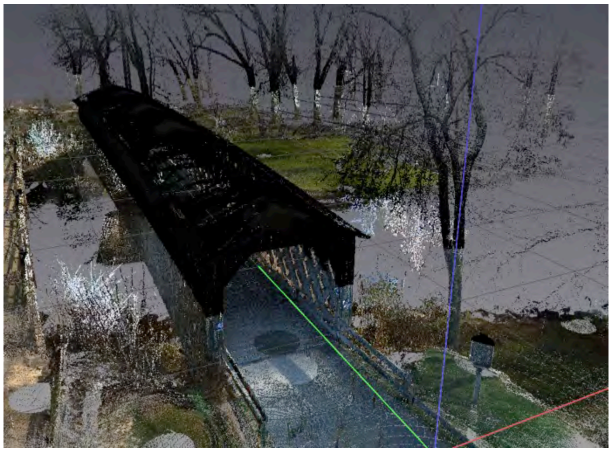
Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges

Final Report



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BACKGROUND

Covered bridges are part of the fabric of American history, and several hundred historic covered bridges still exist today. Although much effort is expended to preserve these structures, the high cost of restoration, neglect, vandalism, and arson often take their toll, and many are lost forever. One of the more famous bridges from "Bridges of Madison County" movie fame was burned in 2003 and Hurricane Irene destroyed a number of New England bridges in 2011. Because we cannot completely prevent these types of incidents from occurring, the National Park Service's Historic American Engineering Record (HAER) has efforts underway to document historic structures. Their Level I documentation is defined in the Secretary of the Interior's Standards and Guidelines for Architectural and Engineering Documentation and consists of measured and interpretive drawings, large-format photographs, and written historical reports. To assist in this effort, newer technologies need to be explored that can provide as-built records at a faster rate and with more accuracy.

The University of Minnesota Duluth's Natural Resources Research Institute (UMD NRRI), in cooperation with the US Forest Service received funding from the USDA Forest Products Laboratory for a cooperative research and demonstration project under the National Center for Wood Transportation Structures. Additional funding support was obtained from the City of Zumbrota, Minnesota, via funds they accessed from the Operational Research Program (OPERA) of the Minnesota Local Road Research Board.

OBJECTIVE

This project will examine the technical feasibility of using laser scanning technologies for obtaining as-built records for historic, covered timber bridges. A secondary objective was to identify other applications of this technology, notably for transportation considerations.

LITERATURE REVIEW SUMMARY

Three-dimensional (3D) laser scanners are instruments that record precise and accurate surface data of objects in a nondestructive manner. These instruments use an infrared beam of light to calculate and record the distance to an object, typically as data points with spatial coordinates. This data is then analyzed using various types of computer software to generate a final detailed image of coordinates and dimensions. 3D laser scanners have successfully been used to digitize objects of various sizes ranging from small diagnostic artifacts to large, complex sites of monumental architecture (Faro 2009).

There are a wide number of companies that manufacture various types of 3D laser scanners. Generally, these units use LiDAR (light detection and ranging) technology, where laser pulses determine the distance to an object or surface. The distance to an object is determined by using time-of-flight between transmission of a pulse and detection of the reflected signal. A point cloud of data is then collected and processed into the true shape of the object. The FARO scanner used in this project used a phase shift technology rather than time of flight. This means that instead of a single pulse being reflected and the time of flight measured, constant waves of varying length are projected. Upon contact with an object, they are reflected back to the scanner. The distance from the scanner to the object is accurately measured by measuring the phase shifts in the waves of infrared light (FARO 2011).

Several bridge projects were noted in the literature review. The Pennsylvania DOT completed an initial study in 1999. In this study, the goals were to evaluate the technology for creating as-built drawings. A comparison of traditional and 3D scanning estimated an overall time savings of 100+ man hours was achieved through the use of 3D scanning (Foltz 2000). Based on this assessment, the PennDOT purchased two laser scanners in 2000. A second assessment was completed by Jaselskis et al in 2003, showing that laser scanning could be used cost effectively for preliminary surveys to develop TIN meshes of roadway surfaces and to measure bridge beam camber in a safer and quicker fashion compared to conventional approaches. Other applications noted in this publication showed potential applications for laser scanning to include developing as-built drawings of historical structures such as the bridges of Madison County.

PROJECT ACTIVITIES

Task 1. Establish access to laser scanning equipment

It was originally projected that it would be possible to lease the necessary 3D laser scanning technology needed to complete this project for the budgeted amount of $2,500. However, the 2010 technology package from leading manufacturers (FARO, Inc.) would cost over $100,000 to purchase and over $5,000/month for a lease package. However, after continued discussions with one equipment manufacturer (FARO, Inc.) our project team was introduced to a 3D Laser scanning company from Milwaukee, Wisconsin that would conduct the laser scanning of 6 bridges and help us with some data processing. This company, SightLine, LLC (Milwaukee, WI) was retained using a contract for professional services and conducted the laser scanning for the project's six bridges.

Task 2. Identify six historic covered timber bridges for evaluation

The bridges for scanning and assessment during this project were located in Wisconsin, Iowa and Minnesota and are shown in Table 1. Contact was made with the appropriate government or administrative staff for each bridge and permission secured. It should be noted that four of the bridges to be scanned would include the historic Madison County, Iowa bridges.

Table 1.--Covered bridges that were identified for inspection based on their geographic location, size, ease of access and suitability.

<table>
<tr><th>State</th><th>City</th><th>Bridge</th><th>Built (yr)</th><th>Span (ft)</th><th>National Register of Historic Places</th><th>Design</th></tr>
<tr><td>Wisconsin</td><td>Cedarburg</td><td>Red</td><td>1876</td><td>120</td><td>March 14, 1973</td><td rowspan="6">Lattice through truss</td></tr>
<tr><td>Iowa</td><td>Winterset</td><td>Roseman</td><td>1883</td><td>106</td><td>September 1, 1976</td></tr>
<tr><td>Iowa</td><td>St. Charles</td><td>Imes</td><td>1870</td><td>81</td><td>February 9, 1979</td></tr>
<tr><td>Iowa</td><td>Winterset</td><td>Hogback</td><td>1884</td><td>106</td><td>August 28, 1976</td></tr>
<tr><td>Iowa</td><td>Madison County</td><td>Cutler-Donahoe</td><td>1871</td><td>79</td><td>October 8, 1976</td></tr>
<tr><td>Minnesota</td><td>Zumbrota</td><td>Zumbrota</td><td>1869</td><td>120</td><td>February 20, 1975</td></tr>
</table>

Cedarburg, Wisconsin Covered Bridge Overview

The last remaining historic covered bridge in Wisconsin, the “Red Bridge” was built in 1876. Located just outside the city of Cedarburg, Wisconsin in Ozaukee County, the bridge is directly adjacent to the new roadway. According to Ozaukee County (2011), “Built in 1876, the original span measured 120' long and 12' wide. Its construction was of a certain type of pine found near Baraboo, Wisconsin. All of the timber and planks were cut and squared in a mill near that city. The lumber was then hauled to the proposed site on Cedar Creek where all pieces were fitted and set in place. The type of construction is known as lattice truss with interlacing 3 x 10 inch planks all held together by 2 inch hardwood pins and floored with three inch planking. In 1927, a center abutment was placed to carry the heavier traffic of automobiles and trucks.”

Figure 1.--Image of the Cedarburg Covered Bridge (Cedarburg, WI) in 1934.


Figure 2.--Photo of the Cedarburg Covered Bridge in 2010.

Madison County, Iowa Covered Bridge Overview

The Bridges of Madison County (Iowa) are world famous, as they are excellent examples of the construction of covered bridges in the 1870-1880's. As noted on the Madison County, Iowa web site (2011), "Our historic, world-famous covered bridges were popularized by Robert James Waller's novel, *The Bridges of Madison County,* and the feature film starring Meryl Streep and Clint Eastwood. Five of the original covered bridges remain, all listed on the National Register of Historic Places. The bridges were covered by order of the County Board of Supervisors to help preserve the large flooring timbers that were more expensive to replace than the lumber covering the sides and the roof. Most of the construction was done by farmers to pay their poll taxes. The bridges were usually named for the nearest resident."

Four bridges were selected for laser scanning in Madison County and they included the Roseman, Imes, Hogback and Cutler-Donahoe Bridges. Photographs of these bridges follow in Figures 3-6.

Figure 3. -- Roseman Bridge, Madison County, Iowa (2010).

Figure 4.--Imes Bridge, Madison County, Iowa (2010).

Figure 5.--Hogback Bridge, Madison County, Iowa (2010).

Figure 6.--Cutler-Donahoe Bridge, Madison County, Iowa (2010).

Zumbrota Bridge Overview

Minnesota's only remaining truly historic covered bridge is located in the City of Zumbrota. Listed on the National Historic Register it was originally constructed in 1869 and relocated in 1932, 1979 and finally in 1997. It currently spans the Zumbro River in the 65-acre Covered Bridge Park. Considered a lattice through truss design, it is now a pedestrian only bridge that spans 120 ft. A special documentary of the bridge and its important to the history of Zumbrota can be found at http://www.youtube.com/watch?v=EVFd1YwcHww&feature=related. As a measure of its importance to Zumbrota, an annual covered bridge festival occurs every June. An image of the bridge is shown in Figure 7.

On September 23-25, 2010, the Zumbro River flooded, creating a dangerous situation for the Zumbrota Covered Bridge. As Figures 8 and 9 show, floodwaters rose to nearly the same elevation as the bottom of the bridge. Additional river cresting could have caused substantial damage to the bridge, requiring the need for having as-built documentation, created during the scanning that took place in late July 2010. This is one very important example of the value of this project, creating new historical records should they be needed to repair or reconstruct a piece of Minnesota’s history.

Figure 7.--Zumbrota Bridge, Zumbrota, Minnesota (2011).

Figure 8.--Zumbrota Bridge on September 23, 2010 during flooding on the Zumbro River (Photo courtesy of kstp.com).

Figure 9.--Zumbrota Bridge on September 23, 2010 during flooding on the Zumbro River (Photo courtesy of fox9.com).

Task 3. Conduct field tests with 3D laser scanning equipment on identified bridges and complete post-processing of the scan data.

The laser scanning was completed by UMD NRRI cooperator and contractor, Sightline, LLC (Milwaukee, WI). Approximately 20-30 scans were completed for each bridge from a variety of angles using a FARO LS880 Laser Scanner. Figure 10 shows a FARO laser scanner being used to inspect a historic covered bridge.

The scanning process consisted of scans that were completed by Sightline and the processing of the data by UMD NRRI. The following steps were completed and an estimate of the time duration provided for each step:

1. Paper "targets" are placed in numerous locations on the bridge for use in linking up to 30 individual laser scans together. *Time duration: 2 person-hours.*

2. A 3D laser scanner (FARO Laser Scanner LS880) was used to conduct the scan. The scanner is placed at several vantage points inside and outside the bridge, such that all visible surfaces of the bridge can be documented. Individual scans are completed in approximately 15-20 minutes. When a single scan is completed, it is saved to a computer as an .ls file. It is highly recommended that a computer with significant computing power and high levels of RAM memory be used to process the millions of data points created during the scanning process. *Time duration: 10 person-hours.*

3. After all visible portions of the bridge have been scanned, the software files are linked using

FARO Scene software. This software allows an individual to identify the targets placed prior to the scanning process and use them to link or attach one scan to another. The process of linking two individual scans is repeated several times until all scans have been compiled into one large scan depicting the entire bridge. *Time duration: 9 person-hours.*

4. Once a bridge has been completely assembled using all of the individual scans, it can be exported as a point cloud, depicting all visible aspects and actual dimensions of the bridge. This cloud of data was then exported into AutoCAD using an add-in provided by Kubit USA. This add-in allows a user to import point cloud files in addition to the ones inherently recognized by AutoCAD 2011 and has additional modeling tools for working directly with point cloud data in AutoCAD. Once a point cloud has been exported into AutoCAD, it can be divided into multiple cross-sections. This is done so that specific components of the bridge can be seen more clearly. From this point, two and three-dimensional (2D and 3D) models of the bridge can be generated. *Time duration: 40+person-hours.*

Laser Scanning Results

There are a number of types of images that can be presented from the processing of the point cloud data. These images include a point cloud image resulting from only one scan, a point cloud image created from multiple scans, a parametric picture created from a point cloud scan, a point cloud image imbedded in AutoCAD, and 2D/3D AutoCAD images. These images can be created using Faro Scene software or AutoCAD 2011 with a Kubit USA add-in.

Figure 8.--A Faro laser scanner used to scan a historic covered bridge.

As to the project activities, the majority of the scan processing for the Cedarburg, Wisconsin bridge was completed by Sightline LLC. The processing of the scan data for the Madison County, Iowa bridges and the Zumbrota, Minnesota bridge was completed by the UMD NRRI. The project team decided that based on the processing time estimates detailed in point cloud and

3D AutoCAD data would provided for the Cedarburg, Imes and Zumbrota Bridges, with only point cloud data for the Hogback, Cutler-Donahoe and Roseman Bridges. All of the digital point could be further processed to develop detailed dimensional information, as the point cloud images are considered accurate data. The point cloud images could also be further processed using kubit USA add-ins for AutoCAD 2011. Each bridge scan and AutoCAD images are shown in the following sections.

Cedarburg, Wisconsin Covered Bridge

Figures 11-18 show various images created from 3D laser scanning conducted during the project for the Cedarburg, Wisconsin bridge. A poster presentation was prepared based on this bridge and presented at the Grand Opening of the USDA Forest Products Laboratory Centennial Research Laboratory. A copy of this poster is located in Appendix A of this report.

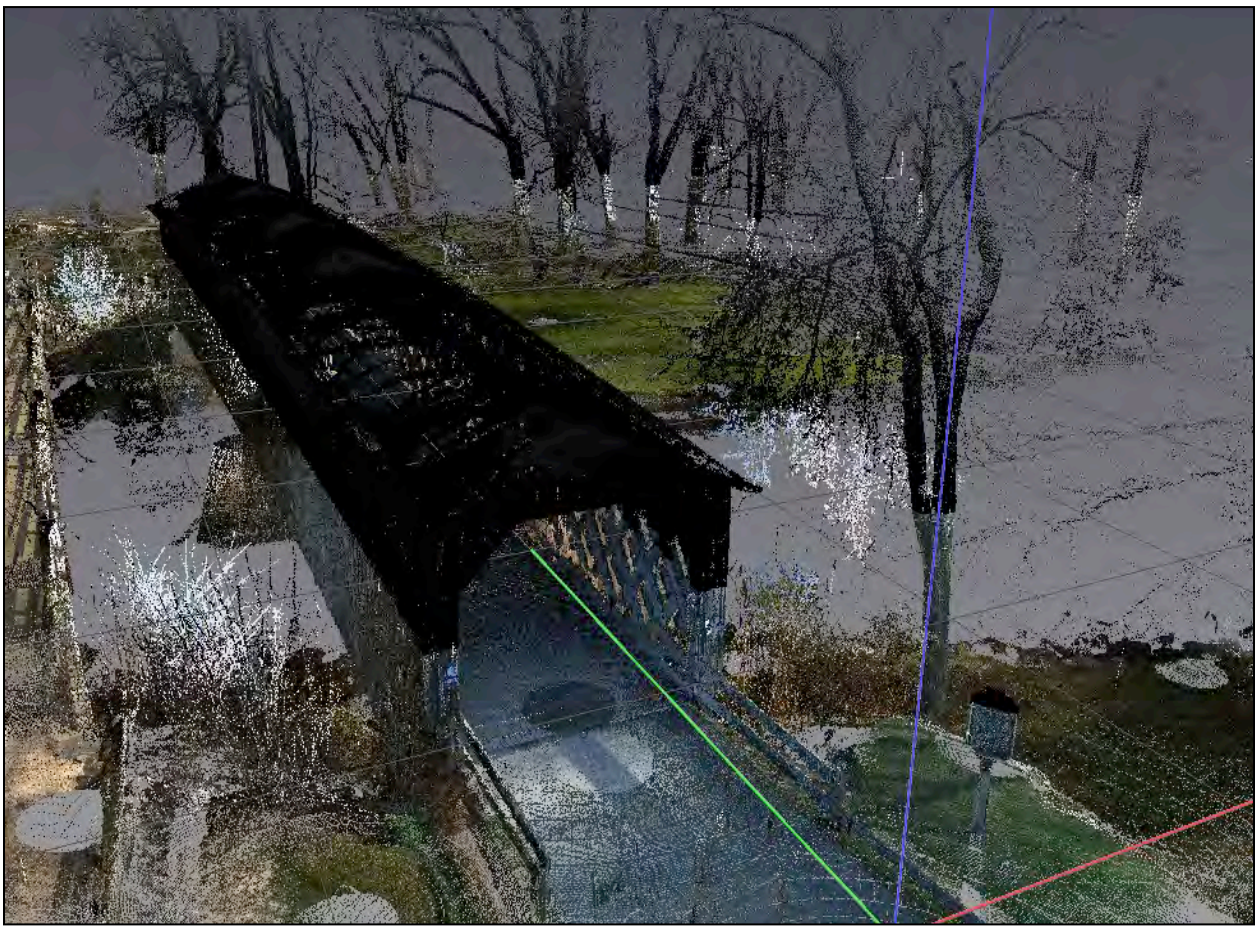

Figure 11.--Point cloud image of the Cedarburg Bridge (SightLine LLC).

Figure 12.--3D AutoCAD image of the Cedarburg Bridge embedded in point cloud data (SightLine, LLC).

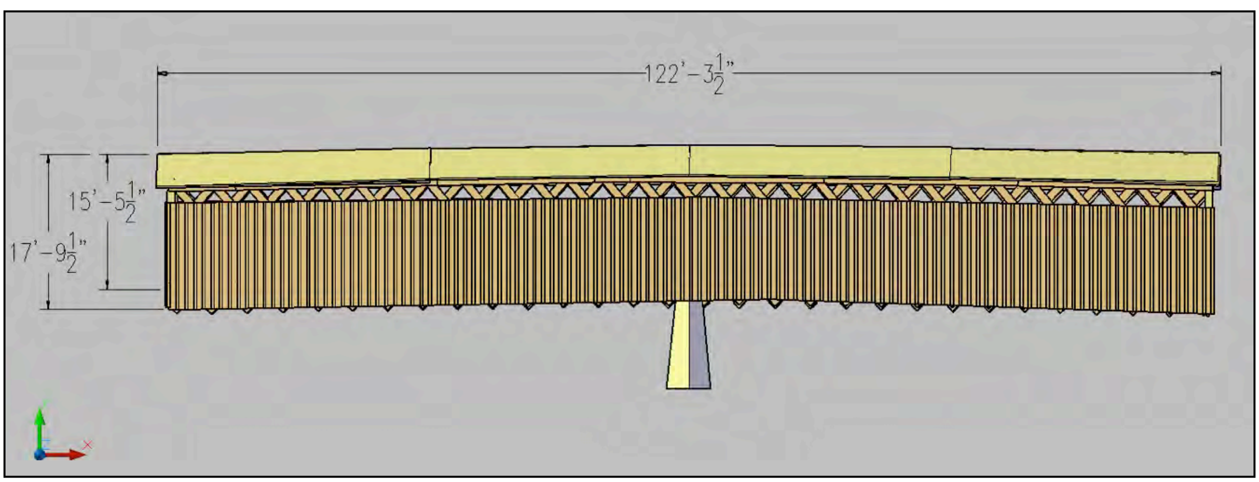

Figure 13.--Dimensioned 2D AutoCAD image of the Cedarburg Bridge (SightLine, LLC).

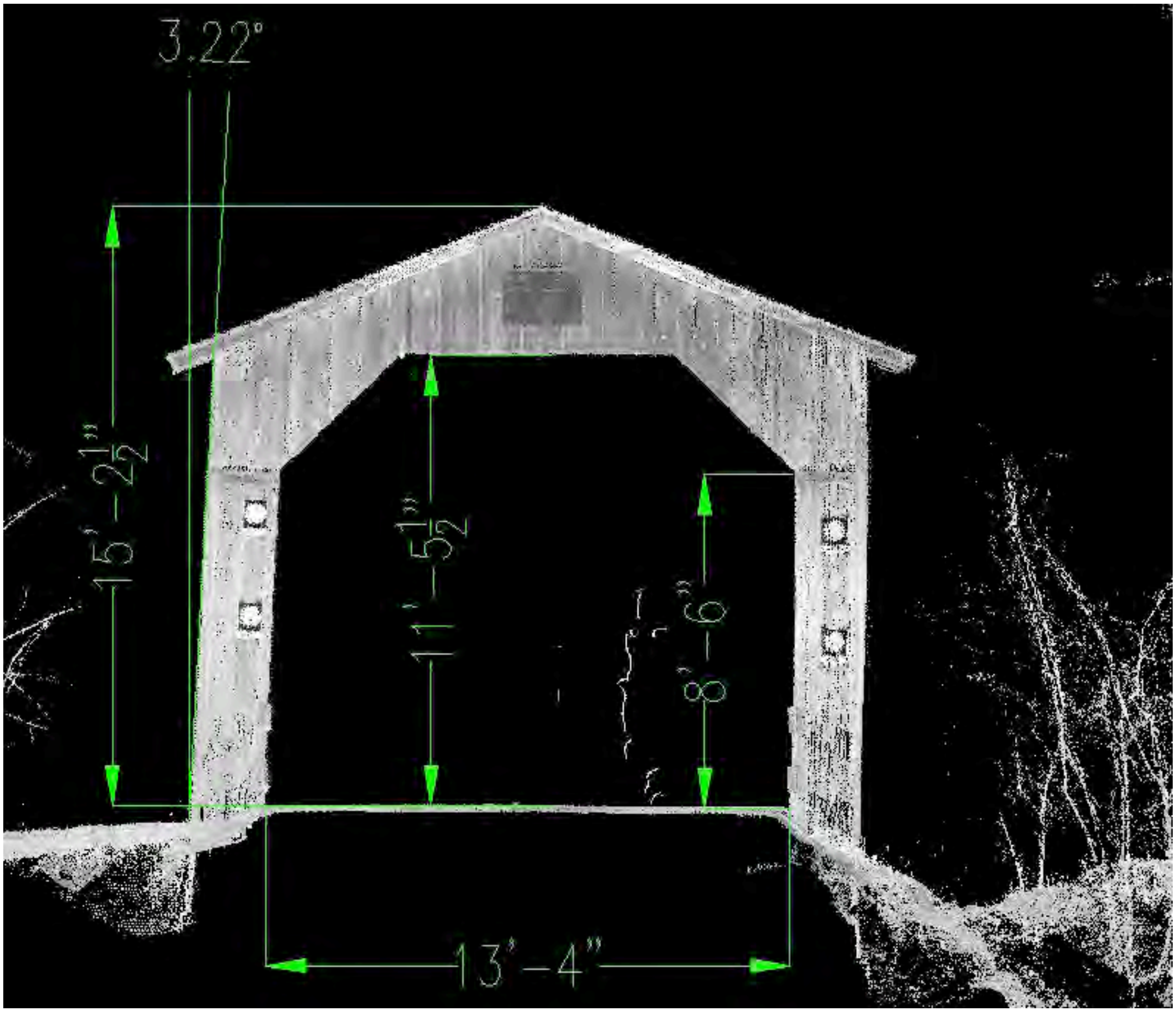

Figure 14.--Dimensioned point cloud image of bridge entry on Cedarburg Bridge (SightLine, LLC).

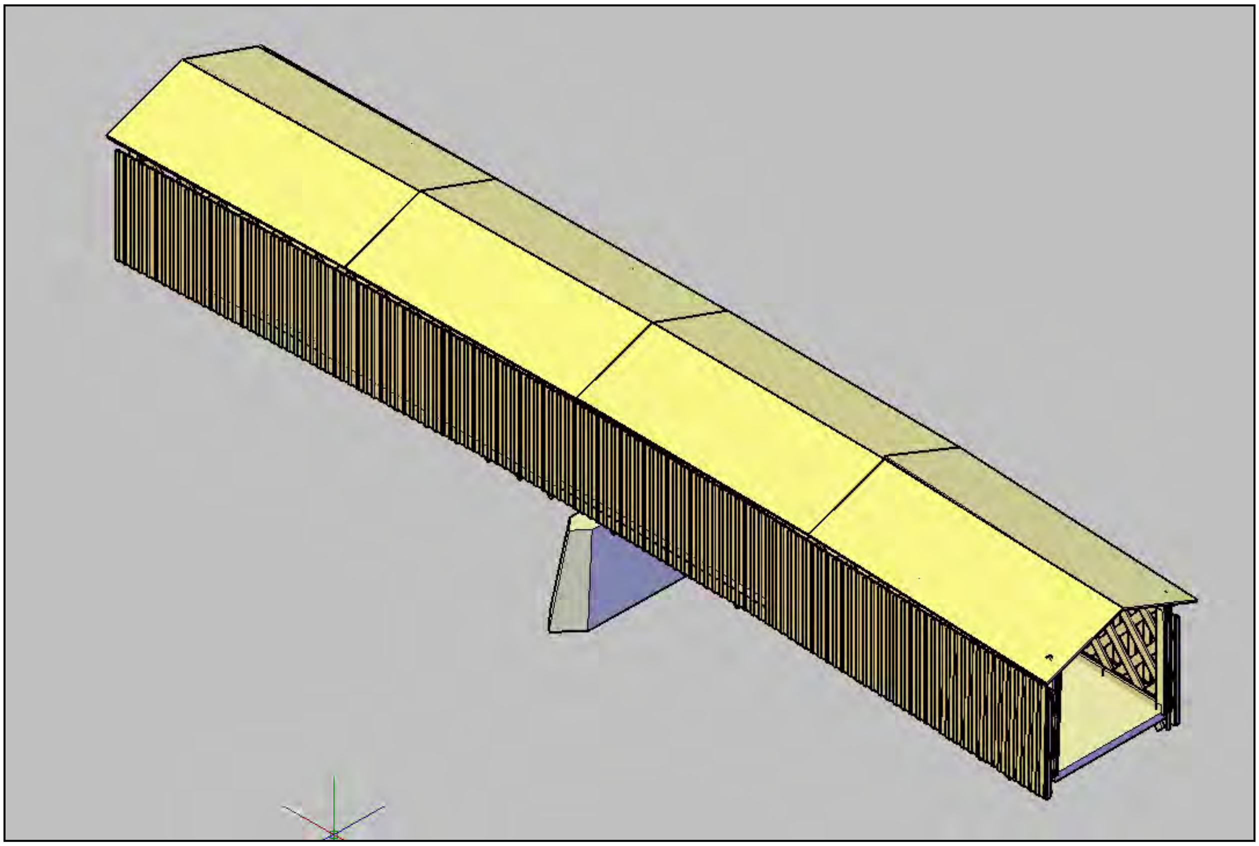

Figure 15.--CAD image of the Cedarburg Bridge (SightLine, LLC).

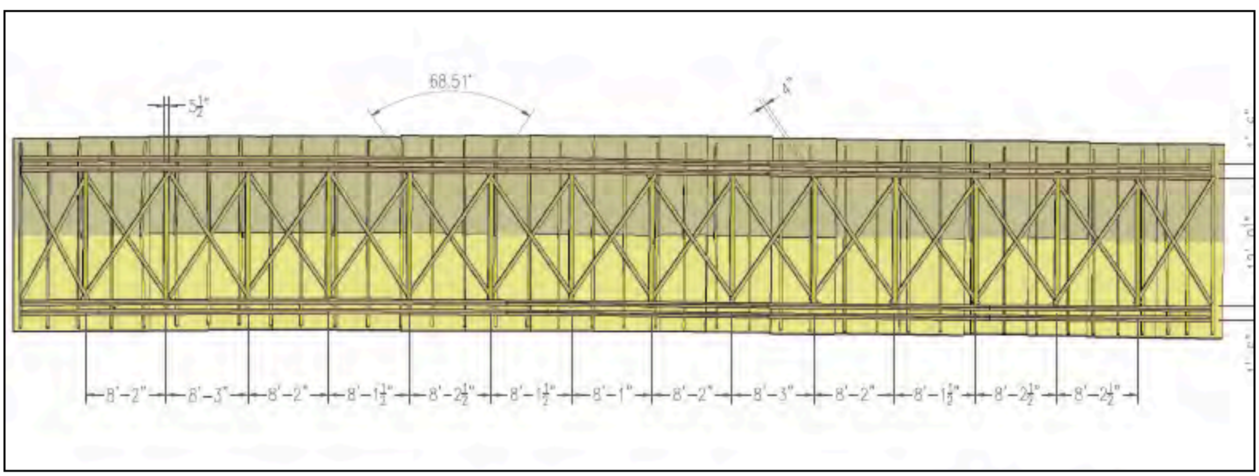

Figure 16.--CAD dimensions of ceiling structure of the Cedarburg Bridge (NRRI).

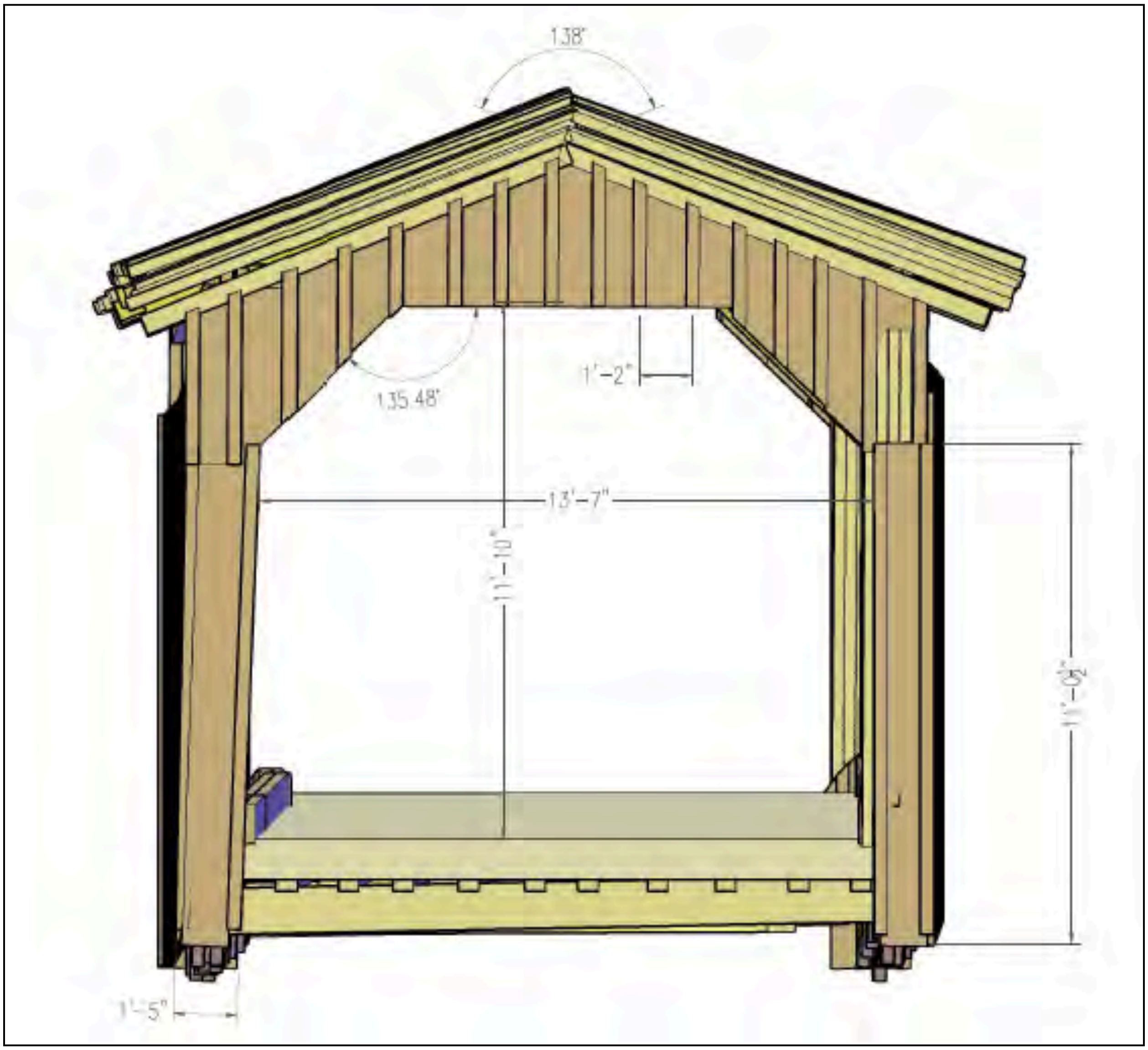

Figure 17.--CAD drawing and dimensions of front entrance of the Cedarburg Bridge (NRRI).

