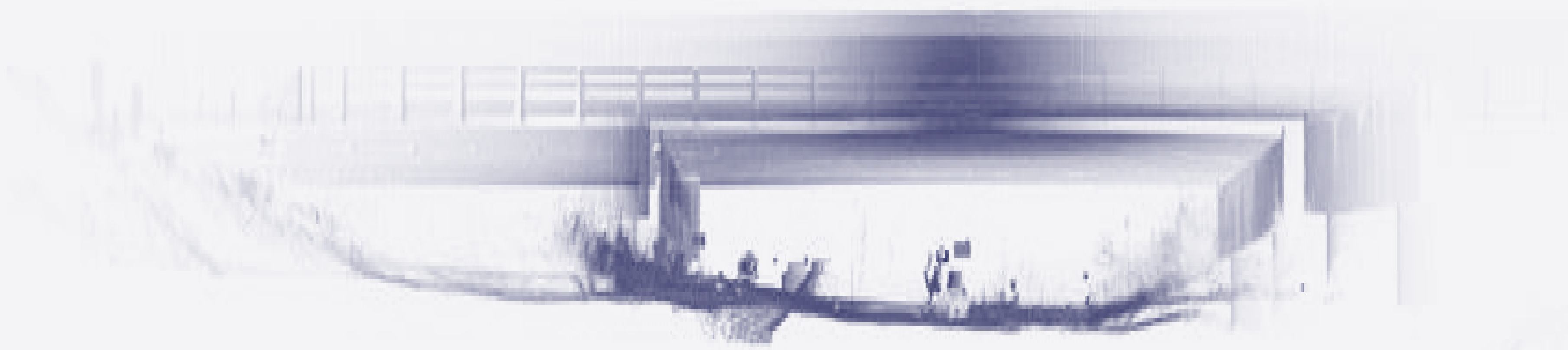

LIDAR BASED BRIDGE EVALUATION

PH.D DEFENSE - WANQIU LIU

UNC CHARLOTTE

Advisor: Dr. Shen-en Chen

Acknowledgement

UNC CHARLOTTE

- **Dr. Edd Hauser**
- **Dr. Gary Teng**
- **Dr. Srinivas Pulugurtha**
- **Dr. Jing Zhou**
- **USDOT-RiTA Project No.** DTOS59-07-H-0005

Outline

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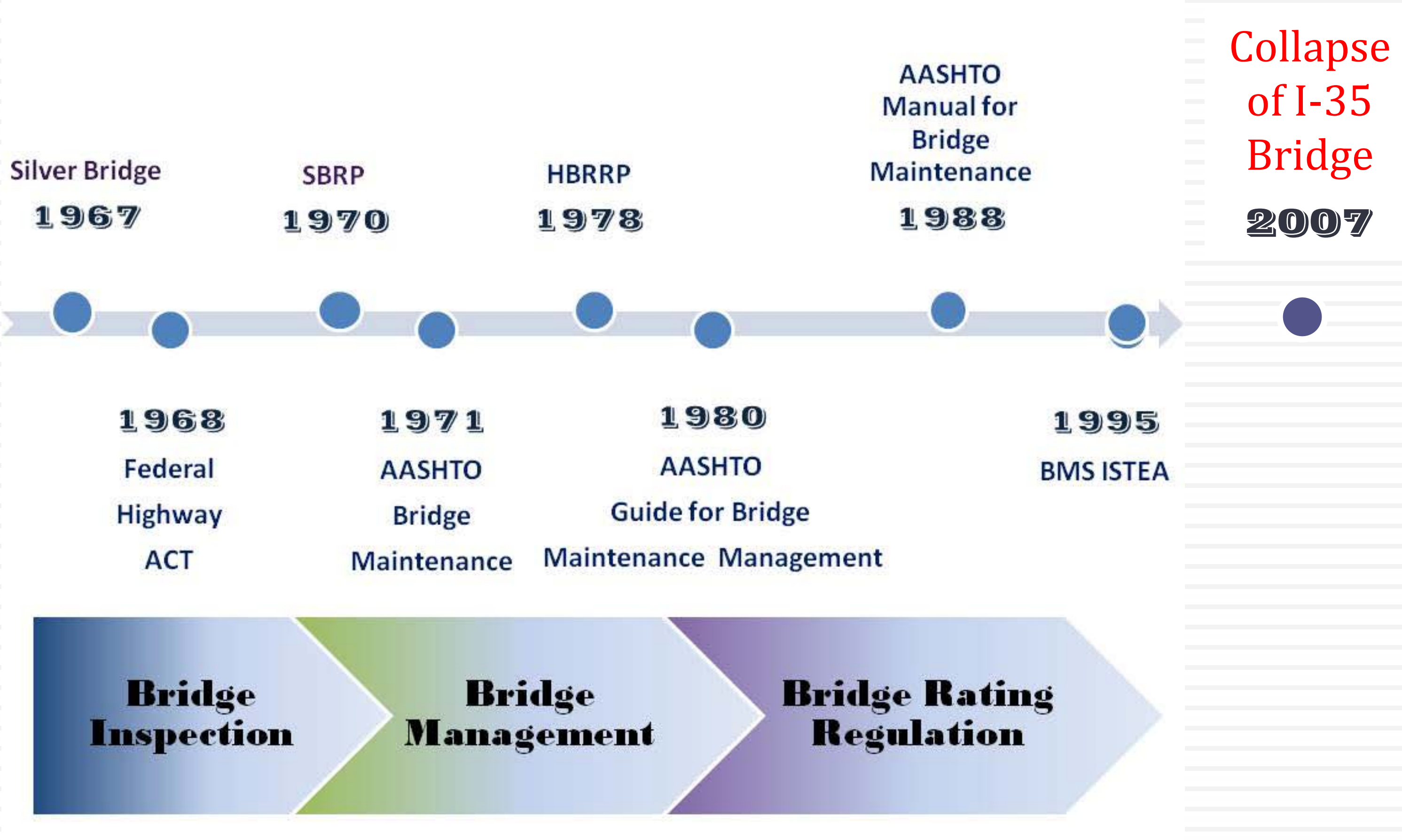
- Introduction
  - Why Remote Sensing?
  - What's the Cost?
- Summary of Potential Applications in Bridge Inspection and Management
- Terrestrial LiDAR Applications in Bridge Inspection
  - Traditional Photogrammetry vs 3D LiDAR
  - LiDAR based Bridge Evaluation (LiBE)
  - Bridge Rating Based on Quantitative Evaluation
- Data and System Validations
- Conclusion
- Future study

Bridge Inspection and Management History



Background

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Bridge Issues

- 70% were built before 1935
- 26% structurally deficient or functionally obsolete
- The annual need is $17 billion and only $10.7 billion can be allocated
- The inspections are mainly visual based
- Quantitative measurement rarely documented

Advantages of Remote Sensing

- Large coverage area
- Easy and up-to-date data collection
- Large amount of information
- Evaluation repeatable
- More accurate than visual inspection

Research Objectives

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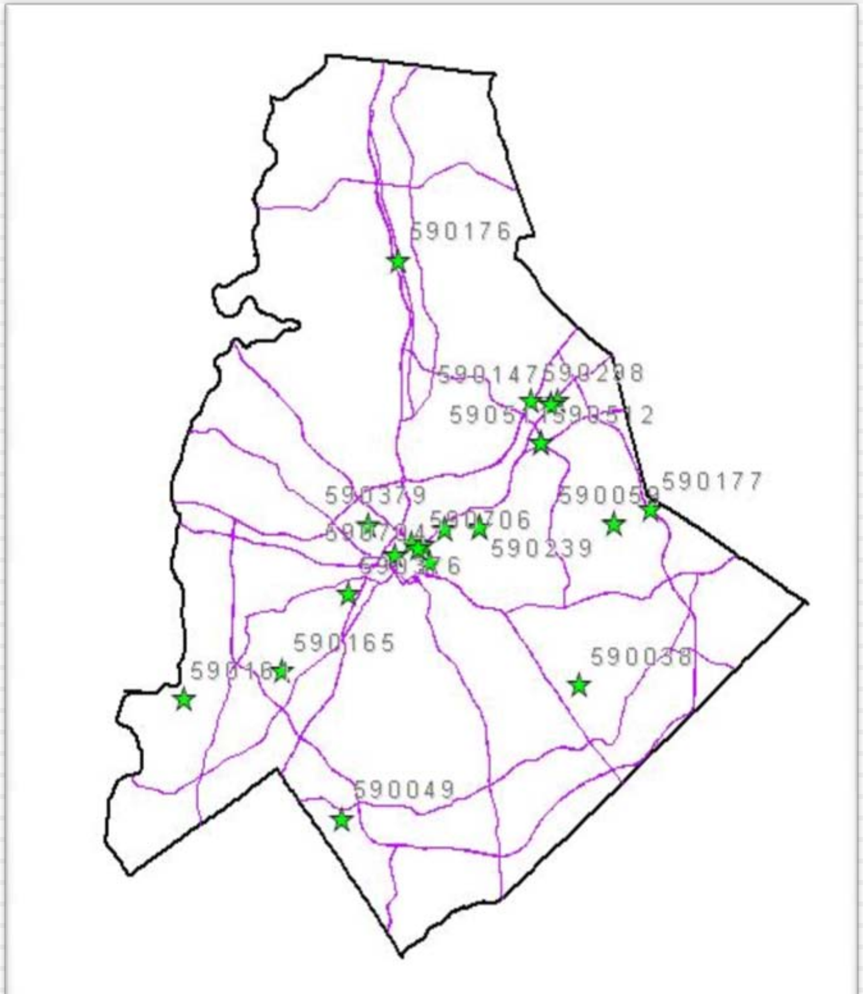
- Evaluate remote sensing applications for bridge health monitoring through a Cost-Benefit analysis.
- Investigate resolution requirements of 3-D LiDAR scanner for bridge evaluation.
- Develop an automatic bridge surface damage detection and quantification system based on LiDAR.
- Develop bridge clearance evaluation system based on LiDAR data.
- Develop an automatic bridge displacement measurement system for bridge static load testing based on LiDAR data.
- Establish LiDAR-based bridge rating.

