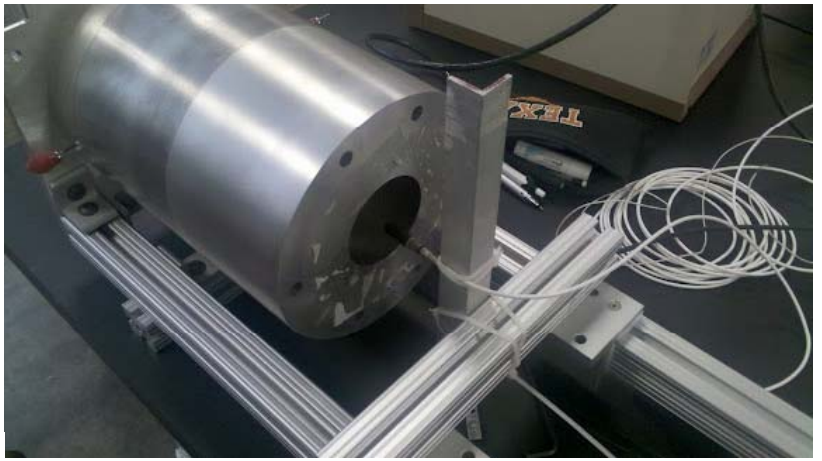


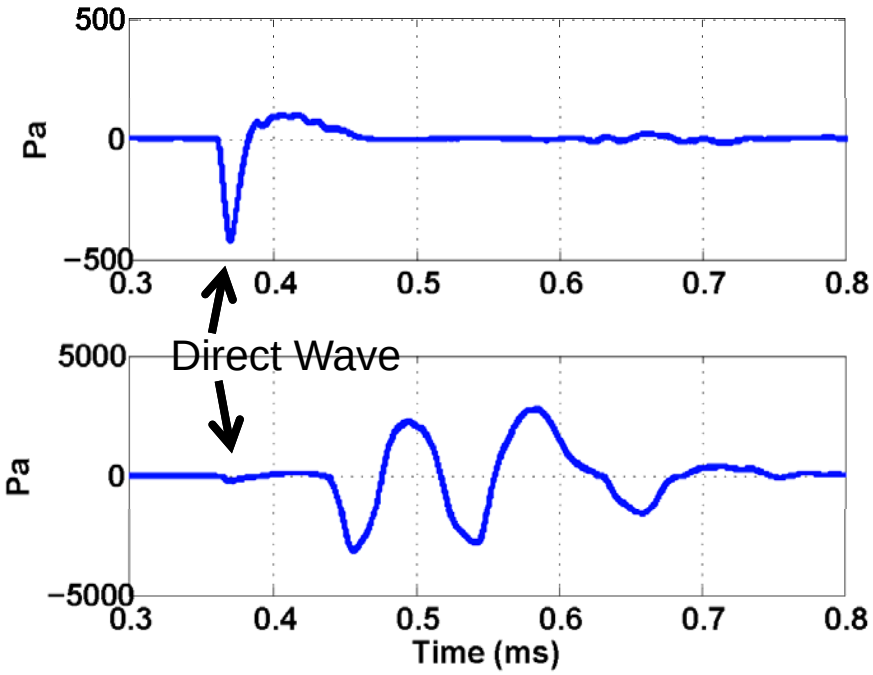
Focused Spark Source

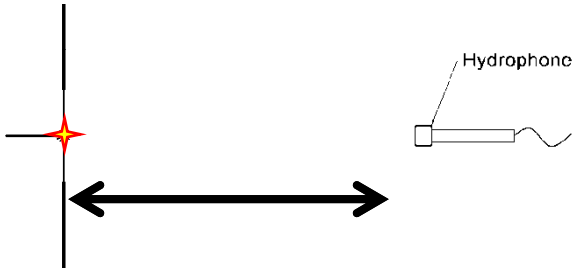
Acoustic waves focused by an **ellipsoidal reflector.**