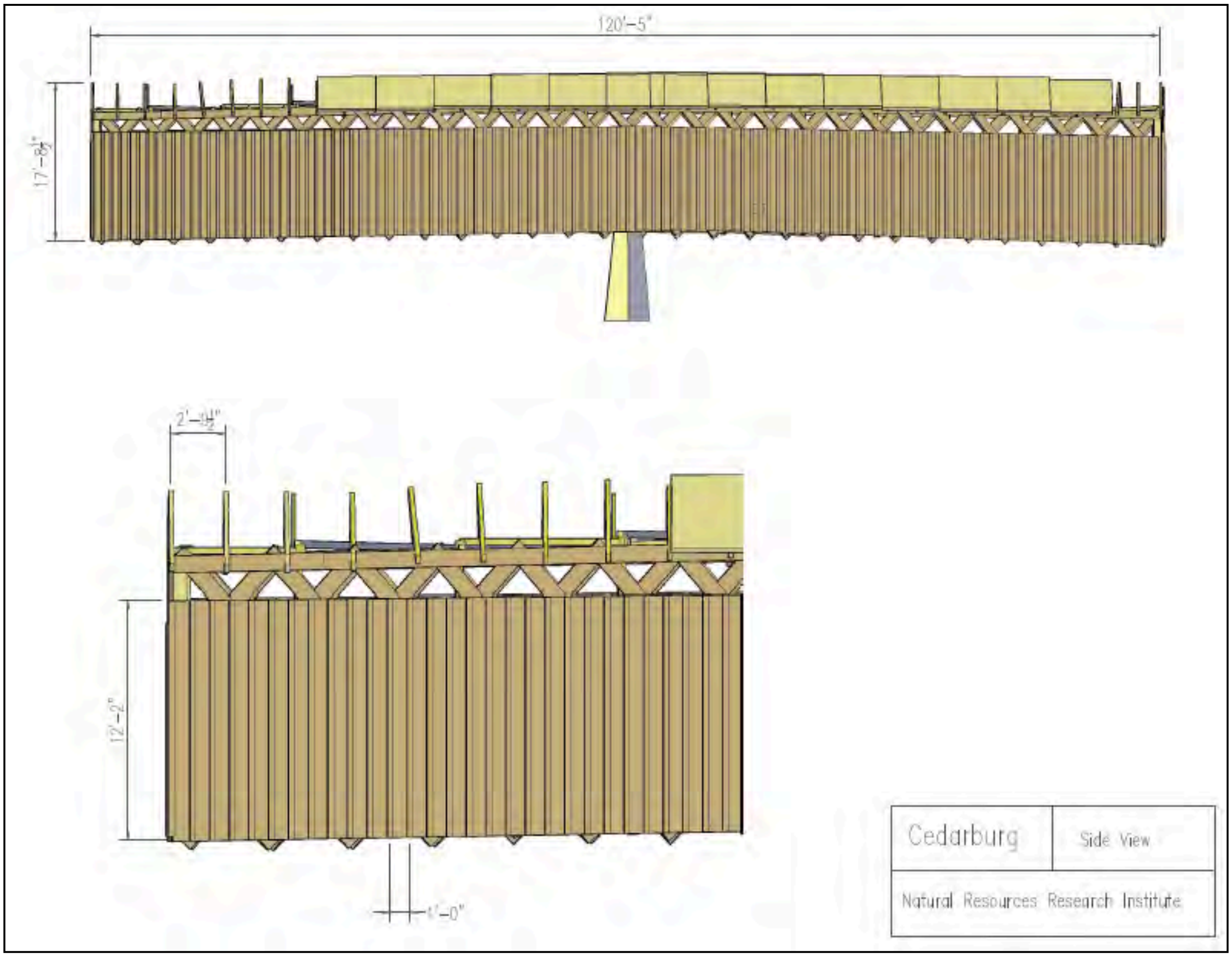

Figure 18.--CAD drawing and dimensions side wall and trusses of the Cedarburg Bridge (NRRI).

Imes Bridge, Madison County, Iowa

Figures 19-26 show various images created from 3D laser scanning conducted during the project for the Cedarburg Bridge. This includes point cloud images and AutoCAD drawings created from the point cloud images. The Imes Bridge is the only one Madison County Bridge where the point cloud data was used to create AutoCAD drawings. Our project team has all of the point cloud data that could be used in the future to create AutoCAD drawings for the other Madison County bridges (Hogback, Cutler-Donahoe, and Roseman) scanned during the project.

For the Imes Bridge, the data shows the accurate dimensions and shape of the bridge at the time of scanning. No corrections were made o straighten any bridge members, such as would be done to create new construction drawings. Figures 19-26 show that the bridge is no longer perfectly plane, but that it has twisted and moved over time.

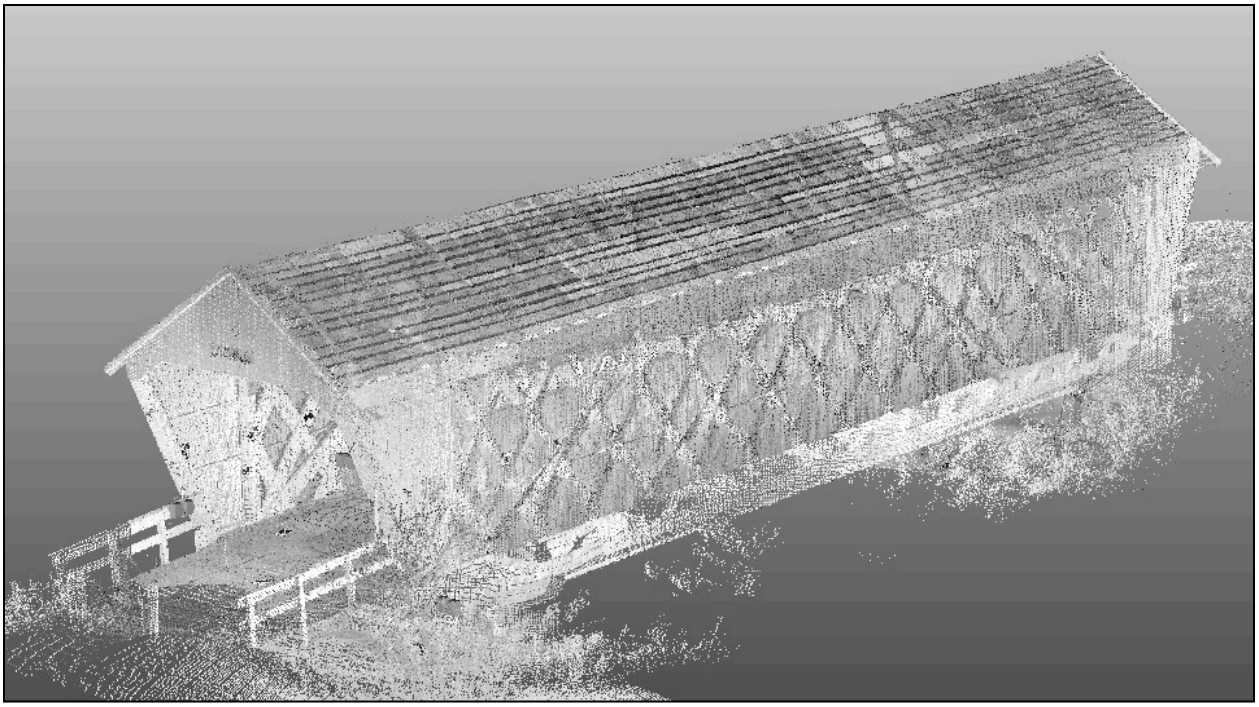

Figure 19.--Point cloud image of the Imes Bridge (NRRI).

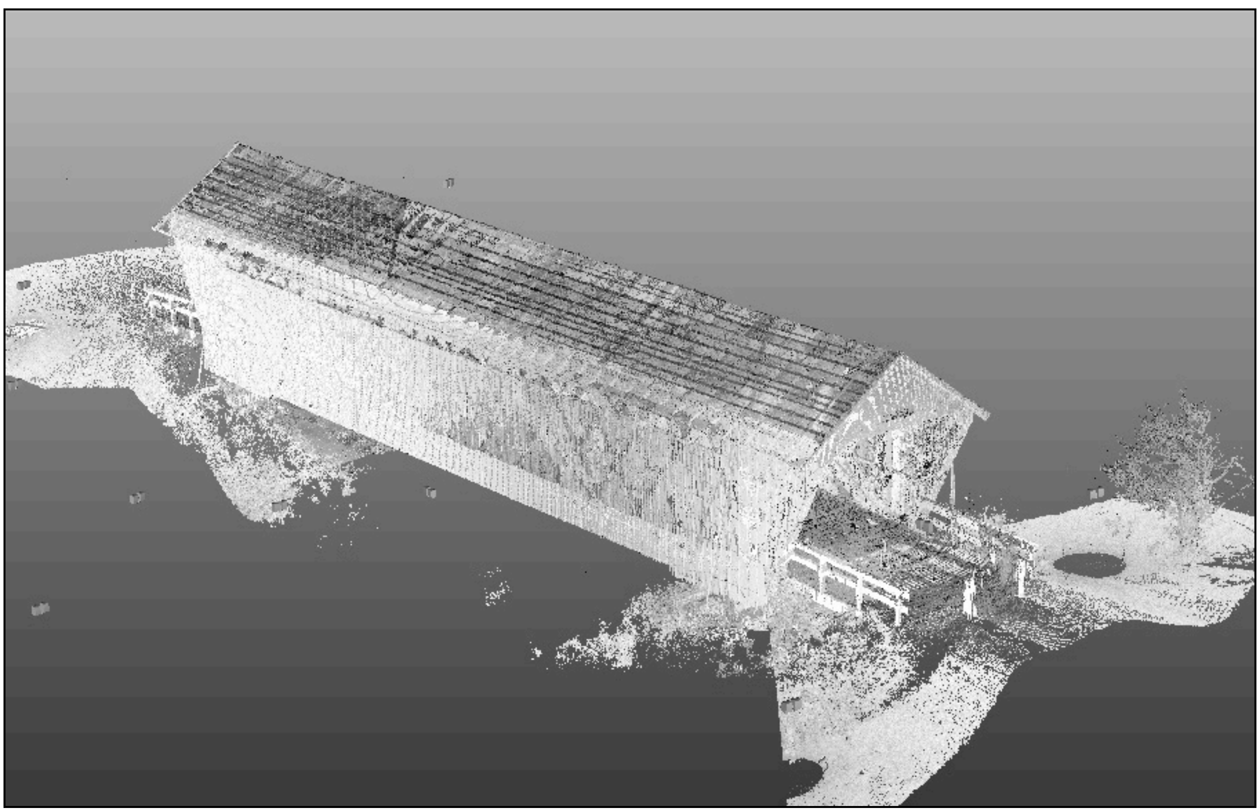

Figure 20.-- Point cloud image of the Imes Bridge (NRRI).

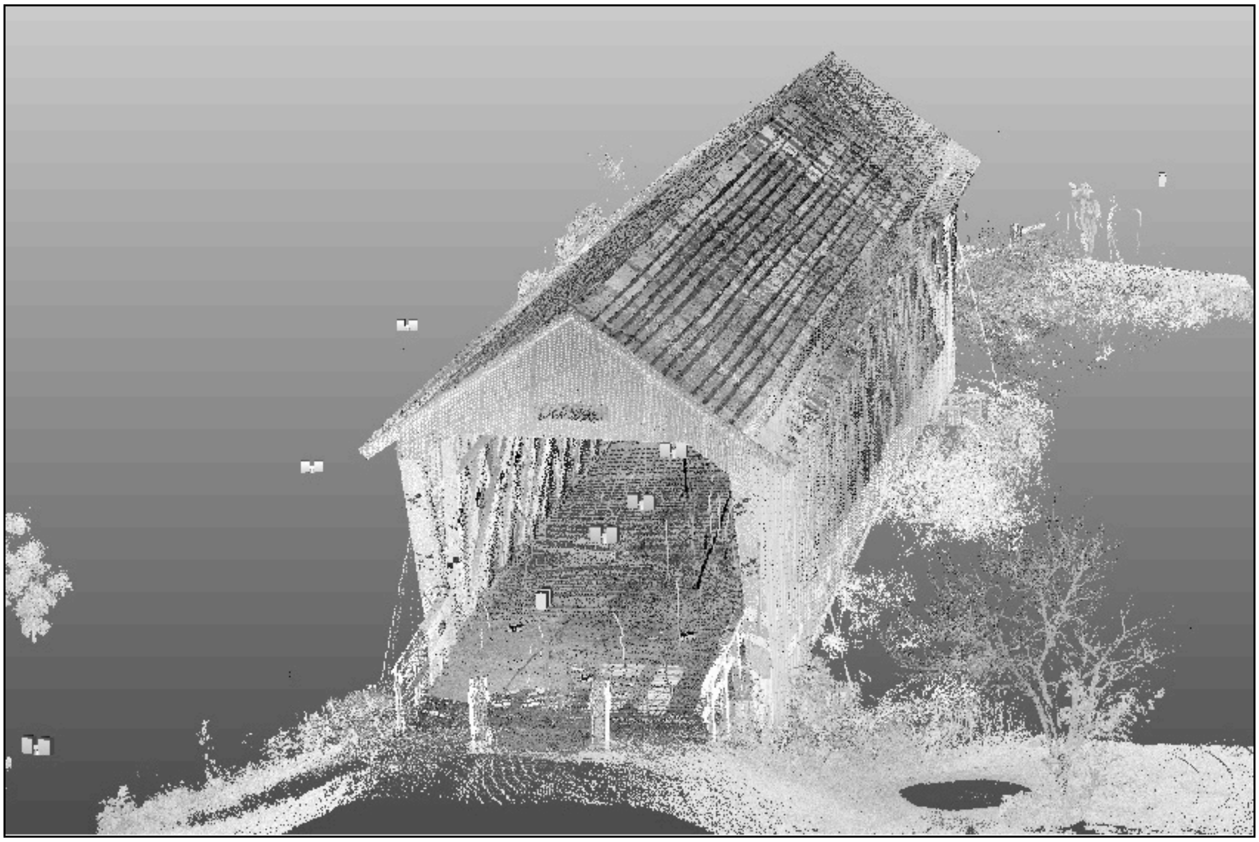

Figure 21.-- Point cloud image of the Imes Bridge (NRRI).

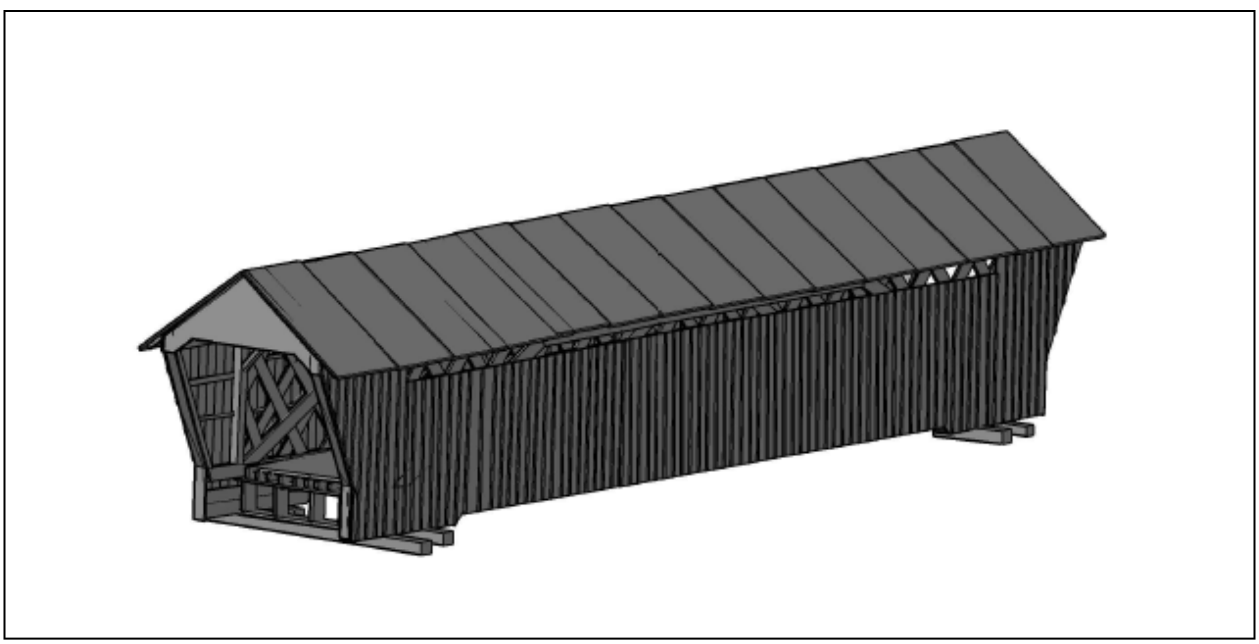

Figure 22.--Isometric 3D AutoCAD image of the Imes Bridge (NRRI).

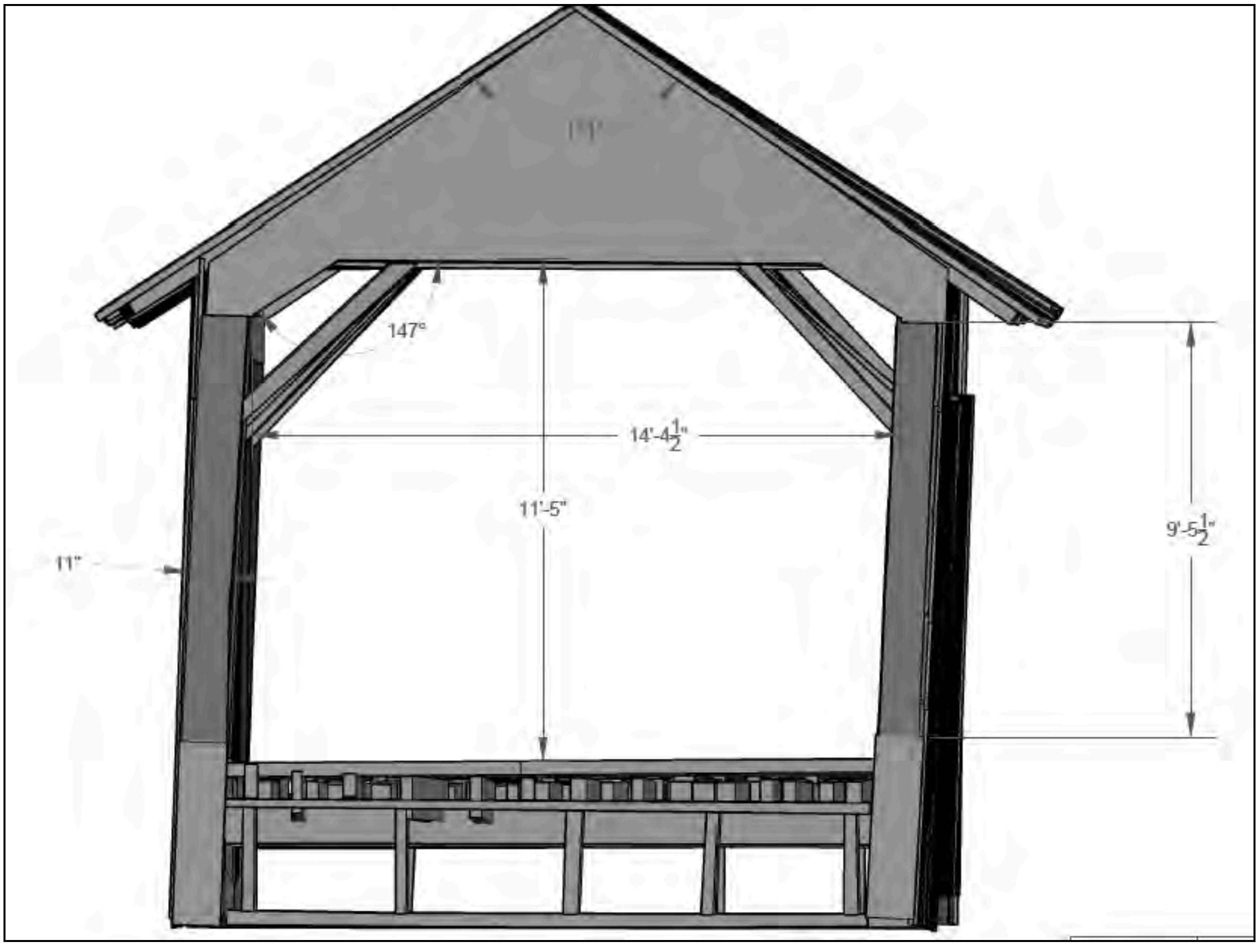

Figure 23.--Dimensioned 3D AutoCAD image of the Imes Bridge showing the existing rotation and out-of-plane nature of the bridge (NRRI).

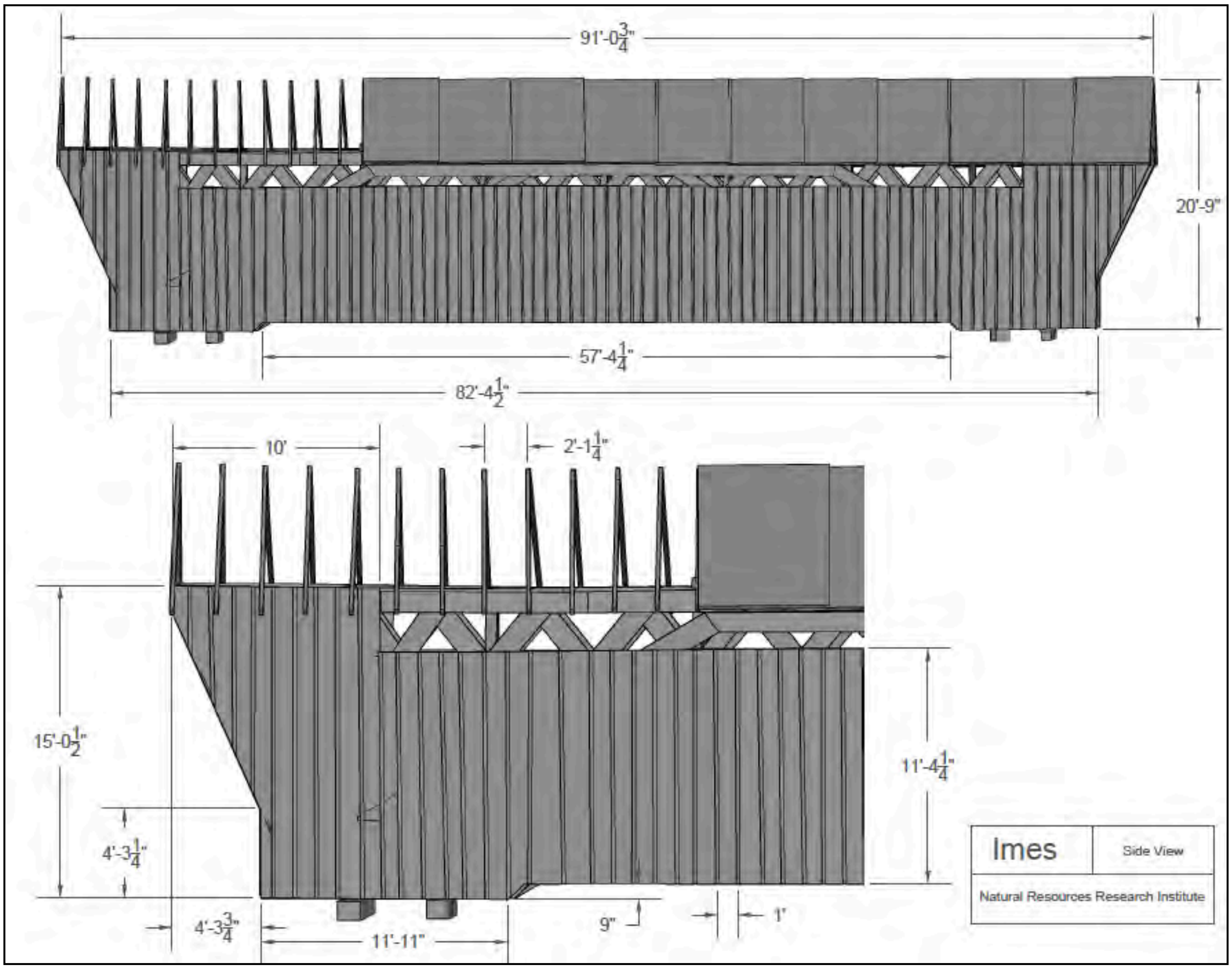

Figure 24.--Dimensioned 3D AutoCAD side view image of the Imes Bridge (NRRI).

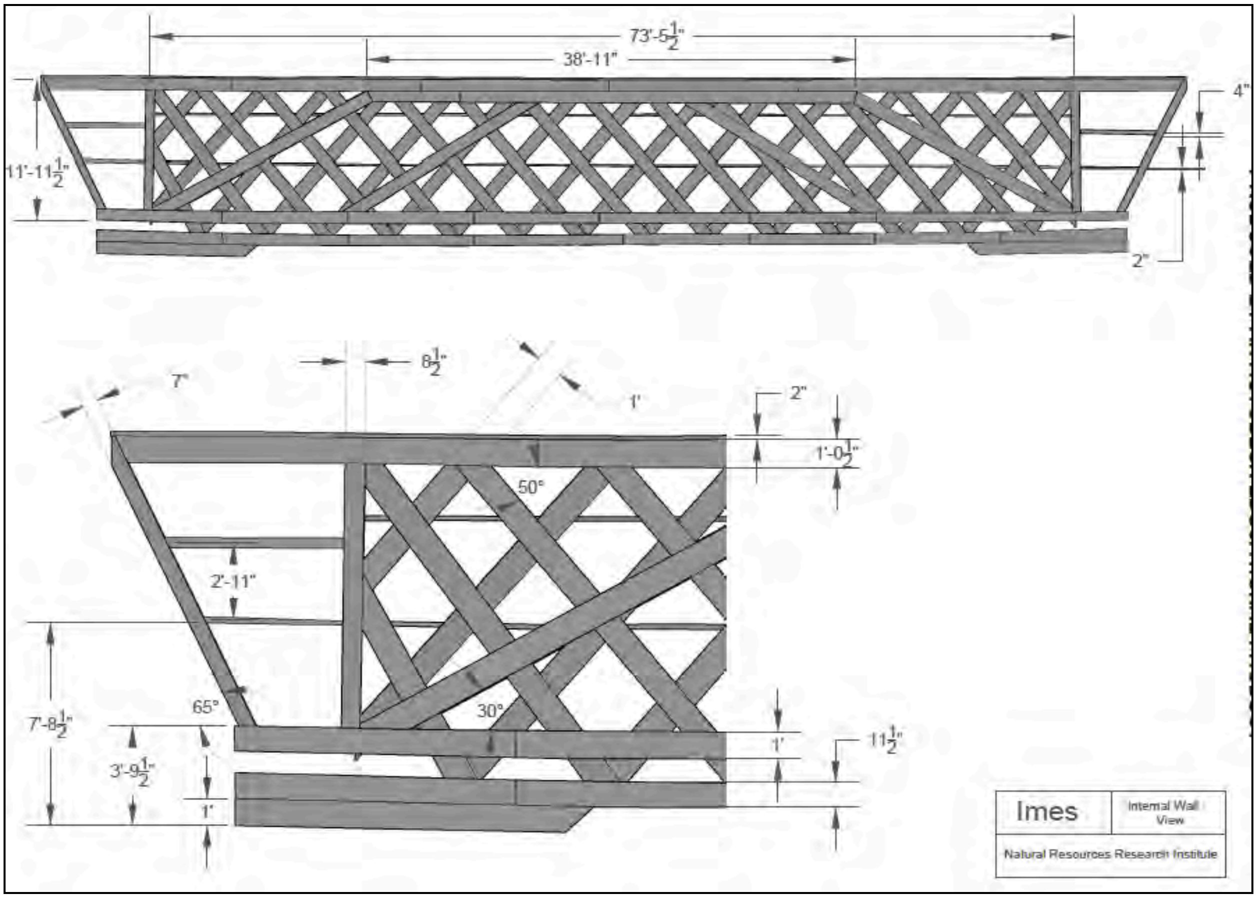

Figure 25.--Dimensioned 3D AutoCAD internal side wall image of the Imes Bridge (NRRI).

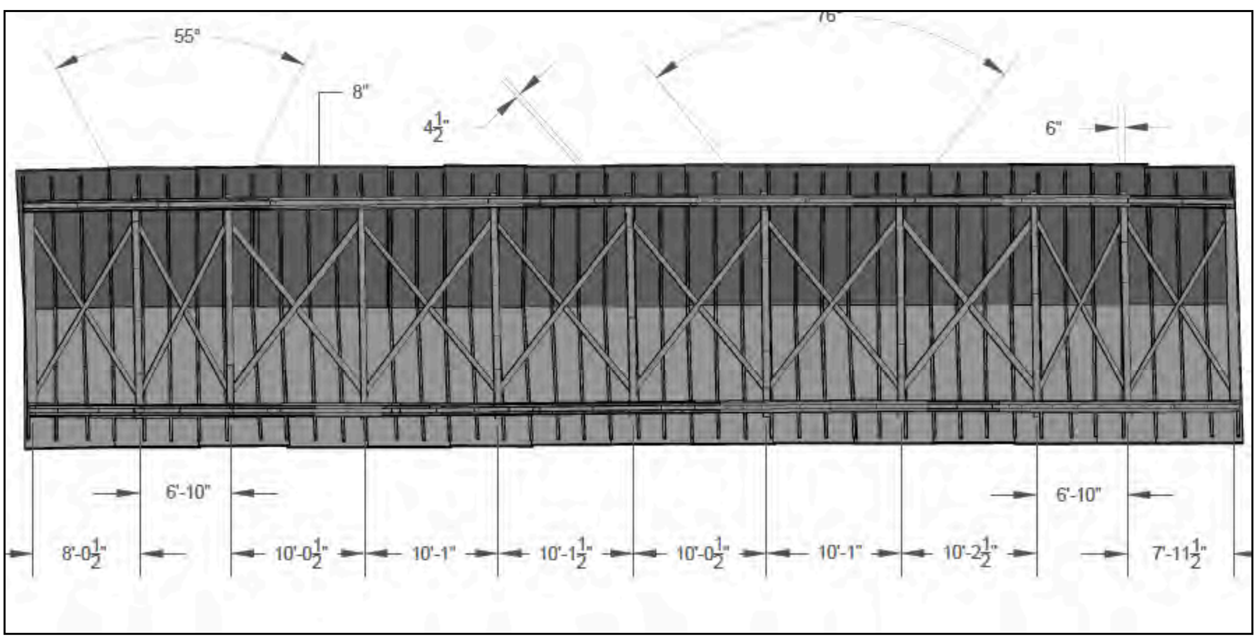

Figure 26.--Dimensioned 3D AutoCAD ceiling image of the Imes Bridge (NRRI).

Roseman Covered Bridge, Madison County, Iowa

Figures 27-30 show various point cloud images created from 3D laser scanning conducted during the project for the Roseman Bridge, located in Madison County, Iowa. These point images are fully dimensioned computer files that can be used to determine dimensions, skew of the bridge, deflection and other characteristics as needed, without importing into AutoCAD or other software platforms.