Scope of Work



Bridge Number	System	Condition	Sufficiency Rating	Status	Type
590084	NCDOT	Poor	82.1	Obsolete	PPC Cored Slab
590140	NCDOT	Fair	77.5	Obsolete	RC Girder
590147	NCDOT	Fair	47.5	Deficient	RC Girder
590179	NCDOT	Fair	72.3		Concrete
590239	NCDOT	Fair	78.2		Steel
590296	NCDOT	Fair	94.7		PC
590511	NCDOT	Good	80.4		RC Deck
590512	NCDOT	Good	80.4		RC Deck
590038	NCDOT	Fair	30.4	Deficient	RC Deck
590049	NCDOT	Fair	48.4	Deficient	RC Deck
590059	NCDOT	Poor	11.8	Deficient	Steel Plank
590108	NCDOT	Fair	100	Deficient	RC Deck
590161	NCDOT	Fair	63.7	Obsolete	Steel
590165	NCDOT	Poor	48.2	Deficient	Steel
590355	NCDOT	Fair	70.3	Obsolete	RC Deck
590177	NCDOT	Fair	29.1	Deficient	Steel
590255	CDOT	Fair	77.7	Obsolete	Steel
590376	CDOT	Fair	84.83	Deficient	Steel
590379	CDOT	Fair	29.3	Deficient	PC
590700	CDOT	Poor			Steel
590702	CDOT	Good			Steel
590704	CDOT	Fair			Concrete
640024	NCDOT	Poor	30.1	Deficient	Concrete
I-77					

How costly?

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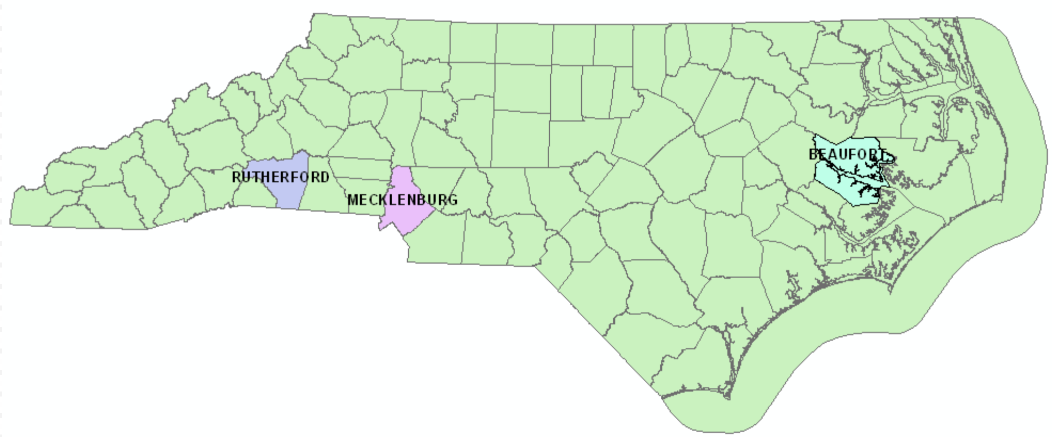
Inspection Improvement cost = (Research+Data collection) cost per bridge per year × County Bridge Number

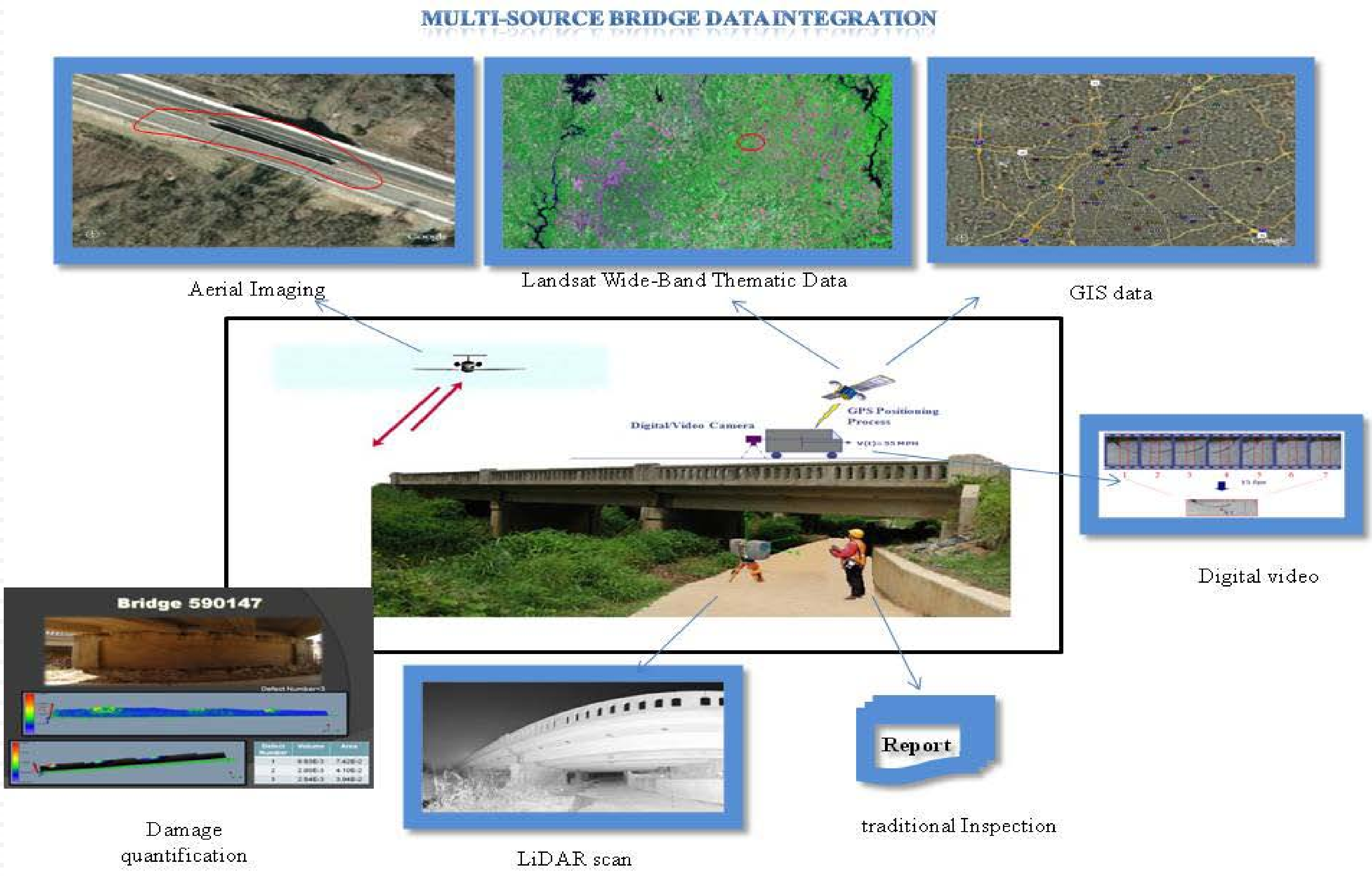
Coating cost = County recoating area × Coating unit price

Cost reduction from bridge replacement = County average bridge replacement cost × Deterioration rate × County average bridge replacement cost × Deterioration reduction rate

	NPV	CBR
Mecklenburg	**$104,661**	**1.329**
Beaufort	**$160,893**	**1.394**
Rutherford	**$832,986**	**1.779**



Applications of Remote Sensing for Bridges (NCRST-Bridge Project)



How to Apply Remote Sensing for Bridge Health Monitoring

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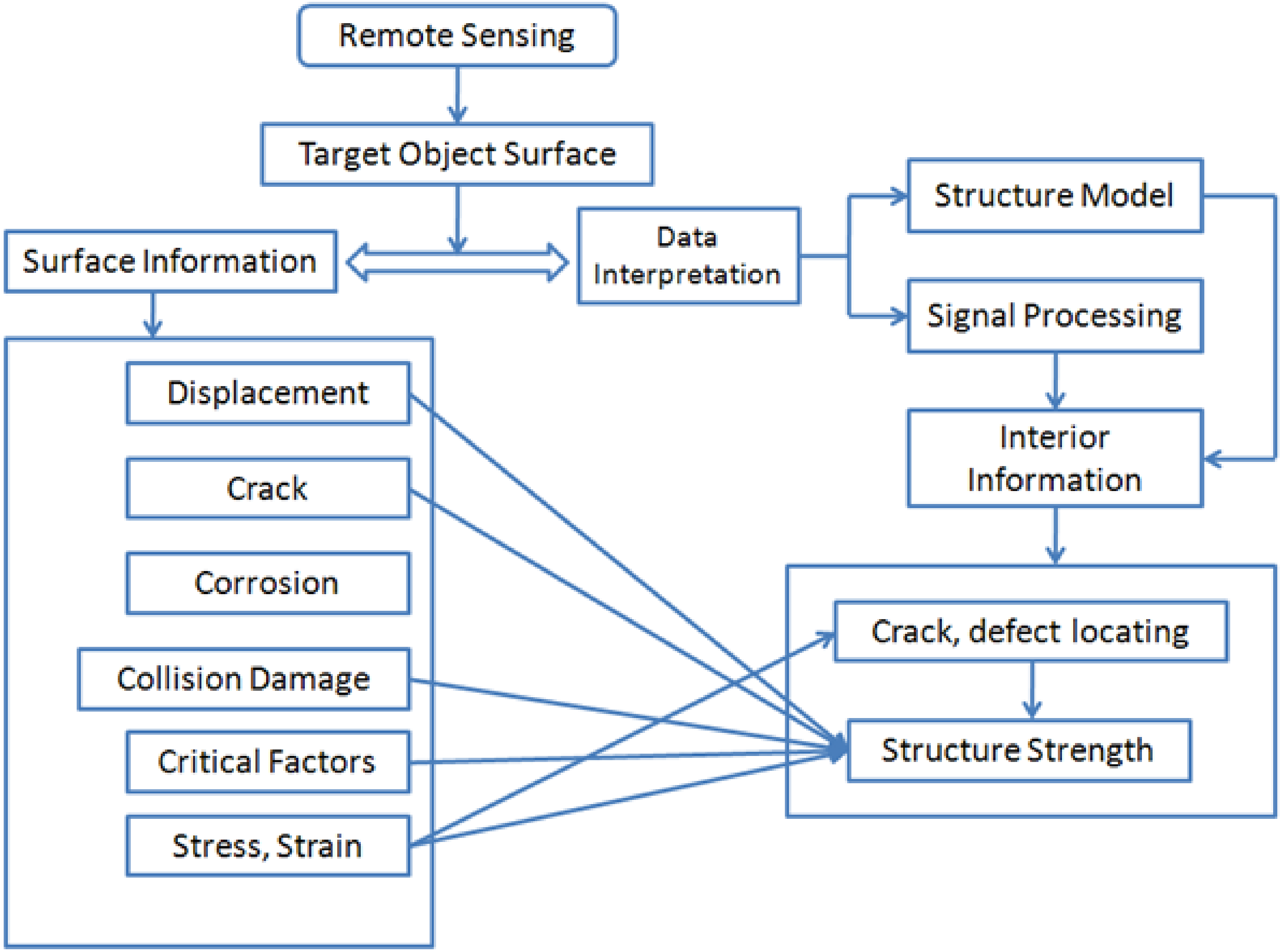
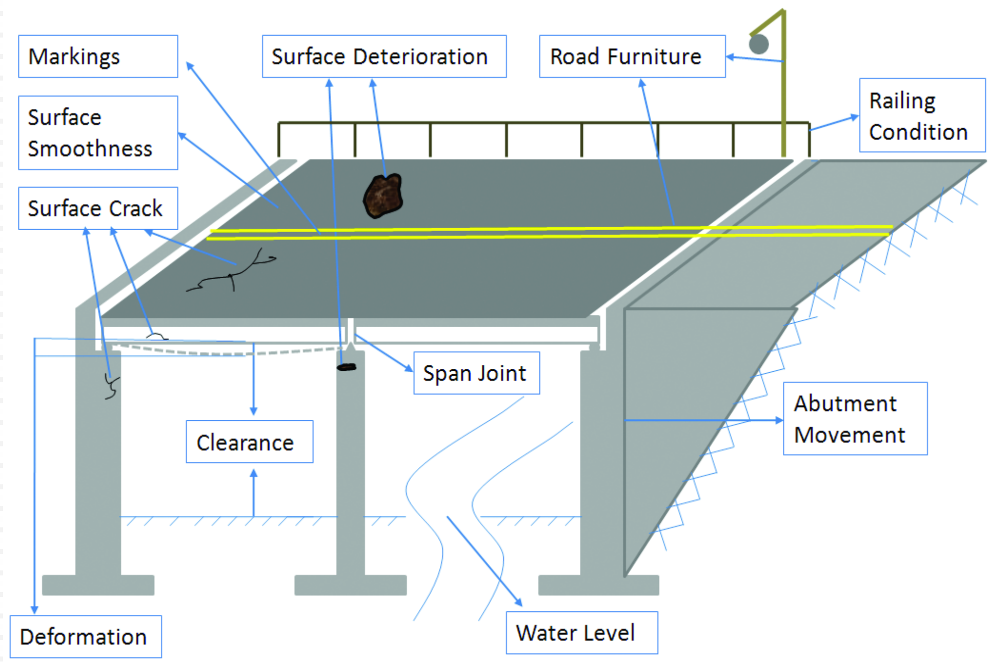


