Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Bridge Construction Monitoring using LIDAR for Quantified, Objective Quality-Control Quality-Assurance (QOQCQA)

Project No. 19STUNM02

Lead University: University of New Mexico

Final Report

August 2020

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Acknowledgements

The authors want to thank the following collaborators who supported this research: New Mexico Department of Transportation (NMDOT), City of Albuquerque, Center for Advanced Research and Computing (UNM), Microsoft, Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), Air Force Research Laboratory (AFRL), Central New Mexico Community College (CNM), Native American Community Academy (NACA), Canadian National Railway (CN), BNSF Railway, Union Pacific Railroad (UP), Los Alamos County (LAC), Association of American Railroads (AAR), and Federal Railway Administration (FRA.)

TECHNICAL DOCUMENTATION PAGE

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
19STUNM02		

4. Title and Subtitle	5. Report Date
Bridge Construction Monitoring using LIDAR for Quantified, Objective Quality-Control Quality-Assurance (QOQCQA)	August 2020
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
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9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Transportation Consortium of South-Central States (Tran-SET) University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**11. Contract or Grant No.**
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
United States of America Department of Transportation Research and Innovative Technology Administration	Final Research Report August 2019 – August 2020
	14. Sponsoring Agency Code

15. Supplementary Notes

Report uploaded and accessible at Tran-SET's website (http://transet.lsu.edu/).

16. Abstract

Transportation infrastructure construction quality control and quality assurance demands construction monitoring by field inspectors. Currently, these inspectors monitor infrastructure by measuring and photographing structures. These tasks allow them to assess any correction decision during construction or to inform about the quality of the construction process for the future. In order to promote and objective decisions obtained during infrastructure construction, the proposed research project developed and implemented a methodology to measure construction progress and compared it with the designed 3D shape, quantifying the difference. This proposed project includes implementation for the development of DOT standards that could be added in near future bridge construction documents. The New Mexico Department of Transportation (NMDOT) showed a strong interest in this topic. The experience of the PIs on bridge design and construction, field inspection, and LIDAR technology was integrated in order to evaluate the results with impact both in research and in industry. Specifically, the research results outline recommendations about standards for implementation of technology in specifications for NMDOT or other DOTs.

17. Key Words	18. Distribution Statement
LIDAR, reinforced concrete, construction inspection, specifications, data acquisition	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	35	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m	square meters	10.764	square feet	ft^2
m	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m	cubic meters	35.314	cubic feet	ft^3
m	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
C	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AAR	Association of American Railroads
AFRL	Airforce Research Laboratory
ASCE	American Society of Civil Engineers
CARC	Center for Advanced Research and Computing
CN	Canadian National Railway
CNM	Central New Mexico Community College
FRA	Federal Railway Administration
LIDAR	Light Detection and Ranging
QCQA	Quality-Control Quality-Assurance
NACA	Native American Community Academy
NMDOT	New Mexico Department of Transportation
SHM	Structural Health Monitoring
SNL	Sandia National Laboratories
SMILab	Smart Management of Infrastructure Laboratory
SOE	School of Engineering
TTCI	Transportation Technology Center, Inc.
UAV	Unmanned Aerial Vehicle
UNM	University of New Mexico
USDOT	U.S. Department of Transportation

EXECUTIVE SUMMARY

This project developed and implemented a methodology which measured construction progress and compared it with the projected 3D shape, then quantifying the difference. The results of this project supported the development of DOT standards which can positively impact near future bridge construction documents. The participation of experts in infrastructure maintenance and LIDAR sensing within this project enabled students to get exposed to industry careers related to infrastructure management and maintenance using new technologies.

The New Mexico Department of Transportation (NMDOT) was interested in exploring new technology available and implementing it in the Quality-Control Quality-Assurance (QCQA) during the concrete pour and concrete finishing phases of bridge construction. There are no 3D requirements in the form of LIDAR measurements satisfying QCQA standards for the constructed concrete structures (especially for bridge decks). According to NMDOT, the current QCQA requirements are limited to the measurement of discrete points. If the entire volume/surface could be compared with the designed profile (in 3D) then the quality of the finished surface would be quantified and objective with more precision.

State departments of transportation are facing three related problems without the mentioned technology: (1) the quality of the construction is not comparable across different projects, and errors may be carried over without being noted causing future costs, or unsafe structures; (2) high quality construction projects cannot be rewarded, and low-quality projects go unnoticed; (3) since errors cannot be measured, the standards cannot be changed or imposed.

With the proposed automation of a measuring technique and the objective score that is determine with the data collected on near real-time, new requirements can be imposed, and the quality of the constructed surface as compared with the design surface can be increased. Consequently, from the strong interest of the NMDOT in this topic alongside the experience of the PIs on bridge design, bridge construction, field inspection, and LIDAR technology yielded the results with impact both in research and in industry (specifically, recommendations about standards for implementation of technology in specifications for NMDOT or other DOTs).

1. INTRODUCTION

Bridges play a vital role in the north American transportation networks *(1)*. There are more than 614,387 bridges in the United States, which are mostly owned by state or local governments *(2)*. The highest percentage of highway bridges were built in the late 1950s and early 1970s, almost 40% bridges have been in use more than 50 years *(2)*. In recent years, the number of bridges with structural defects has been increasing. Expenditures for bridge maintenance and replacement have risen, accounting for $10.5 billion out of $12 billion in total bridge capital outlays in 2004 *(3-4)*. The bridge quality monitoring process during the construction period is critical to ensuring the safety of bridges *(5-15)*. The proposed research project developed and implemented a methodology to measure construction progress and compare it with the projected 3D shape and quantifying the difference. This project proposed a first step towards the development of USDOT standards that can be added in near future bridge construction documents. The conceptual objective of the mentioned project is displayed in Figure 1. Figure 1 shows a 3D view digitally collected overlaid with the rail rebar layout in the field. As shown in this figure, the inspector manually installs the rebar in the field, however the 3D view of the rebar collected digitally can assist as an objective quantification of rebar spacing, once it is saved in the computer. Another advantage shown in this figure is that the digital information can be analyzed globally, as opposed to the field inspection, where as shown in the figure the technician only has access to the nearby rebar. The participation of experts in infrastructure maintenance and LIDAR sensing provided students with exposure to industry careers related to infrastructure management and maintenance using new technologies.

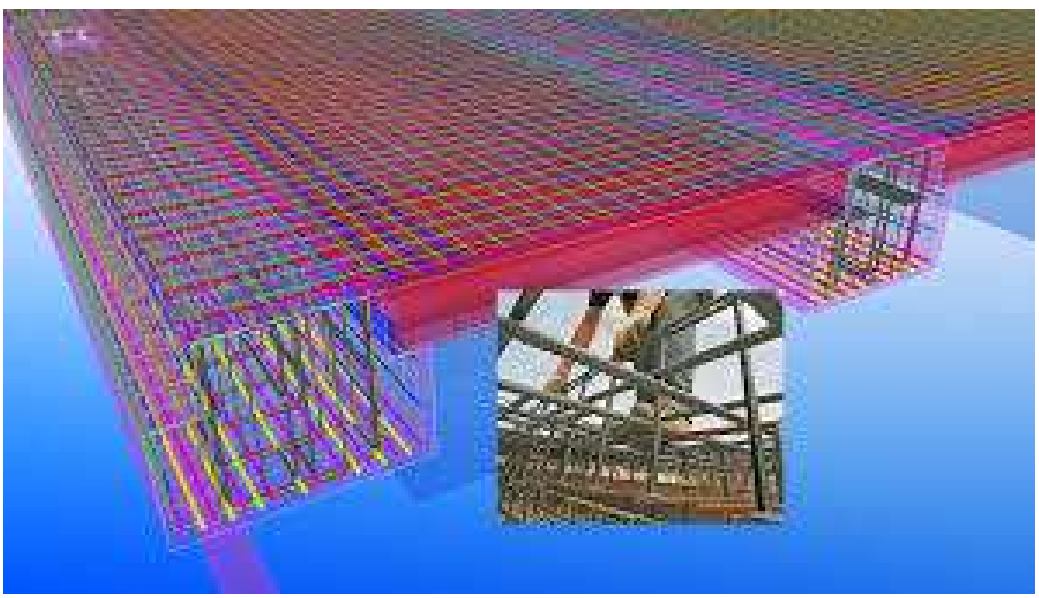


Figure 1. LIDAR to monitor construction activities.

1.1. Background

The New Mexico Department of Transportation (NMDOT) was interested in exploring new technologies available and implementing these in the quality-assurance quality-control (QAQC) process of bridge construction, in particular during concrete pour and concrete finishing *(16-17)*. If the entire volume/surface could be compared with the designed profile (in 3D) then the quality of the finished surface would be quantified, and a score could be associated with the quality.

1.2. Research Methodology

This research project employed a methodology using LIDAR. LIDAR was tasked to measure construction progress and compare it with the projected 3D shape, quantifying the difference *(18-20)*.This project proposed the implementation of this methodology for the development of DOT standards that can be added in near future bridge construction documents. The PI has discussed this project closely with Kathy Crowell from the NMDOT bridge design group, and they agreed to also support this research.

This project sought to increase the technical collection of data during construction *(21-26)*. A multi-disciplinary team from the University of New Mexico (UNM) collaborated with NMDOT to measure the 3D reinforcement layout during bridge construction using LIDAR. The approach proposed by this UNM team, supported by the input of infrastructure owners' guarantees, the broader impact of this research has been attained. Figure 2 shows the rebar construction process in the field conducted by field technicians, where they are manually installing reinforcement bars with measurements and inspections they conduct simultaneously, prior to concrete pour. As shown in this figure, the field technicians walk on top of the rebar cage to observe spacing and they adjust manually as needed on real-time, based on their visual observation.

Figure 2. Bridge reinforcement during construction.

1.3. Future Funding Proposals on LIDAR Technology for Bridge Monitoring

The results of this project exhibit the significant impact LIDAR technology has on the promotion of monitoring and evaluation of bridge systems *(27-29)*. Researchers redefined this technology to empower bridge construction inspectors in acquiring measurements and quantifications of the condition of bridge reinforcement during construction *(30-32)*. This empowerment enables a potential standardization of this technology across the NMDOT and the bridge construction industry *(33)*. Furthermore, the results of this project show that using LIDAR equipment and software/hardware tools can help enable the construction inspector to collect accurate progress data of the bridges. One patent has been disclosed by the PIs and the graduate student in the UNM patent office related to LIDAR technology for bridge inspection. New proposals using the preliminary data will be submitted to the USDOT, Federal Railway Administration (FRA), National Science Foundation (NSF), and USDOT pool funds.

Nonetheless, this research's risk-reward ratio is low since the collaborators' quality increases the impact of the study in two different departmental units at UNM. Additionally, the strong partnership with the NMDOT guarantees the high impact of this research and allows UNM students to collaborate with a different institution throughout the project, and more specifically, to interact in researching outside of the state of New Mexico, broadening the potential impact for regional students. Another aspect of this project is the experience of the PI and co-PIs in offering STEM courses related to this research. The active participation of the PI and Co-PI have supported student exposure to research that is strongly tied to innovation and entrepreneurship. Collaborating with NMDOT and their bridge group provides an excellent opportunity for knowledge dissemination at different levels in higher education, but also in pre-college education in the region of New Mexico *(34-41)*.

2. OBJECTIVES

This section presents the objectives obtained for this project. The objectives of this research were divided into two phases: research phase and implementation phase.

2.1. Research Phase

The accomplishment of the project objective(s) in the Research phase required the following tasks:

1. Researchers have established with NMDOT a prototype route for choosing the LIDAR needs and specifications required for this project.
2. In collaboration with NMDOT, elaborated scientific hypothesis on preliminary testing and validation in the CoreSLAB structure company.
3. Developed an experiment in the CoreSLAB and reported the results to NMDOT. Researchers tested and checked the new LIDAR technology to the bridge wingwall reinforcing bar measurement using input from objectives 1 and 2.
4. Researchers involved both students and industry in 3.
5. Established preliminary specifications for bridge deck QOQAQC.
6. As part of the research objectives, researchers also shared the LIDAR technology measurement algorithm with other universities, industry, and owners.
7. At the end of the project, the researchers conducted one workshop with NMDOT and presented the achievements to NMDOT project review committee.
8. In collaboration with NMDOT, selected one bridge of interest to test the outdoor implementation and write the results.

