Photogrammetric Analysis of Concrete Specimens and Structures for Condition Assessment

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ABSTRACT

Deterioration of civil infrastructure in America demands routine inspection and maintenance to avoid catastrophic failures from occurring. Among many other non-destructive evaluations (NDE), photogrammetry is an accessible and realistic approach used for non-destructive evaluation (NDE) of a civil infrastructure systems. The objective of this paper is to explore the capabilities of photogrammetry for locating, sizing, and analyzing the remaining capacity of a specimen or system using point cloud data. Geometric interpretations, composed from up to 70 photographs are analyzed as a mesh or point cloud models. In this case study, concrete, which exhibits a large amount of surface texture features, was thoroughly examined. These evaluative techniques discussed were applied to concrete cylinder models as well as portions of civil infrastructure including buildings, retaining walls, and bridge abutments. In this paper, the aim is to demonstrate the basic analytical functionality of photogrammetry, as well as its applicability to in-situ civil infrastructure systems. In concrete specimens defect length and location can be evaluated in a fully defined model (one with the maximum amount of correctly acquired photographs) with less than 2% error. Error was found to be inversely proportional to the number of acceptable photographs acquired, remaining significantly under 10% error for any model with enough data to render. Furthermore, volumetric stress evaluations were applied using a cross sectional evaluation technique to locate the critical area, and determine the severity of damages. Finally, findings and the accuracy of the results are discussed.

Keywords: Photogrammetry, nondestructive evaluation, point cloud, mesh model, 3D surface model, civil, infrastructure, concrete

1. INTRODUCTION

Tunnels, bridges, highways and railways in America are suffering from rebar corrosion, and natural material, and structural degradation. In order to effectively monitor Americas civil infrastructure, it is vital that engineers are able to conduct an unabbreviated evaluation on the surface condition of structures. As a result, non-destructive evaluation (NDE) techniques are becoming an utmost necessity. Engineers ought to be able to view the surface features from all possible viewpoints and angles. Current contact or visual (NDE), such as acoustic emissions, ultrasonic testing, strain gauge measurements, linear variable differential transformer (LVDT) measurements, and ground penetrating radar (GPR) all require skilled technicians and expensive equipment to produce meaningful results. Non-contact evaluation like photogrammetry, laser or lidar, allow for a much simpler collection of data to be evaluated. While laser scanners can collect a significant amount of information, the equipment cost is relatively high.[1] Photogrammetry offers a thorough solution to the problem of surface damage detection and allows for the simple quantification of the recognized failure perimeters. With a high resolution camera, photogrammetric data can be collected from miles away, even a satellite has the capability to collect photogrammetric data. This allows for a simplified collection of defect data, and allows for qualitative as well as quantitative evaluation in a 3D space. By requiring only a data collection of photographs, photogrammetry allows for all aforementioned data to be collected at a significant enough rate that the inspections could be much more frequent while less expensive. This means more data, and ultimately a more in depth understanding of a systems overall health, both immediately and over time.

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The objective of this paper is to demonstrate the basic analytical functionality of photogrammetry, as well as its applicability to in-situ civil infrastructure systems. The primary parameters discussed in this paper are the number of photographs, location or defect, size, length and shape of defect. The effects of software choice, light, resolution, surface texture, and data collection techniques are also discussed. Starting first with the detailing of the theoretical background of photogrammetry. The paper then moves into, the experimental procedure, tools, and techniques for data collection are described and discussed. Followed by, results from numerical simulation, and computer aided analysis. Relationships between error with respect to input photographs are defined for locating and sizing defects. A photogrammetric volume, and a cross sectional stress analysis is conducted, damage is defined, and the critical area is determined for a damaged specimen. Thereafter, the applicability of in-situ photogrammetry is tested. Finally findings are summarized and discussed.

2. THEORETICAL BACKGROUND

2.1 Perspective geometry

With roots stretching back to Renaissance painters such as the revered Leonardo Da Vinci,[2] photogrammetry is effectively an art-form as well as a visual science. Photogrammetry uses perspective geometry from given photographs to construct 3D images. The camera serves as the perspective center, and allows for the projection of key features through the perspective center. From different perspective, the location of a point or object can be defined differently. This invariance based on the perspective center allows for the object or points location to be defined in three dimension rather than two by allowing for coinciding projections of spacial information. The "actual" location of an object is plotted in cartesian coordinates (x ,y, z) based on the intersection of perspective lines from multiple perspectives each with its own respective angle and location of projection. Photogrammetric invariances can be expressed not only in terms of lines on a single plane, but also in consideration of lines crossing multiple planes. By establishing a redundant matrix of invariance through multiple planes, the function of projection can be established through the perspective center.[2] This can be described with a collinearity condition in which a point measured, the camera or perspective center, and the captured image are all connected with a straight line.[3]

2.2 Parallax and Stereo Vision

The fundamental concept of photogrammetry is triangulation[4] Triangulation, is quintessentially a calculation of disparity between two points from a known point. Two of the most fundamentally applied concepts in photogrammetry are the parallax and the concept of stereo vision. Both are geometric calculations with respect to spacial differences in multiple frames. Stereo vision, which can be best exemplified by the human eyes, is a calculation of the disparity between two or more perspectives, allowing for depth perception. A parallax is the difference in location of an object between two points. Taking photographs along a single flight path illustrates how it is possible to use a parallactic difference to uncover information about a point. Points closer to a perspective center will have a much larger parallax than a point which is farther away. By calculating the variation in location between several points of perspective, it is possible to calculate the location in relative space. The concept of triangulation and calculation of disparity is the fundamental building block of photogrammetry which makes point cloud modeling both possible and effective.

