Proceedings of The National Conference
On Undergraduate Research (NCUR) 2014
University of Kentucky, Lexington, KY
April 3-5, 2014

# Non-Intrusive Monitoring of Civil and Mechanical Structural Deflection: A 3D Imaging Approach

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## Abstract

Ongoing monitoring of structures for safety and level of service is becoming an important topic due to public concern of the state of infrastructure, particularly in the United States. Photogrammetry is capable of measuring deflections of structures, which can be used to assess the usability of the structure. The overarching goal of this research is to test the feasibility of applying photogrammetry for structural quality control, assurance, and analysis in the fields of civil, construction, and mechanical engineering. Variables in this research include number of features marked, number of known lengths in the scene, and distance between the camera stations and the object targeted for measurement. Two experiments, one in the lab and one in a field environment, were conducted. The results of these experiments verify the accuracy of the photogrammetry method proposed, which is arguably one of the most attractive options among other techniques.

**Keywords: Photogrammetry, deflection measurement techniques, 3-D modeling**

## 1. Introduction

Construction projects are some of the most complex and costly undertakings that consumers and governments make every day, and there is always a deadline and budget for them. This makes cutting costs and making efficient use of time a crucial element in the construction management. A particularly expensive fix is when the structure that is put up does not meet the specifications that were planned. This is designated as differences between as-built and as-designed plans. This can cause threats to level of service, leaving the structure standing but unsafe to operate. Being able to quickly and effectively measure the differences between as-built and as-designed of structural shape, size, and position is a crucial element to preserving level of service and safety. Applying photogrammetry solves this problem by using images from multiple angles and matching them to measured distances. This is done by utilizing modern computer programs such as Photomodeler® and MATLAB®. By matching similar points on different photos, a 3-D point cloud of the structure can be created to determine how much it has deflected.[1] This method only requires off-the-shelf cameras, compared to other measuring techniques requiring expensive equipment and/or many man hours.[2] A minimal amount of photos are needed, which can be quickly done freehand or on a tripod.

This research evaluates the feasibility of applying 3D imaging method for measuring deflections by verifying its accuracy. The analysis will include taking photos of a structural member, processing them in photogrammetry software, extracting the 3D coordinates from said software, and inputting them into matrix form for calculations. With this knowledge at hand, construction and other engineering crews will more efficiently be able to identify problem members that are deflecting unexpected amounts.

## 2. Background

There are established methods of measuring deflections, although they tend to be more expensive and/or time consuming. In the case of field techniques, augmented reality superimposes the geometric outline of the structure onto its current outline, giving a qualitative displacement to the user wearing the camera.[3] Total station technology has been around for a while, and has recently expanded to measuring small deflections of short-span railway bridges using robotic theodolites.[4] In the case of non-interferometric methods, image correlation captures random splotches of complementary colors in a single pattern, and measures the displacement of the copy of the original gray value distribution.[5] Speckle photography involves capturing light waves of a hologram of the object, which produces fringes as the surface goes under displacement.[6] Geometric Moire, or grid method, overlays black and transparent lines on a member. When the darker lines coincide with the lighter ones, they create black fringes which give reference for measurement.[7]

Interferometric methods are similar to the prior except they are sensitive to a higher magnitude. This, however, is somewhat offset when exposed to the environment which can distort accuracy to a degree.[2] Moire interferometry is similar to the grid method above except it uses coherent light (mostly lasers) to form an optical assembly on the surface of the object through a diffraction grating. As the member deflects, the fringe patterns are formed from the diffracted wavefronts. The average area tested is on the order of 25 square centimeters.[8] Electronic speckle pattern interferometry targets the object and a coaxial reference beam onto a television camera. This coarse speckle structure, the initial state of the object, is stored and subtracted from the television camera to obtain the displacement.[5] As a whole, these methods are optimum in a lab setting. As said with many of these methods, they require training and experience to use the software. Some are also insensitive to small displacements.[2]

## 3. Methods

The overall objective of this research was to design experiments to validate the accuracy of photogrammetry techniques applied to measuring structural deflections. Determining the minimum number of points and known distances in the scene gave a baseline for achieving an accurate measurement. For this, two experiments were conducted, one in an indoor setting and one outdoors. The first focused on a small deflection with photos taken from a close distance, determining the accuracy of the proposed method. Following the successful outcome, the next experiment moved to a more realistic setting to measure larger deflections from a more realistic distance to calculate the effects on the accuracy and feasibility of this method. The minimum number of points and known distances for a successful project were also determined.

