

Memo

To: T. Ahlborn, D. Harris, L. Sutter, R. Shuchman, J. Burns
From: H. de Melo e Silva, C. Brooks
CC: A. Endsley, R. Oats, K. Vaghefi, R. Hoensheid, R. Dobson, J. Ebling, D. Dean
Date: October 13, 2011
Number: 21
Re: Summary of Field Demonstration Including Sensor Evaluation and Update of the DSS.

3D OPTICAL BRIDGE-EVALUATION SYSTEM (3DOBS)

The 3DOBS, a demonstration of 3D optics technology, was successfully deployed to all field demonstration bridges to collect 3D bridge surface data. The field system consisted of a Nikon D5000 digital single lens reflex (DSLR) camera, vehicle mount, and a camera triggering device. The camera triggering device was programmed at the Michigan Tech Research Institute (MTRI) to enable the camera to capture photos at one frame per second (fps).

Easily transported in the bed of a light duty pickup truck the 3DOBS took 15 minutes to setup. For collecting the imagery, the truck was geared down to “4x4 low” and idled across the bridges at a speed of about 1 mph (see Figures 1 and 2 for the system in data collection mode). This allowed for at least 60% overlap of the resulting photos with the camera mounted 9 ft above the bridge deck surface, needed for photogrammetric image collection. The total time needed to make a full collect (two passes, one pass per lane) of the bridge was about 10 minutes. Breakdown of the system took another 10 minutes which translates to total collect time of 35 minutes per bridge (see Figure 3 for an example of the 3DOBS when broken down into its parts). With a faster camera that could take more frequent images, the speed of data collection could be increased and the data collection time could be decreased to less than 10 minutes per bridge for a full collection.



Figures 1 & 2: The 3DOBS being deployed on Willow Road bridge over US-23 during August, 2011 field demonstrations.



Figure 3: The disassembled 3DOBS being transported to bridge field demonstration sites.

The resulting photos from the Willow Road bridge (see Figure 4) were processed in the commercial software package Agisoft PhotoScan Professional to generate 3D models of the bridge deck surface. Using the labeled bridge locations from the team's onsite bridge grid system, the models were given a coordinate system and were then exported out of PhotoScan Professional as a Digital Elevation Models (DEM) seen in Figure 5. The bridge DEM is being used

in Esri ArcGIS to calculate the size and volume of individual spalls as well as generate a map showing the spalled areas and calculating the percent of the bridge that is spalled. These are the types of condition data that will be integrated into an overall bridge health signature. The same post-processing described here for Willow Road bridge will be completed for the Mannsiding and Freer Road bridges within the next few weeks.



Figure 4: Photos of Willow Road bridge taken with the 3DOBS showing a 60% picture overlap for photogrammetric image creation.

As shown in Figure 6, it is possible to calculate the volume and area of spalls on the bridge deck using data collected by the 3DOBS. The output above has a 5 mm by 5 mm ($\sim 0.04 \text{ in}^2$) horizontal resolution and appears to be detecting vertical changes as small as 2 mm (smaller than 1/12 of an inch). The analysis team is currently investigating ways to automate the calculation of this type of bridge deck condition data that will be used as part of the overall bridge signature. During the next quarter, the team will be completing of these analyses, and processed data, that helps to indicate bridge superstructure condition, will be included in the project's Decision Support System (DSS).

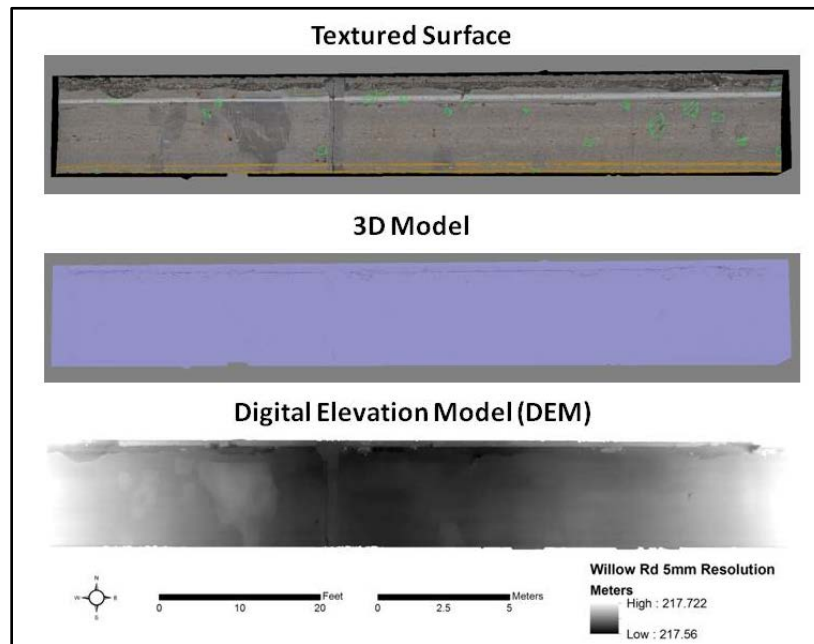


Figure 5: Examples of the PhotoScan Professional output. A textured surface and 3D model are generated from the photos with no additional user input needed. A DEM is generated after the user sets up a coordinate system by adding reference points.

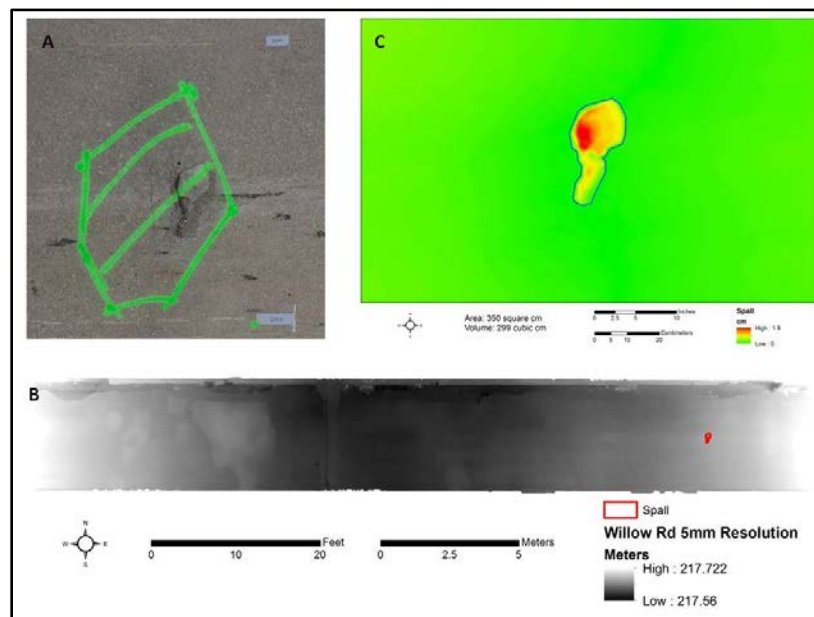


Figure 6: Analysis of a spall on Willow Road bridge based on 3D data collected with the 3DOBS at Willow Road bridge. A spall ('A' – within the green area marked by the Michigan Department of Transportation (MDOT) as a delamination) can be located on the DEM of the west bound lane ('B' – red area). Area and volume estimates can be calculated in Spatial Analyst (see 'C'). The spall above has an area of 350 cm² and a volume of 299 cm³.

The total percent of spalled area was also calculated and analyzed using ArcGIS Spatial Analyst with the 3D data collected. Figure 7 shows an example of the 3D bridge deck data having been analyzed and categorized into spalled versus unspalled areas. The total spalled area is 6.08% of the total bridge surface. As an example of additional data that can be calculated, the average area of a spall is 673 cm^2 ($\sim 104 \text{ in}^2$) and 0.8% of the area within 7.5 cm ($\sim 3 \text{ in}$) of a bridge joint is spalled; 5% of the area outside of this bridge joint area is spalled. As stated, the analysis team is now focusing on automating these types of analysis so that remote sensing results can be transformed into metrics for inclusion in an overall bridge signature.

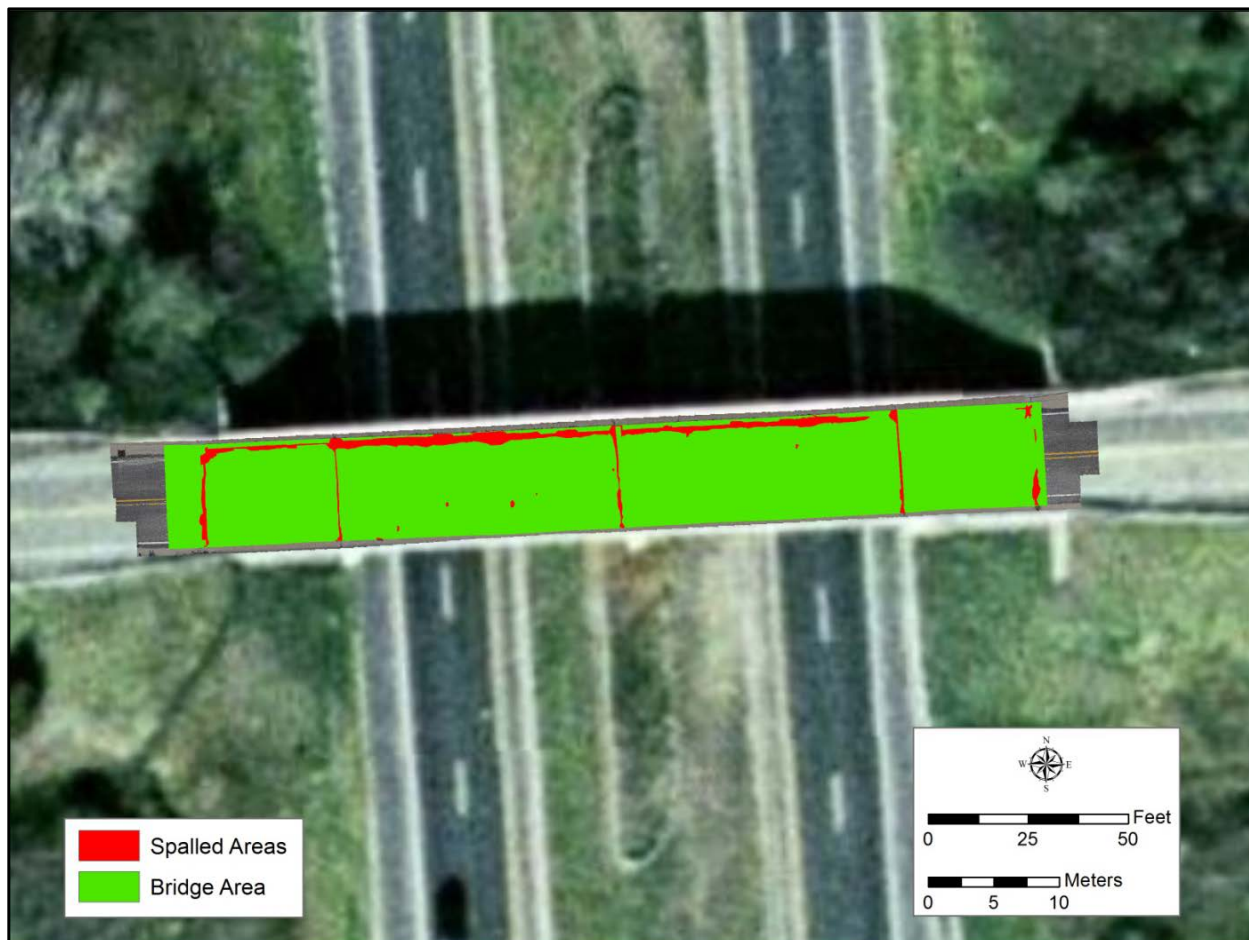


Figure 7: Example of calculating percent spalled area for Willow Road bridge using the 3DOBS data as the input and ArcGIS as the analysis software.

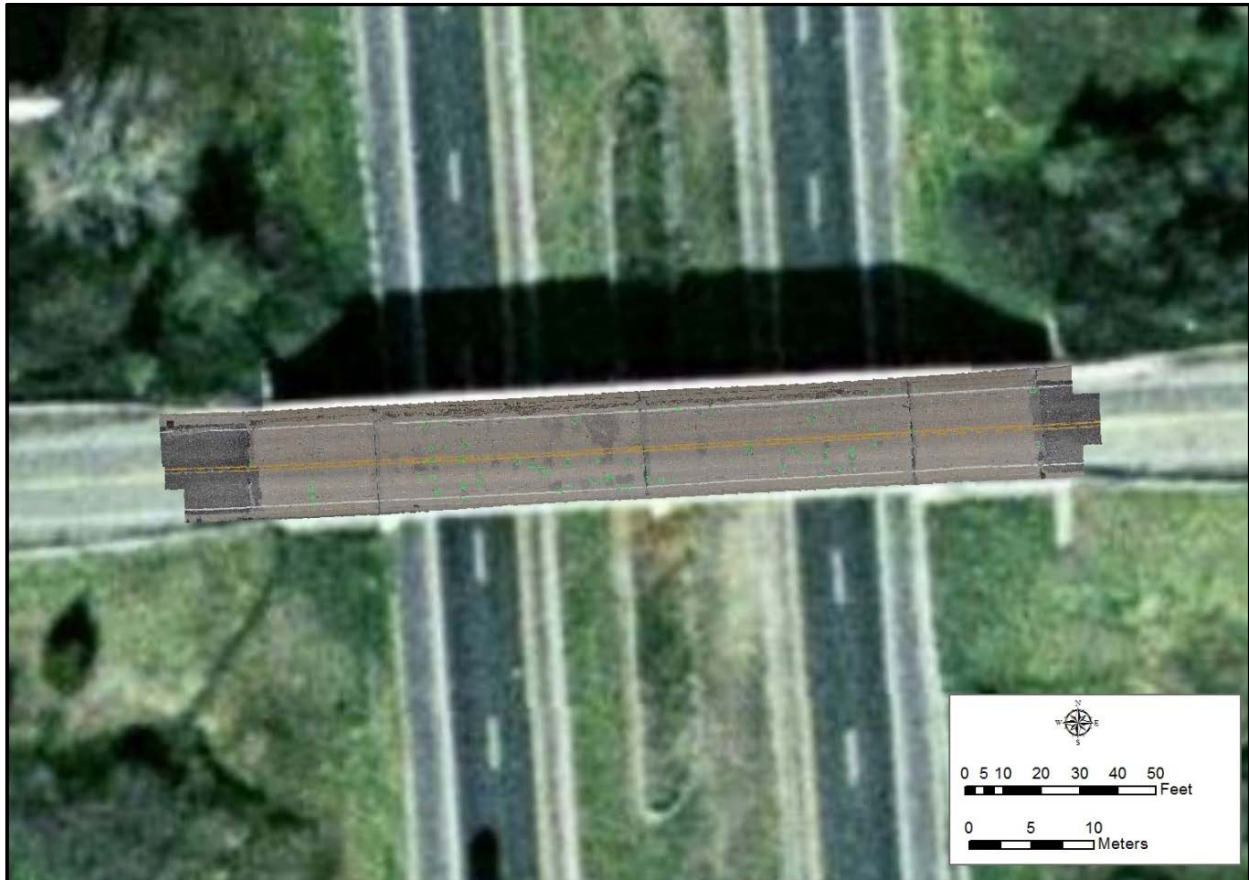


Figure 8: A composite image of Willow Road bridge deck that can be used to evaluate its condition as serve as a reference to understand deterioration over time, as collected by the 3DOBS.

Benefits, Limitations, and Next Steps

The primary benefits of the 3DOBS are: low cost to purchase components, rapid deployment, limited time needed to collect data on the bridge, and that the team has demonstrated how to derive useful metrics of bridge deck condition, such as percent of spall plus volume and area of spalls. The total system cost (\$4,320) as currently developed is: \$3,500 for Photoscan Professional, \$700 for the D5000 (including default kit lens), \$20 for the camera triggering device, and \$100 for the vehicle mount. A department of transportation (DOT) could purchase a single license (or other limited number) of Photoscan Professional to process the data while deploying several hardware setups at a cost of \$820 per system. A higher-end camera capable of more frames per second such as the Canon EOS 7D, with kit 28-135 mm lens (\$1,700), would enable faster data collection.

The primary limitation on the current system is the speed at which data can be collected. Ultimately, the goal would be to gather data at full standard, 24 fps (some cameras can now exceed this speed). However, the highest resolution high definition video (1,920 pixels by 1,080 pixels) is still only equivalent to 2 megapixels (mp), versus a 12.3 mp photo from the D5000 or a 18 mp photo from the EOS 7D, meaning a significant sacrifice would be made in image quality and resulting resolution of the DEM products. For the time being, a deployable system that can resolve features 5 mm (~0.2 in) or smaller would need to be a DSLR camera.

Also limiting practical deployment, but being actively worked on, is the automation of analyzed output that is meaningful to bridge inspectors and that can be rapidly included in a bridge condition DSS. This is anticipated to be resolved within the next quarter.

The 3DOBS system can be deployed as developed and demonstrated through this project, and has in the team's opinion already reached a level beyond the research stage. Additional development during this study will improve the current system with more automated output. Future development beyond this stage would be intended to lead to a completely field-ready system that a DOT could purchase from a vendor (if desired) or assembled by a DOT itself, with a software tool that works with existing DOT software to create bridge deck condition indicator data such as percent of spall by surface area for a bridge. The team proposes to write a "How to Deploy the 3DOBS" manual depending on project sponsor input and Technical Advisory Committee (TAC) interest, as a logical next step for reaching a field ready system.

As demonstrated at the recent Association of Environmental and Engineering Geologists (AEG) Conference in September, 2011, it is noteworthy that a United States government agency, the U.S. Bureau of Reclamation, has developed and deployed a similar system on a practical basis for mapping 3D surfaces of dam spillways; for an example output from their pole- and balloon-mounted systems, see <<http://www.usbr.gov/pmts/geology/3dphotogrammetry.pdf>>. This is a technology that is now practical to deploy thanks with less expensive cameras, cheaper and more powerful close-range photogrammetric processing software, and an understanding of the value of 3D data in end-users.

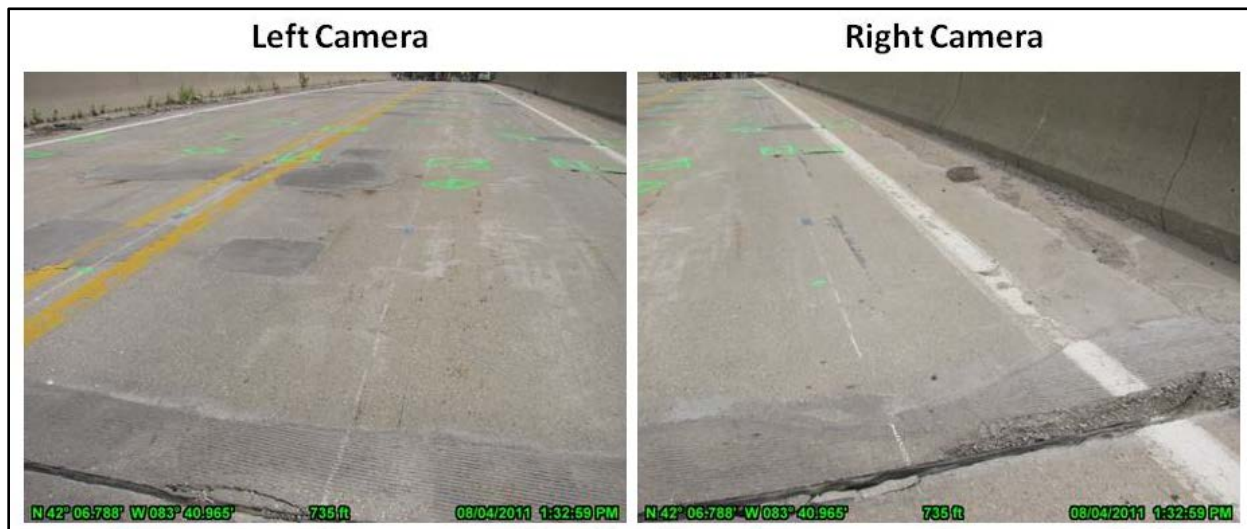
BRIDGE VIEWER REMOTE CAMERA SYSTEM (BVRCS)

The BVRCS, a demonstration of Google Street View style photography technology, deployment consisted of two Canon PowerShot SX110 IS cameras, a Garmin GPSMAP 76CSx GPS unit, and a laptop installed with Breeze Systems PSRemote camera control software. The cameras were mounted to the front of the vehicle and oriented so that the overall field of view would capture an entire lane width (see Figures 9 and 10). The vehicle was driven at a speed of less than 5

mph while the cameras took pictures once every 4 seconds in order to capture the entire bridge using the PowerShot SX110 IS cameras (see Figures 11 and 12). This allowed the team to ensure that the digital photographs were not blurred and the detail of the bridge deck was preserved through in-focus photographs. Lighting conditions at the bridge did not affect the quality of the photos captured; these conditions ranged from sunny to completely overcast skies.



