Project 1873 | October 2019

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Bridge Monitoring Using a Digital Camera: Photogrammetry-based Bridge Dynamics Monitoring

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California State University Transportation Consortium

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REPORT 19-29

BRIDGE MONITORING USING A DIGITAL CAMERA: PHOTOGRAMMETRY-BASED BRIDGE DYNAMIC DEFORMATION MONITORING

Yushin Ahn, PhD
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October 2019

A publication of

Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 19-29	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Bridge Monitoring Using a Digital Camera: Photogrammetry-Based Bridge Dynamic Deformation Monitoring		**5. Report Date** October 2019 **6. Performing Organization Code**
7. Authors Yushin Ahn, PhD, https://orcid.org/0000-0002-5305-6396 Scott Peterson, PhD Maryam Nazari, PhD		**8. Performing Organization Report** CA-MTI-1873
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.** **11. Contract or Grant No.** ZSB12017-SJAUX
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplemental Notes		

16. Abstract

Monitoring the health of bridges uses various sensors and techniques and provides quantitative and reliable data on the condition of bridges. Among measurable quantities, vibration induced by traffic loads has been known as a good indicator of the condition of bridges, serviceability to pedestrians, fatigue analysis, etc. Here we use non-metric, off-the-shelf, Digital Single-Lens Reflex camera (DSLR) as a sensor and apply a photogrammetric approach to measure three bridges live load traffic vibration.

We first tested our approach with shake-table equipment and showed the reliability of the methodology we use through measuring magnitude and frequency of the shake-table, which was then applied to two highway and one local bridges. The results show that vibrational magnitudes are well within the design recommendations of the American Association of State highway Transportation (AASHTO) and that frequencies are in the range of similar bridges that previously published. Furthermore, by providing velocity and acceleration computed from camera derived displacement, we showed that the proposed method is cost-effective and feasible as well as having a good potential for bridge health monitoring.

17. Key Words Digital Camera, Bridge, Structure health monitoring, Inspection equipment, Image processing	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 25	**22. Price**

Form DOT F 1700.7 (8-72)

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ACKNOWLEDGMENTS

The authors thank Editing Press, for editorial services, as well as MTI staff, including Executive Director Karen Philbrick, PhD; Deputy Executive Director Hilary Nixon, PhD; Graphic Designer Alverina Eka Weinardy; and Executive Administrative Assistant Jill Carter.

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EXECUTIVE SUMMARY

Monitoring the health of bridges uses various sensors and techniques and provides quantitative and reliable data on the condition of bridges. Among measurable quantities, vibration induced by traffic loads has been known as a good indicator of the condition of bridges, serviceability to pedestrians, fatigue analysis, etc. Here we use non-metric, off-the-shelf, Digital Single-Lens Reflex camera (DSLR) as a sensor and apply a photogrammetric approach to measure three bridges live load traffic vibration.

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I. INTRODUCTION

Monitoring the health of bridges uses various sensors and techniques and provides quantitative and reliable data on the condition of bridges. Bridge monitoring was performed with exhaustive tests that involved hands-on/visual investigations to spot material straining, shifting or chipping. Structural evaluation of bridges is important because it prevents accidents from natural occurrences and unstable shifting, while, in many cases, visual inspection is carried out for routine checkup. The visual inspection tends to be labor intensive and subjective in nature, therefor, quantitative analysis from sensors are in need for objectivity.

When it comes to bridge behavior, there are three types of dynamics. 1) Dead load deflection - deflection from the weight of material itself, 2) Live load deflection - deflection caused by the combined bridge and vehicle weight and 3) Live load (traffic) derived vibration. Many bridge constructions use pre-stressed bridge girders which make deflection hard to evaluate the health of bridges unless this amount has been measured right after construction.

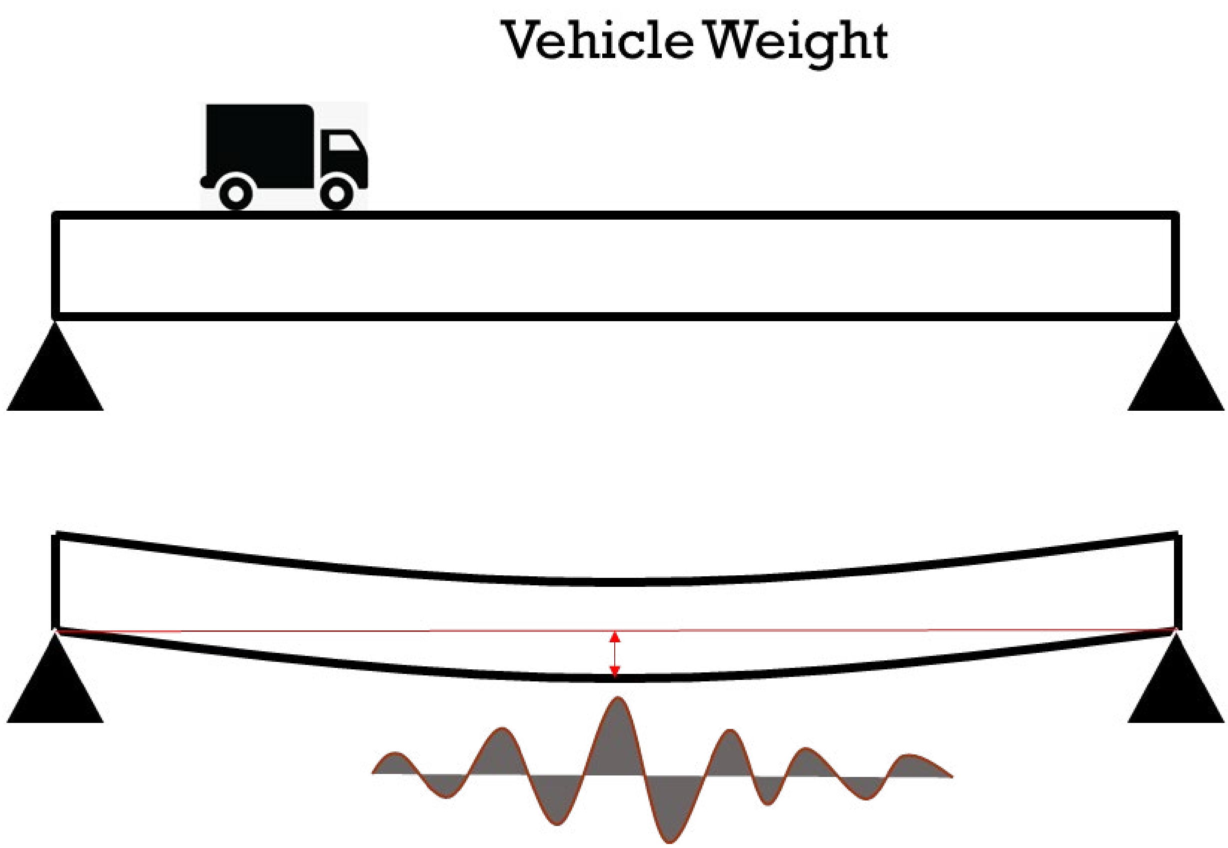


Figure 1. Illustration of Traffic Live Load from Vibration. The red arrow indicates deflection from weight of bridge and vehicle. The wave illustrates the traffic induced vibration.