### a) Camera calibration

As with all projects in Photomodeler®, a calibration of the cameras has to take place to set the parameters of the project. This is done by simply following the instructions of the specific software being used. For this software, it requires only printing given RAD targets (specially coded for automatic detection by the software), taking pictures of them with the camera desired to be calibrated, and uploading them to the software to solve for the parameters (Figure 1).

Figure 1. Camera calibration process

## b) Photograph taking

Two Canon EOS SLR 5D III cameras, Canon EOS Rebel T3i 18-55mm IS II kits, Canon EF 35mm f/1.4L USM Wide Angle Lenses, Sunpak 7575 Professional Heavy Duty Tripods, and Ravelli APLT4 61-inch Light Weight Aluminum Tripods were used to take high quality photographs. For the settings of the cameras, the indoor experiment had an F-stop=2.0 and ISO=100 in Av mode. Because of the change in surroundings, the only difference in the outdoor experiment was changing the F-stop to 13.0. The direct sunlight on the beige colored brick in the background resulted in too much light exposure for the original F-Stop setting. This change effectively reduced the brightness of the photos.[9]

### *i) Indoor experiment design*

The initial experiment was conducted in a laboratory setting, more specifically using a concrete compression machine (Figure 2). During stress tests, it is capable of recording displacements of the solid steel plate of the load frame to the thousands of an inch, satisfactory for our baseline displacement (i.e. ground truth) to compare the measurement data. The concrete specimen used for displacement was marked with four RAD targets, with 24 targets placed uniformly in the scene (Figure 2). Four pre-calibrated scale bars of a known length were placed uniformly in the scene to set the coordinate system with correct units. Three camera stations were set up to capture the scene from multiple angles. Taking photos with large angle separation yields smaller residual errors[10], thus stations were placed as shown in Figure 3. The center camera station was placed 79 inches orthogonally from the structural member, the two outsides ones at 62 inches. Photos from each camera station were taken in a landscape and portrait orientation. The concrete specimen underwent a displacement, followed by taking the same set of photos.