Figures 9 & 10: The BVRCS being deployed on Freer Road bridge to capture a photo inventory.



Figures 11 & 12: Example photos taken with the BVRCS of Freer Road field demonstration bridge. Photos show that a full lane width was captured including overlap of the center of the right lane.

The set-up, deployment, and breakdown of the BVRCS at each of the field demonstration sites happened within a 30 minute time-frame. The purpose of the BVRCS is to capture a location-tagged set of photographs of a bridge so that bridge inspectors can easily and inexpensively

review a bridge at a later point and over time as more photo inventories are taken, while working from the office. This is intended to optimize field time and enable review of high-resolution photos of a bridge, especially its deck.

Once the photographs were taken, they were processed into a location-tagged, geographical information system (GIS) and Google Earth-compatible files (e.g., shapefiles and Keyhole Markup Language (KML) files) using the commercially available GeoSpatial Experts GPS-Photo Link software. The photo locations were displayed within ArcGIS and Google Earth and included hyperlinks to the full-resolution original photos; other geospatial software that can read shapefiles and KML files would also be able to use these data. Figure 13 shows an example of the GPS-Photo Link output being displayed in Google Earth, including the ability to see a preview of the photo before linking to the original full-resolution photo. A

"watermarked" version including the GPS coordinates, date, and time showing where and when the photo was taken can also be linked to, as also shown in Figure 13. The photos can reside on a DOT desktop computer, a server for multiple-user access within an office, or made accessible to a web server so they can be accessed in the field or from remote offices. The project team is currently working on including the location-tagged bridge photos from the demonstration bridges in the DSS to demonstrate how they can help understand the condition of multiple parts of a bridge at a point in, and over, time.

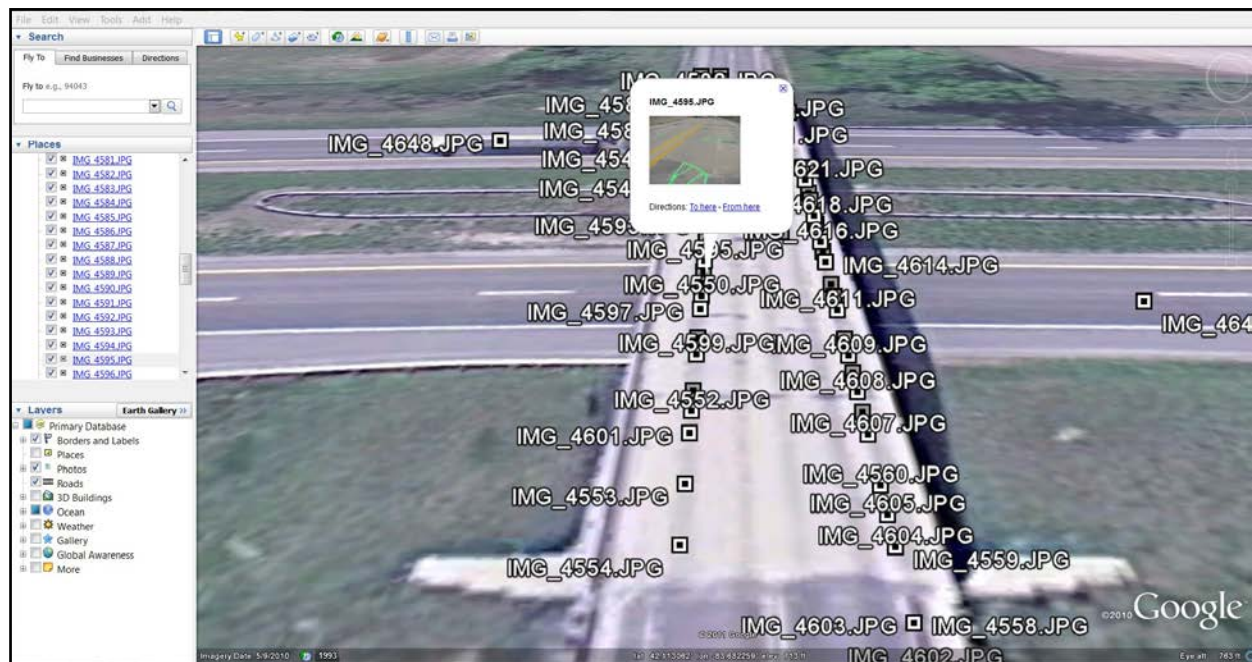


Figure 13: Example of the location of the digital photographs being displayed in Google Earth; each box contains a hyperlink to a full-resolution view of the photo taken at that location.

The project team also developed an additional version of the BVRCS that could capture a photo inventory of the underside of a bridge. In order to accomplish this task, the BVRCS was modified so that a camera faced straight-up, and a lighting source was added to address potential shadow areas. The BVRCS-Underside was developed by the project team and deployed at all bridges. This system was mounted in the bed of a truck and used the same base as the 3DOBS. An attachment was added that had two 500 watt work-lights with one of the D5000 cameras mounted to it. Due to being underneath a bridge with the sky blocked, collection of exact location-data with a GPS was not practical with the BVRCS-Underside. The same 3DOBS camera triggering device was also used. Again the truck drove at a speed of about one mph and captured photos at a rate of one fps (see Figure 14). Similar to that system, a faster camera would enable increased driving speeds. This system was easily transported and was set up, deployed and broken down within 25 minutes.



Figure 14: Example photos taken with the BVRCS-Underside of Willow Road bridge.

Benefits, Limitations, and Next Steps

The primary benefits of the current version of the BVRCS (both bridge deck and underside versions) is that they can be deployed using inexpensive hardware, they can quickly set up and taken down (10 minutes or less to collect data), they existing commercially-available software for photo processing, and that this system creates an easily viewable photo inventory of the condition of a bridge that can be compared to future photos. For the bridge deck version, the photos are location-tagged using GPS and can be accessed and queried using commonly available geospatial software such as ArcGIS and Google Earth. The total system cost (\$1,140)

as currently developed is: \$500 for the two PowerShot SX100 IS cameras, \$190 for PSRemote camera control software, and \$350 for the GPS-Photo Link software.

The primary limitations of the setup include data collection speed, the need to assemble a working system from separate parts, and the use of non-high-end GPS. Similar to the team's 3DOBS, higher-end cameras would enable faster data collection. However, the PSRemote software only works with certain cameras and cannot take photos faster than about once every four seconds (with the cost being \$95 for the Canon version and \$175 for the Nikon version, see <<http://www.breezesys.com/>>). The team's solution for the BVRCS-Underside, as for 3DOBS, has been to adapt some existing MTRI camera control software to take photos at a rate of 1 fps. Ideally, the combined camera hardware, control, and photo processing system would be available from vendors that a DOT could contract with for services for field deployment.

In the meantime, a working and immediately useful system can be assembled based on the results of the current project. The team proposes to write a "How to Deploy the BVRCS" manual depending on project sponsor input and TAC interest, as a logical next step for reaching a field ready system.

GIGAPAN SYSTEM (GigaPan)

Collecting multiple digital photographs and stitching them into a single gigapixel (or larger) image was not previously considered as a bridge condition assessment technology. However, the MTRI team had a GigaPan available from a previous, non-bridge related project. As the system is capable of creating gigapixel (1,000 megapixels or more) high-resolution photos that can be used to help inventory a bridge's visual condition at a particular point in time, the project team decided to deploy it along with the other technologies while out at the field demonstration bridges.

The GigaPan consisted of a GigaPan EPIC robotic camera mount, a PowerShot SX110 IS, and a camera tripod (see Figure 15). This system was deployed at all three bridges and collected both side (fascia) profiles and undersides of the bridges. The setup and break down times for the GigaPan were both less than 10 minutes. Collection times ranged from 20 minutes up to 4 hours, depending upon the size of the area being captured and the amount of photos taken. The end results were between 1- and 10-gigapixel photos for a particular part of a bridge, such as its fascia (see Figure 16).

While the resulting images are very large in size (hundreds of megabytes to several gigabytes), the GigaPan website provides the ability to share the full-resolution versions of these images at no current cost. The project team has loaded two gigapixel examples onto the <http://www.gigapan.org/> website for easy example access, and to make it possible to rapidly integrate the results into the DSS. This type of image hosting could be provided through an existing DOT or contractor website, but using the <http://www.gigapan.org/> website means that an already optimized streaming service for these high-resolution images can be used for at least demonstration of a method of implementation. These two links provide access to full-resolution gigapixel-equivalent example photos taken at two of the selected bridges: Willow underside <http://gigapan.org/gigapans/84465> and Mannsiding looking north along south-bound US-127 <http://gigapan.org/gigapans/84462>.



Figure 15: An example of the GigaPan being used to collect high-resolution bridge inventory photos during August, 2011 field demonstrations at Willow Road bridge.



Figure 16: Profile view of Willow Road bridge looking south along US-23 from a GigaPan image. The full resolution version of this photo captures the entire side of the bridge at very high resolution in a gigapixel image.

Benefits, Limitations, and Next Steps

A primary benefit of the GigaPan is that it uses relatively inexpensive hardware to create a high-resolution photo inventory of parts of a bridge, available as a single gigapixel image stitched together from many hundreds or thousands of digital photos. The EPIC camera mount owned by MTRI costs \$299; a higher-end version with faster robotic arm and capable of using more cameras costs \$895 (see <<http://www.gigapansystems.com/>>). The EPIC camera mount comes with the GigaPan Stitch software that easily stitches together the multiple single images into a single larger image. The project team used one of its \$250 PowerShot SX110 IS cameras while newer systems can use DSLR cameras.

A primary limitation is the length of time it can take to collect the photos needed to create a gigapixel image. Some of the image collections during field demonstrations took the team slightly over three hours. Also, the resulting number of images takes storage space capable of holding 1,000 or more 7-to-12+ megapixel images. It also takes approximately 4-to-6 hours to stitch together the images. Making the data available to end users requires a server that can stream large images to end users, although fortunately so far the GigaPan project (see <<http://www.gigapan.org/>>) is providing this service free of charge. If a very high-resolution photo inventory of various parts of a bridge is valuable to a DOT within these limits, then the GigaPan is ready for deployment at the current time. With server space, processor power, and data streaming speeds generally increasing, then the large size of files generating through GigaPan data-collection should be less of a limitation in the near future.

The team proposes to write a "How to Deploy the GigaPan" manual depending on project sponsor input and TAC interest, as a logical next step for having a user-ready system. A review of GigaPan capabilities and practicality in the near future is recommended once new versions have been released and DOTs have increased their computer and server capabilities.

THERMAL INFRARED (ThIR)

Field demonstration of ThIR imagery was conducted on the selected pre-stressed concrete bridges using the data collection procedure based on the proposed method in technical memorandum n^o 20. ThIR images were collected on the top of the bridge deck by pulling the cart with a "homemade tripod" over the bridge (see Figure 17) on the specific grid pattern (see Figures 18 and 19) that was drawn on each bridge prior to data collection. This cart system can be adapted to a vehicle-based mount.



Figures 17 & 18: ThIR camera mounted on the cart with “homemade tripod” system and chalk and duct tape grid layout on Freer Road bridge.

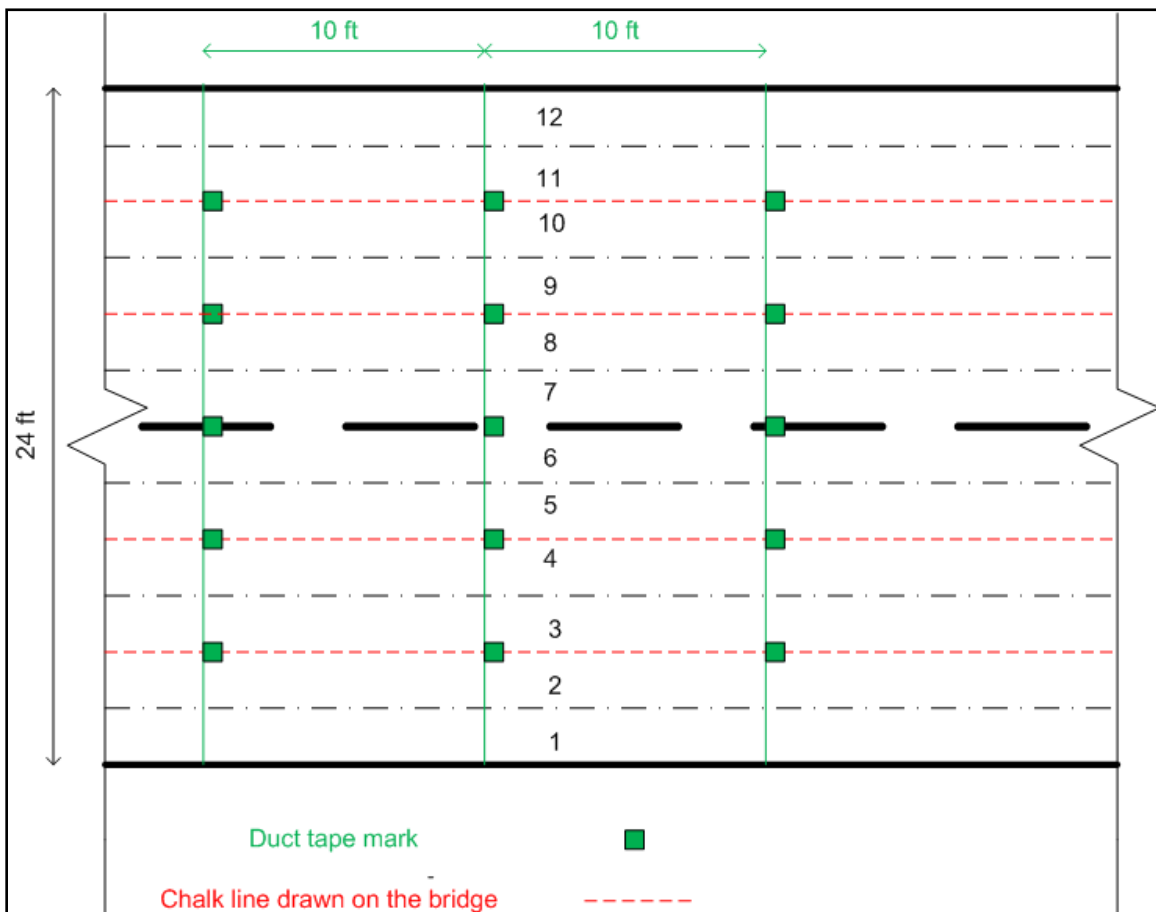


Figure 19: General grid pattern what was used on each of the bridge decks.

Collecting ThIR images from the bottom of the bridge was done by standing on the shoulders or closed lanes underneath each bridge using the FLIR ThermoCAM SC640 camera and by using a bucket truck and the FLIR i7 camera to get closer to the surfaces of interest and compare the differences.

The first approach to ThIR data analysis after the bridge deck data collection was to stitch all the images together to get the overview of the entire deck. Figure 20 shows the results of this approach for the Freer Road bridge. Calculating the percentage of delamination was the next step in the process which was accomplished by analyzing each image in Microsoft Excel (this method was discussed in technical memorandum n^o 15) and calculating the total percentage of delamination by adding the percentage of delamination for each image. Table 1 shows the result of this calculation for the Freer Road bridge. This bridge was rated as a “satisfactory bridge” based on the most recent inspection in June, 2010.

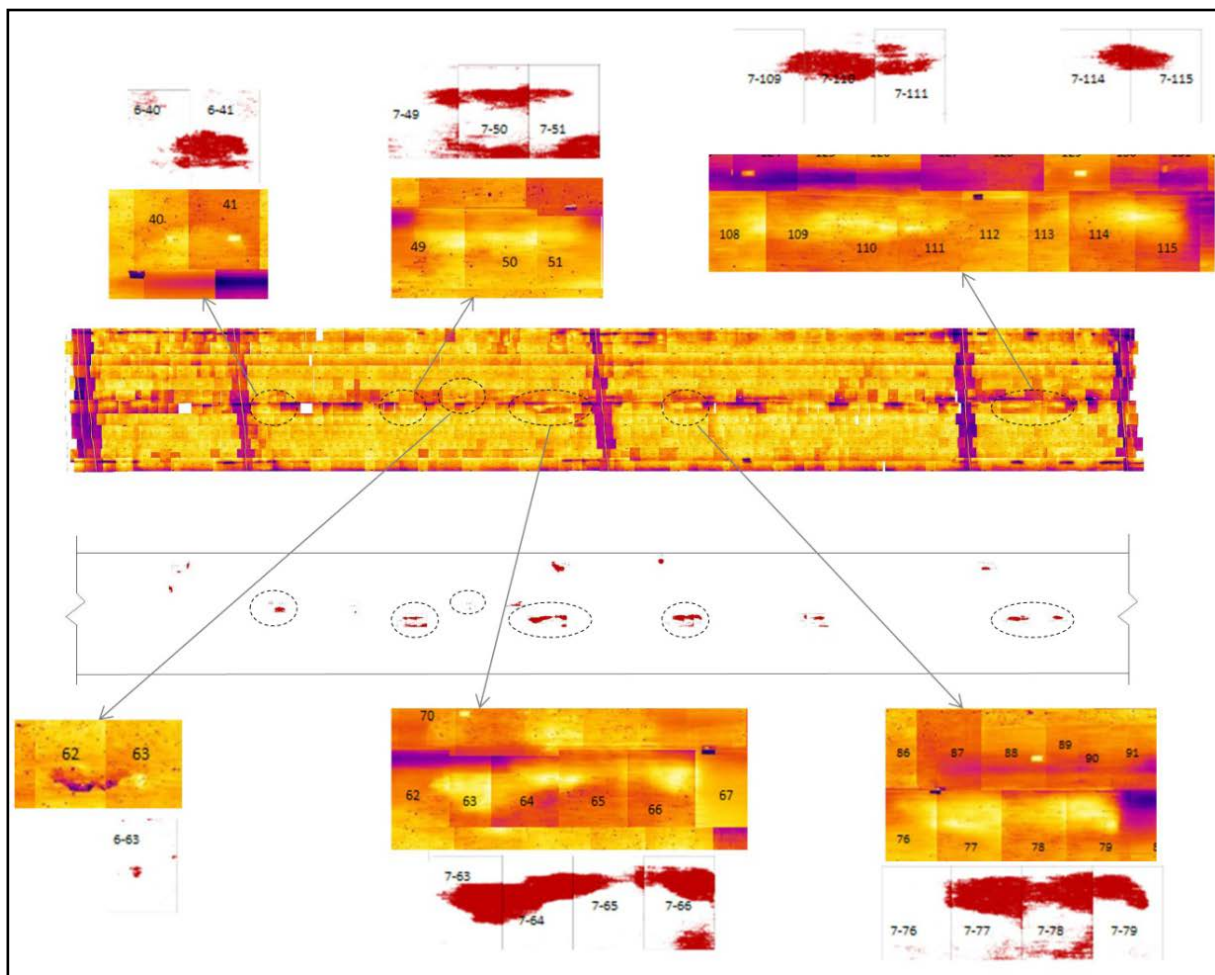


Figure 20: Free Road bridge deck delamination map created by ThIR images and Excel spreadsheet.

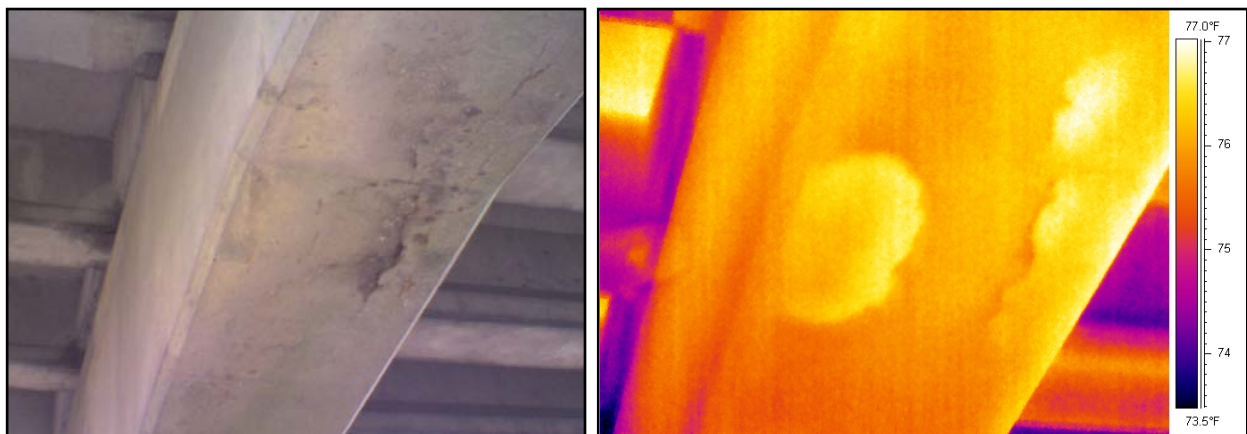
Total Delaminated Area (ft ²)	22.95
Total Bridge Area (ft ²)	5,015.75
Percentage of Delamination (%)	0.46

Table 1: Percentage of delamination calculation for Freer Road bridge.