Applications of Remote Sensing for Bridges (NCRST-Bridge Project)



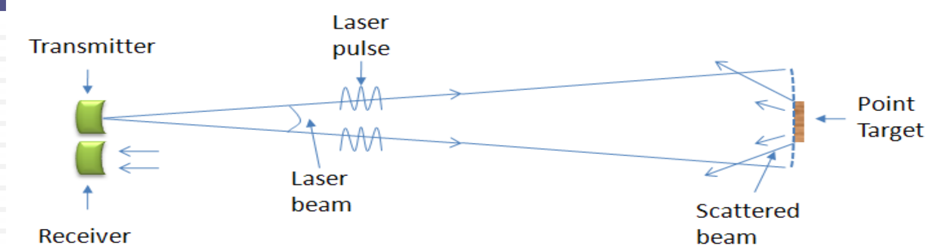
Applications and Required Resolutions of Remote Sensing Imagery

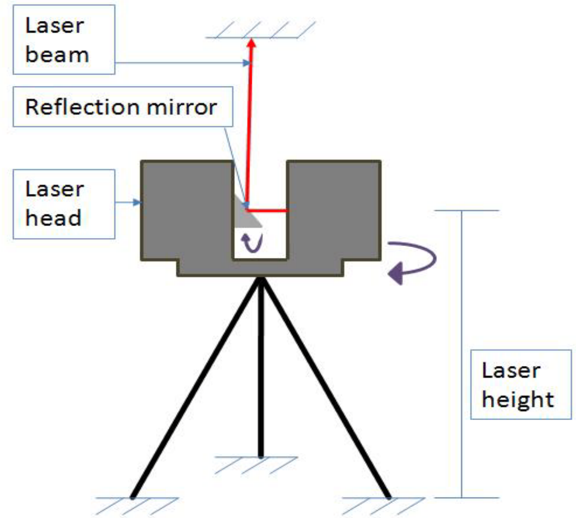
Cause	Observations	Required resolution	Cause	Observations	Required resolution
					Bridge deck
Sun shadow	Shading	1m	Abutment shift	Relative displacement	0.025m
Rain dampness	Shading	0.5m	Pier displacement		0.025m
Car accident		1m	Bridge deck displacement		
Section loss		**0.5m**	Deck punch-through	Large openings	0.5m
Deterioration		0.1m	Deck corrosion		0.5m
Chemical spill	Discoloring	0.1m	Wear at joint	Gap at expansion joints	0.1m
Collision	Deformation	0.1m			
					Wearing surface
New wear surface	Discoloring	1.0m	Cracking	Shading	0.005m
Raveling	Local discoloring	0.5m	Potholing		0.1m
			Rutting		0.1m
		Railing			**Curb**
Missing railing		0.5m	Cracking	Shading	0.005m
Cracking	Shading	**0.005m**	Spalling		0.1m
Section loss		0.1m	Alignment	Curb edge detection	0.5m
Spalling		0.1m	Collision damage	Shading, edge detection	0.1m
		River bank (1 miles)			**Sidewalk**
Pollution	De-vegetation	1m	Deterioration	Shading	0.1m
Smaller flow	River channel widening	0.5m			**Drainage device**
		Traffic	Scaling potion		0.1m
Increase in ADT		1m			**Land use**
Increase in trucking			*Surrounding land use*	Changes in image	1m
Rush hour traffic					**Geometry of bridge**
Loading condition			Edge detection	Horizontal misalignment	0.5m
					Utilities
Light shape, cables		0.1m	*Traffic line*		1m

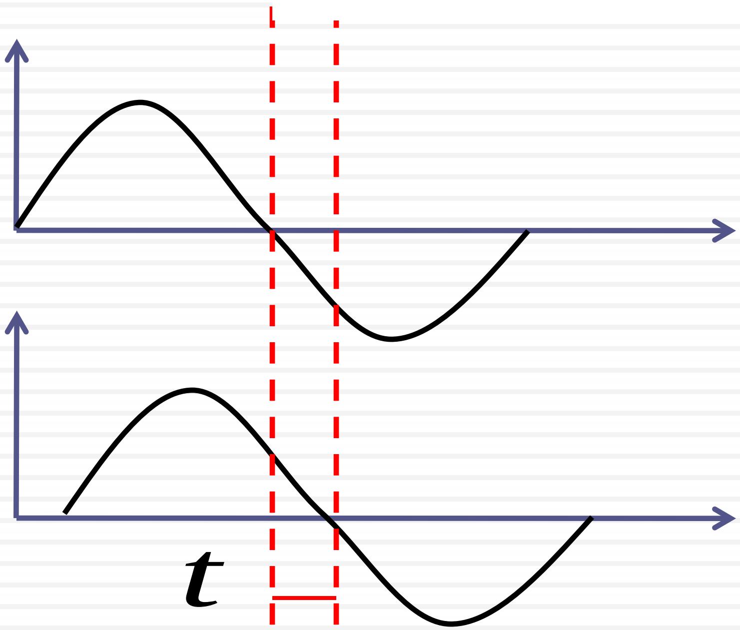
Applications of Terrestrial 3D LiDAR Scanner

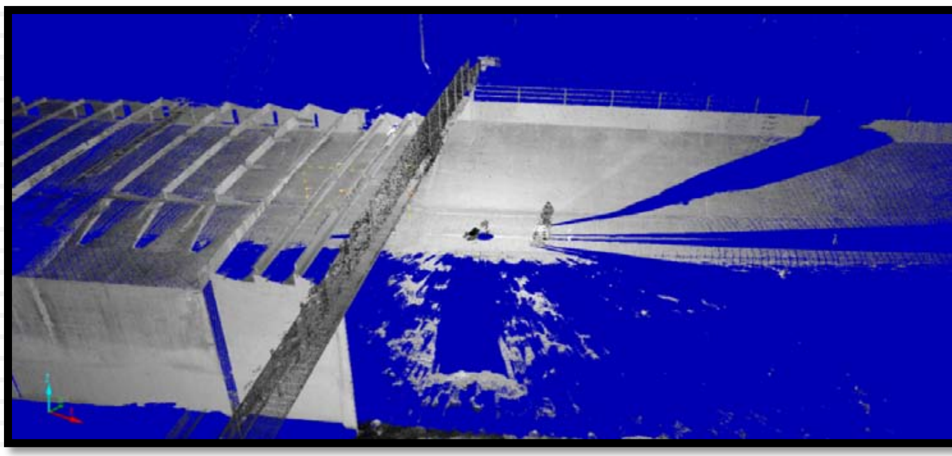
- Automatic bridge damage detection and quantification
- Automatic bridge clearance measurement
- Bridge displacement measurement
- FE Model Updating
- Bridge Forensics
- Pre- and Post-Blast (Extreme Event) Assessments
- Traffic (Trucking) Loading Quantification

Laser scan technology









$$2R = c \times t$$

$$c = 3 \times 10^{8}$$

Differences between LiDAR Scan and Photogrammetry

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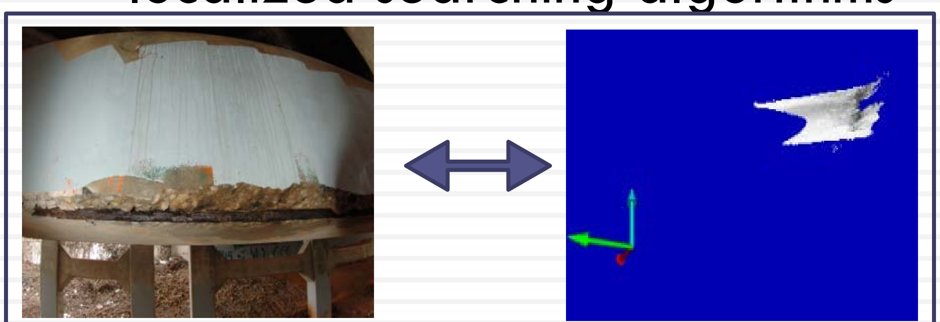
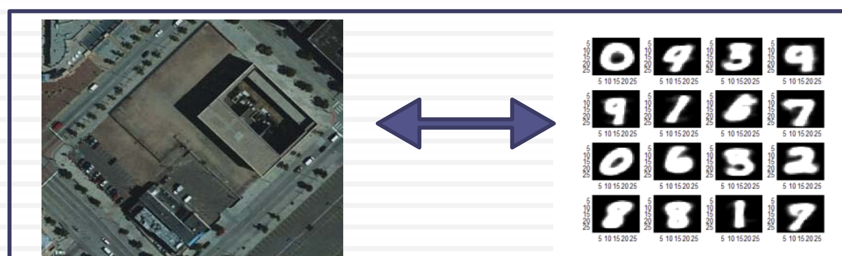
- LiDAR
  - 3D point cloud
  - 3D coordinates automatically registered from a single viewpoint
  - Millions of datapoints (scan points)
  - Deal with 3D point clouds and reflectivity
- Photogrammetry
  - 2D imagery
  - 3D coordinates extractable via multiple view shots and complicated feature matching processes
  - Datapoints dependent to photo quality and digitization technique
  - Deal with reflectance

