Memo

To: USDOT/RITA research team members

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CC: P. Hannon

Date: January 14, 2011

Number: 11

Re: Laboratory Study Progress Update

The fourth quarter afforded significant progress in our feasibility studies for promising remote sensing technologies. Activities for each commercially available technology that is being investigated are summarized below.

3D PHOTOGRAMMETRY

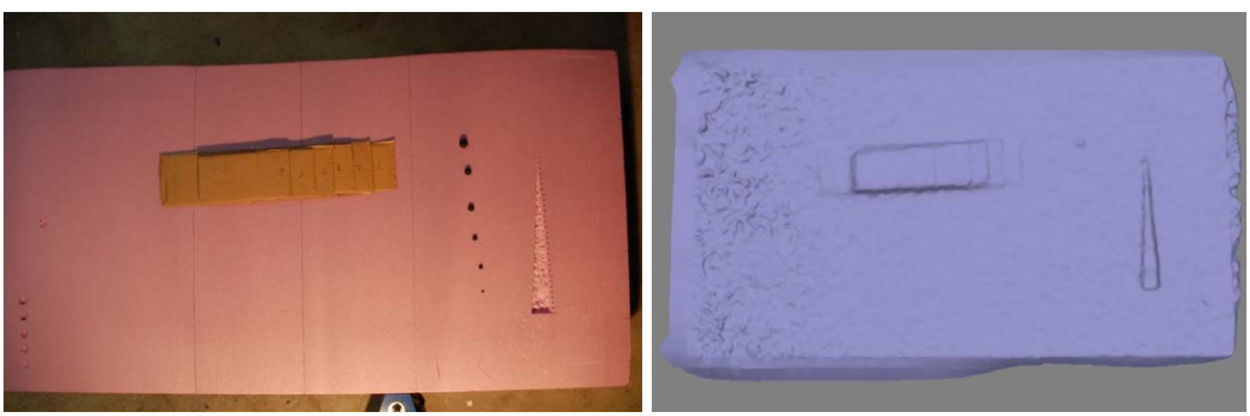
3D photogrammetry is the generation of 3D models from stereo pairs of imagery in order to obtain depth and height information, and is part of the 3D optics technology assessment. Stereo images have to be collected with a 60% overlap in order to generate these models. Challenges being looked at include spalling, scaling, cracking and surface roughness. Along with assessing the accuracy of the technique two different modeling programs will be compared to see how they affect the outcomes of the measurements.

AgiSoft PhotoScan is a 3D modeling commercial software program that can generate 3D models with minimal digital photographic inputs. Once photos are uploaded, the software processes them without having to calibrate cameras, user input of camera parameters or manually aligning the photos. While extensive calibration is required with Eos PhotoModeler, this software package will also be considered. The cameras used to record the images are two different digital single lens reflex (DSLR) models; a Nikon D5000 and a Canon EOS 7D.

Preliminary Studies

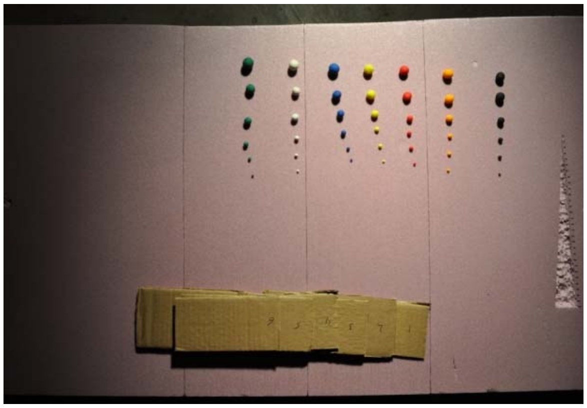
Various experiments were performed to test the cameras and software limitations using a piece of foam board, which was used for its ease to shape and attach extra pieces. A wedge shape was carved into the board that allowed us to determine the horizontal resolution of the program, which relates to the width of cracks on bridges. Pieces of cardboard were arranged in a stair-step fashion that shows the programs limit to resolve height or depth measurements. Finally, different colored spheres were added (see Figure 1a) to show if there would be problems with generating accurate models due to poor contrast and the different sizes show what the resolution is with respect to generating rounded features.