By the end of this project, researchers have finished all the research objectives but field bridge construction experiments and the update of specifications because of the COVID-19 epidemic. When safely so, after COVID-19 has lowered the concern of safety, the researchers will test the bridge construction and validate it with other means of measurement. Subsequently, they will compare these results and the specifications requirements between the field research on a bridge and the current laboratory testing. With the bridge data, the researchers will propose the update of the specifications. This will occur in the implementation phase due to COVID-19.

2.2. Implementation Phase

The results of this research have been shown to infrastructure owners both in a webinar and in the workshop. Infrastructure owners have expressed their interest in committing resources to further developing LIDAR technologies to inspect transportation infrastructure, more specifically, NMDOT. The following implementation steps are:

1. Development of an algorithm to use LIDAR point cloud 3D data for bridge deck inspections demonstrated in laboratory size settings to NMDOT during the workshop.
2. Benchmarking of the results of using the LIDAR point cloud 3D data processing algorithm comparing benefits for field implementation: safety, accuracy, and time (reinforcing bar spacing measurement, shown to NMDOT).
3. The teaching of LIDAR scanner technology to undergraduate students with field experiments (March 2020).
4. Cooperating and communicating the LIDAR sensing technology and point cloud data processing with Virginia Polytechnic Institute and State University and the University of Nebraska-Lincoln.

5. Transferring the research developments with the bridge engineer in NMDOT and construction inspectors in CoreSLAB and the technical staff in LIDAR technology company GeoSlam.
6. Trimester reports to panel review to receive feedback in the technology.
7. Demonstration at the international webinar: the 1st Smart Management of Infrastructure Workshop.

The proposed research equipment and analysis methods provided evidence that with LIDAR technology, inspectors increase their ability to quantify bridge construction quality objectives faster, more accurate, and more safely. The project's Results were presented to the industry, including, but not limited to: Federal Railway Administration (FRA), US Department of Transportation (USDOT), and NMDOT. In the implementation phase, the objective was to identify the needs of industry for the practical implementation of LIDAR sensing. The further development of LIDAR sensing applications addressed those. The implementation's final contribution was that LIDAR technology algorithm applications were developed not only to address structural inspections from a precision standpoint, but also in areas of demand of industry and owners from their day-to-day operations.

3. LITERATURE REVIEW

This section presents a literature review to covers two topics: bridge reinforcing bar placement evaluation and the potential of LIDAR technology as automatic data capturing visualization tool. The reviewed literature includes books, journal papers, technique reports, conference papers, thesis, and dissertations.

3.1. Bridge Reinforcing Bar Placement Evaluation

3.1.1. Specifications for Bridge Reinforcing bar Construction

This section first discussed the importance of bridge reinforcing bar placement. According to Standard Specifications for Highway and Bridge Construction *(42)*, the general placement guidelines for bridge reinforcing bar are recommend:

- The Contractor shall firmly support reinforcing bars in deck slabs with approved devices spaced at intervals not exceeding 3.3 ft. The Contractor shall securely tie down reinforcing bar mats in Bridge decks to girders and forms to prevent upward movement during concrete placement.
- The Contractor shall not allow the spacing between adjacent reinforcement bars to vary more than 1/2 inch (13mm) from the dimensions shown in the Contract.
- The Contractor shall place and maintain reinforcement bars within 1/4 inch (6mm) of the vertical dimensions shown in the Contract.
- The Contractor shall not allow the concrete cover over the top layers of reinforcement to be less than two (2) inches.
- The Contractor shall check the top elevation of the reinforcement unit before and after placing the concrete. If the reinforcement unit is not maintained within the specified tolerances, the Contractor shall make corrections.

According to Standard Specifications for Highway and Bridge Construction (NMDOT, 2019 edition), the checking guidelines for bridge reinforcing bar are recommend:

- Clearances and respective tolerances for bridge deck reinforcing must be given special attention when checking. The Contractor shall place bottom reinforcing bars with a minimum cover of one (1) inch. Except in cases where reinforcing bars are not parallel to form corrugations, the Contractor shall center the bars (approximately) in the bottom layer of the primary reinforcement over the valleys of the forms when necessary to achieve the minimum concrete cover. The Contractor shall not allow the distance from the top of the slab to the main slab reinforcement's bottom layer to be less than the dimension shown in the Contract.
- Clearance of bottom reinforcement from the bottom of the slab must be given special attention when checking. The clearance shall be the nominal clearance shown on the plans with a tolerance of minus 3 mm (1/8 inch) and plus 6 mm (1/4 inch).
- Distance from the bottom of the slab to the top of the top mat of reinforcement must be given special attention when checking. When all top reinforcing is of the same diameter, the nominal distance is to be maintained with a tolerance of minus 6 mm (1/4 inch).

3.1.2. Reinforcing Bar

The Contractor shall provide deformed bars in accordance with AASHTO M 31, Grade 60, or ASTM A706, Grade 60, at the nominal dimensions in accordance with Table 540.2.1:1 "Nominal Dimensions of Reinforcement." Table 1 shows the weight and dimensions of reinforcement bars corresponding to each bar size. AASHTO M31 Grade 40 may be used for Reinforced Concrete for Minor Structures (Section 515 only). The installation of the reinforcing bar is critical for the success of the overall bridge.

Table 1. Nominal Dimensions of Reinforcement.

Bar size	Nominal Weight (lb/ft)	Diameter (inch)
No. 3	0.376	0.375
No. 4	0.668	0.500
No. 5	1.043	0.625
No. 6	1.502	0.750
No.7	2.044	0.875
No. 8	2.670	1.000
No. 9	3.400	1.128
No. 10	4.303	1.270
No. 11	5.313	1.410
No. 14	7.650	1.693
No. 18	13.600	2.257

3.1.3. Current Bridge Reinforcing Bar Placement Evaluation

Previous research reviews that develop an efficiency real-time information on work-face operations can help engineers and managers make a quick grade decision.

One inspection method of the reinforcing bar placement before the concrete pour is a visual inspection by the clerk of works or equivalent. Using a steel tape to check the cover thickness will, and any spacers that have fallen off or been broken will need to be replaced. In addition, there is also a surveyor who will check the steel level according to the required level on the design drawing. If these levels are satisfactory, and the clerk has completed the visual checks, the pour will proceed. Figure 3 shows an example of using conditional method tape measurement to inspect the rebar location and rebar construction quality. In this figure, the inspectors use a steel tape to measure the rebar cage bay by bay, and it normally need more than one people to conduct this measurement. One people hold the tape on the rebar surface and the other one help to record the measurement.

Figure 3. Bridge reinforcement placement inspection during construction.

The quality and durability of bridges depend heavily on the quality control during construction, particularly on the quality of reinforcing bar placement. At present, bridge inspection mainly uses visual inspection and manual defect measurement. However, manually inspect the reinforcing bar location is a time-consuming, expert-dependent and error-prone procedure. Extracting necessary information about the number, location, and size of the reinforcing bar is a major task for bridge inspectors. The most common on-site evaluation methods for field inspection of reinforcing bars are manually and need to be improved.

3.2. LIDAR Sensor for Transportation Infrastructure Applications

Currently, LIDAR (Light Detection and Ranging) is being used to collect large amounts of data that can be used to reconstruct 3D cloud points with high fidelity. However, to date, there is no capability for collecting 3D clouds of data that can be used to inform about the quality of the reinforcing bar layout in the real-time or practical level of detail. If LIDAR scanning would be accessible and simplified to this application, the owner and the engineer would be able to quantify at the site automatically about the actual quality of the reinforcement, so objective quantification of the reinforcing bar would be made accessible across bridges and construction sites. The strong interest of the NMDOT in this topic and the experience of the PIs on bridge design and construction field inspection, bridge sensing technology, and LIDAR have identified that this is a topic of interest that can have an impact both in research and in the industry (specifically, recommending standards for implementation of technology in specifications for NMDOT or other DOTs).

Ongoing research has already started, and it is being funded by Tran-SET center of transportation. Research to date includes a literature review of existing LIDAR technology in academia and industry and preliminary software familiarity of the supported student. The preliminary stage has also identified that the emphasis of this support will be in the practical implementation of LIDAR data collection in the field so standards can be made that can be used for the construction environment and schedules. The emphasis will be in accelerated data collection and data processing that enables a quick return of information about the reinforcement quality in the field in real scenarios of construction. A preliminary literature review has identified that the top reinforcing bar is of higher interest and also different reinforcing bar types in terms of requirements for repeatability of the proposed methodology across projects.

The use of laser scanning in construction has been documented widely in various studies. Tang, P., Huber, D., et al. have reviewed related techniques on the automatic reconstruction of as-built building information models from laser-scanned point clouds in 2010. Many other researchers have implied a laser scanner on the quality control of bridge deck construction, bridge damage evaluation, and post-disaster assessment. However, the use of laser scanning to locate reinforcing bar prior to pouring concrete has not been widely documented. Only little published research on 3D image data to control drilling for embeds into reinforced concrete bridge decks and building reinforcing bar recognition. The laser scanner can produce high-density point clouds that could be used for 3D mapping. The main limitations of laser scanners include acquiring the data and their size, which limits their mobility. And the 3D imaging laser scanning method is mixed pixel phenomenon, range errors for thin structures, range jumps at reflectance and color boundaries, and large errors due to specular reflection. Luckily, the new laser scanners are more compact and more accurate. The benefits of laser scanning varied in various form factors to meet mission requirements (vehicle-mounted, pole-mounted, sUAS airborne, manned airborne).

4. METHODOLOGY

This section covers the completion of two tasks at the beginning of the project that are essential for the practical roadmap implementation with the NMDOT. For Task 1, the PIs established with NMDOT a prototype route for choosing the LIDAR needs and specifications required for this project. For Task 2, the PIs collaborated with NMDOT to elaborate scientific hypothesis on preliminary testing and validation in the laboratory.

4.1. Establish with NMDOT a prototype route for choosing the LIDAR needs and specifications required for this project

LIDAR (Light Detection and Ranging) is a scanning laser technology that can collect 3D point cloud data of objects. A LIDAR system (which can be installed on anything, from an airplane to a simple tripod) emits up to 1 million pulses per second in a scanning mode, and each point can hit the nearest line of sight target. The light reflected back to the scanner is measured, and the distance is calculated based on the speed of light. Figure 4 shows the essential components of LIDAR system. Generally, as shown in Figure 4, a LIDAR system is consisting of a camera, high speed shutter, lens and light as the signal generator, then LIDAR measures distances by illuminating the object with laser light and measuring the reflection with a sensor.