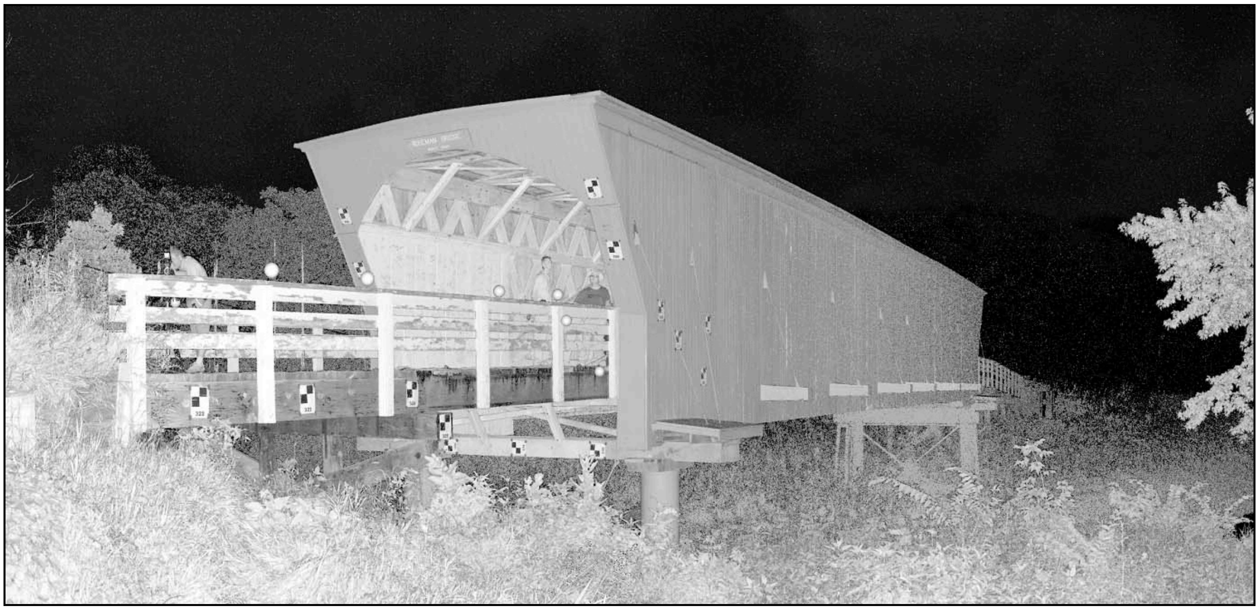

Figure 27.-- Planar view of a single laser scan of the Roseman Bridge (NRRI).

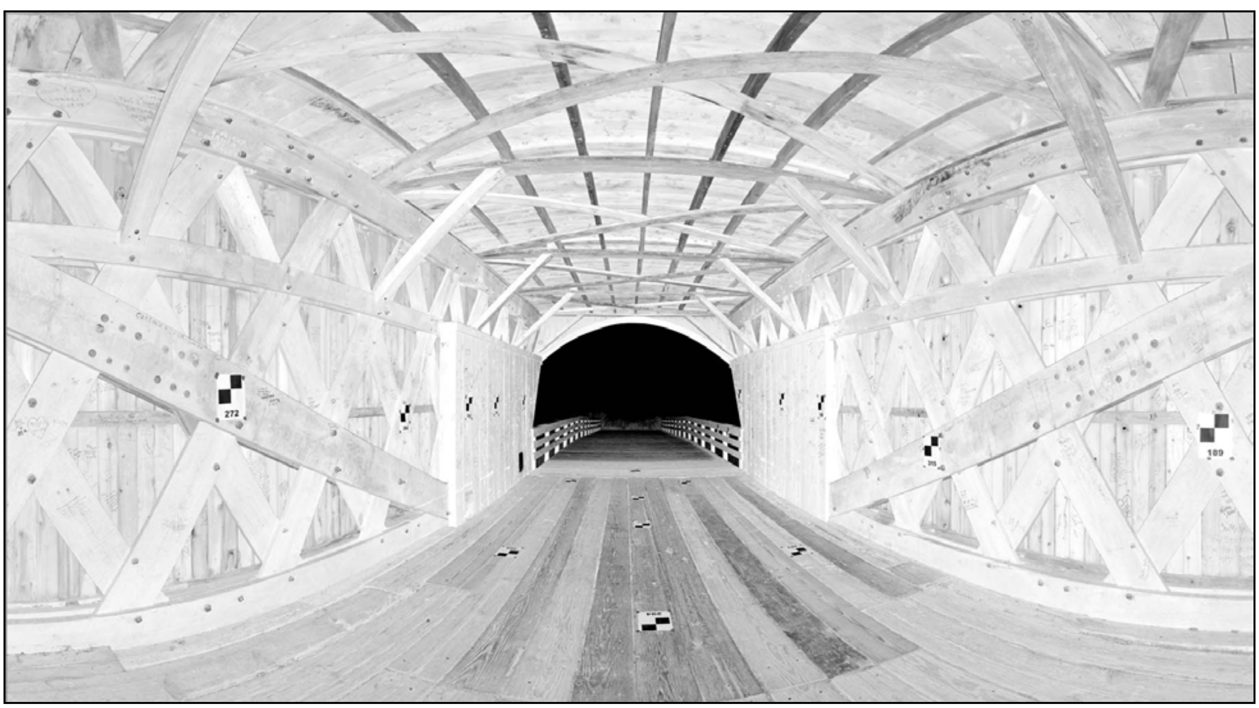

Figure 28.-- Planar view of a single laser scan of the Roseman Bridge (NRRI).

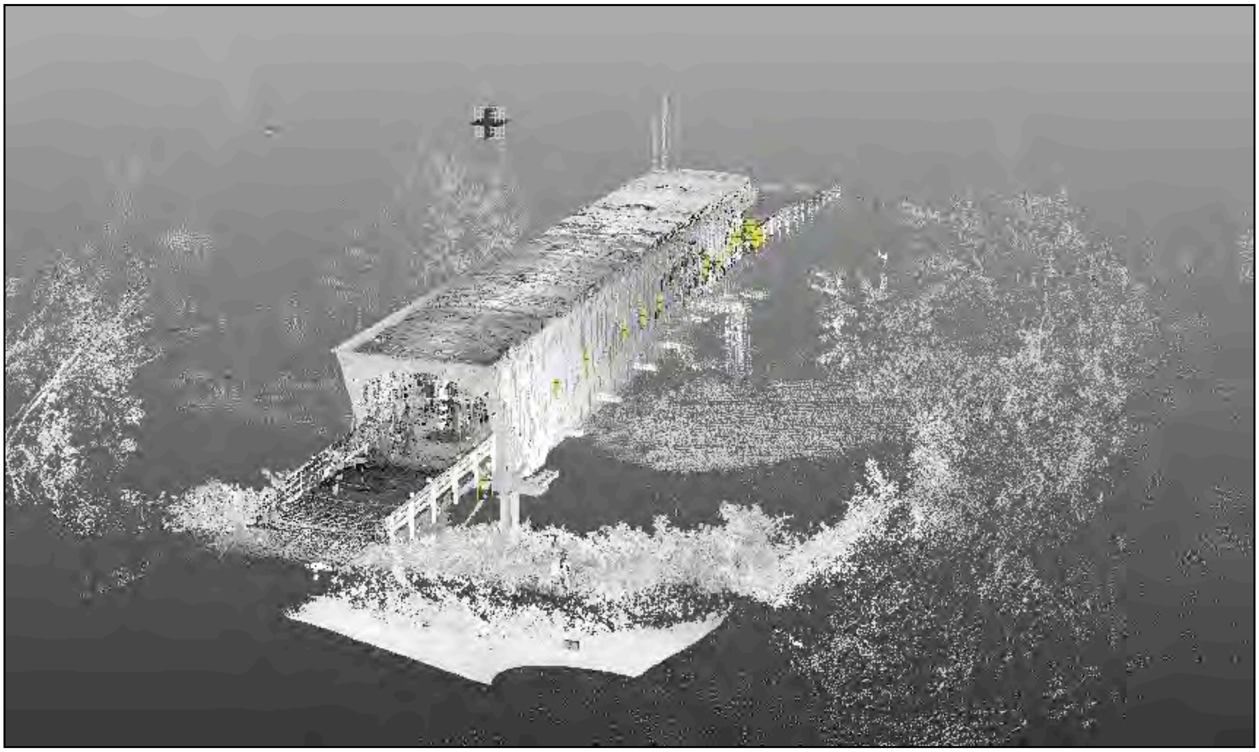
Figure 29.--Point cloud image of the Roseman Bridge (NRRI).


Figure 30.--Point cloud image of the Roseman Bridge (NRRI).

Hogback Covered Bridge, Madison County, Iowa

Figures 31-34 show various point cloud images created from 3D laser scanning conducted during the project for the Hogback Bridge, located in Madison County, Iowa. These point images are fully dimensioned computer files that can be used to determine dimensions, skew of the bridge, deflection and other characteristics as needed, without importing into AutoCAD or other software platforms.

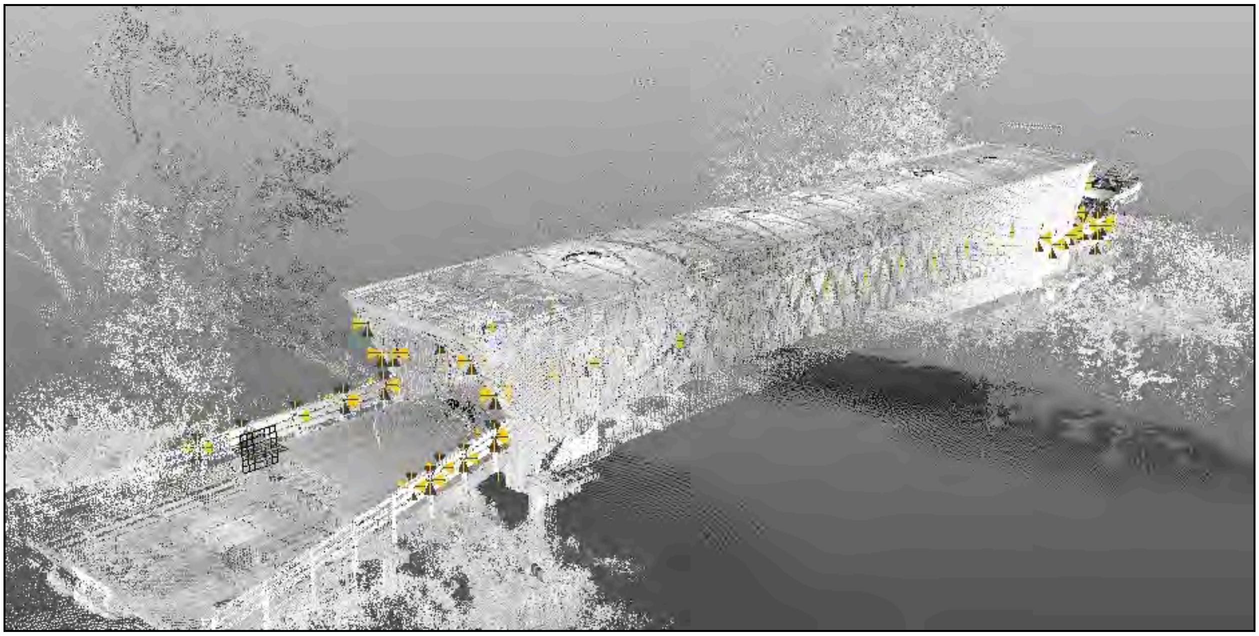

Figure 31.--Point cloud image of the Hogback Bridge (NRRI).

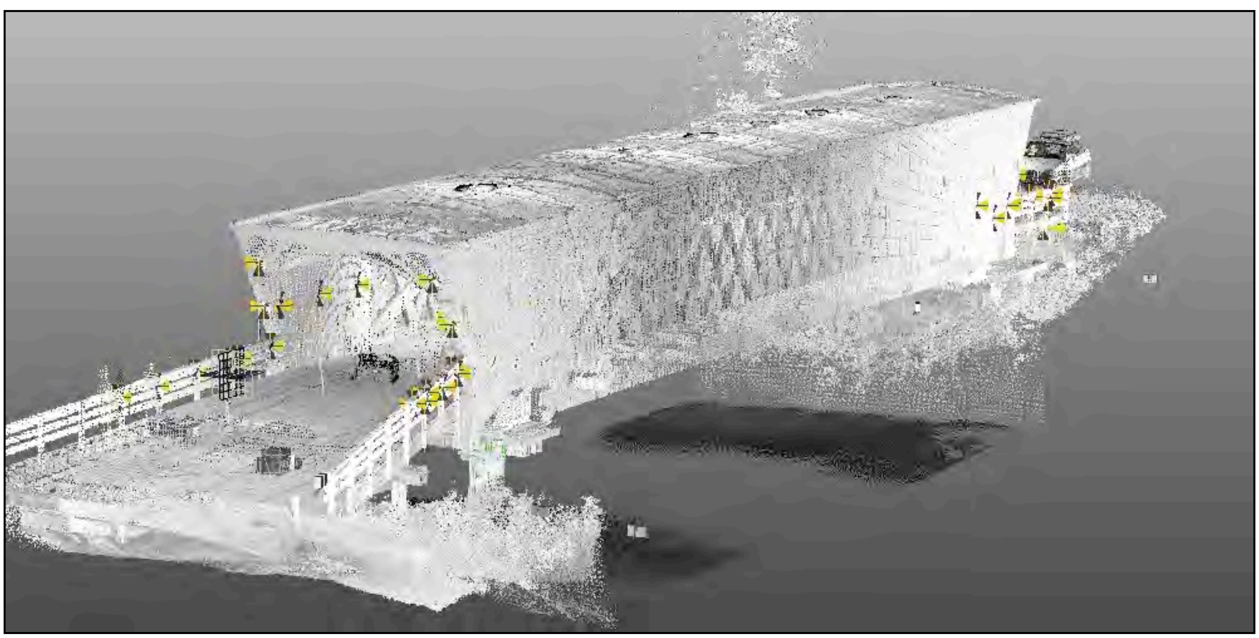

Figure 32.--Point cloud image of the Hogback Bridge (NRRI).

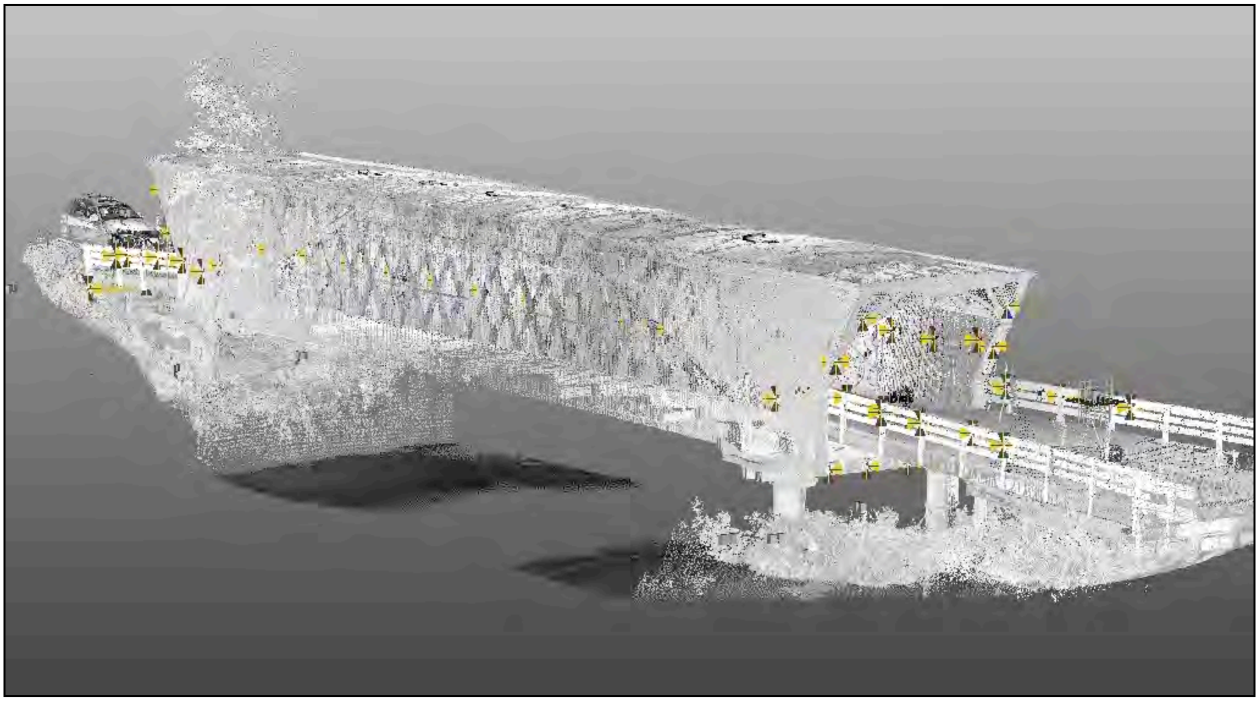

Figure 33.--Point cloud image of the Hogback Bridge (NRRI).

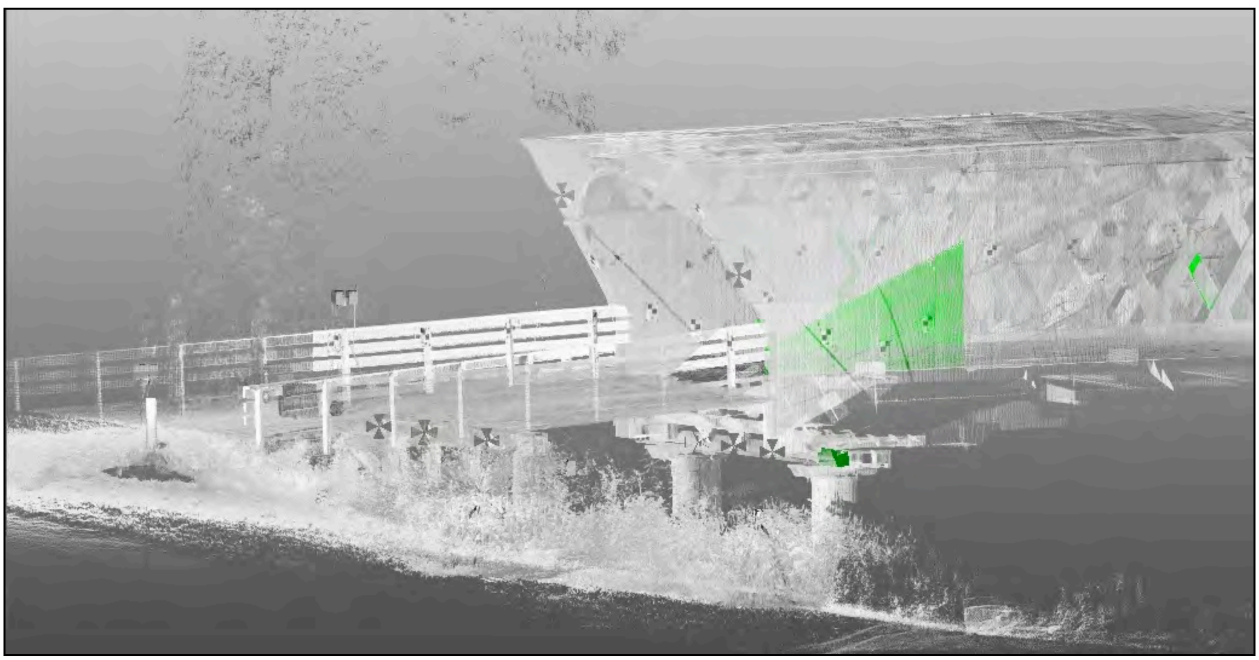

Figure 34.--Point cloud image of the Hogback Bridge (NRRI).

Cutler-Donahoe Covered Bridge, Madison County, Iowa

Figures 35-37 show various point cloud images created from 3D laser scanning conducted during the project for the Cutler Donahue Bridge, located in Madison County, Iowa. These point images are fully dimensioned computer files that can be used to determine dimensions, skew of the bridge, deflection and other characteristics as needed, without importing into AutoCAD or other software platforms.

Figure 35.--Point cloud image of the Cutler-Donahoe Bridge (NRRI).

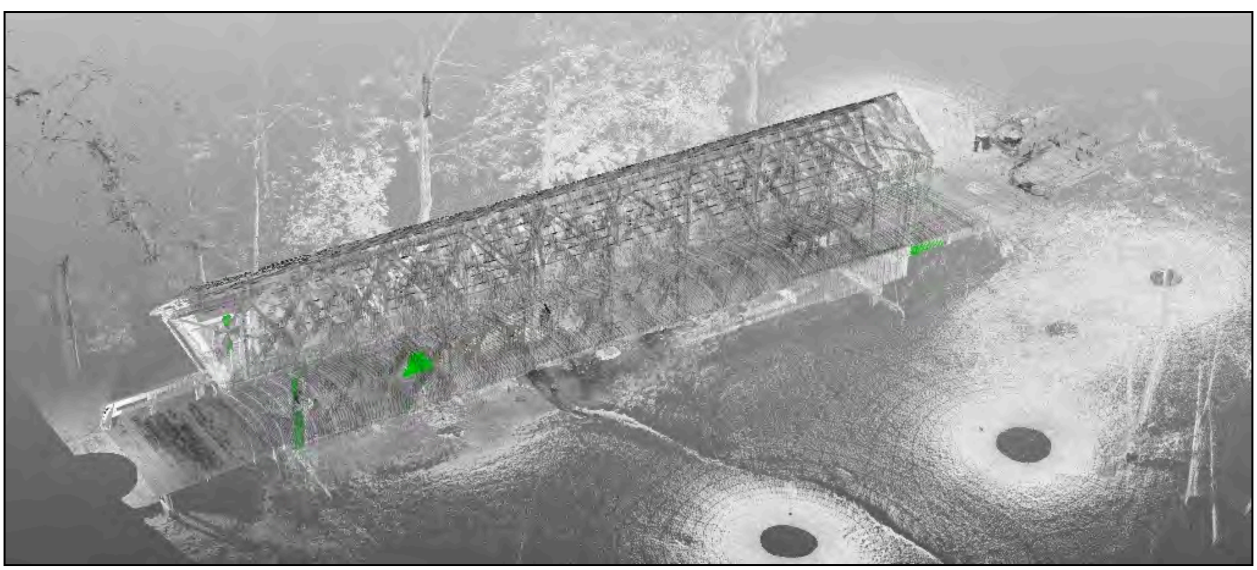

Figure 36.--Point cloud image (enhanced with clear view software setting) of the Cutler-Donahoe Bridge (NRRI).


Figure 37.--Point cloud image of the Cutler-Donahoe Bridge (NRRI).

Zumbrota Covered Bridge, Zumbrota, Minnesota

Additional project funds were received from the Minnesota Local Road Research Board OPERA Research Program to conduct three-dimensional laser scanning of the most significant historic covered bridge in Minnesota, located in Zumbrota. The bridge, built in 1869 (relocated several times) is now located in a city park, spanning the Zumbro River. Figures 38-49 show various point cloud images created from 3D laser scanning conducted during the project. These figures show each different type of possible image that can be created using Faro Scene software or AutoCAD 2011 with a Kubit USA add-in. These images include a point cloud image resulting from only one scan, a scalar image created from a point cloud scan, a point cloud image created from multiple scans, a point cloud image imbedded in AutoCAD, and 2D/3D AutoCAD images. All of the scan data, images and figures were provided to the City of Zumbrota for any further processing as appropriate.

In contrast to the Imes Bridge, significant efforts were made to straighten the dimensions of the bridge in AutoCAD in an effort to create a drawing that could be used to construct a new bridge. This was a significant undertaking, and added nearly 40 hours of processing time to the data processing. This process creates a drawing that would be more consistent with the original construction of the bridge, not the current shape and condition.

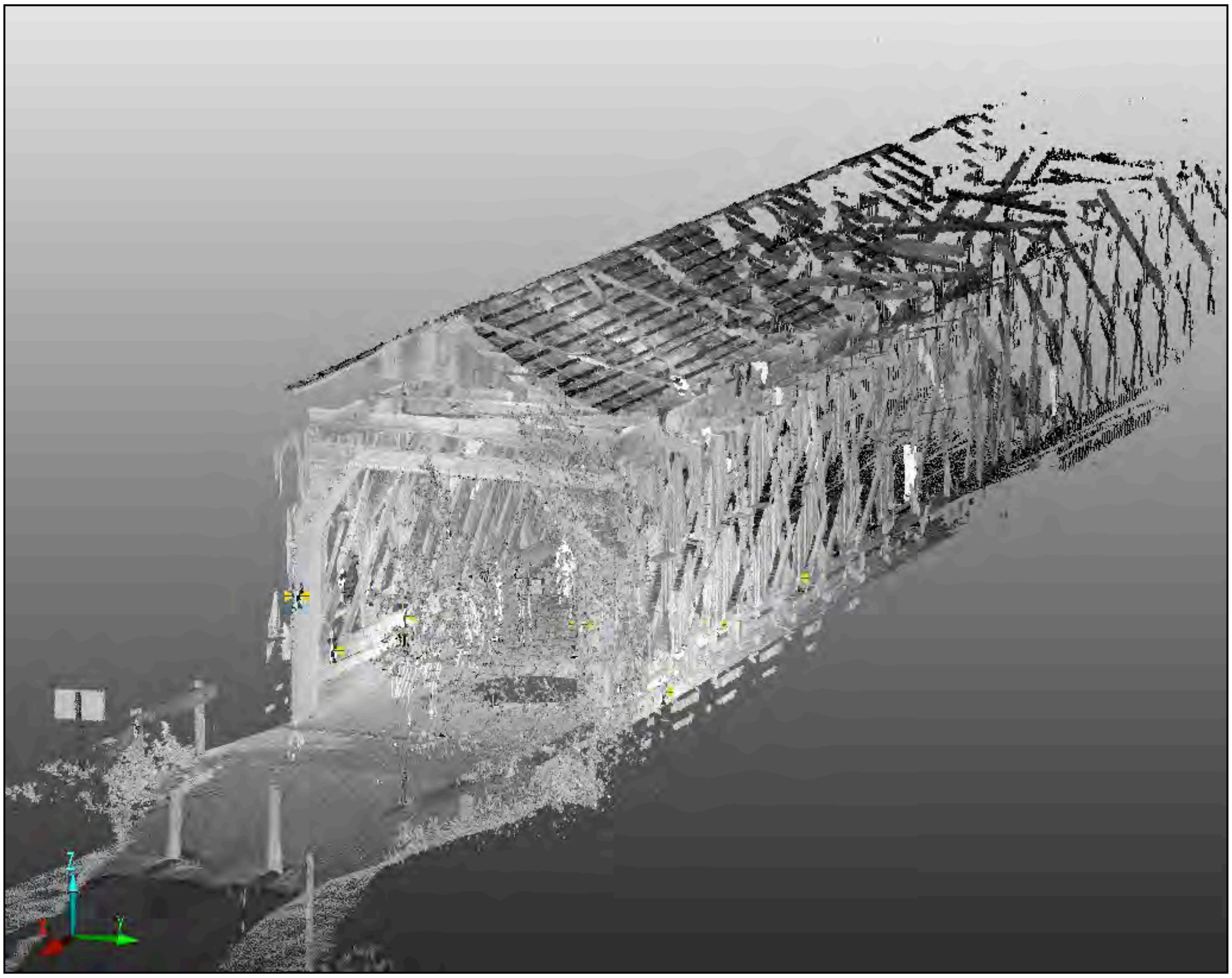

Figure 38.--A point cloud image from the Zumbrota Bridge created from a single interior scan processed with Faro Scene software.

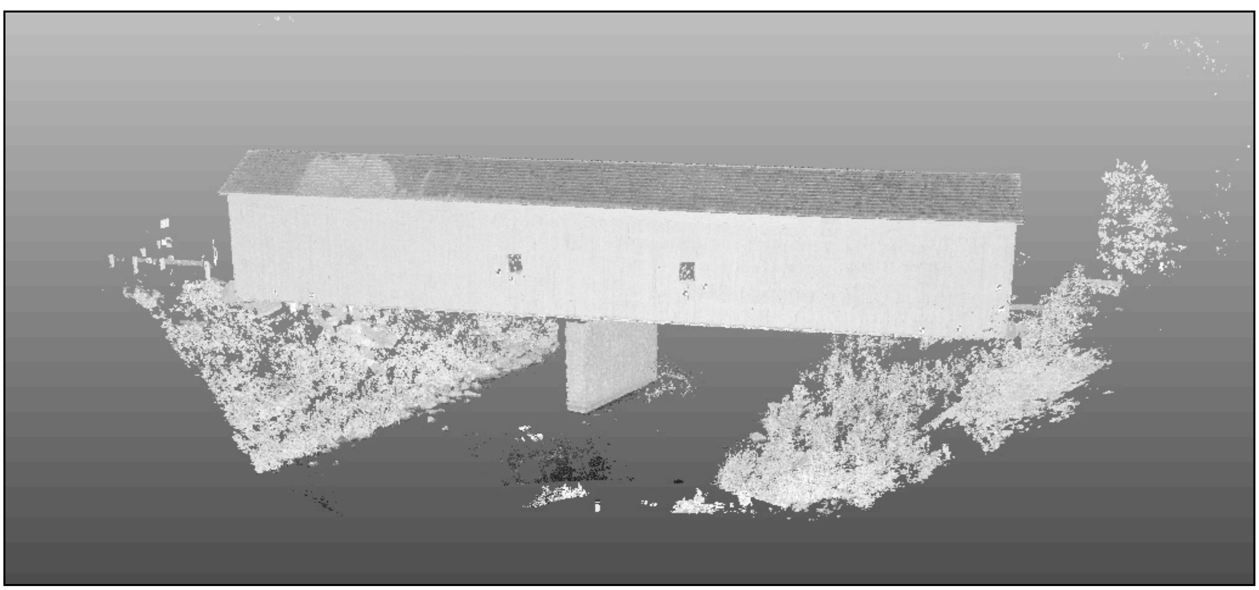

Figure 39.--A point cloud image from the Zumbrota Bridge created from a single exterior scan processed with Faro Scene software.

Figure 40.-- A scalar image of the outside of the Zumbrota Bridge created from a single exterior scan processed with Faro Scene software.

Figure 41.--A scalar image of the inside of the Zumbrota Bridge created from a single interior scan processed with Faro Scene software.