Image Processing

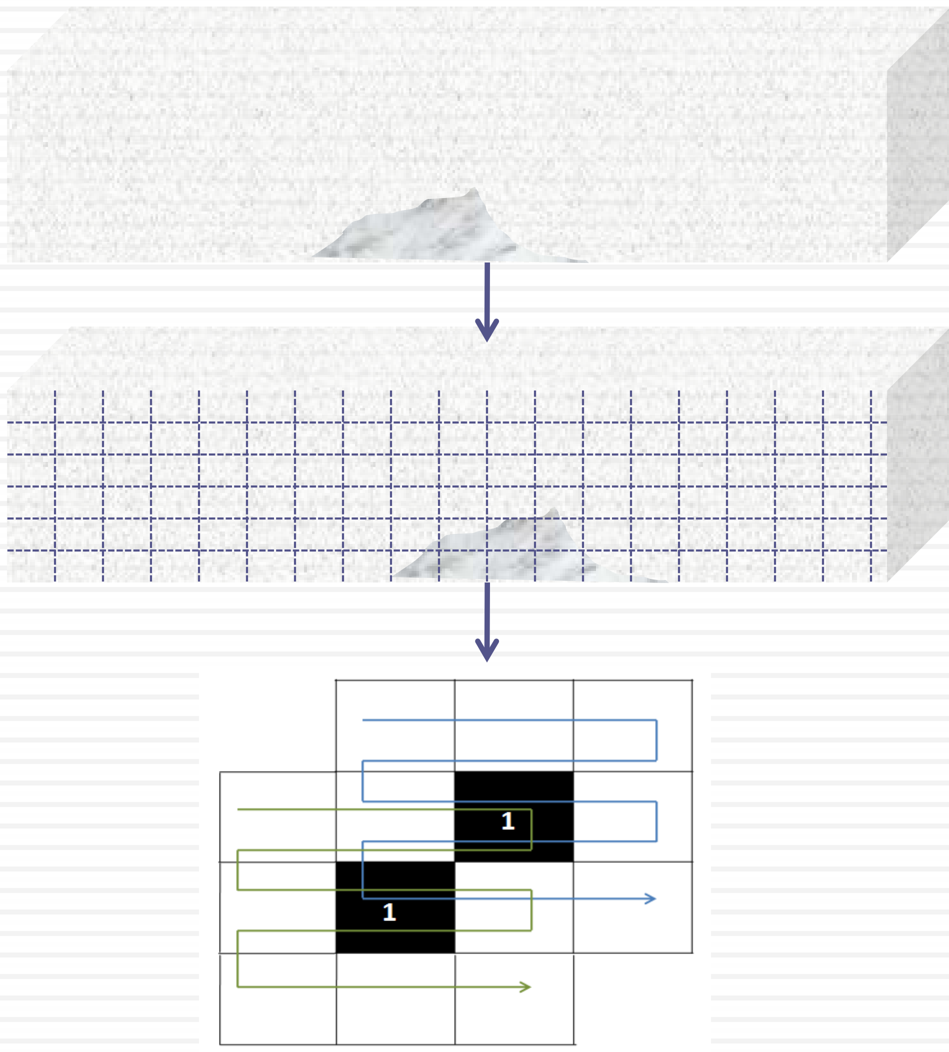
- LiDAR
  - Point geometry evaluation
  - Cartesian coordinate and Linear Newton-Leibniz Direct Integration
  - Feature detection using curvature and gradient (finite differences)
  - Spatial matching using localized searching algorithms

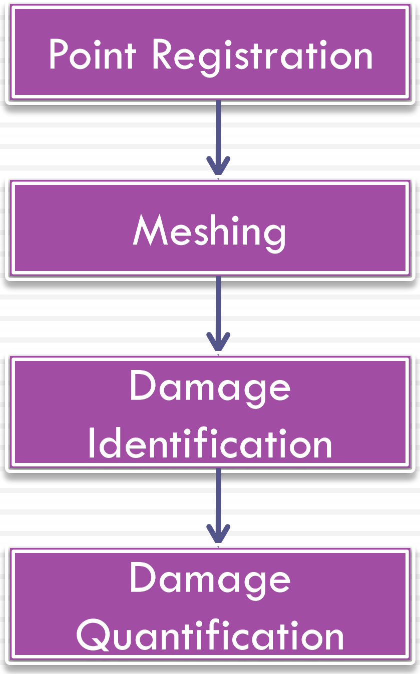


- Photogrammetry
  - Pixel contrast evaluation (quantization)
  - Pixel coordinate and linear transformation
  - Feature detection using contrast threshold and vectorization
  - Multiple image integrate processing for spatial analysis