Spark gap ~ 5mm

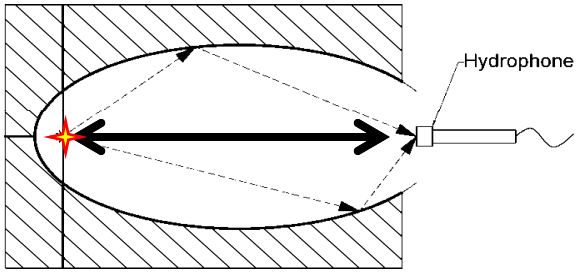
Peak pressure > 160 dB







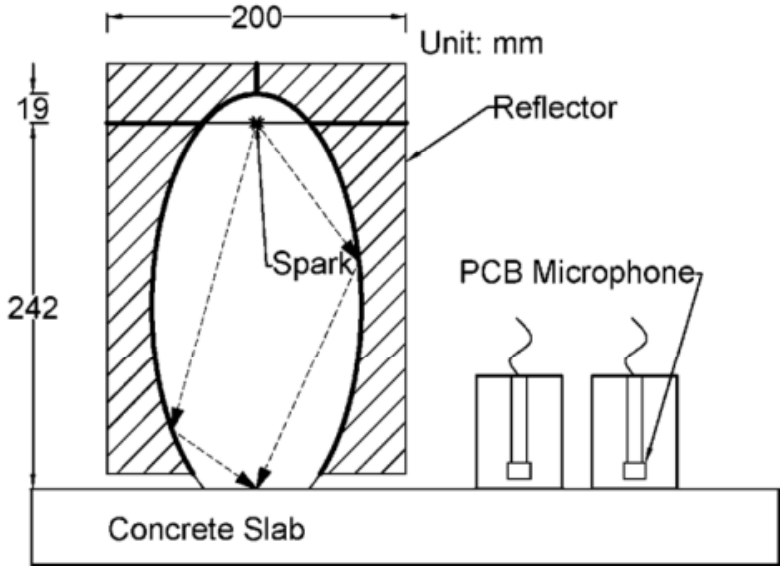
24.24cm



Spark Source in Surface Wave Testing

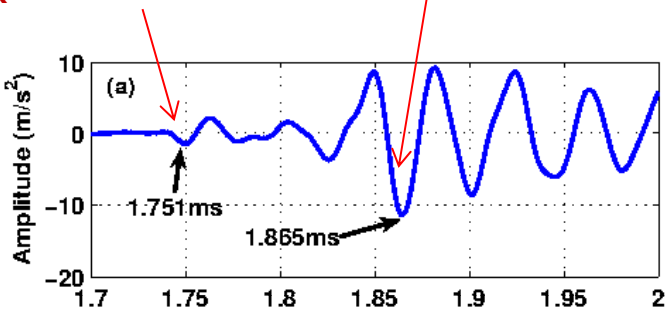
Receiver: accelerometer and microphone

Specimen: 190 mm concrete slab



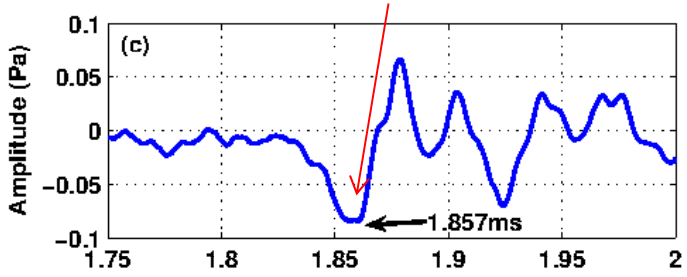
Surface wave from the direct spark

Surface wave from the focused spark



Accelerometer

Surface wave from the focused spark

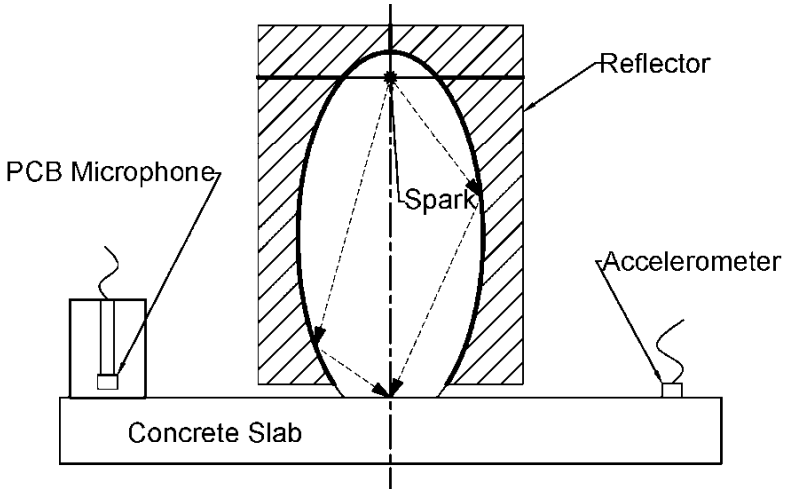


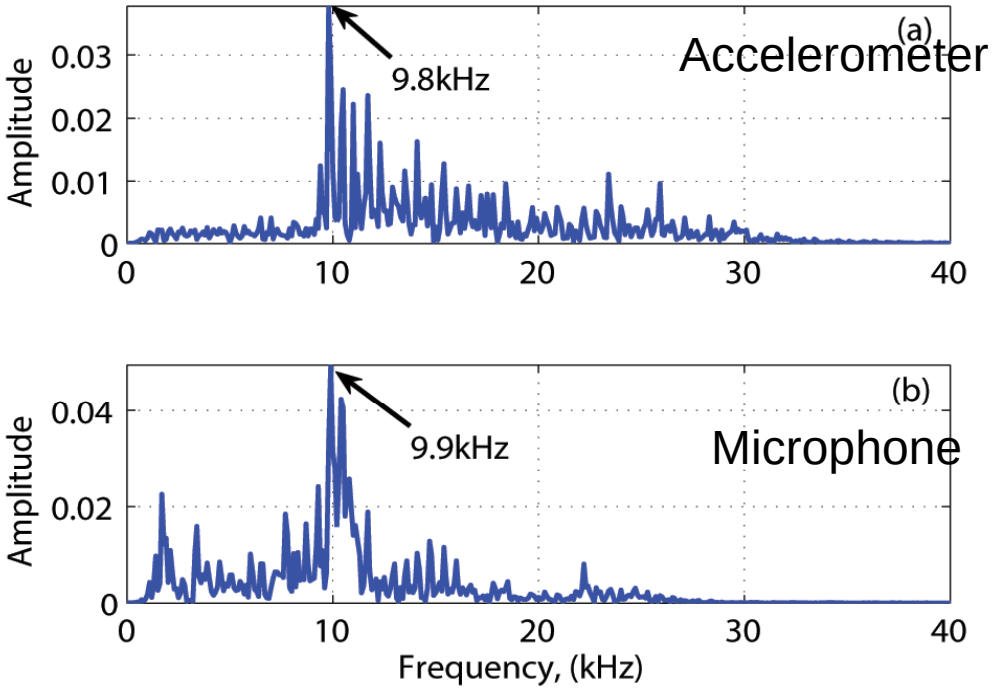
Microphone

Spark Source in IE Testing

Receiver: accelerometer and microphone

Specimen: 190 mm concrete slab (IE frequency around 10kHz)





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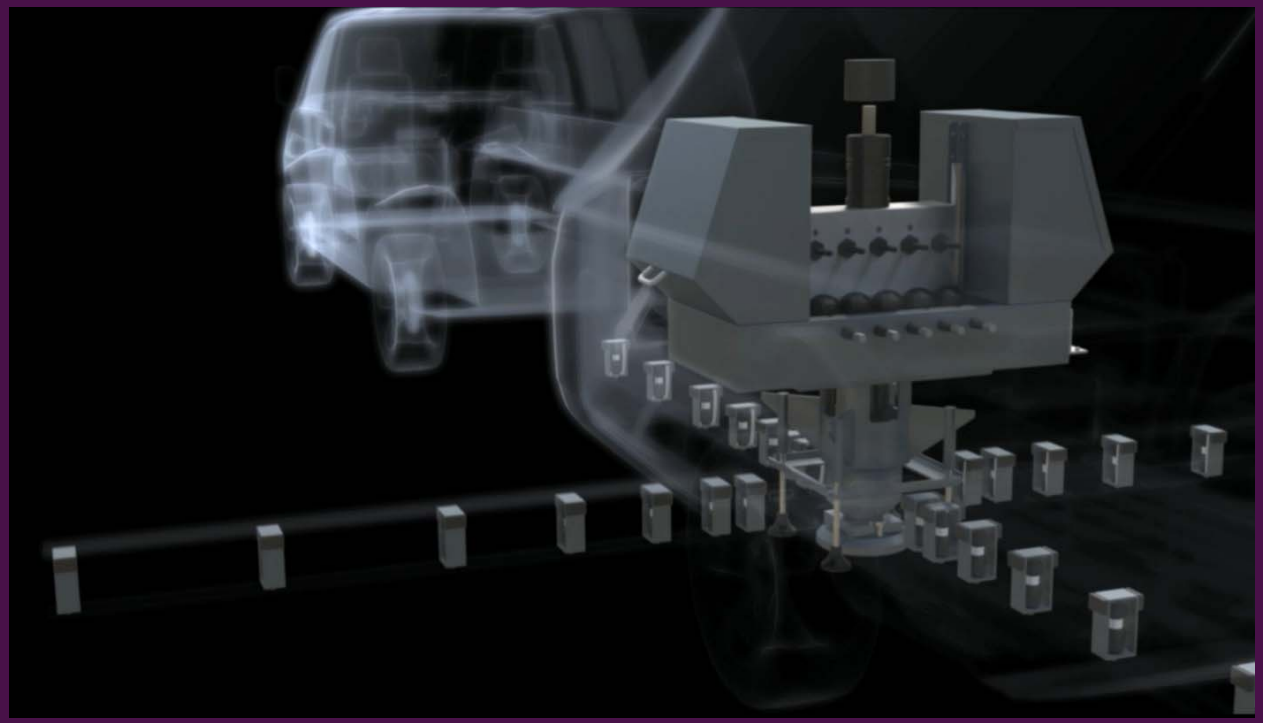
Global Structural Assessment (GSA) System



State-of-the-Art – Bridge Capacity Estimation

Analytical Load Rating

- Based on design-type assumptions
- Employs simplistic, *a priori* models
- Unreliable (Pratt Truss versus I-35W)

Engineering Judgment

- Driven by visual appearance
- Typically lacks appreciation for mechanics

Load Testing

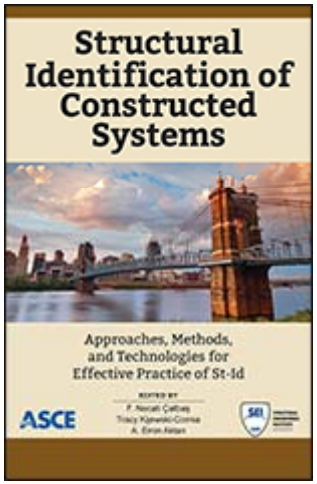
Diagnostic-Level

- Uses service loads
- Employs simplistic models
- Based on irrational model-experiment correlation

Proof-Level

- No model
- Uses large loads (many times service loads)
- Unrealistic and dangerous

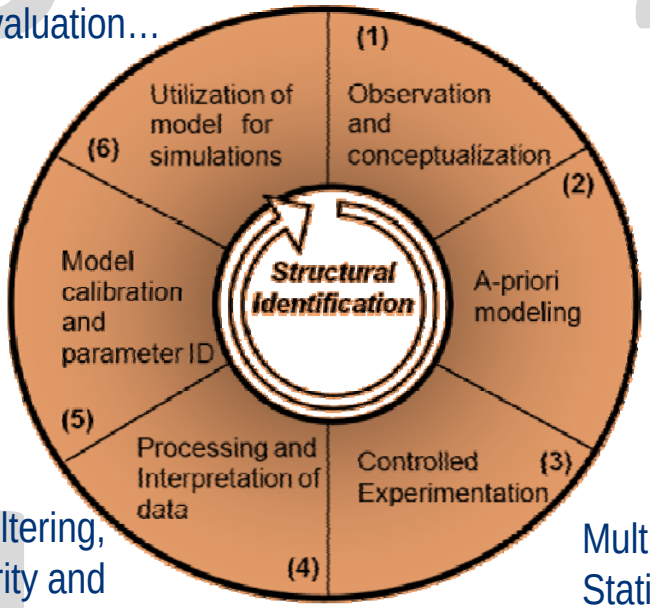
State-of-the-Art – Bridge Capacity Estimation



Load Ratings, Scenario Analyses, Vulnerability Assessment, Retrofit Evaluation…

Heuristic Knowledge
Automated Parameter ID
Bayesian Model Updating…

Data Processing (Filtering, Averaging), Linearity and Repeatability, Experimental Data Processing…