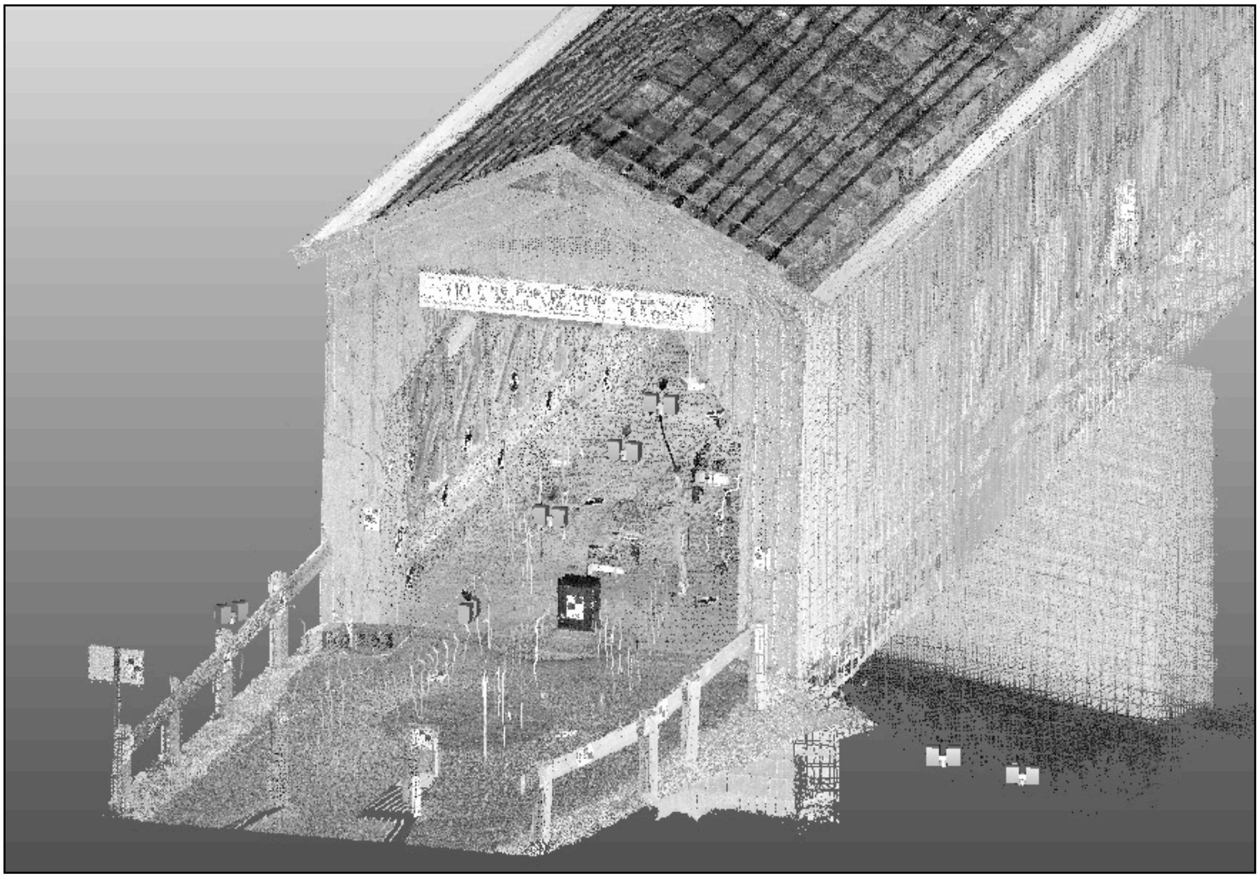

Figure 42.--A point cloud image of the Zumbrota Bridge created from multiple scans and linked together with Faro Scene software.

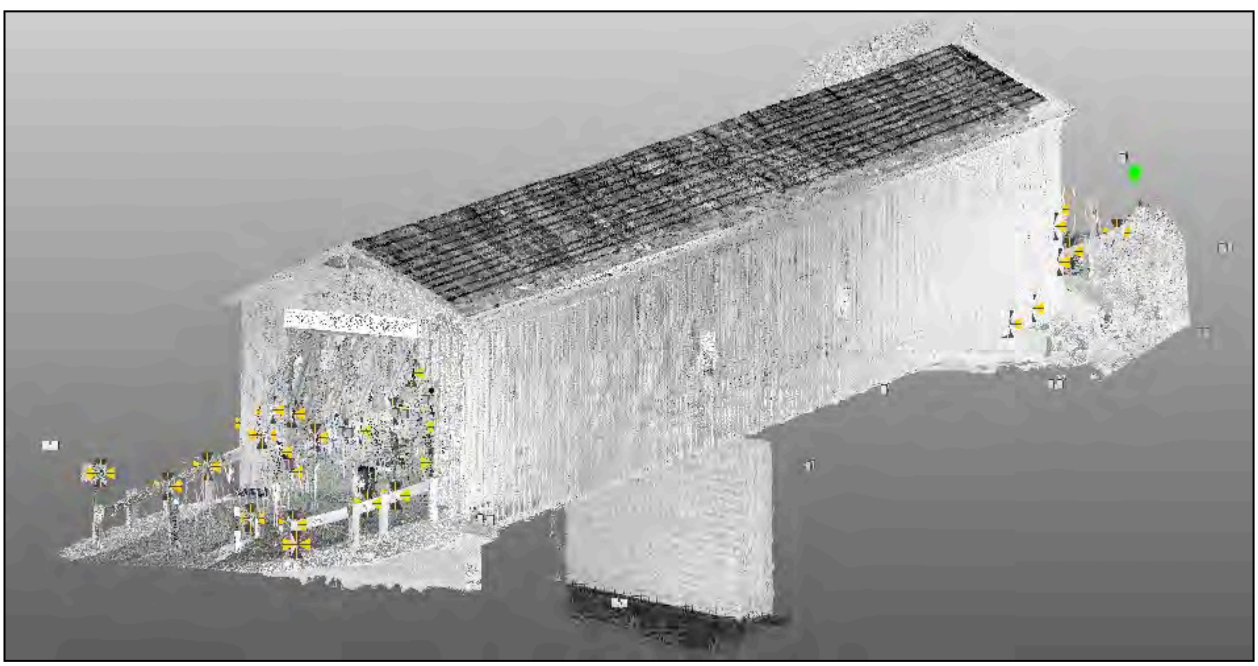

Figure 43.--A point cloud image of the Zumbrota Bridge created from multiple scans and linked together with Faro Scene software.

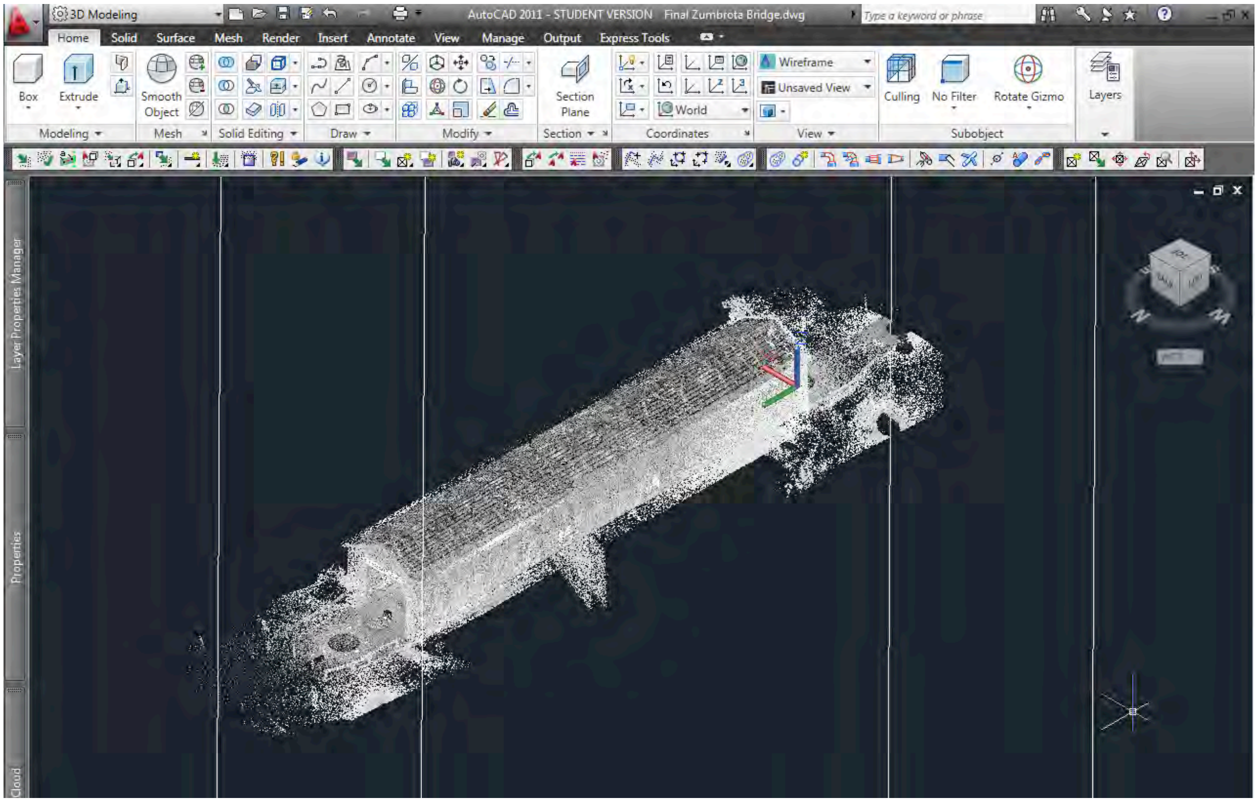

Figure 44.--A point cloud image of the Zumbrota Bridge created from multiple scans and linked together with Faro Scene software, imbedded into AutoCAD with a Kubit USA add-in.

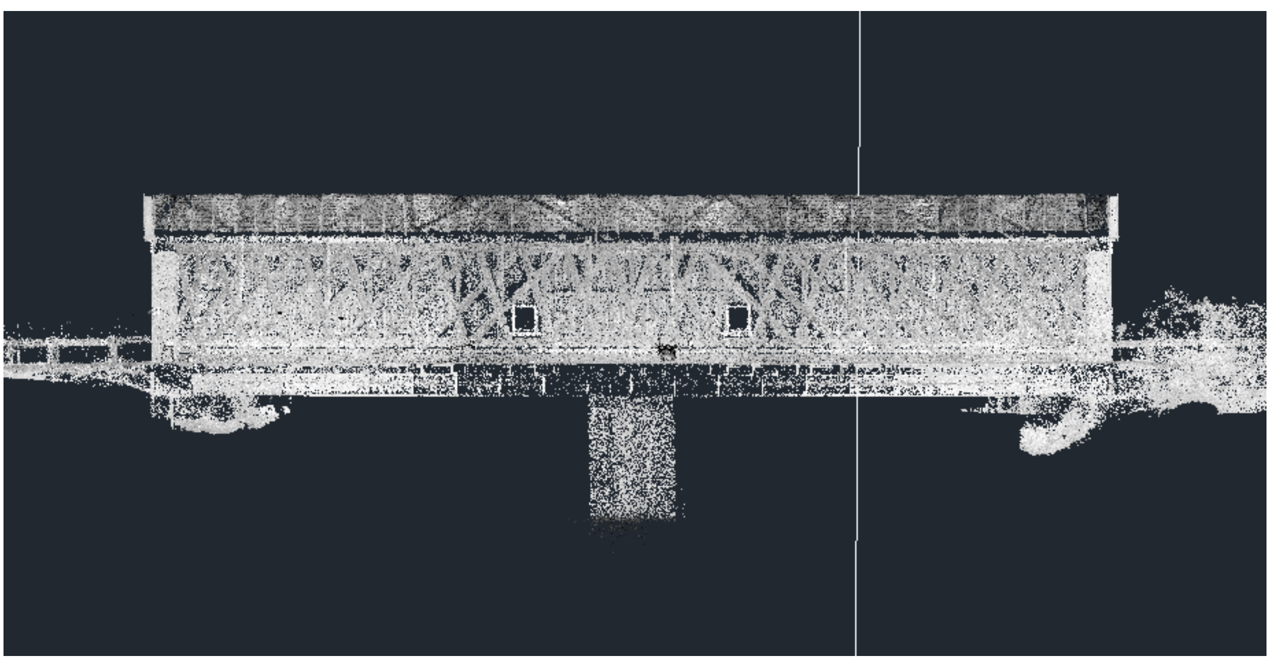

Figure 45.--A point cloud image of the Zumbrota Bridge created from multiple scans and linked together with Faro Scene software, imbedded into AutoCAD with a Kubit USA add-in.

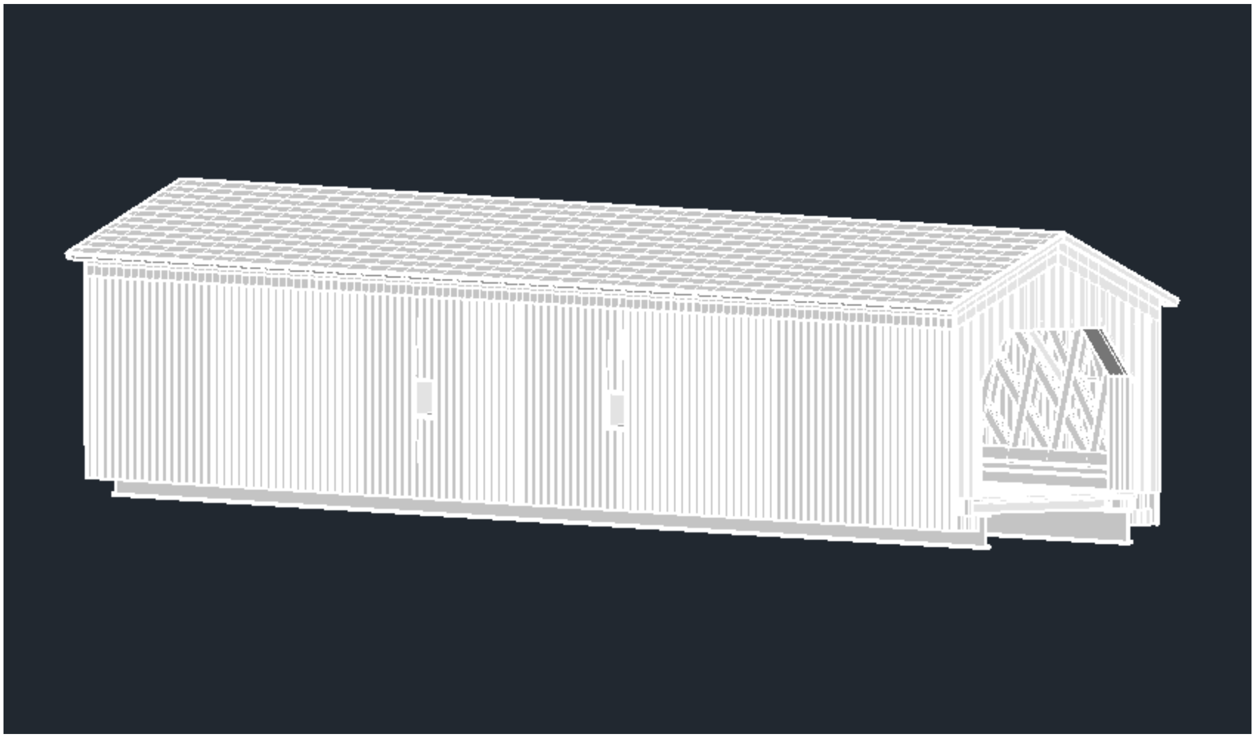

Figure 46.--An AutoCAD 3D image of the Zumbrota Bridge created from scanning data.

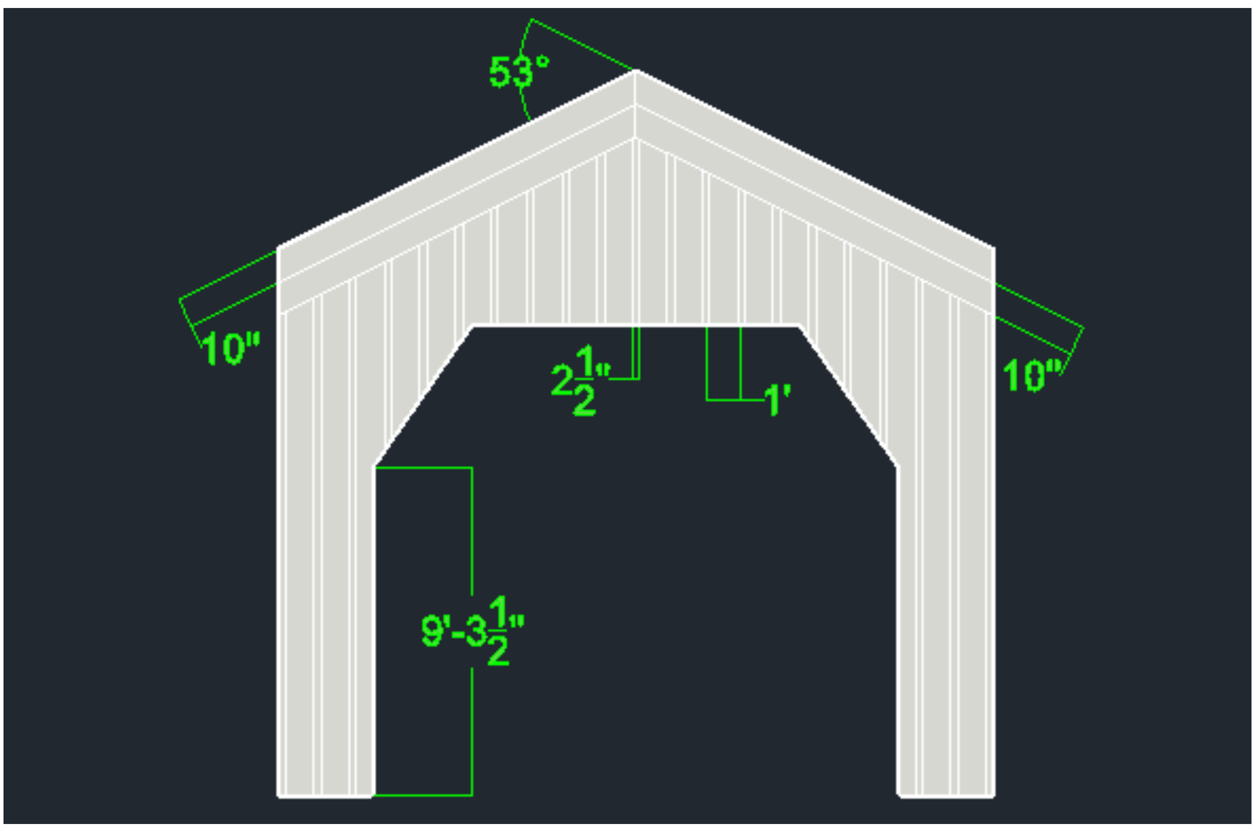

Figure 47.--An AutoCAD 2D image of the Zumbrota Bridge created from scanning data.

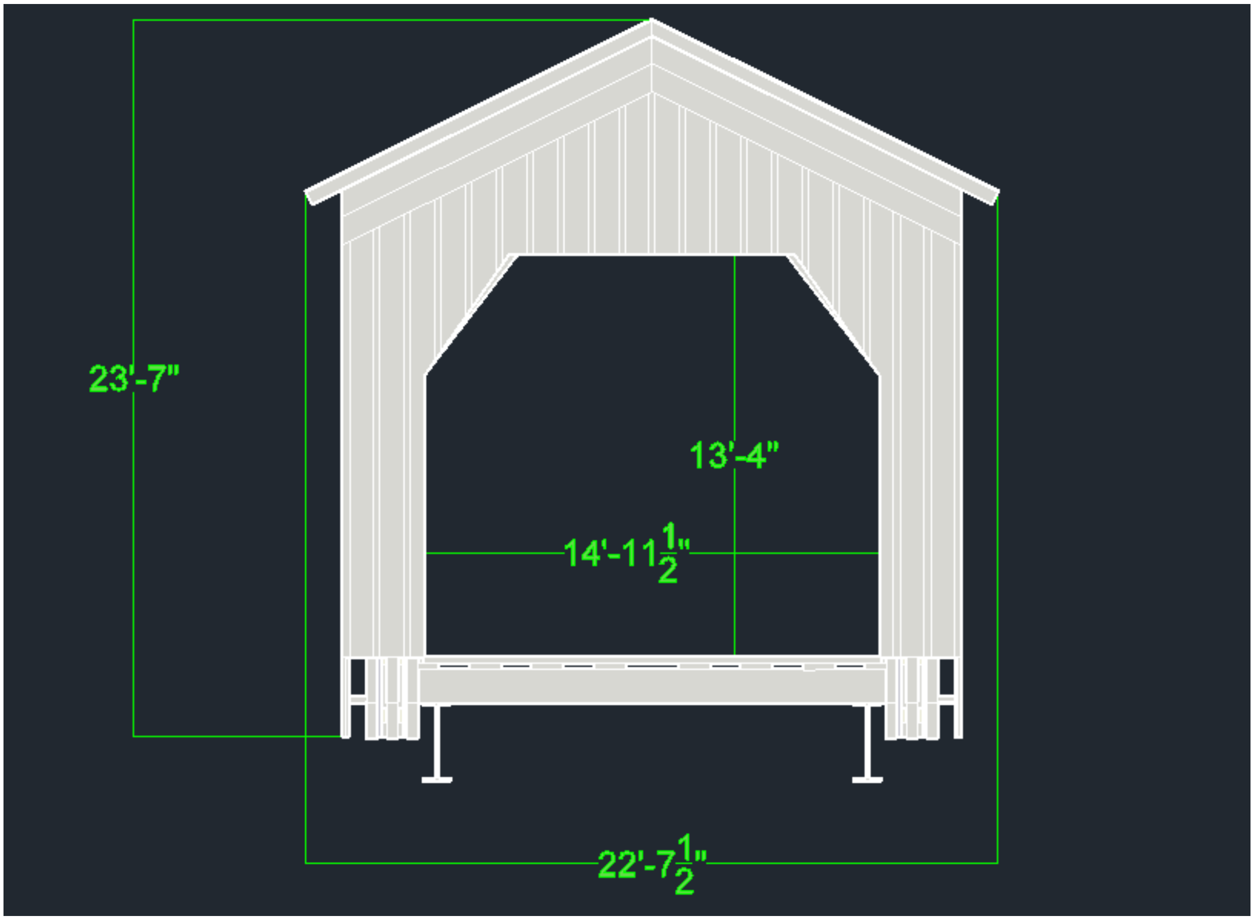

Figure 48.--An AutoCAD 2D image of the Zumbrota Bridge created from scanning data.

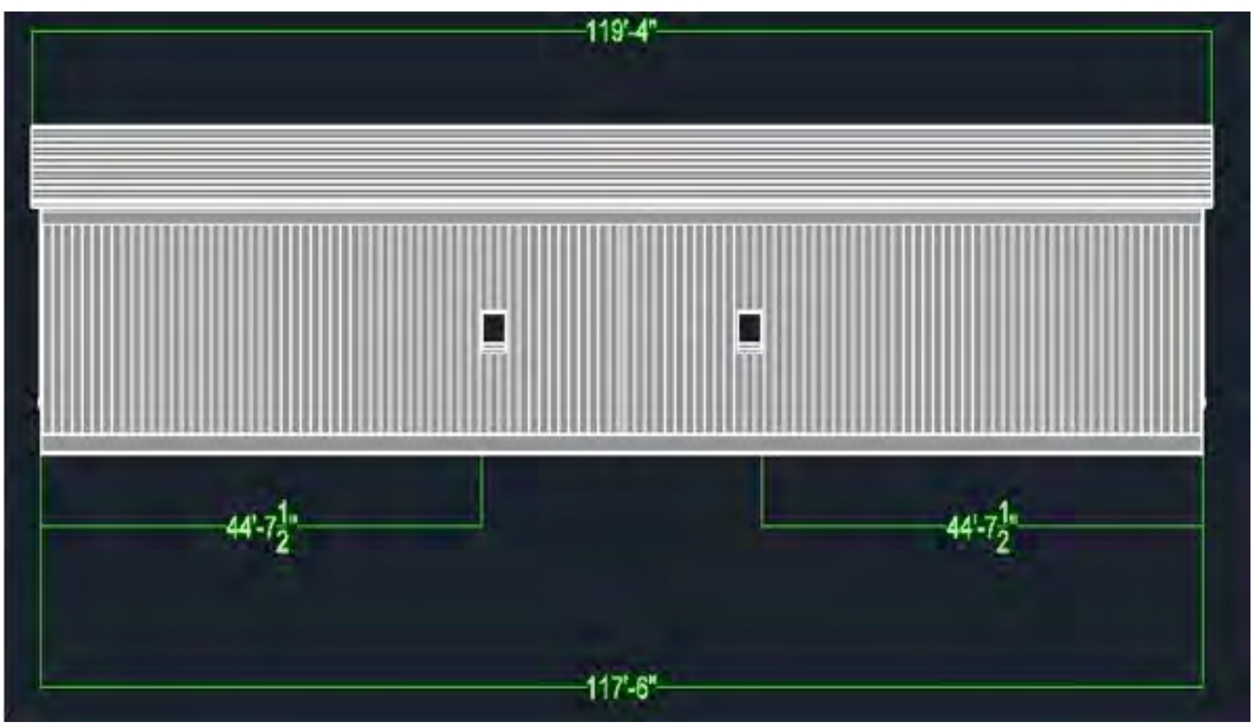

Figure 49.--An AutoCAD 2D image of the Zumbrota Bridge created from scanning data.

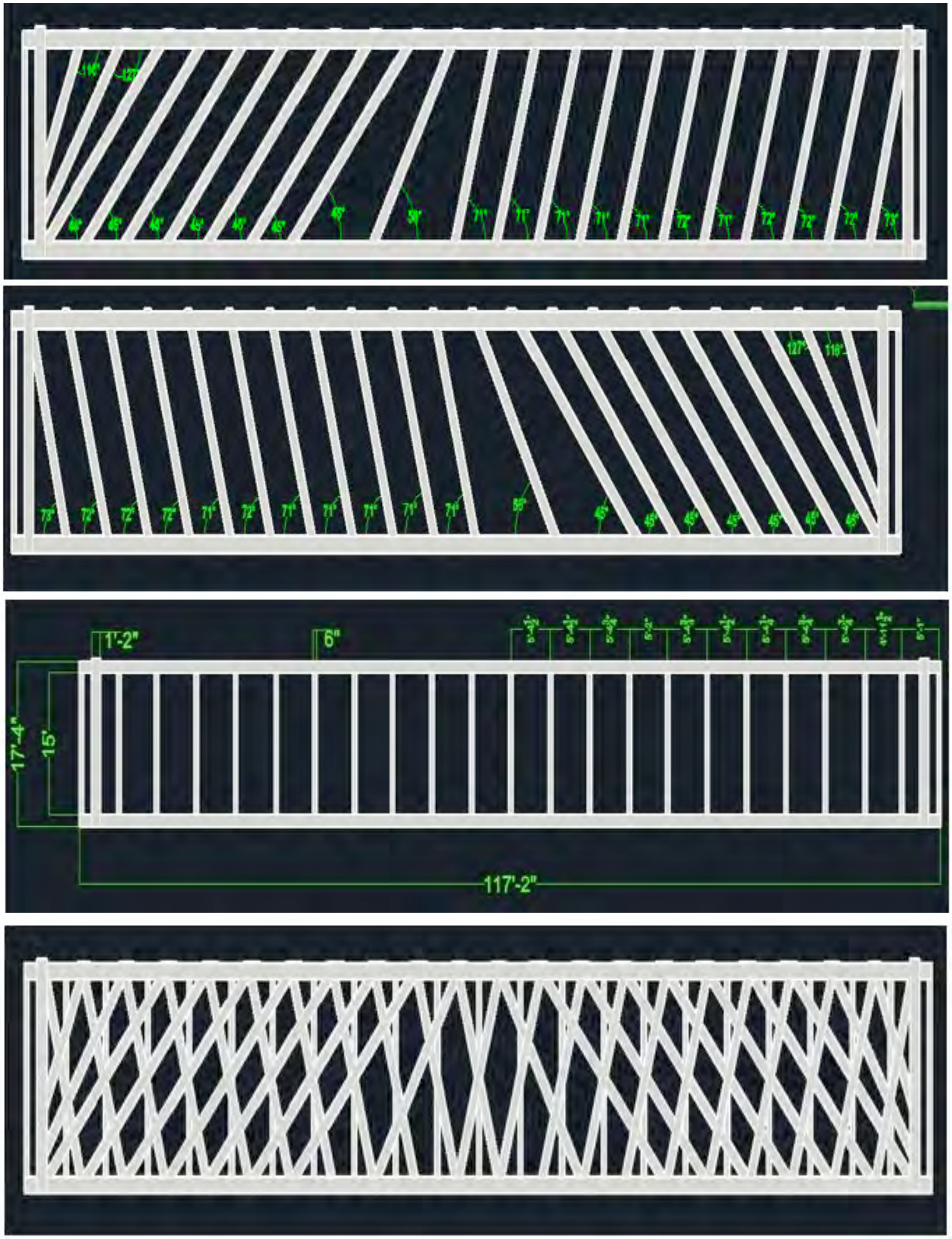

Figure 50.--Three AutoCAD 2D images (top 3) of wall components used to create a composite of the Zumbrota bridge wall.

Rapid Prototype Development

Following processing and development of the 3D scanning images, a digital 3D CAD file was used to generate a 1/100th 3D scale replica of the bridge at the Northern Lights Technology Center of UMD NRRI. In processing the data, we found that it would only be possible to produce an accurate external version of the bridge. We could not create a true replica of the inside of the bridge since a 1/100th scale of a 6 inch wide beam would only have a thickness of 0.06 in. This is below the thickness that can be created using rapid prototyping, and these thin members would not have strength since many of the beams and members are only connected at the ends. Vanguard Si2 selective laser sintering (SLS) equipment from 3D Systems was used to create the scale replica of the bridge. Figure 51 shows the 3D image that was used by the Vanguard unit to create the 1/100th model shown in Figure 50. Since the scan data was corrected to achieve straight members, this model would be consistent with the true nature of the bridge at construction, not the condition of 2010.

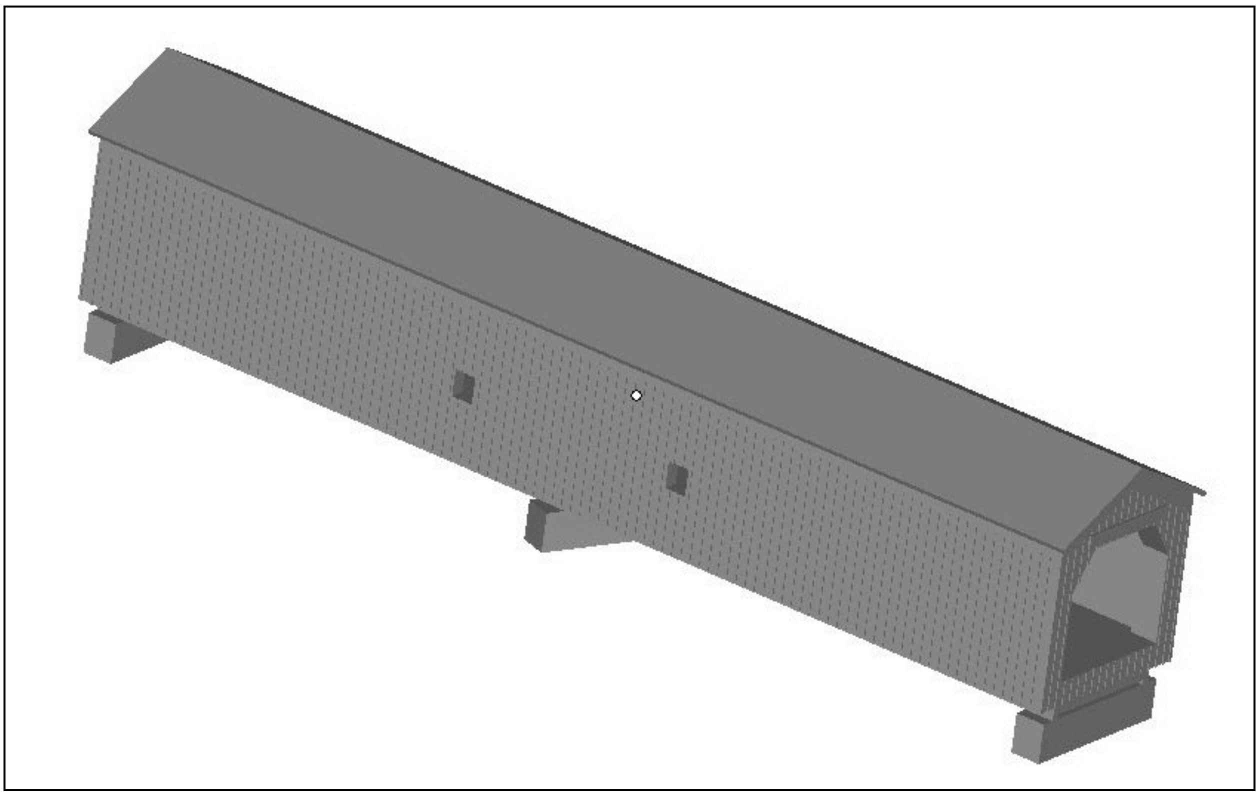

Figure 51.--A 3D isometric image used to produce a 1/100th model using selective laser sintering rapid prototyping equipment.