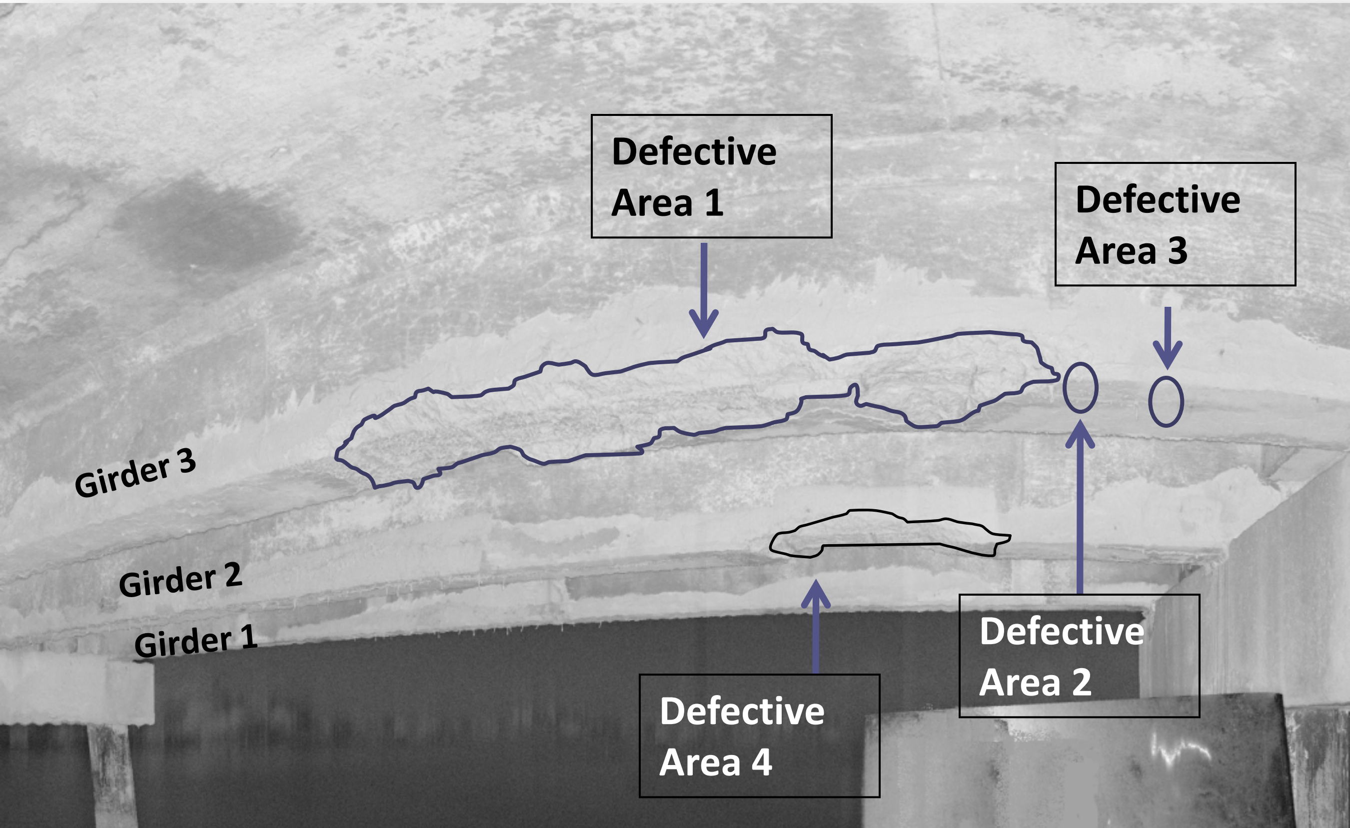


Methodology-Damage Detection and Quantification

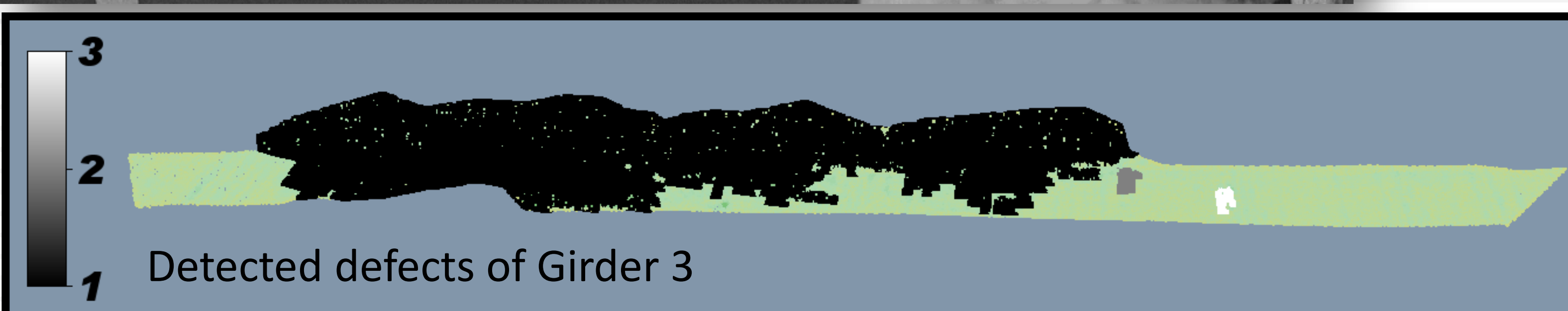




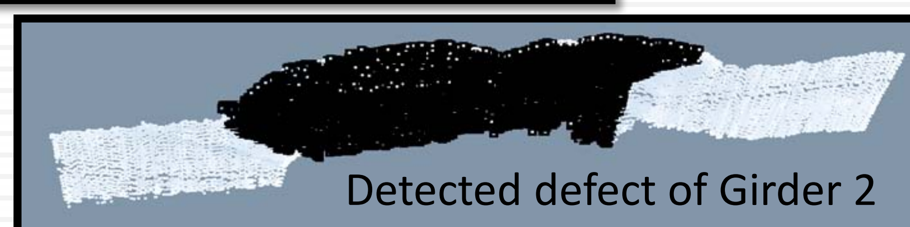
Example

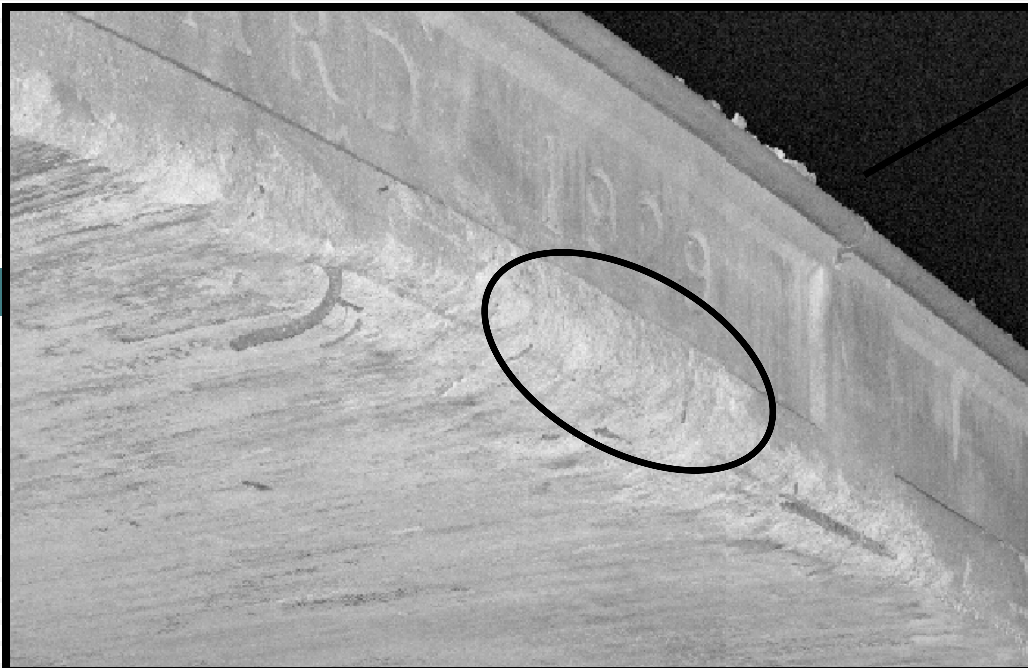


	Area (m2)	Volume (m3)
1	0.507	0.0285
2	6.62E-4	2.63E-5
3	2.13E-4	7.11E-6
4	0.225	0.0156



$$G(C,R)=\left|\frac{z(C+\alpha,R)-z(C-\alpha,R)}{\sqrt{(x(C+\alpha,R)-x(C-\alpha,R))^2+(y(C+\alpha,R)-y(C-\alpha,R))^2}}\right|+\left|\frac{z(C,R+\alpha)-z(C,R-\alpha)}{\sqrt{(x(C,R+\alpha)-x(C,R-\alpha))^2+(y(C,R+\alpha)-y(C,R-\alpha))^2}}\right|$$





Taken Mar. 8, 2009

Taken June 13, 2009 (South)

Photo taken June 13, 2009 (North)

Methodology-Clearance Measurement

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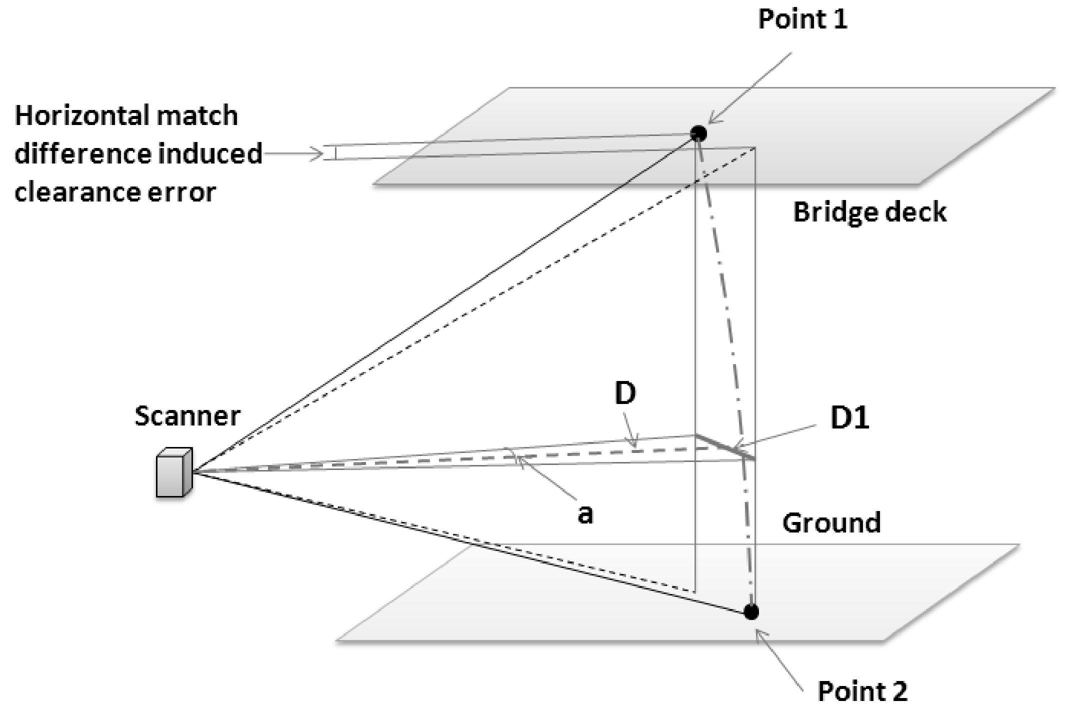
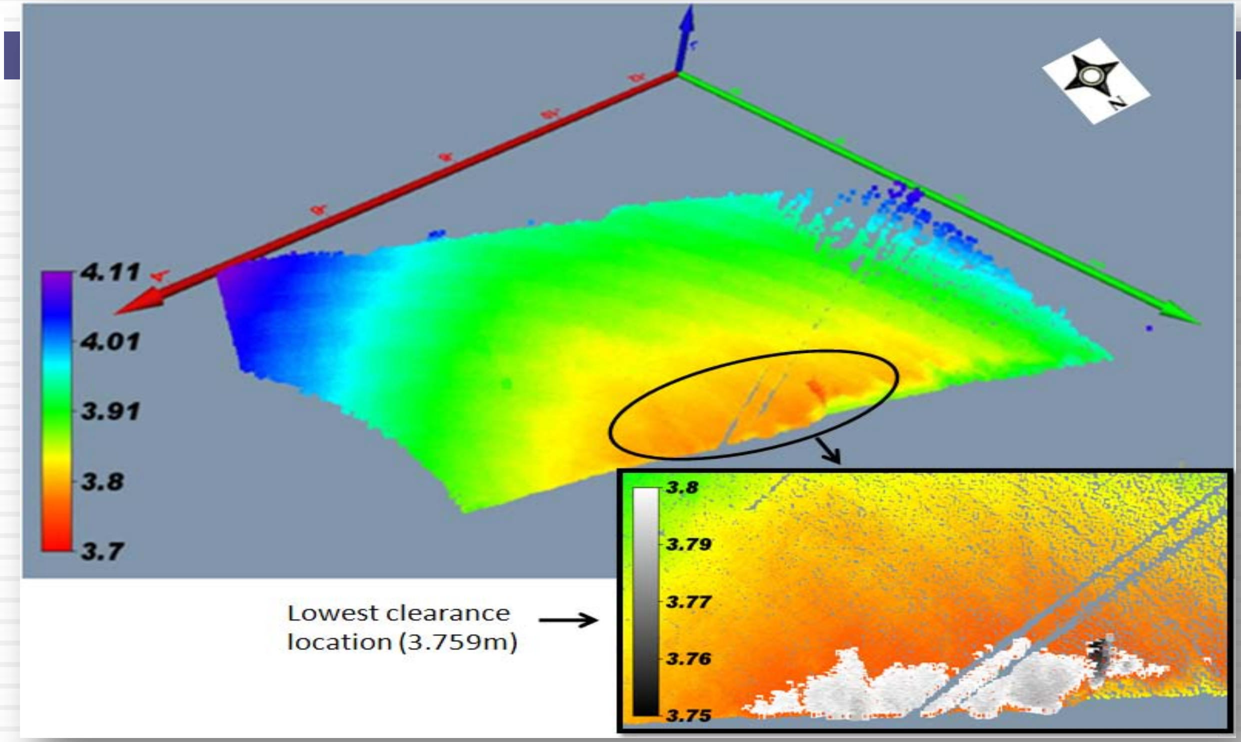
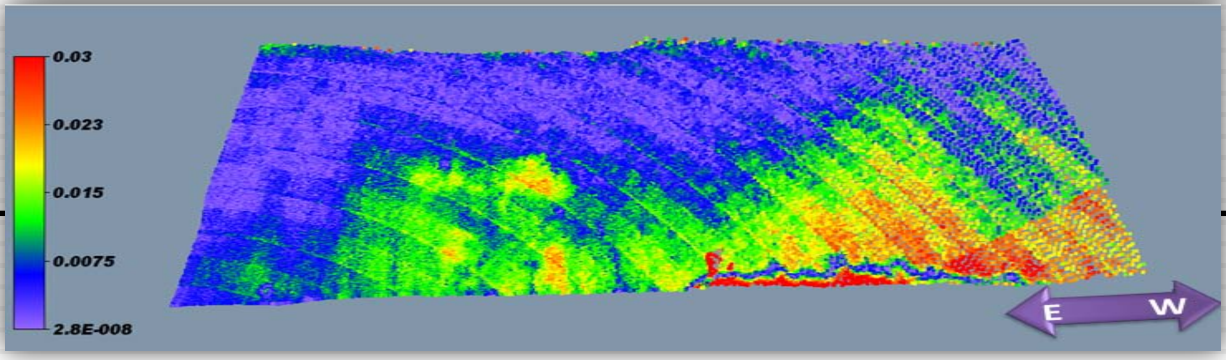


Match Error: 0.016m at 25m distance

$$h1 \leq 2 * \pi * \frac{Dd}{9000}$$

Clearance Measurement--Example





Advantages of LiBE

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- Provide accurate quantitative bridge assessment- currently lacking in bridge inspection procedures
- Automated system allows direct bridge evaluation without further analysis: suitable for non-technical personnel, i.e. bridge inspectors.
- Easy to develop and apply evaluation standards