2.3 Fiducial markers, scaling, and resolution

Since photogrammetry is a visual science, the quality or resolution of the image, and the level of texture or variance in the image is paramount. Fiducial markers, also called key points or control points, are points used to calculate the transformation function between perspective frames.[5] Control points can be established manually or, computed through the recognition of a unique feature in an image. In other words the more gradient an image is, the more information it stores and easier it is to model. Concrete is a particularly good surface from a photogrammetric standpoint because concretes surface stores a very unique texture pattern allowing for much more fiducial markers to be identified than a painted, smoother, reflective or otherwise uniform surface. Furthermore, damages in concrete such as cracks, concrete spalling, and exposed corrosion among other damages add to the uniqueness of the surfaces being modeled. Therefore, it can be argued that the more damaged a structure is the more effective the photogrammetric modeling can be.

Similarly, resolution is largely responsible for the amount of fiducial markers, or control points which can be rendered. Because resolution is a function of technical equipment, as well as level of light it stands to reason that a better camera, and a bright day would produce higher levels of quality in the imaging. Consequently, a photogrammetric engineer is expected to conduct a thorough inspection of his or her data to make sure all of the images are not subject to motion blur or any other noise which with disrupt the overall imaging. Additionally it is recommended to apply filters. Applications of filters can be done when the system or specimen undergoing modeling is subject to harsh conditions in which shadows, lighting or accessibility make it too difficult to acquire enough sensible data to construct a relevant model for condition assessment.

3. EXPERIMENTAL PROCEDURE

3.1 Data Collection

Data collection or photo acquisition is typically accomplished in photogrammetry with two general motives. Using Unmanned Aircraft Vehicle (UAV) for land surveying the technique is generally a nadir collection. This is achieved by taking the photographs from a position perfectly perpendicular to the surface being modeled. This technique is effective for terrain mapping and land surveying because an (UAV) can be set to a given flight path with set photographic intervals. In this approach, a predefined approximate forward overlap of 60% and side overlap of 20% between frames (images taken), is assumed. Large amounts of data can be calculated in this fashion, however the single projection angle can minimize the quality of rendering.

The second technique is an oblique, or non-perpendicular to target approach (Figure 1). Oblique photogrammetry is motivated by the need to construct a model for a specific feature, structure, or object. In this paper, the second technique is adopted. In the oblique approach, using angles approximately between 35° - 55° conserves most of the information, while gaining more perspective information from the planar disparities. The additional data allows higher quality image rendering, focusing on quality of data rather than quantity. The ideal conditions for modeling a specimen obliquely calls for taking oblique images around the object from three heights in increments which allow for side overlap between frames of approximately 30%. Typically between 40 to 70 photographs can construct an effective model. Yet, models with low (less than 10% error) can be observed with as little as 12 photographs. the introduction of UAV's into the market allows modeling civil infrastructures obliquely much more possible as the "above-the-head" privileged point of view is the main motivation and key feature that makes photogrammetry and remote sensing much more feasible.[6]

In these experiments, a 4th generation Apple Iphone was used to generate the concrete cylinders which were evaluated with a very low margin of error. Images can be collected with almost any digital camera without suffering from too many complications or limitations[7] It should be noted that the level of noise in an image is a more deterministic variable than the quality of camera, or equipment used. Autodesks 123D catch software allows artists and engineers alike to create comprehensive and accurate three dimensional objects from collected photographs. Once Autodesks 123D catch software has constructed the 3D pointcloud, it is exported into Meshalb, an open source software created by ISTI-CNR,[8] as a 3D object or (.obj) file. the project which was originally started as a course project, is a powerful mesh and point cloud analysis tool.

3.2 Defining the coordinate system

Once in Meshlab, a local coordinate system can easily be manually defined. Transformation from relative to absolute coordinate systems is contingent on manual identification of global control points.[9] The matrix of the point cloud can be translated, rotated, scaled, and cut to size manually, within the confines of the program. A locally defined coordinate system with an effective origin allows one to keep track of relative locations of defects in both physical space, as well as within the Meshlab world . Once scaled to its physical space equivalent a model can be used to locate the physical location of a defect, and regular maintenance including photogrammetric evaluations would allow for the progressive modeling of damage over time. Subsequently this technique could lead to the development of equations describing the maturation of damages in a structure.

