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Research Article

Leveraging Point Cloud Data for Detecting Building Façade Deteriorations Caused by Neighboring Construction

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Abstract: Building facade deterioration due to aging and nearby construction sites is a continuous public safety concern. Within the past half-decade, there have been more than twelve-thousand complaints regarding falling debris from building facades in NYC, where it has around 1 million aging buildings. Thus, an effective method for facade inspection is essential for property owners and inspection agencies. Nowadays, 3D laser scanners are widely utilized for their ability to capture as-is conditions. However, an appropriate scanning setting when facing distinct types of tasks, such as crack detection and progression of damages on building façades is essential to expedite the data collection process. The overarching goal of this research is to compare the datasets captured through different settings of laser scanners (i.e., resolution and scanning distance) for crack detection and to evaluate the measurement accuracy of the detected/progressed cracks. In this study, we report back on the analysis performed on point clouds obtained with terrestrial laser scanners for crack detection. The results provide a performance analysis of terrestrial scanning systems and corresponding settings for crack detection. Findings can provide an alternative way to comply with the laws (e.g., Local Law 11/98 in NYC) that require periodical evaluations of buildings in cities.

***Keywords**:* laser scanning, crack detection, façade inspection, prolongation of construction damage.

1. INTRODUCTION

The City of New York (NYC) has nearly one million aging buildings, requiring continuous maintenance and renovations. Especially the upgrades on building facades are of public safety concern and require immediate notice for problems. For instance, there were 12,000 complaints reported on "debris falling" or "in danger of falling" from the buildings in NYC within the last couple of years (DOB 2018). Hence, owners of buildings that have more than six stories are required to conduct a façade inspection every five years and comply with the NYC construction code (NYCCC 2008). Current Façade Inspection Safety Program (FISP) needs to be accomplished by qualified exterior inspectors (Eschenasy 2016), and the façade condition for each inspection cycle should be compared with the inspection result from the last cycle. The existing approach greatly relies on human practice of visual inspection,

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taking photos, and drawing sketches, which is time-consuming and requires physical access to the façade that might create safety concerns for inspectors and surrounding public.

3D laser scanning technology can aid this process with the feature of capturing the as-is surface condition for accurate documentation without close physical access (Laefer et al. 2014). Point cloud data obtained with 3D laser scanning technology can provide a 3D model serving as a baseline condition for the comparison in the next inspection cycle. However, with different scanner settings, the level of detail of the data captured and the time required for the data collection process vary. To leverage point cloud for façade inspection, a recommended scanning setting should be provided. In addition to this, an analysis of how much of the thresholds (set for facade cracks in local codes) can be accurately captured with laser scanners is required.

For this study, the authors conducted experiments to evaluate the feasibility of leveraging point cloud data for façade inspection and to find recommendation settings for detecting cracks of various sizes. Foam boards were cut to simulate cracks by changing the width, length, and orientations based on the thresholds from the local codes. During the experiments, different combinations of scanning parameters (i.e., the resolution and the scanning distance) were adjusted to find the preferable setting for crack detection at a given size when using Terrestrial laser scanners. The result of this study can serve as a guide when inspectors are conducting the FISP with the 3D laser scanning technology to improve data capturing process.

Background Research

This study focused on leveraging the point clouds data for building façade condition inspection. The point of departure for this study is organized as a) local laws and construction codes regarding building inspection, and b) previous efforts on crack detection and measurement with 3D Laser Scanning technology.

Local Laws and Construction Codes

The NYC Department of Buildings (DOB) issued a series of construction code and Rules of the City of New York (RCNY) for building inspection. These documents serve as guidelines when conducting FISP and monitoring historical neighbor buildings during construction. Rules related to FISP include: qualification of inspector and regulation for inspection agency (1 RCNY 101-07, 1 RCNY 101-06), guide for inspecting exterior walls and filing a report to the government (1 RCNY 103-04, 1 RCNY 103-09), and actions to protect the neighbor properties by monitoring the cracks during soil works and excavations ("2014 NYC Building Code" 2014). The visual façade inspection focuses on the surface condition such as erosion, missing components, and cracks. Based on the width, cracks are divided into three groups: hairline cracks (opening < 0.04"), slight/small cracks (0.04" < opening < 3/16"), and large cracks (opening > 3/16") (Eschenasy 2016). An ideal scanning process should capture the cracks in different groups, and the cracks in point cloud should be measurable with good accuracy. The threshold offered by Eschenasy is set as the benchmark in this case study. Cracks widths are simulated in the provided values, captured by different scanning settings, and the performance of different settings is evaluated by measurement error percentage (MEP).