Bridge Rating based on the Quantitative Evaluation-Damage

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NBIS Ratings

BRIDGE I & A FORM1 (60)A

BRIDGE INSPECTION RECORD AND SUMMARY

INSPECTION TYPE ROUTINE
BRIDGE NO. COUNTY ROUTE OVER
STRUCTURE TYPE RC DECK ON PPC GIRDERS, SIP FORMS, APPROACH SLABS
ROUTE ORIENTATION N - S SPANS 1@50'0, 1@60'0, 1@50'0 COMPOSITE

EVALUATION CODE : 0 -2 CRITICAL, 3 & 4 POOR, 5 & 6 FAIR, 7 -9 GOOD

INSPECTION ITEM			GRADES
DECK ITEMS			
1. WEARING SURFACE			
2 DECK NO. OF EA TYPE SPN GRADE RATES SI & A ITEM 58	a. CONCRETE	3	6
	b. TIMBER		
	c. STEEL PLANK		
	d. OPEN GRID		
3 RAILING	a. CONCRETE		
	b. TIMBER		
	c. ALUMINUM		8
	d. STEEL		
4. CURBS, WHEELGUARDS, PARAPETS, MEDIANS			7
5. WALKWAYS (ON OR ATTACHED TO STRUCTURE)			7
6. DECK EXP JTS. OR DEVICES. NO OF EACH	a. STEEL PL OR FINGER		
	b. MISC PREFAB DEVICES	2	8
	c. COMPRESSION SEAL		
	d. STANDARD JOINTS		
	e. OPEN JOINTS		
7. DECK DEBRIS (INCLUDE EXCESS SAND/GRAVEL)			7
SUPER STR. (FM. 1 (90)B TRUSS) ITEM 59			
10. LONGITUDINAL BEAMS OR GIRDERS			8
11. LONGITUDINAL JOIST OR STRINGERS			
12. INT. DIAP'S, X-FRAMES, BRACING & CONN'S			8
13. END DIAP'S, CURTAIN WALLS, & CONN'S			8
14. FLOOR BEAMS AND CONNECTIONS			
15. BEARING ASSEMBLIES (INCLUDE MISALIGN)			8
16. DRAINAGE SYSTEM (ON STRUCTURE)			8
17. MOVABLE SPAN MACHINERY			
SUB STR. ITEMS. ITEM 60 (INCLUDE SCOUR)			
35. TIM SUB STR.	a. ABUT. & INT. BENT CAPS & RISERS		
	b. PILES, POST, SILLS, & BRACING		
	c. BULKHEADS, WING'S & TIE BACKS		
36. CONC SUB STR.	a. ABUT. & INT. BENT CAPS		8
	b. ABUT. & BENT COL'S BREASTWALLS		8
	c. ABUT. & INT. BENT PILES		
	d. BACKWALLS, WING'S, RETAIN. WLLS		8
	e. ABUT. & BENT FOOTINGS & SILLS		
37 STEEL SUB STR	a. ABUT. & INT. BENT CAPS & RISERS		
	b. PILES, BRACING, AND BULKHEADS		
38 FOUNDATION PILES TYPE MATERIAL			
39. SLOPE PROT., RIP-RAP (INCLUDE DRAINAGE)			8
40 FENDER SYSTEMS			
41 DRIFT			8

ITEM 61			
45 CHANNEL & CHANNEL PROT.	a. WATERWAY		8
	b. ALIGNMENT		8
	c. SCOUR		8
	d. SLOPE PROT., RIP-RAP, DIKES, ETC.		8
50 APPROACH ROADWAY CONDITION			7
51 APPROACH SLABS			7
52 PAINT SYSTEM		CODE	
53 UTILITIES			8
54 RESPONSE TO LIVE LOAD			8
55 ESTIMATED REMAINING LIFE			48
60 REGULATORY SIGN NOTICE ISSUED			No
61 PROMPT-ACTION NOTICE ISSUED			No
62 PRESENTLY POSTED			No
63 TOT. FIELD INSP TIME (INCLUDE WRITE UP)(M/H)			6
64 TOTAL SNOOPER INSP. TIME (HRS)			0
65 TOTAL TRAFFIC CONTROL TIME (M/H)			0
70 SI&A GENERAL CONDITION RATINGS			
a. DECK		ITEM 58	6
b. SUPERSTRUCTURE		ITEM 59	8
c. SUBSTRUCTURE		ITEM 60	8
d. CHANNEL & CHANNEL PROT.		ITEM 61	8
71 SI&A FIELD APPRAISAL RATINGS			
a. WATERWAY ADAQUACY			8
b. APPR. RDWY. ALIGNMENT			8
72 FIELD SCOUR EVALUATION			O
USE OF INSP. ACCESSIBILITY EQUIPMENT			
SNOOPER (CODE P, S, 4, OR N)		No	No
LADDER			No
OVERSIDE LADDER			No
BUCKET TRUCK			No
BOAT			No
OTHER			
SPECIAL INSPECTION REQUESTED FOR			
NOTE			
80 INSPECTED BY:			
81 REVIEWED BY			

Bridge Number	Sufficiency Rating	Type	Area (m2)	Volume (m3)	Damage Ratio	Maximum Depth (m)	**Damage Rating**
190147	30.3	RC Girder	8.07E-2	9.19E-3	0.0333	0.259	**46.3**
			4.55E-2	2.97E-3			
			3.59E-2	2.43E-3			
590179	72.3	Concrete	2.52E-2	2.85E-4	0.0481	0.031	**69.0**
			1.56E-2	1.29E-4			
			1.43E-4	1.14E-6			
			9.43E-4	7.24E-6			
590255	77.7	Steel	2.00E-1	5.98E-3	0.0497	0.162	**59.1**
590379	29.3	Prestressed Concrete				No damage	
590700		Steel				No damage	
590702		Steel	2.05E-2	3.38E-4	0.0049	0.042	**78.5**
590704		Concrete	4.94E-3	9.84E-5	0.0091	0.080	**70.7**
			4.85E-3	1.04E-4			
			2.97E-1	1.06E-2			
640024	29.9	RC Deck	5.07E-1	2.84E-2	0.2169	0.332	**38.8**

$$R = 100 \times \left[1.0 - 0.7 \times \sqrt{\gamma} - 0.3 \times \left(\frac{AD}{0.075}\right)^{\frac{AD}{M}}\right]$$

$$R = 100 \times \left[1.0 - 0.7 \times \sqrt{\gamma} - 0.3 \times \left(\frac{AD}{0.075}\right)^{\sqrt{\frac{M}{AD}}}\right]$$

IF $A > 0.075$

Bridge Rating based on the Quantitative Evaluation-Clearance

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Rating Criteria

Rating	Local Road	Interstate/Freeway	Railroad
9	>5.02 m	>5.48 m	>7.46 m
8	4.87 m~5.02 m	5.33 m~5.48 m	7.31 m~7.46 m
7	4.57 m~4.87 m	5.03 m~5.33 m	7.01 m~7.32 m
6	4.27 m~4.57 m	4.88 m~5.03 m	6.70 m~7.01 m
5	4.10 m~4.27 m	4.50 m~4.88 m	<6.70 m
4	<4.10 m	<4.50 m	--

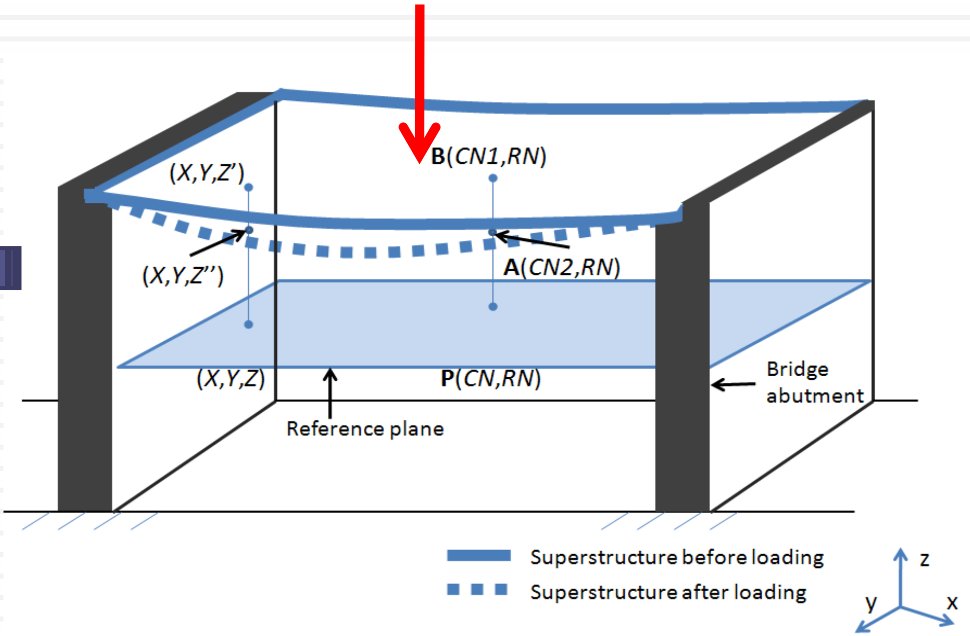
Bridge Number	Sufficiency Rating	Bridge over	Clearance Inventory (m)	LiBE Measured (m)	**Clearance Rating**
590179	72.3	Railroad	6.325	6.333	**5**
590239	78.2	Railroad	6.782	6.993	**6**
590298	94.7	Railroad			
590511	80.4	Highway	4.750	4.980*	**6**
590512	80.4	Highway	5.588	4.980*	**6**
590038	45.5	Water	---	---	**---**
590049	45.3	Water	---	---	**---**
590059	35.6	Water	---	---	**---**
590108	48.2	Railroad	7.010	7.090	**7**
590161	63.7	Water	---	---	**---**
590165	4	Water	---	---	**---**
590355	70.3	Highway	5.004	4.870	**5**
590177	29.1	Water	---	---	**---**
590255	77.7	Railroad	7.290	10.993	**10**
590379	29.3	Water	---	---	**---**
590700		Highway	4.064	4.110	**4**
590702		Highway	4.242	4.250	**5**
590704		Highway	3.759	3.760	**4**

Bridge Displacement Measurement in Static Load Testing

Abnormal Deformation

Abnormal Load Distribution

Capacity Validation



Strain Measurement: $$\epsilon = -\frac{d^2 v}{d^2 x} y \approx \frac{v(x+h) - 2v(x) + v(x-h)}{h^2} y$$