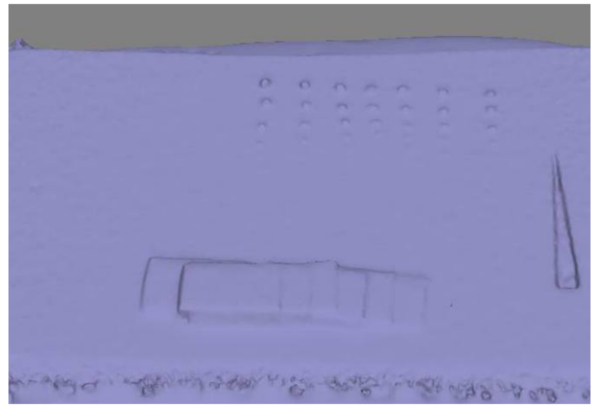
The camera was mounted directly above the board at a translation stage that allowed photos to be taken at precise intervals across the length of the board. This initial experiment showed that this program has a resolution of about 4mm in both the horizontal and vertical directions within this setup. Tests were also conducted with a single light source that illuminated the board from various angles to determine how the lighting and resulting shadows affected the model. All of the tests produced similar results and demonstrated that photos can be taken throughout daylight hours without concern over reducing resolution or accuracy.



Figures 1a & 2a: First experiment with foam board in the lab with original photo on the left and 3D model on the right.

Test runs were also performed to consider how the quantity of photos affected the resulting model. Models were generated using three, 20, and then 48 photos. This experiment showed that increasing the number of photos noise was reduced and produced a clearer more accurate model without a change in resolution. Also differences in contrast did not appear to play a significant role in generating a model as all spheres greater than 10mm in diameter were discernable in the 3D model for all colors (see Figures 3a & 4a).

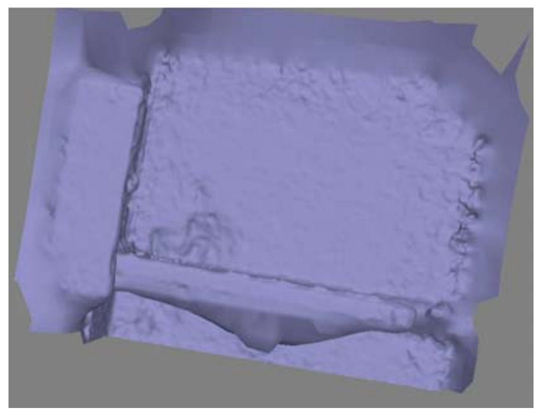




Figures 3a & 4a: Next set of experiments to determine contrast relevance and using different illumination angles with original photo is on the left and model on the right.

The first in-field test was conducted by taking the camera and capturing spalls on the underside of the 6 Mile Bridge over US-23 north of Ann Arbor, MI (see Figures 5a and 6a). 3D models of spalls were generated by taking four to six photos in a line, with the spalls being located approximately 2.5 meters above where the photo was taken (see Figures 7a & 8a). Spalls at a distance were of importance to demonstrate how a 3D setup could be deployed to measure the length, width, and depth of spalls that would otherwise require equipment to reach. Calculations of resolution attained by this camera, distance, and number of photos are currently being related that to desired measurement sensitivities.

Figures 5a & 6a: Researcher taking photos of the underside of 6 Mile Bridge at US-23 near Brighton, MI. The distance from the camera to the spalls was approximately 2.5 meters (8 feet). Photo taken of spall on deck bottom surface from the field test shown above at 6 Mile/US-23 Bridge.



Figures 7a & 8a: Models generated from the infield photos with textured model on the left and shaded model output from PhotoScan on the right.

What's next for 3D Photogrammetry

Testing will continue with fundamental experiments to determine what size defects can be seen and processed by the equipment and software using specimens of multiple sizes with various types of challenges. Given success with these tests, other factors will be looked at in a more rigorous fashion.

Through testing with this technology we are hoping to gain a better understanding of the capabilities that can be provided in assessing the condition of the bridge deck. This will be completed through the different works expected to be completed in the future.

After laboratory testing is done, it is also planned that a camera will be mounted to the rear of a vehicle that will take photos at a predetermined rate that will allow for a 60% overlap of the images. The camera will be driven over the bridge in both directions covering one lane at a time. A 3D model will then be generated for the whole bridge. Some of the issues that will be looked at:

- What size crack can be seen
- What size spall or scalling can be seen
- Measure surface roughness
- Change shooting distance to determine what affect that has
- Look at how on-the-field shooting angles affects the accuracy
- Look at different light conditions
- What would be the right amount of photos for appropriate accuracy

Turning a 3D model into a "good, medium, poor" rating for sections of the bridge deck, as described in the technical memorandum nº 10 Decision Support System (DSS) description, will be another future step. The goal is to demonstrate the capabilities and limitations of 3D optics, tune the setup to ensure needed indicators are being measured, and to generate information for inclusion in the DSS, while keeping within an inexpensive system that could be easily and rapidly deployed by a Department of Transportation to bridges of interest.