Figure 1 illustrates the traffic derived vibration. The AASHTO recommends the maximum design deflection to be L/800 and L/1000 for non-pedestrian bridges and pedestrian bridge respectively, where L is the length of the bridge span.

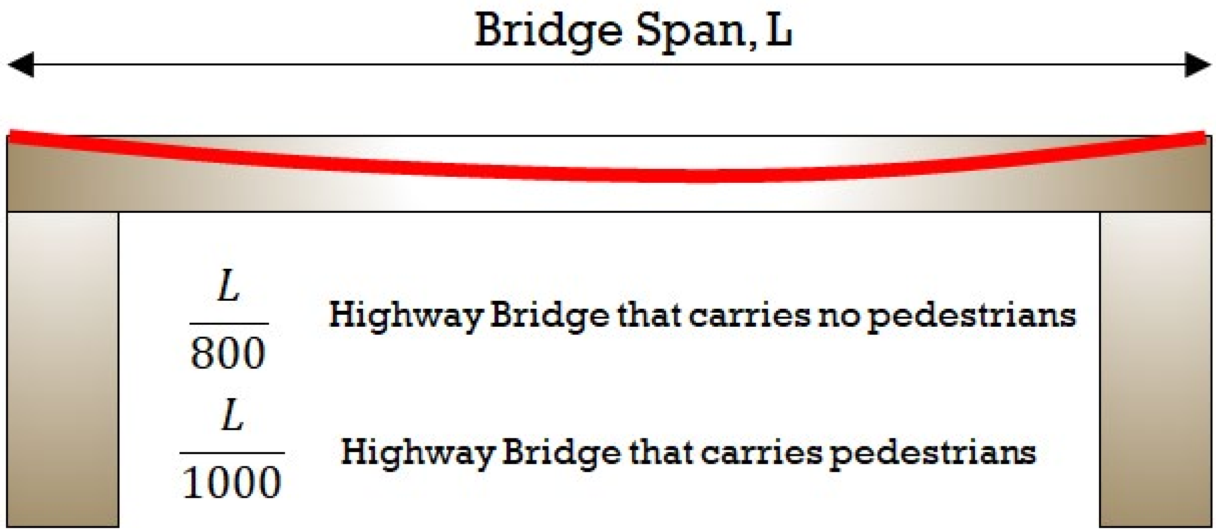


Figure 2. AASHTO Bridge Design Recommendation

For example, 20 meter long spans of bridge are allowed to have 20m/1000 = 20 mm maximum deflection. In this project the target bridges are 1) short span with a length of 6-30 meters and 2) medium span with a length of 30-100 meters. The maximum changes the bridge deflection vertical vibrations are 20 mm and 50 mm, respectively.

There have been various methods to measure these motions. Those methods include the use of stain gages, accelerometers, Global Navigation System[1] (GPS), Light Detection and Ranging, LiDAR scanner,[2] optical sensors and total station[3] (surveying equipment).

In this research we focus on the vertical vibrations induced by traffic using the photogrammetric approach. The magnitude and frequencies of a bridge will be our main objective. When compared to the other methods, camera system provides a cost-efficient procedure in remote sensing which is non-contact in data collection.

The use photogrammetric methods in bridge health monitoring is not new. A great number of studies have been applied in measuring dead load deflection.[4] Camera-based vibration studies have been limited by hardware, i.e. the recording more frames per second than normal videos. Recently the advancement of digital camera technology has made vibration analysis more approachable.[5]

Here, a simple method to measure bridge vibrations—magnitude and frequency is introduced.

II. PHOTOGRAMMETRY BASED MEASUREMENT

In this chapter the focus will be on 1) the specifications of the camera that was used in this research, 2) the geometry of the camera used to compute pixel size, distance to object and foal length, 3) verification of the reliability of the camera system using a series of shake-table tests.

CAMERA

The Camera that was used for this research study is a SONY Cyber-shot RX10 IV, DSLR camera as shown in Figure 3. It has 24-600mm zoom lens, 3” sensor size, and 20.1 Mega Pixels (5472x3648) still picture.

Figure 3. SONY Cyber-Shot RX10 IV, the Camera Used in This Study

The main camera feature that is required for this project is high video resolution and the slow-motion capability. This camera captures 1080x1920 dimension video up to 960 frame per second (fps). Table 1 summarizes for detailed specification of the camera.

Table 1. Camera Specifications

Specification	Content
Pixels	21.1 Megapixels (5472 X 3648)
Sensor	1” (13.2 X 8.8 mm) CMOS
Resolution	3840 x 2160p: 30fps, 25fps, 24fps 1920 x 1080p: 60 fps, 50 fps, 30 fps, 25 fps, 24 fps 1920 x 1080p: 240 fps, 480 fps, 960 fps 1920 x 1080p: 250 fps, 500 fps, 1000 fps
Zoom Lens	Effective focal length: 8.8 - 220 mm Equivalent focal length: 24 – 600 mm
Shutter speed	Mechanical: 4 – 1/2000 second Electronic: 4 – 1/32000 second

CAMERA GEOMETRY

Simulated pixel size with varying focal lengths ranging from 8.8 to 220 mm is applied in this research. The computation is based on a 30 meter distance to object and a varying focal length.

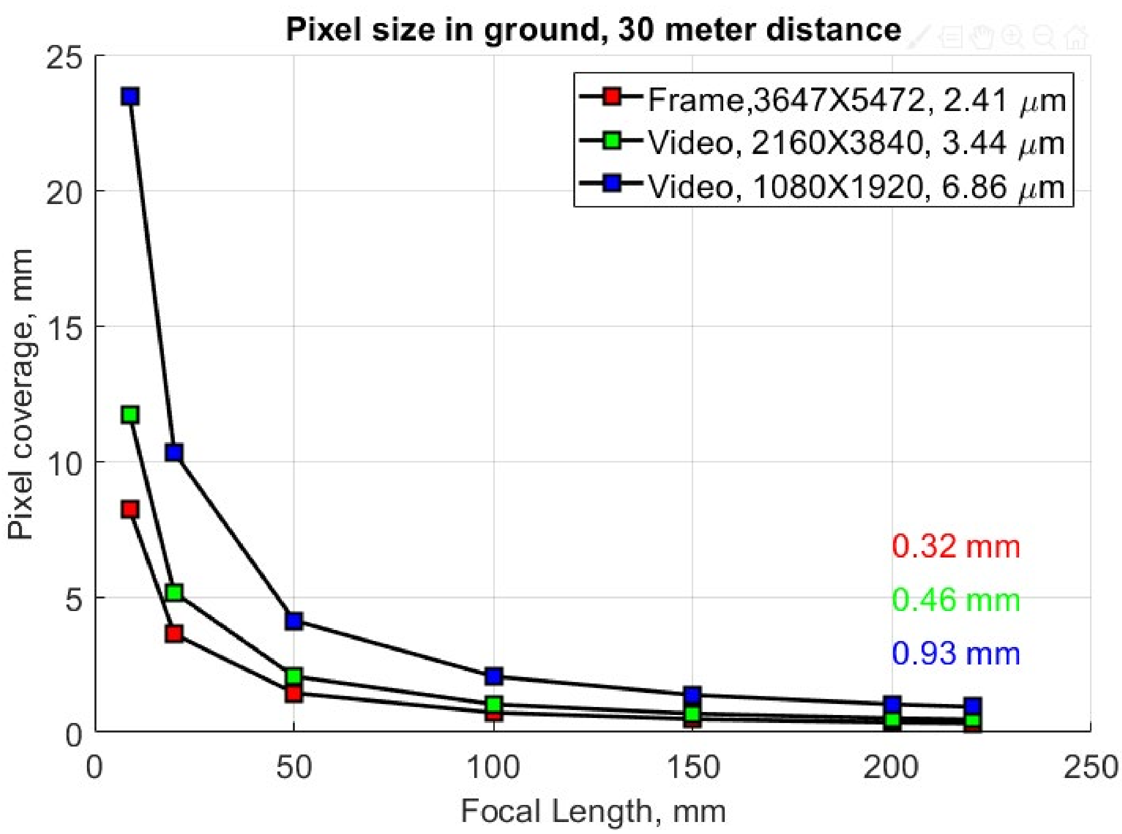


Figure 4. Camera Geometry. The ground coverages for a pixel of image are displayed.