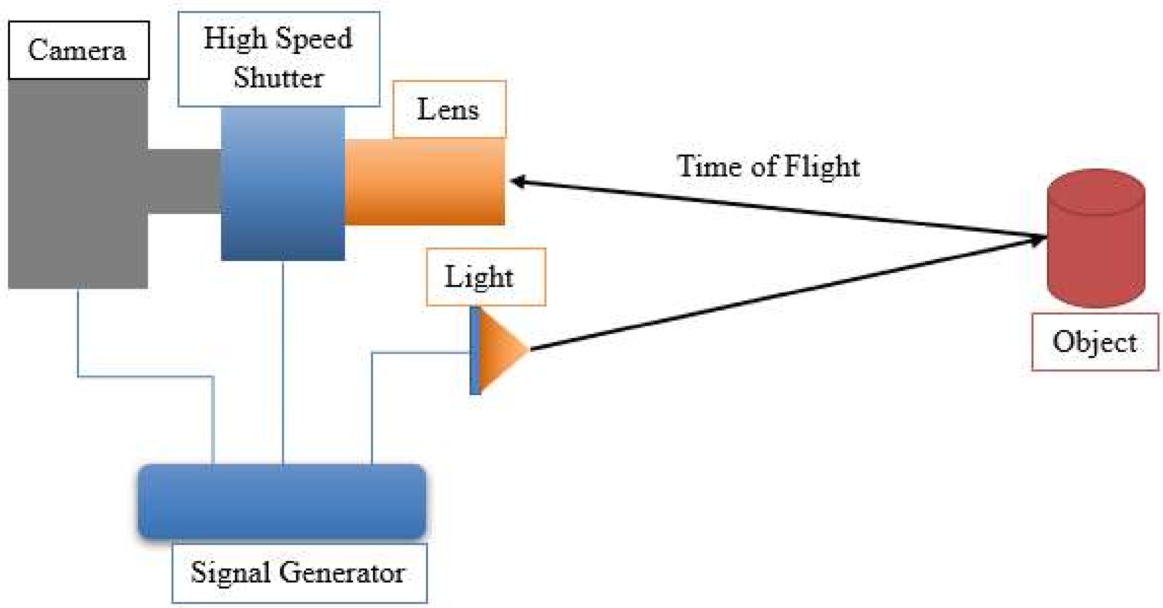


Figure 4. Basic Components of LIDAR System.

The following characteristics of LIDAR exhibit its potential to be used in the transportation systems.

- Only technology for detailed remote sensing of structure obscured by vegetation.
- Works at night.
- Easy to develop and apply evaluation standards.
- Combines surveying, imaging and high-speed 3D scanning in one revolutionary solution can be used for structural inspection.

- Detailed standards through American Society for Photogrammetric Engineering and Remote Sensing (ASPRS).
- Widely deployed by transportation agencies (trusted) and survey companies.
- Available in a variety of form factors to meet mission requirements (vehicle mounted, pole mounted, UAS airborne, manned airborne).

LIDAR scanner equipment can be useful tools during bridge reinforcing bar construction inspections need high resolution and high accuracy. Table 2 presents a list of relevant popular LIDAR scanners in the marketplace. The popular LIDAR scanners in the market have high accuracy and light-weight. The scanner's brand is FOCUS^{S} 350, Lecia Station P40, Leica S Station C10 and Trimble X7 3D. They have the similar shape design and scanning range is up to 300 m except Trimble X7 3D, the measuring accuracy is millimeter level and the weight is portable. However, consider the price and accuracy, the researchers choose the ZEB HORIZON scanner.

Table 2. Popular LIDAR Scanner.

LIDAR Brand	**FOCUS^{S} 350**	**Leica Station P40**	**Leica S Station C10**	**Trimble X7 3D**
Appearance				
Scanning range	0.6m - 350m	0.4m - 270m	0.1m - 300m	0.6m - 80m
Measuring Accuracy	+/-1mm	+/-1.2mm	2mm	2mm
Angular Accuracy	19" vertical; 19" horizontal	8" horizontal; 8" vertical	12" horizontal; 12" vertical	21" horizontal; 21" vertical
Field of view	360° ×300°	360° ×290°	360° ×270°	360° ×282°
Power supply	19 V	24V DC, 10-240 V AC; Battery	15 V DC, 90 – 260 V AC	Rechargeable Li-lon battery 11.1V, 6.5Ah
Data storage capacity	32 GB	256GB internal solid-state drive (SSD) or external USB derive	80 GB onboard solid-state drive (SSD) or external USB device	256 GB Solid State Drive (SSD), (512GB or more for best performance)
Weight	4.2Kg	12.25Kg	13 Kg	5.8 Kg
(W×D×H) mm	230 × 183 × 103	238 × 358 × 395	238 × 358 × 395	178 ×170 ×353

After comprehensive consideration and discussion with NMDOT on their needs for LIDAR in the field, informed by a field visit to a bridge construction on November in 2019, researchers decided to utilize the LIDAR scanner from GeoSLAM. The product model is ZEB HORIZON. This scanner is great for indoor and outdoor use, including spaces where features are positioned further apart. Moreover, it is lightweight, simple to use, fast to capture and easy to process, making it even more desirable. The technical specifications are shown in table 3. Table 3 shows the range of the LIDAR scanner is 100m, field of view is 360° ×270°, the relative accuracy is 1 cm to 3 cm, the scanner weight is 3.7 Kg. In future research, the new model GeoSLAM Zeb Revo Real-Time scanner will be considered.

Table 3. ZEB HORIZON Technical Specification.

Range	100m	
FOV	360° ×270°	
Protection class	IP 54	
Processing	Post	
Data logger carrier	Backpack or shoulder strap	
Scanner weight	3.7kg	
Colorized point cloud	√	
Intensity	√	
Referenced imagery	√	
Scanner points per second	300,000	
No. of sensors	16	
Relative accuracy	1 - 3 cm	
Raw data file size	100-200MB /min	ZEB HORIZON Scanner

4.2. In collaboration with NMDOT, elaborate scientific hypothesis on preliminary testing and validation in the laboratory.

In order to explore a scientific hypothesis of the new proposed approach and solution with the selected LiDAR, the research team visited in November 2019 a bridge construction with the NMDOT. During this bridge inspection and with meetings over the phone afterwards, the NMDOT outlined the objectives of the scanning for UNM. As a result, the proposed hypothesis from UNM is that the scanning can collect rebar spacing that is more accurate and in a faster, safer, and convenient inspection process than the current tape measurement with LiDAR. To validate this hypothesis, the researchers proposed a methodology following four steps: (1) rebar scanning; (2) registering the point cloud model; (3) comparing the LIDAR model to the CAD blueprint system; and (4) assessing the accuracy to check the hypothesis. Figure 5 shows the detailed workflow of bridge scanning by the LIDAR system. The researchers worked on this project follows the detail steps as shown in Figure 5. Firstly, set a bridge rebar cage objective, the used LIDAR scanner scan the rebar cage, build the point cloud model, and compared the point cloud model with CAD system. Based on the comparison, researchers can get the accuracy assessment of the rebar construction quality.

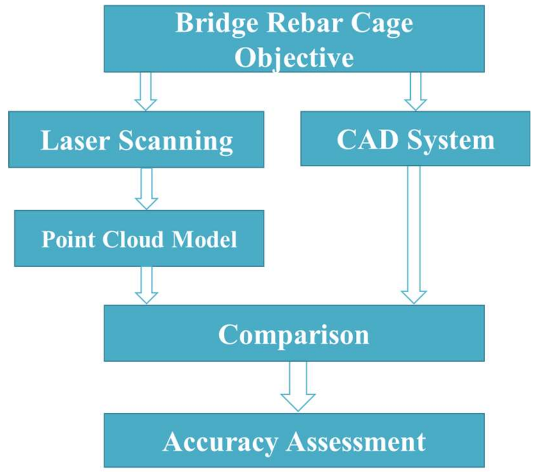


Figure 5. Workflow of Bridge Scanning by LIDAR System.

The methodology presents a LIDAR scanning based geometric data collection process for bridge reinforcing bar using a case study. Researchers created 3D models for the bridge reinforcing bar cage with LIDAR scanned data for further analysis, such as visualization, geometric feature extraction. We compared both the current bridge designed data from the CAD system and the LIDAR scanning data in data collection, data processing, and data interpretation. A comparison of these processes showed that the LIDAR scanning process could provide more accurate and comprehensive data, which can be used for future bridge QCQA data needs.

5. RESULTS

This section advances the results from Chapter 4 in the following subsequent tasks: developing experiment in the laboratory, propose objective assessment of rebar quality with NMDOT, and report the results to NMDOT, and receive their feedback prior to bridge testing. The PIs prepared the ZEB LIDAR scanner equipment for the experiment and conducted first experiment in a wingwall rebar cage in CoreSLAB, which is a structure being scanned in the field, which is more advanced that the laboratory conducted prior for validation. The authors analyzed the result data and finished the progress report of this experiment and communicated with NMDOT, prior to testing the method for barriers for implementation in the field. The researchers tested this methodology in the bridge construction and validated it with other means of measurements in the field, such as tape measurers which made this difficult in the field. The results from the bridge scanning confirmed that the objective inspection of rebar can be attained even in a real bridge site. The final contribution of this research development is that the researchers have proposed a new procedure that prioritize the change of specifications that recommend using LiDAR for collecting spacing, and furthermore, proposed a new LiDAR informed quantification of the quality of the inspection prior to concrete pour. The subsequent sections outline the research results that support the practical implementation based on the technical achievements of this work and the feedback from NMDOT on this process.

5.1. Scan Object: Wingwall Reinforcing bar Cage

Bridge wingwalls are the retaining walls adjacent to the abutment of the bridge. Wing walls are provided at both ends of the abutments to retain the earth filling of the approaches. There are more than 13,000 integral abutment bridges in service in the USA. Wingwalls are a necessary component of the most integral abutment bridges to retain the fill that supports the roadway. Wingwalls design, construction, orientation and connection details can impact the forces induced in and the distribution of the forces throughout the structure. Figure 6 shows the picture of a bridge wingwall. For the bridge in Figure 6, the precast wing walls are adjacent to the abutments and act as retaining walls. They are generally constructed of the same material as those of abutments. The wing walls can either be attached to the abutment or be independent of it.

Figure 6. A constructed bridge with cantilevered flared wingwalls.

5.2. Experiment Setup

This experiment developed an automated quality assessment technique for precast reinforcing bar cage. Figure 7 (a) shows the schematic of the overall hardware configuration for the proposed technique. It is assumed that the reinforcing bar cage and the LIDAR scanner positioned above the rebar cage scans the whole surface in a single scan. Figure 7(b) shows the necessary steps for the proposed reinforcing bar spacing quality assessment technique, which includes data acquisition, data processing, reinforcing bar data extraction, reinforcing bar spacing estimation and quality assessment. The research group conducted an experiment in the CoreSLAB Construction Site. A wingwall reinforcing bar cage with a size of $104.5\ inches \times 64\ inches$ was chosen as the testbed. The LIDAR scanner selected was a GeoSLAM ZEB HORIZON Scanner. Figure 7 (a) shows the LIDAR scanning setup, the LIDAR scanner is on the top of the rebar cage, and the researcher held the scanner walk around the rebar cage and collected the rebar data in 30 seconds. Figure 7 (b) shows the experiment framework of experiment data process, including data acquisition, 3D reconstruction, and quality evaluation.

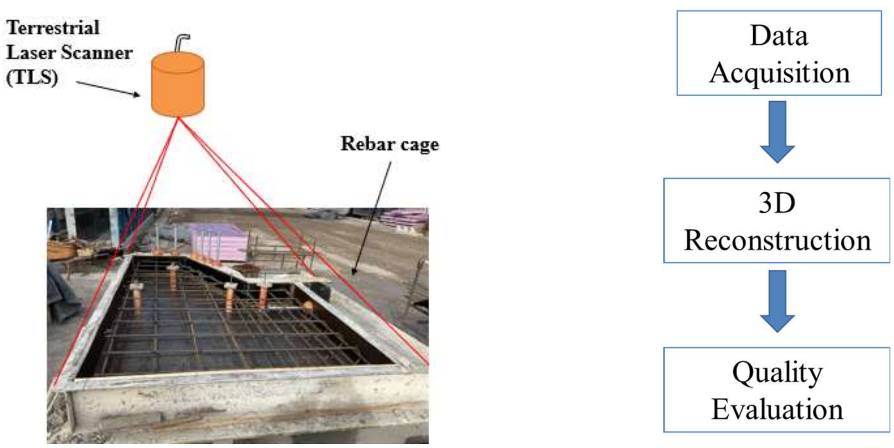


Figure 7. LIDAR Reinforcing bar scanning: (a) setup; (b) framework.