THERMAL INFRARED

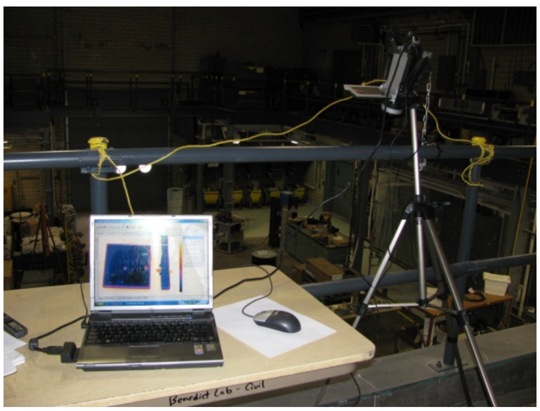
Thermal infrared (IR) inspection technique is based on measuring the radiant temperature of the concrete deck by using a thermal IR camera. The concept behind this technique is that the anomalies and subsurface delaminations interrupt the heat/energy transfer through the concrete. Thus, surface delaminations will appear as hot or cold spots on the thermal IR image.

Determining the subsurface anomalies within concrete slabs and depth of the delaminated areas are objectives in this experimental plan. Experiments were performed using a FLIR SC-640 Thermal IR camera (research & development grade), a digital thermal hygrometer (measuring ambient temperature & humidity), and proprietary software.

Preliminary Studies

Laboratory testing was conducted on the thin concrete slabs which were built with simulated delaminations. These slabs are ‘filled’ with impurities such as rebar, plastic bags, ping-pong balls, a plastic bottle, and so on. The layout of the impurities and size of these specimens are detailed in technical memorandum nº 5.

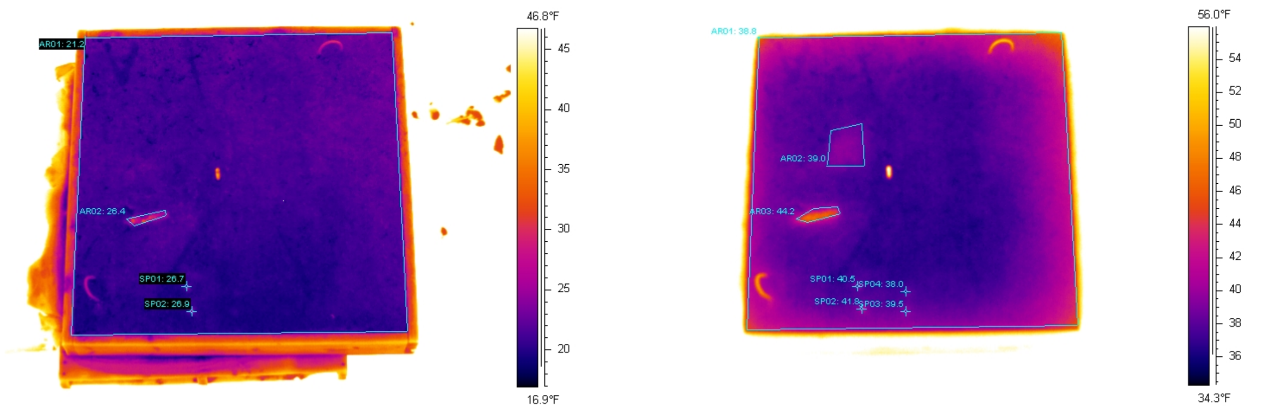
The slabs were placed outside in the cold where they spent over 24 hours. They were then brought in to the lab, which has a significantly higher temperature than outside and thermal IR images were taken inside the lab as the specimens warmed up. Test set up shown in Figures 1b & 2b.



Figures 1b & 2b: Laptop, FLIR camera, one of the slabs, and a concrete railroad tie.

Slab AB (12-07-2010)

A thermal IR camera was set up at a distance of 15.2ft from the slab to take images every ten minutes during a six-and-a-half hour period (8:27am to 4:00pm). The lab temperature was around 69.8˚F and the relative humidity was 9.8%. The emissivity was considered 0.95 for the concrete slab. Figures 3b and 4b below are the two images, which were taken at 8:27am and 11:58am respectively.