The delamination map created can help bridge inspectors locate and quantify the delaminations on a bridge deck, however this method is labor intensive and require an operator to move images around to find the correct location of the image. Also, it needs reference points such as pieces of duct tape on the surface to help in the stitching procedure. Another method being developed by the project team is using The MathWorks MATLAB to automatically stitch the photos and calculate the area of delamination.

Possible delaminated areas on bridge piers and under the deck were visible on several of the ThIR images taken from these locations, however calculating the area of delaminations based on number of pixels is not accurate because the cameras were not completely perpendicular to the surfaces. However, current bridge inspection practice under the bridge involves lane closure and use of a bucket truck, which does not occur on a biennial base. Therefore, locating these areas can be helpful to bridge inspectors identifying these areas without lane closures.

Figures 21 and 22 show the delaminated areas on a bridge pier of Willow Road bridge. All the four inspected bridges were pre-stressed I-beam bridges which did not have many delamination problems on the girders; problems that have been observed by the research team were mostly located on the deck bottom surface and piers.



Figures 21 & 22: Optical and ThIR images showing delaminated area on a Willow Road bridge pier.

Benefits, Limitations, and Next Steps

Detecting delaminations on a concrete bridge is a major challenge for DOT inspectors as the current practice methods, hammer sound and chain drag, are labor intensive, time consuming, and require lane closures over and under the bridge. ThIR imagery is a technology that can assist bridge inspectors with detecting delaminations faster and easier than what is currently being done, which is the primary advantage for deploying this technology.

As it has been mentioned in technical memorandum n^o 20, weather conditions and the time of day play an important role in having an accurate data set. During this field demo for all selected bridges, weather condition was partially to mostly cloudy. Data collection time was between 10:30 am and 2 pm as planned. More research is required in this field to improve the system by possibly adding heaters and use active thermography method.

The i7 ThIR camera is a handheld device which costs around \$1,995. Although this camera is easy to use and has the ability to produce similar results as the more expensive cameras, it is not as efficient. This camera has smaller field of view (FOV) and lower resolution (14,400 pixels) than the more expensive cameras. Not having the options of taking ThIR images at time increments and taking optical images as well as ThIR images are the main disadvantages of this model. The ability of a camera to take images at time increments is necessary to use this technology at any rolling speed. Taking optical images of the bridge as well as ThIR images is one of the important components of data collection to help bridge inspectors re-visit the collected data at a later time and separate the noise and surface staining from the delaminated areas. FLIR software is not included in the price of this camera and it has to be purchased separately. A hand-held FLIR option that has higher resolution (19,200 pixels) including both optical and ThIR imaging capability is the E40 at around \$4,195. Comparable FLUKE options are the Ti10 and the TiR; either for around \$4,495.

The ThermaCAM SC640 (307,200 pixels) has the option to collect data at time increments up to 30 fps which helps in collecting the data at rolling speeds and creates a sequence of images for each pass. Also, this camera has the option to collect optical images as well as ThIR images which can be stored on one device. The proprietary software of this camera has the option to analyze the images and help in detecting and calculating the area of delaminations. While not being part of FLIR's current line-up, this research and development camera is estimated to cost around \$40,000.

Although this technology is promising in identifying delaminations (see Figures 21 and 22), this method of data collection is not completely practical for bridges at the current stage of

development. The field demonstration data collection method was designed based on the available ThIR cameras and their limitations. The lens on the ThermaCAM SC640 has a focal-length of 40 mm which limits the horizontal field of view of this camera to about 2.7 ft wide at a height of 6.2 ft. This FOV limits the possibility of installing the camera on the back of the truck (similar to the 3DOBS) – the camera would be to be installed at a height of 24 ft (very impractical) to be able to capture a lane that is about 10 ft wide. The lens on this camera can be replaced with a calibrated 19 mm lens at the cost of about \$10,000; which would increase the FOV to a width of 10 ft at a more sensible height of about 12 ft. However, using the 19 mm lens can cause image distortion along the edges which can create inaccuracy in the pixel analysis of the image.

The first approach of data analysis (originally proposed in technical memorandum n^o 15) is labor intensive and time consuming for analyzing the large amounts of data. While MATLAB programming is in progress for processing large amounts of data it requires more research time to make it applicable for bridge inspection practices. Although the ThIR camera and the proprietary software is commercially available, a package which is specific for bridge data analysis and delamination detection is not currently developed and requires further research in this area.

There is a future in using ThIR to detect bridge delaminations, but simultaneous development in data collection procedure and a specific software package need to happen to make this technology user ready for bridge inspectors and transportation authorities.

DIGITAL IMAGE CORRELATION (DIC)

DIC was implemented on MDOT structure n^o 1713 – Mannsiding Road over US-127 north-bound. The objective with this field deployment was to verify the capabilities of the technique and application for structural health measurements such as displacement and strains. The complete north-bound Mannsiding Road bridge system has three major spans; two approach spans over each shoulder and a center-span over the US-127 north bound lanes.

While part of the original plan, traditional instrumentation (e.g., deflectometers, accelerometers, strain gauges) for correlation purposes was not deployed as planned. However Light Detecting and Ranging (LiDAR) was used as a possible validation technique for DIC deflection measurements.

Implementation of DIC consisted of a creating a contrasting dot pattern on the structural I-beam span (of the center-span), and setting up an elevated (at center-span) camera-lens system. Before testing began, the half-point and quarter-point locations on the 60.25 ft center-span north-most girder were marked with duct tape to easily identify the testing locations before a washable water-based spray-paint was used for the creation of a speckle pattern on the exterior girder. A MDOT bucket truck was used for the creation of these larger and smaller refined marks constituting the speckle pattern which are necessary for tracking pixel movement using DIC (see Figures 23 and 24).

The camera was placed at a 20 ft standoff distance from the target surface on a rigid tripod (4.25 ft) located on a scaffolding platform (10 ft). The overall height of 14.25 ft placed the camera perpendicular with the exterior girder (see Figures 23, 25, and 26).



Figures 23 & 24: DIC setup at Mannsiding Road bridge and detail of girder with speckle patterns.

The predetermined bridge span was stressed by both a quasi-static and dynamic live-load generated by a live-load test truck. A live load truck with a weight of around 57 kip (see Figure 25) was used during load testing. The truck was guided along the exterior lane path at a crawl speed below 10 mph. During loading, images were captured by a Canon EOS 7D DSLR with the EF 70-200 mm f/2.8L USM lens on the exterior girder at the quarter span location. This test was repeated three more times with two of those trials remaining at focal length of around 85 mm and the third was at a focus length of around 135 mm.

The camera was then moved horizontally to capture images at a 45° angle to the girder surface at the half-point. This test was repeated three times at crawl speeds at a focal length of around 135 mm and the third was a focal length of around 200 mm. The speed on the truck was increased to about 40 mph and a series of images were taken at this speed shooting at the

more defined speckle pattern quarter-point location. To conclude this testing, a static test was performed with the truck parked at the quarter-point location. Additionally, a series of static tests were done on the bridge as well with no truck (load) on the bridge.



Figures 25 & 26: Load truck going over bridge and close-up of camera and tripod setup on scaffolding.

The dynamic test was performed to determine how accurately DIC can optically sense, and capture, bridge vibration. The dynamic tests performed at posted speed were completed to mimic actual service conditions. The images were numbered automatically by the camera's firmware, and each of the images was correlated with the known load applied to the bridge span at that time. All of the truck measurements and distances on the bridge were collected to be able to use further in finite element analysis (FEA) bridge model. The field experiment with scaffolding preparation and image capturing from loading on the exterior girder took about an hour. The total time for the application of the speckle pattern took about 15 minutes.

The images gathered with the camera were processed in Correlated Solutions Vic-2D for strain and displacement measurements. The next step involved formatting and processing the images into Vic-2D. Expected results from this testing would expect to show quasi-static behavior where there is a higher value that drops due to displacement from the loading truck and then returns back or near the point of origin as the truck drove across and off of the half-point and quarter-point locations. The values of the change in position (displacement) the images file numbers (time elapse) are quite varied from set to set. Figure 27 shows a sample graph from the raw data of the quarter-point set from one of the crawl speed run series.

From this graph, very erratic movement is shown. With all this noise and variation displayed, trend lines and linear graphical relations were attempted to characterize the movement. This approach was used in all sets with not a lot of consistency between them. Looking at Figure 27,

it reveals a change in displacement of at least four inches (down vertical direction). Now, with all conditions considered such as a standoff distance of 20 ft and a slight degree movement of the camera from a wind disturbance, the camera could easily move and correlation could indicate larger movement than what actually occurred (perhaps, something as large as four inches). This leads to further investigation of the data files being produced in the VIC software. A re-examination of the 'V' (vertical displacement) of the pixel location, 'c' as interpreted through the software was investigated to ensure the data presented is the data that is expected.

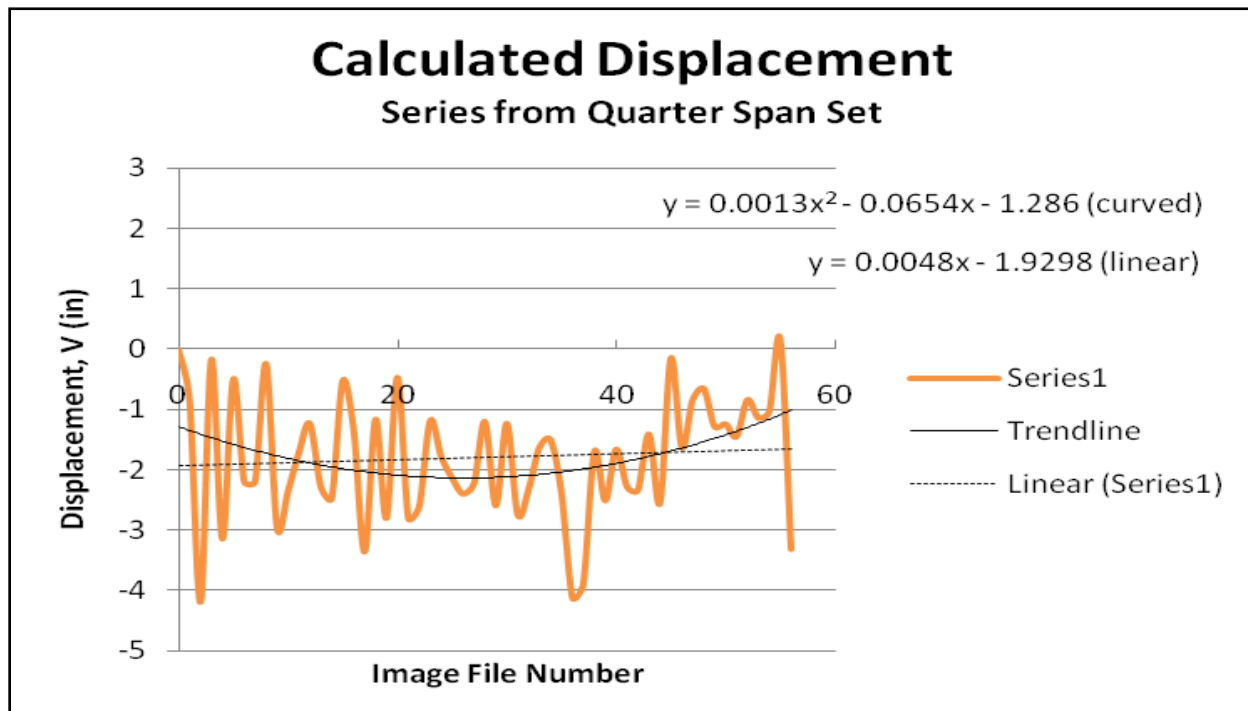


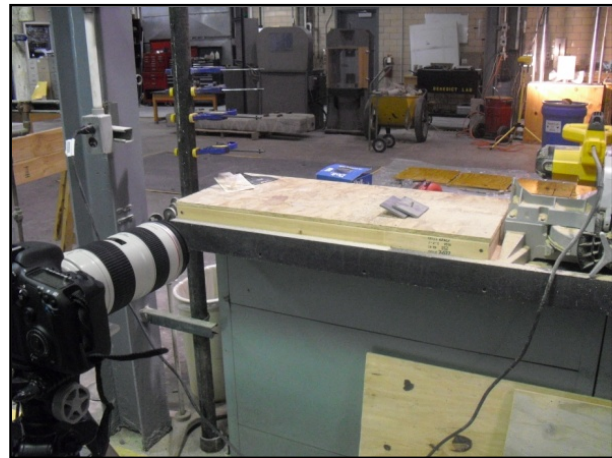
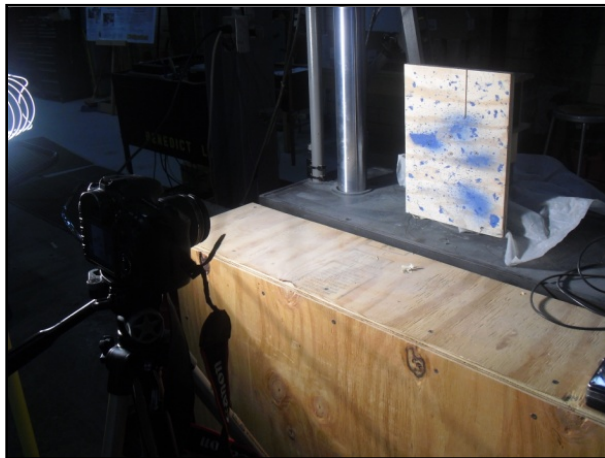
Figure 27: Vic-2D graphical plot of calculated displacement for a test series.

Through this investigation, it was evident that this random graph display was presented in all the sets due to various environmental effects endured in field testing. During the tests, there still was one lane of traffic next to the camera system on the scaffolding platform which is shown in Figure 23.

Therefore, the wind and vibration effects of the passing traffic were a factor throughout the testing. In addition, other wind movement in the air could impact camera and lens stability as well as movement to the scaffolding itself especially since it was elevated 10 ft for alignment with the bridge girder height. The noise is an issue that was considered and an attempt to factor out or single out somehow was used which is explained in the next section. Additionally,

this testing data will be compared with the LiDAR point cloud data collection that was taken both with the truck and without the load truck once this data is thoroughly processed. Furthermore, this data will also be correlated with a finite element model (FEM) of the Mannsiding Road bridge comparing simulated behavior with actual bridge response. A simple model was created of the bridge girder and the truck loading configurations which were correlated under the maximum value deflection that can be endured with this bridge's measurements. This analysis will be explored further while considering distribution factor analysis for a combined bridge girder- and deck-system.

As discussed, additional laboratory testing was also done to see how well Vic-2D captures movement together with also identifying the dynamic effects of wind and other "outdoor" effects in the camera system as experienced previously in the field. With the same lens settings, tripod, and camera system a series of tests were completed. A rectangular piece of plywood with a distinct speckle pattern was used at 2 ft and 32 ft from the camera; it was subjected to cyclic movements at two varied displacements on an MTS 810 Material Test System. Figures 28 and 29 show the setup of the speckled board and camera at the two different distances.



Figures 28 & 29: Benedict lab testing setups at 2 ft and at 32 ft.

At the closest distance, 2 ft, two different trials were completed; with (fan on camera) and without wind. Table 2 shows the percent difference in displacement values as calculated in Vic-2D software as compared to the data collection from the 810 Material Test System; the values had little error at 1.8%, but with wind simulation the change in displacement increased almost by half. For the 32 ft testing scenario, the camera was placed on the loading platform of a Fairbanks-Morse floor scale located on the MTU's Benedict Laboratory (see Figure 30).

Test Number/Type	Test Frequency	Expected Displacement	MTS Measurements	Vic-2D Measurements	Percent Difference
T1 - no wind	0.25 Hz	0.25 in	0.2468 in	0.2515 in	1.8%
T2 - wind	0.25 Hz	0.25 in	0.2462 in	0.2521 in	2.4%

Table 2: Test measurement comparisons at 2 ft with wind and no wind.

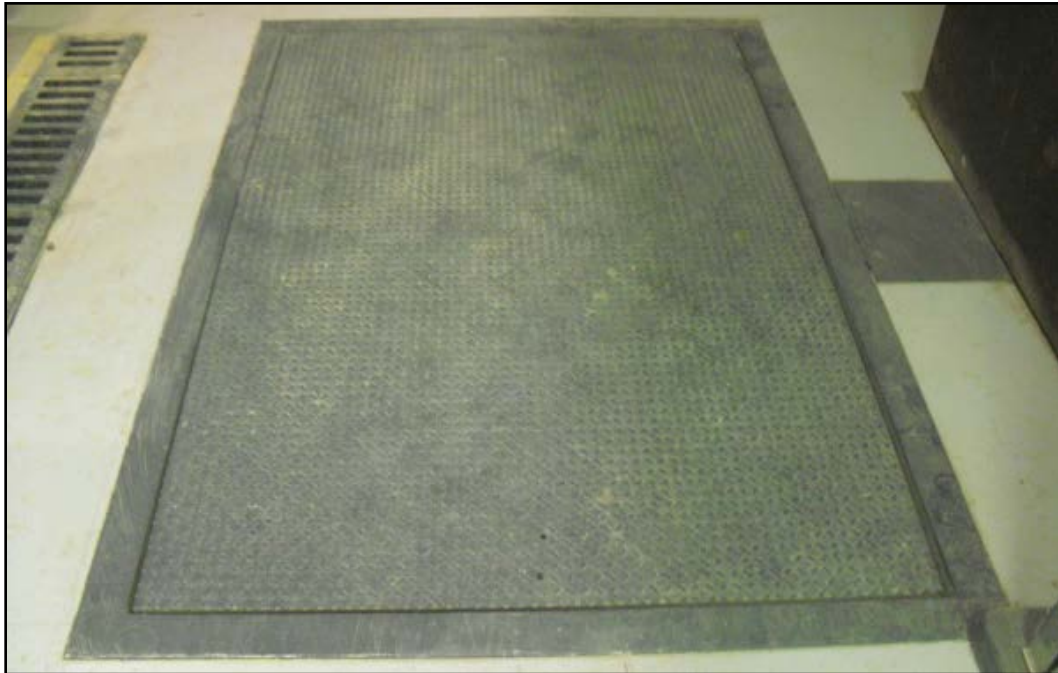


Figure 30: Floor scale loading platform used to simulate scaffolding movement.

The floor scale platform can easily move with a person walking or a simple shift of weight by objects. The camera and tripod were placed on the platform and images were taken of the rectangle speckled board. This test was repeated with a person moving on the platform to demonstrate a field like simulation of the scaffolding setup. Table 3 shows the results from the processed images in Vic-2D compared to the 810 Material Test System data and the percent differences.

In this battery of tests, it was shown that the displacement values differ drastically when tests are repeated with and without movement. In Test 4, there was so much movement that the data could not be compared. This graphical representation is shown in Figure 31. Again, Tables 2 and 3, show the re-examined approach of the 'V' (vertical displacement) of the pixel location, 'c' as interpreted through the software. These tests are very comparable to the same type of noise identified in the field results.

Test Number/Type	Test Frequency	Expected Displacement	MTS Measurements	Vic-2D Measurements	Percent Difference
T1 – without movement	0.25 Hz	0.25 in	0.2457 in	0.2578 in	4.8%
T2 – without movement	0.25 Hz	0.50 in	0.4966 in	0.5070 in	2.1%
T3 – with movement	0.25 Hz	0.50 in	0.4974 in	0.7414 in	39%
T4 – with movement	0.25 Hz	0.25 in	0.2482 in	-----	-----

Table 3: Test measurement comparisons at 32 ft; movement and no movement.