Previous Efforts on Crack Detection & Measurement

Mainly two 3D techniques have been evaluated in previous research efforts for crack detection and measurement in both exterior building walls and the structure elements. These include a) point cloud and mesh generated from images by 3D reconstruction technology, and b) point cloud data obtained with 3D laser scanning. 3D reconstruction technology generates 3D models (i.e., point cloud, mesh) from images. Studies have proved the feasibility of this technology in crack detection (Zhang 2014, Rabah et al. 2013, Torok et al. 2014). However, the process of generating a point cloud from images can be time-consuming (Zhang 2014) and the detailed inspection of the detected cracks is still missing (Rabah et al. 2013).

Therefore, in this study, the authors conducted experiments using laser scanner and evaluated cracks captured in the point cloud. Point cloud data and stereo images were studied on crack detection and measurement during the past decade and proved to be able to detect cracks that are larger than 2mm (Tsai and Li 2012, Sarker et al. 2017, Laefer et al. 2010, Laefer et al. 2014, Anil 2015). The influence of individual scanning parameters (i.e., scanning range, sample interval, and the angle of incidence) for crack detection was studied by simulating the cracks on hydrostone (Anil 2015). Researchers also simulated cracks to validate a developed equation for calculating the minimum detectable crack width regarding the laser scanner settings and the depth of the target (Laefer et al. 2014). However, numerous assumptions were needed to utilize the equation such as known crack depth; vertical cracks with a rectangular cross-action, and the same elevation with the scanner, which can hardly be met in real-life cases.

To better leverage the 3D scanning technology into building inspection, a recommendation on scanner settings that work well on capturing cracks with different width, length, and orientations should be provided. In this study, experiments were conducted to test the ability to capture cracks in different width, length, and orientation with different combinations of scanning distance and resolution and further elaborated in the following sections.

Case Study

Previous studies examined the reliability of capturing cracks with laser scanners by comparing the number of cracks captured with 2D images and manual inspection (Laefer et al. 2010) without investigating the measurement accuracy based on established thresholds. An experiment conducted with simulated cracks was focusing on the building wall damaged from earthquakes based on the Federal Emergency Management Agency guidelines (Anil 2015). However, Anil’s experiment only tested the effect of the individual parameter on the measurement result without providing a recommendation scanning setting.

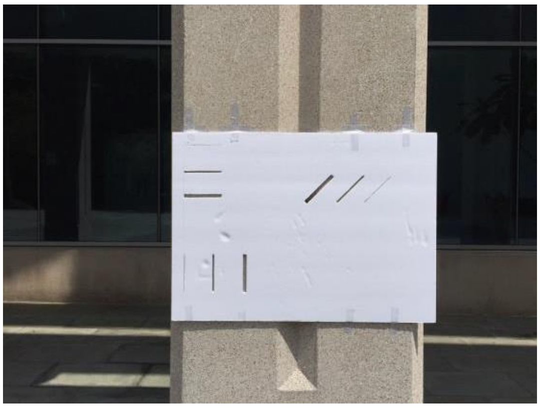
In this study, experiments were conducted to evaluate the influence of different combinations of scanning settings (i.e., scanning distance and resolution) on the obtained point clouds based on the crack detection feasibility and measurement accuracy. The experiments were designed based on the FISP guidelines issued by the NYC DOB and the testing thresholds for crack widths are set by Eschenasy (2016). The authors simulated cracks with different width, length, and orientation. Furthermore, the testing parameters for laser scanners are scanning distance and the resolution.

The quality† is set constant as 4X (which means the observation time for each scan point is 8μs comparing to the 1μs at quality 1X. With the increased observation time, the signals are stronger, leading to a smaller ranging noise in the distance measurement) and the values of the testing parameters for both cracks and laser scanner are listed in Table 1.

Table 1. Parameters designed for the experiment

Crack width (mm)	1, 5, 7
Crack length (cm)	10, 15
Orientation	0, 90, 45
Scanning Resolution*	1/1, 1/2, 1/4
Scanning distance (m)	3, 5, 7

*: With the 4X quality, point distance‡ for the selected resolutions are: 1.5mm/10m (resolution = 1/1), 3.1mm/10m (resolution = 1/2), and 6.1mm/10m (resolution = 1/4).



(a). Foam board for cracks simulation.