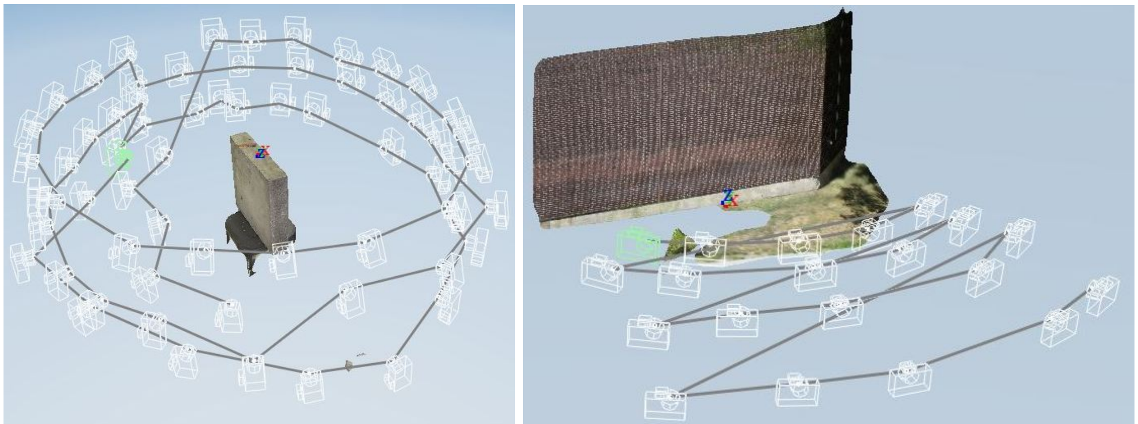

Figure 1. Typical photo acquisition for a lab specimen (left) and a masonry-concrete wall (right)

3.3 Data Analysis

In this research, Meshlab was used for the geometric assessment of 3D point cloud models. Meshlab allows the user to register known points as well as define reference points within a coordinate system. It allows the user to evaluate lengths widths, volumes, surface areas, cross sections and profiles. All of the information from Meshlab can be extracted as raw point data, and manipulated in MATlab, excel, and many other computational softwares. Multiple models can be stitched together, cut, smoothed, filtered, and added to. Models can be easily scaled, viewed as point cloud, mesh, and even textured models. Meshlab was chosen for this research because of it's accessibility, and versatility. The accuracy of other 3D analytical programs, such as Rhinoceros in conjunction with these techniques has not been tested.

4. RESULT AND ANALYSIS

In the following section results from lab specimens are evaluated for their effectiveness in locating and identifying the size/severity of damages. Using cross sectional evaluation on concrete specimens the areas of high risk are define by stress mapping. Additionally possible application for in-situ structures will be discussed and evaluated for effectiveness

The two models, Model 1 (shattered) and Model 2 (intact) (Figure 2) were each modeled using the 70 and 64 photographs respectively. Once the primary models were established they were rendered at variant levels of photographs, and subsequently evaluated for their level of error with respect to photographs used to render. As the number of photographs decreases the level of overlap between image frames effectively drops and the quality of rendered models as a result, decreased proportionally. Models are defined with progressing roman numeral to express decreasing quality. The results are tabulated, graphed, and modeled using an exponential fit below.

4.1 Locating Coordinates and Defect Sizes

The first step in identifying the capability of these techniques was to test the ability of the photogrammetric models at differing number of photographs per rendering. Two concrete cylinder specimens were used. On Model 1, the shattered concrete cylinder, three representative defect points (**PP0**, **PP1**, and **PP2** (x, y, z)) were drawn placed on the specimen and then located photogrammetrically (Figure 3) . For this evaluation the origin was locally placed at a point easily recognized visually. The location of the origin, was chosen to allow for easy localization of target areas both in real and point cloud modeling space. Of the three points, one **PP2** was placed on a straight path from the origin, **PP0** and **PP1** were placed on the far side of the cylinder to test the photogrammetric capability to account for dimensional changes in the x, y, and z directions. These three points as well as the origin are represented by the red dots on Figure 2.

PP2 exhibited the least amount of error, as it was the closest to the origin and consider only translation in the z direction; at point (0, 0, 20). **PP0** and **PP1** located at (9.2, 3.5, 15.5) and (8.2, 4.6, 9.5) respectively