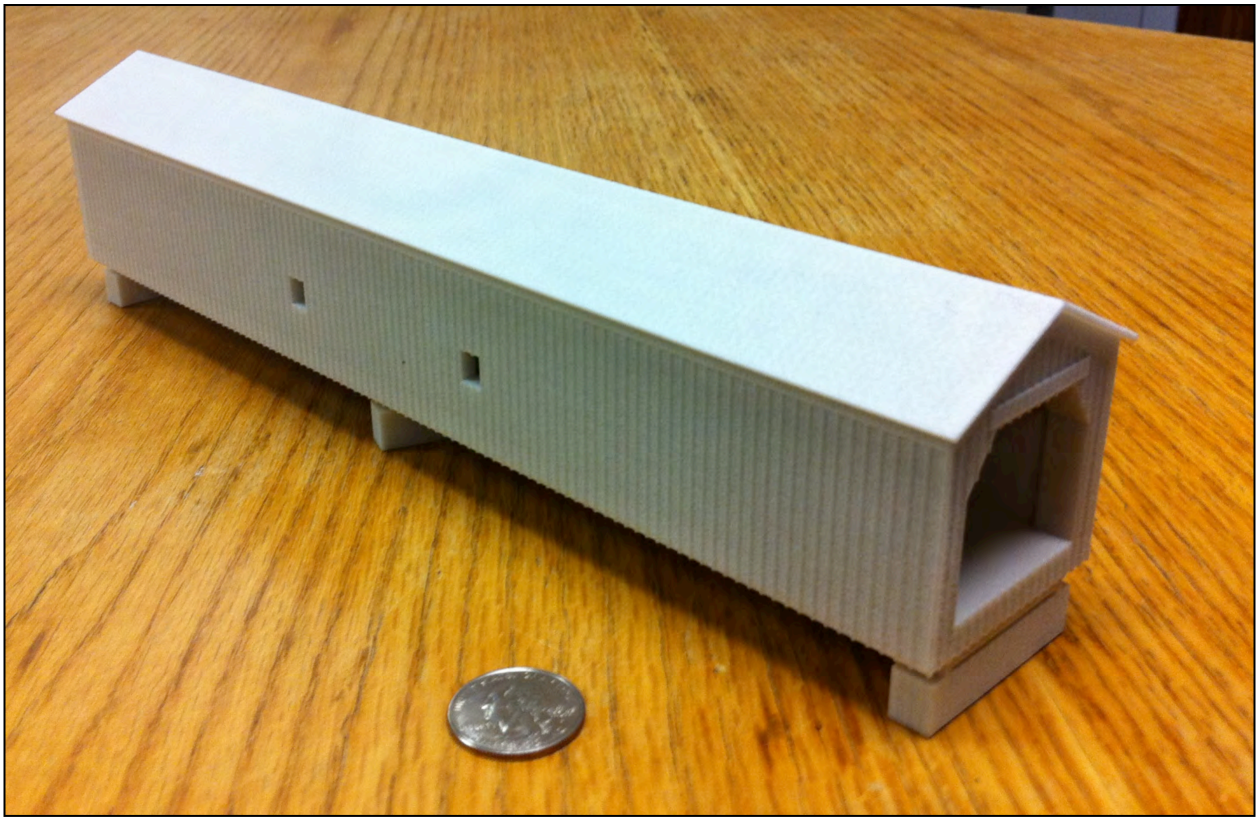

Figure 52.--A 1/100th model of the Zumbrota Bridge created using selective laser sintering rapid prototyping equipment.

Task 3. Perform field measurements on identified bridges. Compare/contrast laser scanning equipment results with field measurements.

One of the objectives of the project was to assess the accuracy of laser scanning to determine accurate dimensions of the bridges. The Faro laser scanner used for the project was rated at an accuracy of ¼ in at 150 feet of distance. However, the typical distance of the laser scanner in this project ranged from 50-100 ft, improving the accuracy over the rated number. For this phase of the project, only the Madison County Iowa bridges were measured to verify the accuracy. In order to conduct this task, digital photos of each bridge were taken as soon as the project team arrived. These photos were then printed on a portable printer and used to record the accurate dimensions measured with traditional tape measures (1/16th accuracy). Figure 53 shows the portable printer used on site in this project.

Each bridge was then scanned using the laser scanner at up to 20+ locations. The raw scan data was processed into point cloud data. The locations measured using traditional measuring equipment on the photographs were then located in the digital files and the digital dimensions noted. Based on this data, a comparison between the actual and digital measurements was taken. The comparison data is reported for each of the four Madison County bridges in the following sections. Fourteen to sixteen locations were samples for each bridge with a very small error noted. This mean error of the 14-16 measurements ranged from 0.04 - 0.08 in. (1.01 - 2.02 mm), within the rated accuracy of ¼ inch at 150 ft.

Figure 53.--Laptop and printer for printing pictures on site during the laser scanning process.

Imes Covered Bridge, Madison County, Iowa

Figure 54-56 show the locations on the bridges where the actual measurements were collected using traditional tape measures to a resolution of 1/16 in. Once the point cloud was developed from the multiple laser scans of a bridge, the data was extracted from the digital file and simply compared for accuracy. Table 2 shows the results of this comparison, showing that the laser scanning is a very accurate means of determining dimensions for use in creating as built documentation.

Figure 54.--Locations where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

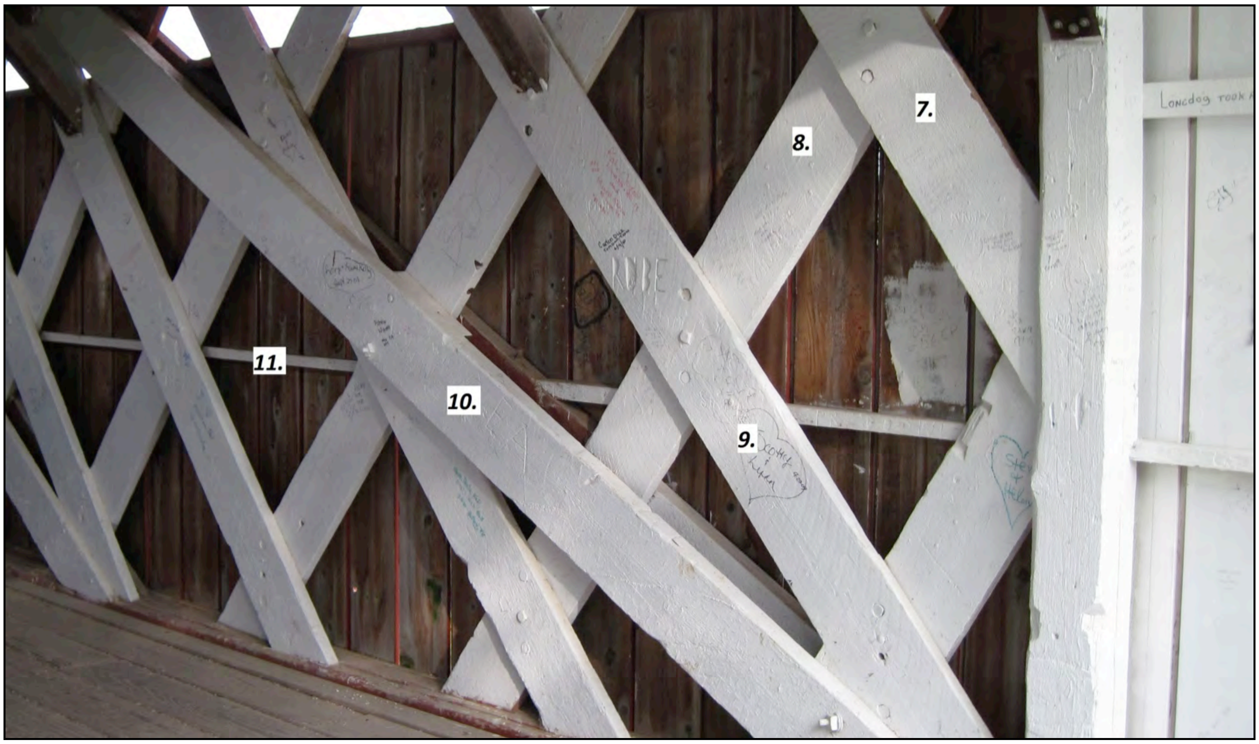

Figure 55.--Locations where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

Figure 56.--Locations where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

Table 2.--Comparison of measurement data from traditional tape measures and point cloud measurements for the Imes Covered Bridge, Madison County, Iowa.

Member Number	Method for Measurement			Difference Between Tape and Point Cloud	
	Tape Measurement (1/16 in.)	Point Cloud			
		3 Points (in.)	Mean (in.)	(in.)	(mm)
1	2.88	2.68 2.76 2.74	2.73	0.15	3.77
2	2.88	2.84 2.84 2.64	2.77	0.10	2.58
3	11.25	11.40 11.20 11.04	11.21	0.04	0.93
4	5.50	5.24 5.40 5.64	5.43	0.07	1.86
5	11.50	11.32 11.20 11.38	11.30	0.20	5.08
6	11.50	11.40 11.48 11.56	11.48	0.02	0.51
7	11.75	11.72 11.84 11.62	11.73	0.02	0.59
8	11.63	11.52 11.52 11.60	11.55	0.08	1.99
9	11.75	11.76 11.80 11.80	11.79	0.04	0.93
10	12.13	12.24 12.04 11.80	12.03	0.10	2.50
11	1.75	1.76 1.68 1.64	1.69	0.06	1.44
12	11.88	11.84 11.72 11.80	11.79	0.09	2.24
13	11.63	11.84 11.44 11.52	11.60	0.03	0.64
14	11.75	11.88 11.72 11.80	11.80	0.05	1.27
15	12.00	11.96 12.08 11.80	11.95	0.05	1.35
16	1.88	1.80 1.80 1.88	1.83	0.05	1.23
		Average Difference		0.07	1.83

Hogback Covered Bridge, Madison County, Iowa

Figures 57-58 show the locations on the bridges where the actual measurements were collected using traditional tape measures to a resolution of 1/16 in. Once the point cloud was developed from the multiple laser scans of a bridge, the data was extracted from the digital file and simply compared for accuracy. Table 3 shows the results of this comparison, showing that the laser scanning is a very accurate means of determining dimensions for use in creating as built documentation.

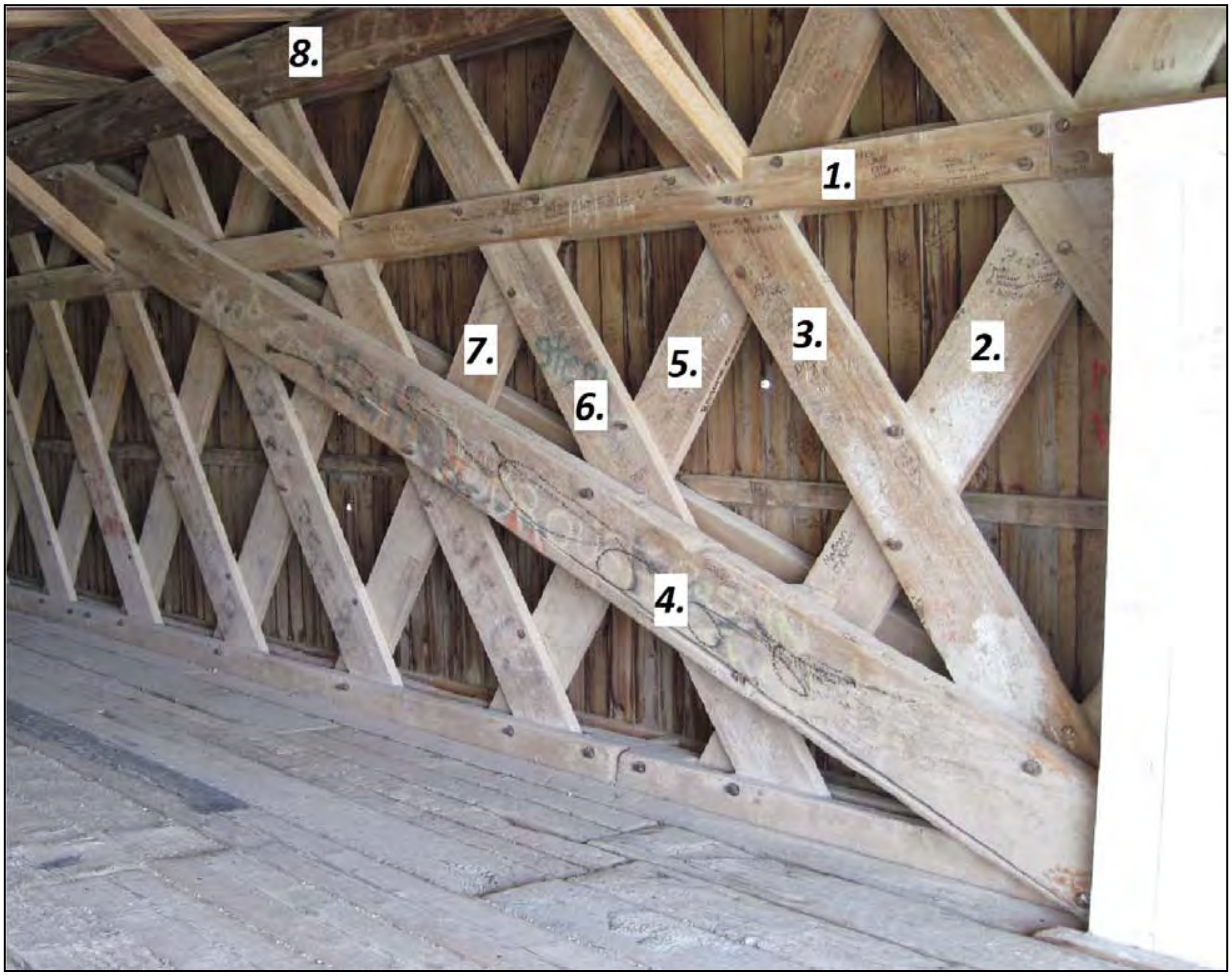

Figure 57.--Locations where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

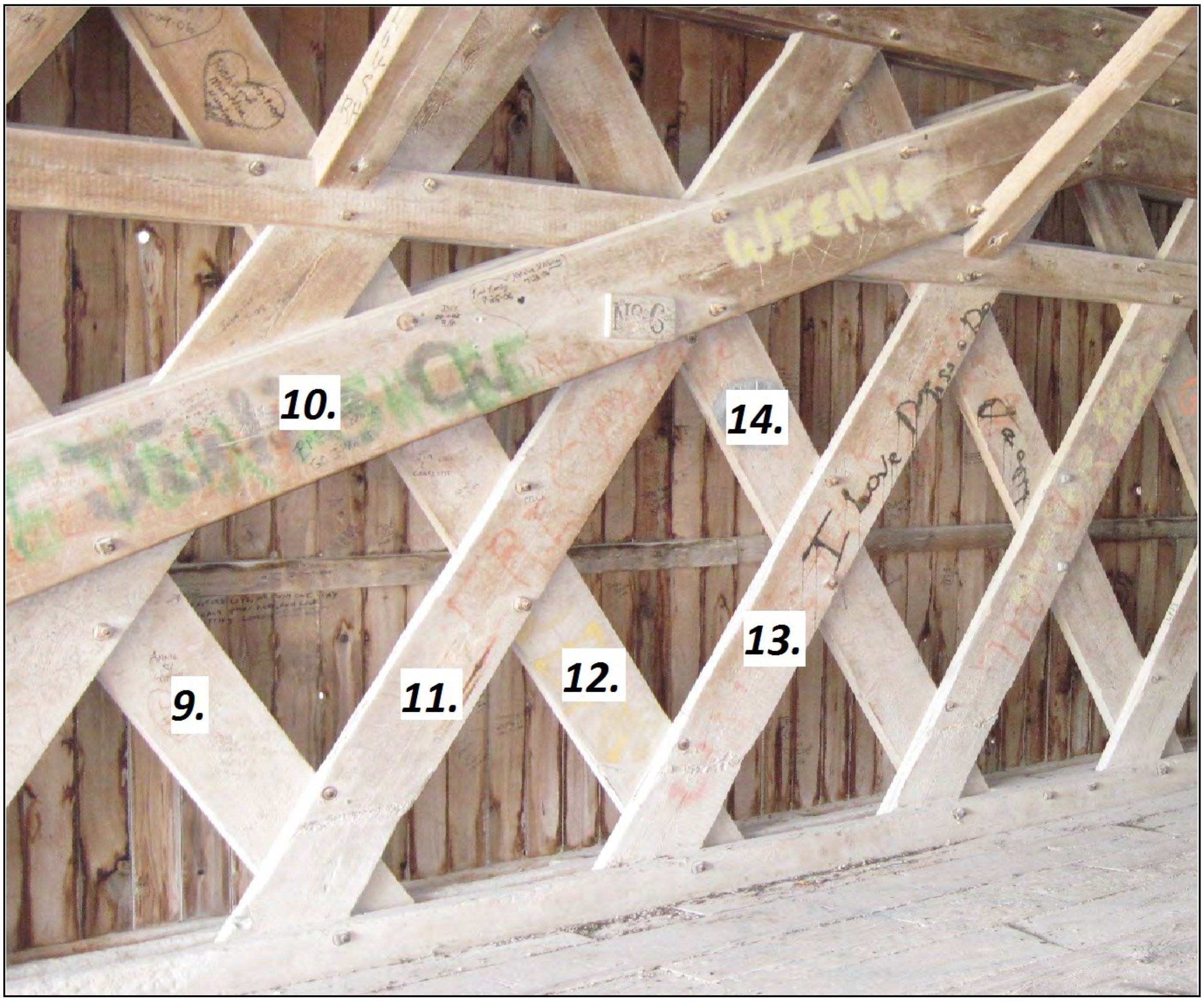

Figure 58.--Locations on the Hogback Bridge where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

Table 3.--Comparison of measurement data from traditional tape measures and point cloud measurements for the Hogback Covered Bridge, Madison County, Iowa.

Member Number	Method for Measurement			Difference Between Tape and Point Cloud	
	Tape Measurement (1/16 in.)	Point Cloud			
		3 Points (in.)	Mean (in.)	(in.)	(mm)
1	8.00	7.96 8.04 8.08	8.03	0.03	0.68
2	11.75	11.84 11.76 11.56	11.72	0.03	0.76
3	12.00	12.16 12.04 12.00	12.07	0.07	1.69
4	15.75	15.96 15.68 15.68	15.77	0.02	0.59
5	11.38	11.20 11.28 11.52	11.33	0.04	1.06
6	11.88	11.96 11.80 11.68	11.81	0.06	1.57
7	11.63	11.60 11.48 11.68	11.59	0.04	0.97
8	14.88	14.96 14.88 14.80	14.88	0.01	0.13
9	11.38	11.20 11.40 11.24	11.28	0.09	2.41
10	15.88	16.00 15.76 15.88	15.88	0.01	0.13
11	11.50	11.40 11.48 11.64	11.51	0.01	0.17
12	11.75	11.64 11.80 11.64	11.69	0.06	1.44
13	12.00	11.84 11.84 12.00	11.89	0.11	2.71
14	12.00	11.72 11.84 12.04	11.87	0.13	3.39
		Average Difference		0.05	1.26

Roseman Covered Bridge, Madison County, Iowa

Figures 59-60 show the locations on the bridges where the actual measurements were collected using traditional tape measures to a resolution of 1/16 in. Once the point cloud was developed from the multiple laser scans of a bridge, the data was extracted from the digital file and simply compared for accuracy. Table 4 shows the results of this comparison, showing that laser scanning is a very accurate means of determining dimensions for use in creating as built documentation.

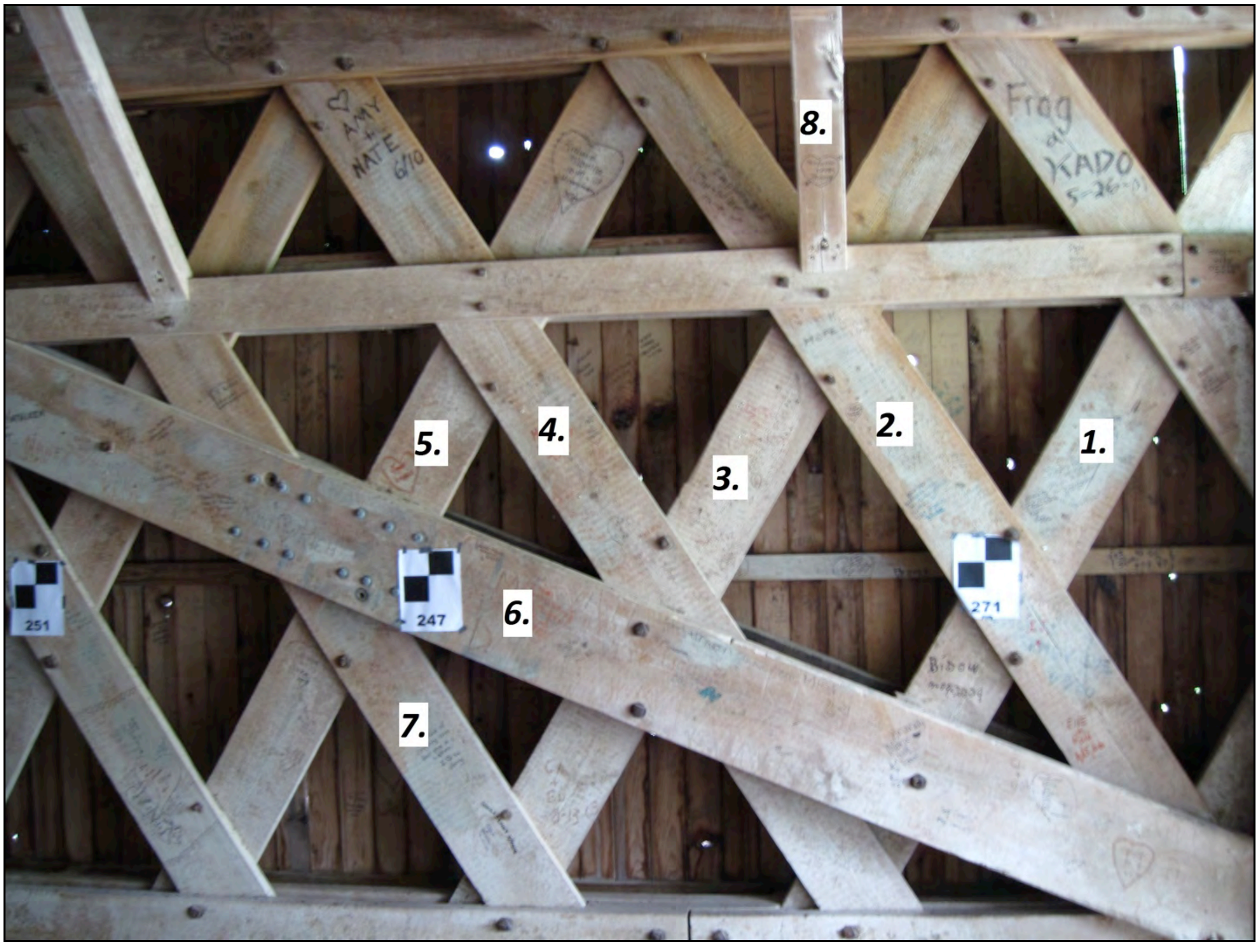

Figure 59.--Locations on the Roseman Bridge where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

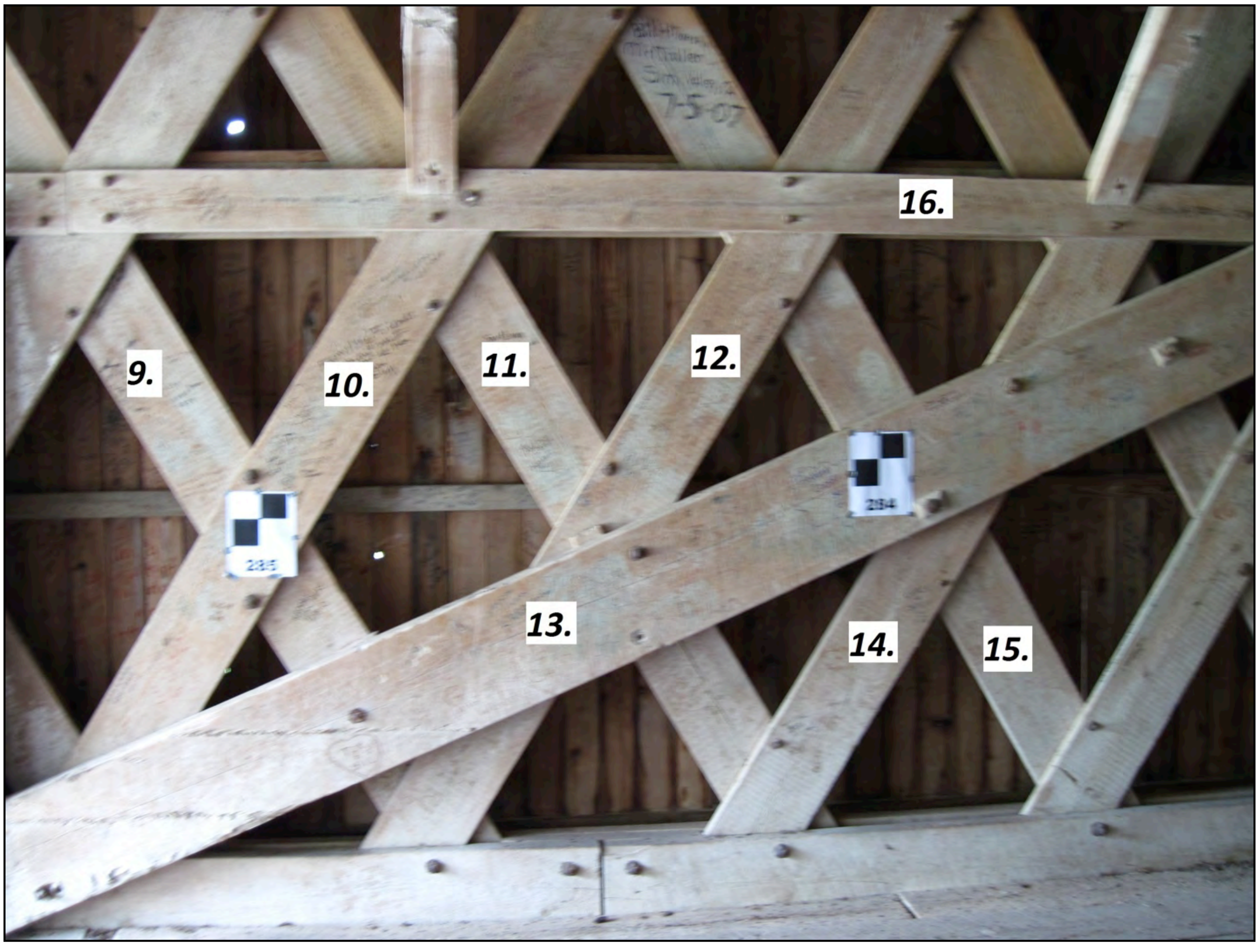

Figure 60.--Locations on the Roseman Bridge where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

Table 4.--Comparison of measurement data from traditional tape measures and point cloud measurements for the Roseman Covered Bridge, Madison County, Iowa.

Member Number	Method for Measurement			Difference Between Tape and Point Cloud	
	Tape Measurement (1/16 in.)	Point Cloud			
		3 Points (in.)	Mean (in.)	(in.)	(mm)
1	11.63	11.76	11.62	0.01	0.13
		11.50			
		11.60			
2	11.88	12.00	11.91	0.03	0.80
		11.92			
		11.80			
3	11.88	11.96	11.84	0.04	0.89
		11.72			
		11.84			
4	11.75	11.64	11.71	0.04	1.10
		11.72			
		11.76			
5	11.88	11.76	11.79	0.09	2.24
		11.84			
		11.76			
6	15.75	15.52	15.69	0.06	1.44
		15.60			
		15.96			
7	11.63	11.72	11.61	0.02	0.47
		11.50			
		11.60			
8	5.88	5.92	5.84	0.04	0.89
		6.00			
		5.60			
9	11.50	11.52	11.47	0.03	0.85
		11.48			
		11.40			
10	11.50	11.48	11.49	0.01	0.17
		11.56			
		11.44			
11	11.63	11.76	11.71	0.08	2.07
		11.72			
		11.64			
12	11.50	11.60	11.57	0.07	1.86
		11.52			
		11.60			
13	16.00	15.96	15.97	0.03	0.68
		15.96			
		16.00			
14	11.63	11.64	11.60	0.02	0.64
		11.60			
		11.56			
15	11.63	11.56	11.61	0.01	0.30
		11.68			
		11.60			
16	7.63	7.48	7.56	0.07	1.65
		7.56			
		7.64			
		Average Difference		0.04	1.01

Cutler-Donahoe Covered Bridge, Madison County, Iowa

Figures 61-62 show the locations on the bridges where the actual measurements were collected using traditional tape measures to a resolution of 1/16 in. Once the point cloud was developed from the multiple laser scans of a bridge, the data was extracted from the digital file and simply compared for accuracy. Table 5 shows the results of this comparison, showing that laser scanning is a very accurate means of determining dimensions for use in creating as built documentation.