5.3. Experiment Data Collection

The data acquired in this experiment was collected within the CoreSLAB testbed where a wingwall reinforcing bar cage that would be found on a bridge was constructed. The reinforcing bar cage was designed and fabricated to easily simulate various reinforcing bar configurations. The configuration of the reinforcing bar cage uses #5 reinforcing bar. The two layers of reinforcing bar are separated by approximately 4 inches. In this case, the site coordinates of the testbed are predefined using surveying techniques. The inputs for the algorithm are point cloud. Figure 8 depicts the reinforcing bar cage and the corresponding scanning directions. Figure 8 (a) shows the rebar measurement by steel tape, one researcher use the tape to measure the spacing of each bay and the other researcher use a pencil and notebook to record the measurement. Figure 8 (b) shows the rebar data collection by LIDAR scanner. The researcher held the LIDAR scanner on the top of the rebar cage and walked around the it, then the scanning collection can finish in 30 seconds.

Figure 8. Data Collection. Left: Measurement by tape; Right: Measurement by LIDAR scanner.

Foremost, it is necessary to determine the position and scan parameters of the LIDAR scanner to achieve the highest inspection quality. Three main factors, which influence the measurement accuracy of the LIDAR scanner, are (1) distance, (2) incident angles between the scanner and a target structure, and (3) angular resolution of the LIDAR scanner. Once the position and scan parameters of the LIDAR scanner are determined, a region of interest (ROI) covering the precast reinforcing bar cage was selected after a coarse scan. A fine scan was conducted over the ROI, generating a point cloud containing a set of 3D point, i.e., (x_i, y_i, z_i), $i = 1, \dots, N$, where N is the number of total scan points. Note that the scanning and data acquisition was conducted automatically without human intervention. Once the position, scan parameters of the LIDAR scanner and ROI are manually determined prior to the data acquisition. The word "fully automated" used in this study implies that once the raw scan data becomes available, the proposed technique operates in a fully automated way for all data from data processing to quality assessment.

5.4. Automatic Reinforcing Bar Detection Algorithm 1

Before further data analysis, researchers denoised the scanned wingwall point cloud data and get rid of the noise. A total of 4,182,316 points was denoised to 489,484, only 11.7% of raw data. The commercial software CloudCompare was employed to reduce nonrelated data and only keep reinforcing bars. Additionally, the x and y axis of the point cloud was aligned with the direction of the reinforcing bar. Figure 9 below shows the flow chart of algorithm 1. The step-by-step description is sort points along a given axis, slice point cloud into j slices along axis, divide number of points by width of slice, find local maxima density results and the last one is plot resultant locations as rebar estimation.

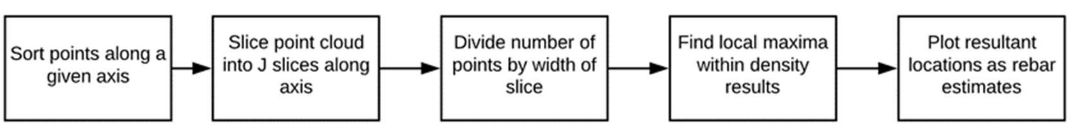
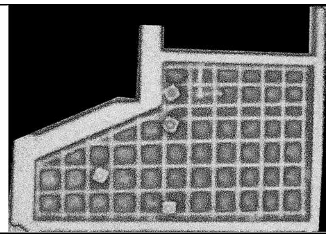
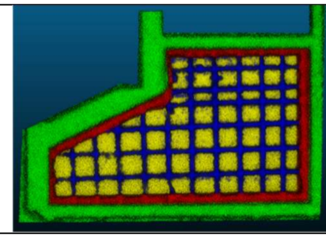
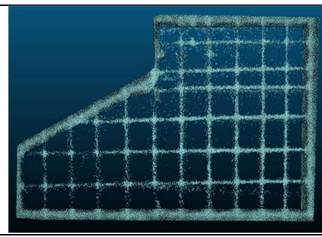
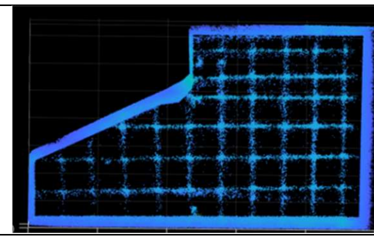


Figure 9. Flow Chart of Processing Algorithm 1.

Table 4 shows the pre-processing of point cloud data. The four figures of this table show the data denoising results of point cloud model. The number of points in the original as-built point cloud is 4,182,316, the number of points after denoising is 2,783,811, the number of top layer point cloud model is 293,690 and the number of bottom layer point cloud model is 217,434.

Table 4. Scanner Data pre-processing.

Scan Date	Number of points in the original as-built point cloud	Number of points after denoising
3/22/2020	4,182,316	2,783,811
		
	Number of points of the top layer	Number of points of the bottom layer
	293,690	217,434
		

The algorithm can be thought of as a one-dimensional density by depth approach. It seeks to obtain the point density along a given axis of the point cloud. To accomplish this, it begins by sorting the data along a given axis. Once the data has been sorted, it divides the points into bins of equal physical distance along the axis; these bins are referred to as "slices" or "layers". It divides the number of points in a slice by the width of the slice to obtain the average density within that slice. By taking a sufficiently large number of slices, the density of the data along an axis can be approximated as a smooth curve between the densities of the slices. Figure 10 shows the diagrammatic point cloud drawing of algorithm 1. The plots along each axis roughly shows the location of rebars. The peaks of x-axis and y-axis show the location of the projection of rebars location in the two-horizontal axis; the peaks of z-axis represent the two elevations corresponding to the two rebar locations of the top and bottom mesh, respectively.

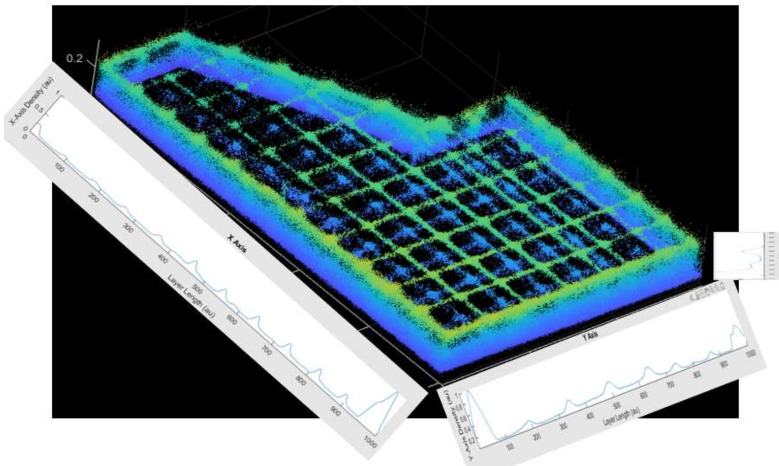


Figure 10. Diagrammatic Drawing of Algorithm 1.

Reinforcing bar perpendicular to a given axis show up as locally dense regions in the corresponding density plot. By extracting these regions as "local maxima" within the density plot, the algorithm can obtain the average location of a given reinforcing bar perpendicular to the corresponding axis. Figure 11, Figure 12 and Figure 13 show results of the density plots. Figure 11 shows the output of different axis reinforcing bar spacing plot. Figure 12 presents the derivative of output of different axis rebar spacing plots. Figure 13 shows the density plots overlayed point data.

Lastly, researchers made a note of the difference between center to center spacing and clear cover. For the reinforcing bar, the algorithm identifies the distance between the centroids of their locations. For clear cover, however, the edge of the formwork needs to be calculated, not the centroid of the formwork wall (which the local maxima would yield). For this, we actually require the "toe" of the maxima associated with an edge. This "toe" will correspond to the closest "near zero" point in the derivative adjacent to the maxima itself. The algorithm can find this point by simply identifying the maxima associated with the formwork wall and following along the derivative curve until it hits zero (or near zero); this point will always be the toe of the slope associated with this maximum and will correspond to the edge of the concrete formwork wall. See Figure 12 for an example of these points plotted on their respective derivative of density curves.

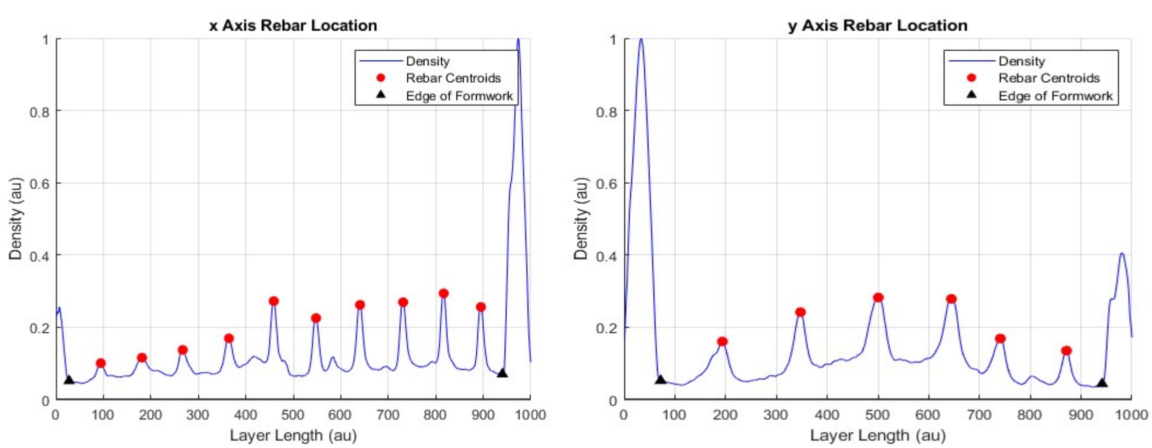


Figure 11. Output of different axis reinforcing bar spacing plot.

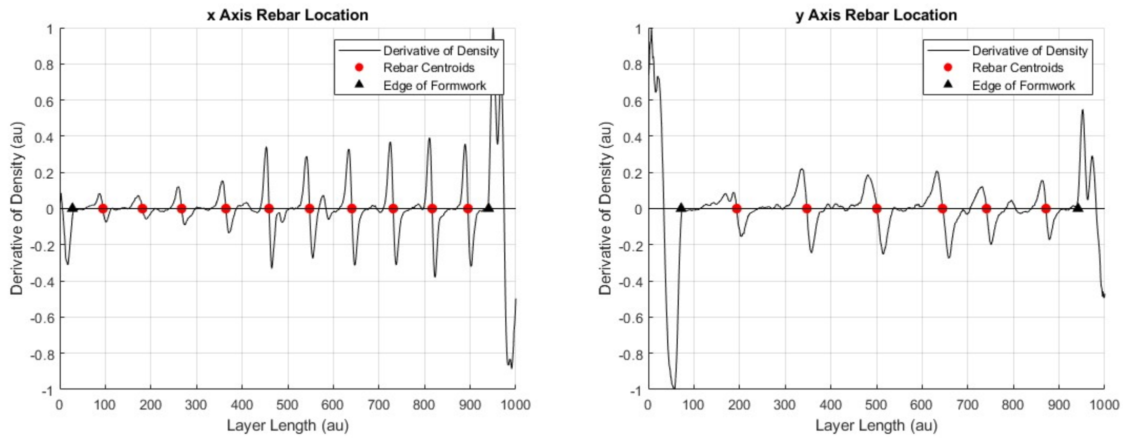


Figure 12. Derivative of Output of different axis reinforcing bar spacing plot.