Figure 2. Model 1 (left) shattered Specimen & Model 2 (right) intact specimen

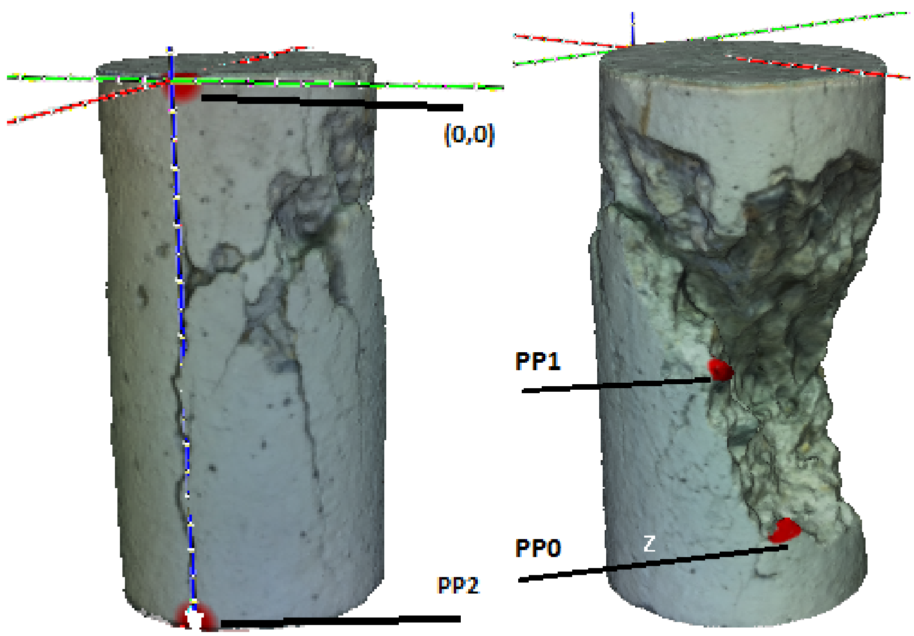

Figure 3. Model 1 Points PP0, PP1, PP2 Representative Defects

Table 1. Error in Locating points Model 1 (Shattered Specimen) (Model Vs Actual)

Model	**Number of Photos**	**Error PP0** (%)	**Error PP1(%)**	**Error PP2 (%)**
I	70	1.868	1.765	0.044
II	48	3.126	3.124	0.155
III	32	3.274	3.274	0.518
IV	16	4.563	4.563	1.245
V	12	5.549	6.275	N/A

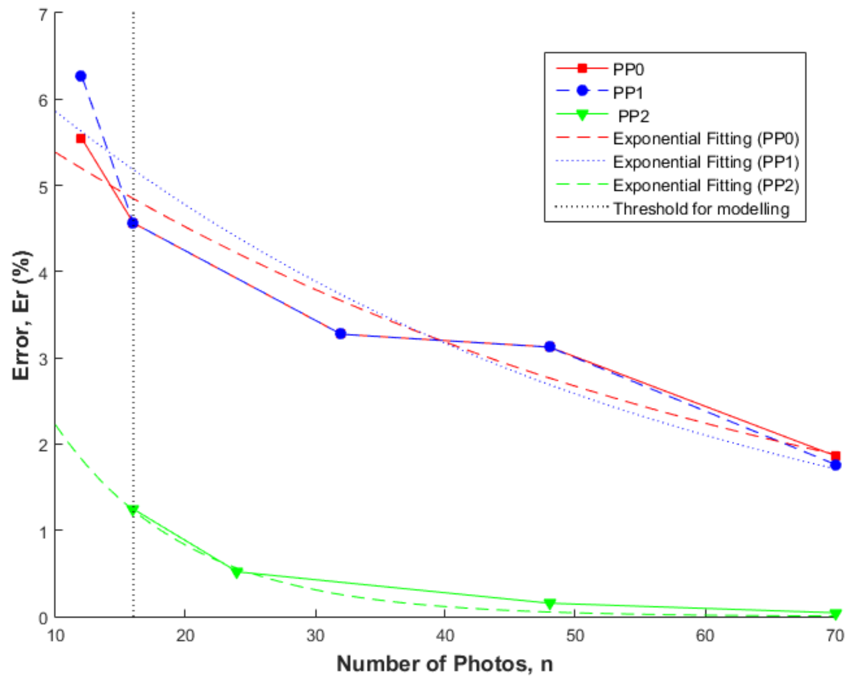

Figure 4. locating points on Model 1 Shattered Cylinder

exhibited approximately the same amount of error as the degradation of the model continues. Yet even at maximum deterioration the locating abilities of the photogrammetric techniques has a maximum error of only 6.275%. On Model 1-V which was unable to fully render. The results are graphed (Figure 4), the vertical dotted line represents the point at which the amount of photographs was not enough to construct a complete model. Errors with estimated coordinates of points **PP0**, **PP1**, and **PP2** were modeled by the fitted curves whose equations are shown in the following, Equations (1), (2), and (3). (Figure 4) illustrates these results.

$$Er|_0^C(n) = 6.414\exp(-0.01751n) \tag{1}$$

$$Er|_1^C(n) = 7.191exp(-0.02048n) \tag{2}$$

$$Er|_2^C(n) = 5.962\exp(-0.0986n) \tag{3}$$

where $Er|_i^C$(n) is the error with respect to photographs taken in Model 1-I through Model 1-V, and n is the number of photographs. Er = error, i = Point considered PP(i), C= Coordinates, and n=number of photographs

These results prove that significantly less error is associated with the identification of a point which is only translated with respect to one direction than a point with translations in multiple directions. **PP2** which is located at (0, 0, 20) was identified with significantly less error than the other two points modeled

The analysis for Model 2 (intact specimen) focused on the accuracy in obtaining the length of a line or "size of defect" photogrammetrically. Whereas points are defined individually, a lines length is not only contingent on the points and there known orientation but also the spaces in between. As such, lengths are generally more influenced by noise in photogrammetry.[5] Three lines were drawn on the cylinder. A straight line on a straight