Figure 2. Concrete compression machine

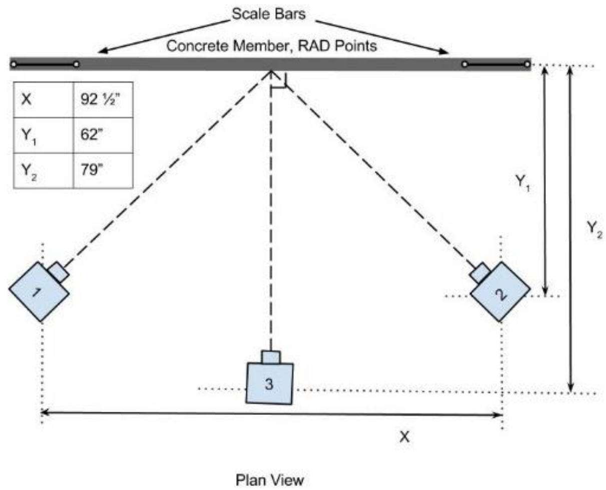


Figure 3. Indoor experiment plan

### ii) Outdoor experiment design

The second experiment of the project was set in an outdoor environment, where a structural member would more likely need measurement. A parcel of grass next to the recreation center at West Virginia University was selected as the site for its proximity to the student's campus, available area to take photos, large flat wall with prominent physical features to mark static points, and relatively infrequent disturbance by passage of students (Figure 4). For this experiment, three pre-calibrated scale bars were used instead of an actual displaced member. By setting them vertically (Figure 4), the top point was marked and referenced as the initial position, and the bottom point as the final position of a structural member that would go through that displacement. The distance from the top point to the bottom point in each scale bar is pre-calibrated to be 30 inches, accurate enough for serving as ground truth in this experiment. This can be done since the main objective is to measure the maximum deflection of a member at one location. It reduced the complication in scheduling a full-scale loading test and gave a very accurate baseline measurement to compare with the results. It would also remove the need to convert the coordinates before the displacement to the coordinate system of the after displacement, as explained in the following data analysis section. The top point of the scale bar was used as the before position, the bottom point was used as the after position. 37 static points were marked on the wall, scale bars, and boxes; six points were marked on three scale bars to imitate three displacements.

Figure 4. Outdoor experiment

Similar to the indoor experiment, scale bars were uniformly placed to set the scale of the scene, three camera stations were set up, and portrait and landscape photos were taken. Instead of taking photos from one distance, the three stations were set 30, 45, and 60 feet orthogonally from the displacement scale bars. The direct distance between the camera stations *x* increased with depth as well to maintain a reasonably similar angle. Additionally, photos were taken with the optical axis angled and orthogonal to the wall (Figure 5). This was done due to variances in accuracy between the two orientations.[11]

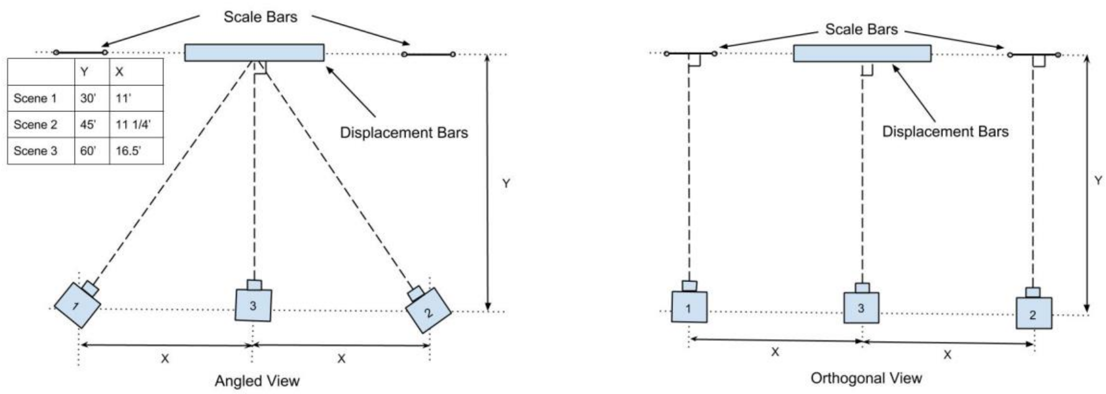


Figure 5. Orientations of camera

Comparison of the results of the different distances gave an indication of the relationship between measurement error and distance from the structural member. Boxes were placed closer to the camera stations to add coordinates that varied in the axis orthogonal to the wall.

## c) Data analysis

### *i) Measuring displacements*

The main tools used to analyze the displacements in these experiments were Photomodeler®, MATLAB®, and Microsoft Excel. Photomodeler® is a software package capable of measuring distances and lengths of objects in photographs. Starting with the upload of the photos taken in the experiments, similar targets were identified across each photo. Using the point marking feature, Photomodeler® was given reference points which helped it solve the camera stations. There were two different types of points marked in this specific study. Static points were in the same location before and after displacement of the member. Dynamic points were marked on the structure that was displaced. For the static points, there must be a minimum of four in at least two photos for the project parameters to be solvable. Of the static points, some were features found naturally in the scene or on objects strategically placed in the scene to maximize the coverage of the photo. The "coverage" refers to the percent area of the photo which has a marking on it. For example, marking points on the edges of the field of view would yield a coverage of approximately 100%, while marking points only at the very center of the photo would yield a coverage of approximately 0%. Using the scale feature, the coordinate system was set in the project by using the points on the scale bars to mimic its real life counterpart. Photomodeler® automatically processed the 3D coordinates of the marked targets in the photos. The "Point table - All" feature gave 3D coordinates of the points that had been marked in the project. These coordinates were extracted into multiple Excel files, organized by the distance the photos were taken from and the camera used, and identified as portrait or landscape.