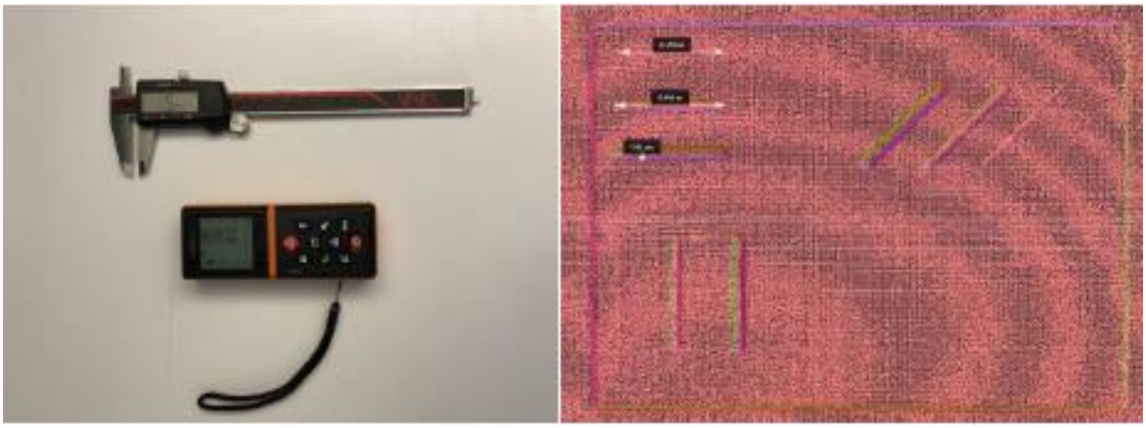
(b). Scanning set-up.

Figure 1: The experiment set-up.

Cracks were simulated by cutting openings on a foam board. The FARO Focus S 150 terrestrial laser scanner was used for point cloud data collection. The experiment set-up is demonstrated in Figure 1 (a) and (b). A digital laser distance meter (Figure 2 (a)) was used to control the range from the laser scanner to the target plane. Since the simulated cracks are manually cut, the value of crack width and length might not be the same as designed. Crack width and length measured by a digital caliper (Figure 2 (a)) with accuracy up to 0.01mm are set as the ground truth, and the actual values are shown in Table 2.

† This parameter determines the level of noise in the resulting point cloud. The available options are: 2X, 3X, 4X, 6X, 8X. For resolution 1/1, only 2X, 3X, and 4X are available. To reduce the noise level, the best available option, 4X, is selected as constant Quality through this experiment.

‡ The distance between two points captured with point cloud in mm with scanning distance of 10m.



(a). Digital caliper and laser distance meter. (b). Measurement in the point cloud processing tool.

Figure 2: The measurement process

For each crack in the point cloud data, the measurement is obtained in a point cloud processing tool. By changing the color setting to “Normal”, which displays the points with different colors according to the direction of normal for that point, the edge of cracks can be observed better in the point cloud data. To reach a better measurement result, the coordinate is updated so that the x-axis is perpendicular to the target plane. Distances measured along the y-axis and z-axis between two points selected on edge with accuracy at 0.1mm are the widths and lengths of the cracks. Figure 2 (b) shows an example of the measurement in a point cloud obtained with resolution 1/1 at a distance of 3m from the target plane.

Table 2. Ground truth value for the experiment

Crack Length (cm)	Crack Width(mm)	Crack Orientation	Width (mm)	Length (cm)
10	1	0	1.27	10.06
		45	1.14	10.07
		90	1.27	10.06
	5	0	5.22	10.31
		45	4.86	10.23
		90	4.79	10.11
	10	0	9.75	10.31
		45	9.67	10.27
		90	9.92	10.34
15	1	0	1.52	15.11
		45	1.18	14.86
		90	1.25	14.89
	5	0	4.77	15.06
		45	5.08	14.91
		90	5.17	14.97
	10	0	9.89	15.08
		45	10.11	14.92
		90	9.00	14.84

To evaluate the measurement result from the point cloud, the error percentage (EP) is calculated with the Equation 1. For each crack, the measured values of the widths and lengths are the averages from five consecutive measurements.

For each scanning setting, the EP is the average of three EP: horizontal, vertical, and inclined 45 degrees. The average error percentage for different scanning settings with cracks of different width and length are shown in Table 3.

$$error\ percentage = \frac{|Measured\ Value - Ground\ Truth|}{Ground\ Truth} \quad (1)$$