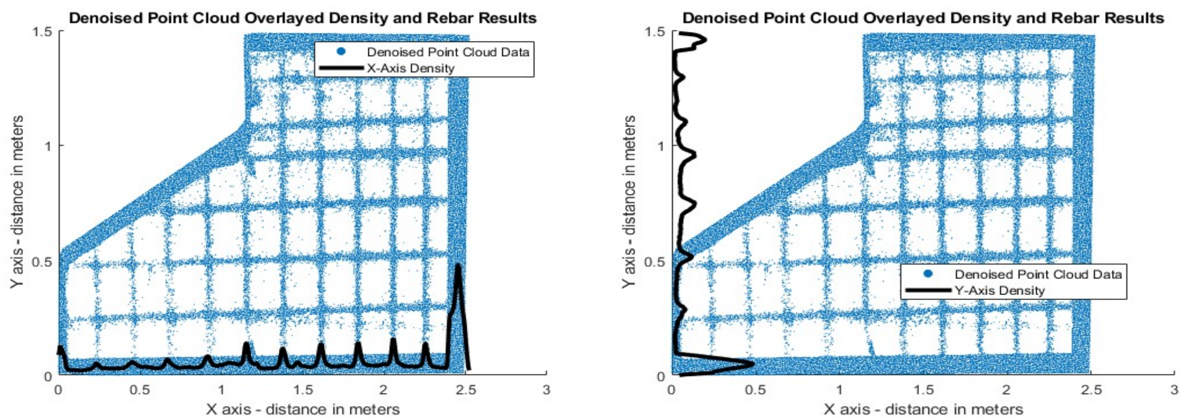


Figure 13. Density plots overlay point data.

Figure 14 shows the spacing of the two axis of the wingwall reinforcing bar cage according to the proposed algorithm. Figure 14 shows the spacing for side rebar of the rebar cage. The LIDAR measurement is calculated by MATLAB and marked by black number; the tape measurement marked by red number. Figure 14 shows the comparison result of LIDAR measurement and the tape measurement.

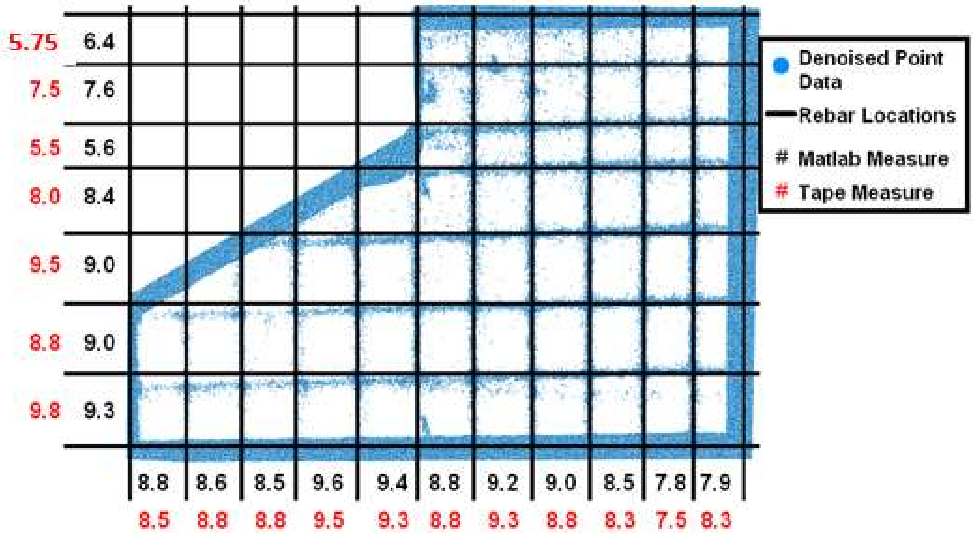


Figure 14. Reinforcing bar Locations Plotted Over Point Data with Measurements Labeled.

Table 5 shows the comparison of the algorithm results using the LIDAR data with the spacing using the tape measurement. As shown in the table, the largest absolute error for X axis is 0.4 inches, and the largest absolute error for Y axis is 0.6 inches.

Table 5. LIDAR Measurement and Tap Measurement Comparison.

X axis	Tape (inch)	LIDAR (inch)	Error (inch)	Y axis	Tape (inch)	LIDAR (inch)	Error (inch)
Spacing (1-2)	8.5	8.8	0.3	Spacing (A-B)	9.8	9.3	-0.5
Spacing (2-3)	8.8	9.0	0.2	Spacing (B-C)	8.8	9.0	0.2
Spacing (3-6)	8.8	9.1	0.3	Spacing (C-D)	9.5	9.0	-0.5
Spacing (4-5)	9.5	9.4	-0.1	Spacing (D-E)	8.0	8.4	0.4
Spacing (5-6)	9.3	9.2	-0.1	Spacing (E-F)	5.5	5.6	0.1
Spacing (6-7)	8.8	8.8	0	Spacing (F-G)	7.5	7.6	0.1
Spacing (7-8)	9.3	9.4	0.1	Spacing (G-H)	5.8	6.4	0.6
Spacing (8-9)	8.8	8.6	-0.2				
Spacing (9-10)	8.3	8.5	0.2				
Spacing (10-11)	7.5	7.8	0.3				
Spacing (11-12)	8.3	7.9	-0.4				

The tolerances on reinforcing bar position, according to ACI 117, is the permitted variation from a given dimension—in other words, how far off the reinforcing bar is from what is shown in the drawings. For example, if the clear distance between the outside of a reinforcing bar and the face of a 6-inch-wide concrete beam is specified to be 2 inches, the tolerance allows it to be no less than 1 5/8 inches. The tolerance on the position of longitudinal bars is much more relaxed: ±3 inches. This is because the positions of the longitudinal bars are not critical, as long as the proper cover is maintained, and the specified number of bars are included. The proposed algorithm can measure the spacing errors with less than 3 inches, therefore, is adequate for the measurement of longitudinal bars.

5.5. Automatic Reinforcing Bar Detection Advanced Slicing Algorithm

This section updated the algorithm based on the feedback from NMDOT experts, which was shown in a teleconference on August 2020. The updated research estimated the location of each rebar in every bay; hence each rebar has an associated position in each bay and direction. If one rebar is bent accidentally during construction, the projection algorithm may not detect that level of details of inner rebar bays.

In order to increase the accuracy of the measurement algorithm, researchers advanced the algorithm by finding average of each cluster, get the reinforcing bar location of each bay. Figure 15 shows the diagrammatic drawing of the advanced algorithm. As shown in the figure, the red arrows represent the spacing of each bay for the rebar cage in the automatic reinforcing bar identified by the data.

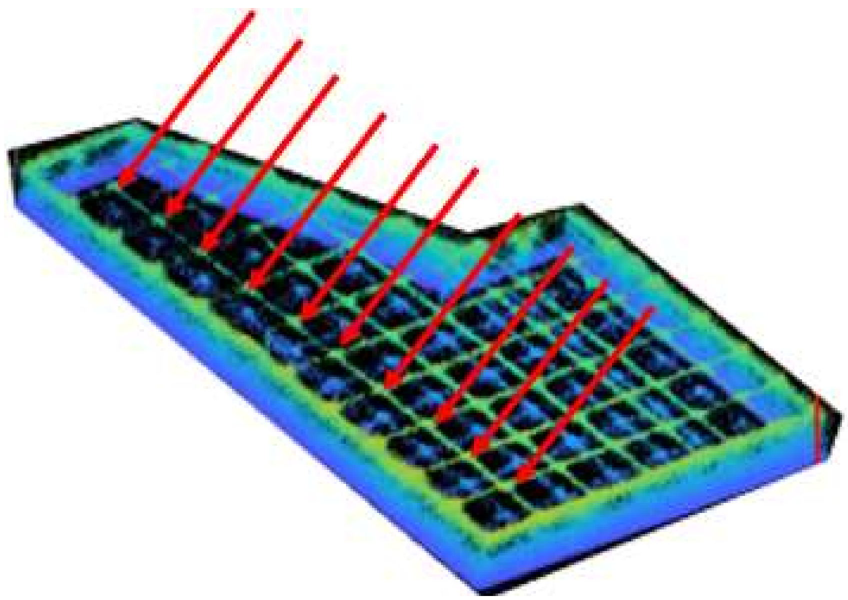


Figure 15. Diagrammatic Drawing of Advanced Algorithm.

Automatic reinforcing bar identification for X axis followed the steps like below:

1. Automatic splicing in X direction in between peaks
2. Measure automatic splicing
3. Find the Y and Z locations of each reinforcing bar in every bay being measured
4. Automatic measurement of Y axis and Z axis for all bays in X axis could be found

Figure 16 shows the data processing of X axis. Figure 16 shows specifically one example of one bay automatic determination of Y and Z axis. By applying the same algorithm to Y axis, Automatic measurement of X and Z for all bays in Y axis, as shown in Figure 17.

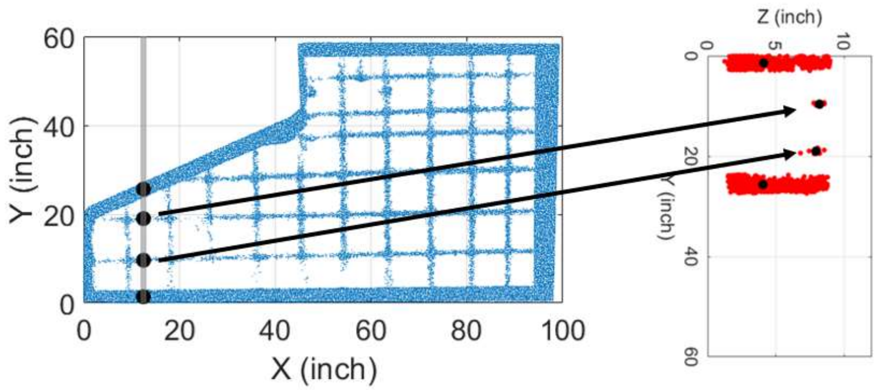


Figure 16. Diagrammatic Drawing of Slicing X-Axis.

Therefore, the automatic reinforcing bar identification algorithm for X axis and Y axis is shown in Figure 18. The value in blue color is the spacing of X axis, while the value in red color is the spacing of Y axis. This figure shows how the algorithm captures the slope in Z axis which can demonstrate that the algorithm is indeed able to measure the slope of the rebar in the field.

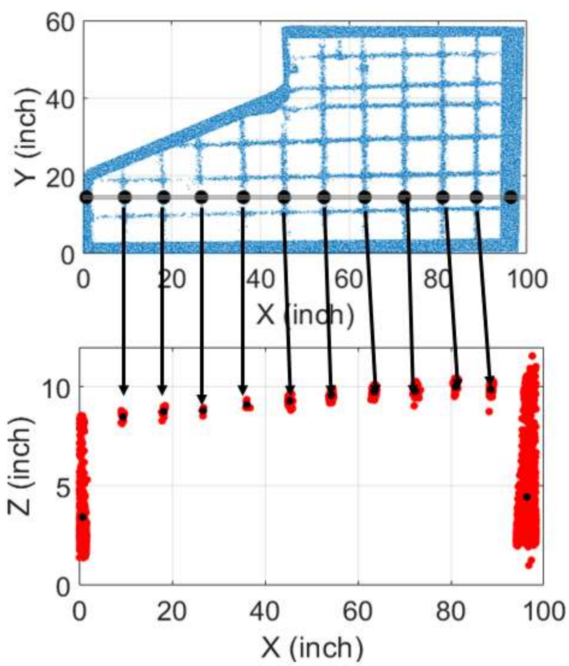


Figure 17. Diagrammatic Drawing of Slicing Y Axis.

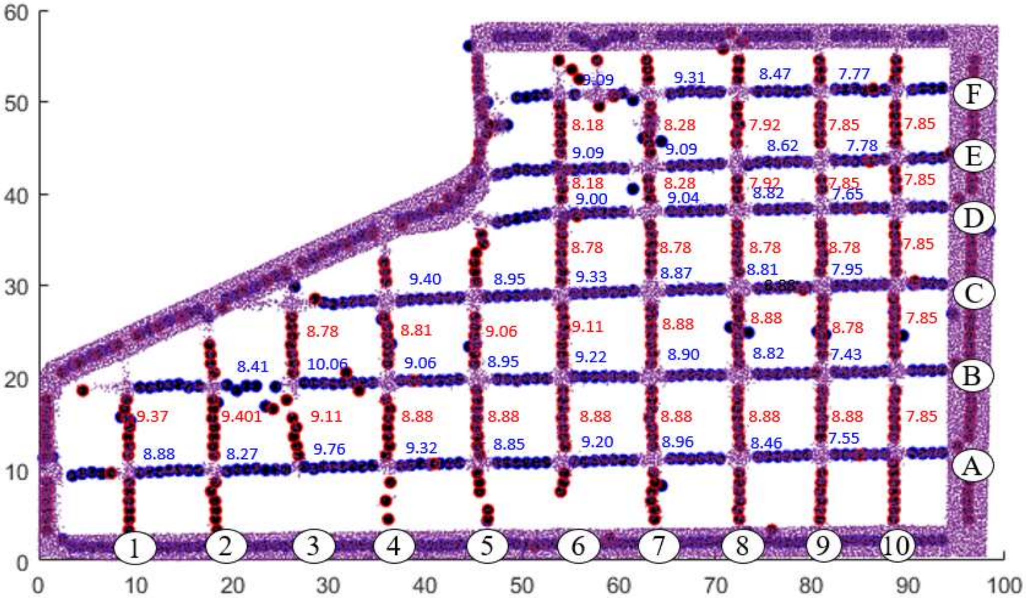


Figure 18. Spacing of each reinforcing bar along X and Y axis.