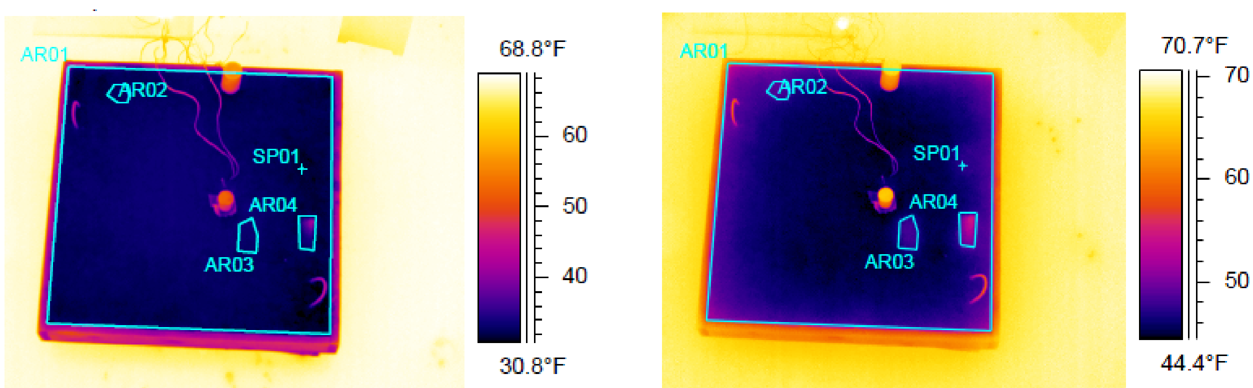


Figures 3b & 4b: Images taken at 8:27am and 11:58am respectively.

As shown in these images, the plastic bottle (which is very close to the surface) and ping-pong balls appear as hot spots in the thermal IR images and indicated delaminated areas close to the surface. Other delaminations, which were deeper appeared in the thermal IR images after a few hours, but they have lower thermal contrast compared to the ones closer to the surface.

Slab CD (12-17-2010)

The thermal IR camera was set up at a distance of 16.67ft from the slab to take images every 10 minutes during a seven hour period (9:28am to 4:30pm). The lab temperature was around 72.3˚F and the relative humidity was 13%. The emissivity was considered 0.95 for the concrete slab.



Figures 5b & 6b: Images taken at 9:28am and 12:58pm respectively.

Figures 5b and 6b are thermal IR images of the slab CD, which were taken at the start of the experiment and after three-and-a-half hours respectively. Areas three and four on these images shows defect D7, which is two pieces of Styrofoam 5/8 and 1.5 inches thick located four inches from the bottom of the slabs. Figure 7b is a graph of the average temperatures of these areas during the seven hour experiment period.

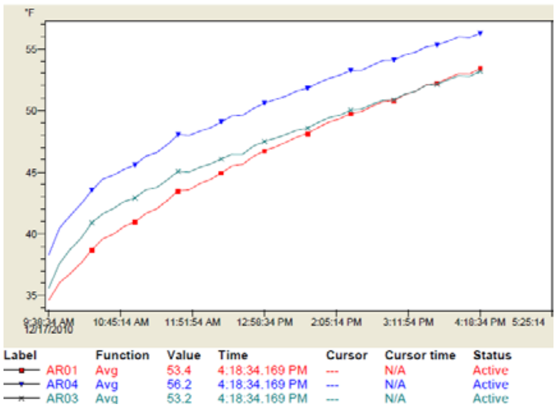


Figure 7b: Average temp vs time for areas 3 and 4.

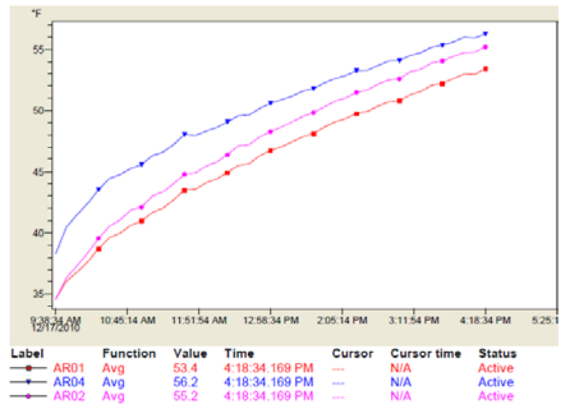


Figure 8b: Average temp vs time for area 2.

This graph shows that the maximum contrast between the delaminated areas and the average temperature of the slab appears after approximately 2.5 hours. Figure 8b shows the same graph for area two, which is a piece of wood 1.5” thick. Comparison of Figures 7b and 8b shows the difference in thermal conductivity between Styrofoam and wood, which causes the different heat/energy flow through the impurity and temperature contrast in the thermal IR image.