Figure 4 shows that pixel sizes of frame picture 3647x5472, video 2016x3840 and video 1080x1920 are 2.41 μm, 3.44 μm and 6.86 μm respectively. Then the coverages in object space that represents actual coverage of a pixel is 0.32 mm, 0.46 mm and 0.93 mm. Considering the bridge span length of 20 meters, the AASHTO design manual recommends a maximum deflection of 20 mm. If half of this deflection should be measured, 8-9 pixel displacement is of interest, which can be resolved by using the normalized cross correlation algorithm.

SHAKE TABLE

A shake-table is an experimental platform that mimics the ground motion excitation. This table is commonly used to evaluate the seismic performance of civil engineering structures such as building, railroad, bridges etc. An example of a shake-table is shown in figure 5.

Figure 5. A Photograph of a Shake-Table at the Civil and Geomatics Engineering, California State University at Fresno.

This custom-made shake-table at Fresno State has the following specifications, shown in table 2.

Table 2. Shake-Table Specification at Civil and Geomatics Engineering, California State University at Fresno

Specification	Content
Maximum Payload	20 KIP
Dimensions	7 ft X 8 ft
Frequency	20-50 Hz
Maximum horizontal displacement	5 inches on each side

For digital cameras as bridge monitoring equipment, a Sony RX10 DSLR camera was tested to ensure it detects motion and retrieves the shake-tables original feedback. That is magnitude and frequency of shake table test.

SHAKE TABLE TEST RESULTS

Shake-table often has been used for feasibility test.[6] Two sets of harmonic motions were applied using the shake-table. The magnitude and frequency of these two sets were 0.25 and 1 inch and 0.78 and 1.17 Hz respectively.

Normal video was recorded with 59.9401 frames per second, since the frequency can be well retrieved by 60 frames per second resolution.

Initially the focal length of 10.0925 mm was calculated using the ratio between the focal length, the object width, the object distance and the sensor size.

Focal length = Distance (2330.45 mm)*object size in image (8.2367mm)/object size (1908.18 mm) = 10.0925 mm. Then the coverage of a pixel in ground space of 1.5875 mm/pixel was calculated.

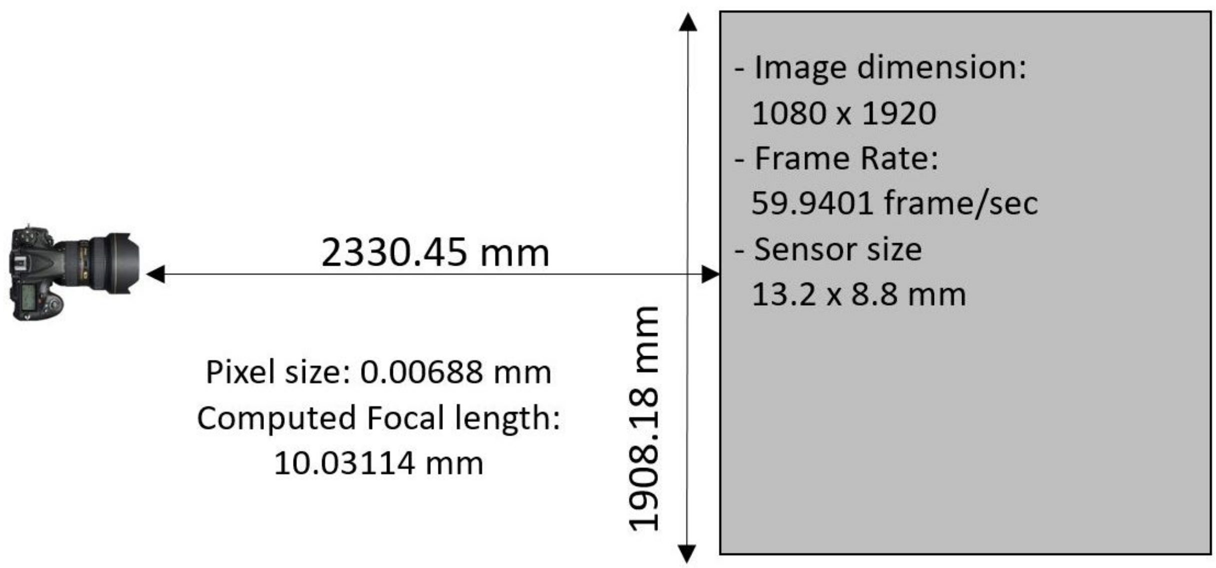


Figure 6. Shake Table Camera Setting. Distance from Camera to shake table and shake table width are measured.

FEATURE TRACKING USING 2D NORMALIZED CROSS CORRELATION

2D normalized cross correlation is one of the most commonly used method in photogrammetry to find conjugate points in two images (Figure 7).

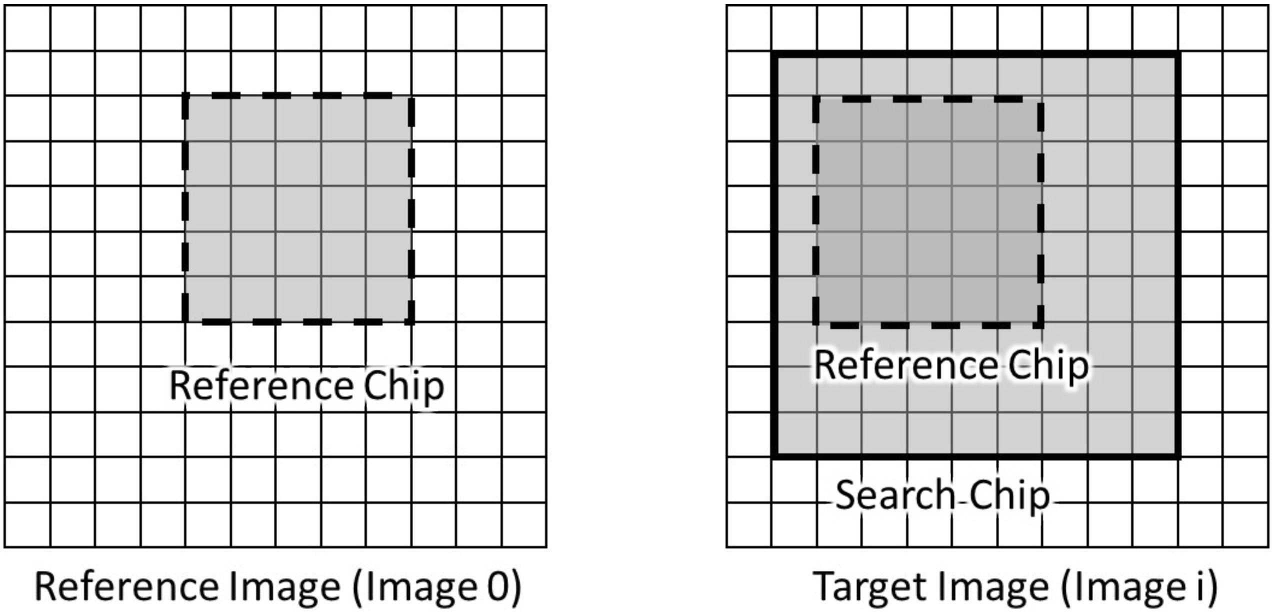


Figure 7. Illustration of 2D Normalized Cross Correlation. Image 0 indicates base image or the first image and Image i indicates the rest of images.