Bridge Displacement Measurement - Example

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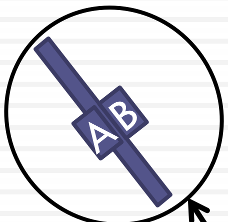
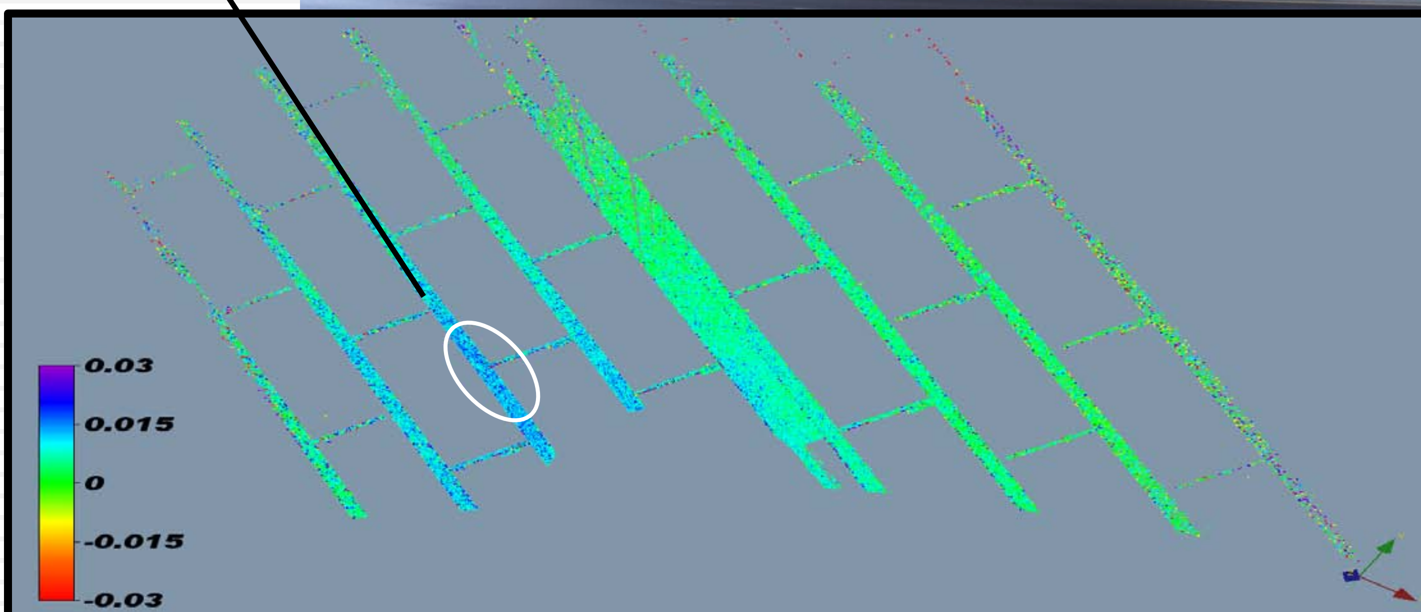
Truck Position





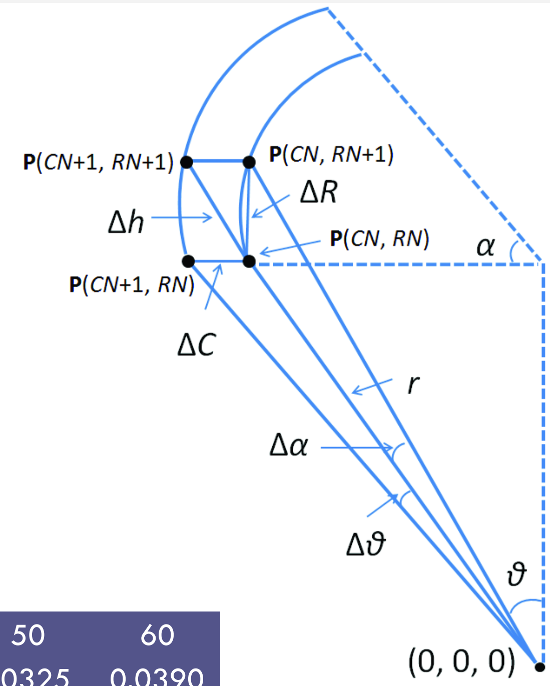
Error Analysis

$$\Delta C = Z(\mathbf{M}(CNN,RNN)) \times (\tan(\vartheta + \Delta\vartheta) - \tan(\vartheta))$$
$$= Z(\mathbf{M}(CNN,RNN)) \times \sin(\Delta\vartheta) / (\cos(\vartheta)\cos(\vartheta + \Delta\vartheta))$$

$$\Delta C \approx \Delta\vartheta \times Dd^2 / Z(\mathbf{M}(CNN,RNN))$$

$$\Delta R \approx \Delta\alpha \times r$$

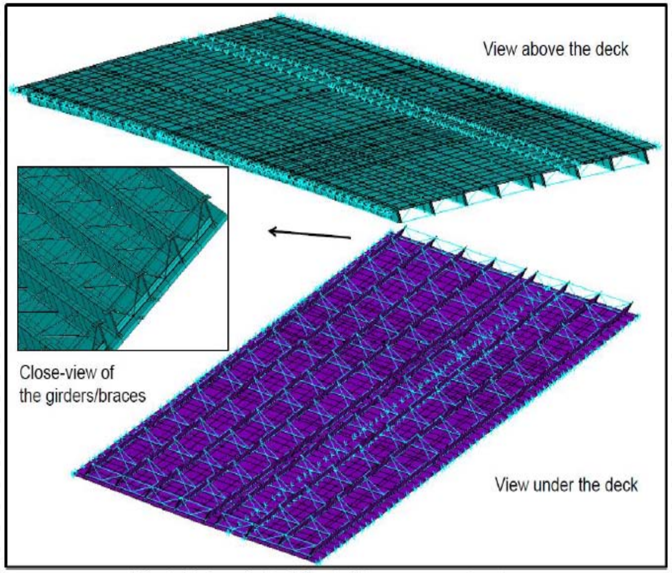
$$\Delta h \approx \sqrt{(ac \times Dd^2/Z(\mathbf{M}(CNN,RNN)))^2 + (r \times ar)^2}$$

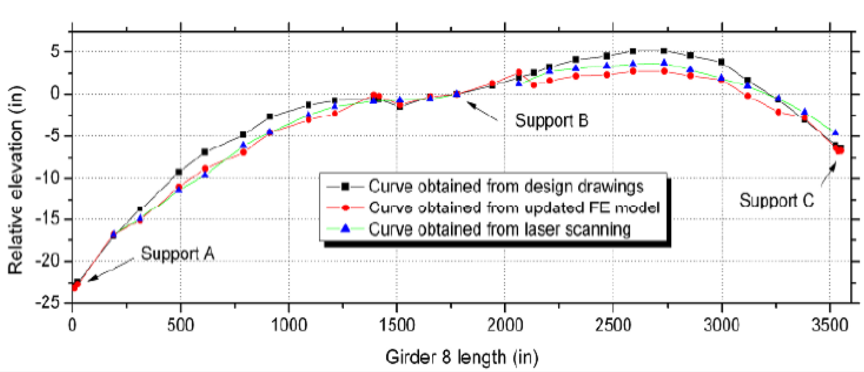


	6	10	15	20	30	40	50	60
ΔR	0.0022	0.0057	0.0092	0.0126	0.0193	0.0259	0.0325	0.0390
ΔC	0.0045	0.0126	0.0283	0.0503	0.1132	0.2012	0.3143	0.4526
Δh	0.0050	0.0138	0.0298	0.0519	0.1149	0.2028	0.3160	0.4543
0.5Δh	0.0025	0.0069	0.0149	0.0259	0.0574	0.1014	0.1580	0.2271
0.2Δh	0.0010	0.0028	0.0060	0.0104	0.0230	0.0406	0.0632	0.0909

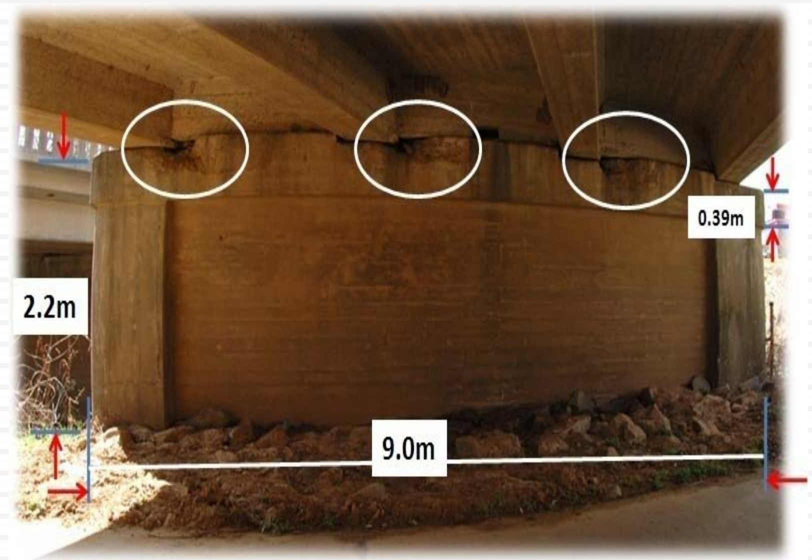
Other Applications

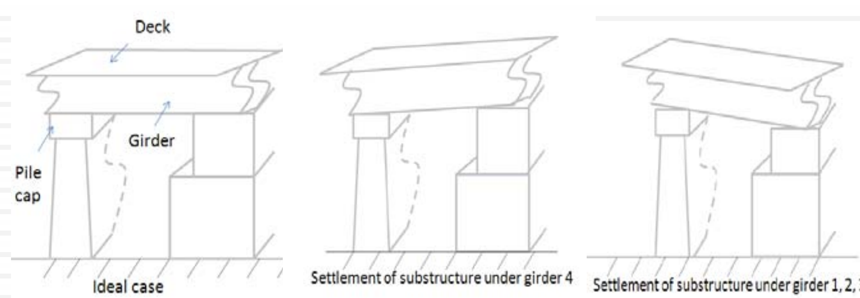
FE Model Updating



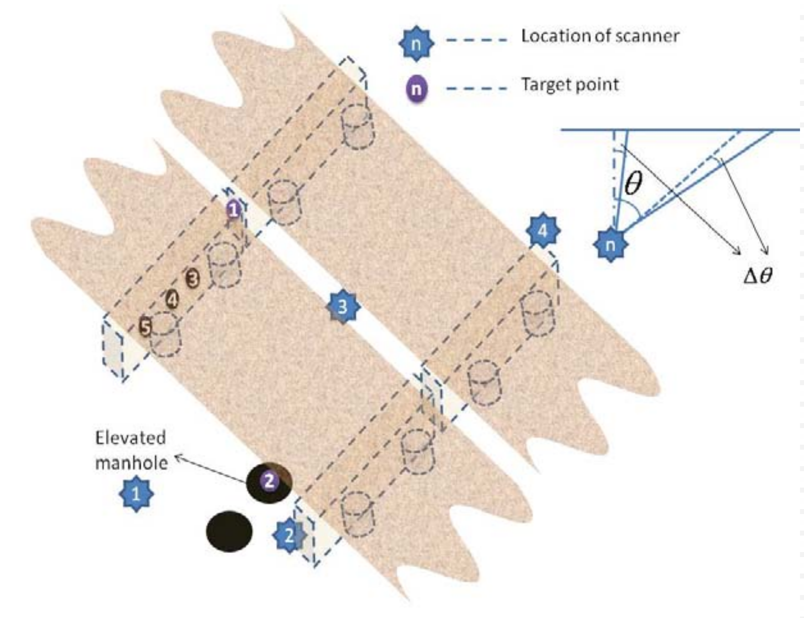


Forensic Engineering





Scan Data Accuracy Validation



Point No.		Scan 1 (m)	Scan 2 (m)	Scan 3 (m)	Scan 4 (m)	Standard deviation (m)
1-3	Distance between points	6.362	6.427	6.443	6.439	0.03259
	Distance to scanner (1)	21.678	23.389	9.222	26.483	
3-4	Distance between points	1.226	**1.252**	**1.251**	1.235	0.01095
	Distance to scanner (3)	16.010	19.170	11.683	31.663	
4-5	Distance between points	**3.673**	**3.671**	3.686	3.658	0.009927
	Distance to scanner (4)	14.980	18.502	12.487	32.697	
2	Diameter of well	0.681	0.675	0.666		
	Distance to scanner (2)	9.375	5.144	14.599		