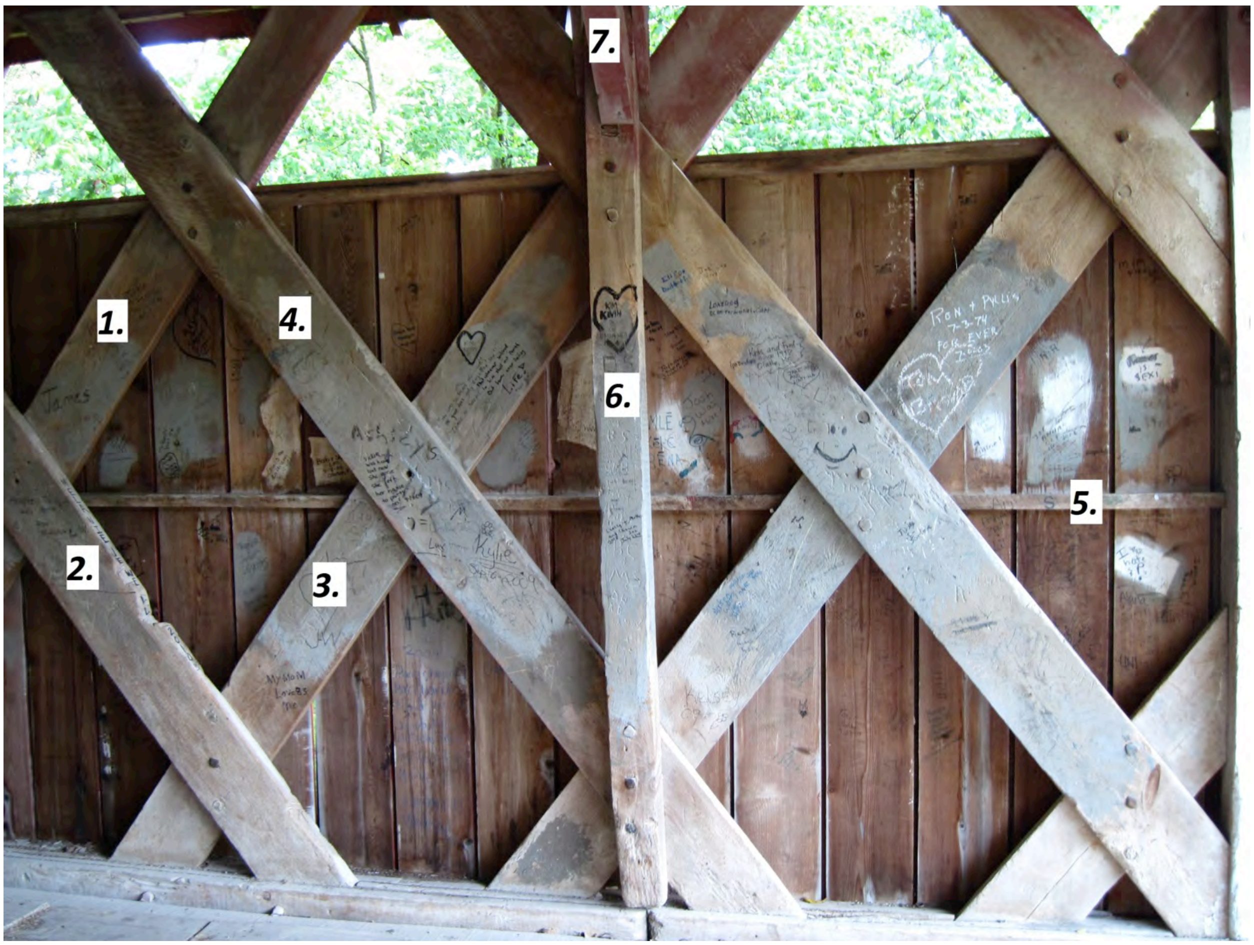

Figure 61.--Locations on the Cutler-Donahoe Bridge where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

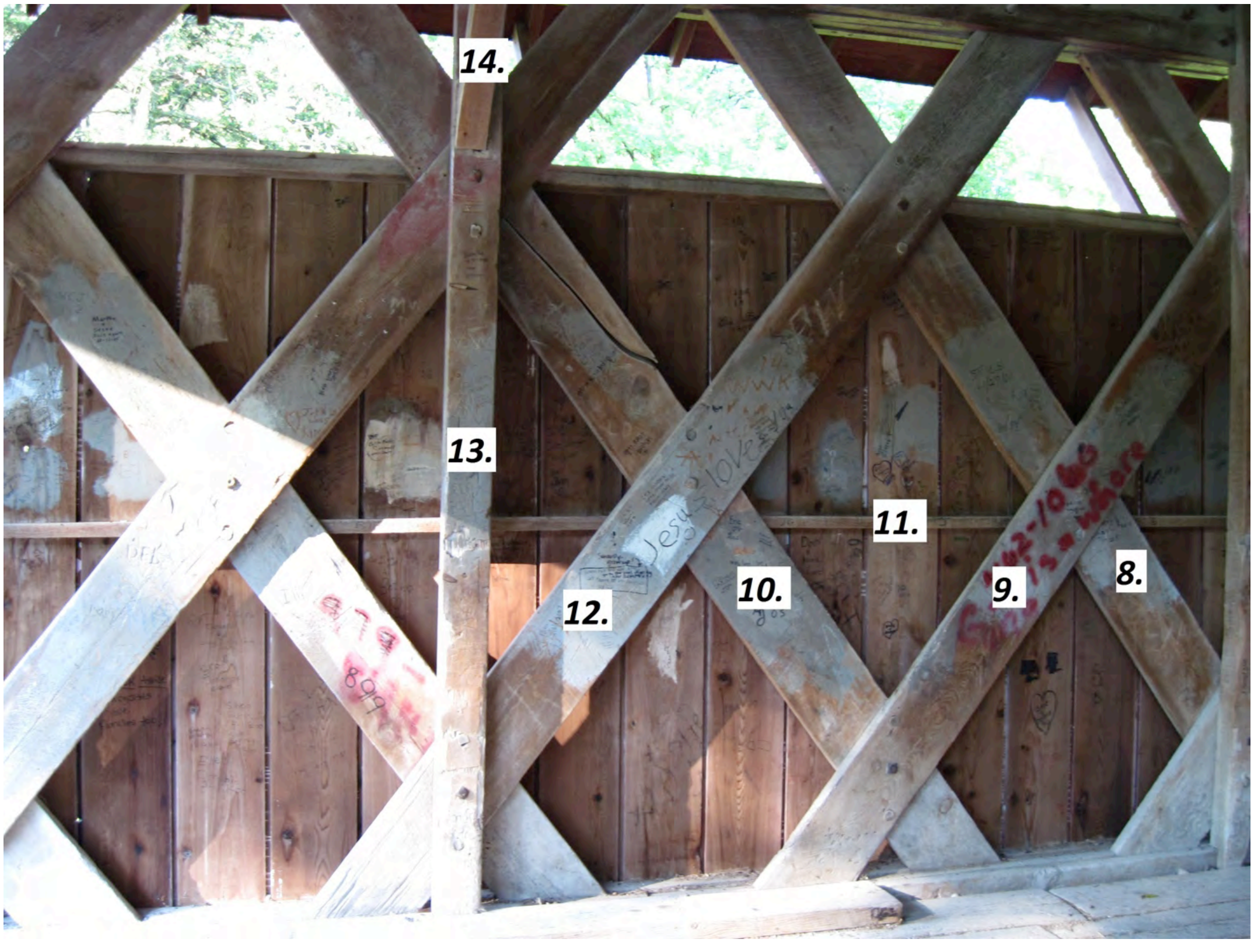

Figure 62.--Locations on the Cutler-Donahoe Bridge where comparison measurements were taken using traditional tape measures and extracted from the digital point clouds created from the laser scanning process.

Table 5.--Comparison of measurement data from traditional tape measures and point cloud measurements for the Cutler-Donahoe Covered Bridge, Madison County, Iowa.

Member Number	Method for Measurement			Difference Between Tape and Point Cloud	
	Tape Measurement (1/16 in.)	Point Cloud			
		3 Points (in.)	Mean (in.)	(in.)	(mm)
1	11.63	11.60 11.64 11.40	11.55	0.08	1.99
2	11.63	11.72 11.48 11.52	11.57	0.05	1.31
3	11.75	11.60 11.76 11.76	11.71	0.04	1.10
4	11.50	11.48 11.72 11.68	11.63	0.13	3.22
5	1.75	1.76 1.64 1.80	1.73	0.02	0.42
6	5.88	5.80 5.72 5.68	5.73	0.14	3.60
7	3.75	3.68 3.80 3.80	3.76	0.01	0.25
8	12.00	11.96 11.84 11.88	11.89	0.11	2.71
9	11.50	11.56 11.56 11.80	11.64	0.14	3.56
10	12.00	12.16 12.04 11.96	12.05	0.05	1.35
11	1.63	1.64 1.72 1.56	1.64	0.01	0.38
12	12.00	11.92 11.88 11.68	11.83	0.17	4.40
13	5.75	5.68 5.72 5.72	5.71	0.04	1.10
14	3.88	3.60 3.88 3.72	3.73	0.14	3.60
		Average Difference		0.08	2.07

CONCLUSIONS

This project successfully demonstrated the potential for using 3D laser scanning to accurately develop as-built documentation of historic covered bridges as a means to develop historical documentation. The following conclusions can be made from the project.

- Three dimensional laser scanning can be used to rapidly scan historic covered bridge structures. There are a number of technologies and commercial vendors available. A commercial FARO scanner was used in this project and operated by using a phase shift technology rather than time of flight. This means that instead of a single pulse being reflected and the time of flight measured, constant waves of varying length are projected. Upon contact with an object, they are reflected back to the scanner. The distance from the scanner to the object is accurately measured by measuring the phase shifts in the waves of infrared light.

- Post-processing of the scan data requires experience and skill to cost-effectively create as-built documentation. The staff at Sightline, LLC was very efficient in linking the 3D scans, importing them into AutoCAD® and creating detailed 2D and 3D CAD drawings. Our project student engineer faced a steep learning curve, but developed an excellent skillset in processing the files during the project. For experienced staff, this technology can reduce the time associated with creating as-built documentation.

- A 3D scanner can be used to create a range of outputs that include point cloud scans, parametric images, and 2D and 3D AutoCAD® drawings. For historic covered bridges, this information can be used for a variety of purposes including as-built documentation and structural assessment, while also providing detail on the land topography adjacent to the bridge.

- One of the objectives of the project was to assess the accuracy of laser scanning to determine accurate dimensions of the bridges. Each bridge was then scanned using the laser scanner at up to 20+ locations. The raw scan data was processed into point cloud data. The locations measured using traditional measuring equipment on the photographs were then located in the digital files and the digital dimensions noted. Based on this data, a comparison between the actual and digital measurements was taken. The comparison data is reported for each of the four Madison County bridges in the following sections. Fourteen to sixteen locations were samples for each bridge with a very small error noted. This mean error of the 14-16 measurements ranged from 0.04 - 0.08 in. (1.01 - 2.02 mm), within the rated scanner accuracy of ¼ inch at 150 ft.

- The project resulted in a number of public relations stories and information. Appendix D contains several stories that were published by Faro Technologies and several newspapers.

- The background developed by the UMD NRRI project team provided the stimulus to successfully apply for the 2011 University of Minnesota Infrastructure Investment Initiative (I^3), resulting in the purchase of a 2011 3D laser scanner. It is envisioned that the access to this equipment will allow the project team to investigate and demonstrate other potential wood science or forestry applications, as well as provide opportunities for other University of Minnesota staff to work on other areas as noted in Appendix C.

PRESENTATIONS AND REPORTS

There were several reports and presentations completed during this project located in Appendix D.

Brashaw, B.K. and S. Anderson (2010). Use of laser scanning technology to obtain as-built records of the Zumbrota covered bridge. NRRI Technical Report NRRI/TR-2011/04. University of Minnesota Duluth.

Brashaw, B.K., R. Vatalaro, S. Anderson, P. Anstey, W. Krueger, R.J. Ross and X. Wang. 2011. Use of laser scanning technology to obtain as-built records of historic covered bridges. Proceedings: 17th International Symposium on Nondestructive Testing and Evaluation of Wood. Sopron, Hungary (written paper and presentation).

National Center for Wood Transportation Structures. 2009. Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges. Research in Progress. RIP-4714-017. USDA Forest Products Laboratory. 2 p.

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Brashaw, B.K. (2010). Use of laser scanning technology to obtain as-built records of the Zumbrota covered bridge. NRRI Technical Report NRRI/TR-2011/04. University of Minnesota Duluth.

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Madison County, Iowa. "Madison County, Iowa - The Bridges of Madison County." *Madison County, Iowa - Madison County, Iowa Chamber of Commerce*. 2011. Web. 06 Oct. 2011. http://madisoncounty.com/index.php?page=the-bridges.

Ozaukee County. History Of The Covered Bridge. *Ozaukee County, Wisconsin*. 2011. Web. 06 Oct. 2011. http://www.co.ozaukee.wi.us/history/bridge.html.

APPENDIX A

Poster of Cedarburg, Wisconsin Historic Covered Bridge presented at Grand Opening of the USDA Forest Products Laboratory Centennial Research Building, June 2010

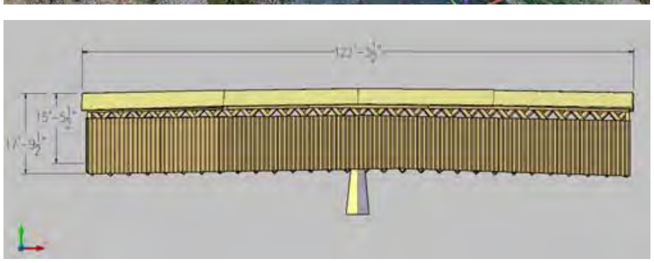
Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges

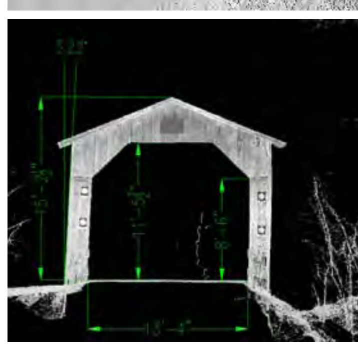
Documentation of covered timber bridges is important to preserving their bridge life histories, as many are being lost forever. 3D laser scanning techniques are being used by a cooperative Forest Service, University of Minnesota Duluth and Sightline LLC team to document bridges in a rapid, accurate, and cost-effective manner. An implementation approach is being developed for using laser scanning on historic covered bridges.

UMD Duluth – Natural Resources Research Institute
Forest Products Laboratory – 100 Years of Service 1910–2010
SightLine LLC – High Definition Laser Scanning & As Built Documentation Services
FARO

Cedarburg, Wisconsin “Red” Bridge

Laser scanning with 120,000 measurements/second was used to create 3D images of this covered bridge. Vendor specific software processes the raw data into detailed scan images that can be converted into accurate computer-aided design (CAD) images, allowing for detailed, historical documentation of structures.





Core funding by the National Center for Wood Transportation Structures:

U.S. Department of Transportation Federal Highway Administration

USDA Forest Products Laboratory

National Park Service

Iowa State University

APPENDIX B

"Bridging the Old with the New: Historic bridges are preserved with laser technologies"
NRRI Now Autumn 2010 Newsletter Article

"Documenting the Bridges of Madison County using Laser Scanners"
Faro Technologies Inc.

"Lasers Uncover Town of Cedarburg Bridge History"
Milwaukee Journal Sentinel

"Scanner To Draw Madison Bridges In 3-D"
Des Moines Register (Iowa)

"Scanning for Posterity"
Winterset Madisonian

A Great University on a Great Lake

University of Minnesota Duluth

Natural Resources Research Institute

NRRI Now

Autumn 2010

Sunrise over Lake Superior. NRRI receives U.S. EPA funding for Great Lakes Restoration Initiative research.

~Growing Strong Industries

~Developing New Ideas

~Nurturing Natural Resources

Cutler-Donahue bridge in Madison County, Iowa.

Digital point cloud image.

Bridging the old with the new

Historic bridges are preserved with laser technologies

When the Zumbro River crested at 22.8 feet in September, local residents actually felt a bit of relief. At least it didn't reach the projected 28 feet that would have been a worse disaster for the town of Zumbrota, Minn.

Flooding in Goodhue County this summer was devastating to many businesses and homeowners, but another close call came when the swollen river just skimmed the bottom of the town's historic covered bridge.

Had the water reached its projected crest, however, work by NRRI this summer would have proven invaluable. Into the future, the covered bridges of Madison County in Iowa and Minnesota's one remaining covered bridge in Zumbrota are digitally imaged – down to the knot holes – and preserved for posterity.

Madison County has lost 13 of its original 19 covered bridges, built in the late 1880s – the last destroyed by arson in 2009. With no engineered drawings of the bridges, rebuilding from preserved pictures and inaccurate plans would require a lot of guesswork. The USDA Forest Products Laboratory contacted NRRI wood products Program Director Brian Brashaw to find a way to preserve the details of the remaining bridges.

Brashaw partnered with Faro Technologies, Inc. and SightLine, LLC to create computerized renderings using a 3-D laser scanning device that collects millions of points on any object. Each bridge took SightLine 6-8 hours to gather the raw scan data. NRRI intern Sam Anderson could then process the data into a digital "point cloud" (see photo above) and AutoCAD images.

"This is a great demonstration of the potential of this equipment," said Brashaw. "The bridges are a big tourist draw to these rural areas. And there are other new opportunities. We can figure out how to apply this technology to manufacturing plants, measure volumes of forest stands, or gather accurate landscape measurements for stream remediation projects."

After completing 30-plus scans on each bridge, each one is photographed, tape-measured and the information is processed with unique software provided by kubitUSA. The digital files are then sent to the USDA Forest Products Lab. With the Zumbrota bridge records, a 1/100th scale replica built in NRRI's rapid prototyping center was also included. The digital collection will eventually be added to the Library of Congress and each community will receive detailed information for their historical archives.

"We enjoyed working on this project with NRRI," said SightLine President Penny Anstey. "The bridges are important to the economy and history of these communities. And this is what we got into this business for, to preserve history."

Documenting the Bridges of Madison County using Laser Scanners

"The amount of information gathered is incomparable and simply cannot be matched using traditional methods. The tremendous versatility of the data, whether it be 2D or 3D drawings or models or a virtual fly-through, the FARO Laser Scanner is ideal for archiving environments for the future."

FARO®

Disasters can quickly destroy decades and even centuries of our historic and cultural heritage. Natural occurrences such as hurricanes, tornadoes, and earthquakes or manmade threats like arson and vandalism are unfortunate realities. Three dimensional laser scanning is an excellent means to create documentation and it allows us to preserve our history forever despite these potential dangers.

The following project is part of an initiative by the National Park Service's Historic Engineering Record to document historic structures. The University of Minnesota-Duluth's Natural Resources Research Institute received a grant from the Federal Highway Administration as well as funding from the USDA Forest Service, Forest Products Laboratory. They then contracted with SightLine, LLC to document several covered wooden bridges including four bridges in Madison County, Iowa. Should there be any misfortunate circumstances, these bridges can either be replicated as they stand today or just preserved and archived.

SightLine (www.sightlinescan.com) is a 3D laser scanning and as-built documentation service company located in Milwaukee, Wisconsin. They have an extensive background in documenting a wide array of structures for archival, renovation, alteration, modernization, BIM (building information modeling) and creating as-built drawings.

These historic covered bridges were made famous by Robert James Waller's novel "The Bridges of Madison County" and the 1995 film of the same name. After one of the more famous bridges from the novel and movie was lost to arson, an effort is being made to properly document these bridges for posterity.

Covered bridges such as these are an important part of the history of America. There are few if any drawings of these structures and they are very difficult to reproduce should something happen to them. Today, there are still several hundred of these historic bridges remaining across the country. Despite efforts to preserve them, neglect, vandalism and the high cost of restoration have taken their toll. Many of these bridges have been lost or in threat of being lost forever.

"We are honored to document these historic bridges and to take part in preserving our historical heritage," said Penny Anstey, President and William Krueger, Vice President of SightLine.

Project Outline

In the past, traditional methods would have been used for documentation. These would include the use of tape measures, photographs, and hand written notes. Speaking from experience, there are many problems associated with using these methods. For instance, inaccurate measurement, miscalculated data, inaccurate data or basic human error can be common.

Laser scanning technology provides a rapid, accurate, and cost-effective way to document these architectural structures and allowed SightLine to capture five covered wooden bridges in five days of scanning. Of course, there is more work beyond the scanning; there is time needed for processing the data and for creating the actual drawings. In the end, laser scanning is far more efficient collecting data and the accuracy is unsurpassed. The end result of the project provided a 3D virtual model of each bridge.

In simple terms, the scanner is a laser range finder, it sends out a beam of light that locates a point in space of whatever it hits and logs that point in the computer, it does this 100,000 times per second. These points are then used to form 3D point clouds to create precise documentation. Every point in the cloud can be located and measured. By collecting a tremendous amount of data very quickly, laser scanning captures an exact moment in time and provides data that can be examined and referred to at any point in the future.

Using Technology to Save the Past

To achieve the goals of this project, SightLine used a FARO Laser Scanner. FARO's laser scanner is not only fast and accurate, it is also portable. This allows SightLine to easily work in remote locations. Laser scanning is extremely efficient and effective for documenting in less than hospitable circumstances.

"We can get all of the widths and thicknesses of the boards and all of the little idiosyncrasies unique to each bridge. We can capture wood grains and even the graffiti inside a bridge," said Mr. Krueger. "The FARO Laser Scanner is really a wonderful tool."

The Laser Scanner is very easy to set up, including the laser target environment. Basically, set up the scanner and go. This fast, accurate, and hands-off approach is invaluable for gathering an immense amount of data that can be stored indefinitely and consulted at any time for any reason.

SightLine's primary service is providing clients with easy-to-use results in the form of 2D or 3D drawings, or models. FARO allows them to quickly and accurately provide these clients with a clear understanding of their project so they can move forward with confidence – eliminating potential surprises.

"With a snapshot, there's a visual image, but you can't really measure anything accurately from a photo," said Mr. Krueger. "With a laser scanner you can."

Scanning for Posterity

By documenting these bridges with a FARO Laser Scanner, SightLine was able to complete each bridge in a matter of hours rather than the weeks it would take using traditional methods to acquire so much information and detail. When it comes to simply archiving environments for future reference, literally years worth of data is gathered in mere days.

"The amount of information gathered is incomparable and simply cannot be matched using traditional methods," said Ms. Anstey. "The tremendous versatility of the data, whether it be 2D or 3D drawings or models or a virtual fly-through, the FARO Laser Scanner is ideal for archiving environments for the future."

Researchers say that the scans done by SightLine and the FARO Laser Scanner will serve as a guide for repairing or rebuilding the bridges should they be damaged or destroyed.

"Rest assured, should anything ever happen to these bridges, they can be rebuilt," said Mr. Krueger. Ms. Anstey concluded, "The application of this technology is limited only by your imagination."

JSOnline
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JOURNAL SENTINEL
2010, 2008 Pulitzer Prize Winner for Local Reporting

Lasers uncover Town of Cedarburg bridge history

Tom Lynn

William Krueger, vice president of SightLine, uses a 3-D laser scanner to document how the covered bridge was constructed. The scanners were moved several times along the length of the bridge to ensure all sides of boards were measured by the lasers.

3-D scanning shows how 1876 span was built

By Don Behm of the Journal Sentinel

Posted: April 15, 2010

Town of Cedarburg — A 134-year-old covered bridge was given laser treatment Thursday.

Lasers did not remove wrinkles or other blemishes from the aging pine boards and planks, though there is graffiti scratched and painted on the wood.

And there has been some settling over the years - a slight tilt to the left is visible at the north entrance - that could benefit from cosmetic carpentry.

Two scanning lasers were used to measure each piece of the historic bridge, inside and out, and the distances between planks and trusses and ceiling beams and floorboards, said William Krueger, vice president of SightLine LLC of Milwaukee.

Continuous scanning - recording 120,000 measurements per second - created 3-D images of the structure, formerly known as Red Bridge, Krueger said. The scanners, which rotate 360 degrees, were moved several times along the length of the bridge to ensure all sides of boards were measured by the lasers.

The information will provide a detailed, as-built description to benefit workers in the future if the covered bridge, with lattice walls, ever needs to be rebuilt, said Penny Anstey, SightLine president. The scanners even detected a slight rise in the center of the bridge floor.

The measurements, and the images created, are more accurate and complete than original drawings, Anstey said.

The bridge, at Ozaukee County's Covered Bridge Park, was built in 1876. This might be the last intact covered bridge at its original location in Wisconsin, according to county parks officials.

Red Bridge was not retired from vehicle use until 1962, when it was bypassed in favor of a new bridge for Covered Bridge Road. The retired 120-foot-long bridge spans Cedar Creek north of state Highway 60. It is used by pedestrians and bicyclists.

The laser part of these devices is similar to the rangefinder a golfer or hunter might use, Anstey said. The narrow beam of energy determines the distance to an object by measuring the time it takes to reflect off the object and return to the scanner.

Inside the covered bridge, the lasers became substitutes for tape measures. Hundreds of thousands of measurements were gained in less than four hours.

Gathering 'fine detail'

"Measuring this by hand would have taken several days to several weeks, but you would not have such fine detail," Krueger said. "Lasers capture the nuances of the original construction, showing where some beams might have been placed an inch further apart than others."

Pine logs for the bridge were cut from the Baraboo Hills and cut into planks at a mill there before being hauled to Cedarburg, according to a history of the bridge on Ozaukee County's Web site.

Lattice walls were formed by 3-inch-by-10-inch planks held together by 2-inch diameter oak pins, or pegs. Holes were drilled into the planks and the pins were pounded into the holes.

SightLine is working with the USDA Forest Products Laboratory in Madison, the National Park Service and the University of Minnesota-Duluth to record the current condition and original construction of several historic covered bridges in the Midwest. After Cedarburg, SightLine's lasers will measure four covered bridges in Madison County, Iowa.

One reason for the project is to document the bridges before they become victims of arson or neglect, said Brian Brashaw, director of wood materials and manufacturing at UM-Duluth's Natural Resources Research Institute.

One bridge seen in the 1995 movie "The Bridges of Madison County" was destroyed in an arson fire last year, Brashaw said.

Brashaw, a structural engineer, saw little evidence of wood rot or neglect, apart from the graffiti, at the Cedarburg bridge.

The Des Moines Register | TUESDAY, JULY 13, 2010 | STATE EDITION

Metro&Iowa

Scanner to draw Madison bridges in 3-D

Plans of the spans don't exist, so the images could be used in rebuilding them, should the need arise.

By REGINA ZILBERMINTS
rzilbermin@dmreg.com

Madison County officials will have more accurate renderings of the area's historic covered bridges as part of a project to test new technology.

SightLine, a Milwaukee company, this week is slated to begin scanning the bridges, made famous by the book and movie "The Bridges of Madison County."

The firm will use a laser scanner to collect millions of points and create three-dimensional renderings of four of the six area bridges: Roseman, Imes, Hogback and Cutler-Donahoe.

The scanner "will draw every board and every bolt" of the bridges, SightLine President Penny Anstery said. "With traditional methods, measures can be off. The scanner doesn't forget and doesn't make mistakes."

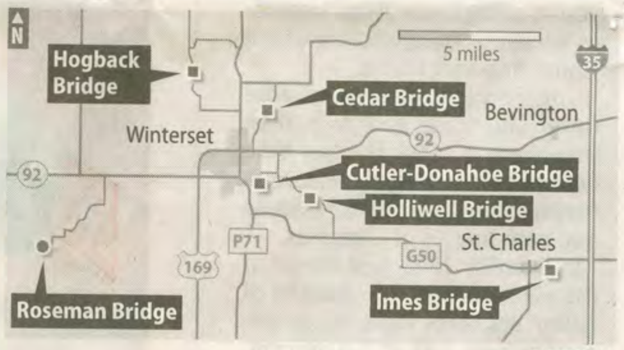
That information, combined with photographs, can be used to rebuild a bridge if needed.

When a bridge burned down in 2002, engineers rebuilding it had to guess at the plans using photographs and measurements of other bridges, county engineer Todd Hagan said.

The county doesn't have any original plans of the structures.

This is new technology, and the project by the U.S. Forest Service's Forest Products Laboratory is scanning six bridges — four in Iowa, one in Wisconsin and one in Minnesota.

"It's a systematic, scientific approach to assessing this technology and its use for historic timber bridges," said Bob Ross of the labo-



THE REGISTER

BRIDGES

FROM PAGE 3A

ratory.

If successful, officials can use it on timber bridges nationwide.

"There's been a real interest in preserving and conserving historic infrastructure, and we're responding to that," Ross added.

The $100,000 project is funded through the Federal Highway Administration.

Each bridge will take about four hours to scan.

It will take an additional two weeks to complete the renderings.

In addition to the images, SightLine will create a short movie so viewers can "walk through" the bridge.

"We're trying to preserve a little bit of history," Hagan said. "The main goal is to preserve what they have. We don't like to replace or replicate them. It's not the same. But when we get them scanned, if we do lose them, at least we'll have some accurate plans or electronic documents."

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Scanning for posterity

Laser scanning to aid in historic preservation

The bridges of Madison County are going 3D, but they won't be showing in theaters. Instead, the 3D laser images gathered by a company called SightLine will be used to aid in the historical preservation of the valuable wooden structures.

It all began when the United States Department of Agriculture Forestry Laboratories in Madison, Wisc., contacted the research branch of the University of Minnesota Duluth. As part of the Natural Resources Research Institute (NRRI), Principal Research Shop Foreman Robert Vatalaro was hired to participate in the project. NRRI Program Director Brian Brashaw then contacted SightLine President Penny Anstey in Milwaukee.

"This sort of project is right up our alley," said Anstey with a smile.

This project is the second bridge laser scan that SightLine has done.

"This is what we do; we scan and then create drawings so that the detail of these bridges will be preserved. If something was to ever happen, then with these drawings, the bridges could be rebuilt down to the last detail," Anstey said.

And she means the last detail. The expensive laser scanning equipment is 100-percent accurate down to a knothole, according to

Scanning

Continued on page 2A

SightLine business partners William Krueger and company president Penny Anstey survey progress of a laser scan on the Roseman Covered Bridge.

Brenda Clifton appointed to the Winterset school board

Clifton joins Shane Pashek, Jeff Nicholl, Mike Motsinger and Karen Brookhart on the five-member board

The Winterset school board Monday tapped Brenda Clifton as the newest member of the five-member board.

Clifton was among three Winterset city residents who submitted letters of application for the position following the resignation of school board member Sarah Kelley, who moved out of the district. Clifton, Michele Shortley and Scot Clark all submitted letters to the school board asking to be appointed as an interim director — school board member — on the panel.

The school board is com-

A scan-do kind of job

Scanning

Continued from page 1A

Anstey's business partner William Krueger.

"We document everything we are hired to do; in this case we can draw every board and beam on the bridge; the scanner is so exact it will even pick up the grain of the wood and the writing on the walls," Krueger said.

The project began on Monday with the scanning of Roseman Bridge. Imes Bridge will be scanned second, with Hogback third and Cutler-Donahue the last bridge to be scanned before the week is out.

With it taking roughly four hours per bridge, the laser scan is a lengthy process, but not nearly as involved as the traditional methods of documenting a historical building, according to Anstey.

"What will take us the better part of a week, could possibly have taken months with the traditional methods of measuring and drawing," Anstey said.

Laser scan technology is also more accurate as the scanner collects everything that is visible.

"It works like a range finder on a golf course-the mirror spins, the laser hits it, it goes out, hits a surface, comes back and is registered on the scanner by creating a point-cloud image, which is basically millions of dots that make up the image," Anstey explained the scanning process.

Using foam target balls and marker sheets to target the line of sight, the images are then linked together creating a complete and whole image as opposed to the pieces it was scanned in.

Though it may seem like the machines are doing most of the work, there is still a lot left to be done after the scanning process is over.

"It still takes time to get the images back into the office and do the drawings, but you have the images and everything you need right there," Kreuger said.

After the images are scanned, they appear like a black and white photograph. The next process is to actually digitally photograph the bridges as well so the color image can be overlaid on the black and white one. Computer-Aided Design (CAD) drawings will then be done by engineer intern Sam Anderson to complete the process. The end result sent to the USDA Forestry Labs will be a collection of accurate drawings and laser images preserving the way the bridges look forever.

"It's faster and more accurate than any traditional methods could ever be," said Anstey and Krueger who both started out documenting in the traditional way. About the only thing that restricts this method of documentation is the rain as the scanners cannot operate in inclement weather.

Even the many visitors that stopped by the bridge on Monday posed no problem to the scanner's capabilities.

"As people walk through the bridge and the scanner pics them up, they show as just a little splice – we take that out, and it's like they weren't even there," Anstey said.

Visitors to the bridge were very understanding and curious about the process.

"I think it is great; it's good to record these images historically in case anything ever happens," said bridge tourist Richard Kenney. Kenney and his wife Gail traveled from Malvern, Ark., to visit the bridges for the first time on Monday.

"There have been loads of people come through while we have been working; I didn't realize what a big tourist attraction these bridges were; they're a big deal," said Vatalaro.

The laser scan captures the minutest detail of the bridges; as Kreuger said, it is comparative to a "snapshot in time."

When the group is fin-

Madisonian photo/Charlotte Underwood

Penny's pride: Penny Anstey owns a company which has six-figure toys like this high definition laser scanner being used to scan several area covered bridges.

Scanning

Continued on page 8A

Covered bridges go high-def

Scanning

Continued from page 2A

ished by Thursday, the images of the four bridges will truly be captured in time and preserved on file with the USDA Forestry Laboratories.

"I feel honored to have been chosen to work on this project; I like history and our heritage. It shows all the work that the pioneers had to put into the infrastructures to put this country together," Krueger said.

"This is what we got into this business for, the historical preservation aspect," Anstey said proudly.

—Charlotte Underwood

photo by Charlotte Underwood

Surreal look. A laser scan of the interior of Roseman Covered Bridge, one of four covered bridges to be scanned, with the imagery to be archived for historic purposes.