MATLAB® was used in this project to automatically extract the coordinates from Excel so they could be converted into matrix form. The first step for the indoor data matched the different coordinate systems from before and after the displacement. Since the same camera had to be used to capture the scene from all three directions (and therefore moved in between displacement), the camera station locations were not identical for the before and after displacement scenes. Coordinate system matching was made by utilizing the absolute orientation quaternion method proposed by Dr. Berthold Horn. With the "before displacement" coordinates in the form

$$A = \{(x_1, x_2, \dots x_i);\ (y_1, y_2, \dots y_i);\ (z_1, z_2, \dots z_i)\} \quad \text{[12]} \tag{1}$$

They were converted into the "after displacement" coordinate system by applying the 3D rotation matrix and translation vector and scale factor

$$A_{new} = s \times R \times A_{cam\ i} + T \quad \text{[12]} \tag{2}$$

Where s, R, and T were determined by Dr. Horn's MATLAB® code.[12]

With the before and after coordinates in the same coordinate system, the displacement between the before and after coordinates were calculated using the 3D distance equation

$$d = \sqrt{(x_f^2 - x_i^2) + (y_f^2 - y_i^2) + (z_f^2 - z_i^2)} \tag{3}$$

### *ii) Minimum number of points assessment (outdoor experiment)*

The accuracy of the project with fewer marked points was measured by evenly taking out points in the analysis of each scene. An even distribution of points in the entire photograph was kept as much as possible while removing the points in order to maintain a desirable coverage in the photos (Figures 6 & 7). The minimum number of points for the project was set to 19. This was because six were used in displacement calculations, ten were used in setting the scale (which was kept constant), and three were used to set the coordinate system.

Figure 6. First set of points removed

Figure 7. Second set of points removed

### *iii) Minimum number of scale bars assessment (outdoor experiment)*

While marked scale bars were taken out of the analysis of each scene, the accuracy of the project with less known distances in the scene was examined. Only the scale property of the two points from each bar was removed, not the points themselves. For this reason, the order which they were removed was unimportant.

## 4. Results

### a) Indoor experiment

The accuracy of the displacement of the concrete specimen extended to the hundredths place measured with an error of 0.001875 inches, calculated by

$$Error = \frac{\sum_{n=0}^{p} |\Delta x_{real} - \Delta x_i|}{p} \tag{4}$$

The maximum percent deviation from the measured value was found using equation (5),

$$\%\ Error_{point\ i} = \frac{|\Delta x_i - \Delta x_{real}|}{|\Delta x_{real}|} * 100 \tag{5}$$

Coming out to 0.0656% of the baseline value of 7.9827 inches, shown in Figures 8 and 9.