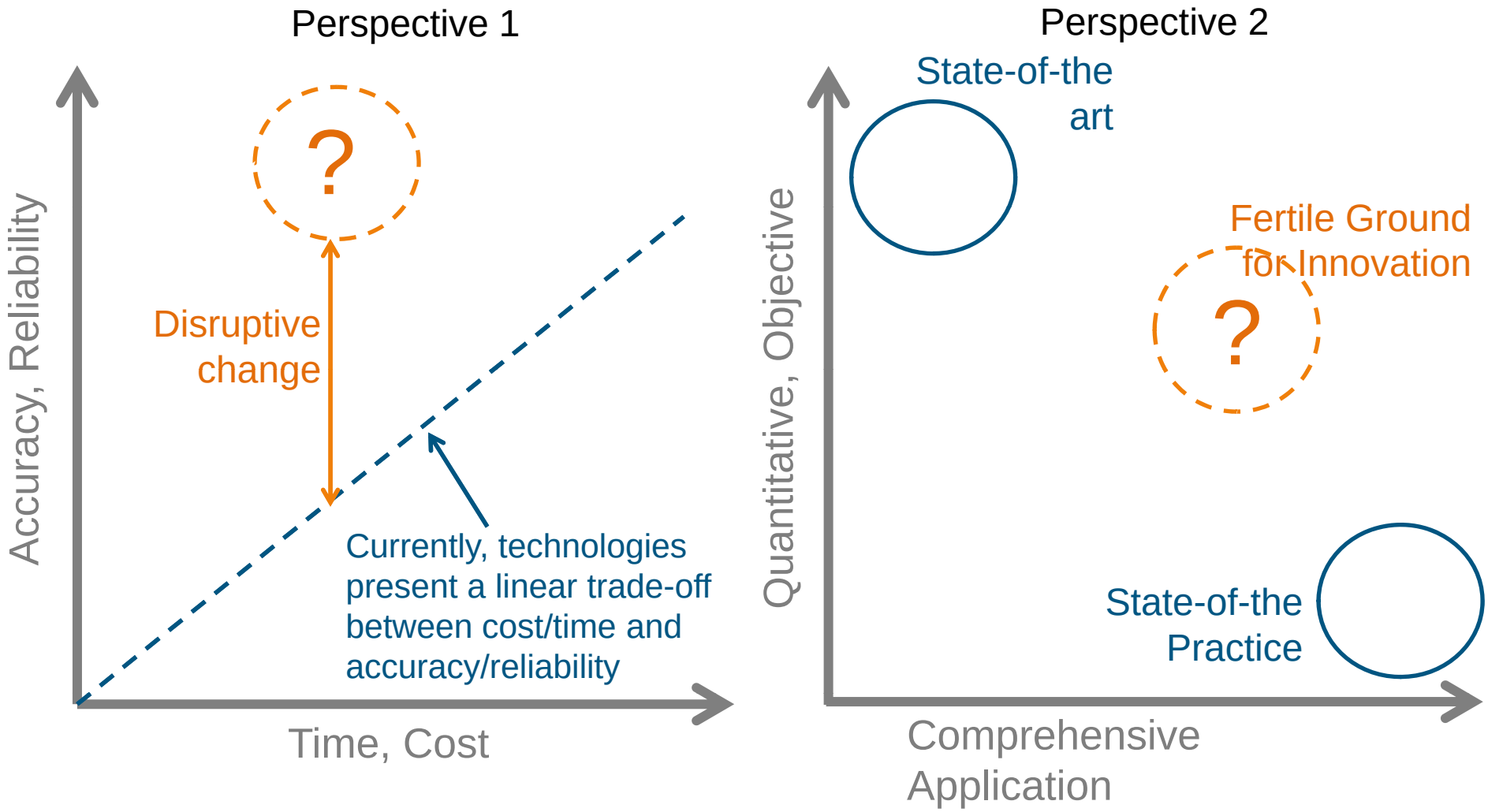
Document Review, Site Visits, Inspection, Material Sampling…

Model Type Selection
Sensitivity Studies
Measurement Predictions
Instrumentation Design…

Multi-Modal Instrumentation
Static/Crawl-speed Truck Testing
Environmental Monitoring
Dynamic Testing…

Design and implementation of Structural Health and Performance Monitoring Systems

Innovation Space



THMPR (Targeted Hits to Measure Performance Responses)

Step 1
Rapid modal impact testing using a self-contained mobile device

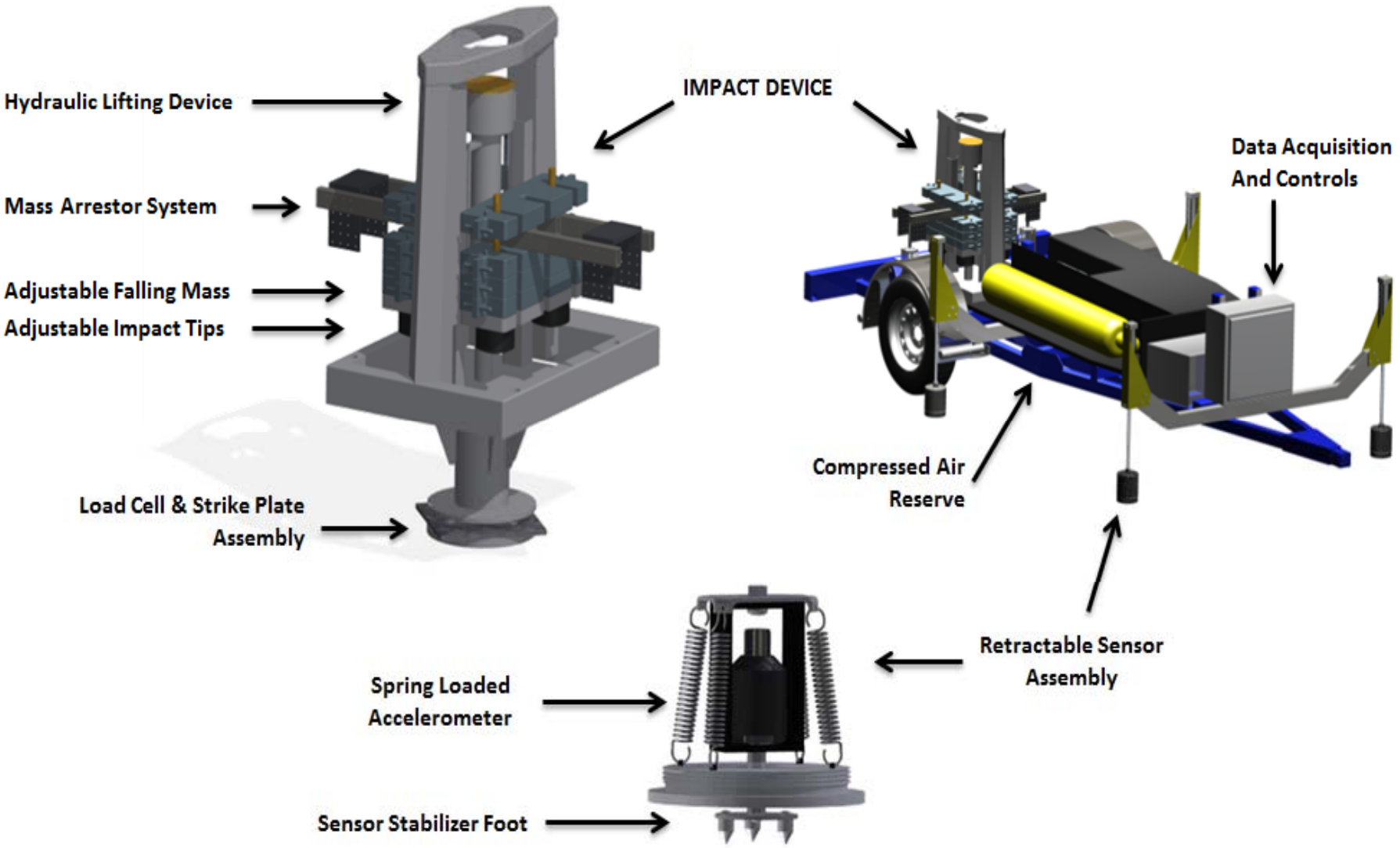
Step 2
Semi-Automated pre- and post-processing to obtain global frequencies and mode shapes