APPENDIX C

Alternate Uses for Laser Scanning

Alternate Uses for 3D Laser Scanning Technology
In this project, 3D laser scanning technology was used to create as-built documentation of the historic cover bridges in North America. There are a number of commercial manufacturers of 3D scanners listed on Thomas Net and a list can be found at the following web location: http://www.thomasnet.com/products/laser-scanning-systems-3d-43279504-1.html.

There are a number of applications that 3D laser scanning are used for. A brief list and summary of the applications was provided by Faro Inc. (2011) and includes:

ARCHITECTURE AND CIVIL ENGINEERING APPLICATIONS
- Excavation control: Simple and precise volume and dimension control of excavations.
- Deformations control: Documentation of deformation processes and monitoring of countermeasures.
- Facades inspection: 3D dimensional inspection of building shells and facade components before final assembly.
- Structural analysis and maintenance: Rapid and cost effective control of the specified load-bearing capacity of supporting structures as well as wear and tear.
- Free-form components inspection: Precise dimensional check of complex components such as free-form shape elements.
- Built environment: Precise geometrical recording of existing properties as the basis for conversions or extensions.
- Construction progress monitoring: Seamless capture and monitoring of construction progress for legal and technical documentation.

PROCESS INDUSTRY AND DIGITAL FACTORY APPLICATIONS
- Conversions and extensions: Precise 3D documentation of the current state of the property as the planning basis for conversions and extensions.
- Offsite production: Possibility of precise-fit off-site assembly, thanks to exact 3D CAD data and dimensional control.
- Asset management: Simplification of facility management, maintenance, training, etc. through comprehensive 3D master data, simulations and training in virtual reality.
- Site supervision: Improved coordination between different trades and comprehensive documentation and supervision of all work.

INSPECTION AND REVERSE ENGINEERING APPLICATIONS
- Reverse engineering: Copies of products and components for which there are no construction plans and/or CAD data available.
- Interior fixtures and fittings: Precise 3D CAD documentation of complex interiors of ships, cars or aircrafts as a basis for planning of conversions.
- Manufacturing documentation: Complete 3D documentation of the manufacturing status of complex machine components.
- Quality control: Precise 3D documentation and dimensional inspection of large and complex components such as rotor blades, turbines, ship propellers, etc.

FORENSIC AND ACCIDENT SCENE APPLICATIONS
- Rapid and complete 3D recordings of crime and accident scenes or insurance damage: All details of relevance in any subsequent reconstruction of the crime or accident are covered.

Similarly, in order to develop appropriate safety concepts for events, laser scans deliver the relevant 3D topography information.

HERITAGE APPLICATIONS

- Complete and detailed documentation of historical structures or excavation sites: Whether for restoration or scientific analysis purposes, for securing protected buildings or for virtual presentations of historical sites that must not be accessed by visitors.

APPENDIX D

Papers and Presentations

Research in Progress

Natural Resources Research Institute

National Center for Wood Transportation Structures

Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges

Documentation of covered timber bridges is important to preserving their bridge life histories, as many are being lost forever. New laser scanning techniques will be used by a cooperative Forest Service and University of Minnesota Duluth research team to document several of these bridges in a rapid, accurate, and cost-effective manner. An implementation approach will be developed for using laser scanning for historic covered wood bridges.

3D laser scanning technologies are used to document as-built conditions of historic structures, such as this 1905 bridge built by A.Y. Bayne & Co. It is currently located on the grounds of Minnesota's St. Louis County Richard H. Hansen Public Works and Transportation Complex.

Background

Covered bridges are part of the fabric of American history, and several hundred historic covered bridges still exist today. Although much effort is expended to preserve these structures, the high cost of restoration, neglect, and vandalism often take their toll, and many are lost forever. One of the more famous bridges from "Bridges of Madison County" movie fame recently burned down. Because we cannot completely prevent these types of incidents from occurring, we should at least properly document these bridges for posterity. The National Park Service's Historic American Engineering Record (HAER) has efforts underway to document historic structures. Their Level I documentation is defined in the Secretary of the Interior's Standards and Guidelines for Architectural and Engineering Documentation and consists of measured and interpretive drawings, large-format photographs, and written historical reports. To assist in this effort, newer technologies need to be explored that can provide as-built records at a faster rate and with more accuracy. This research will explore the use of laser scanning technology to scan existing bridges for purposes of obtaining as-built records of physical dimensions and construction features. Priority will be given to any bridge in danger of collapse or removal. Level I documentation standards will be followed to develop records. This research will lead to the identification and demonstration of laser scanning technology and the development of Level I documentation using this technology.

Objective

This project will examine the technical feasibility of using laser scanning technologies for obtaining as-built records for historic covered timber bridges.

Approach

The technical literature pertaining to laser scanning technologies will be reviewed, and appropriate laser scanning equipment will be obtained. Six historic covered timber bridges will be selected for evaluation, field tests using the laser scanning equipment will be conducted, and conventional field measurements of the selected bridges will be collected. Laser scanning measurements will be compared with field measurements, and a final report will be prepared.

Expected Outcomes

The outcome of this project will be compiled information on the use of laser technologies and interpretation of results for obtaining as-built records for historic covered bridges. This information will be available in both electronic and printed formats. Emphasis will be placed on the use of graphics, with particular emphasis on the ability of laser techniques to accurately record important bridge details.

Timeline

A literature review will completed during spring and early summer 2009. Field testing, including securing the necessary equipment, identifying bridges, and acquiring field data, will be completed during summer, fall, and winter 2009. Data analysis will be completed during spring 2010.

Cooperators

U.S. Forest Service, Forest Products Laboratory
University of Minnesota Duluth

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Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges

Brian K. Brashaw

University of Minnesota Duluth

Mississippi State University

17th International Nondestructive Testing and Evaluation of Wood Symposium

September 15, 2011

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Covered bridges are part of the fabric of American history, and several hundred historic covered bridges still exist today.

The high cost of restoration, neglect and vandalism has resulted in the loss of many bridges. Hurricane Irene also reminded us of the power of natural disasters.

Jim Cole/Associated Press

Historical Documentation
National Park Service

- Level I documentation:
  - Measured and interpretive drawings
  - Large-format photographs
  - Written historical reports

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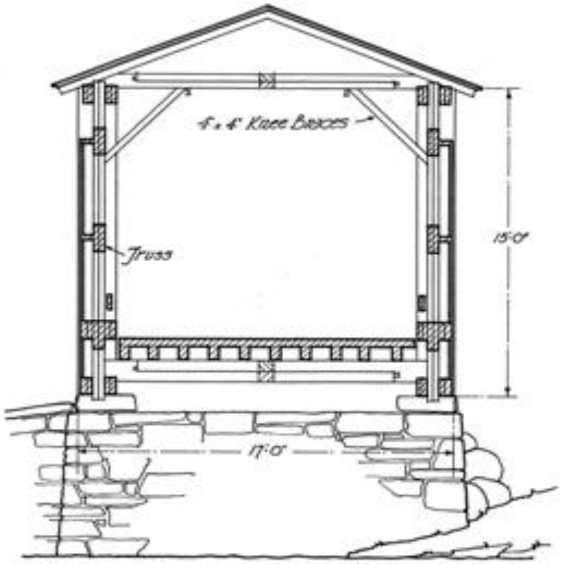
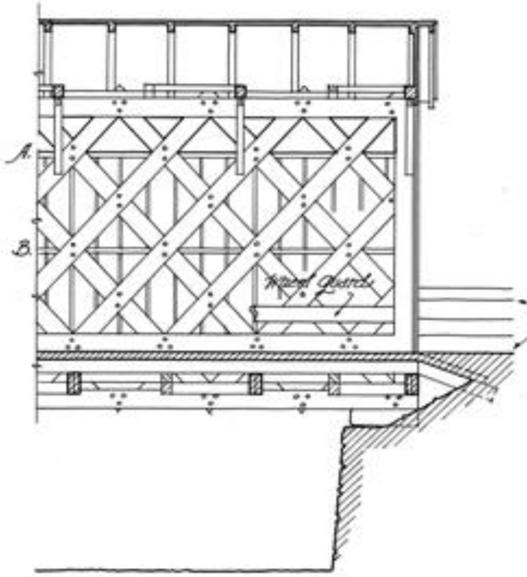
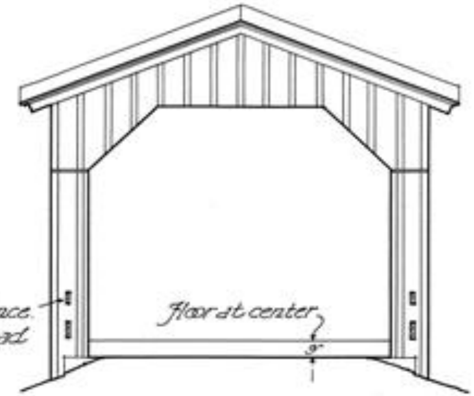


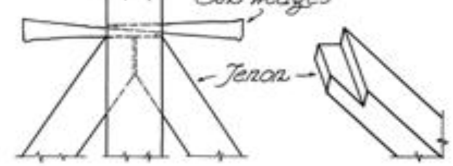
Transverse Section



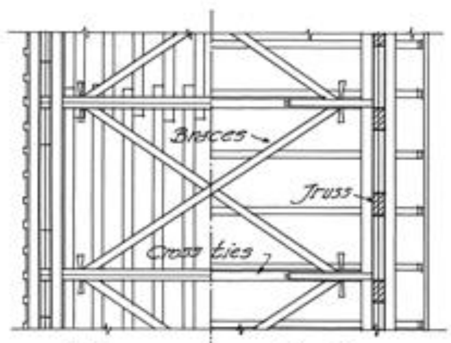
Longitudinal Section



End Elevation



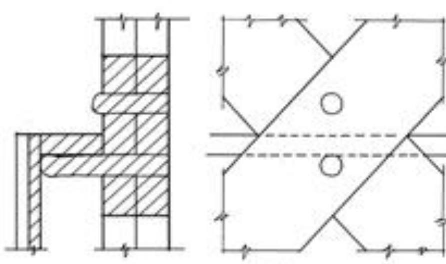
Intersection of Cross Ties & Diagonal Braces



Floor & Roof
Plans of Construction

Legend

All parts of structure are of pine except as noted. Abutments are of stone. Boards at sides & ends are 1"x12" with joints covered by 1"x4" battens. Roof is of cedar shingles supported on 3"x4" rafters spaced 30" to 36" o.c. Cross tie beams at floor are 2-2"x12" notched & bolted at ends. Diagonal braces are 4"x6" tenond into cross tie beams & wedged with oak wedges size 2"x2" at but. Construction at ceiling same except cross ties 5"x8" & braces 4"x4" in size. Floor joists are 6"x8" over which are laid 2"x4"s on edge forming floor of bridge. Truss members are 3"x10" fastened at joints with 2" dia. oak pins with exterior ends rounded. At A each lower & at B every other lower pin projects to support 2"x6"s onto which are nailed the boards & battens. Fastened to sides of truss at top, bottom & at floor line are continuous members, each of 2-2"x6"s.



Section at A   Elevation
Intersection of Truss Members

Scale in Meters

Scale in Feet
Sect. Plans & Elev.
Details

Clarence W. John, Del.   Hugo Logemann, Mens.

U.S. DEPARTMENT OF THE INTERIOR OFFICE OF NATIONAL PARKS, BUILDINGS, AND RESERVATIONS BRANCH OF PLANS AND DESIGN	Town of Cedarburg	NAME OF STRUCTURE THE COVERED BRIDGE	Ozaukee Co. Wisconsin	SURVEY NO. 28-12 Apr. 2 1934	HISTORIC AMERICAN BUILDINGS SURVEY SHEET 2 OF 2 SHEETS	INDEX NO.

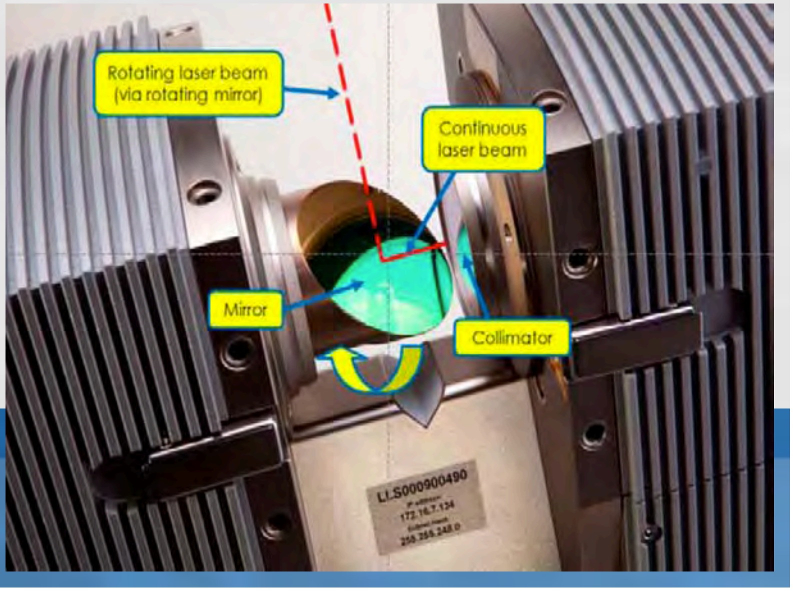
New technologies need to be developed, identified and implemented that quickly, accurately and cost-effectively.

Laser Scanning

- Can create detailed 3D images.
- This image is an assembly of millions of 3D measurement points which provide an exact digital reproduction of existing conditions.

Technology Overview

- A laser beam is emitted from a rotating mirror out towards the area being scanned. The laser beam is then reflected back to the scanner by objects in its path. The distance to the objects defining an area is calculated as well as their relative vertical and horizontal angles (Faro 2011).



Objective

- To examine the technical feasibility of using laser scanning technologies for obtaining as-built records for historic, covered timber bridges and demonstrate its potential.

Work Plan

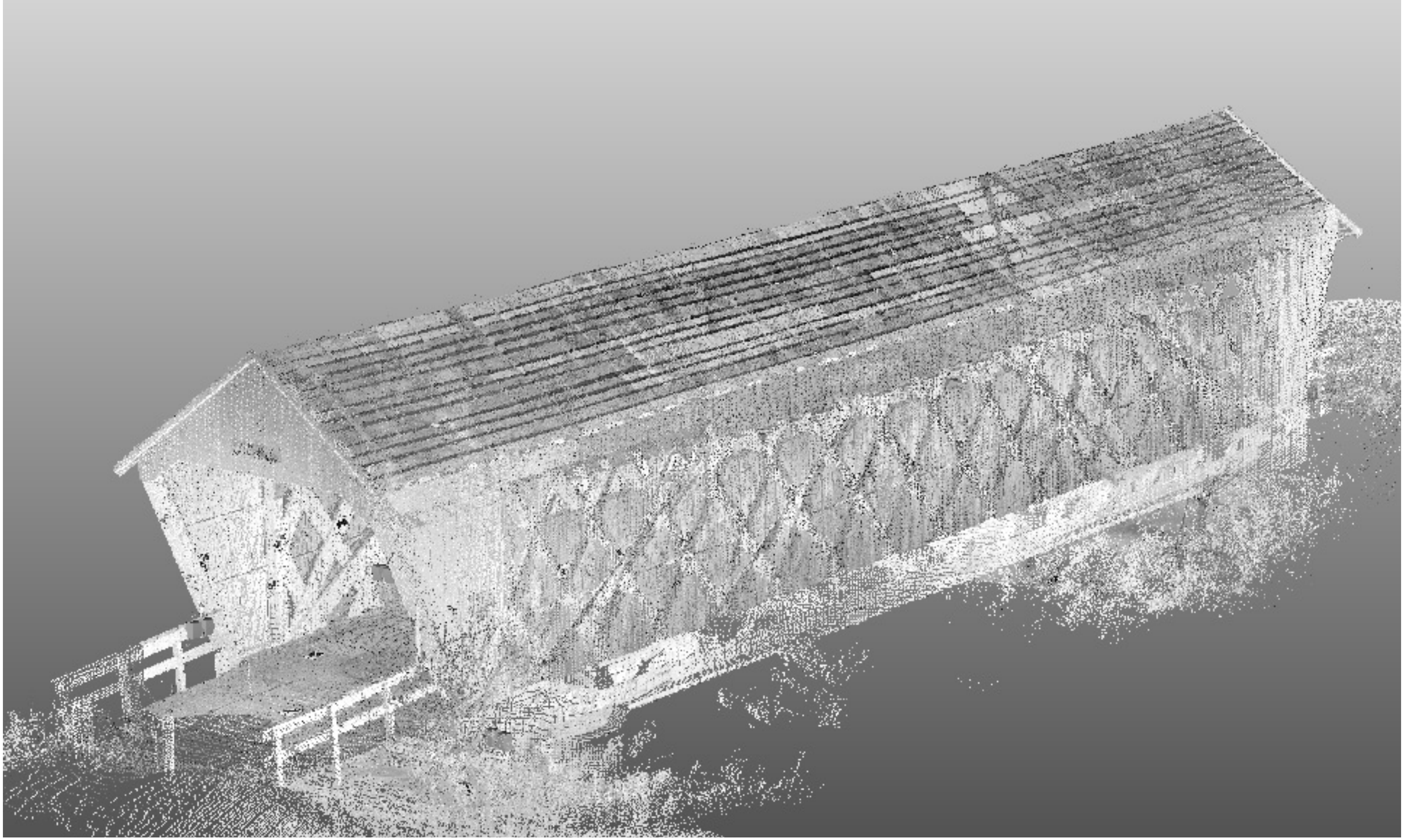
- 6 bridges selected in Minnesota, Wisconsin and Madison County, Iowa
- Faro 3D Scanner used by Sightline LLC and Faro
- Use software to connect the scans creating a 3D point cloud image
- Import the scans into AutoCAD® and create 2D and 3D drawings using kubitUSA software
- Create a 1/100th replica of the Zumbrota, Minnesota Bridge using rapid prototyping technology.


FARO

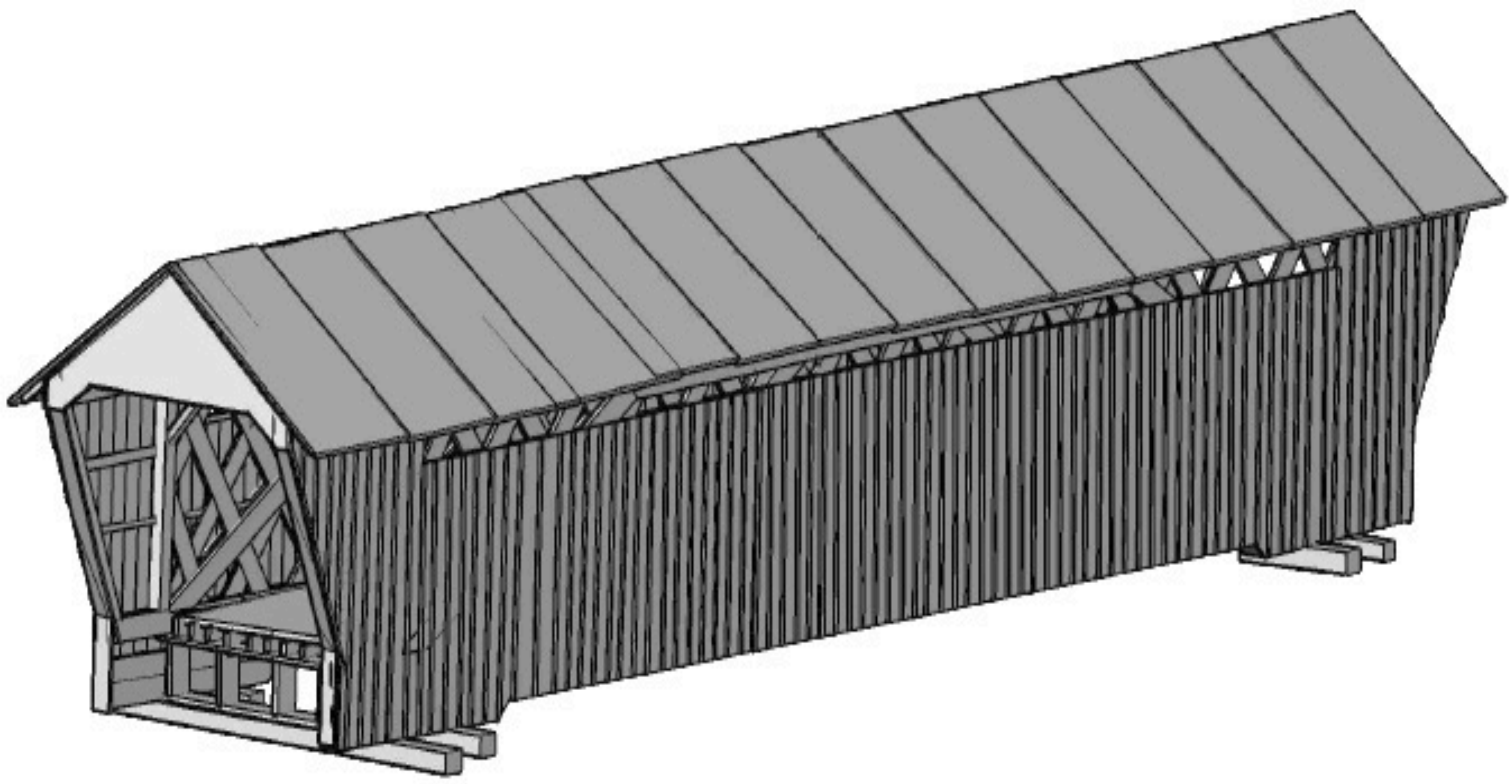
340
339
283
267
224
332
335
348
346

Imes Bridge, Madison County, Iowa, USA

Imes Point Cloud

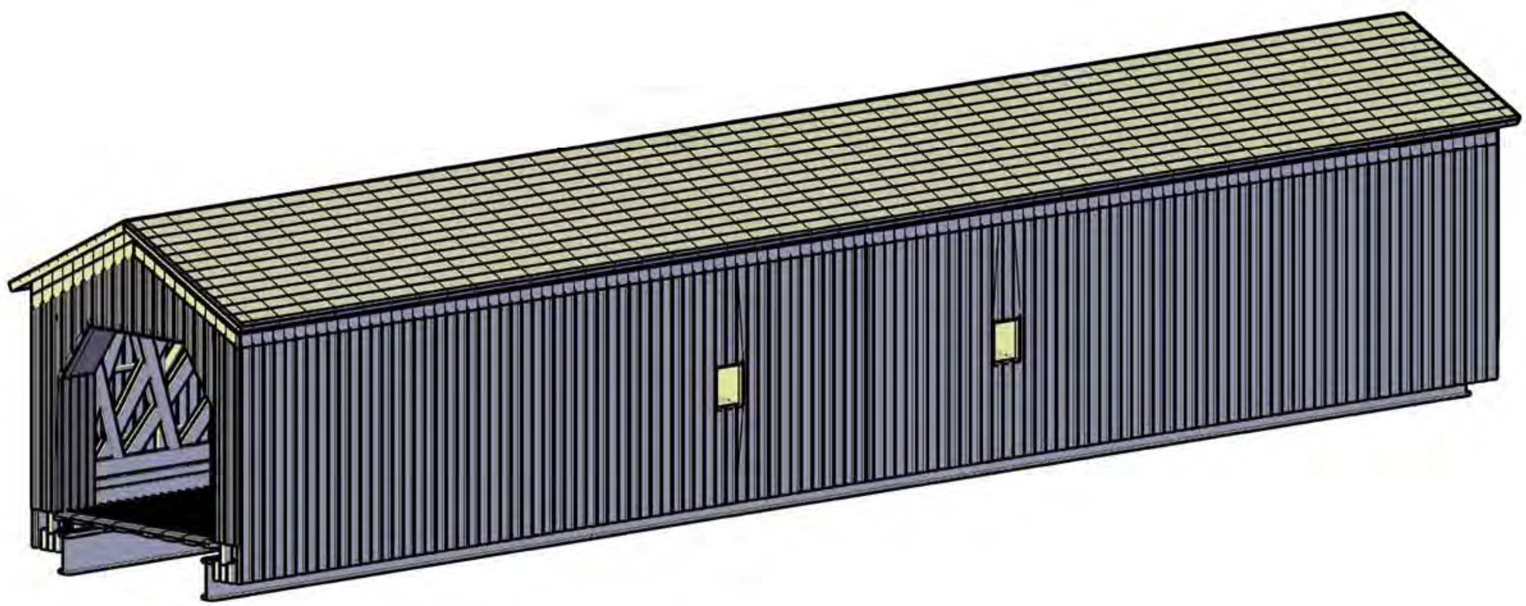


Imes 3D AutoCAD®

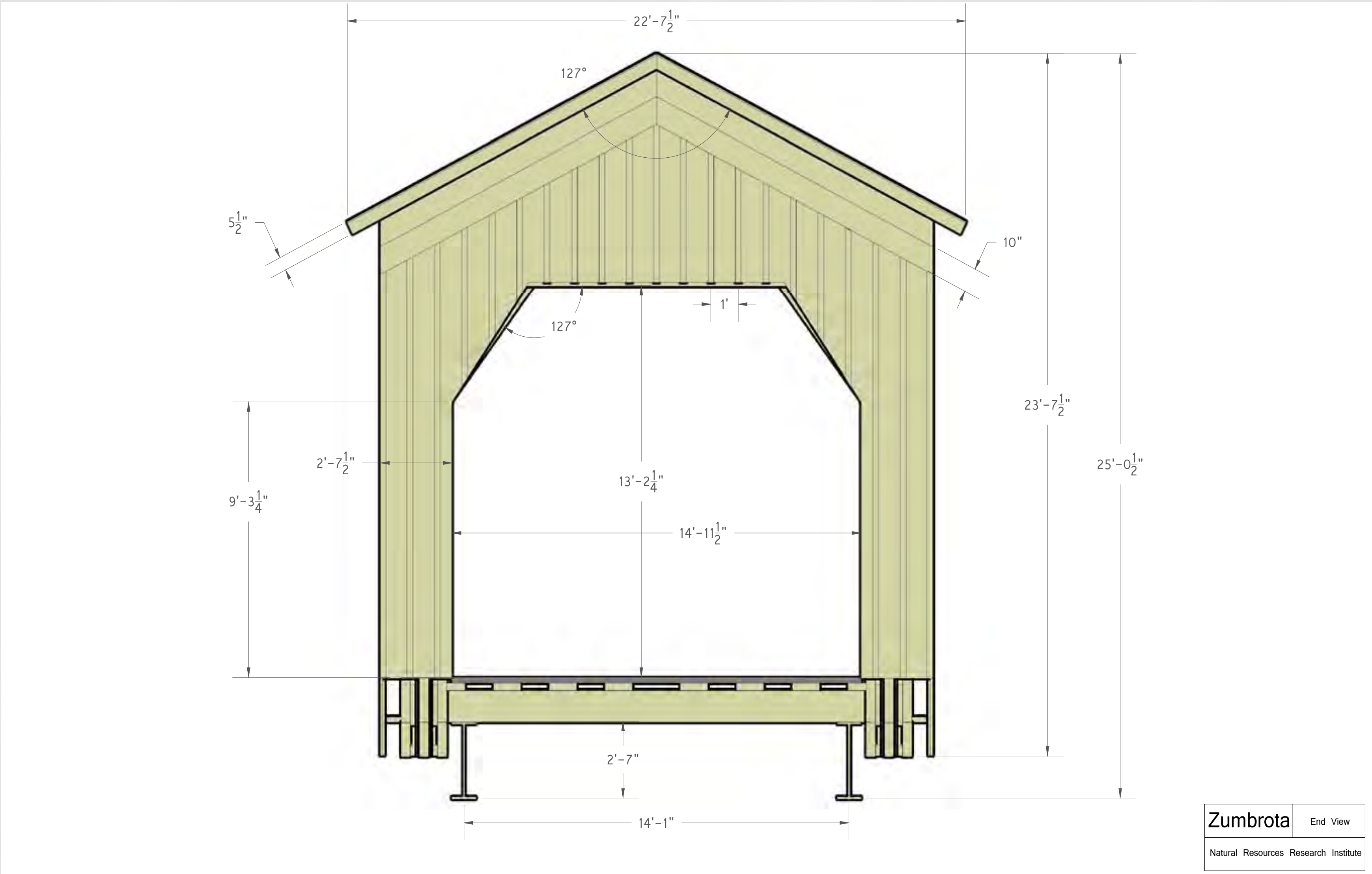


Zumbrota, Minnesota USA

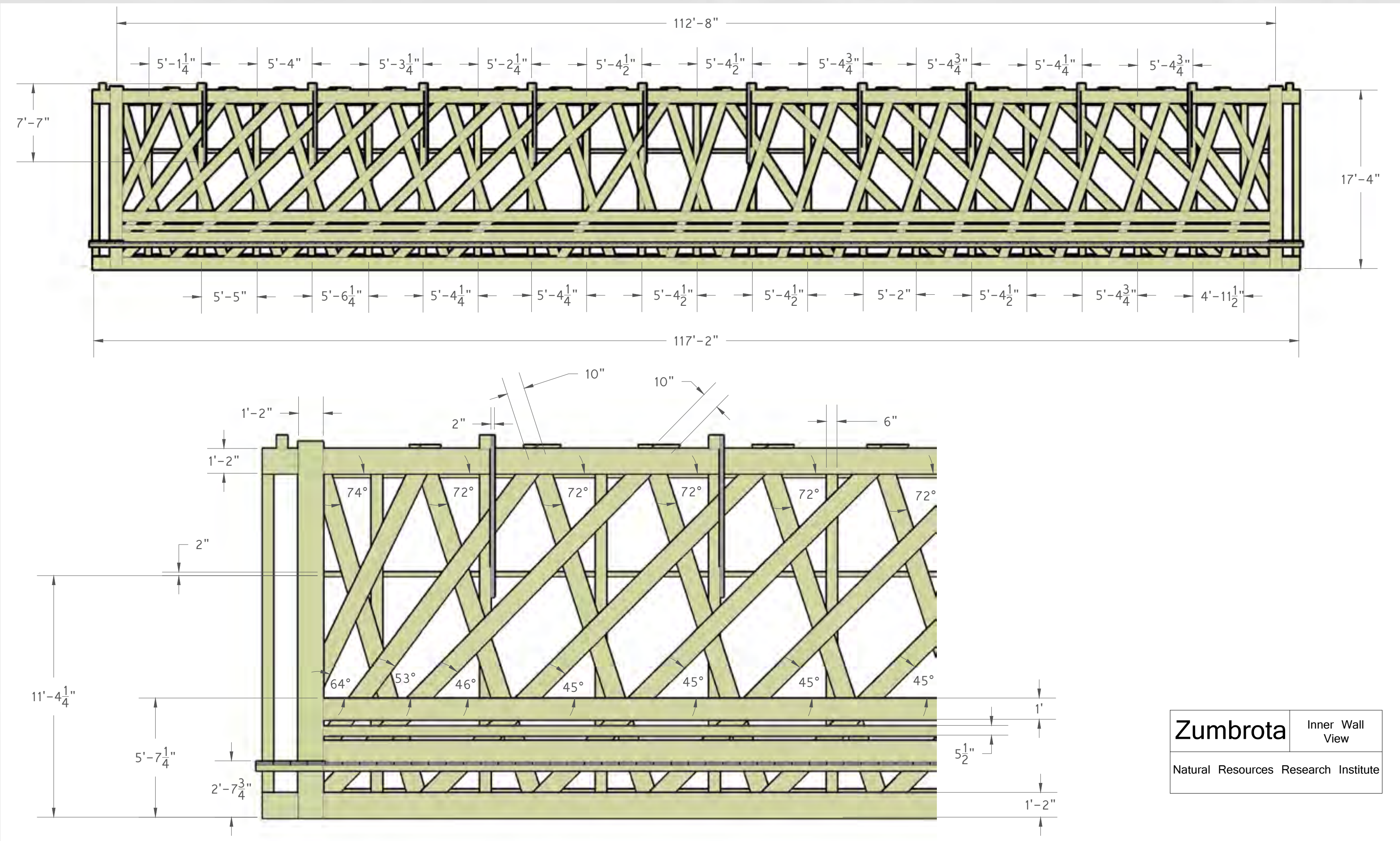
Zumbrota Isometric 3D CAD View



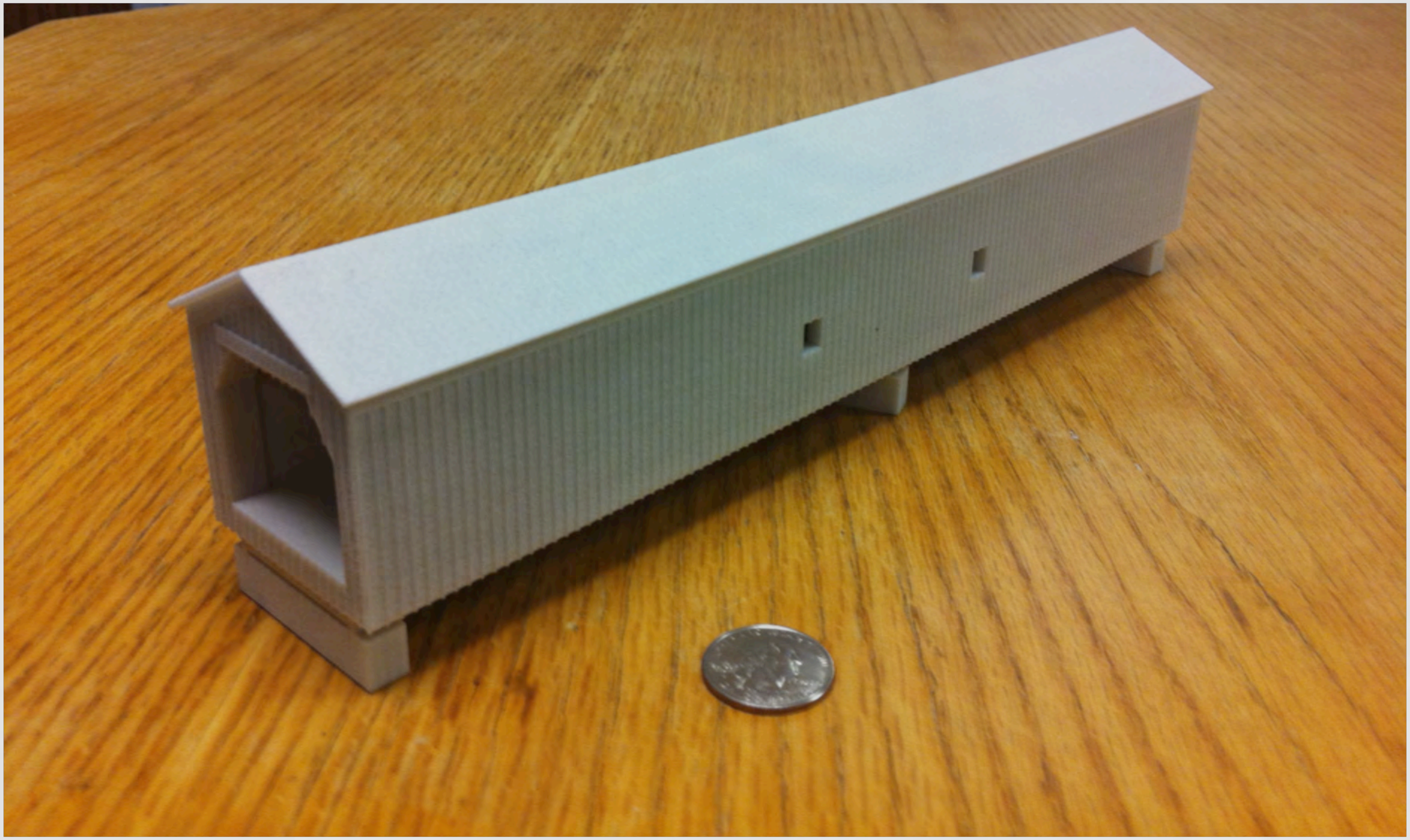
Autocad® Image Of The End Wall



Autocad® Image Of The Side Wall



Creation of a 1/100th Replica Using Rapid Prototyping Technology



Process Time

Step	Time Duration
Setup and place targets	2 person-hours
Conduct multiple scans (up to 20)	8 person-hours
Link scans	8 person-hours
Produce images	30-60 person-hours