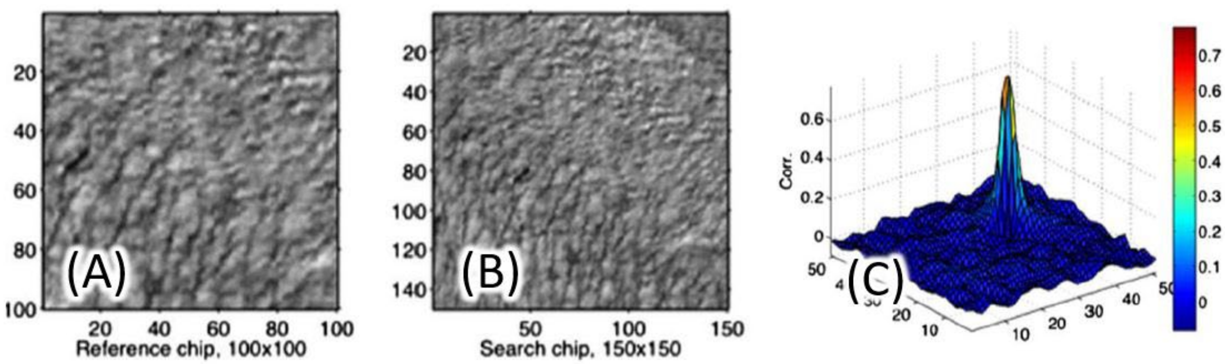


Figure 8. The algorithm produces the pixel displacement (c) with reference (a) to the base image (b). I.e the motion occurred through frames. The result is 2D correlation map and the peak position indicates pixel displacement happens between two image spanned. The displacement is computed from its center location to the peak position.

Here, the reference chip is extracted from the base image (Figure 8b), then the reference chip moves within the search chip (Figure 8a). In each time, 2D cross correlation was computed and finally the correlation map is generated. From the peak which indicates the maximum correlation value (Figure 8c), interchangeable maximum similarity is found. The correlation coefficient is calculated using the below equation.

$$\rho = \frac{\sigma_{R,S}}{\sigma_R \cdot \sigma_S}$$

$$\sigma_R = \sqrt{\frac{\sum\sum(g_R(i,j) - \bar{g}_R)}{nm-1}}, \quad \sigma_S = \sqrt{\frac{\sum\sum(g_S(i,j) - \bar{g}_S)}{nm-1}}$$

$$\sigma_{R,S} = \frac{\sum\sum(g_R(i,j) - \bar{g}_R) \cdot (g_S(i,j) - \bar{g}_S)}{nm-1}$$

Equation 1. Where, subscripts R and S indicate reference and search chip respectively and g(i,j) is the pixel value of position I,j in the image. Once the peak is found, a quadratic surface was fitted using a 3x3 peak around pixels and finding the maximum peak position, yielding sub-pixel accuracy. The quadratic surface is as follow.

$$r = a \cdot i^2 + b \cdot j^2 + c \cdot i \cdot j + d \cdot i + e \cdot j + f - \rho$$

Equation 2. Where, a to f are coefficients of quadratic surface and i,j are pixel location for 3x3 correlation value around the peak.

SHAKE TABLE RESULTS

Two sets of shake table were processed using 2D normalized cross correlation and compared with the original shake-table feedback.

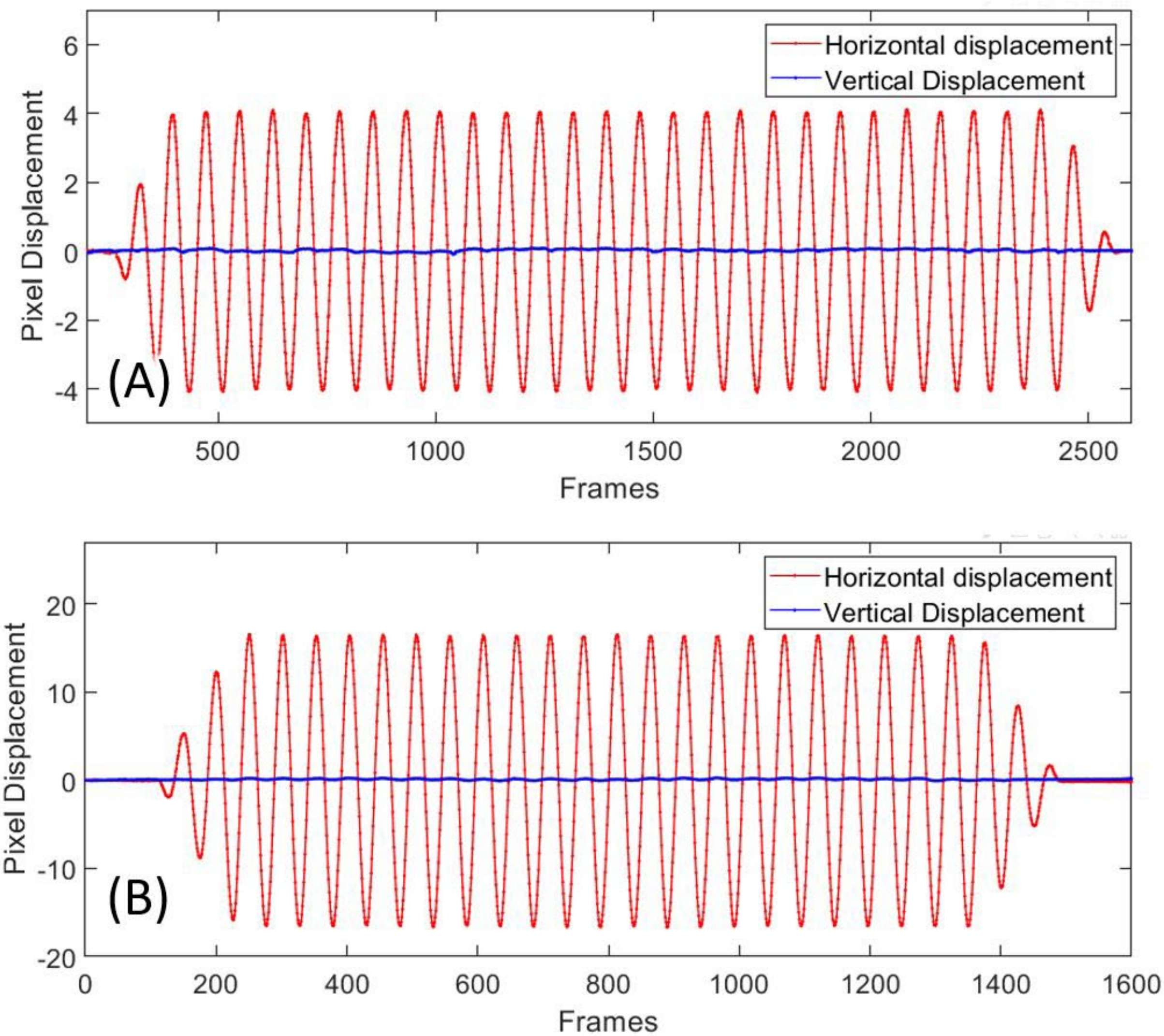


Figure 9. Shake Table Results for Set 1 and 2. Red lines show horizontal displacement and blue lines show vertical displacement. We convert these pixel displacement to mm and inch, metric unit and also count the number of peaks and elapsed time for frequency computation.