Compared the LIDAR measurement value and the design drawing values the error of the construction reinforcing bar cage is gained, which is shown in Table 6. Table 6 lists all the spacing of the rebar cage, totaling 69 bays. The mean error value of LIDAR measurement and designed spacing for X axis is 0.49 inches, the mean error value of LIDAR measurement and designed spacing for Y axis is 0.46 inches.

The advanced algorithm has proved the following functions:

- Can find all the spacing of each cluster along X and Y axis.
- Automatic values.
- It was also computed for Z elevations. It was also calculated for the bottom cage.
- It can be very beneficial for larger concrete decks.

Table 6. LIDAR Measurement vs. Designed Measurement.

X axis	Bay	LiDAR Measurement (inch)	Designed (inch)	Error (inch)	Y axis	Bay	LiDAR Measurement (inch)	Designed (inch)	Error (inch)
①	A-B	9.37	9.00	0.37	Ⓐ	1-2	8.88	9.00	-0.12
②	A-B	9.40	9.00	0.40		2-3	8.27	9.00	-0.73
③	A-B	9.11	9.00	0.11		3-4	9.76	9.00	0.76
	B-C	8.78	9.00	-0.22		4-5	9.32	9.00	0.32
④	A-B	9.21	9.00	0.21		5-6	8.85	9.00	-0.15
	B-C	8.81	9.00	-0.19		6-7	9.20	9.00	0.20
⑤	A-B	9.10	9.00	0.10		7-8	8.96	9.00	-0.04
	B-C	9.06	9.00	0.06		8-9	8.46	9.00	-0.54
	C-D	8.23	9.00	-0.77		9-10	7.55	9.00	-1.45
⑥	A-B	9.20	9.00	0.20	Ⓑ	2-3	8.41	9.00	-0.59
	B-C	9.11	9.00	0.11		3-4	10.06	9.00	1.06
	C-D	8.64	9.00	-0.36		4-5	9.06	9.00	0.06
	D-E	4.90	5.00	-0.10		5-6	8.95	9.00	-0.05
	E-F	8.18	9.00	-0.82		6-7	9.22	9.00	0.22
⑦	A-B	9.10	9.00	0.10		7-8	8.9	9.00	-0.10
	B-C	9.23	9.00	0.23		8-9	8.82	9.00	-0.18
	C-D	8.74	9.00	-0.26		9-10	7.43	9.00	-1.57
	D-E	4.70	5.00	-0.30	Ⓒ	4-5	9.40	9.00	0.4
	E-F	8.25	9.00	-0.75		5-6	8.95	9.00	-0.05
⑧	A-B	9.06	9.00	0.06		6-7	9.33	9.00	0.33
	B-C	9.30	9.00	0.30		7-8	8.87	9.00	-0.13
	C-D	8.63	9.00	-0.37		8-9	8.81	9.00	-0.19
	D-E	4.94	5.00	-0.06		9-10	7.59	9.00	-1.41
	E-F	7.92	9.00	-1.08	Ⓓ	6-7	9.00	9.00	0
⑨	A-B	8.89	9.00	-0.11		7-8	9.04	9.00	0.04
	B-C	9.35	9.00	0.35		8-9	8.82	9.00	-0.18
	C-D	8.63	9.00	-0.37		9-10	7.65	9.00	-1.35
	D-E	4.99	5.00	-0.01	Ⓔ	6-7	9.09	9.00	0.09
	E-F	7.85	9.00	-1.15		7-8	9.09	9.00	0.09
⑩	A-B	9.09	9.00	0.09		8-9	8.62	9.00	-0.38
	B-C	9.49	9.00	0.49		9-10	7.78	9.00	-1.22
	C-D	8.30	9.00	-0.70	Ⓕ	6-7	9.09	9.00	0.09
	D-E	5.40	5.00	0.40		7-8	9.31	9.00	0.31
	E-F	7.53	9.00	-1.47		8-9	8.47	9.00	-0.53
						9-10	7.77	9.00	-1.23
	Mean value of error			0.49		Mean value of error			0.46

5.6. Bridge Reinforcing Bar Construction Quality Scale: preliminary specifications using LiDAR

This section includes work for Task 4 and Task 7. Task 4 need to establish preliminary specifications for QOQCQA. The PIs modified and responded the feedback from the experts of the NMDOT and Tran-SET. The authors established a bridge reinforcing bar construction quality scale and implemented this scale to the rebar construction quality.

According to the ACI 117 specifications for bridge construction tolerances, the acceptable error for reinforcing bar placement is 0.5 inches. The researchers set the quality evaluation scale as equation 1.

$$Scale = 100 - error * 100 \qquad \text{(Eq.1)}$$

$$Scale > 50\ (good)$$

If the error is smaller than 0.5 inches, the scale will be larger than 50. The higher the score is, the better the construction quality is.

According to the mean error in table 6, we can get the scale for X axis is 51, the scale for Y axis is 54. The reinforcing bar construction quality in the floor plan is good.

$$Scale = 100 - error * 100 = 100 - 0.49 * 100 = 51$$

$$Scale = 100 - error * 100 = 100 - 0.46 * 100 = 54$$

In addition, the reading of the elevation placement location of each reinforcing bar and the mean value of elevation error compared with the design value is 0.37 inches. The scale calculated by Eq. 1 is 63, which means the vertical placement quality of the reinforcing bar is good.

By applying the same automatic reinforcing bar identification algorithm, the bottom layer of the scanned wingwall cage quality is good. The quality scale for horizontal reinforcing bar location is 60, the scale for vertical reinforcing bar location is 72.

The conclusion for the advanced algorithm is that with the increasing use of LIDAR scanning technology, rapid and automated bridge construction quality assessment technologies are quickly becoming a reality: benefiting from its operation speed and high data resolution, point cloud data from 3D scanner can be automated for structural components detection. In this paper, a case study has been presented to demonstrate the capabilities of 3D LIDAR scan to quantify the spacing between reinforcing bars. The most significant advantages of using 3D LIDAR scan are: (1) no interference to construction operation and (2) permanent record of the existing conditions.

5.7. Bridge Reinforcing Bar Construction Inspection in Route 66

This section summarizes the bridge inspection conducted in Route 66 to explore the implementation of the new technology in real scenarios. Given limitations by COVID, the team had to wait for approval from UNM to access this bridge with the same technology tested in CoreSLAB, which was possible in November 2020. NMDOT and UNM discussed since August 2020 that even COVID was a challenge, it would be beneficial to add a bridge scanning when possible in this project. UNM made this a priority. On October, NMDOT called the PI informing them of a bridge being available for scanning and UNM arranged the approvals with the School of Engineering, as well that started studying bridge drawings and specifications to test the LiDAR in the field. NMDOT and UNM also discussed the barriers for implementation before, during and after the scanning to complete the tasks of this research in the context of new rebar inspection specifications. From NMDOT's perspective, the LiDAR scanning and the results in the bridge indicate that in the future this technology can be included with some changes in the current contract documents and that are discussed at the end of this chapter.

The bridge was in the historic Route 66, in the East-West direction, in the South side of the existing road and 20 miles East of Tutumcari. The PI coordinated with NMDOT bridge and construction crews to ensure safety precautions were always prioritized. Snow storms delayed the inspection to November 2nd 2020 (Monday.) The drawings informed the scanning preparation. The images of the bridge and the scanning results are shown in the next page.