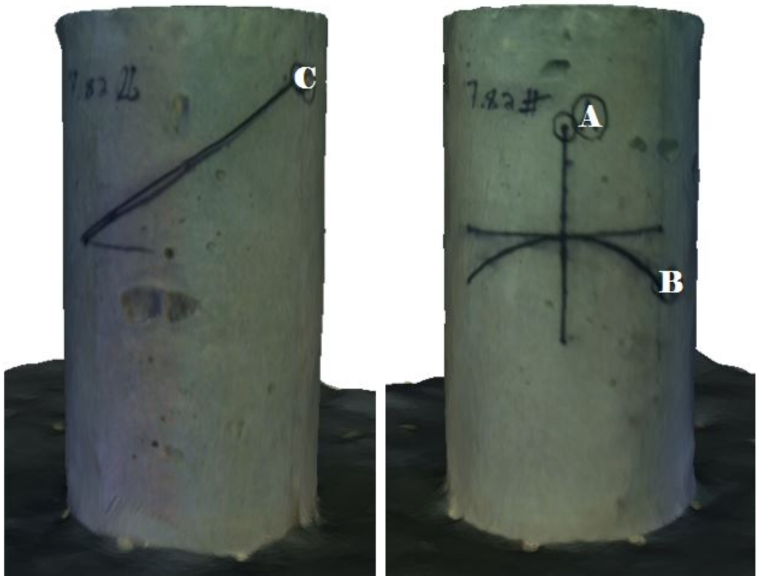

Figure 5. Model 2 Lines A, B, C Representative Defects

Table 2. Error in line lengths Model 2 (Intact Specimen) (Model Vs Actual)

Model	Number of Photos	Error line A(%)	Error line B(%)	Error line C(%)
I	64	0.296	0.718	0.675
II	32	0.210	3.594	2.649
III	16	0.548	2.142	4.356
IV	12	N/A	N/A	N/A

plane A a curved line on a curved surface B and a straight line on a curved surface C (Figure 5). The actual and photogrammetrically calculated lengths are tabulated in (Table 3) As with the previous model the variation with respect to photographs taken was tabulated (Table 2), and graphed (Figure 6) in order to represent the effectiveness of the technique.

In Figure 6, as observed in the evaluation of Model 1, the trendline for Model 2 is decreasing error as the number of photographs increases. This evaluation exhibited a maximum error of only approximately 4.4%. A reasonably low number for civil engineering applications. Line A or defect A, which was a straight line on a straight surface was expected to exhibit the lowest error, and exhibited less than 1% error maximum. Curiously the error in line B shot up as the number of photographs increased from Model 1-II to Model 1-III, this error is most likely due to the complexity of measuring a straight curved line on a curved surface. In order to nullify the effect of this outlier the Error in line B was fit assuming a more linear set of data. However, with all error below 5% it is reasonable to consider the difference as negligible. Line B was in fact the most difficult line to calculate as it a curved line on a curved surface exhibits the most subjection to change. It had exhibited more error

Table 3. Difference in line lengths Model 2 (Model Vs Actual)

	Length(Cm)	Measured(I)(cm)	Measured(II)(cm)	Measured(III)(cm)	Measured(IV)(cm)
A	7.5	7.4777	7.446	7.551	N/A
B	9.1	9.119	8.773	8.859	N/A
C	10	10.055	10.214	10.436	N/A