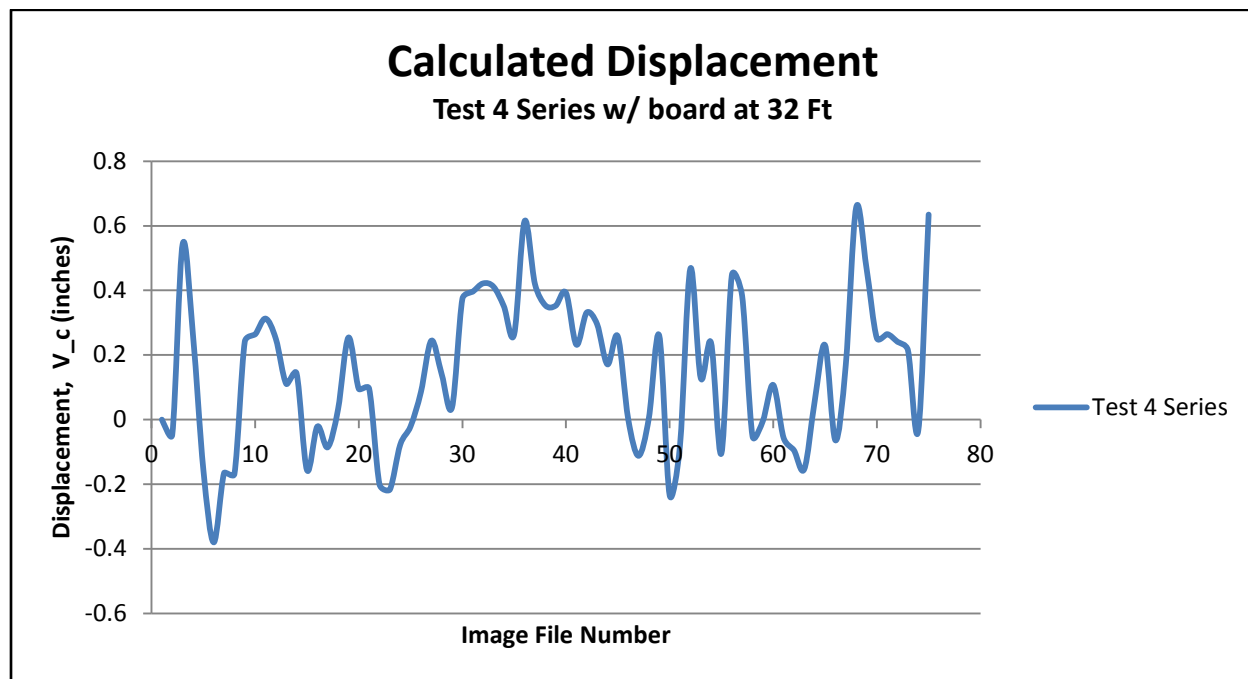


Figure 31: Test 4 results from the 32 ft series testing; test performed with floor scale movement.

Benefits, Limitations, and Next Steps

The benefits of DIC include the flexibility in location for testing as well as time-of-day for image collection (depending on requirements), use of available software for analysis and ability to provide load performance details with single tests.

The total cost of this system currently consists of; ~\$12,000 for Vic-2D, \$3,000 camera and lens system, \$1,000 scaffolding system, \$100 tripod, and \$15 for washable spray-paint. Much of the

DIC system cost depends on the requirements needed for particular testing being conducted (e.g., higher grade lens or camera, different paint used for pattern, better more stable tripod).

The limitations of the software consist of the compatibility with the camera-lens system in the testing environment, the applicability of the speckle pattern to be detected (enough contrast), and actual software specifications. This technology has the capability to obtain the measurements expected (shown in a controlled laboratory setting) but needs further development for field deployment. Ideally, continued testing with better adjusted system setup and instrumentation data correlation would be beneficial in meticulously tracking down displacement in images with time-stamps to track movement incurring on a bridge.

When considering additional testing, it is suggested that both the system performance and system algorithms details may need to be revised. Initially, when applying the pattern, there needs to be assurance that the pattern will be detected at the imposed standoff distance; a “pre-test” needs to be performed to insure this. One of the trial runs for the quarter-point series did not correlate pixels from image-to-image; this gave a non-readable data set for that series. The exact causes of this non-readable set is not known but it is speculated that sunlight during that particular series produced non-desired contrasts with between the speckle pattern and the concrete face on the girder.

Specific to hardware, a more stable testing platform could be used together with a shorter and sturdier surveying-style tripod reducing much noise. Also surrounding the camera and lens with a “shield” could possibly eliminate certain wind conditions. Note that accurately assessing wind and vibration factors is very important. The movement of the camera lens could be tracked using an accelerometers and an algorithm; this could allow for lens movement to be possibly factored out in displacement analysis. A gyroscopically-compensated camera mount, such as one of the Kenyon Laboratories Gyro Stabilizers, could also help in keeping the camera still. Reduction of the standoff distance would certainly reduce the effects of wind and vibration.

There are also numerous changeable parameters within the software that can alter the results. Algorithm details may require further investigation considering bias errors in the accuracy or precision of the software analysis. Bias interpolation of these results can translate into incorrectly interpreted testing data. More investigation into parameters and how they affect results is a major component of the post-processing data analysis.

While DIC has hardware and software that is commercially available and ready for deployment, it is a technology that is currently best suited for laboratory work where most-all conditions

(e.g., wind, vibration) can be controlled. There is a future in using DIC in the field when but there needs to be much hardware development specific for bridge condition tests outdoors.

LIGHT DETECTING AND RANGING (LiDAR)

The field demonstration for LiDAR imagery was conducted on the three pre-stressed concrete bridges, selected in the previous quarter. Data collection procedure for all of these bridges was based on the proposed method in technical memorandum n^o 20. Multiple scan positions were sampled allowing for the equipment to illuminate any “shadows” due to the technologies limitation regarding light of sight measurement. Approximately 8-to-12 scans positions were needed to allow for a complete a 3D point cloud rendering of the numerous faces of the bridge structure. A typical scan position layout is provided to help show where data collection generally took place during the field demonstration (see Figure 32).

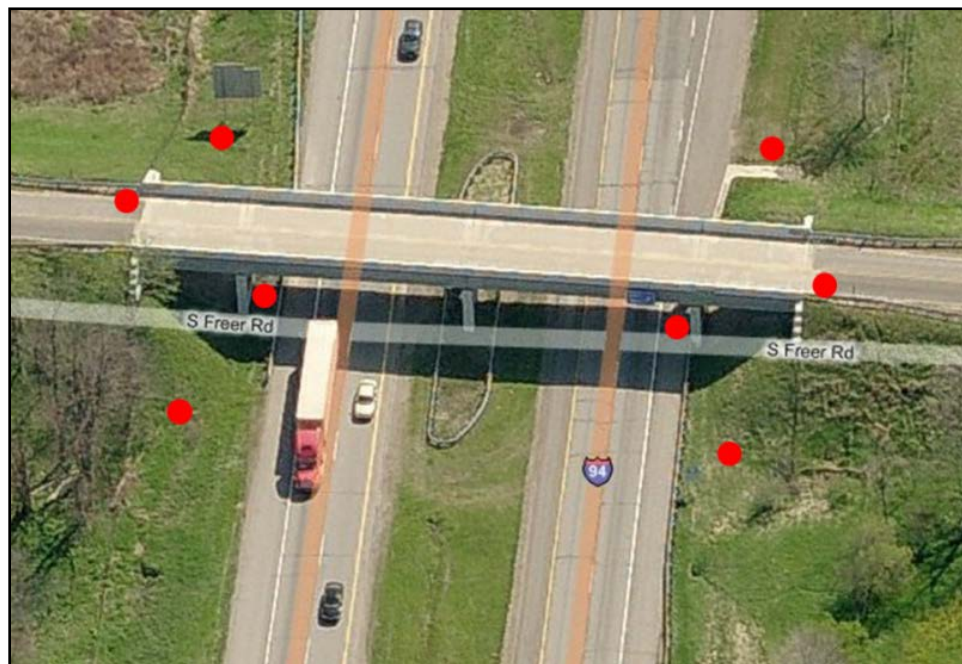


Figure 32: Red dots showing general locations for LiDAR scans to be performed.

Individual collection scans were completed utilizing two separate LiDAR surveying units; a MDOT owned Leica ScanStation C10 and a MTU owned RIEGL LMS-Z210ii (see Figures 33 and 34). The most obvious difference between the two units is the built-in user interface of the ScanStation C10 compared to the required computer connection of the LMS-Z210ii allowing for the ScanStation C10 to be easily re-positioned by a single individual. Scan data is currently

being process to determine individual accuracy of defect detection for each unit. Note that for the first two field demonstration locations in Washtenaw county (Free Road and Willow Road bridges) MDOT's ScanStation C10 was the only source of data collection.



Figures 33 & 34: MDOT's Leica ScanStation C10 and MTU's RIEGL LMS-Z210ii.

Both data streams are being imported into three post-processing programs: Certainty 3D TopoDOT (a Bentley MicroStation application), Applied Imagery Quick Terrain Modeler, and the University of North Carolina at Charlotte (UNC Charlotte) Light Detection and Ranging-based Bridge Evaluation (LiBE) surface damage detection algorithm. Usable 3D data is being created that can be analyzed for condition information using other commonly available software such as ArcGIS.

The ScanStation C10 data was collected by MDOT's Geodetic Surveying, Topographic, and Aerial Mapping Services Unit to help understand the capability of this data source in evaluation indicators of bridge condition. Regarding the LMS-Z210ii (which was deployed only at Mannsiding Road bridge) the collected scans were individually stored using RIEGL RiSCAN PRO which allows for the user to view the data collection in real-time insuring the user that the scan captured all desired features. Once all selected scan locations were scanned, post-processing began immediately on-site by combining the single scans into one master image to ensure cohesiveness (see Figure 35).

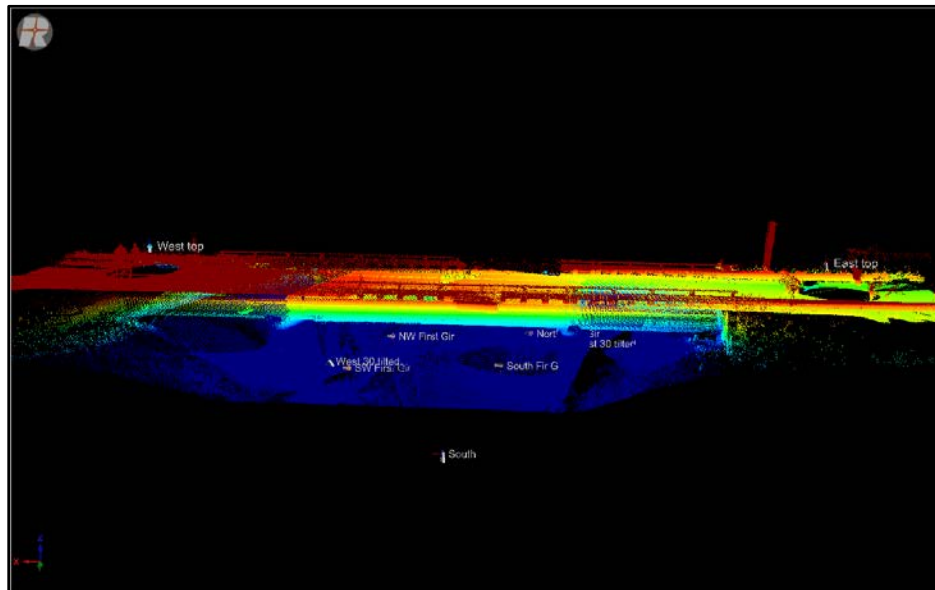


Figure 35: Master scan data image from the LMS-Z210ii and RiSCAN PRO.

While the project team waits for data processing to be completed, they are processing sample data from previous MDOT surveys shared by MDOT in order to establish a documented workflow for processing the LiDAR data into. The current generation of LiDAR sensors, such as the ScanStation C10, can extract data on XYZ location, 8 bit intensity of the return and red, green, and blue (RGB) values from each laser pulse-return.

Another commercial LiDAR processing software package, Cardinal Systems VrOne together with VrLiDAR and was also evaluated by the project team for data analysis processing and analysis capabilities. Based on ease of use so far, Quick Terrain Modeler appears to a practical piece of software for taking LAS-format LiDAR data from MDOT and converting into elevation data that can be analyzed within ArcGIS for bridge condition assessment. MDOT uses a combination of MicroStation and TopoDOT software to process and view its LiDAR data; the project team is investigating if this software can be acquired at a reasonable cost and in a timely manner.

Results from processing of MDOT sample data support the ability of LiDAR data to detect defects in the bridge deck. The combination of XYZ location, return intensity and RGB values provide a dataset sufficient to extract usable information on bridge deck condition. Note that the following scans are from a single LiDAR scan setup; MDOT frequently gathers multiple scans at a bridge in order to form a more complete picture of the bridge environment. Anomalies resulting from passing traffic, decreasing return density with distance from the scanner and buildups of debris on the bridge deck (at the lower right) are evident in the sample images. Multiple scans, additional data processing and site preparation prior to scanning can help

correct these anomalies; Figures 36, 37, 38, and 39 show examples of LiDAR data being displayed with Quick Terrain Modeler so that bridge surface condition indicators, such as the location and depth of spalls can be easily seen and detected.

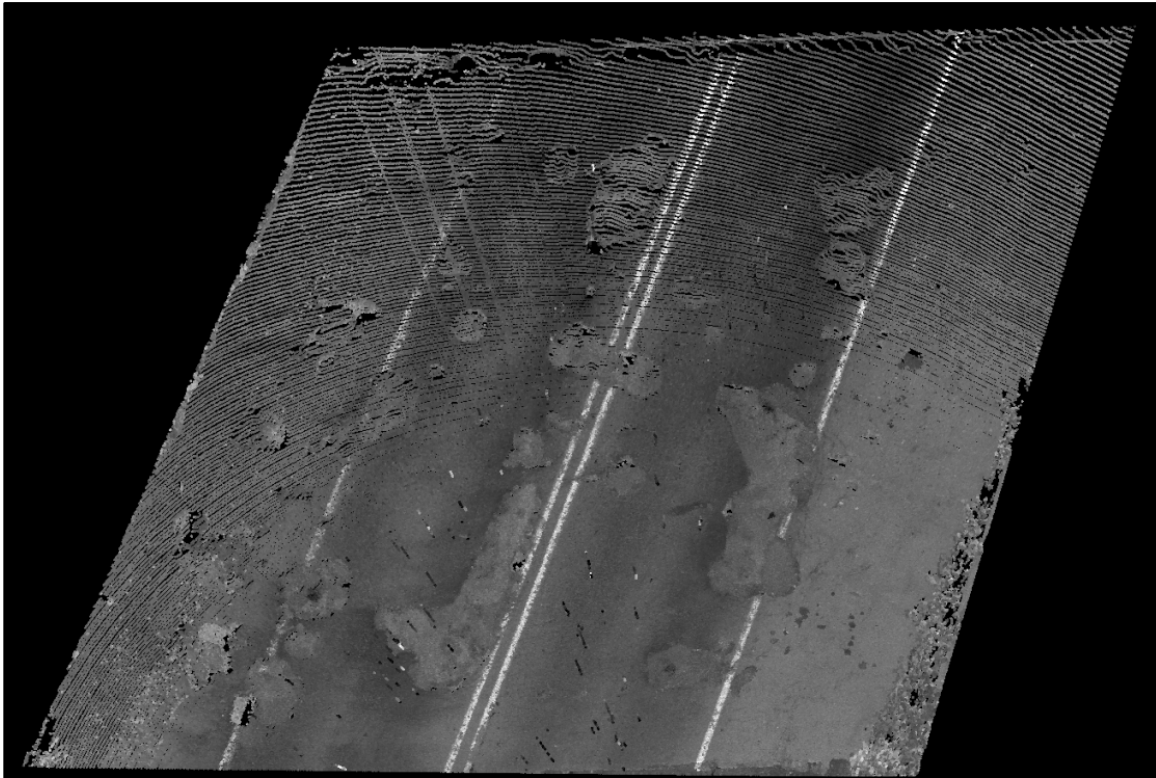


Figure 36: A LiDAR intensity image extracted from an MDOT sample data set (Warren Road over I-275). Deck condition is clearly visible as is increasing point spacing with distance from the scanner.

Figure 39 shows how an MDOT LiDAR survey has captured the presence and depth of an example bridge spall. The project team's added-value to these data is taking them and converting them into indicators of bridge condition that can be integrated into the overall bridge health signature, such as percent spalled, and location and volume of spalls, similar to what can be evaluated with the 3D optical 3DOBS. The LiDAR point clouds will be co-registered to other datasets collected at each study, allowing comparison of different remotely sensed data such as the ThIR imagery and 3D optical DEM. Initial steps have been taken to develop procedures to extract information documenting the area and volume of spalls on bridge decks and support structures from the LiDAR datasets. Fortunately, the team anticipates that spall analysis routines developed for the 3DOBS data can be used with LiDAR data as well, helping with project efficiency and eventual deployment.

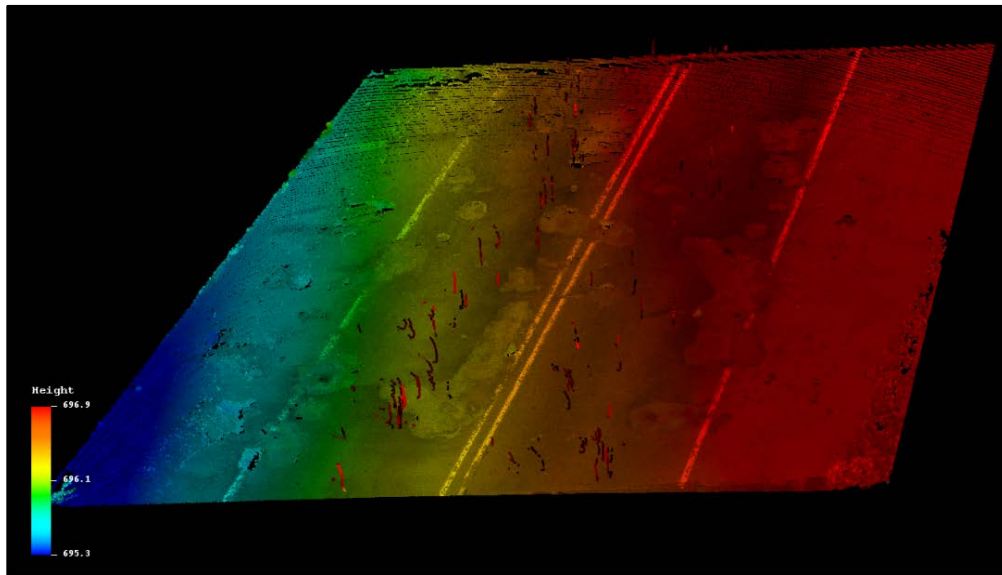


Figure 37: Composite LiDAR elevation and intensity image; deck condition can still be assessed from the intensity image. The bridge deck slopes from upper right to lower left with a total elevation change of about 48 cm.

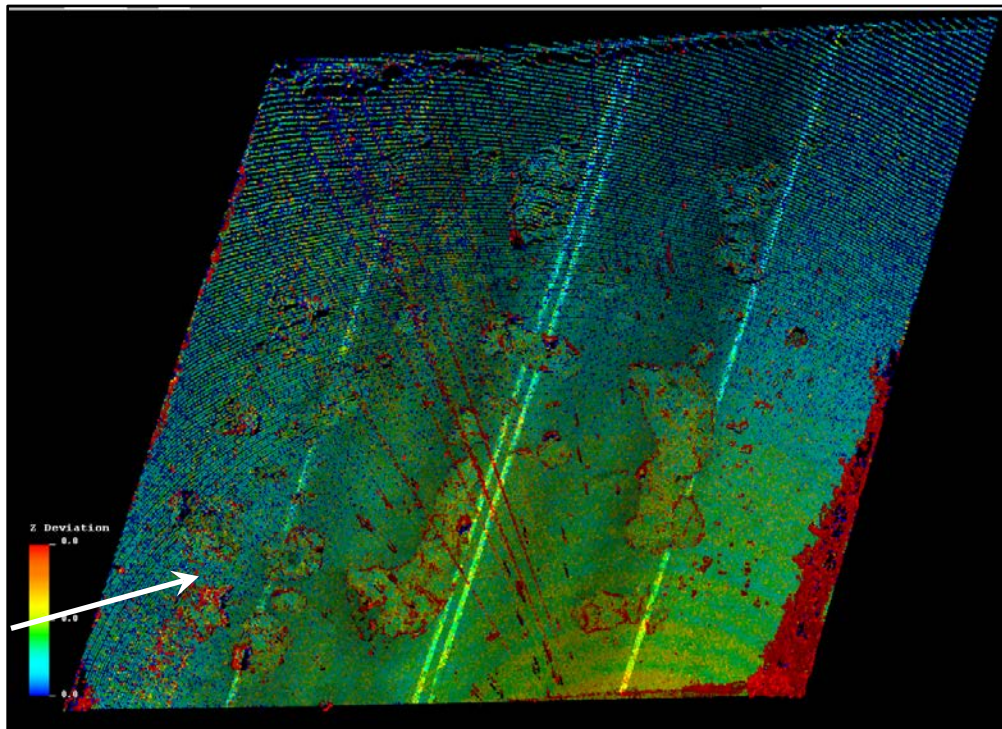


Figure 38: A composite Z-deviation and intensity image showing sharp changes in elevation between returns (red pixels). Outlines of potholes are visible as irregular shapes outlined in red. The large triangle of red pixels at the lower left is an accumulation of debris on the bridge deck. The red lines radiating from the lower right are returns from passing cars that have not yet been filtered out.