What’s next for Thermal IR

With these experiments we expect to get a better understanding of the thermal IR technology and how to employ this technology for detecting bridge deck challenges. Future work with this technology will include further testing, determining the percentage and depth of the delaminated areas, collecting thermal IR information at highway speeds, and determining how different environmental conditions can affect the results.

DIGITAL IMAGE CORRELATION

Digital Image Correlation (DIC) is an optical based remote sensing technology suggested for challenges on the global metric level of the bridge system. Digital images before and after loading are optically compared and details about the structure's deformation and/or rotation information are determined. DIC will be employed for conducting laboratory experiments to verify methodology of the technology and apply it towards bridge condition assessment measurements of dynamic and static bridge behavior.

The overview plan involves laboratory testing of different structure samples such as W-shape structural steel members and concrete bridge pylons (concrete filled pipes) to determine static and dynamic behavior as emulated from bridge structures. Figure 1c below shows the pylons (note steel and concrete) and Figure 2c shows the sample bridge pylon during a compression test.

Preliminary Studies

To date, there has been much preparation for these laboratory tests to be completed in order to measure these particular bridge challenges associated with global-metric bridge interaction. This technique involves taking high resolution digital images and using computer algorithms. For the high resolution digital images, a Canon EOS 7D digital single lens reflex camera (DSLR) was selected for the photo recording device. This camera has been researched and used in image testing in order to gain an understanding of the camera's capabilities and functions.

Figures 1c & 2c: Bridge pylons on a pallet and pylon before a compression test.

In these tests, the standoff distances of the camera will be compared at short distances (within 5 to 10 feet), long distances (greater than 10 feet) and from vertical distances (from the top of the structures at different angles). Unique marks applied to the specimen's surface will enable detection of movement or rotation of the structure. This will allow the method to be analyzed for different displacement measurements in relation to bridge settlement, bridge movement and bridge length. The testing will also be applied to vibration testing in which a corresponding sampling rate for the images with be used for frequency detection. This sample testing involves 2D analysis, but can be further expanded to 3D image analysis with an additional camera implemented in the setup.

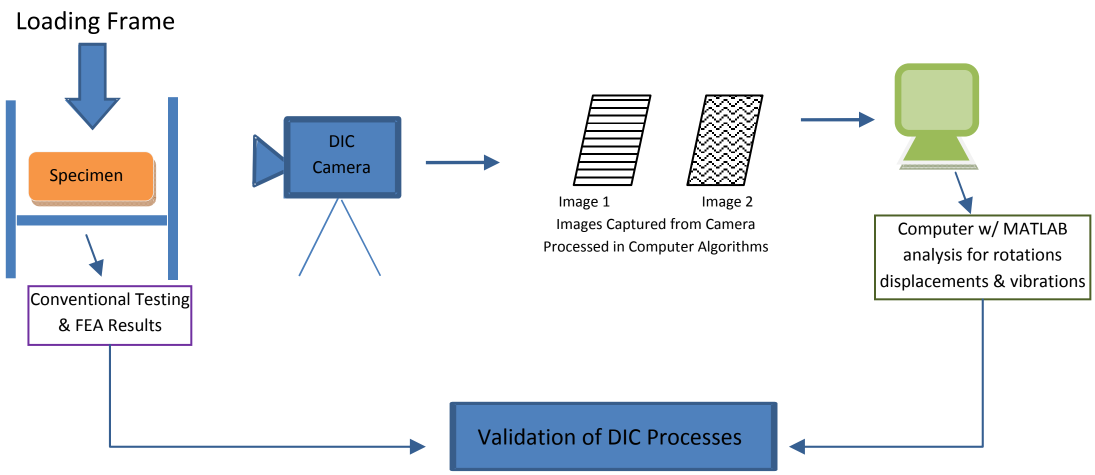


Figure 3c: Concept of Laboratory Setup

What's next for Digital Image Correlation

As stated this camera is used in conjunction with MATLAB computer processing and also involves a certain level of understanding for usage. MATLAB will process the images in a defined pixel by pixel grid analysis. Sample MATLAB program files have been reviewed and altered to correspond to the measurements needed for laboratory tests in measuring these global metric indicators. This correlation technique will be verified with finite element modeling using ANSYS. Modeling of the loading frame setup has been initiated for validation of the DIC measurements. The mechanical behavior and the "global metric challenges" measurements will also be collaborated (see Figure 3c) with computer modeling to compare the measurement results and calibrate the modeling itself. More information on finite element modeling can be found in Technical Memo 13.

RADAR

The goal of this exercise is to investigate the feasibility of utilizing an inexpensive radar system for non-destructive testing of concrete box-beams, girders, and decks to evaluate defects.