Step 3
Automated FE modeling using NBI data and on-site assessment

Step 4
Automated FE model calibration and load rating

Step 5
Reporting

THMPR Components

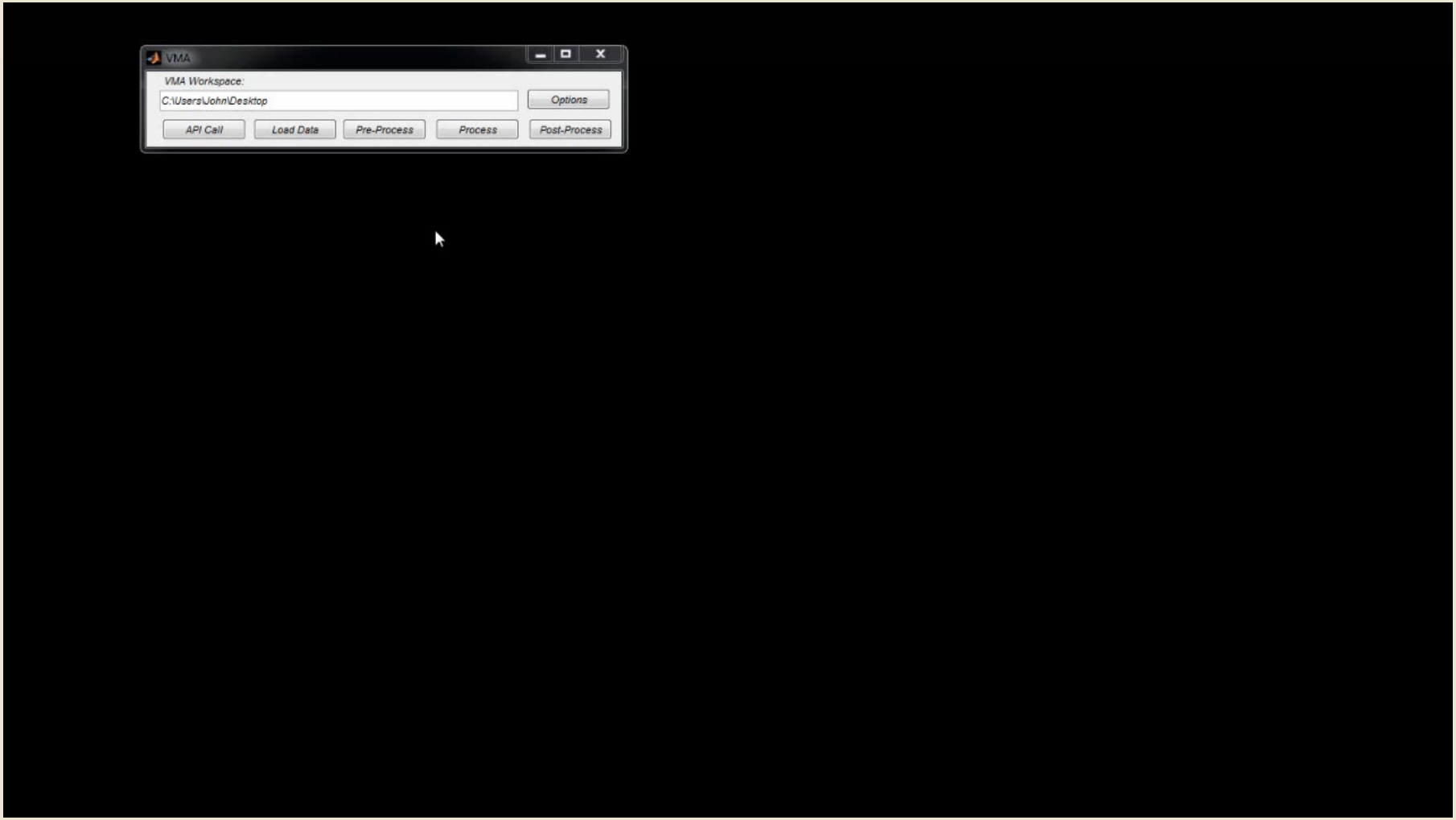


Comparison with Current Approaches

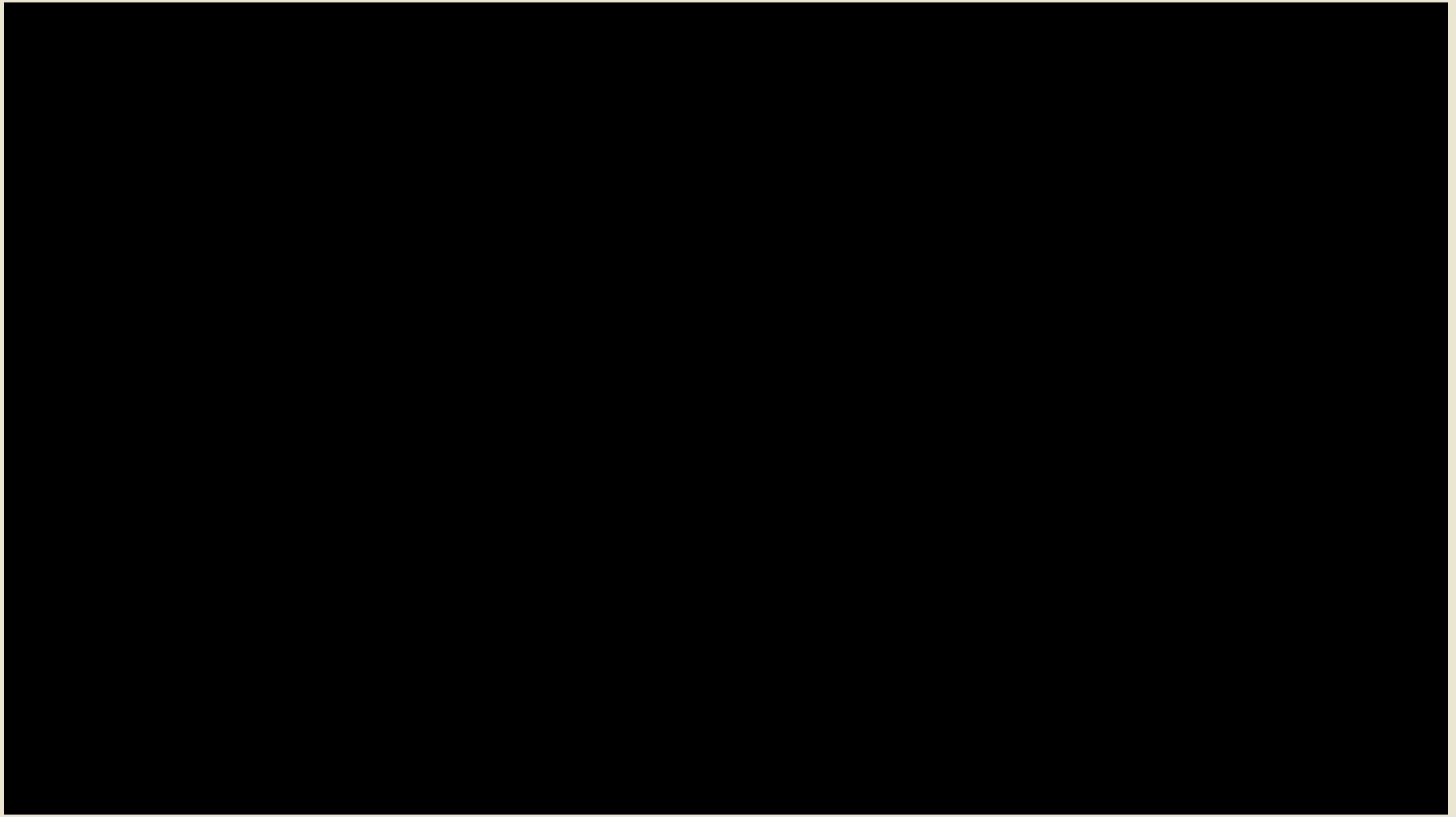
	Technology/ Approach	Cost	Prep. Time	Testing Time	Report Time	Access Equip	Bridge Closure	Overall Quality
Quasi-Static	Ambient monitoring w/ displacement transducers	$30-50K	5-10 days	2-5 day	3-5 days	Yes	Only under-side	Mod
	Load testing w/ displacement transducers	$30-50K	5-10 days	1 day	3-5 days	Yes	Partial 2 hrs	High
Dynamic	Ambient vibration monitoring	$20-30K	5-7 days	2-5 days	5-7 days	Yes	Only under-side	Mod
	MIMO Impact Testing	$40-60K	5-7 days	1 day	5- 7 days	Yes	Partial 2 hrs	High/ Mod
	THMPR	$3-5K	N.A.	1-3 hrs	1-2 hrs	No	Slow downs	Mod