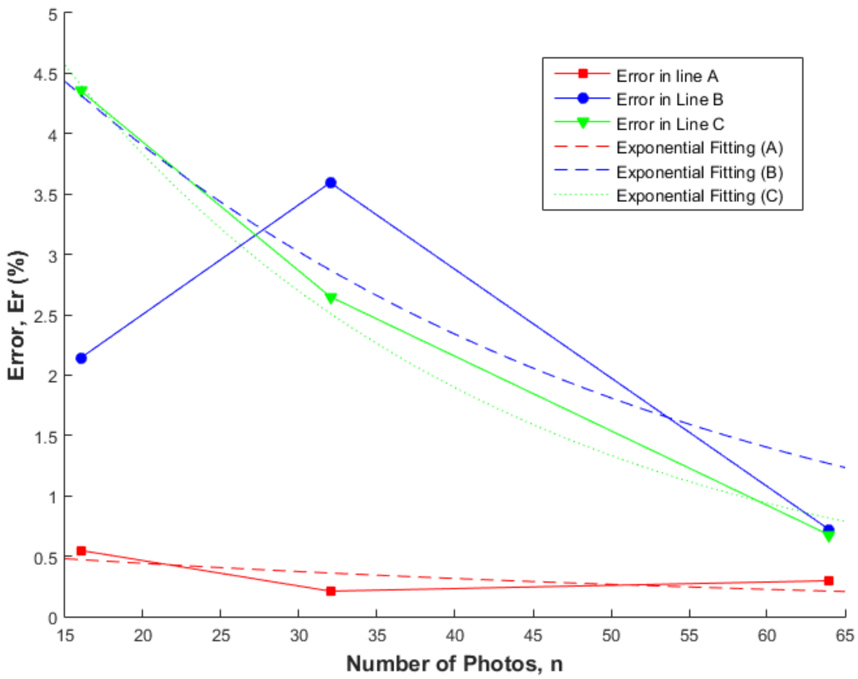

Figure 6. Determining line lengths on Model 2 intact Cylinder

than not only the straight line on a flat plane A, but also more than C the straight line on the curved surface. A exhibited significantly lower error, as the surface disparities did not come into effect. All line lengths were calculated, both physically, as well through the calculation of the sum of disparities of manually plotted points. using 13, 18, and 24 points for lines A, B and C respectively. These relationships are defined mathematically below in Equations (4), (5), and (6). The Error associated as a function of photographs is defined for all three lines in Equations (7), (8), and (9) below.

$$L_A = \sum_{2}^{13} (P_x - P_{x-1} \tag{4}$$

$$L_B = \sum_{2}^{18} (P_x - P_{x-1}) \tag{5}$$

$$L_C = \sum_{2}^{24} (P_x - P_{x-1}) \tag{6}$$

where P_x and P_{x-1} represent manually added points starting from $P_x = 2$

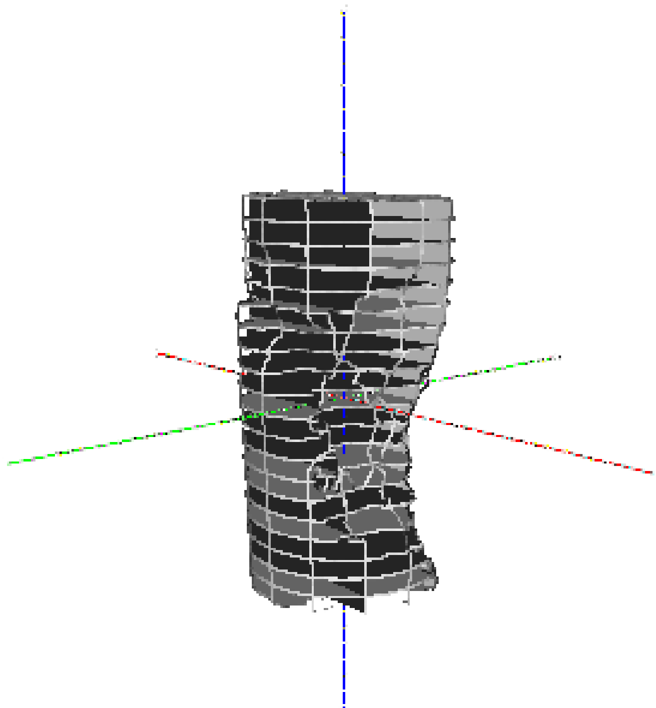

Figure 7. Cross Sectional Analysis of Model 1 (Shattered Cylinder)
Key: [Blue=Z Downward Positive] [Green =y Left Positive] [Red= x Left Positive]

$$Er|_A^L(n) = .6161 \exp(-0.01677n) \quad (7)$$

$$Er|_B^L(n) = 6.506 exp(-0.02558n) \quad (8)$$

$$Er|_C^L(n) = 7.735 \exp(-0.03515n) \quad (9)$$

where $Er|_i^L$(n) is the error with respect to photographs taken in Model 2-I through Model 2-IV, and n is the number of photographs. Er = error, i = Defect considered line (i), L= Length, and n=number of photographs

4.2 Calculating Volume and Maximum Stress

In order to justify the reliability of a photogrammetric volume calculation for damage detection, a brief experiment was conducted. The volume of the shattered cylinder Model 1 was calculated by water displacement. The specimen was lowered into a full container of water of known volume and mass. The amount of displaced water was used to calculate the volume of the shattered cylinder. The intact theoretical volume of a cylinder with a height (h=20cm) and diameter (d=10cm). Then the volumes, of Models 1 and 2 with the lowest error were used to calculate the volumes in meshlab. The values are defined and tabulated in Table 4 for reference. (Note: The coordinate system is redefined for the purpose of this evaluation.)

The results from the volume calculation experiment further verify the quantitative capability of photogrammetry. While the error in the calculation of damages in Model 1, $\mathbf{Er}_1^m$ approached 5% error, it should be noted that a level of human error was involved in the water displacement. Whereas error in Model 2, the intact volume

Table 4. Volume Analysis Using Model 1-I(Shattered Specimen)