First, efforts would be restricted to investigating and understanding the phenomenology of the radar/box beam interaction and develop techniques to enhance features of interest. The next phase would identify the subset of useful techniques which would be evaluated for feasibility of field application and tested for efficacy under field conditions.

Although radar image resolutions are generally insufficient, concluding that the inexpensive radar is not an appropriate measurement system might be premature, since data products other than images can be formed. This is born out by the wealth of literature showing that the application of higher performance, more expensive radar using more standard techniques. Part of the purpose is to demonstrate that useful data products can be generated through less expensive radar systems.

Preliminary Studies

A modified Synthetic Aperture Radar (SAR) processing-code for forming images from the Akela radar was used. The code applies a method known as “Range Migration”, which takes into account the wavefront curvature resulting from the collection geometry. The processing code was modified and tested using data collected from well-known, point scatterers with impulsive response characteristics (corner reflectors) in a controlled environment (the MTRI antenna chamber).

This involved setting up equipment in the chamber to translate the antenna, allowing imaging in the cross range direction (see Figure 1d). The resulting images were used to tune collection parameters in the code to match precisely the collection geometry. The results were well focused images of the point scatterer, as seen in Figure 2d.

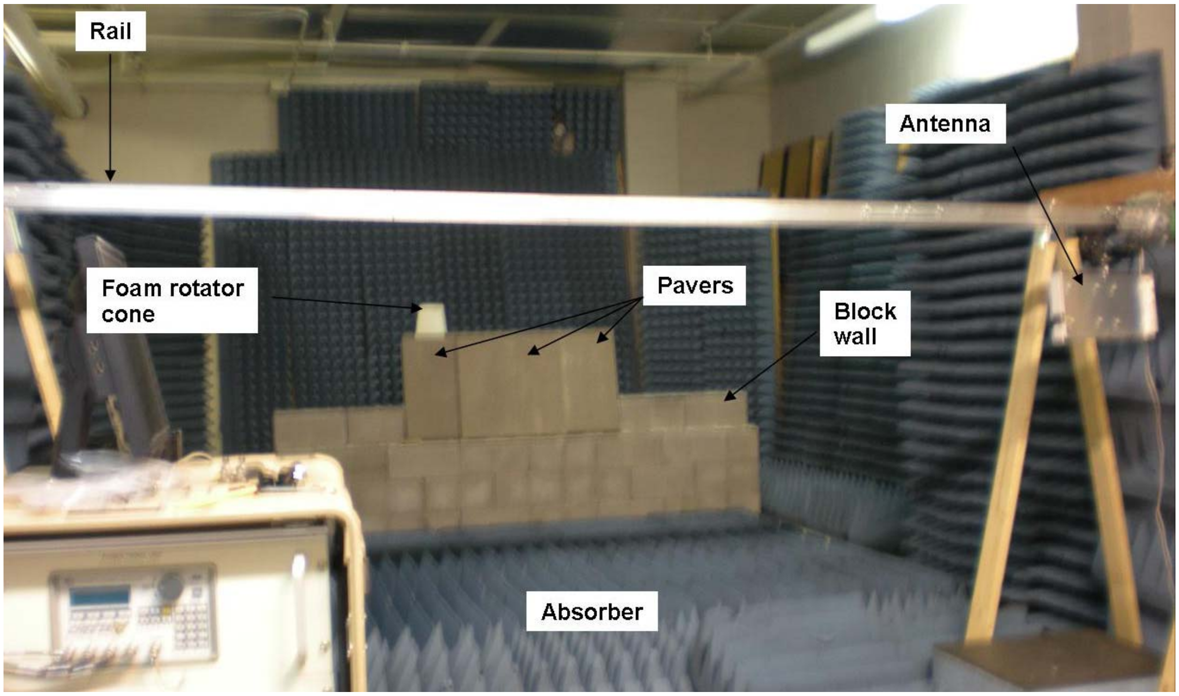
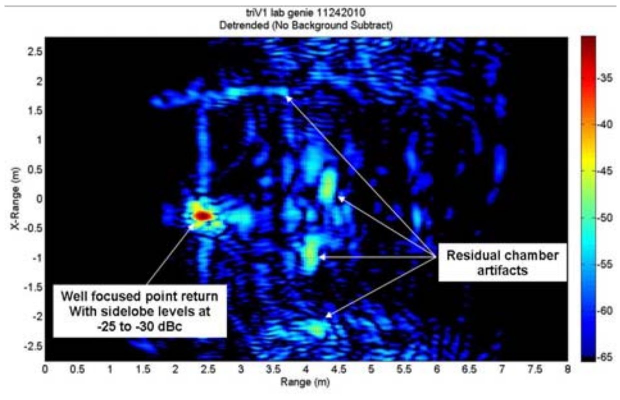
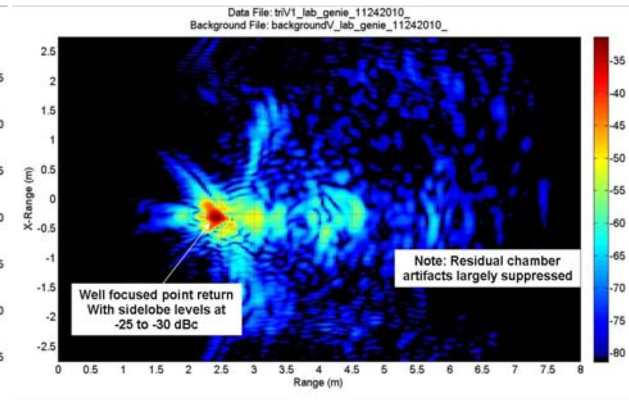