Damage Quantification Accuracy Validation

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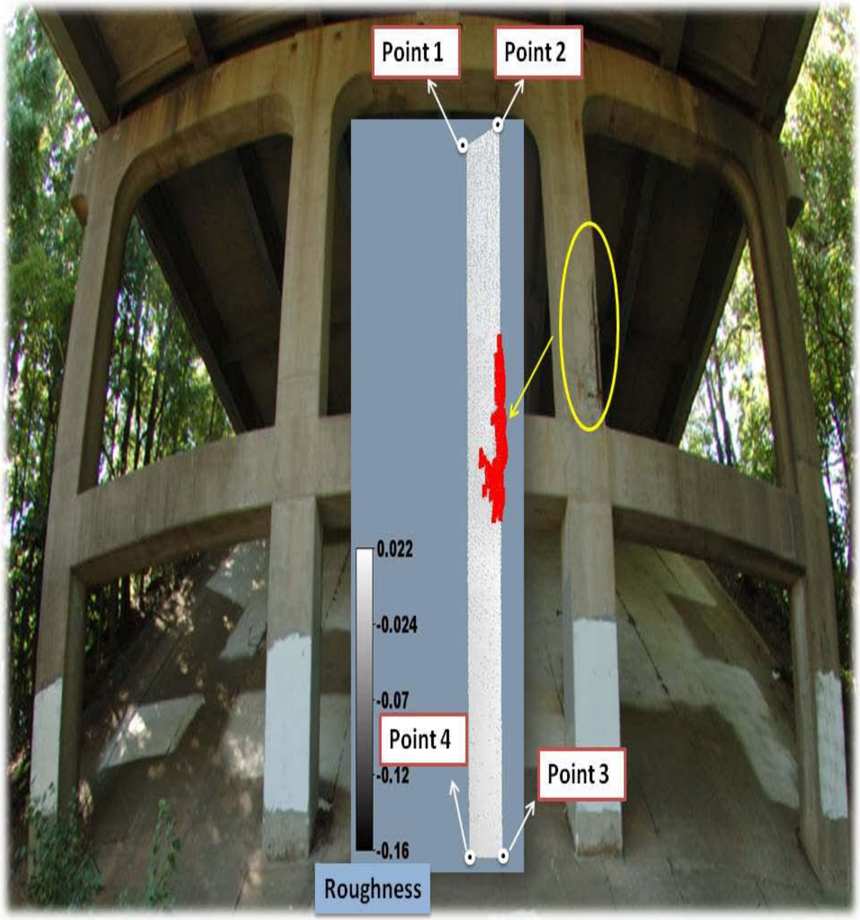
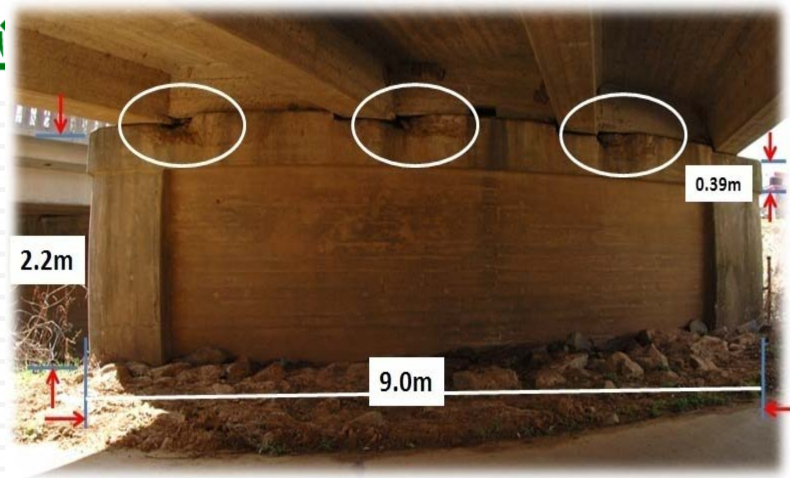
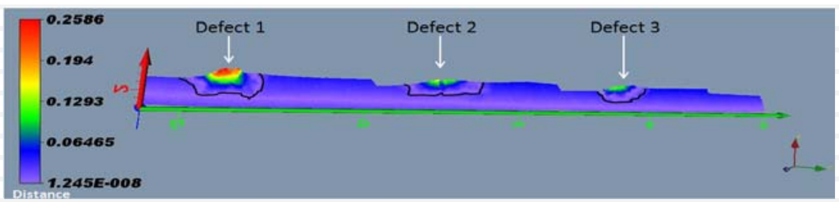
Test No.	Test Method	Total Area (m^2)
1	Four point area (m2)	4.9188
2	LiBE grids 98×11 (m2)	4.9688
3	LiBE grids 195×21 (m2)	4.9676
Difference between test 1 and 2		1.02%
Difference between test 2 and 3		0.02%

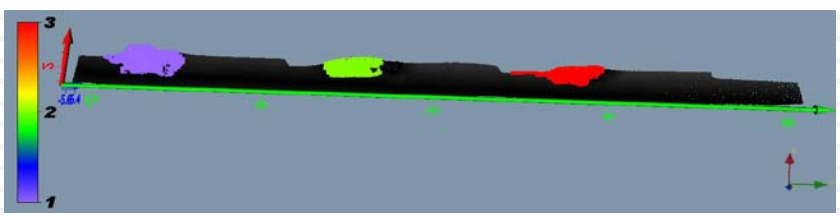
Test Method	Maximum grid distance
Four point area (m2)	7.53m
LiBE grids 98×11 (m2)	0.01m
LiBE grids 195×21 (m2)	0.02m



Damage Detection Accuracy Validation







Test No.	Distance Threshold (m)	Curvature Threshold (m^{-1})	Defect No.	Damage Area (m^2)	Area Dif (%)	Damage Volume (m^3)	Volume Dif (%)
1	0.01	15.0	1	1.66E-1		1.25E-2	
			2	1.29E-1		4.94E-3	
			3	9.75E-2		3.88E-3	
2	0.01	16.5	1	1.58E-1	-4.83	1.25E-2	-0.49
			2	1.29E-1	0.00	4.94E-3	0.00
			3	8.76E-2	-10.11	3.67E-3	-5.49
3	0.01	18.0	1	1.55E-1	-6.93	1.24E-2	-0.73
			2	1.24E-1	-3.61	4.88E-3	-1.09
			3	8.21E-2	-15.75	3.62E-3	-6.68
4	0.01	13.5	1	1.75E-1	5.49	1.26E-2	0.30
			2	1.45E-1	11.88	5.10E-3	3.33
			3	1.05E-1	8.18	3.94E-3	1.43
5	0.01	12.0	1	1.97E-1	18.70	1.27E-2	1.51
			2	1.70E-1	31.68	5.37E-3	8.68
			3	1.41E-1	44.99	4.69E-3	20.83
Deviation	Curvature-2.42 m^{-1}			0.0214 m^2		0.000294 m^3	
6	0.011	15.0	1	1.66E-1	0.00	1.25E-2	0.00
			2	1.16E-1	-9.95	4.82E-3	-2.41
			3	9.47E-2	-2.85	3.85E-3	-0.76
7	0.012	15.0	1	1.59E-1	-4.06	1.24E-2	-0.67
			2	1.16E-1	-9.95	4.82E-3	-2.41
			3	9.47E-2	-2.85	3.85E-3	-0.76
8	0.009	15.0	1	1.71E-1	2.87	1.26E-2	0.36
			2	1.29E-1	0.00	4.94E-3	0.00
			3	9.75E-2	0.00	3.88E-3	0.00
9	0.008	15.0	1	1.75E-1	5.08	1.26E-2	0.64
			2	1.31E-1	1.17	4.95E-3	0.27
			3	9.75E-2	0.00	3.88E-3	0.00
Deviation	Distance-0.00158 m			0.00639 m^2		6.180E-5 m^3	

Conclusions

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- Several LiDAR applications for bridge inspection and management have been identified with the following features:
  - Adequate resolution (0.001m)
  - Has potential to be cost effective tools for bridge inspection (maximum CBR=1.8)
  - Provides direct geometric information – more appropriate than traditional photogrammetry
- LiBE – automated LiDAR point cloud analysis program has been developed
- For damage feature detection – Curvature and gradient techniques have both been implemented for small surficial damage detections
- LiBE can detect and quantify visible surface damages with high accuracy (0.01m×0.01m)
- LiBE can measure bridge clearance and guide clearance improvement construction with the match accuracy in teens of millimeters with in 25m
- LiBE can provide displacement measurement with the match accuracy in millimeters with in 20m
- Ratings based on quantification reflecting bridge conditions
- Several bridges have been rated

Resolution Requirements

Attributes	Resolution requirements
Urban scene	0.5-10 m
Bridge geometry information	0.5m
Traffic counting	1m
Clearance	0.3m
Bridge intolerable abutment movement	25mm
Bridge structure surface defects	13mm
Bridge structure surface cracks	5mm

Future Study

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- Reflectivity information can be used along with geometry information for bridge applications
- Automatic damage classification
- Link surface information with interior damage and capacity loss
- Space borne LiDAR need to be studied for further applications

Questions/Discussions?

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THANK YOU!!!