Conclusions

- 3D laser scanning is an effective and accurate technique for documenting as-built conditions of historic covered bridges.
- Comparisons between digital scan data dimension and actual dimension showed that the scanner used in this study met the manufacturer reported accuracy of 5 mm at a distance of 75 meters.
- Post-processing of the scan data requires experience to cost-effectively create as-built documentation.
- A 3D scanner can be used to create a range of outputs such as point cloud scans, parametric images, and 2D and 3D AutoCAD® drawings.

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- The project team truly appreciates this support.

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Use of laser scanning technology to obtain as-built records of historic covered bridges

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Abstract Covered bridges have been the fabric of American life. Today there are several hundred historic covered bridges remaining in the U.S. Although there is much effort to preserve these structures, the high cost of restoration, neglect, and vandalism takes its toll, and many are lost forever. The U.S. National Park Service's Historic American Engineering Record (HAER) has efforts underway to document historic structures. Their Level I documentation consists of measured and interpretive drawings, large-format photographs, and written historical reports. In order to assist in this effort, newer technologies need to be explored which can provide as-built records at a faster rate and with more accuracy. This paper presents assessment and demonstration of the use of three-dimensional (3D) high definition laser scanning technology to scan existing bridges for purposes of obtaining as-built records. Six covered bridges in Wisconsin, Minnesota, and Iowa were scanned using portable scanning equipment and the resulting scans were processed using computer software to create 3D point cloud images accurate within 5 millimeters. These images were then imported into AutoCAD® for further processing into as-built documentation. Finally, the Zumbrota, Minnesota Bridge was recreated as a 1/100th model using rapid prototyping technology as a demonstration of the technology to create as-built replicas. Information will be presented on the scanning technology, data processing, and cost saving implications of this technology, along with alternate applications in other industries.

Keywords nondestructive evaluation, historic structures, laser scanning, covered bridges, point cloud

1. INTRODUCTION

1.1. General information

Covered bridges are part of the fabric of American history, and several hundred historic covered bridges still exist today. Although much effort is expended to preserve these structures, the high cost of restoration, neglect, and vandalism often take their toll, and many are lost forever. The famous Iowa Cedar Bridge, from the "Bridges of Madison County" movie fame, was destroyed by arson in 2002. Because we cannot completely prevent these types of incidents from occurring, we should at least properly document these bridges for posterity. The National Park Service's Historic American Engineering Record (HAER) has efforts underway to document historic structures. Their Level I documentation is defined in the Secretary of the Interior's Standards and Guidelines for Architectural and Engineering Documentation and consists of measured and interpretive drawings, large-format photographs, and written historical reports. To assist in this effort, newer technologies need to be explored that can provide as-built records at a faster rate and with more accuracy.

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1.2. Laser scanning techniques

Three-dimensional (3D) laser scanners are instruments that record precise and accurate surface data of objects in a nondestructive manner. These instruments use an infrared beam of light to calculate and record the distance to an object, typically as data points with spatial coordinates. This data is then analyzed using various types of computer software to generate a detailed image of coordinates and dimensions. 3D laser scanners have successfully been used to digitize objects of various sizes ranging from small diagnostic artifacts to large complex sites of monumental architecture (Faro 2011).

There are a wide number of companies that manufacture various types of 3D laser scanners. Generally, these units use light detection and ranging technology (LiDAR), where laser pulses determine the distance to an object or surface. The distance to an object is determined by using time-of-flight between transmission of a pulse and detection of the reflected signal. A point cloud of data is then collected and can be converted into the true shape of the object.

Several bridge projects were noted in a literature review. The Pennsylvania Department of Transportation (PennDOT) completed an initial study in 1999 to evaluate laser scanning technology for creating as-built drawings. A comparison of traditional and 3D scanning estimated an overall time savings of 100+ person-hours was achieved through the use of 3D scanning (Foltz 2000). Based on this assessment, the PennDOT purchased two laser scanners in 2000. A second assessment was completed by Jaselskis et al. (2003), showing that laser scanning could be used cost effectively for preliminary surveys to develop meshes of roadway surfaces and to measure bridge beam camber in a safer and quicker fashion compared to conventional approaches. Other applications noted in this publication showed potential applications for laser scanning to include developing as-built drawings of historical structures such as the bridges of Madison County.

2. PROJECT ACTIVITIES

2.1. Selection of historic covered bridges

Six historic covered bridges located in Wisconsin, Iowa and Minnesota were selected for scanning and are shown in Table 1. Contact was made with the appropriate government or administrative staff for each bridge and permission secured. The bridges selected for Wisconsin and Minnesota are their sole remaining historic covered bridge. The four bridges in Iowa include several from historic Madison County, Iowa. All of the bridges scanned were considered lattice through truss design. This paper will focus on the Zumbrota, Minnesota and the Imes, Iowa bridges.

Table 1 - Covered bridges that were scanned based on their location, size, ease of access and suitability.

State	City	Bridge	Built (yr)	Span (ft)	National Register of Historic Places (date accepted)
Wisconsin	Cedarburg	Red	1876	120	March 14, 1973
Iowa	Winterset	Roseman	1883	106	September 1, 1976
Iowa	St. Charles	Imes	1870	81	February 9, 1979
Iowa	Winterset	Hogback	1884	106	August 28, 1976
Iowa	Madison County	Cutler Donahoe	1871	79	October 8, 1976
Minnesota	Zumbrota	Zumbrota	1869	120	February 20, 1975

The bridges of Madison County, Iowa are world famous and are excellent examples of the construction of covered bridges in the 1870-1880s. As noted on the Madison County website (2011), "Our historic, world-famous covered bridges were popularized by Robert James Waller's novel, *The Bridges of Madison County,* and the feature film starring Meryl Streep and Clint Eastwood. Five of the original covered bridges remain, all listed on the National Register of Historic Places. The bridges were covered by order of the County Board of Supervisors to help preserve the large flooring timbers, which were more expensive to replace than the lumber covering the sides and the roof. Farmers to pay their poll taxes did most of the construction. The bridges were usually named for the nearest resident."

Figure 1 - Imes Bridge, Madison County, Iowa (2010).

Minnesota's only remaining historic covered bridge is located in the City of Zumbrota. Listed on the National Historic Register, it was originally constructed in 1869 and relocated in 1932, 1979, and 1997. It now spans the Zumbro River in the City of Zumbrota's Covered Bridge Park. Considered a lattice through truss design, it is now a pedestrian only bridge that spans 120 ft. A special documentary of the bridge and its importance to the history of Zumbrota can be found at www.youtube.com by searching "Zumbrota Bridge." An image of the bridge is shown in Figure 2.

Figure 2 - Zumbrota, Minnesota historic covered bridge (2011).

2.2. Laser scanning

The laser scanning for each of the six bridges was completed by Sightline, LLC (Milwaukee, WI). Approximately 35 scans were completed of each bridge from a variety of angles using FARO LS880 and Photon 120 Laser Scanners. Figure 3 shows a FARO Laser Scanner being used to image a historic covered bridge. The scanning process consists of the following steps:

1. Paper "targets" were placed in numerous locations on the bridge for use in linking individual laser scans together. *Time duration: 2 person-hours.*
2. A 3D laser scanner was used to conduct the scan. The scanner is placed at several vantage points such that all visible surfaces of the bridge can be documented. When a single scan is completed, it is saved to a computer as an .ls file. Individual scans are completed in approximately 5 minutes. *Time duration: 8-10 person-hours.*

Figure 3 - A FARO 3D Laser Scanner used to scan the Imes Bridge.

3. After all visible portions of the bridge have been scanned, the captured scans are processed using software specific to the laser scanner. In this project, the individual data scans were linked together using FARO Scene software. This software allows an individual to identify the targets placed prior to the scanning process and use them to link or attach one scan to another. The process of linking two individual scans is repeated several times until all scans have been compiled into one large scan depicting the entire bridge. *Time duration: 9 person-hours.*

   Once a bridge has been completely assembled using all of the individual scans, it was exported as a point cloud, depicting all visible aspects of the bridge. This cloud of data was then imported into AutoCAD® using add-in software provided by kubitUSA. This add-in allowed a user to import point cloud files in addition to the ones inherently recognized by AutoCAD®. It has additional modeling tools for working directly with point cloud data in AutoCAD®. Once a point cloud was exported into AutoCAD®, it was divided into multiple cross-sections. This is done so that specific components of the bridge can be seen more clearly. From this point, two dimensional (2D) and 3D models of the bridge were generated. *Time duration: 30-60 person-hours, depending on the experience of the person and the level of detail desired.*

3. RESULTS

There are a number of types of images that can be presented from the processing of the point cloud data. These images include a point cloud image resulting from only one scan, a point cloud image created from multiple scans, a parametric picture created from a point cloud scan, and a point cloud image imbedded in AutoCAD®, and 2D/3D AutoCAD® images. These images were created using Faro Scene or AutoCAD® 2011 with a kubit USA add-in.

As to the project activities, the majority of the scan processing for the Cedarburg, Wisconsin bridge was completed by Sightline, LLC. The processing of the scan data for the Madison County, Iowa bridges and the Zumbrota, Minnesota bridge was completed by a student engineer at the University of Minnesota Duluth, Natural Resources Research Institute (UMD NRRI). The project team decided that based on the processing time estimates, that significant detail in point cloud and 3D CAD data would be developed for the Cedarburg, Imes and Zumbrota bridges. The point cloud images and detailed AutoCAD® images are shown in figures 4-7 for the Imes, Iowa bridge and figures 8-11 for the Zumbrota, Minnesota bridge (Brashaw 2011).

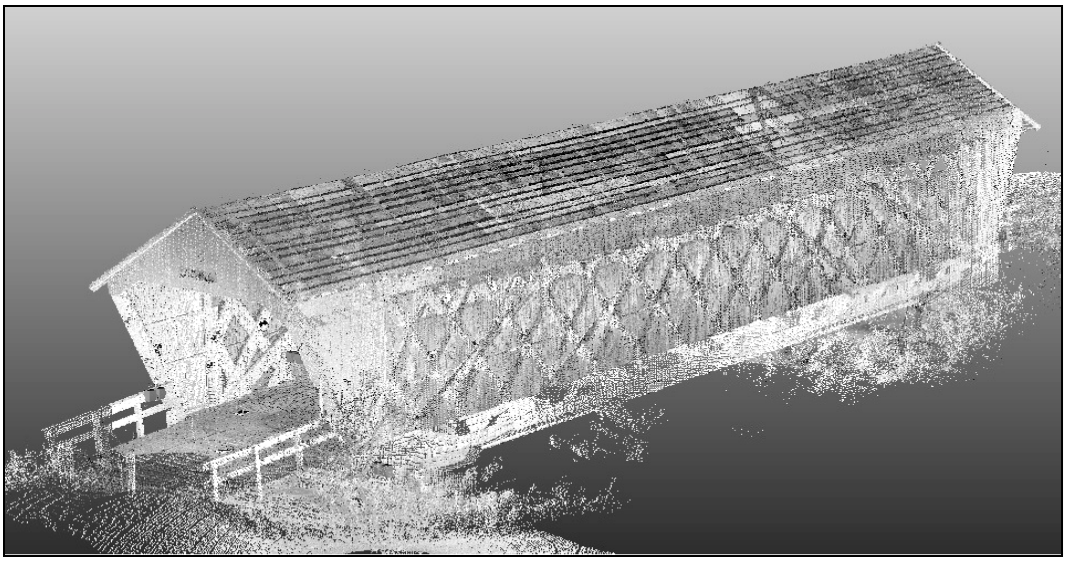

Figure 4 - Point cloud image of the Imes historic covered bridge.

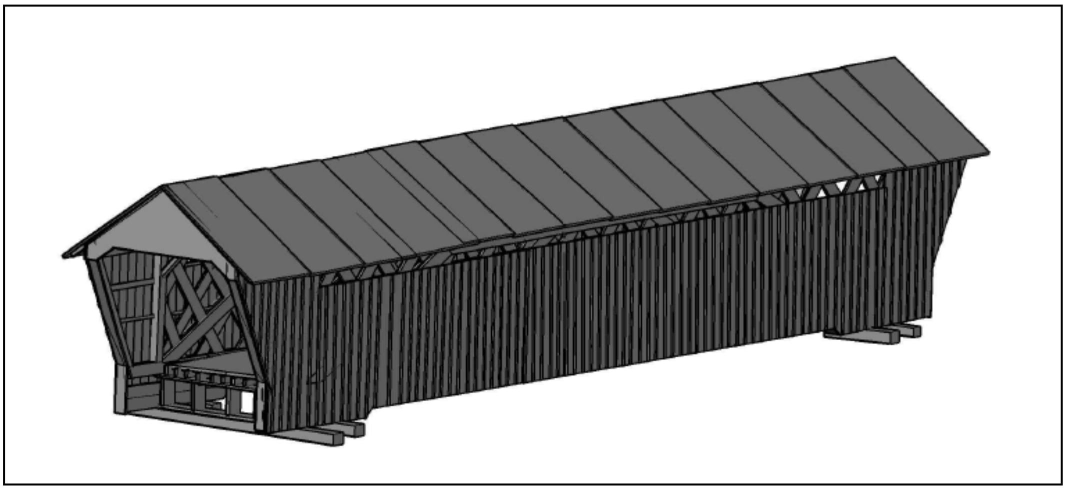

Figure 5 - An AutoCAD® view of the Imes bridge created from 3D laser scanning point cloud data.

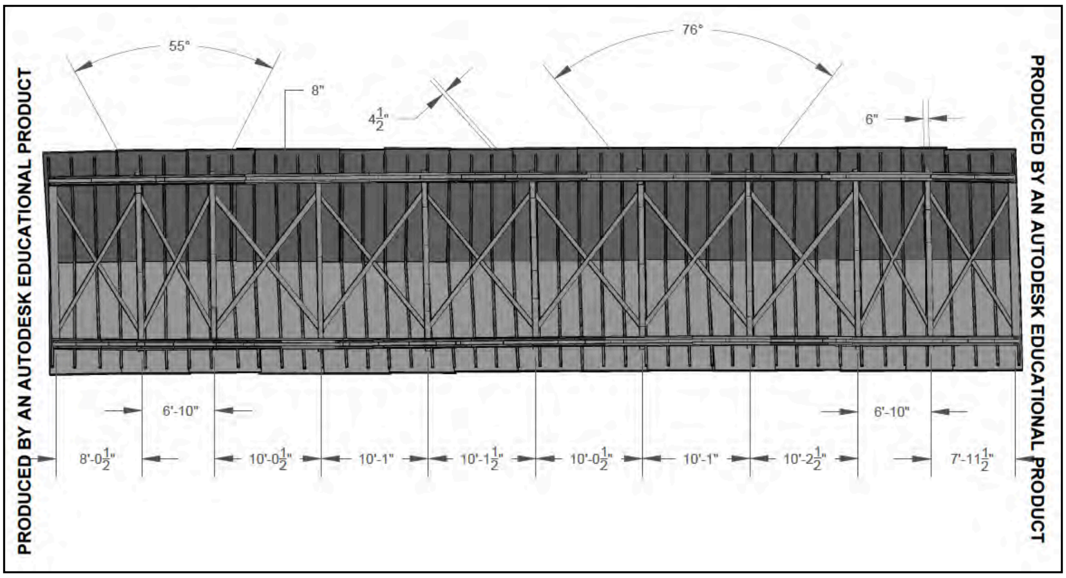

Figure 6 - Roof detail and dimensions of the Imes Bridge created from 3D laser scanning point cloud data.

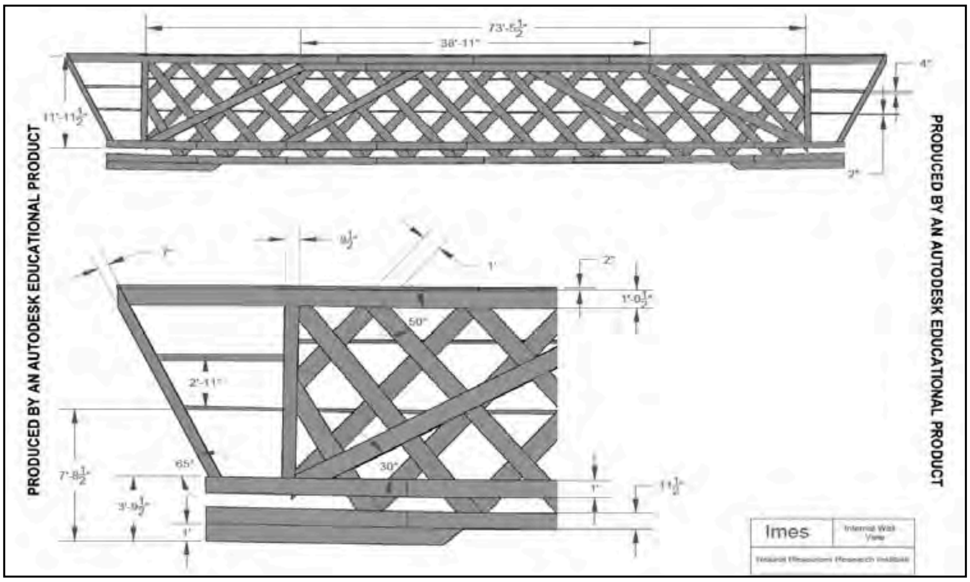

Figure 7 - Internal wall dimensions of the Imes Bridge created from 3D laser scanning point cloud data.

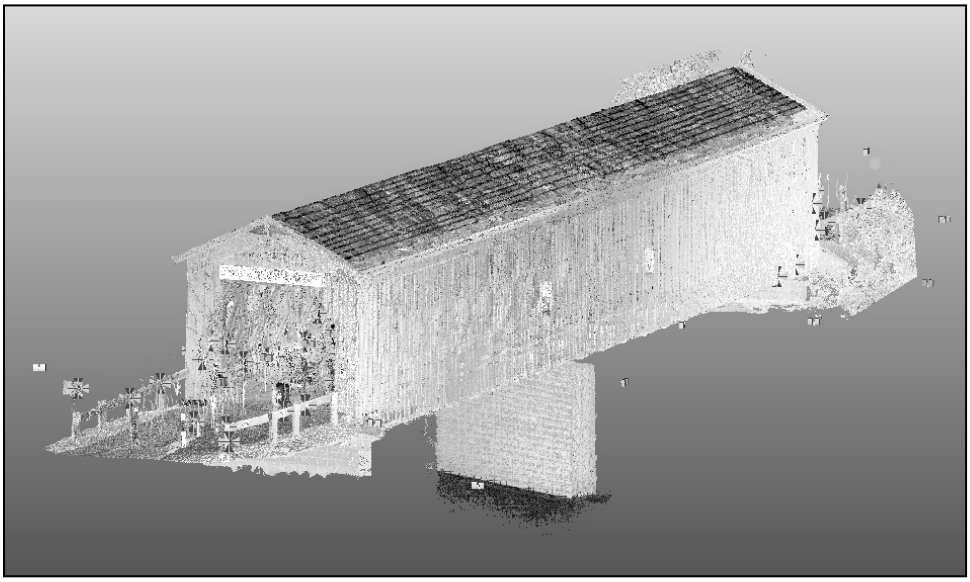

Figure 8 - A point cloud image of the Zumbrota Bridge created from multiple scans.

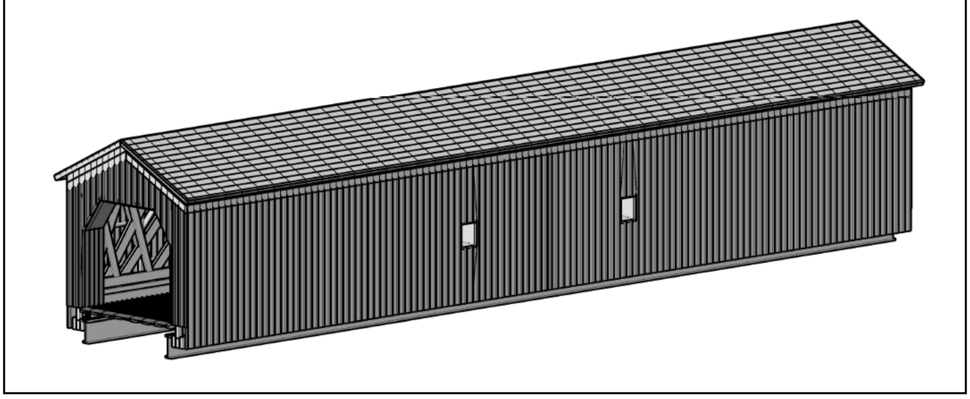

Figure 9 - An AutoCAD® 3D view created from 3D laser scanning point cloud data of the Zumbrota bridge.

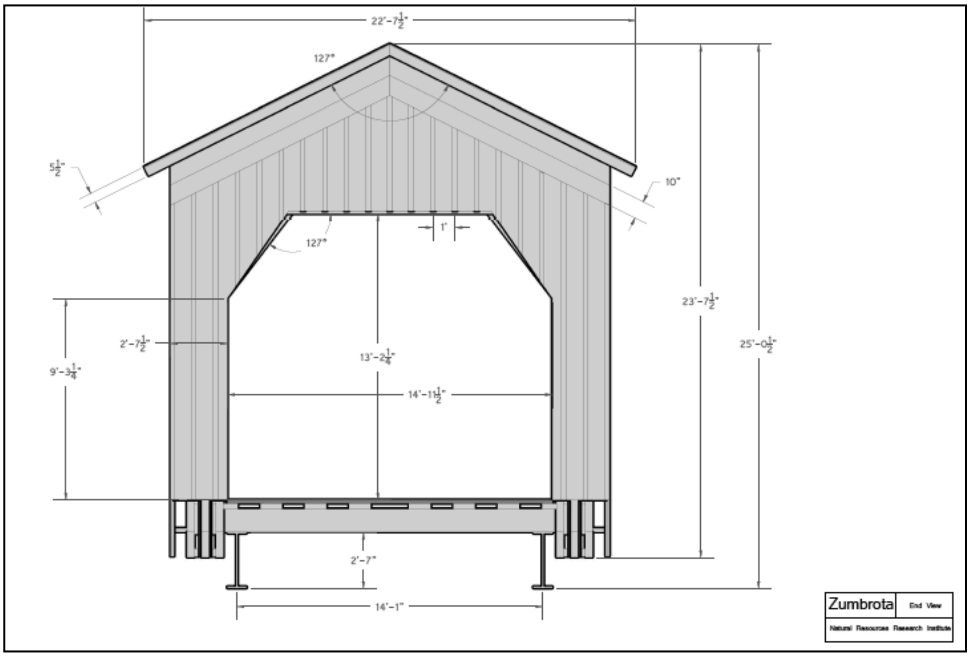

Figure 10 - An AutoCAD® image of the end wall created from 3D laser scanning point cloud data.

At the time of scanning, digital photos of each bridge were taken, printed, and used to record the dimensions of various structural components. Traditional measuring tools such as tape measures and calipers were used to capture the length, width and height of the bridge, along with measurements of roof members, wall members and support beams. This information was then compared to the measurements noted on the digital files created from laser scanning. These results showed that laser scanning provided accurate measurements within the vendor reported accuracy of 5 millimeters (mm) at a distance of 75 meters (m).

Following processing and development of the 3D scanning images, a digital 3D CAD file was fabricated at the Northern Lights Technology Center of UMD NRRI. This file was used to generate a 1/100th 3D scale replica of the Zumbrota Bridge. In processing the data, we found that it would only be possible to produce an accurate external version of the bridge. A true replica of the inside of the bridge could not be produced since a 1/100th scale of a 6 inch wide beam would only have a thickness of 0.06 in. This is below the thickness that can be created using rapid prototyping, and these thin members would not have strength since many of the beams and members are only connected at the ends. Vanguard Si2 selective laser sintering equipment from 3D Systems was used to create the scale replica of the bridge. Figure 11 shows the 3D image that was used and the 1/100th model produced.

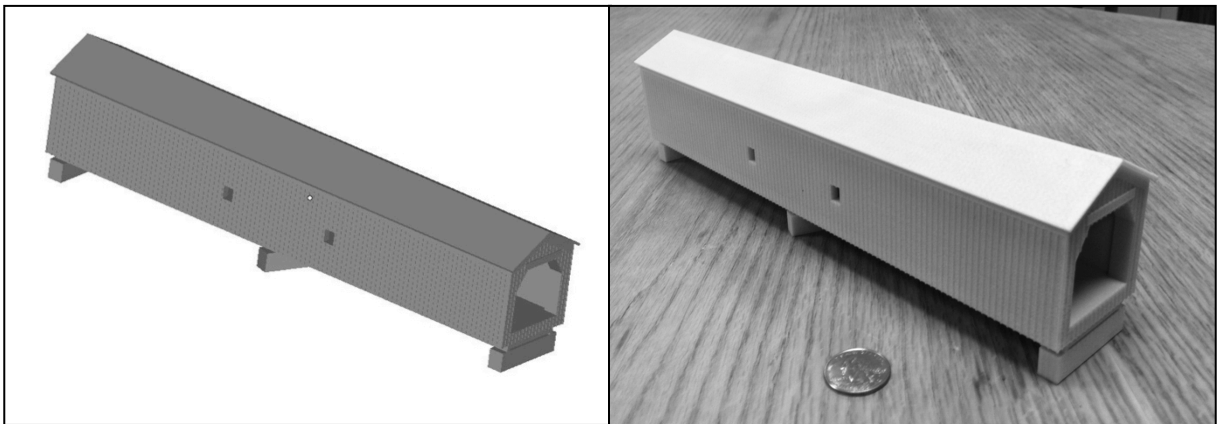

Figure 11 - An isometric 3D model used to create a 1/100th model of the Zumbrota bridge created using selective laser sintering rapid prototyping equipment.

4. ALTERNATE USES FOR LASER SCANNING TECHNOLOGY

In this project, 3D laser scanning technology was used to create as-built documentation of historic cover bridges. There are a number of other applications that 3D laser scanning is used for. A brief list and summary of the applications includes (FARO 2011):

- Architecture and civil engineering applications
    - Excavation and deformation control, facade inspection, structural analysis and maintenance, free-form component inspection, creation of as-built environments.
- Process industry and digital factory applications
    - Conversions and extensions, offsite production, asset management, site supervision.
- Inspection and reverse engineering applications
    - Reverse engineering, interior fixtures, manufacturing documentation, quality control.
- Forensic and accident scene applications
    - Rapid and complete 3D recordings of crime and accident scenes or insurance damage.
- Heritage applications
    - Complete and detailed documentation of historical structures or excavation sites.

5. CONCLUSIONS

Based on the outcomes from this project, the following conclusions are made:

- Three-dimensional laser scanning is an effective and accurate technique for documenting as-built conditions of historic covered timber bridges. Six bridges were scanned using this technology and each bridge took less than one workday. Comparisons between digital scan data and dimension and actual dimension showed that the scanner used in this study met the manufacturer reported accuracy of 5 mm at a distance of 75 meters.

- Post-processing of the scan data requires experience and skill to cost-effectively create as-built documentation. The staff at Sightline, LLC was very efficient in linking the 3D scans, importing them into AutoCAD® and creating detailed 2D and 3D CAD drawings. Our project student engineer faced a steep learning curve, but developed an excellent skillset in processing the files during the project. For experienced staff, this technology can reduce the time associated with creating as-built documentation.

- A 3D scanner can be used to create a range of outputs that include point cloud scans, parametric images, and 2D and 3D AutoCAD® drawings. For historic covered bridges, this information can be used for a variety of purposes including as-built documentation and structural assessment, while also providing detail on the land topography adjacent to the bridge.

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