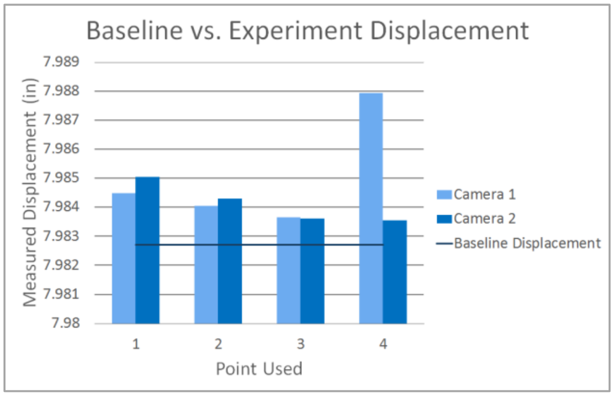


Figure 8. Displacements compared to baseline

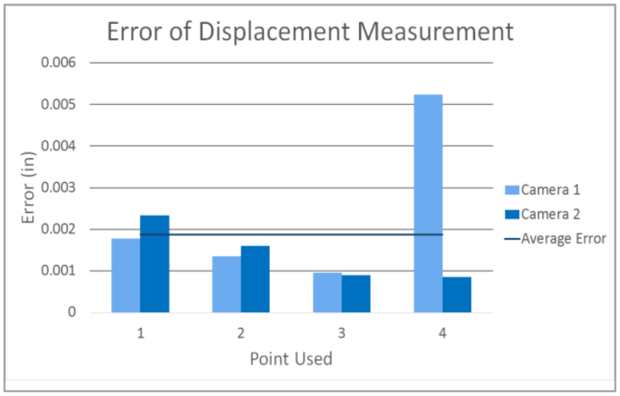


Figure 9. Error of each experiment displacement

Point 4 on camera 1 yielded a larger error compared to the other points. The software which processes the coordinates of the points yields its own small errors, which explained this outlier in the data set. A trend of smaller displacements was apparent, moving from point 1 to point 4.

### b) Outdoor experiment

Figure 10 compares the values calculated through Photomodeler® and MATLAB® against the known (baseline) displacement.

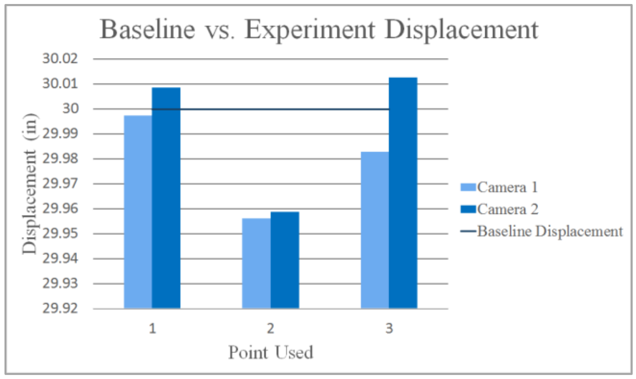


Figure 10. Displacements compared to baseline

As in point 4 in the above data, point 2 in this set yielded a larger error compared to the other points due to small error in the software calculation of coordinates.

Results showed a decreasing linear relationship between more known distances and reduced average error (Figure 11).

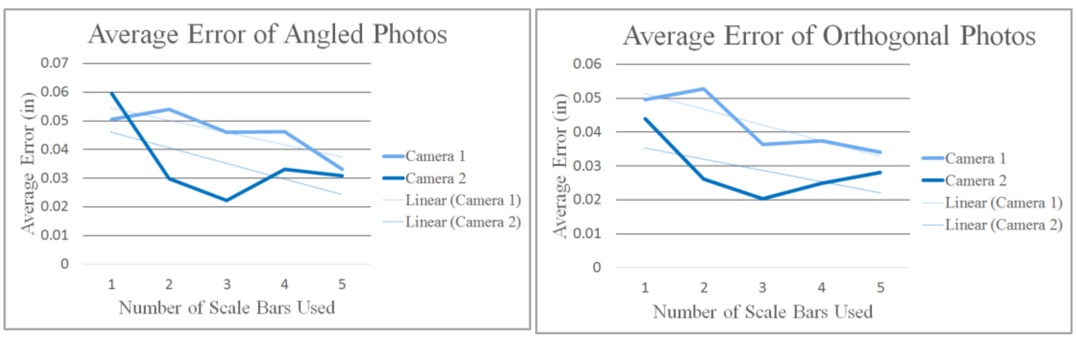


Figure 11. Change in error removing scale bars

Error of the measurement reduced 41.2% and 33.6% with the addition of 4 scale bars, averaging a 0.0064 and 0.00622 inch improvement with each scale bar (using angled and orthogonal photos, respectively). In this sense, the angled photos started out with a larger error, but reduced that error more with each added scale bar.