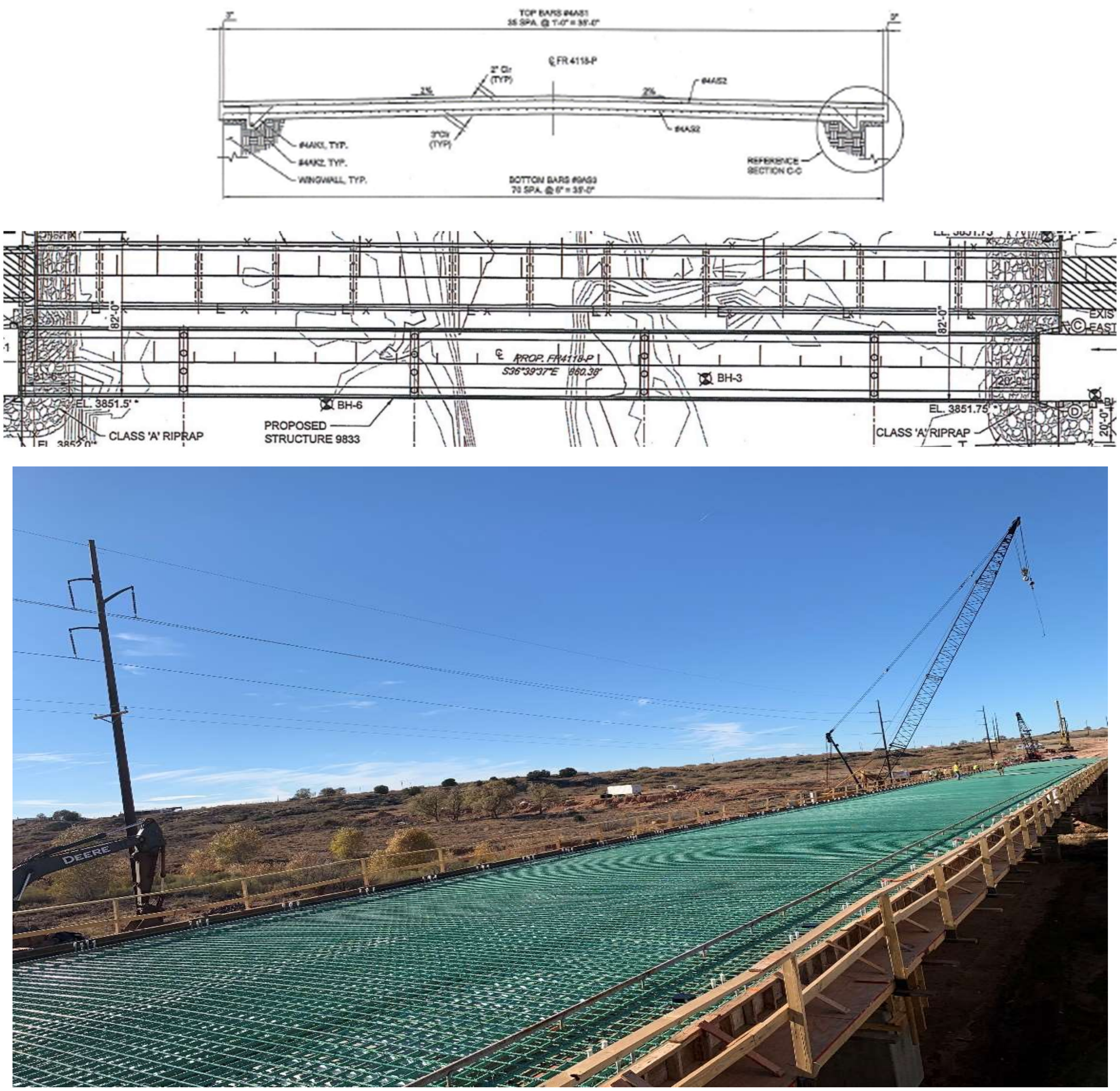
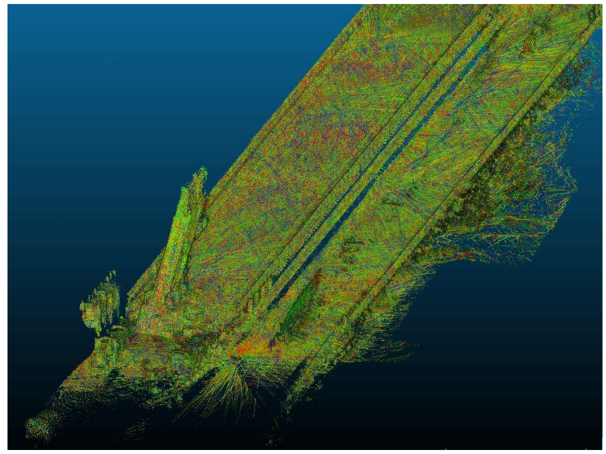
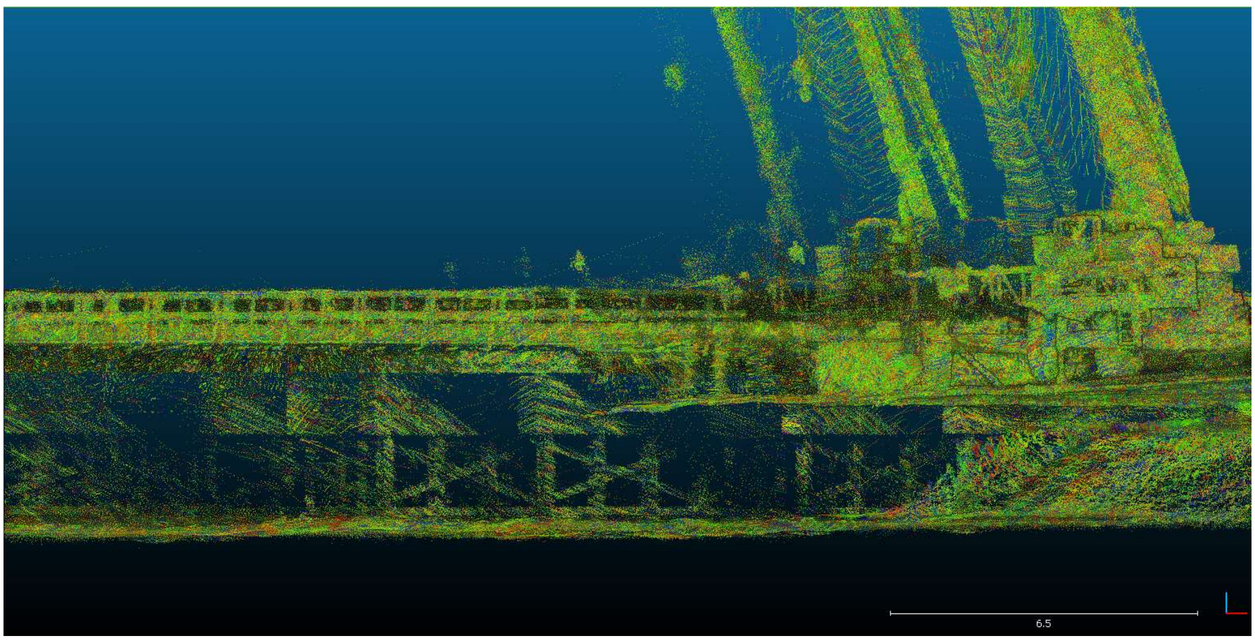


Figure 19. Tutumcari bridge: (top) drawings; (bottom) field construction.



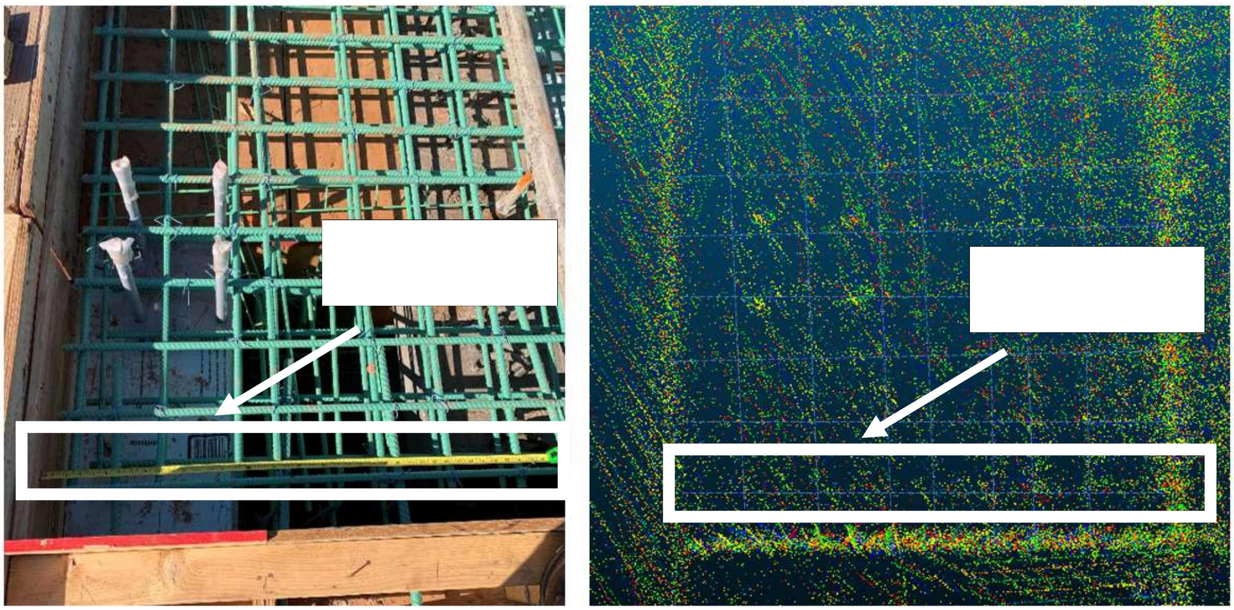
(a) (b)



(c)

Figure 20. Photo and Point Cloud models of Bridge Construction site in Route 66: (a) Photo of bridge construction site; (b) Point cloud model of Bridge Construction site; (c) Detail elevation of rebar view.

Figure 21 shows the reinforcement data processing of the bridge. The PIs used the tape measurement collected rebar spacing at the corner of the bridge, which is shown in Figure 21 (a). The LIDAR data of the spacing is shown in Figure 21 (b). Figure 21 summarizes the comparison example of the first rebar in the transverse direction of the top mat in the South East corner of the concrete deck using the proposed methodology. The LiDAR data also finds other formwork elements such as the four anchors near the edge and the railing used for the concrete pour machine. What is more important is the accuracy of the LiDAR data obtained using this innovative, practical, and implementable approach. The results of comparing the rebar in the field with the rebar in the LiDAR exceeded expectations, even with the bridge from NMDOT in the field. Table 7 summarizes the comparison with both sets of data. The average error with a preliminary estimation of the LiDAR comparison is below 0.50 inches, but based on the precast plant experiment this accuracy can be improved with slower scanning. This will be also discussed in the next section.



(a) (b)

Figure 21. Rebar spacing of bridge: (a) photo of tape measurer; (b) LiDAR data spacing

Table 7. Comparison of Rebar spacing of bridge using tape measurement and LIDAR data.

Spacing (left - right)	Tape (inches)	LIDAR (inches)	Error (inches)
	6.14	5.85	0.29
	6.00	5.50	0.50
	2.51	2.36	0.15
	8.51	8.20	0.31
	7.95	7.04	0.91
Average error			0.43

5.8. Updated Specifications based on Bridge Inspection

This section summarizes the proposed specifications based on discussions with NMDOT on the use of field data to inform decisions on rebar location prior to concrete pour. The research team discussed both with NMDOT and the consulting experts on rebar inspection the importance of conducting a scanning prior to the concrete pour to produce a permanent record of the rebar for future inspections or activities in the field. The update of specifications on DOTs using this LiDAR inspection automatically obtained in the field should include the following points, according to the feedback from NMDOT in this project in January and February of 2021:

- The LiDAR equipment is already accepted as a tool in NMDOT and it is expected to increase its relevance in the years to come.

- The results of this research support further use and investigation of using LiDAR as a tool for permanent record of the bridge construction.
- The analysis of the data from the scanning takes excessive time and it would be of interest to the specifications to specifically indicate the time restrain on scanning and informing the contractor on
    - the spacing
    - the accuracy
    - the score
    - the required action (pass, not pass, rectify, pour concrete, stop)
- The time of the analysis in the field is of top priority for further inclusion of LiDAR in the standard specifications. The officer from NMDOT indicated that their concern is that they have to wait one day to receive the scores.
- The solution of cloud computing was discussed as an option, but there are concerns on infrastructure enabling to do this in remote bridges for practical specifications.

The PhD student therefore has submitted the results reported herein to one journal paper which is currently under review, and preparing two new journal papers. The 2nd journal paper emphasizes the accuracy of the method from a data science perspective in the bridge data. The 3rd journal paper emphasizes the quantification of quality and its implementation in DOTs specifications, using the results of this project.

6. CONCLUSIONS AND FUTURE RESEARCH

The overall objectives of this project were to investigate the application of LIDAR technology to help automatically is going to measure the 3D reinforcement layout during bridge construction. The overall object was decomposed into four research objectives. The first research objective included testing if LIDAR can collect reinforcing data in the field. The second research objective included quantifying the ability of LiDAR to inform QCQA during construction inspections. The third research objective included identifying challenges of using LiDAR for QCQA in NMDOT (technical and implementation). The fourth objective included proposing specifications that would inform how to use LiDAR for construction inspection of reinforced concrete construction. The solution approach to address these four research objectives was divided into two project stages. The first two research objectives corresponded to literature review and algorithm developing. A literature review effort was conducted to gain insights from research studies that LIDAR technology for collecting bridge construction data in the field and informing the inspectors in real time. The third and fourth research objectives corresponded to the case study and quality evaluation standard. A field test study was conducted to address the research question regarding to the applicability of 3D models developed from LIDAR data to help identify the reinforcing bar of bridge wingwall during the construction.

The results of this research are summarized in the following sections, those related to the technical development of new LIDAR technology that are related to the transportation industry, and other outcomes because of education and training. Therefore, the technical findings achieved with this research can be summarized in the following categories:

- Collaboration with owners of infrastructure: workshop, industry feedback, and opportunities for LIDAR technology development based on practical implementation in industry.
- Development and validation of LIDAR technology applications in comparison with current inspection tools and procedures.
- Teaching and training in College level of LIDAR technology and feedback and interest from students to learn about LIDAR technology for transportation infrastructure.

6.1. NMDOT and LIDAR Technology

The result of the various LIDAR technology in bridge inspection progress in the year has contributed to a demonstration of LIDAR technology to NMDOT on its potential to assist bridge inspectors, which was conducted in NMDOT 2020 Paving and Transportation Conference January 9th 2020. Dozens of bridge inspectors attended a practical presentation about the use of LIDAR technology for bridge inspections. The main component of this activity was the dialog from the NMDOT's perspective of what would be useful as a practical application of LIDAR technology for their day-to-day activities. Figure 19 shows the first slide of the presentation summarizing the results of LIDAR technology to more than 300 transportation technicians and engineers in Albuquerque, NM, in January 9th, 2020. The feedback from this presentation was very positive in terms of the interest from NMDOT and engineering firms in advancing this technology towards automatic bridge construction monitoring.

Figure 22. NMDOT Demonstration on LIDAR technology (January 9st, 2020).