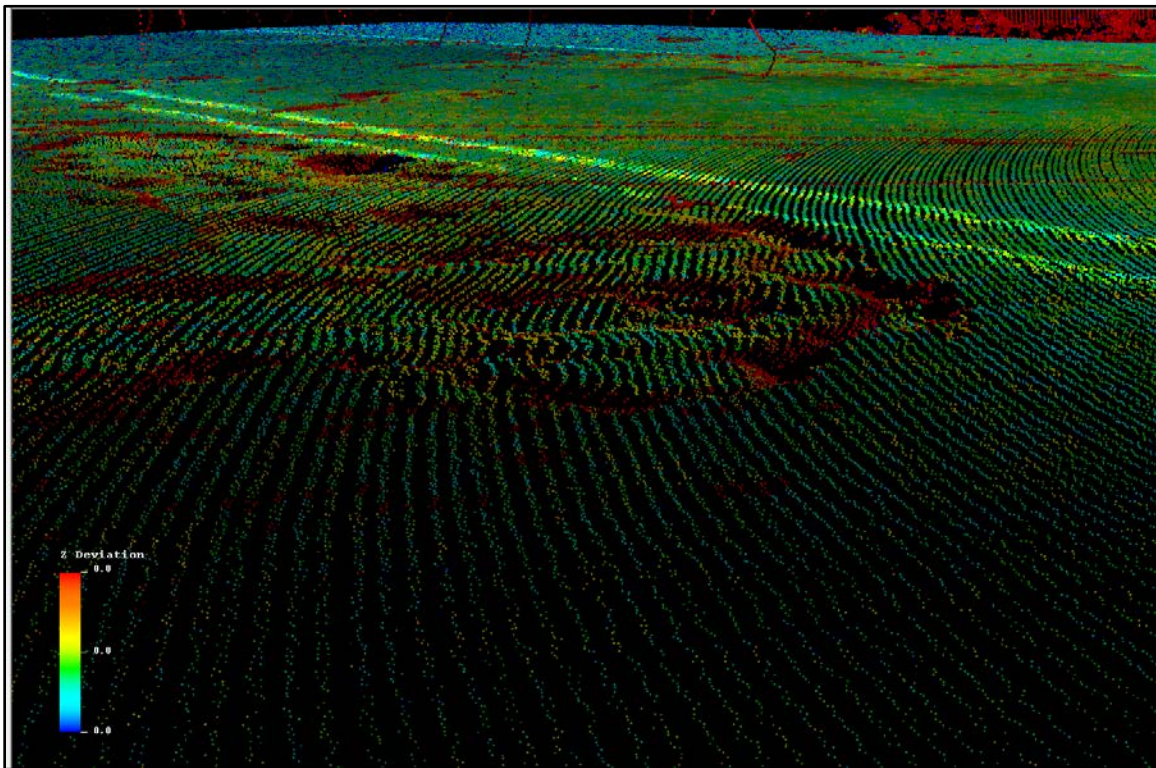


Figure 39: Demonstration of how LiDAR has captured the location and elevation values for a bridge spall. View is from the lower left looking toward the center right (white arrow) of the image. As in Figure 38, red pixels indicate rapid elevation change between returns. Further processing is expected to be able to extract deck damage area and volume values from the data.

A side by side comparison of a Google Street View image with the LiDAR intensity and Z-Deviation image demonstrates that under certain circumstances, Street View and similar data sources (such as data from the BVRCS) can be useful to validate interpretation of the LiDAR images (see Figures 40 and 41). The LiDAR data were collected fall, 2010 by MDOT but the collection date of the Street View image, while appearing recent, is unknown.

Figure 42 shows the same LiDAR data as in the previous figures, but now converted into an elevation raster file being used and displayed within ArcGIS. ArcGIS was selected because the same type of spall analysis routines developed for 3DOBS data can be used with LiDAR elevation data. The project team is currently further developing these routines with the goal of making them as automated as possible. Anticipated inputs into the bridge health signature include percent spalled for a bridge deck surface, amount spalled for bridge structure supports, and volume and location of spalls.

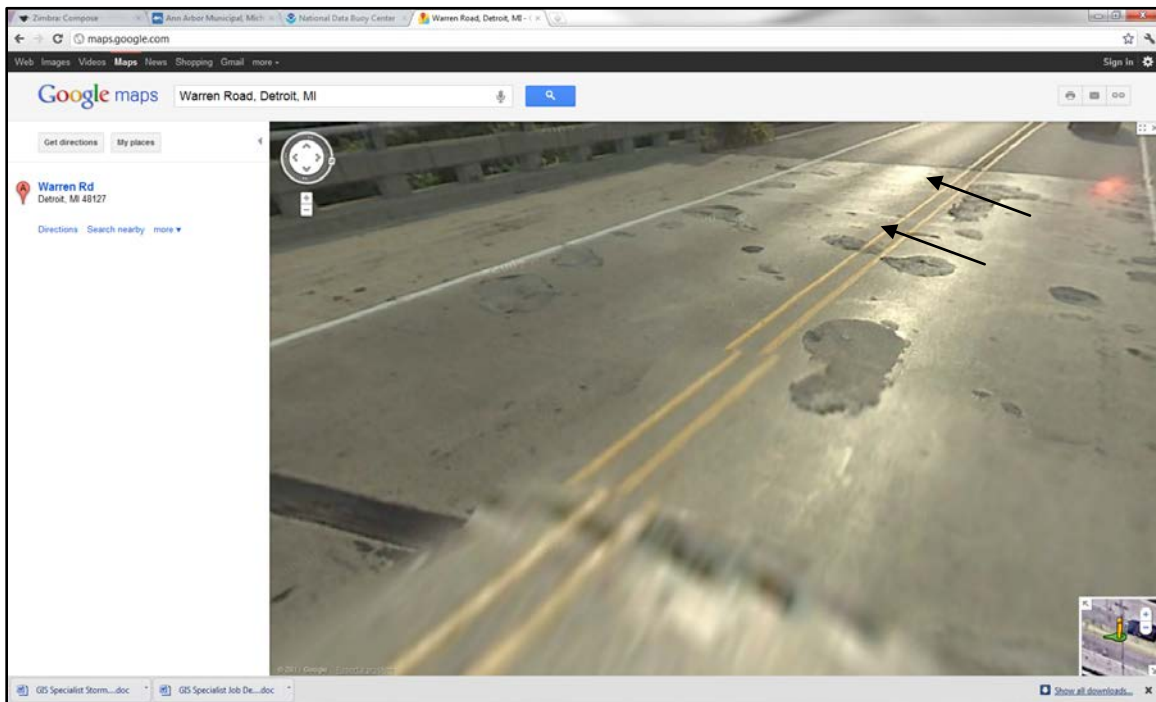


Figure 40: Street View image of the western-most span of the Warren Road bridge showing patches on the bridge deck.

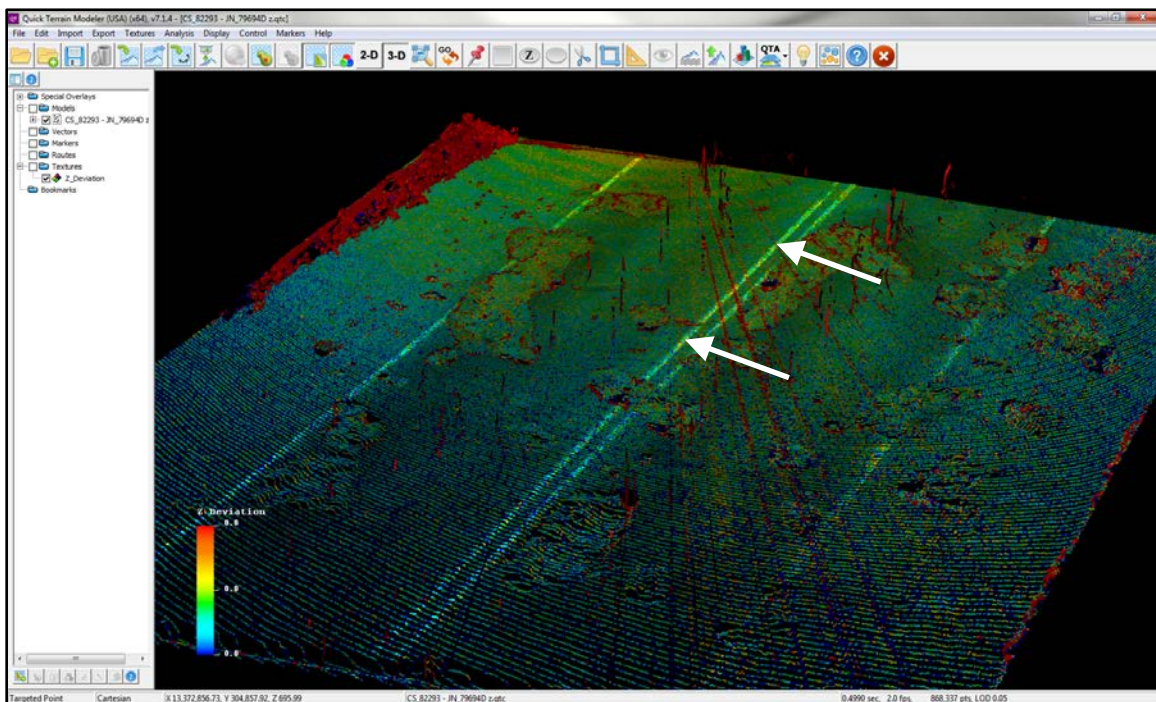


Figure 41: LiDAR intensity and Z-deviation image of the westernmost span of the Warren Road bridge from a similar perspective as Figure 40. Arrows point to the same features in each image.

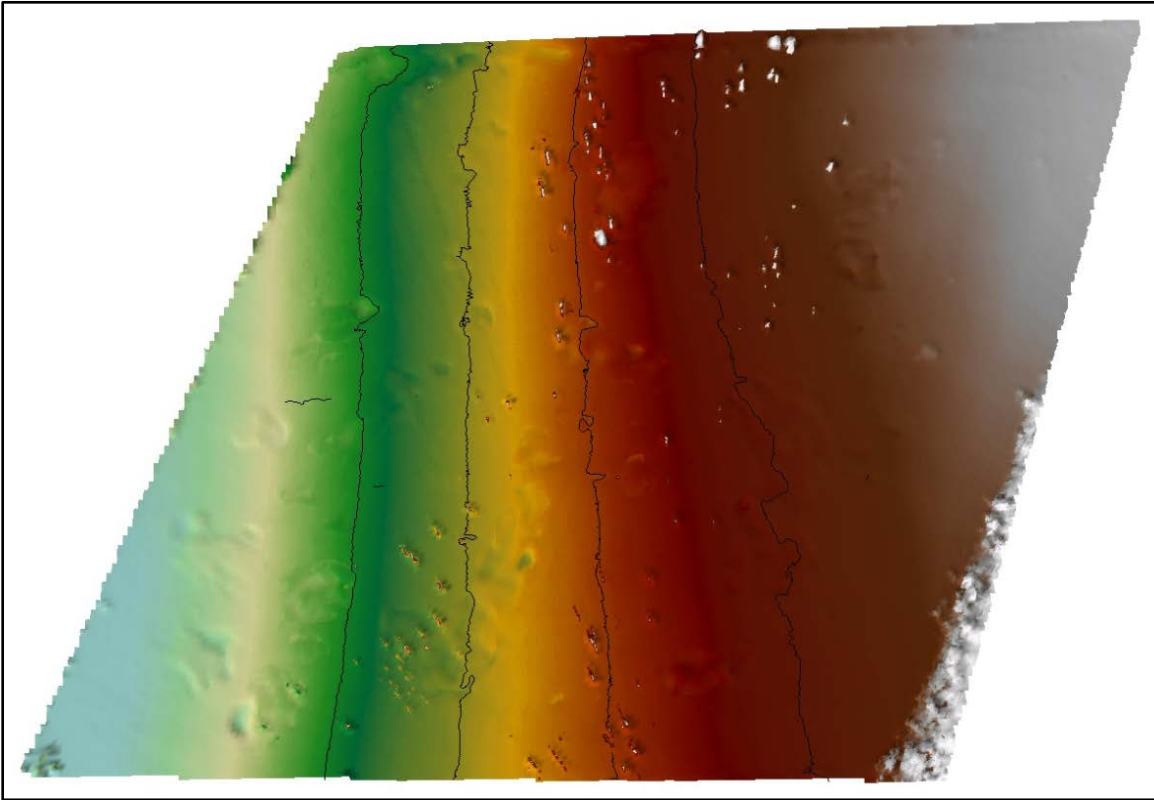


Figure 42: DEM derived from LiDAR data, exported from Quick Terrain Modeler and displayed in ArcGIS Arc Scene. Low-high is from lower left to upper-right. Generally, positive deviations from surrounding bridge deck are returns from passing vehicles, negative deviations are considered to be spalls. Orientation of this scene is similar to the previous LiDAR figures.

Benefits, Limitations, and Next Steps

As it has been mentioned in technical memorandum n^o 20, LiDAR is a line of sight instrument and requires repositioning to illuminate shadowed areas increasing collection time and required labor. However the primary limitation of LiDAR is that systems are expensive; the ScanStation C10 system used by MDOT cost around \$125,000. Multiple detailed scans to inventory most of a bridge can also take several hours, including set up time for geo-registration points. This technology has two main variables affecting practical use for bridge condition assessment, beyond system cost: resolution and collection time. To achieve desired feature resolution with the current models, increased collection time is required. Processing of LiDAR data into an initial usable form can also take significant time (two weeks or more depending on data-set size). Also, a workflow into bridge condition information for LiDAR data needs to be established as it not has typically been used for this purpose, but this project is

working on that process. LiDAR data has more commonly been used for inventory of information such as bridge clearance; our team's value is to analyze its capability to help developed bridge condition metrics.

The primary benefit of using LiDAR is that DOTs are already acquiring and using LiDAR systems as part of their day-to-day operations, or obtaining these services regularly from established vendors. Adding another reason to collect data (to help evaluate bridge condition) could be a relatively easy addition to existing DOT activities. The project team is providing a demonstration of how LiDAR data can be converted into bridge condition information by establishing a documented workflow whose eventual goal is integration of the analyzed data into the project's DSS.

Once the team has completed this development of LiDAR data to bridge condition workflow, the next step will be to assess the technical and financial feasibility of implementation of such a system in DOT operations. Because this technology is already used by DOTs, it may stand a better chance of being implemented than other technologies that would be new to most DOTs, such as the 3DOBS. The critical part will be establish and document a practical workflow that uses software tools commonly available to DOTs, such as ArcGIS, or that may be new but are not overly expensive, such as Quick Terrain Modeler (\$995 for a license that can operate on multiple computers).

Note that LiDAR units are developing quickly and current models provide more practical resolution to data collection time results. The RIEGL VZ-4000 has the potential to reduce collection time by 75% while maintaining similar scan clarity. Trying to compare similar systems, the LMS-Z210ii requires a hard data connection to a laptop reducing mobility while the VZ-4000 has an integrated touch screen eliminating the mobility issue. Additionally, the LMS-Z210ii requires tie points to fuse the individual scans together while the VZ-4000 has an on-board GPS eliminating the need for tie points. The current state of the practice regarding LiDAR only shows that with the ever advancing field of technology will continue to shrink the gap between research grade and practical application.

The VZ-4000 has an associated capital cost of around \$150,000. Since the equipment is in current uses by numerous DOTs as an inventory and surveying tool the trained individuals are already in place within the agencies to operate the unit. Additionally, the movement to mobile LiDAR platforms is already occurring. Private consulting firms nation-wide have begun to notice the potential and mobile LiDAR units traveling at slower than highway speeds are currently being deployed, such as the Optech Lynx Mobile Mapper and the Ambercore TITAN Mobile Laser Scanning System.

ULTRA WIDE BAND IMAGING RADAR SYSTEM (UWBIRS)

To assess the utility of UWBIRS, a demonstration of synthetic aperture radar, measurements to sense the interior of concrete bridge component structures and identify potential structural defects such as delaminations, two types of imaging radar measurements were collected at the test sites. In the 2D imaging modality, the radar sensor obliquely illuminated the bridge deck surface as it was moved along a linear path parallel to the deck surface. This type of data collection produces a 2D map of the radar reflectivity of the deck, which may indicate areas of internal defect and/or delamination. This type of collection is consistent with a concept of operation that has a radar system mounted on a moving vehicle to produce maps of deck radar reflectivity that identify areas of concern. This type of collection could also be performed by a standoff airborne sensor.

In the 3D imaging modality, the radar illuminates the bridge at a normal angle of incidence, and the radar is scanned over a two dimensional plane parallel to the bridge structure under test. Data from this form of collection can be used to produce a three dimensional map of the radar reflectivity, which may indicate areas of internal defect. This type of data collection is consistent with a concept of operation that uses the radar system to make a detailed internal survey of a suspect area.

A portable UWBIRS was developed at MTRI to emulate the performance of commercial radar sensors for the field demonstrations. The radar system consists of a commercially available AKELA RF Vector Signal Generator and Measurement Unit (AVMU), connected to a pair of wideband exponential taper horns. The AVMU operates in a stepped frequency continuous wave (SFCW) mode, with pulse modulation to bind the time delays over which data are collected. The AVMU collects data over 387.5 MHz to 3,000 MHz, with a nominal output power of 17 dBm. The 1.1 lb unit can operate using portable power sources. The radar is controlled using a laptop computer, and all of the instrument's operating parameters are under user control via a graphical user interface. As discussed below, the radar system was deployed on a portable, reconfigurable translation fixture to collect frequency diverse data as the radar sensor was scanned in one and two spatial dimensions at the field demonstrations.

A 2D radar data collection refers to a measurement where the radar collects electromagnetic backscattering measurements over a range of radio frequencies as the radar is moved linearly along one spatial dimension. The resulting data set is a two dimensional array of scene backscattering measurements as a function of frequency and sensor location.

To collect 2D radar data an apparatus was constructed at MTRI which moves the radar antenna along one dimension, parallel to the object being measured. This system is made using aluminum framing and an electric motor drive system for consistent sensor motion. The rail along which the radar antenna is translated allows for approximately 2.8 m of sensor motion, which is only limited by the current size of the side support rails and motor drive mechanism (see Figure 43).

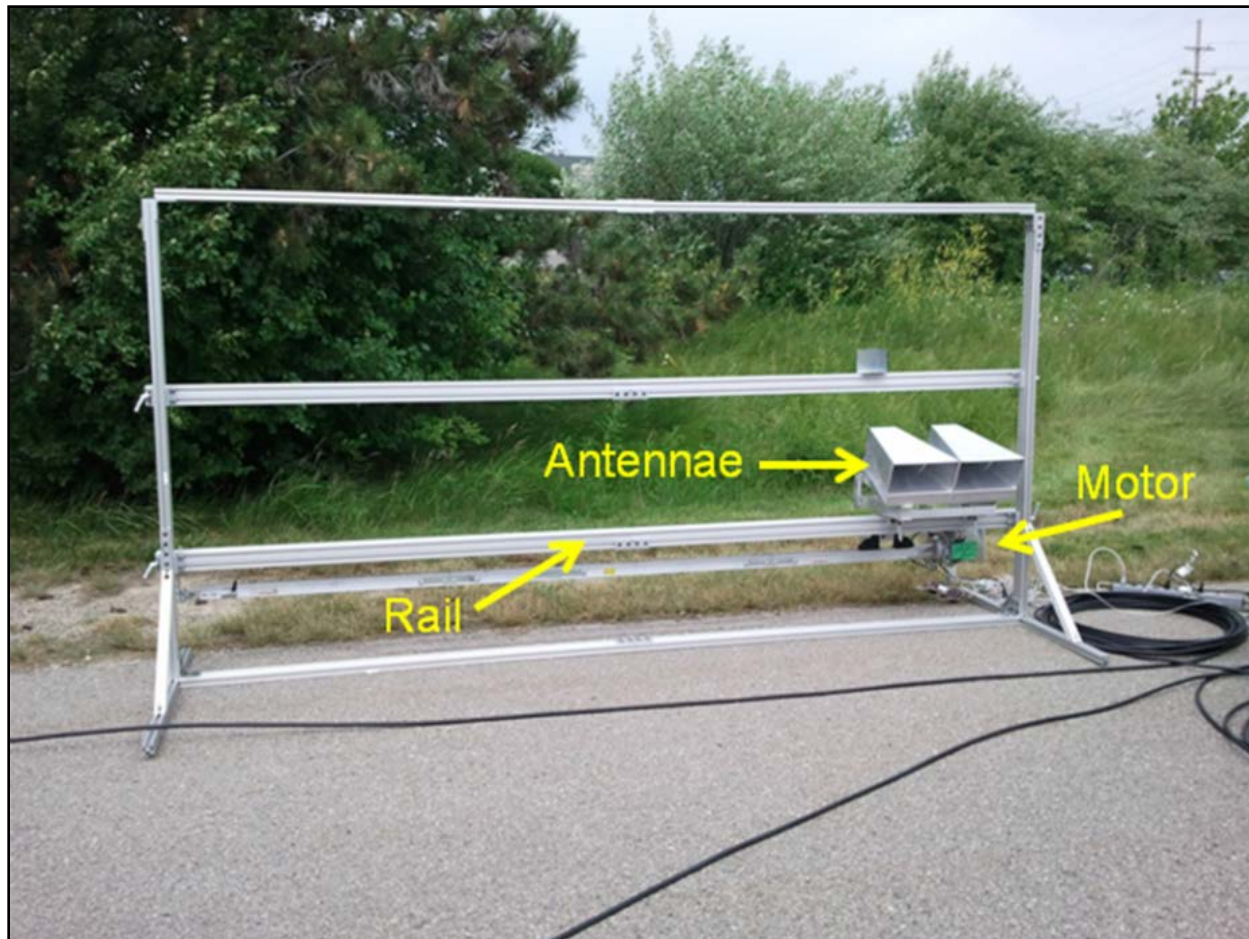


Figure 43: 2D Radar translator apparatus.