For more points marked in the project, there was not a significant decrease in average error associated with the project (Figure 12).

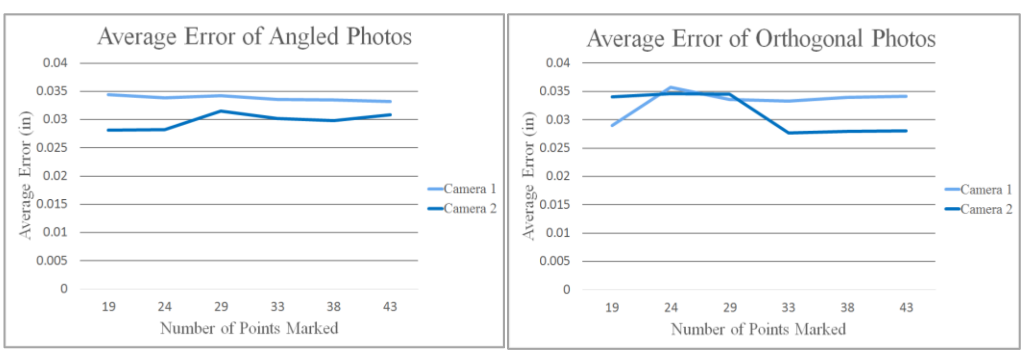


Figure 12. Change in error removing points

The orthogonal photos varied more in error as points were added, whereas the angled photos kept a more constant value, making incremental changes. Both sets started and ended with the same error, giving 0.002 inches.

## 5. Discussion

Photogrammetry should continue to be studied to provide a low-cost and highly effective option for projects that have limited viewing capabilities of a desired member. A number of benefits arise from using photogrammetry to measure deflections. DSLR cameras are very affordable and often are already owned by construction companies for other purposes. They are also user-friendly and have a small learning curve, if any. With that said, there are a few expected, uncontrollable factors that will affect the accuracy, including: lighting, optical axis angle to the normal axis of the front face of the member, and human error in accurately marking points in software. These should all be taken into account when considering the error yielded by this method.

While a significantly large number of photos can be taken to minimize residual errors for measurements, it is often not viable in the field to take over ten photos from multiple angles. A given member is often not viewable from every direction in space. There are often physical barriers that get in the way such as structures, property lines, treacherous terrain, waterways, and more. With the data suggesting deflections can be measured with great accuracy with a large number of photos, there is a need to further investigate how the number of photos used in a scene affects the accuracy of the model. Further application can also include a streamlined process. While managing with only a few points here, it might be more beneficial to mark more dynamic points on a structure to find the deflection along the entire member. Data mining may prove to be cumbersome when more dynamic points are used, so using software to make this an automatic process can save much time. These same methods should be applied in the field at construction sites in future experiments. As the indoor to outdoor experiment revealed new challenges and more realistic barriers to overcome, so applying this technology will also introduce a new wrinkle.

## 6. Conclusion

Given the method employed and results obtained from the lab and field experiments, photogrammetry is a feasible method for analyzing structural deflections. The methods laid out accurately measured the degree which a structural member would displace, laying the foundation for effectively managing quality control. The degree to which one is satisfied with the accuracy depends on the application. Increasing the number of points in the project did not seem to increase the accuracy of the measurements significantly. Increasing the number of scale bars, however, reduced the average error of the displacements by a significant amount. There are a variety of software packages available for analyzing the photos which are competitive and have their different advantages.

## 7. Acknowledgements

The author would like to take this opportunity to thank the National Aeronautics and Space Administration for their financial support in this project, Dr. Fei Dai for his support and direction, and for the organizers of the NCUR conferences for giving undergraduate students this incredible opportunity.

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