Table 3. Shake Table Feed Data and Camera Derived Results

	Shake Table Feeds		**Camera Derived**	
	Amplitude	**Frequency**	**Amplitude**	**Frequency**
Set 1	0.25 inch	0.78 Hz	0.25 inch	0.782 Hz
Set 2	1.00 inch	1.17 Hz	1.0216 inch	1.172 Hz

The amplitude and frequency results derived from the camera indicate that the camera can reliably be used for extracting the shake-table motions. When compared with the original table feedback data, the results showed less than 0.3 % errors for amplitude and frequency. Note that a pixel covers 1.5875 mm and conservative error for subpixel accuracy is 0.1-0.3 pixels. The difference of 0.55 mm is well acceptable within the 2D correlation error budget.

III. TEST WITH BRIDGES

TEST SITE: THREE BRIDGES

Two highway bridges and one local bridge were chosen, with the distances from camera to each bridge of 45.74, 26.75 and 37.05 meters, respectively.

Figure 10. (A) Site Overview, (B) Bridge 1, Short Spanned Highway Bridge, (C) Bridge 2, Medium Spanned Highway Bridge, and (D) Bridge 3, Medium Spanned Local Bridge

Bridge 1: Undercrossing Bridge on Route 41. Each are two-span 4'-0" deep, cast-in-place/ post tensioned box girder structures with multi-column bends within the median of Friant Ave. The span lengths of each vary, but they are roughly 90'-11" (span 1) and 90'-4" (span 2) for the left structure (front structure in Figure 10B) and 89'-3" (span 1) and 81'-5" (span 2) for the right structure. The width of these structures vary due to the existing on-ramps on the outside of each. These bridges were originally constructed in 1989. The right structure was widened to the inside in 2008.

Bridge 2: Overcrossing Bridge on Route 180. This is a 4-span (135', 134', 143'-9", 113'), 146' wide, 5'-9" deep, cast-in-place/post-tensioned box girder structure with a multi-column bent within the median of Route 180. This bridge was constructed in 1999.

Camera frame was set at 480 fps and recorded when vehicles were passing by. Leica GNSS and Total station were used to estimate the dimension and ground control data (See appendix for Field work).

The span lengths of 30.06 meters, 44.23 meters and 34.64 meters were measured. AASHTO deflection criterion for those bridges are 30.06 mm, 44.23 mm and 34.64 mm.

IV. RESULT AND DISCUSSION

First, horizontal and vertical pixel displacement were computed using the 2D cross correlation. Horizontal pixel displacement of ±0.27, ±0.58 and ±0.27 pixels were observed due to off-level of camera and non-perpendicularity to bridge façade. Also, vertical pixel displacement and its vibration patterns were observed, as shown in the following figure 10-12.