THMPR Data Collection

Automated Pre- and Post-Processing

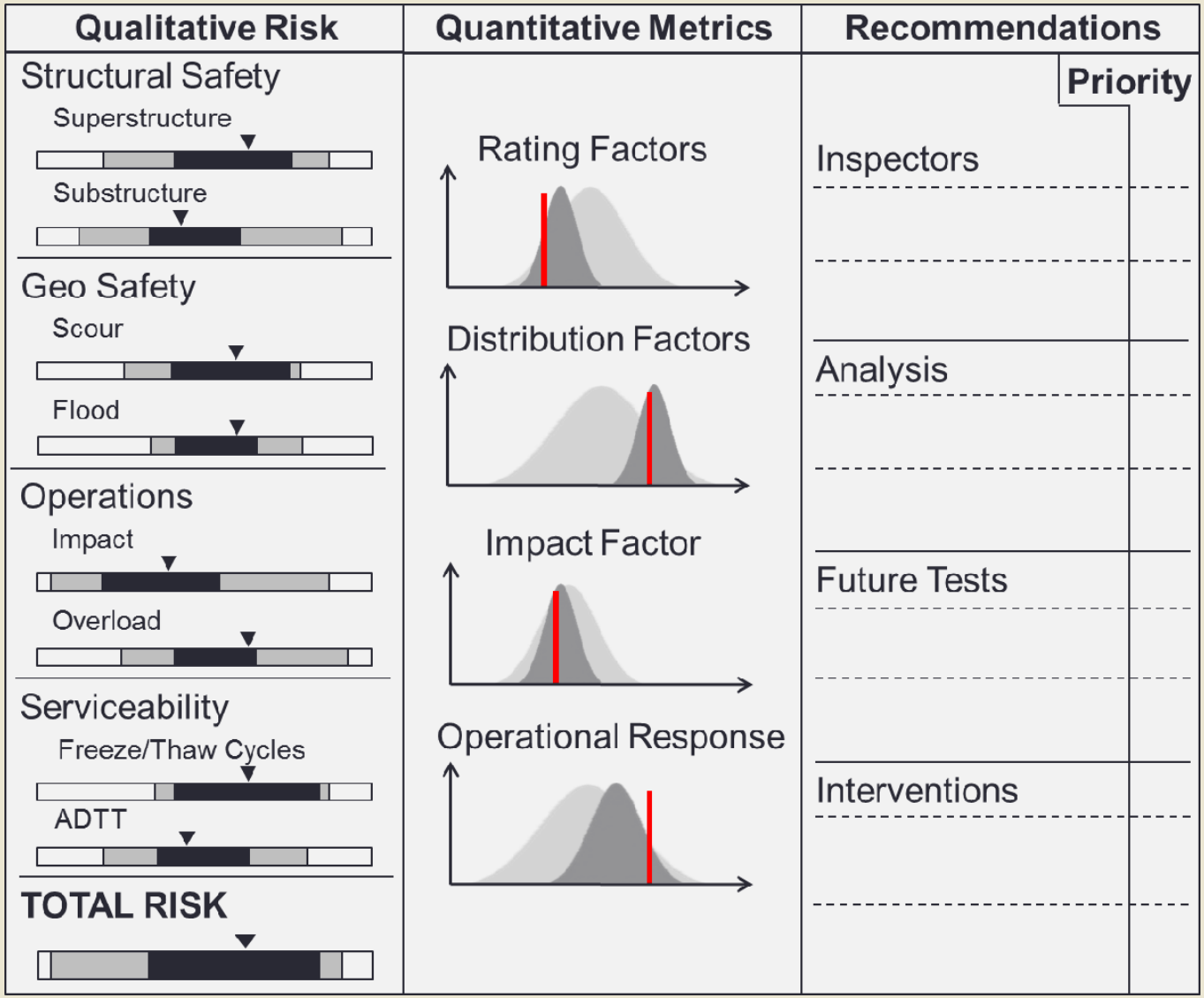


Automated FE Modeling



Automated Model Calibration and Rating

Example Reporting



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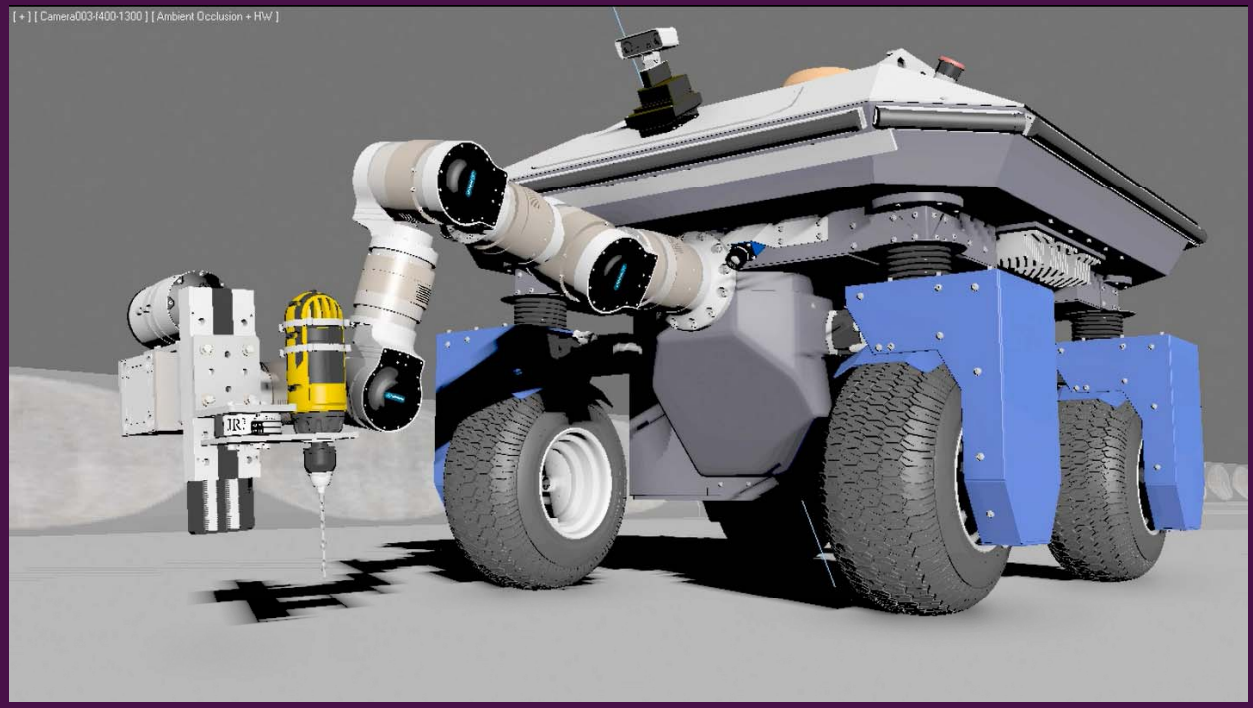
Nondestructive Rehabilitation (NDR) System



NDR System

Objectives

1. To develop **novel materials** that:
   a) can be **easily delivered** to damaged areas (fine delamination and cracks),
   b) will **restore structural integrity** of members,
   c) and are **durable.**
2. To utilize **high-precision robotics** for **autonomous, rapid and minimally invasive delivery** of repair materials.

Repair Composites Mix Design

Alumino-Silicates

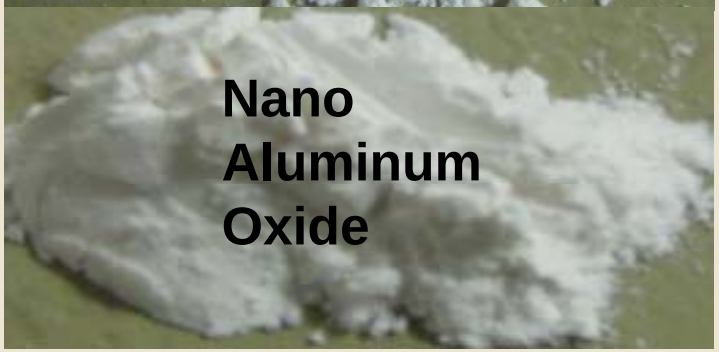
Phosphates

Carbon Fibers

Different mix-designs were prepared

Variables included:

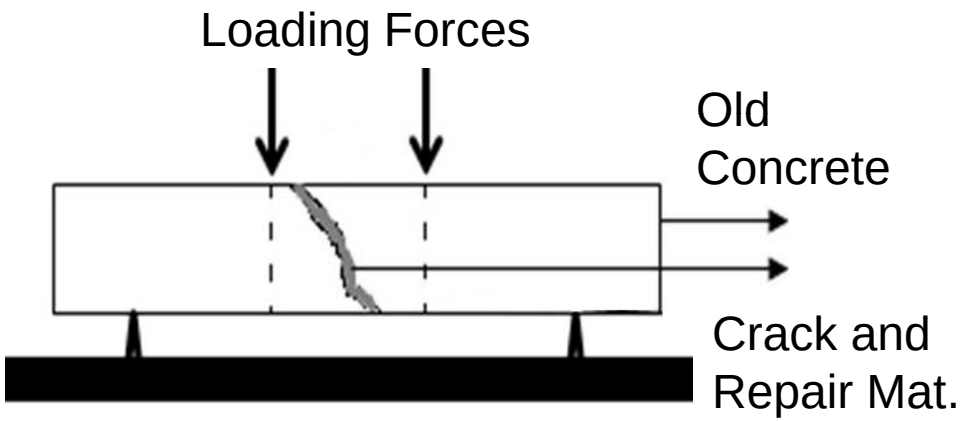
- **size of the particles,**
- **nano particle content,**
- **compositions,**
- **curing conditions, and**
- **testing samples**



Flow Test - Filling of a Delamination

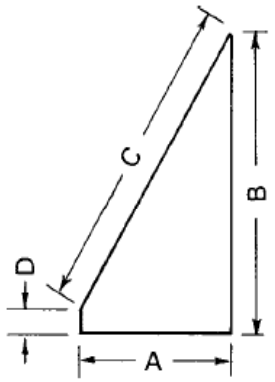
Bond Strength Testing

1. Three point bending- flexural strength/ modulus of rigidity (ASTM C 78)
2. Bond strength of repair materials by Slant shear (ASTM C 882)



Experimental setup for bond strength of flexural specimen

Slant shear samples according to ASTM C882



Dimensions	in.	mm
A—Diameter	3.000	[75±2]
B—Height	5.598	[140±2]
C—Slant height	6.000	[150±2]
D—Base height	0.402	[10±2]

Durability Testing

Freeze/Thaw

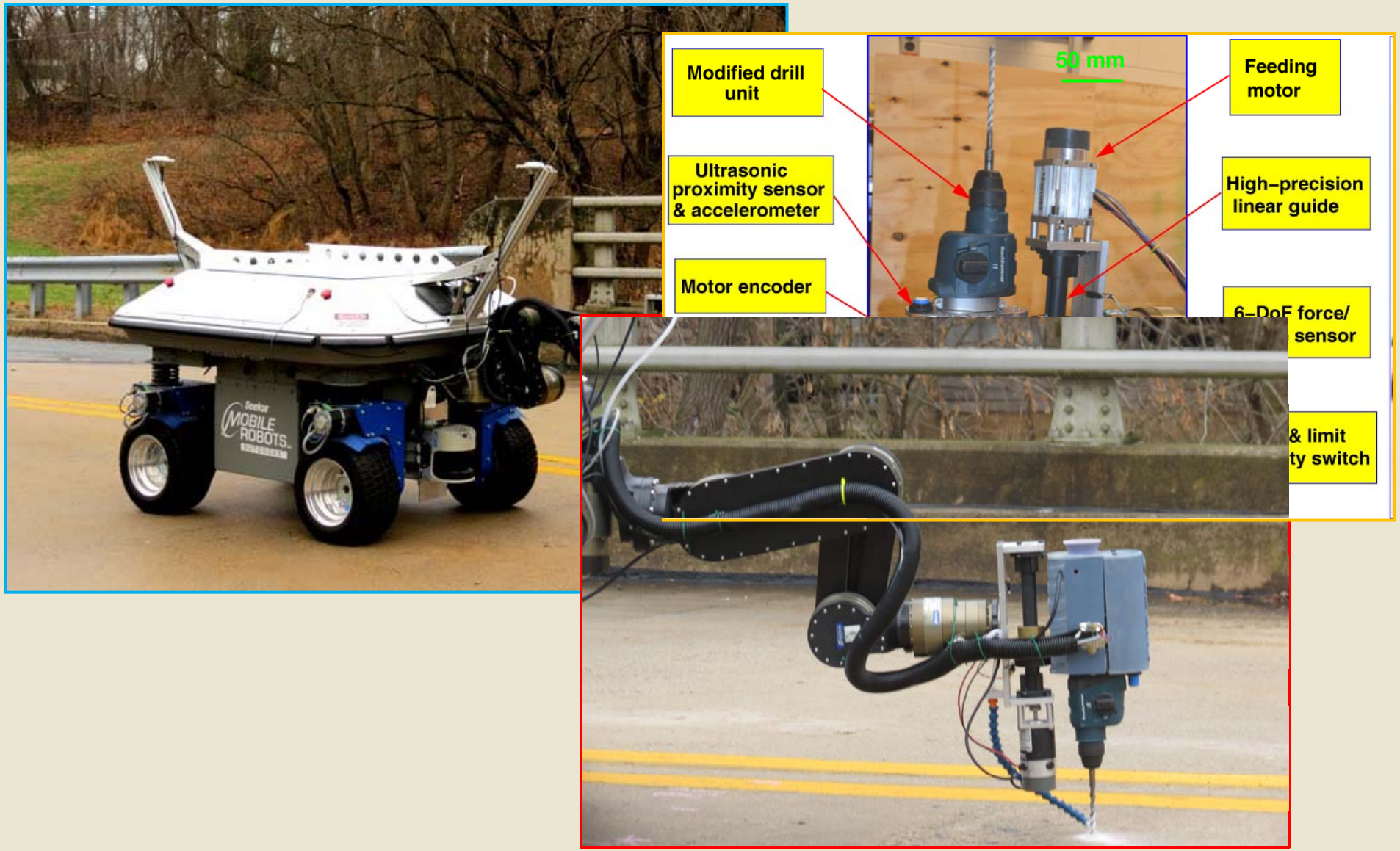
ASTM D6944 Standard Practice for Resistance of Cured Coatings to Thermal Cycling