Figure 1d: MTRI antenna chamber with Lab Genie set up.

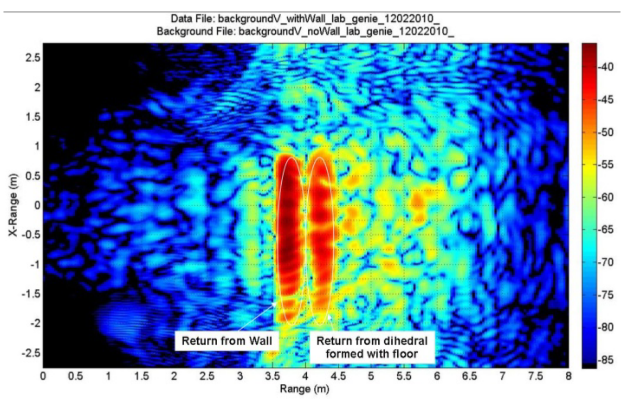
De-trending was successfully used to reduce noise from internal leakage and some residual chamber artifacts. With de-trending any linear trend is removed from each frequency step over the synthetic aperture. This removes artifacts that are stationary relative to the antenna motion such as internal noise and some artifacts in the scene (see Figure 2d). Some residual "non-stationary clutter" from the chamber that was still evident was reduced by employing background subtraction. In this technique, the scene is imaged with no targets of interest (image of clutter background), then targets of interest are introduced, and the scene is re-imaged. The clutter background data is subtracted coherently from the target data, resulting in better suppression of clutter as well as internal radar noise as evident in Figure 3d (software was developed to perform this task).

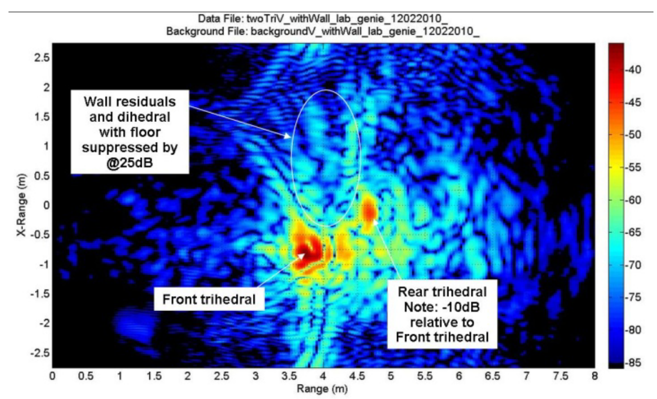




Figures 2d & 3d: Example of focused point scatterer with residual chamber noise and Point scatterer image employing background subtraction.

A concrete block wall was imaged to simulate the front surface of a box beam. Resulting images revealed internal structure of the hollows and solid areas (Figure 4d) of the wall and were consistent with Xpatch simulations of cinder-block walls in the literature[1].