Table 3. Average error percentage

AEP Designed Scanning		**1mm**		**5mm**		**10mm**	
		10cm	15cm	10cm	15cm	10cm	15cm
3m, 1/4	Width	70.95%	**100.00%**	9.25%	16.81%	8.98%	7.04%
	Length	8.07%	39.62%	1.92%	1.76%	1.13%	3.92%
3m, 1/2	Width	**100.00%**	35.88%	5.16%	10.53%	5.91%	5.41%
	Length	34.68%	5.04%	2.96%	0.91%	1.68%	0.88%
3m, 1/1	Width	21.14%	43.78%	4.07%	7.20%	3.21%	7.30%
	Length	3.93%	35.03%	2.73%	2.15%	2.01%	0.45%
5m, 1/4	Width	**139.15%**	68.91%	7.36%	8.02%	3.59%	3.67%
	Length	3.73%	5.44%	2.38%	1.74%	1.15%	2.37%
5m, 1/2	Width	66.75%	39.63%	4.34%	10.95%	7.39%	6.93%
	Length	7.21%	0.24%	3.82%	0.88%	2.79%	0.59%
5m, 1/1	Width	64.01%	**100.00%**	8.14%	20.33%	2.60%	6.15%
	Length	33.00%	67.44%	1.93%	0.95%	0.90%	0.72%
7m, 1/4	Width	**100.00%**	**100.00%**	**100.00%**	16.14%	**100.00%**	11.55%
	Length	**100.00%**	**100.00%**	1.04%	0.38%	3.86%	2.36%
7m, 1/2	Width	85.83%	91.68%	7.76%	15.45%	6.03%	12.81%
	Length	67.76%	67.33%	3.03%	1.47%	36.95%	2.84%
7m, 1/1	Width	**109.45%**	**100.00%**	21.26%	23.65%	8.00%	4.55%
	Length	7.12%	66.99%	5.20%	1.21%	3.93%	0.70%

Bold: undetectable with the settings.

However, for some scanning settings, the edge of cracks in the obtained point cloud was hard to detect. In these situations, the measured result is set as 0, leading to the error percentages end up being 100%. An example of this situation is demonstrated in Figure 3. The area marked by red rectangular are the cracks in 1mm, which were not possible to be measured in this point cloud dataset. Cracks in 1mm are only detectable with the best settings: resolution 1/1 at the distance of 3m, while the average error percentage for hairline cracks is still above 30%. Since cracks below 1mm are mostly not perceivable during a visual inspection (Eschenasy 2016), this result is unsurprising.

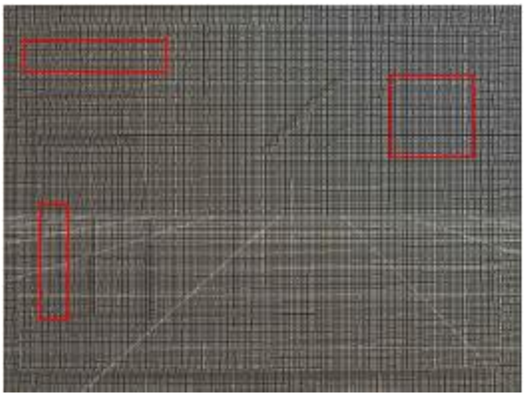


Figure 3: The cracks captured with resolution 1/4, scanning distance 7m

From the average error percentage (AEP) shown in table 3, it is obvious that the error percentage, with both width and length measurement, is negatively correlative with the crack width. The minimum width measurement AEP with cracks in 5mm is reached in point cloud obtained by the best scanning setting (resolution 1/1, at 3m), which is 5.63%. The minimum width measurement AEP with cracks in 10mm is achieved with resolution 1/4 at 5m from the target plane, which is 3.63%. For the measurement of crack length, the minimum AEP appears at resolution 1/4 at 7m for cracks in 5mm (0.71%), and resolution 1/1 at 5m for cracks in 10mm (0.81%).

To find a setting works well for cracks in different width and length, both the AEP for length and width measurement should be taken into account. From the line chart shown in Figure 3, for cracks in 5mm width, the best result appears with the resolution 1/1 at 3m (8.08%), and the second good result appears at the resolution 1/4 with a scanning distance as 5m (9.75%). For cracks in 10mm width, the best result appears with the resolution 1/1 at 5m (5.19%), and the second good result appears at the resolution 1/4 with a scanning distance as 5m (5.39%). However, the time consumption for the former one (resolution = 1/1) is 2h and 10mins for the latter one (resolution = 1/4). Taking both time-efficiency and measurement accuracy into account, the recommended scanning setting for conducting facade inspection would be resolution 1/4, and the scanning distance is 5m from any target building.

Conclusion and Future work

The objective of this study is to test how different parameters with the 3D laser scanners influence the ability to detect cracks with different length, width, and orientations. The result shows that even with the highest resolution, the scanner cannot obtain a point cloud for accurate measurement if the distance from the scanner and the target plane is large. The recommended scanning setting from this experiment would be resolution 1/4 at the scanning distance of 5m for target cracks with a width in 5mm and 10mm. Cracks with a width equal to or smaller than 1mm are not able to be measured accurately in the point cloud dataset. This study is conducted with manually select the edge of cracks, which is time-consuming and error-prone. Future work will focus on the implementation of algorithms that can automatically detect and classify cracks based on the width in the point cloud data.

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