Wetting

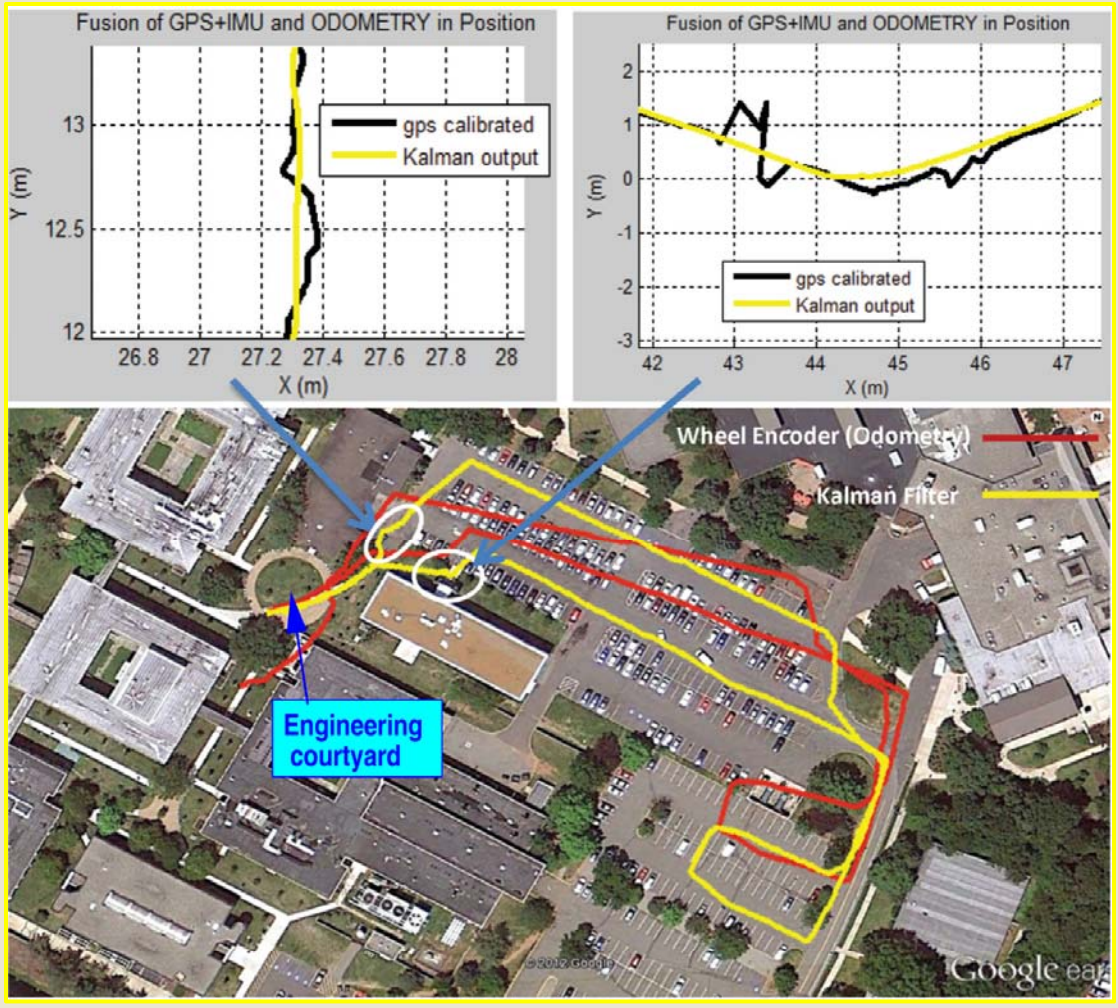
Strength and Durability Test Results

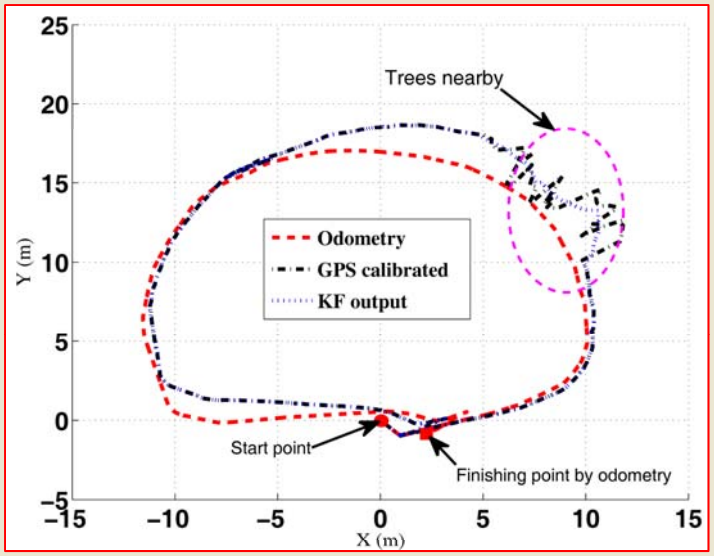
- The **composites performed very well** in all strength and durability tests.
- In flexural testing the **repaired section was stronger than parent concrete**.
- The **joint did not break in the slant shear test**. The cylinder behaved like the original uncut cylinder.
- Full scale beam test confirmed that the **composite can restore structural integrity of members**.
- The **deterioration was minimal under both wet-dry and freeze-thaw conditions**.

Rehabilitation Robot Prototype



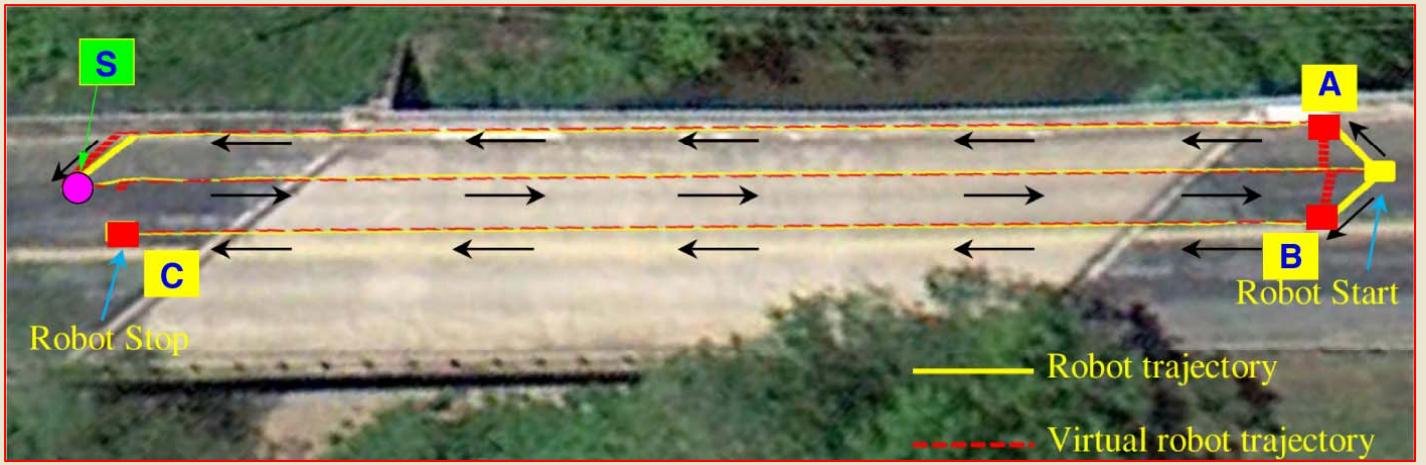
Reliable and Robust Robot Localization



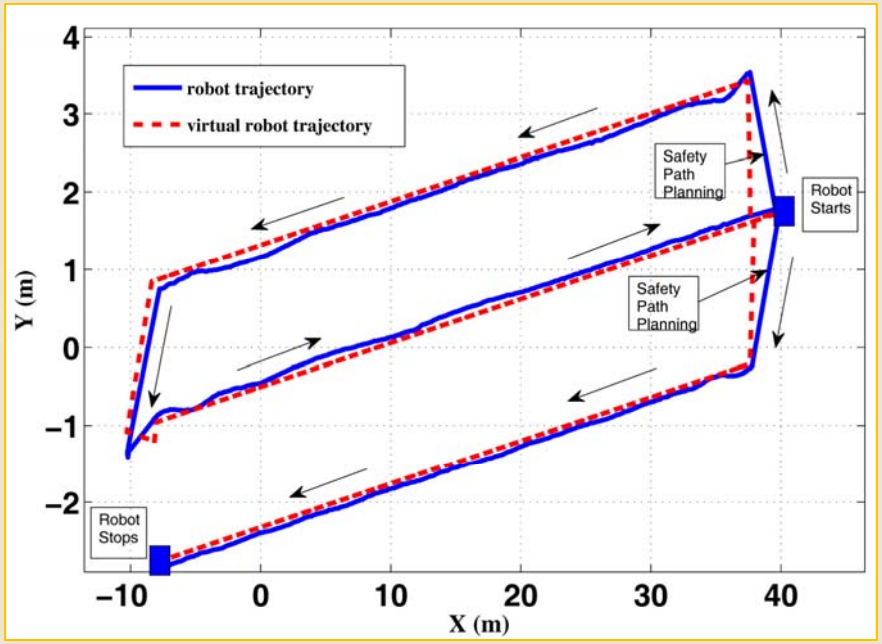


Extended Kalman filter design to fuse **GPS, IMU and wheel odometry** for reliable and robust robot localization.

Field Testing and Deployment

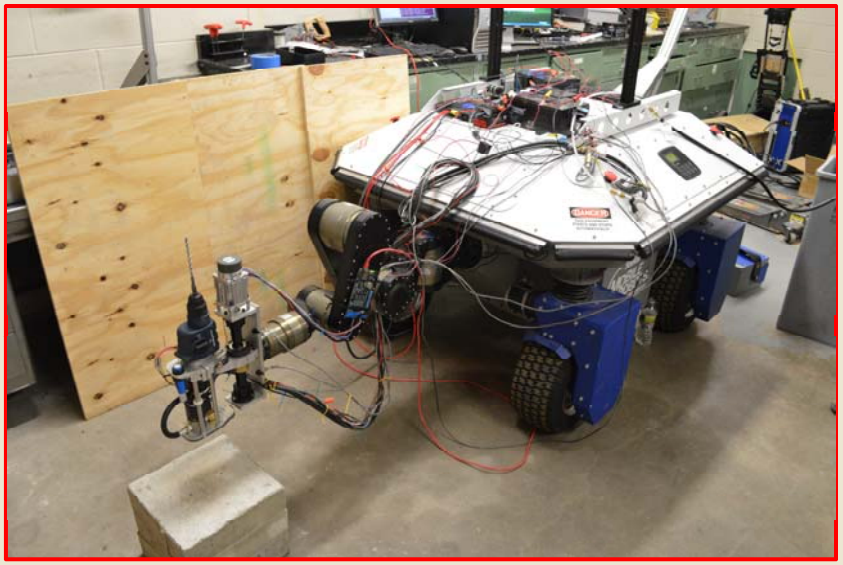


- Extensive field testing for localization and navigation scheme on a local bridge in Warren County, New Jersey, since summer 2012.
- Successful field testing and demonstration in Virginia in Nov. 2013.