6.2. Industry Impact of LIDAR Project

The result of the various LIDAR technology in bridge inspection progress has collaborated with leaders in CoreSLAB Structures (CONN) Inc. Since 1975, CoreSLAB Structures is a premier producer of precast/prestressed concrete products. Over the last four decades, they have emerged as a major supplier of structural, architectural and hollow core solutions to markets in Canada and the United States. Researchers talked to the manager of CoreSLAB Structures, they showed great interest in the LIDAR application in bridge construction inspection quality control and quality assurance. Researchers conducted testing using GeoSLAM Ltd Mobile LIDAR scanner of a bridge wingwall reinforcing bar cage in the construction field of CoreSLAB in March 22nd, 2020. The scanning result was used to develop new software that can help construction inspectors of the future using LIDAR equipment during construction. Figure 20 shows the group picture of collaboration with Industry (March 22nd, 2020). From the left to right is the research group member PhD student Xinxing Yuan, the undergraduate student Odey, the manager of CoreSLAB Matt Manning, and high school student Shuang.

Figure 23. Collaboration with Industry (March 22nd, 2020).

6.3. Inaugural SMILab Workshop (SMIWeb) supported by Tran-SET

The first-ever SMIWeb workshop, July 9th, 2020, was directed at researchers, students, and professionals from industry interested in learning about new technologies with practical implementation in smart structures technologies. Senior researchers presented their unique projects and contributions to the engineering field. The emphasis was to increase awareness about future directions in smart structures that can be of interest in the next decade. LIDAR for bridge inspections was presented by Ph.D. student Xinxing Yuan. The 1st SMIWeb workshop supported by TRANSET attracted more than 100 researchers and professional engineers worldwide. Figure 21 shows the webinar pictures. The left is the screenshot of 108 attendance zoom profile, the right picture is Xinxing Yuan's presentation of "Bridge Construction Monitoring using LIDAR for Quality-Control, Quality Assurance (QCQA)".

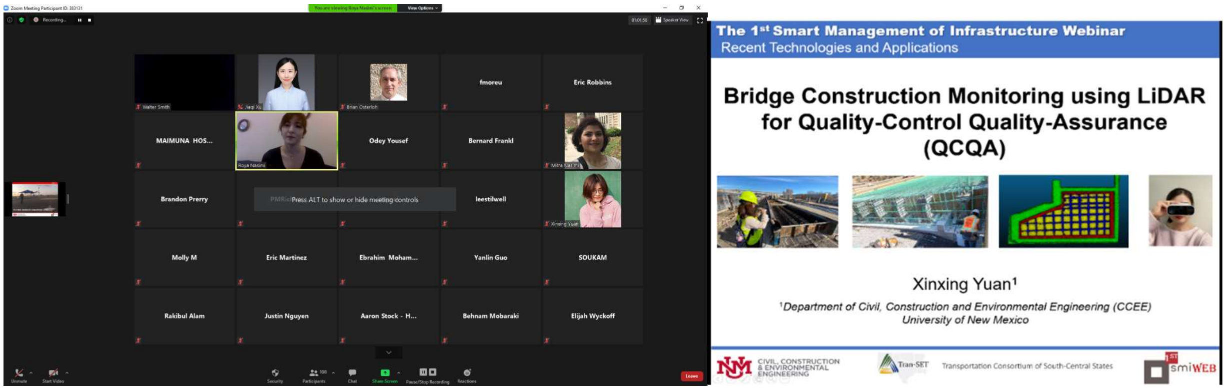


Figure 24. Shared Research on LIDAR Technology in SMIWeb (July 9th, 2020).

6.4. Communicating and Training LIDAR Technology

The LIDAR team is adapting LIDAR's ability to measure and quantify changes in structures in real time to attract other sources of support to research. The research on LIDAR was communicated in Women's Issue in Transportation in California, Irvine. See Figure 22. Figure 22 shows the picture of researcher communicated with other women researchers of LIDAR project. In this Figure, the PhD student is standing with the chairman Therese McMillan and other committee members during the conference. As seen in this image, the participation of the PhD student benefitted from interactions with nationwide leaders in transportation that can become critical for post-PhD career opportunities. Additionally, the PhD researcher shared the LIDAR technology with several universities included two senior PhD students from Carnegie Mellon University and University of Michigan, respectively, PhD student from Virginia Polytechnic Institute and State University, and PhD student from University of Nebraska-Lincoln. Figure 23 shows the image of the researcher shared with the LIDAR research with other PhD seniors. Figure 24 shows the presentation of the LIDAR technology to around 200 Menaul school students. In both figures it is evident that the PhD student is highly involved in the bridge monitoring community by sharing her research with other PhD students and hosting them during their visit to UNM and SMILab, which will be beneficial for her career during and after PhD studies. Similarly, the PhD student is committed to serve the local community in Albuquerque and specifically, she drove to their school to encourage them to pursue a career in engineering. It is critical to the mission of the University to have an impact in the youth and inspire minorities and female students to believe in themselves to pursue a career in transportation. This was one on the objectives of this project and the figures show these events.

Figure 25. Communicated with other women researchers of LIDAR project.

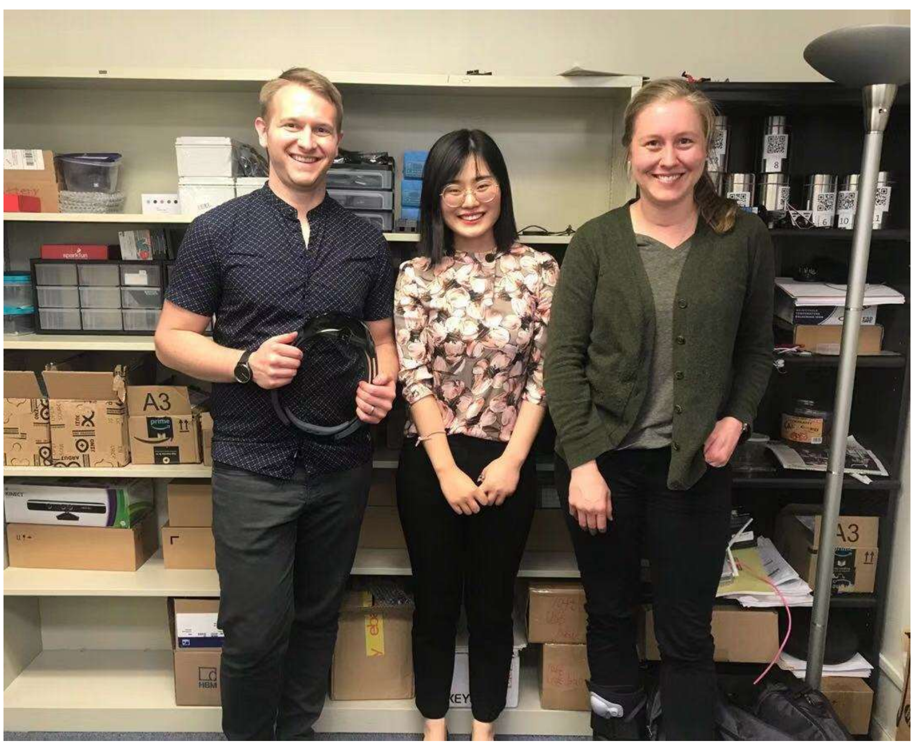


Figure 26. Communicated the LIDAR research with other Ph.D. seniors.

Figure 27. Presented the LIDAR technology to Menaul school students.

6.5. Patent Innovation

A patent has been approved on the LIDAR technology titled "The Automatic Quality-Control Quality-Assurance Inspector (AQQI)" based on this project. UNM Rainforest Innovations has filed intellectual property on this exciting new technology. Market application of LIDAR technology would be

- US Department of Transportation (USDOT)
- Construction Project Inspection
    - Reinforcing bar Inspection
    - Construction Progress
    - Quality Control/Quality Assurance
    - Automatic determination of strength quality during construction using real-time structural capacity using exact reinforcing bar layout in the field during construction
- Other automatic applications for LiDAR include:
    - Assess the condition of assets in construction
    - As-built mapping and documentation
    - Situational awareness for vehicle navigation
    - Inundation/flood modeling
    - Landslide monitoring/modeling
    - Erosion monitoring/modeling
    - Automatic accident scene documentation

6.6. Future Research

Researchers are going to use a ZEB Horizon with quick release UAV mount to collect the bridge data in the field construction site. The UAV with LIDAR scanner can collect 3000,000 data points per second from the bridge, without need for GPS. The direct involvement of the bridge group from NMDOT will guarantee the practical quantification of QAQC of bridges in DOTs using new technologies Field Implementation. Figure 25 shows the UAV SLAM LIDAR scanner collect the data in the field bridge construction site. For the real bridge construction site, the dimensions of the rebar cage are hundred feet, there are dozens of constructions works work together in one site. The UAV SLAM can collect the big rebar cage in a short time by flying around the rebar cage.

Figure 28. UAV SLAM LIDAR Scanner Data Collection.

Researchers tried to use low-cost sensors to inspect the reinforcing bar cage in the laboratory. Azure Kinect D.K. is a developer kit with advanced Artificial Intelligence (AI) sensors for sophisticated computer vision and speech models. Designed for versatility, it combines an advanced depth sensor and spatial microphone array with a video camera and orientation sensor—with multiple modes, options, and SDKs. Azure Kinect sensor only cost hundreds of dollars. The scanning range needs to be improved for field testing. Figure 26 shows the low-cost sensor Azure Kinect. The left is the Azure Kinect sensor in the sensor box, the right picture shows the PhD student wearing the sensor. Figure 27 shows the laboratory validation by Azure Kinect sensor in CARC, UNM. The left picture of Figure 27 is the handmade bar cage, the right picture is the Azure Kinect sensor scanned point cloud model of this handmade bar cage. Figure 28 is the field test of Azure Kinect sensor in the CoreSLAB. The left picture of Figure 28 is the researcher hold the sensor at the corner of the bridge rebar cage to scan the rebar data, the right picture of Figure 28 is the detail of bridge rebar cage, Azure Kinect sensor and operation laptop.

Figure 29. Azure Kinect sensor.

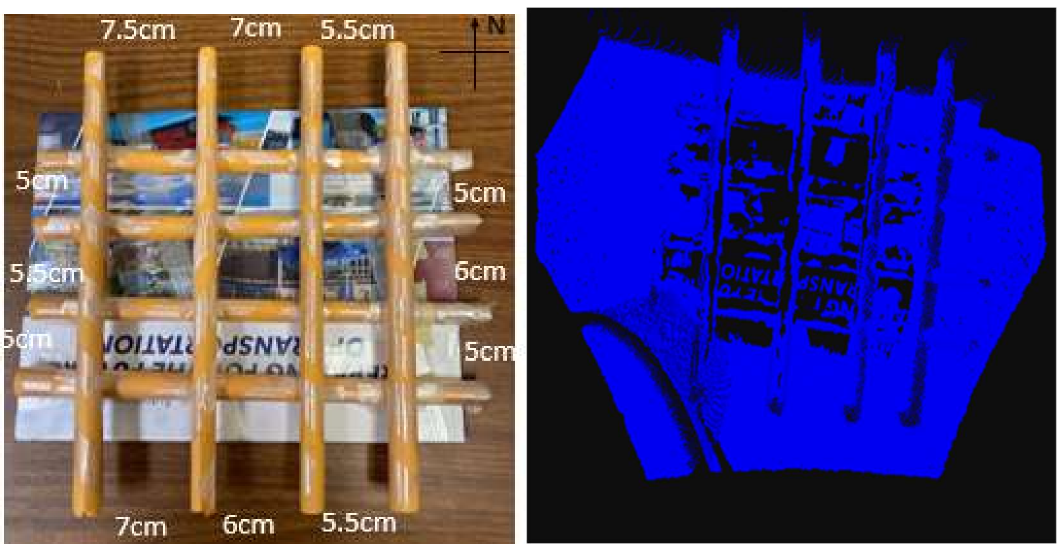


Figure 30. The laboratory validation by Azure Kinect sensor in CARC, UNM.

Figure 31. Field Testing using Azure Kinect scanner in CoreSLAB.

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