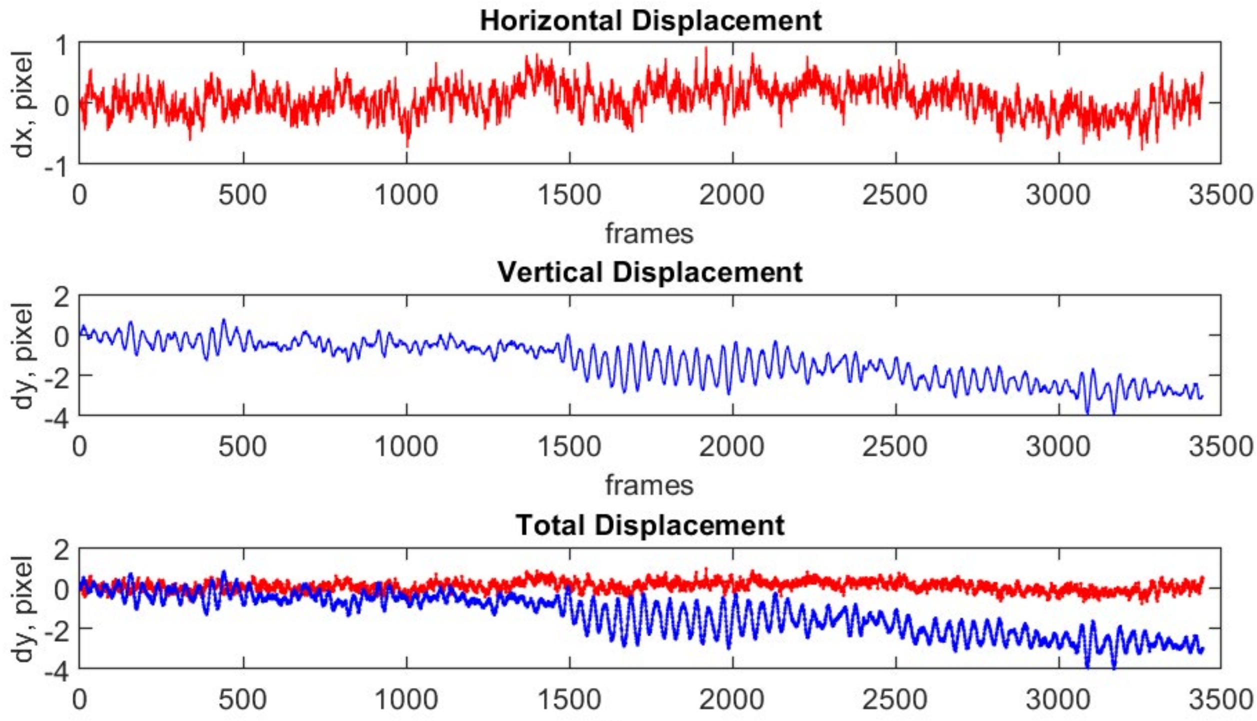


Figure 11. Horizontal and Vertical Pixel Displacement for Bridge 1

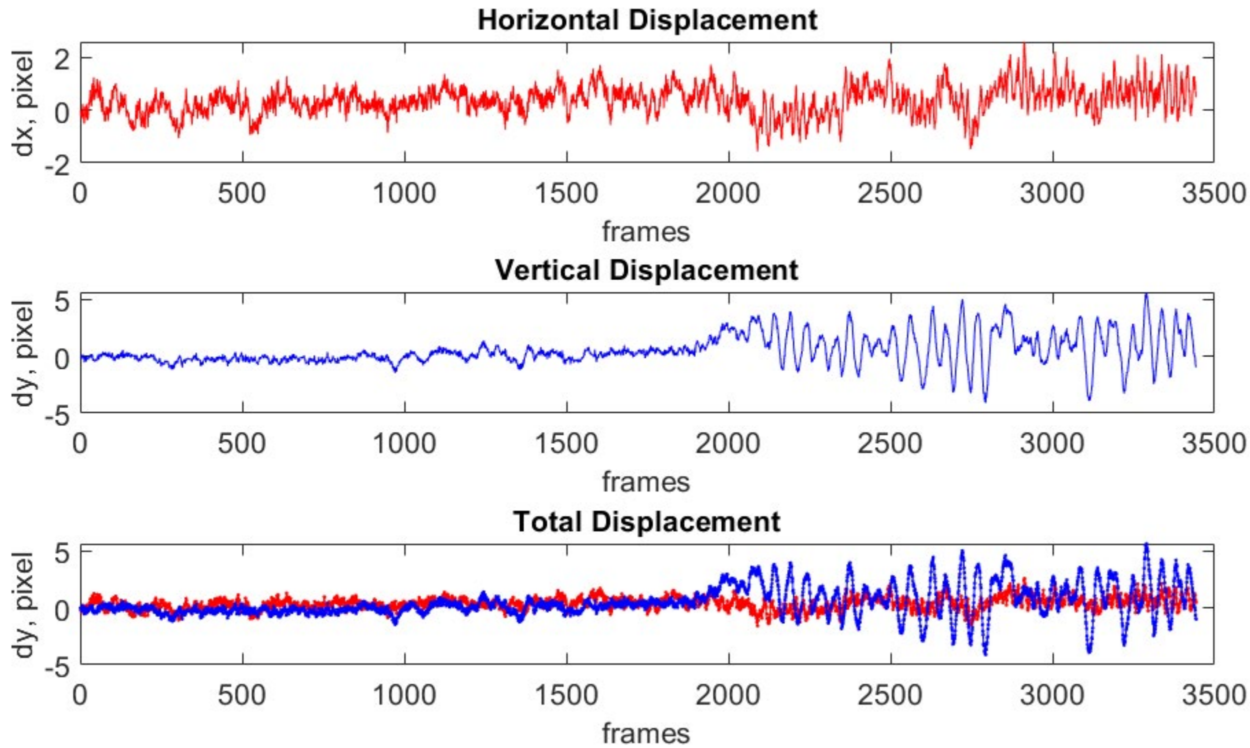


Figure 12. Horizontal and Vertical Pixel Displacement for Bridge 2

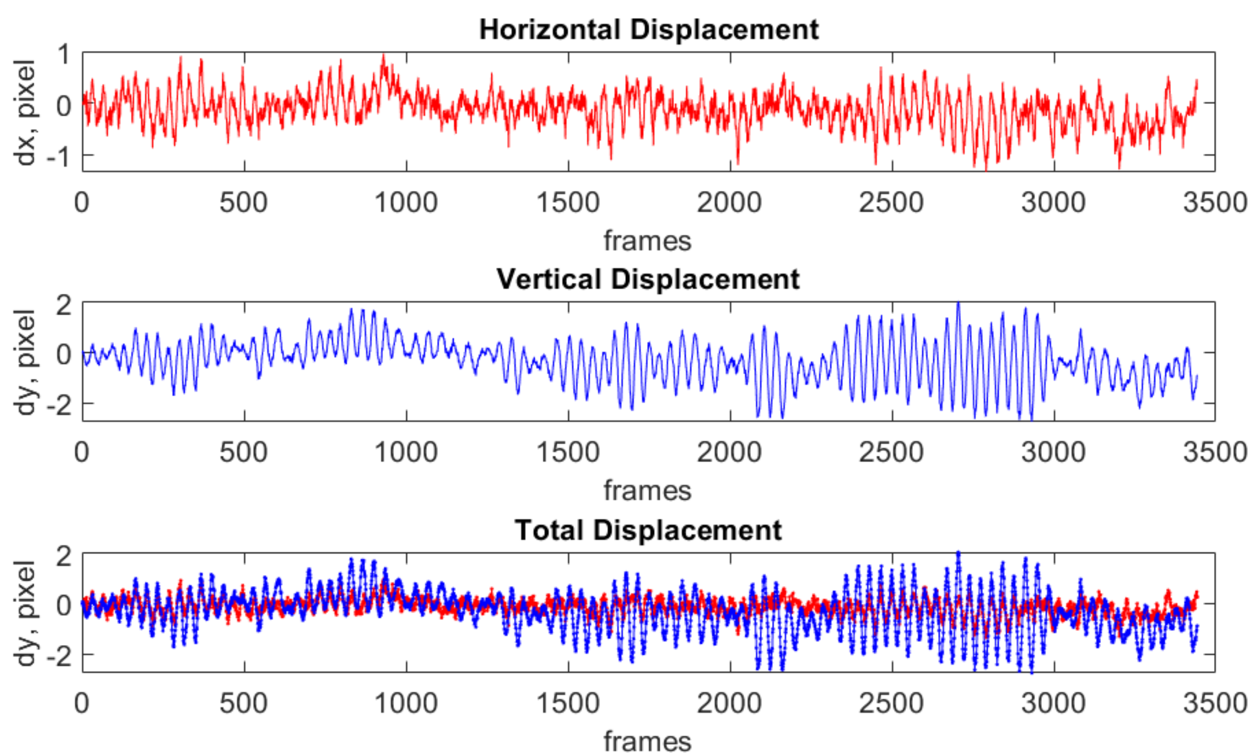


Figure 13. Horizontal and Vertical pixel displacement for Bridge 3

Table 4. Camera Derived Vibration Magnitudes and Frequencies for Testing Bridges

	Bridge 1	Bridge 2	Bridge 3
Object distance, meter	45.74	26.75	37.05
Span length, meter	30.06	44.23	34.64
Pixel size (mm)	1.42	0.84	1.16
Pixel magnitude (pixel)	3.64	9.43	4.78
Displacement magnitude (mm)	5.20	7.87	5.53
Frequency	12	9.6	13.82

Figure 10, 11, 12 and Table 3 summarize the camera derived vibration results. For each bridge, magnitudes and frequencies are (5.2 mm, 12 Hz), (7.87 mm, 9.6 Hz) and (5.53 mm, 13.82 Hz) respectively. Note that the spans for the bridges are 30.06 m, 44.23 m and 34.64 m. AASHTO design vibration when L/1000 are applied, are 30.06 mm, 44.23 mm and 34.64 mm.

Bridge vibrations reached 17%, 18% and 16% of recommending magnitudes following the AASHTO criterion.

For frequency component, the existing results from a previous study conducted by Williams et al. were used and compared with the camera-derived frequency range.[7]

Table 5. Existing Frequency Result[8] Typical Power Output for Heavy and Light Vehicle on Bridges, Averaged Over 2.5 Second

	Vehicle	Resonant Frequency of Generator
Bridge A (New)	Double decker bus	6 Hz
	Car	12 Hz
Bridge B (Old)	Articulated heavy goods vehicle	4.5 Hz
	Car	14.5 Hz

C.B. Williams of the University of Sheffield in the United Kingdom did a bridge feasibility and vibration sensor study. This project focuses on an electric generator that moves the bridge to signal the wireless, cheap, and disposable sensors. They concluded with some data as shown in the table below, and that the output power can be used to power an acceleration sensor.