Robotic Drilling and Filling Testing

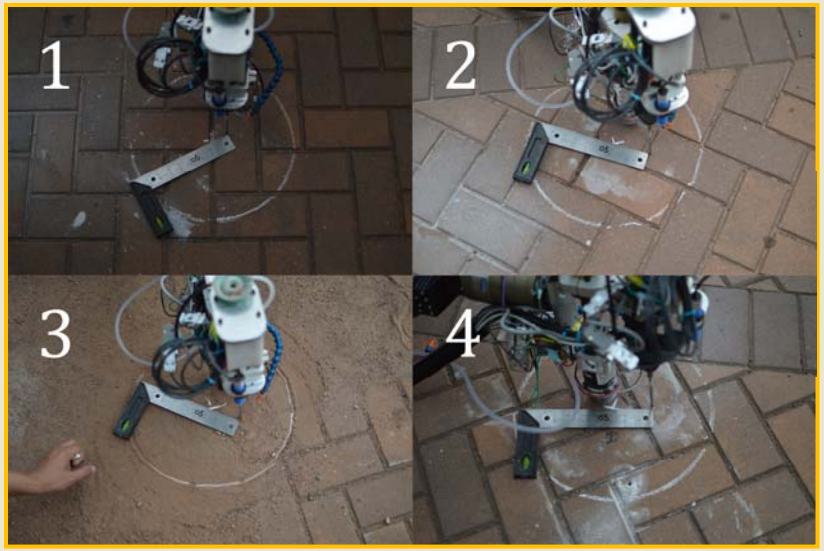
- Designed and implemented **motion planning and control for the mobile manipulator system** in ROS environment.
- Completely **integrated with drilling/filling unit**.
- Extensive drilling and filling testing on more than 300 holes (indoor laboratory without robot motion) in a continuous mode without major interruption.

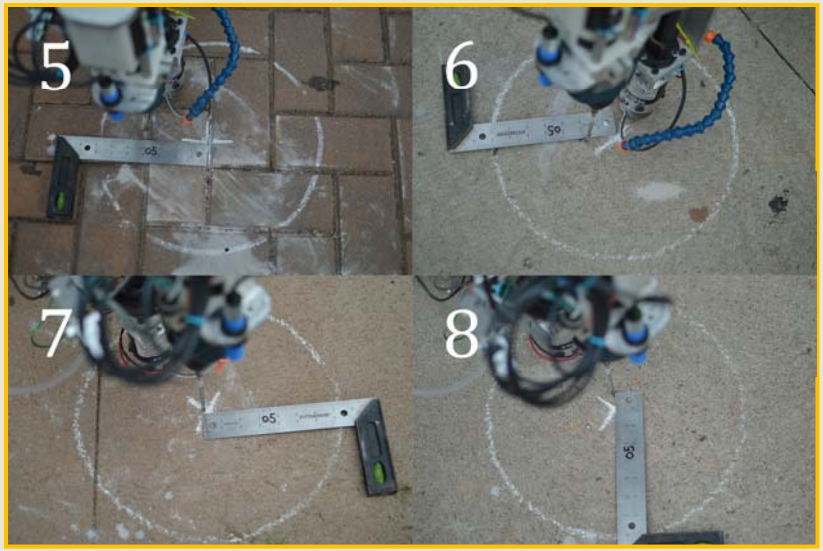


On-Campus Drilling and Filling Testing

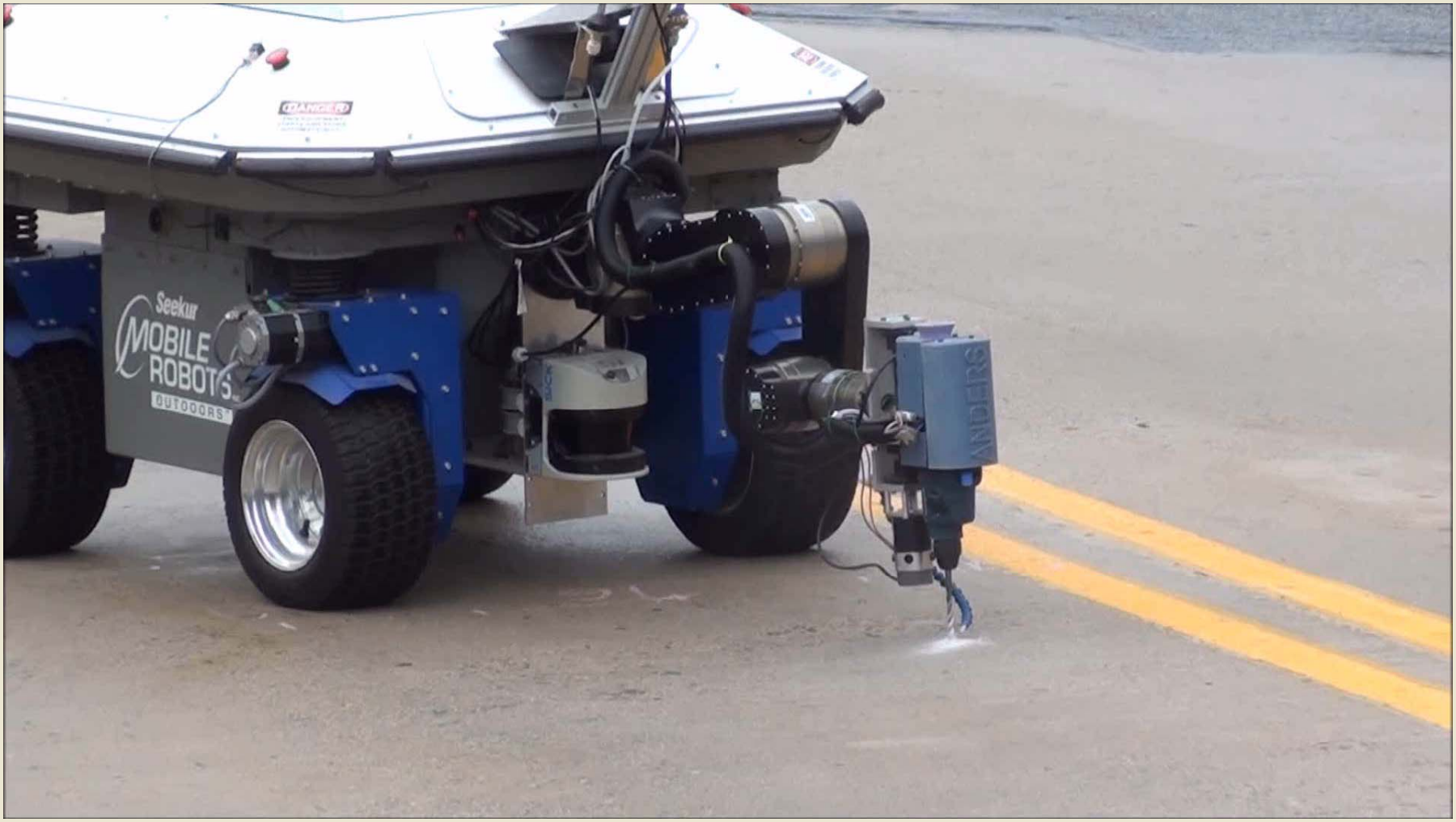
Testing: Fully autonomous driving, drilling and filling with fluids at given locations.

Results: For eight hole positions, the mean error was 2.06 in and the variance of error 0.97 in.





Rehabilitation Robot in Action



ANDERS

Anticipated Impacts

Anticipated Impacts

- ANDERS products have potential for **transformational change in how bridge deterioration is evaluated, monitored and possible inadequacies mitigated**. This includes:
  - Rapid identification of **early stage deterioration**,
  - Rapid and quantitative assessment of **global performance** (e.g. capacity), and
  - Application of **novel materials** and rapid and **minimally invasive deployment** strategies for early intervention.
- Application of the developed technologies will lead to **longer lives and reduced bridge life cycle costs**.

Anticipated Impacts

- ANDERS technologies **enable more quantitative, objective and accurate measures of bridge performance.**
- ANDERS products **remove the most significant barriers related to the application of advanced technologies**: time, cost, need for expert interpretation, and need for extended traffic interruptions.
- ANDERS products , with some modifications, will find **applications in evaluation, monitoring and rehabilitation of other infrastructure assets**, like highway and airport pavements, tunnels, etc.

Acknowledgments

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