An optical position encoder is attached to the motor to record antenna along-track positions at the start of each radar frequency sweep. The operating parameters of the radar AVMU are configured to illuminate a constrained area of the scene to be imaged via appropriate time gating, and to have the appropriate settings for the particular measurement (e.g., frequency span, gain, etc.). In operation, the radar sweeps frequency and collects scene backscattering measurements as the antenna translates down the rail. After the measurement has finished,

the 2D data (e.g. scene backscattering verse frequency and sensor location) are saved and post-processed into imagery and/or other products.

A 3D radar data collection refers to a measurement where the radar collects electromagnetic backscattering measurements over a range of radio frequencies as the radar is moved linearly along two spatial dimensions. The resulting data set is a three dimensional array of scene backscattering measurements as a function of frequency and the sensor position in two spatial dimensions.

The 3D apparatus is identical to the 2D setup, except the side support rails are lengthened allowing for approximately 2.5 m of translation in that dimension (normal to the motorized rail direction). This added length is necessary to achieve roughly equivalent spatial resolution in this dimension as in the along rail dimension. This 2D translation of the radar sensor results in 3D data – frequency and sensor position in two spatial directions corresponding to the two translation directions. In this configuration the motor drive rail system is set at one end of the side support rails, data are collected in the same manner as the 2D scan, and then the drive rail system is repositioned by a specified amount for the next measurement. These data are saved and then post processed into a 3D radar image.

The 3D apparatus can be oriented with the side support rails either vertical, with the antennas pointing horizontally (at various angles), or horizontal, with the antennas pointing either up or down. This allows 3D measurements to be made of vertical structures such as walls, as well as horizontal structures, such as the underside of bridge structures, in order to attempt to evaluate their sub-surface features. In the vertical configuration the translator apparatus moves the antennas in a plane perpendicular to the ground, while in the horizontal configuration, the translator apparatus moves the antennas in a plane parallel to the ground. The horizontal orientation was utilized to make measurements of the underside of the bridge deck. Post processing is identical in either orientation. Figure 44 shows the translator apparatus in the horizontal orientation.

The first set of measurements occurred on the Freer Road bridge. Over the course of three days, 2D bridge deck measurements and 3D measurements of a section of the bridge underside were made using the portable imaging radar system described above.

2D measurements of the entire bridge deck were made by setting up the translator apparatus in its vertical orientation such that the radar antenna would be moved parallel to the direction of travel on the road. A measurement was taken with three fiducial corner reflectors set in the area to be imaged, and then this measurement was repeated with the fiducials removed. The

translator apparatus was then moved 10 ft (~3.05 m) further along the bridge deck and these measurements were repeated. This method of moving the translation apparatus along the road at intervals also served to simulate mounting of the radar to a vehicle and driving in one lane while imaging another.

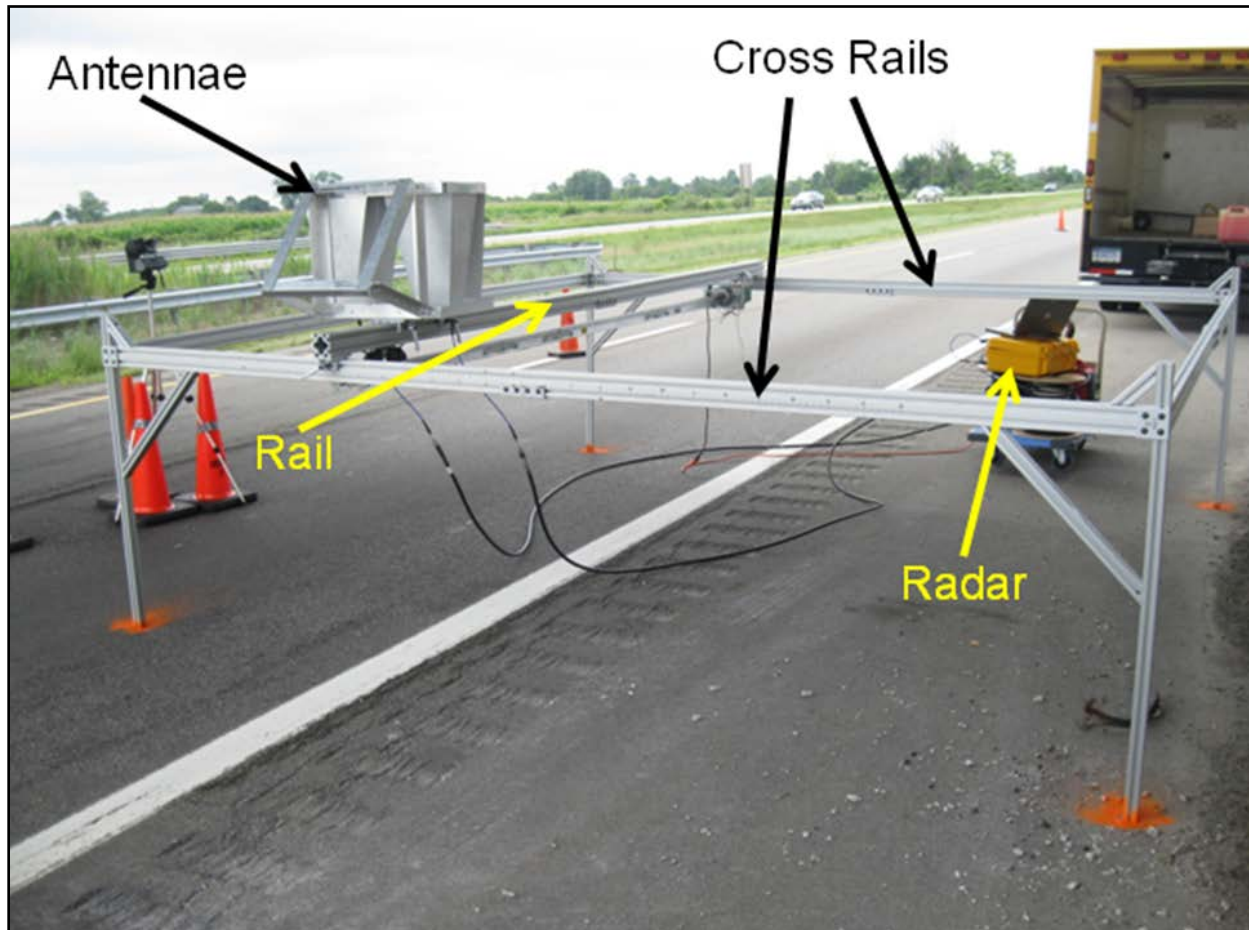


Figure 44: Translator apparatus configured for 3D imaging in horizontal orientation.

The 2 ft (~0.61 m) by 10 ft (~3.05 m) grid system (see Figures 19 and 45) that was laid-out on the bridge deck was useful for it served as a locator by placing one corner of the translator apparatus, as well as the fiducials on grid markings (see ThIR section). Care was also taken to orient the translator along the selected grid line. The selected grid line for the translator apparatus positioning was close to the center of the bridge, but representative of where a vehicle mounted radar antenna would travel. In this way, the individual images taken at each 10 ft interval along the bridge could not only be stitched together, but also features in the resultant images could be registered to locations on the bridge deck. Figure 45 shows a sketch representing the grid markings laid out on the Freer Road bridge.

The translator apparatus was placed and moved along the grid line 'c' with the antennas pointing west at the Freer Road bridge. The radar timing gates were set such the center line of the road all the way to the guard rail barrier was in the scene. The south-most corner of the translator apparatus was placed on successive 10 ft grid markings such that it was moved along the road from south to north. The along-road grids from 0 to 160 were imaged.

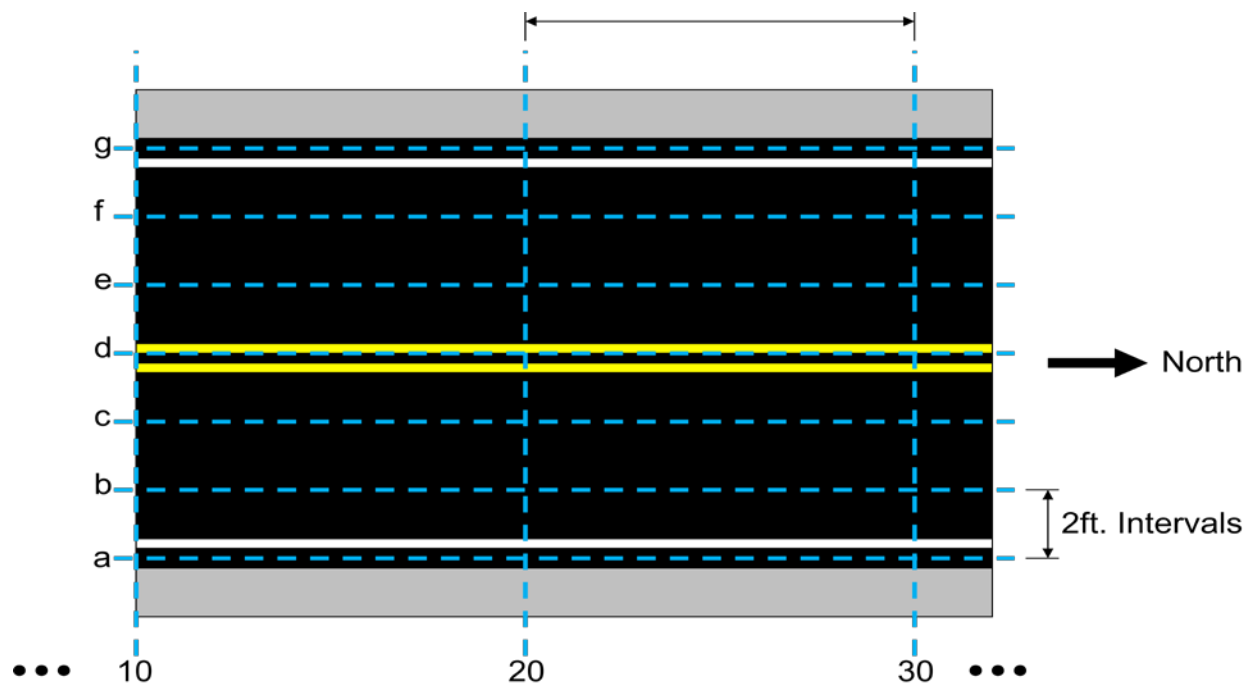


Figure 45: Representation of Freer Road bridge grid markings.

For the collection on August 2nd, two furniture dollies were employed to roll the translator apparatus from one grid mark to the next. Further, the other equipment (radar, cables, generator, and laptop) was placed on a small wheeled cart. In this way the apparatus and equipment could be much more easily moved along the bridge, allowing for more efficient data collection. The translator apparatus with the furniture dollies is shown in Figure 46. It also provided a concept of operation for how such a system could be adapted for use on a moving vehicle, such as DOT data collection vehicle (see Figure 46).

The east half of the Freer Road bridge was imaged. The translator apparatus was moved along the 'e' cross-road grid line from along-road grids 0 to 160. Prior to making the measurements the gate settings from previous day were configured and checked to ensure scene covered the center of the road to the edge with some overlap. The antennas were pointed east and the east (north-bound) lane of the bridge deck was imaged.

3D imaging of a portion of the underside of the Freer Road bridge was undertaken. To accomplish this, the translator apparatus was configured in its extended, horizontal orientation below the bridge with the antennas pointing up at the underside of the bridge. The motorized rail was placed such that it translated the antennas in the cross-road direction (relative to the road on the bridge above). Every effort was made to attempt to keep this direction of travel normal to the along-road direction (relative to the road on the bridge above). The set up of the translator apparatus is shown in Figure 46. Note that the apparatus was set up at the south end of the bridge, extending into right hand, east-bound lane of I-94.



Figure 46: More "mobile" translator apparatus and radar equipment. It is easy to view how such a system could be adapted for use on a moving vehicle.

Prior to commencing measurements, the radar time gating was adjusted such that the nearest part of the underside of bridge was just within scene, and the farthest end of the range gate was set to be approximately 5.8 m farther down-range.

Beginning with the motorized rail at the position furthest from the bridge supporting structure, a measurement was made by translating the antennas along the rail. The motorized rail was then successively moved by 2 cm closer to the bridge support structure and measurements made each time. Unfortunately, rain on the morning of August 3rd delayed the beginning of the measurements until approximately 11 am. Since the road closure on I-94 had to be removed by 2 pm, the apparatus had to be disassembled beginning at 1:30 pm. Therefore, only a partial data set was collected.

Radar measurements were collected at the Willow Road bridge. Over the course of two days, 2D bridge deck measurements and 3D measurements of a section of the bridge underside were made using the portable imaging radar system described above.

2D radar measurements were collected over the entire Willow Road bridge deck. The translator apparatus was moved along the 'b' cross-road grid line from along-road grids 0 to 220 with the antennas pointed to the north and along the 'd' cross-road grid line from 220 back to 0 with the antennas pointed to the south. Prior to making the measurements the gate settings were configured and checked to ensure the scene covered the center of the road to the edge with some overlap. As before, images were made at each position with, and without, fiducials in order to aid in image registration.

3D radar measurements of a portion of the underside of the Willow Road bridge were collected. To accomplish this, the translator apparatus was configured in its extended, horizontal orientation below the bridge with the antennas pointing up at the underside of the bridge. The motorized rail was placed such that it translated the antennas in the cross-road direction (relative to the road on the overpass above). Every effort was made to attempt to keep this direction of travel normal to the along-road direction (relative to the road on the overpass above). Note that the apparatus was set up at the west-end of the bridge, extending into the right-hand, south-bound lane of US-23. Figure 47 shows the geometric orientation of the translator apparatus relative to the bridge support structure.

Prior to commencing measurements, the radar time gating was adjusted such that the nearest part of the underside of bridge was just within scene, and the farthest end of the range gate was set to be approximately 5.8 m farther downrange.

Beginning with the motorized rail at the position furthest from the bridge supporting structure, a measurement was made by translating the antennas along the rail. The motorized rail was then successively moved by 2 cm closer to the bridge support structure and measurements made each time. A complete 3D set of measurements was taken within the 9 am to 4 pm road

closure constraints. The portable system was also deployed at the Mannsiding Road bridge. However, equipment malfunctions prevented collection of any useable radar data during the scheduled lane closures.

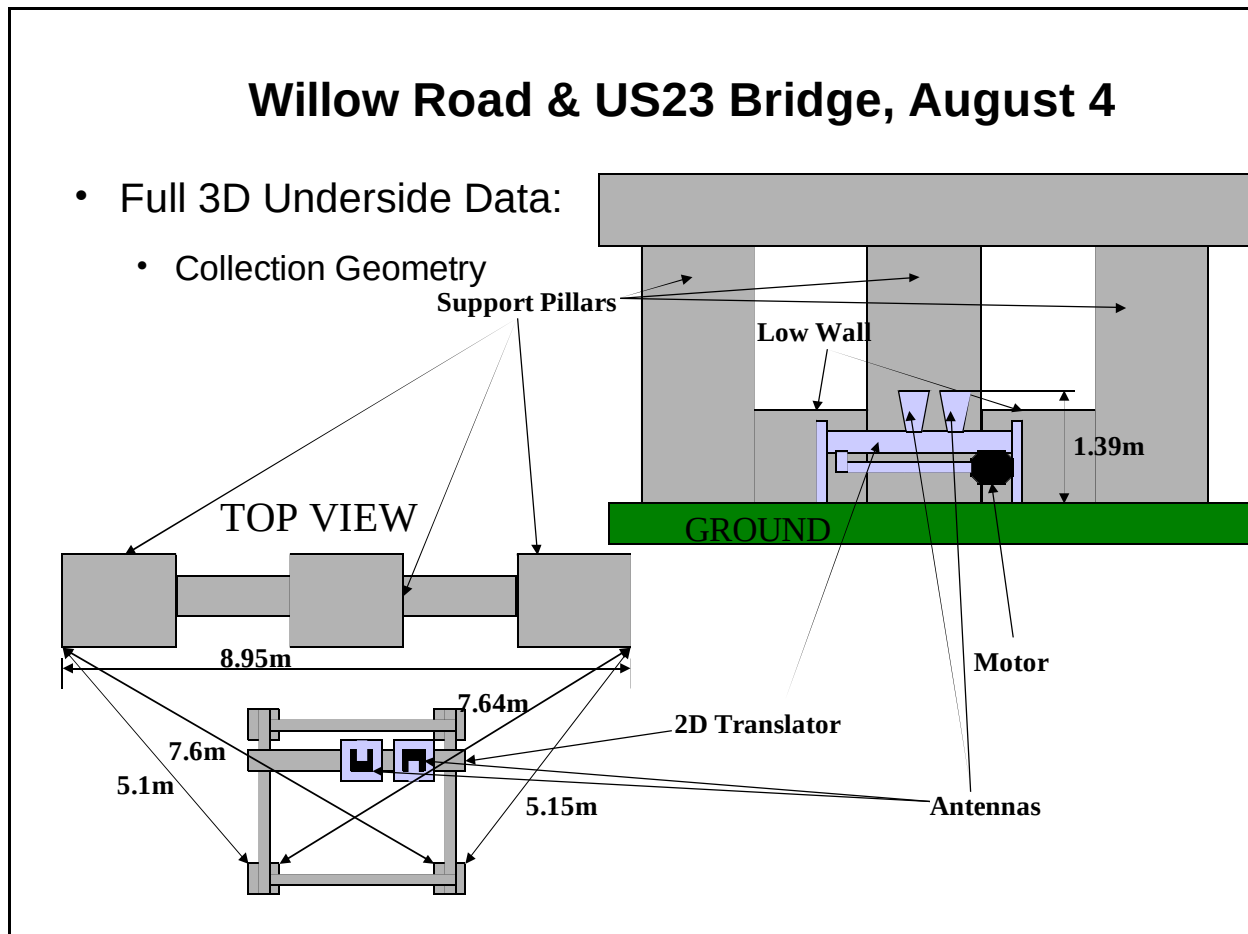
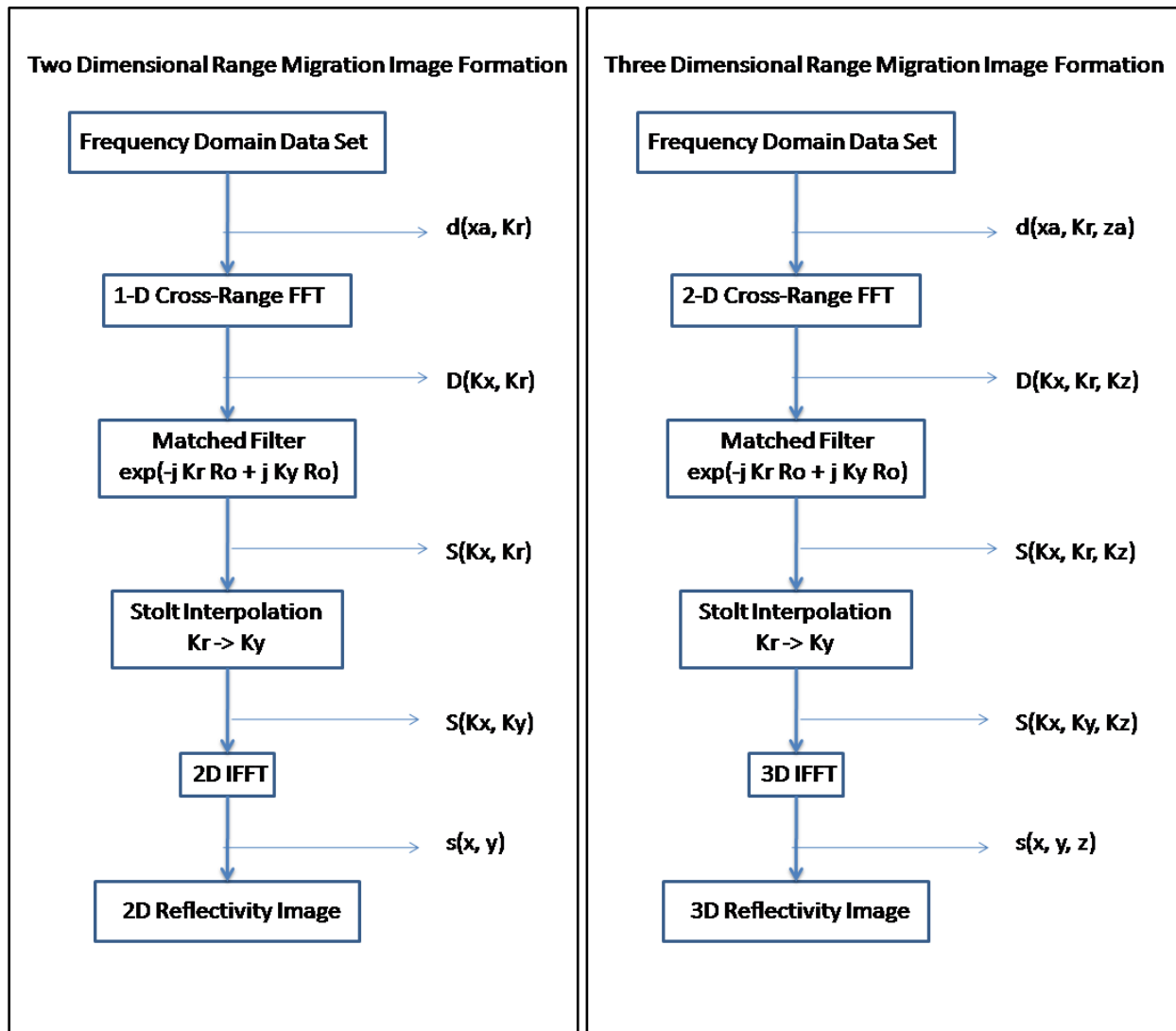


Figure 47: Geometric orientation of translator apparatus for Willow Road bridge structure.