Compared to Table 4, the camera derived frequencies seem to be within similar ranges (i.e. 6 - 14.5 Hz.)

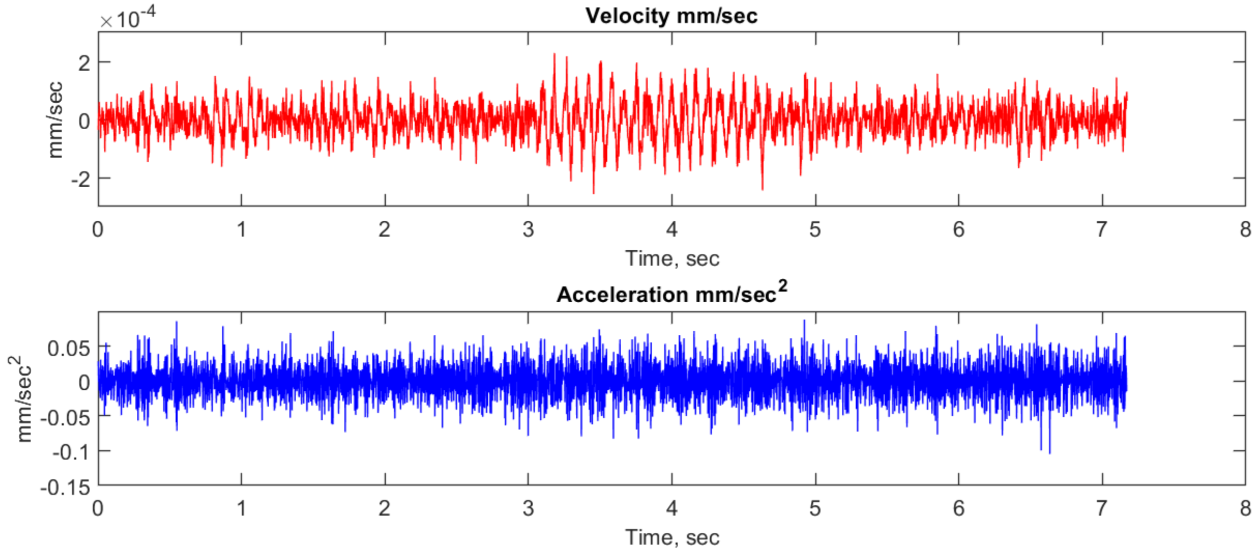


Figure 14. Camera Derived Velocity and Acceleration of Bridge 1

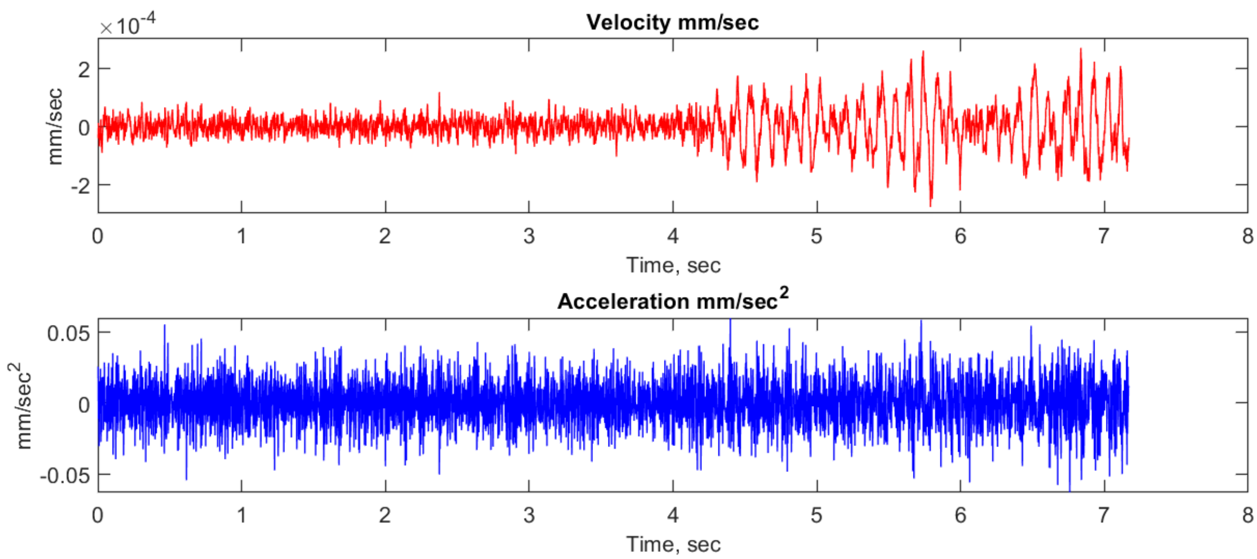


Figure 15. Camera Derived Velocity and Acceleration of Bridge 1

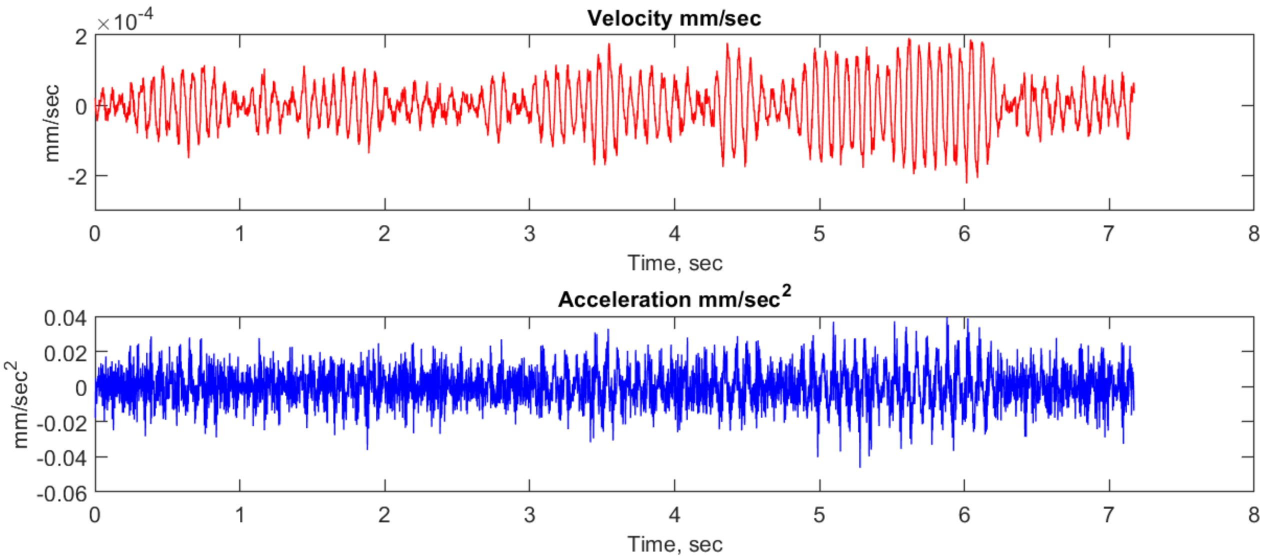


Figure 16. Camera Derived Velocity and Acceleration of Bridge 1

Once vertical displacements are computed, velocity can be computed by differencing displacement and dividing it by the time interval. Further, acceleration can be computed from the velocity. Figure 13, 14 and 15 show camera derived acceleration for the bridges and they, ±0.02 mm/sec^2, are within the range shown by Williams.[9]

V. CONCLUSION

This study presented photogrammetric technique for bridge dynamic monitoring study. First a shake table study was conducted to indicate the applicability of using digital camera for measuring the shake table's magnitude and frequency. Then, a field study was campaigned for two highway bridges and one local bridge. Using the fullest use of current DSLR camera—zoom lens and slow motion, bridge vibrations from traffics (i.e. vertical vibration in terms of magnitude and frequency) were measured. Further, the camera derived velocity and acceleration from displacements were presented.