Parameter	Value	Unit
$\mathbf{V}_1^m$(Volume Calculated via Meshlab of Model 1(shattered))	1436.947	(cm^3)
$\mathbf{V}_2^m$(Volume Calculated via Meshlab of Model 2 (intact))	1525.034	(cm^3)
$\mathbf{V}_1^a$(Volume Calculated via water displacement)	1369.848	(cm^3)
$\mathbf{V}_{in}$(Theoretical Volume of an intact Cylinder)	1570.796	(cm^3)
$\mathbf{V}_d^a$(Volume of damage (actual) (V_{in}- V_1^a))	200.948	(cm^3)
$\mathbf{V}_d^m$(Volume of damage calculated in meshlab(V_{in}- V_1^m))	133.849)	(cm^3)
$\mathbf{V}_d^a$(Volume of damage actual ((V_{in}-V_1^a))	12.793	(%)
$\mathbf{V}_d^m$(Volume of damage calculated in meshlab(V_{in}-V_1^m))	8.521	(%)
$\mathbf{Er}_2^m$(Error in meshlab intact volume calculation using Model 2 data(intact))	2.913	(%)
$\mathbf{Er}_1^m$(Error in meshlab damage calculation using Model 1 (shattered) data)	4.898	(%)

error $\mathbf{Er}_2^m$ was calculated with an error less than 3%. Both values can be considered acceptable in assessing the condition of the specimen. Following volume calculation, a cross sectional analysis on the damaged Specimen, (Model 1) was used to evaluate its relative stress. The Specimen was cut cross sectionally perpendicular to the Z axis at 21 locations with an incremental (δz = 1 cm) from z= -10 cm through zero and up to z=10 cm.

For the purpose of interpreting the experimental data, the cross sectional areas were normalized based on the difference in the error between the Meshlab and actual volumes. (Equation 10)

$$A^m_{z(adj)} = \left[1 - \frac{Er^m_1}{100}\right] \times A^m_z \tag{10}$$

where $\mathbf{A}^m_{z(adj)}$ = the adjusted cross sectional area, and $\mathbf{A}^m_z$ is the unadjusted cross sectional value obtain photogrammetrically. The Primary $\mathbf{A}^m_z$ and adjusted $\mathbf{A}^m_{z(adj)}$ cross Sectional areas are provided in Table 5. Damage (**D**) was calculated using an intact theoretical area $\mathbf{A}_{z(in)}$ and is defined (Equation 11)

$$D = \frac{(A_{z(in)} - A^m_{z(adj)})}{(A_{z(in)})} \times 100(\%) \tag{11}$$

Stress (σ) was calculated by applying a uniform load of 1 Newton to the cylinder.

These results showed that photogrammetry not only can calculate the volume of a specimen or system, but also can identify the critical section (which is the cross section with the highest stress) vital information for the condition assessment of civil infrastructure.

4.3 Application to in-Situ Structures

From the laboratory results above, it is reasonable to deduce, that photogrammetric techniques posses the capabilities to locate, size, and evaluate damages in real structures. Computational analysis like stress evaluation may prove to be very useful in evaluating the critical section of a bridge pier or girder. However very little in-situ experimental data is available. For in-situ structural evaluations, the use a fiducial marker of known size to establish a scale, can accommodate the localization, and sizing of defects similarly to the techniques described in this paper. In order to demonstrate the capability of photogrammetry to be used for condition assessment of in-situ infrastructure, one in-situ evaluation example is provided. This case study is the crack length estimation of a large crack found on the abutment of the Lincoln St. bridge in Lowell, MA (see Figure 8).

Using a total of 81 points the length of the crack was calculated to be 599.5289 cm. From 14 spot check locations the average thickness of the calculation was calculated to be 1.1176 cm. These values represent the capability for preliminary quantification of surface damages in civil infrastructure.

Table 5. Cross Sectional Stress Evaluation Model 1 shattered cylinder

Z(coordinate)	$\mathbf{A}_z^m$ (cm^2)	$\mathbf{A}_{z(adj)}^m$ (cm^2)	$\mathbf{A}_{z(adj)}^m$	σ **(Stress)(Pa)**	**Damage(%)**
Z(-10)	37.915	36.057	0.0036	277.334	54.090
Z(-9)	83.058	78.989	0.00789	126.59	-0.572
Z(-8)	82.635	78.587	0.00785	127.247	-0.0602
Z(-7)	80.877	76.916	0.00769	130.011	2.0674
Z(-6)	77.521	73.723	0.007	135.642	6.132
Z(-5)	73.834	70.217	0.007	142.415	10.5963
Z(-4)	71.978	68.451	0.006	146.088	12.844
Z(-3)	71.090	67.608	0.00676	147.91	13.918
Z(-2)	66.988	63.707	0.00637	156.969	18.8861
Z(-1)	65.587	62.375	0.00623	160.320	20.581
Z(0)	63.394	60.288	0.00602	165.868	23.237
Z(1)	60.107	57.163	0.00571	174.938	27.218
Z(2)	59.124	56.228	0.00562	177.848	28.409
Z(3)	61.458	58.447	0.00584	171.0936	25.582
Z(4)	63.457	60.348	0.00603	165.703	23.161
Z(5)	65.957	62.726	0.006272	159.421	20.133
Z(6)	69.616	66.205	0.006	151.044	15.704
Z(7)	74.379	70.736	0.00707	141.371	9.936
Z(8)	77.147	73.368	0.00733	136.299	6.584
Z(9)	80.250	76.32	0.00763	131.0284	2.827
Z(10)	68.090	64.75	0.00647	154.428	17.551