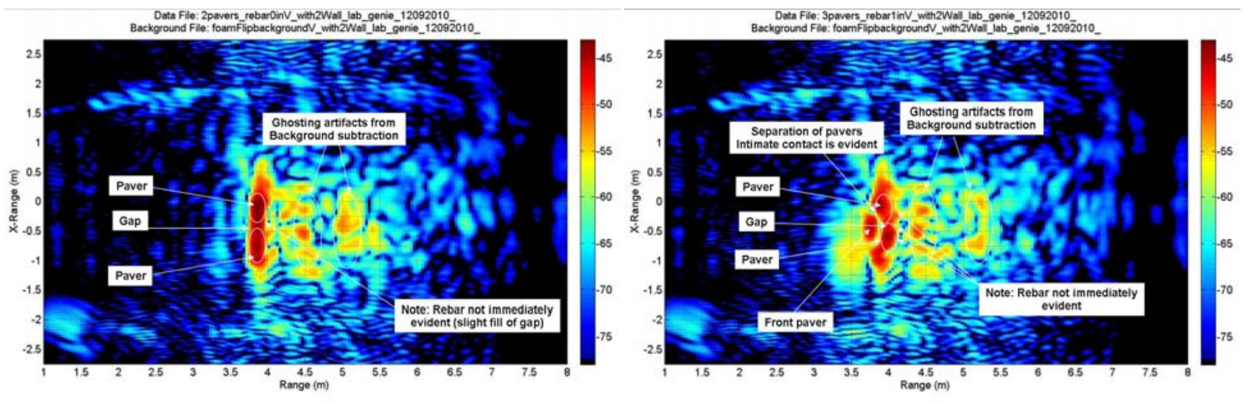


Figures 4d & 5d: Block wall with background subtraction and Corners in front of and behind block wall.

Imaging 2’x2’x2” concrete pavers, as being more representative of actual box beam construction, allowed us to simulate cracks and hollows by careful placement of the pavers. The radar was configured to provide 6cm spatial resolution in both range and cross-range. We imaged two pavers under several conditions; in close edge contact, with a 1mm gap between them, with a 25mm gap between them, and with Ø0.5in rebar in the gap and behind them. We

[1] Traian Dogaru, Le, Calvin, “SAR Images of Rooms and Buildings Based on FDTD Computer Models”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 47, No. 5, May 2009

also imaged three pavers with the third paver being placed over the gap/seam between the other two pavers. As seen in Figure 6d, the background subtracted images correctly depict the two pavers, but the sub-resolution cell sized gaps (i.e. smaller than 6cm) were not readily distinguished. In Figure 7d, the 3 pavers are all readily distinguished as separate entities, despite the third paver being laid directly against the other two (extremely small seams). The reinforcing bar was visible to a trained eye.



Figures 6d & 7d: Background subtracted image of two pavers with rebar behind and Background subtracted image of three pavers with rebar behind.

As expected, the radar could not clearly highlight gaps smaller than the resolution limit between the pavers (which simulated cracks). This prompted us to apply another technique to the processing known as “coherent change detection”. This technique is comparable to background subtraction, however it is typically employed by imaging a scene, then re-imaging that scene at some time later then coherently subtracting the later image from the original image of the scene. In this way, changes of a fraction of wavelength can be highlighted due to the radar’s inherent sensitivity to phase.

To illustrate the technique, we chose an image of the two adjacent pavers as the background image, and an image of the two pavers positioned with a 1mm gap between them. Figure 7d shows that the gap and the paver that was moved are clearly shown. This shows potential for inexpensive radar to clearly indicate physical changes that are significantly smaller than its resolution cell size (~3in^2).

What's next for Radar

The results show that the inexpensive Akela radar is capable of penetrating concrete, and the measured attenuation is consistent with the expected values for this material. Also, background subtraction processing is clearly preferable to de-trending when background data is available, although de-trending is readily applicable in the field while background subtraction may or may not be.

Performance could be improved by compensating for frequency/phase non-linearities of the system/antenna. This could make relatively low cross-section targets (such as rebar and small chunks of concrete) more readily observable in the presence of the strong return from the main structure of walls/beams. A higher gain antenna could improve system signal-to-noise ratio and improve detection of smaller cross section features of interest.

Extending background subtraction to employ change detection could be a powerful tool, although, as with background subtraction, spatial registration of the images used must be achieved to within a fraction of a wavelength of the radar signal. This means repeating measurements to within this accuracy, or measuring the errors to this accuracy. There may also be some means to do registration in software using prominent scatterers in the scene such as the large return from the face of the concrete. Combining the radar data with some of the optical techniques being explored could also prove to be extremely powerful.

Finally, we were somewhat limited in gaining good understanding of the phenomenology of the problem by not having an actual box beam available. Getting measurements of an actual box beam will help our understanding, and allow development of processing techniques better tuned toward extraction of features of interest. The following are considered necessary next steps:

- Improve calibration of the radar/antenna
- Investigate higher gain/better frequency response antennas
- Make field measurements of true box beam with and without flaws
- Evaluate whether these methods have practical application in the field
- Demonstrate how the processed radar data can be displayed in a way that is easily understandable to non-experts as part of the project's Decision Support System