The scene backscattering measurements collected as a function of frequency and sensor location can be processed into spatial maps (images) of radar reflectivity using back-projection or range migration algorithms. Range migration algorithms were selected for the initial processing since they are computationally more efficient than the back-projection approach.

Two dimension radar measurements of the scene, specifically radar backscattering measurements as a function of frequency and radar sensor location along a straight line can be processed into a 2D map of radar reflectivity using the 2D Range Migration Algorithm (2DRMA). The algorithm is outlined in Figure 48 and derivation is given in Carrara, et al. (1995).



Figures 48 & 49: 2D and 3D range migration image formation algorithm.

Given the radar measurements as a function of position and frequency, the Fourier transform of the data is taken along position, and are multiplied by a matched filter. The resulting data are interpolated in the frequency direction to form an estimate of the image spectrum that is uniformly sampled in spatial frequency space. The 2D Fourier transform is then taken to produce a 2D reflectivity map of the scene. The 2DRMA algorithm has been implemented in MATLAB by the project team, and functioning of the code has been verified both using simulated sensor data and actual radar measurements of test arrays.

3D radar measurements of the scene, specifically radar backscattering measurements as a function of frequency and sensor location scanned over a 2D plane can be processed into a 3D

map of radar reflectivity using the 3D Range Migration Algorithm (3DRMA). The algorithm is outlined in Figure 49 and derivation is given in in Lopez-Sanchez and Fortuny-Guasch (2000).

The algorithm is very similar to the 2D approach. Given the radar measurements as a function of 2D position and frequency, a 2D Fourier transform of the data is taken along the two position directions, and are multiplied by a matched filter. The resulting data are interpolated in the frequency direction to form an estimate of the image spectrum that is uniformly sampled in spatial frequency space. The 3D Fourier transform is then taken to produce a 3D reflectivity map of the scene. The 3DRMA algorithm has been implemented in MATLAB, and functioning of the code has been verified both using simulated sensor data.

Data from the 2D and 3D radar data collections from Freer and Willow Road bridges, have been processed using the algorithms described earlier. The 2D radar measurements of the bridge deck have been processed into radar reflectivity maps of the bridge deck. Analysis of the 3D radar measurements of the bridge substructure is in progress.

2D radar reflectively maps (images) were produced using the range migration algorithm. Data from each of the translation stage measurements were combined, and the resulting single data file was processed as if the data came from a radar sensor on a moving vehicle. Images of the two lanes of the Willow Road bridge deck when calibration reflectors were placed in the scene are shown in Figure 8. The figure shows the Willow Road deck geometry, with potential delamination sites from the ground truth survey, to the left. It is these types of analyzed radar results that the project team plans to integrate into the DSS to show where radar has detected these likely delamination results, as well as the locations and percent of delamination. These data will contribute to the overall bridge health signature being developed for this project.

The 2D radar reflectivity map on a 35 dB color scale in the center, and the amp with the delamination site superimposed to the right. These images were generated from radar backscattering measurements spanning the full 750-to-3,000 MHz frequency range. The point-like returns in the images are the localized returns from the calibration reflectors. The point-like response of the calibration reflectors in the images verify that the collected data have been successfully processed into imagery. The variable, distributed returns are the returns from the deck subsurface (see Figure 50).

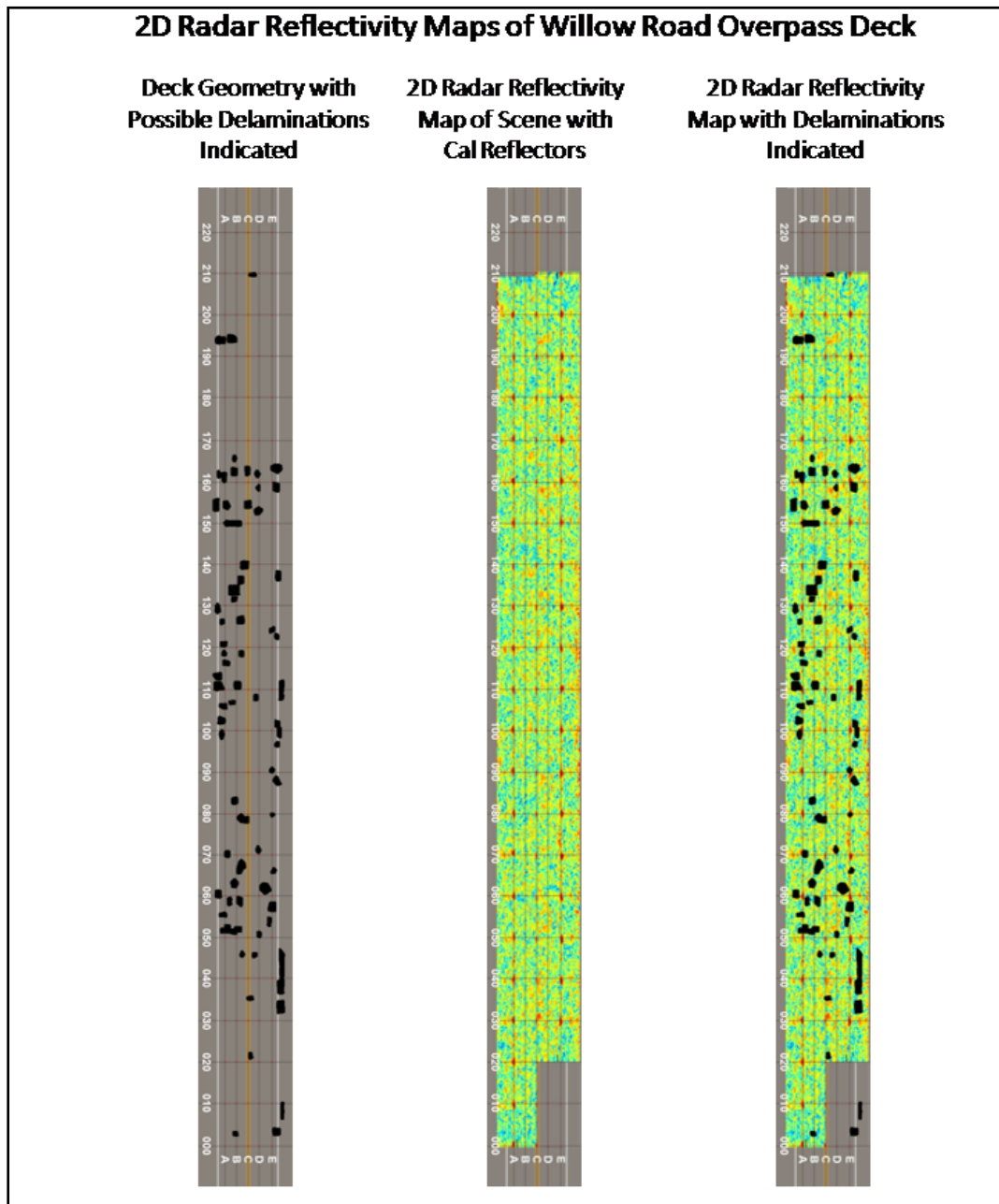


Figure 50: 2D radar reflectivity maps of the Willow Road bridge deck with calibration reflectors. These results are examples of what will be integrated into the DSS, such as locations and amounts of likely delaminations.

Images of the two lanes of the deck without calibration reflectors are shown in Figure 51. These images show just the returns from the deck. In upcoming work, these images will be quantitatively compared with the ground truth data to see if the variations in the distributed

radar returns can be correlated with suspected areas of delamination. 2D radar reflectivity maps (images) were also produced from data collected at the Freer Road bridge with the same process used for the Willow Road bridge data. However, an initial assess of the result suggest that collected data were of poorer quality, and the data are currently being reprocessed to try to improve the resulting imagery.

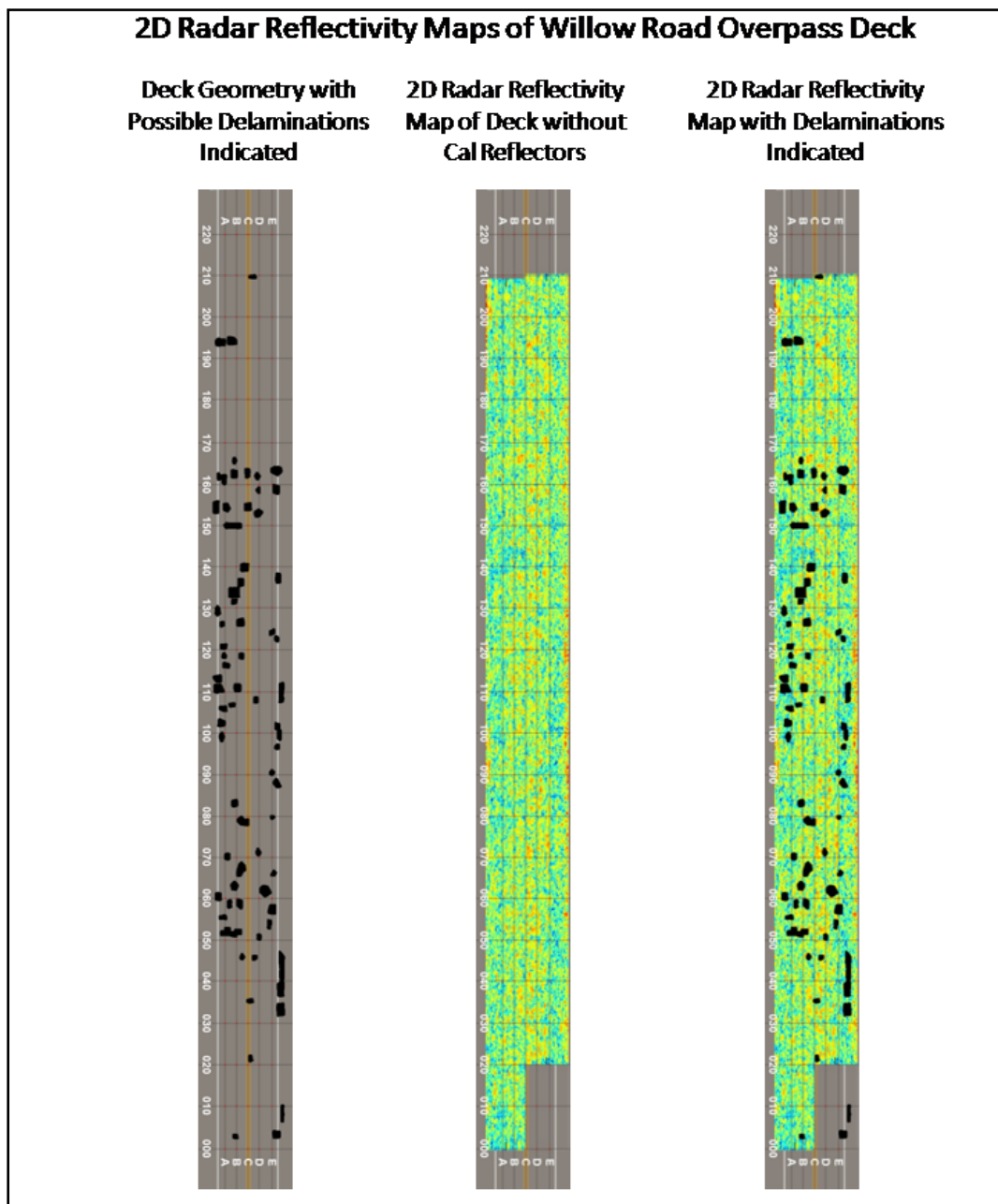


Figure 51: 2D radar reflectivity maps of the Willow Road bridge deck without calibration reflectors.

Benefits, Limitations, and Next Steps

2D and 3D radar measurements of concrete bridge deck and substructure were collected during the field demonstrations at Freer Road and Willow Road bridges using a portable UWBIRS. The data collected at Willow Road bridge were of higher quality and than that collected at Freer Road bridge; thus, the Willow Road bridge data have been processed into 2D imagery. The Freer Road bridge analysis is continuing in the next quarter. Data were not collected at Mannsiding Road bridge due to hardware problems.

Software has been developed to produce both radar reflectivity maps from both 2D and 3D radar data collections. The implementation of the software has been validated on both simulated data and test target measurements.

The primary benefit at this point in the data analysis is that the 2D radar reflectivity maps generated from data collected at Willow Road bridge show variation in intensity potentially due to bridge deck internal structure and/or defects. The team's next step will be to complete the upcoming work on quantitatively comparing the radar reflectivity maps to the ground truth information gathered during the field demonstrations, in order to evaluate the utility of the radar data and system for deck condition assessment. The team also plans to investigate the use of alternate imaging parameters and/or post-processing to enhance measurement performance.

The primary limitation at this point is that the overall system would need continued development in order to become a commercially available setup for DOTs and bridge inspectors. Additional work on making a vehicle mounted 2D system would be needed and such a system would have to be developed in a future stage of a bridge condition-related project. Additionally, MTRI is continuing to develop software-based algorithms to analyze and compare the data to ground truth. The team anticipates moving the analysis software tools forward significantly during the next quarter to complete production of results useful for the DSS and the overall bridge health signature.

ADDITIONAL TECHNOLOGIES UNDER EVALUATION

In addition to the primary technologies described above, there are four additional technological applications of remote sensing that continue to undergo evaluation as part of the study. These are technologies that are not tied to the same locations and field time limits as the field demonstrations due to the inherent capabilities of the remote sensing technologies themselves,

so have not been further detailed in this technical memorandum which is focused on the field demonstration results. While the evaluation process of these technologies was not a focus during the field demonstration, a more detailed effort will be the focus of the end of this quarter and the beginning of the next so their capabilities can be documented for USDOT-RITA. They are briefly reviewed here. The technologies and their applications are:

- Using Synthetic Aperture Radar (SAR) speckle to assess bridge deck condition and also to image the interior of a box-beam.
- Using Interferometric Synthetic Aperture Radar (InSAR) to assess bridge settlement.
- Using Multispectral Satellite Imagery (MSI) to assess bridge deck condition.

Synthetic Aperture Radar (SAR)

In the Transportation Applications of Restricted Use Technology (TARUT) study (see <http://www.tarut.org/>), C. Roussi, R. Shuchman, and C. Brooks from MTRI published a method to use complex InSAR data from the commercial Intermap corporation to assess road condition via remote sensing (Brooks et al. 2007). The Intermap corporation's InSAR data collection platform is airplane based, giving the potential to assess large number of bridges with a single data collection. To build from the TARUT study methods, the remote sensing team has obtained the necessary InSAR data for the field demonstration bridges so that they can compare their SAR speckle-based technique to the field data and MDOT inspection results, providing critical ground truth. Previously, using SAR speckle retrieved higher-resolution road condition results than traditional methods such as the International Roughness Index (IRI) or the Pavement Surface and Evaluation Rating (PASER) system. With the necessary data now in hand, the analysis of this information is currently underway to derive a bridge deck surface condition indicator that can be rapidly derived for multiple bridges.

To assess the utility of radar to image the interior of concrete box-beam, radar measurements of a box-beam salvaged from a recent bridge demolition were collected in September, 2011 at the Oakland County Road Commission facility in Waterford, Michigan. This works builds from the UWBIRS being tested for this project, and adds value to by reusing technology developed for assessing other parts of bridge structures. The collected data will be processed into a 3D map of radar reflectivity, which will be compared to knowledge of standard beam construction to determine if the interior structure and/or defects can be observed.

The measurement setup is shown in Figure 52, along with a side view of the salvaged box-beam. The portable aluminum frame used to scan the radar antenna over a 2D plane (horizontal and

vertical to the ground) parallel to the side surface of the beam is shown in the figure in the position used to image the beam.

The data were collected using the same hardware and setup in the UWBIRS described earlier in the document. The analysis of the radar data collected in September, 2011 and the resulting 3D radar imagery are currently under evaluation to extract box-beam condition information.

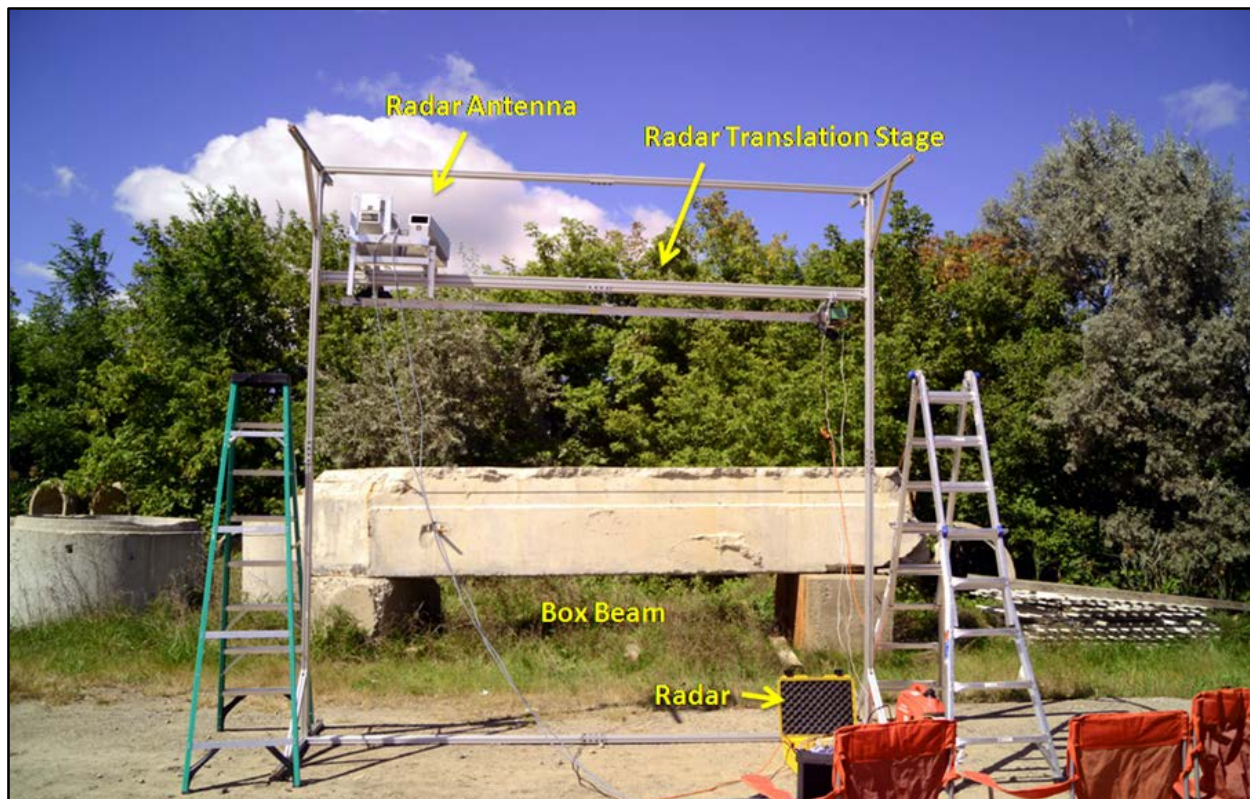


Figure 52: Portable UWBIRS mounted on a 2D translation stage parallel to side of salvaged concrete box-beam at Oakland County Road Commission site in Waterford, MI.

Interferometric Synthetic Aperture Radar (InSAR)

The MTRI remote sensing team is currently investigating the feasibility of using two-pass SAR interferometry to detect bridge deck settlement (i.e., centimeter-level elevation changes). Recent work has indicated that interferometric radar holds promise for being able to measure settlement for features as small as buildings and bridges (Pieraccini et al. 2008 and 2000). Thanks to the TAC, the team has identified three bridge locations (two in Colorado and one in Michigan) for which degree and timing of changes in bridge elevation are known, and are using

before- and after-settlement ERS-2 SAR images to evaluate if those changes can be accurately detected. ITT Visual Information Solutions ENVI SARscape Interferometry Module is being used to conduct the analysis. Results from this analysis are expected during the next quarter.