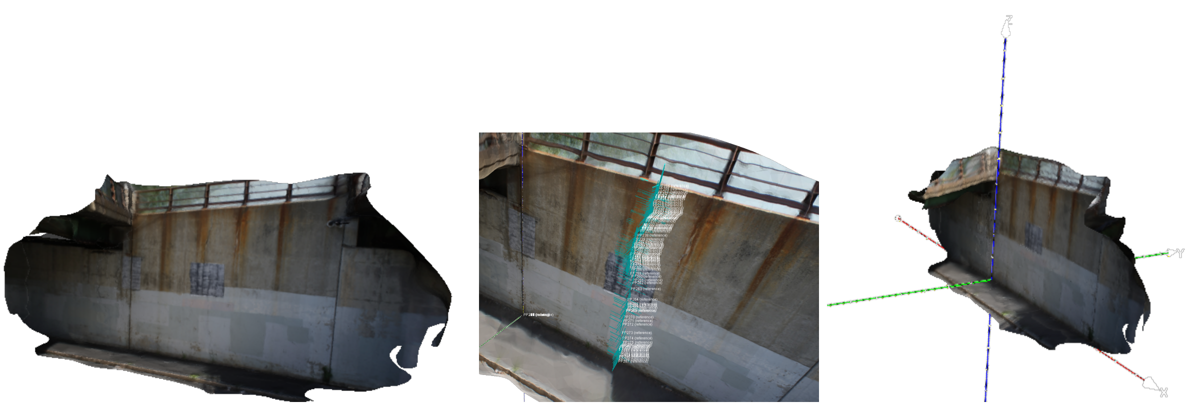

Figure 8. Large Crack on abutment Lincoln St. Lowell MA.

5. SUMMARY AND DISCUSSION

In summary, the use of photogrammetric techniques for the nondestructive surface evaluation of concrete specimen and structures, is possible to determine the size, and location of a defect. It is also feasible to conduct a cross sectional evaluation to the develop stress distribution in a concrete specimen. Photogrammetric techniques require very little input, and provide the user with quantitative results that would otherwise require a substantial, and expensive amount of time to obtain. The primary parameters are discussed in the following

- **Geometry of photograph appropriation:** Photogrammetry relies heavily on perspective geometry to construct the 3D models. Correctly proportioning frame overlapping, and the amount of perspective inputs allows for more points to be defined with more certainty. By using multiple angles, and having sensible overlap in detail, the photogrammetric engineer encourages a strong model with more data, and or less associated error.
- **Number of photographs taken:** The number of 2D photographs has a positive proportional correlation to the effectiveness or accuracy of models. In this paper we demonstrated quantitatively how model error was reduced with an increase in photographs (n)
- **Computational and analytical software:** In this paper the softwares used were Autodesk's 123D catch and ISNT's Meshlab. Both are available for free online. They were chosen for their accessibility and versatility. While many other mesh and point cloud modeling and analysis tools exist, their accuracies have not been compared to the softwares in this study.
- **Defect location:** In this paper Model 1 served as the primary consideration for the effectiveness of locating a defect. The locations of PP0, PP1, And PP2 effectively represented the locating capabilities of this process. All of the error was reasonably low, but it was also demonstrated that when multiple translations (dx, dy, dz) were considered the error would increase. This can be seen by the difference in error between PP2 (which occurred only one direction away from the origin) and PP0, with PP1 which showing a substantially higher error.
- **Geometry of the defect:** Model 2 served in this paper to evaluate the sizing capabilities of photogrammetric evaluation. All of the error was reasonably low. However, using a flat line on a flat plane, a curved line on a curved plane, and a flat line on a curved plane, the reliability of each mode was tested. The flat line on the flat plane exhibited the least error, and the curved line on the curved plane the most.
- **Texture of the modeling surface/ apparent fiducial markers:** Because photogrammetry relies on key features to establish a projective geometry matrix, the availability of easily identifiable features is very important. This can be seen in the ability of the damaged structure (which has much more textures, and corner points.) to be modeled with fewer photographs then the intact specimen.
- **Amount of light measured in lux:** While the amount of light has an obvious role in any optical evaluation, there is not substantial evidence that a difference within an acceptable margin makes any difference.
- **Resolution:** While the resolution of a camera will in fact marginalize error, Model 1 (I-V), and Model 2 (I-IV) were constructed using an Iphone 4 camera. Considering the relatively low error, it seems reasonable to say resolution is a non integral parameter to consider. More so it is important to use only photographs which exhibit a low level of noise to be accounted for.

6. CONCLUSION

In many current, completed, and ongoing research projects, photogrammetric techniques have exhibited broad potential for measurement tasks in civil engineering material testing and large structure monitoring.[10] The information, and experimental data in this paper describes a safe and easy way to preform routine, non-destructive maintenance to civil infrastructure. With our nation in the midst of a period of colossal levels of degradation, when the ASCE ranks our infrastructure at a "D"; meaning we need over $3.6 Billion dollars in reparations. It is utterly important that we begin to invest in safe, and effective ways to inspect, monitor, and quantify the levels of damages in the standing infrastructure. Current techniques are costly and ineffective, photogrammetry in conjunction with subsurface evaluations of structures offers a viable alternative.

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