This research was aimed to verify the feasibility of camera to monitor vibration/estimate bridge vibrations by presenting general indicators such as magnitudes (following AASHTO recommendations), frequency, velocity and acceleration. However, for a complete vibration study, 1) type and speed of vehicles, 2) vehicle weight and 3) multiple vehicles induced vibration patterns should be followed.

APPENDIX A

FIELD CAMPAIGN

In bridge field campaign, we not only take pictures (record video) but also brought surveying equipment for checking layout and getting ground control points (GCP). The field work provides span length, distance from camera to bridge.

Field equipment: Leica GS15 GPS receiver (Battery), GPS Pole, Data Collector, Leica Robotic Total station TS15 R1000 (Battery), Prism, measuring tape, Tripod, prism, Bipod, prism pole, two Nails (Stakes), hammer, Cameras, camera tripod, metal foldable tripod stabilizer.

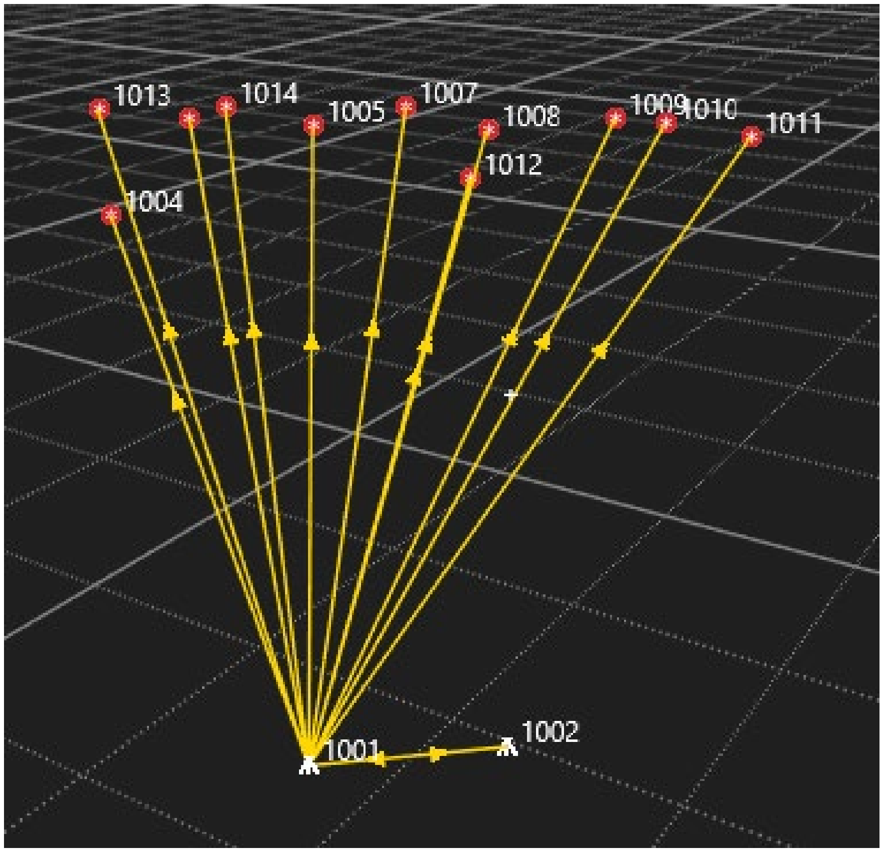
GPS and Robotic Total Station

We start by creating a new job using the static GPS, create a coordinate system in UTM zone 4. Use the static GPS to save coordinates over the nails marking Station 1, then over Station 2. This process provides precise ground control points, and later these stations will be occupied by robotic total station.

Level total station over Station 1, set the total station to lock to prism, back-sight to the prism (set on Station 2). Total station height and prism pole height are measured. Next, take a panoramic pictures of the bridge. We measured between 6 to 10 distinct points which can be easily identified in the camera on the bridge, the rails, under the bridge, on the pillars, etc.

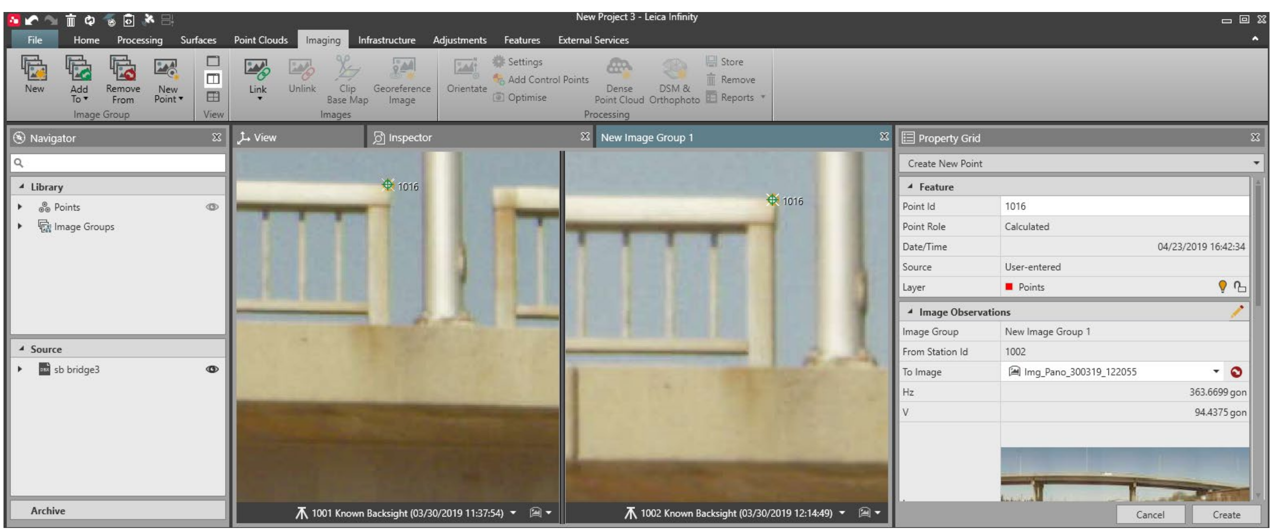
Level the total station over Station 2, set the total station to lock to prism, Backsight to the prism (set on control point one). Next, take another panoramic picture of the bridge.

We set apart two station approximately 1/10th of the distance being measured between total station and the bridge so that Leica panorama photogrammetry can retrieve any missing points accurately.



Digital Data Collector and Leica Infinity

We use a digital data collector for all field work. GPS points, Total station points and panorama images are stored and later imported Leica infinity program. Since, we use UTM zone 4 coordinate system for GPS, all total station measurements are in the same coordinate system.



Point measured by total station are used to compute camera position later using single photoresection. When missed points in the field, we use panarama images to retrive some points.

ENDNOTES

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PEER REVIEW

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