Multispectral Satellite Imagery (MSI)

Another TARUT study method that showed promise was using high-resolution multispectral remote sensing data from satellites and aerial systems to rapidly assess road condition. These methods are being updated by the remote sensing team to see if they can be used on a practical basis to assess bridge deck condition without the need for additional field work. In the TARUT study, the team was able to map road sufficiency rating with 88% accuracy for asphalt roads and 80% accuracy for concrete roads. The primary investigation will be to see if the analysis methods can be applied for features as small as bridges, and if modern high-resolution imagery such as WorldView-2 data can be applied for bridge deck condition assessment. The previous work (Brooks et al. 2007) used a blue imagery band and an infrared imagery band to analyze road condition and these exist in a wide variety of satellite and aerial based imagery collection platforms. Condition results that match available MSI field data will be assessed for inclusion into the DSS.

DECISION SUPPORT SYSTEM (DSS)

This section serves as a detailed review of progress in developing the DSS since the previous quarterly report. Since development began in March, 2011, two data primary bridge data sources, both provided by the project cost-share partner MDOT, have been used in prototyping the bridge condition DSS functionality. One source is the Transportation Management System (TMS) database BRIDGE table export provided by Bob Kelley, TMS database manager at MDOT, which is referred to within the DSS as the “MDOT Bridge Inventory (MDOTBI)” as it contains a unique record with attributes for all 4,405 MDOT-owned bridges. The other source came from Dave Juntunen, MDOT engineer of Bridge Operations, as an Excel-based application for visualizing bridge condition deterioration over time. The table of data that drive the spreadsheet application was imported into the DSS database as the “MDOT Bridge History (MDOTBH)” dataset since it contains non-unique records of bridge condition ratings for each of the MDOT-owned bridges back to circa 2000.

While the MDOTBI (see Table 4) and MDOTBH (see Table 5) tables do not match an existing Pontis bridge inventory database schema, they were the only data then made available earlier this year by MDOT when DSS development began. Nonetheless, the MDOTBI and MDOTBH tables represent two necessary views of important bridge condition data: inventory-level

bridge-to-bridge comparisons of the current infrastructure, and single-bridge condition assessment for individual maintenance decisions. Now that direct read access of MDOT's TMS database has been established, it is apparent that the MDOTBI currently used in the DSS is an export of the TMS database's BRIDGE table with some additional TMS data.

Furthermore, since the fields of the MDOTBI match many of the fields in the BRIDGE table, it should be simple for the DSS team to replace the MDOTBI in the DSS with a proper, Pontis-compliant export from the TMS BRIDGE table. It is important that the underlying database of the DSS be an effective prototype for state transportation agencies throughout the United States. As such, a standard schema is needed or, at the very least, a server framework which emphasizes a standard schema. The Pontis tables from the TMS database appear to the DSS development team to be such a standard. The tables available to the project team in the TMS database are currently being considered for inclusion in the DSS database.

Investigation is ongoing to assess whether or not the TMS database can be directly read by the DSS instead of doing periodic exports of the data from TMS into the DSS. This would substantially reduce the effort to get MDOT data into the DSS and would not require updating as changes to TMS database content would be automatically reflected in DSS queries and visualizations. However, as the TMS database is an Oracle database and the project team does not have an expensive Oracle installation, this may not be possible within this project. In order for the DSS server framework to communicate with the Oracle database it requires certain files which seem to be available only with an Oracle client installation. The free client SQL Developer, which has been used to read the TMS database in a graphical user environment, may not suffice.

Nonetheless, it is possible to easily and rapidly copy TMS database objects to the project team's PostGIS/PostgreSQL database which is used for the DSS. The team's plan is to regularly update the DSS bridge database with queried exports from TMS, and then to clearly label the date of the most recent export to users of the DSS so they will understand how up-to-date the bridge inventory data are that they are using.

The DSS application in the web browser communicates with the server and receives data through various data services. These are resources on the web with an established Uniform Resource Identifiers (URIs or URLs) at which requests for data are received. The data services corresponding to these various datasets are currently implemented in the Django web framework through a RESTful interface. REST refers to Representational State Transfer, a set of documented principles for web development that require stateless communications between server and client use the Hyper Text Transfer Protocol (HTTP) according to certain conventions. These interfaces are currently configured only for delivering data to the DSS as they emit

compact data in Javascript Object Notation (JSON) tailored for the DSS application. In the near future these services could offer XML in an established standard for sharing such data on the web (such as a Web Feature Service or WFS). In addition to separate web services for inventory metrics and historical data (MDOTBI and MDOTBH data, respectively), a third web service has been implemented for client-side applications requiring a distribution of National Bridge Inventory (NBI) ratings, such as the pie chart showing inventory-wide NBI rating distributions.

Field Name	Description	Field Name	Description
region	MDOT region	subrating	NBI substructure rating
brkey	Pontis bridge ID	culvrating	NBI culvert rating
strc_num	MDOT bridge ID	servtypund	Type of service under bridge
facility	Facility carried	sd_fo	Being determined
featint	Being determined	suff_rate	Sufficiency rating
location	Location	materialmain	Material
latitude	Latitude	designmain	Main design type
longitude	Longitude	lanes	Number of lanes
yearbuilt	Year bridge built	num_spans	Number of spans
yearrecon	Year bridge reconstructed	left_sw_width	Left sidewalk width
yearpntd	Year bridge last painted	right_sw_width	Right sidewalk width
yearovly	Year of last bridge overlay	deck_width	Bridge deck width
compute_0012	Not determined	length	Bridge length
dkrating	NBI deck rating	adtttotal	Average daily traffic
suprating	NBI superstructure rating	painttyp_cd	Paint type

Table 4: Field names and descriptions for the MDOT Bridge Inventory table.

Field Name	Description	Field Name	Description
region	MDOT Region	pier_rtg	Pier condition rating
brkey	Pontis bridge ID	culvert_rtg	Culvert condition rating
strc_num	MDOT bridge ID	low_maj_rtg	Lowest major rating
cs_strno	Being determined	superst_rtg	NBI superstructure rating
insp_date	Date of inspection	paint_rtg	Paint condition rating
deck_rtg	NBI deck rating	section_loss	Section loss rating
deck_surf_rtg	Deck surface rating	subst_rtg	NBI substructure rating
deck_bott_rtg	Deck bottom rating	abut_rtg	Abutment condition rating

Table 12: Field names and descriptions for the MDOT Bridge History table.

Recent screenshots of the DSS at its current level of development is shown in Figures 53 through 55. A list of the current features in the DSS:

- Quick links to various MDOT TMS-related websites are available from the top toolbar.
- Tabular data supports multiple column-sorting and -filtering so that complex queries can be constructed within the table. These queries are performed on the server (remote filtering), not merely on the 30 records visible in the table (local filtering).
- The distribution of NBI ratings throughout the inventory or a particular MDOT region can be viewed as an interactive pie chart to be printed or saved to a file with the click of a button.
- The rows of the bridge metrics table can be color-coded by NBI or sufficiency ratings.
- Map markers can be color-coded by NBI or sufficiency ratings. The appropriate will appear based on the symbology.
- The InfoWindow that appears when a bridge's map marker is clicked contains links to automatically zoom to the bridge or launch a directions utility.
- The directions utility provides directions to a bridge from user-specified latitude and longitude coordinates, a street address or an MDOT region office. Turn-by-turn text directions are provided in addition to a route layer on the map.

- Map overlays of MDOT regions and Michigan counties are available.
- Bridges can be spatially filtered by drawing a polygon on the map or by quickly querying the map viewer's current extent.

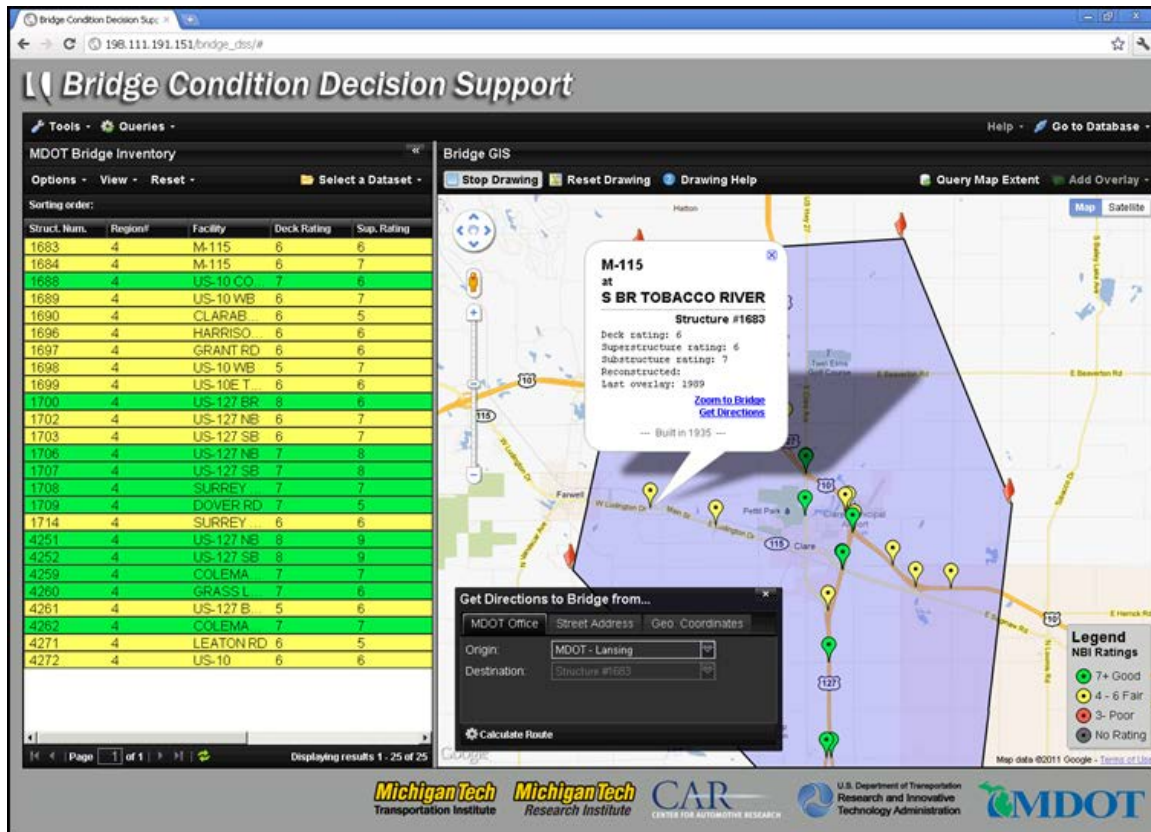


Figure 53: Screenshot of the DSS showcasing several functional elements including table highlighting by NBI rating, map marker coloring by NBI rating, a directions service, InfoWindows for each bridge showing its parameters and links to 'zoom' and 'directions', and spatial filtering on the map by drawing a polygon (shown here in translucent purple).

Some features not yet implemented have been identified and documented in a task-tracking database. These are listed below with some discussion about how each will be implemented over the next quarter:

- In addition to aggregating inventory-wide and by MDOT region, display the distribution of NBI ratings for any Michigan county.
- Link to Street View and the BVRCS results of, or for, a bridge from its InfoWindow.

- Display a detail (summary) view of a bridge's attributes at the bottom of the table when a bridge is selected.
- Showcase bridge photos and recent inspection reports and how they are accessed for the field demonstration set of bridges.
- Allow for charting and plotting of any bridge parameters over time as available in the MDOTBH dataset.
- Allow for parameter (scatter) plots of any two parameters to be displayed.
- Display remote sensing data results in the web browser, such as 3D models of bridges from LiDAR data in the web browser. 3D data will require the use of another software library in the client to support 3D rendering. Ultimately, this feature will most likely launch a separate application, outside of the DSS, to improve its performance.
- Add a utility for visualizing MDOT's strategic goal for bridges. This will require an effective representation of the key elements of this strategic goal within the database; currently, not all required elements are captured in the DSS database.

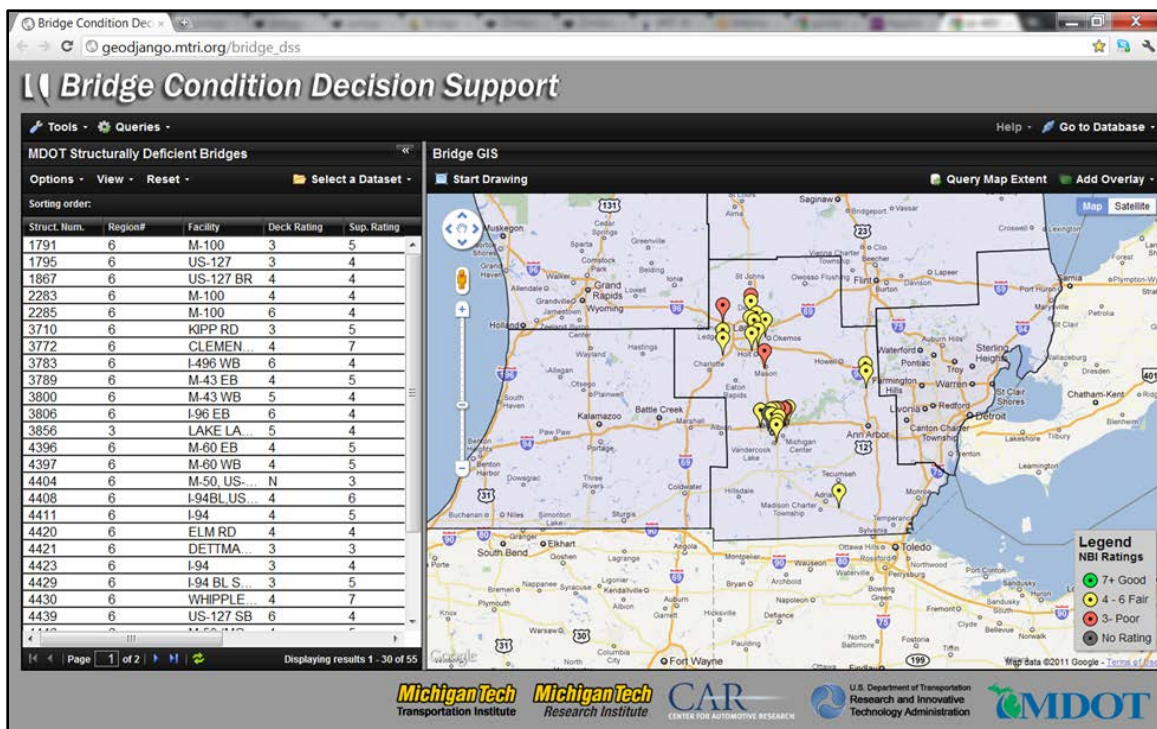


Figure 54: Second screenshot of the Bridge Condition DSS, showing the database of only structurally deficient bridges available in a particular MDOT region.

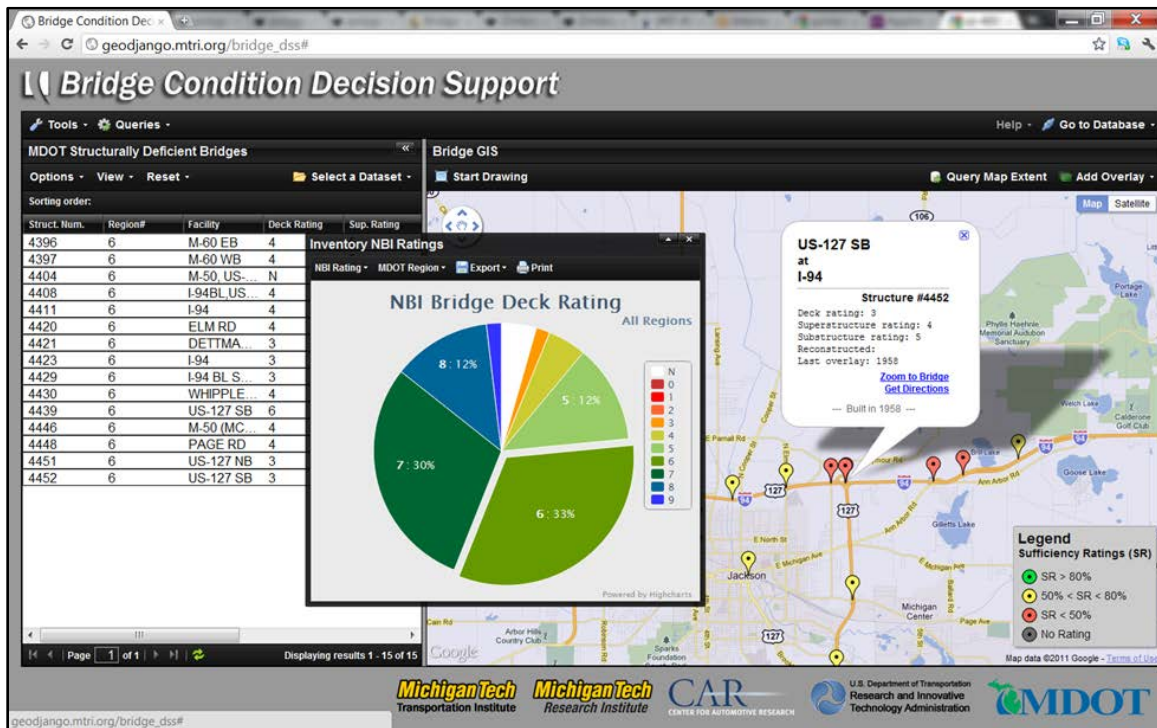


Figure 55: A third screenshot of the current Bridge Condition DSS, showing the DSS's graphing capabilities by displaying NBI bridge deck rating of the structurally deficient bridges selected by the user for Jackson County, Michigan.

Benefits, Limitations, and Next Steps

Of these "next features," the most critical one for development over the remainder of the project is to integrate into the DSS the indicators of bridge condition analyzed and extracted from the various remote sensing technologies deployed in the August, 2011 field demonstrations. From THIR data, based on results so far, the project team anticipates obtaining percent and amount of delaminated area for all field demonstration bridges. The UWBIRS work also should yield location and amount of delamination. It is encouraging that multiple potential methods could be available to a DOT to assess this important bridge condition indicator. The 3DOBS is yielding percent spalled, and volume and location of spalls on the bridge deck by creating a 3D model of the bridge surface using an inexpensive data collection system. DIC can provide the latest information on the loading capacity performance of the structure. The BVRCS and GigaPan are creating a location-tagged high-resolution photo inventory of bridges that can be referenced over time for bridge decks, undersides, and fascia.

LiDAR data is also being used to create a 3D model of the bridge deck surface, calculate volume, location, and amounts of spalls, as well as creating 3D imaging of structural components such as

bridge supports. All of these data have the likelihood of being integrated into an overall bridge health signature, a major goal of this project and a focus area for the remainder of the project. The DSS is intended to provide access to these condition metrics (such as percent spalled or delaminated), representations of the actual remote sensing data (such as a ThIR delamination map or 3D bridge surface), as well as an overall bridge health signature that integrates these remote sensing data, as well as traditional bridge inventory condition data such as recent bridge inspection condition results. This DSS work will continue over the next quarter, but may well require additional time to fully integrate the analyzed remote sensing results once they are all completed, and then to develop logical, easily-understandable ways of representing the data and bridge health signature to DOT users. Fortunately the current DSS level of development provides a strong foundation to make this data representation possible.

This type of DSS development and completion will require interactive TAC, MDOT, and sponsor input and is another reason that additional time may be needed to complete a practical, user-friendly, and easily extendable DSS tool.

REFERENCES

Carrara WG, Goodman RS, Majewski RM (1995), Range Migration Algorithm, Chapter 10 in Spotlight Synthetic Aperture Radar: Signal Processing Algorithms, Artech House, Boston, pp. 401-442.

Lopez-Sanchez, JM, Fortuny-Guasch, J (2000), 3-D Radar Imaging Using Range Migration Techniques, IEEE Trans. Antennas and Propagat., Vol., 48, No. 5, pp. 728-737.

Brooks, C., D. Schaub, B. Thelen, R. Shuchman, R. Powell and E. Keefauver (2007). TARUT pilot studies technical details report. Deliverable 5.3-B. M. D. o. Transportation, Michigan Tech Research Institute.

Pieraccini, M., M. Fratini, F. Parrini, C. Atzeni and G. Bartoli (2008). "Interferometric radar versus accelerometer for dynamic monitoring of large structures: An experimental comparison." NDT & E International 41(4): 258-264.

Pieraccini, M., D. Tarchi, H. Rudolf, D. Leva, G. Luzi, G. Bartoli and C. Atzeni (2000). "Structural static testing by interferometric synthetic radar." NDT & E International 33(8): 565-570.