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# Development of a digital close-range photogrammetric bridge deflection measurement system

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ABSTRACT

This paper introduces a new close-range photogrammetric bridge deflection measurement system that has high accuracy and efficiency, and can be conveniently used by engineers without help from professional surveyors. After a general description of a photogrammetric bridge deflection measurement system, four critical components of the system are addressed in detail: camera selection and settings; camera calibration; network control (reference system and scale); and camera placement. The system configuration is introduced and the system is verified through the laboratory and field tests.

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## 1. Introduction

Close-range photogrammetry has been used for determining the three-dimensional geometry and deformation of bridges since the 1970s. Unfortunately, this technique has not been feasible for wide engineering applications until the 1990s when digital image acquisition and computer processing systems became commercially available. There are many unique advantages of close-range photogrammetry for bridge deformation measurement; for example, it can measure difficult-to-access bridges by taking pictures away from the bridge and record a large amount of 3-D information in a short time [1]. A basic bridge photogrammetric measurement system consists of a camera and accessories, targets, scale bars, and software for photogrammetric processing. Other supplemental instruments, such as a total station or level, may also be used for setting up a coordinate system and checking measurement accuracy.

Over the last several decades, great efforts have been made on making the measurement system more accurate, reliable, convenient, and cost-effective. A thorough literature review on the application of close-range photogrammetry in bridge engineering was made by the authors and the results were published in a separate paper [2]. The development of photogrammetric bridge measurement systems over the last 20 years is summarized in the review [2]. It is apparent that the systems have changed from customized film to fully digitized commercial cameras; from non-retroreflective to retro-reflective targets; from control point surveying to flexible distance-constraint methods (e.g., scale bars); and from self-developed to commercial software packages. Improvements have been made in many areas including camera settings and calibration, target design, camera station placement and network control (establishing coordination system and scale), and software.

Although the systems have been improved steadily, there is still not a turn-key system available to bridge engineers, nor a clear technical guidance for engineers to use. In order to provide engineers with a feasible bridge photogrammetric measurement system, four critical components of the system are addressed in this paper: camera selection and settings; camera calibration; network control (reference system and scale); and camera placement. A system suitable for bridge deflection measurement is proposed on the basis of laboratory and field bridge tests,

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which provides high measurement quality at relative low cost and high user convenience. The system configuration is introduced through the laboratory and field test that is described in the following sections.

## 2. Test layout

### *2.1. Laboratory bridge test layout*

A model bridge in the Materials Laboratory at New Mexico State University (NMSU) was load tested as part of this study. The bridge consists of three W12 × 62 steel girders supporting a reinforced concrete deck, as shown in Fig. 1. Targets (25.4 mm or 1 in. in diameter) were placed on the bridge deck and on the east wall, used for deflection measurement and for system controlling, respectively. Three reference targets (O, A, and B in Fig. 1) with a diameter of 50.8 mm (2 in.) were placed on tripods and adjusted to the same elevation to define a horizontal reference plane. When the control targets on the east wall were not used in a distance-constraint method, these three reference targets were then used together with two scale bars on the east wall to define the coordinate system. Nine dial gages were placed under targets in the middle three rows to evaluate the accuracy of the photogrammetric measurement. Three load cases (designated west, middle, and east load cases) were applied. For each load case, a concentrated load of 49,000 N (11,000 lbs) was applied directly above one of the three girders, 4.8 m (16 ft) or 40% of the bridge length (0.4 L) from the north support. The reader is referred to Jiang [3] for details of the test layout.

### *2.2. Field bridge test layout*

The field test bridge is a steel girder bridge located close to Truth or Consequences (T or C), New Mexico. The bridge has seven simple-supported spans; one span was chosen for the load test (shown in Fig. 2). The test span was 14.9 m (49 ft) long and has six CB30 × 116 steel girders supporting a reinforced concrete deck. Targets were mounted on the six girders of the test span to measure the deflection, and placed on the north and south pier walls (control targets) to set up a coordinate system through a total station surveying. Similar to the lab study, three reference targets were placed on tripods to define a horizontal reference plane (labeled O, A, B in Fig. 2) in order to establish an alternative coordinate system to the control target system. In addition, several targets were placed on the ground to improve the target coverage in the images. Four scale bars were placed underneath the test span, two in a horizontal direction and the other two in a vertical direction. Two fully loaded trucks (each weighing 250 kN or 56 kips) were placed side by side on the bridge to load the bridge with the rear wheels approximately at the mid-span. Three load cases (designated as east, middle, and west) were applied by moving the trucks laterally on the bridge.

## 3. Camera selection, settings, and calibration

### *3.1. Camera selection and settings*

The camera is the most important element in a photogrammetric measurement system. Traditionally, customized metric cameras manufactured especially for photogrammetric measurements are used. Unfortunately, the high cost of metric cameras may restrict the wide application of close-range photogrammetry in bridge measurement. In the late 1990s, however, the use of high-end, commercial off-the-shelf digital cameras allowed for high accuracy measurement as a result of high quality charge coupled device (CCD) image sensors and improved camera

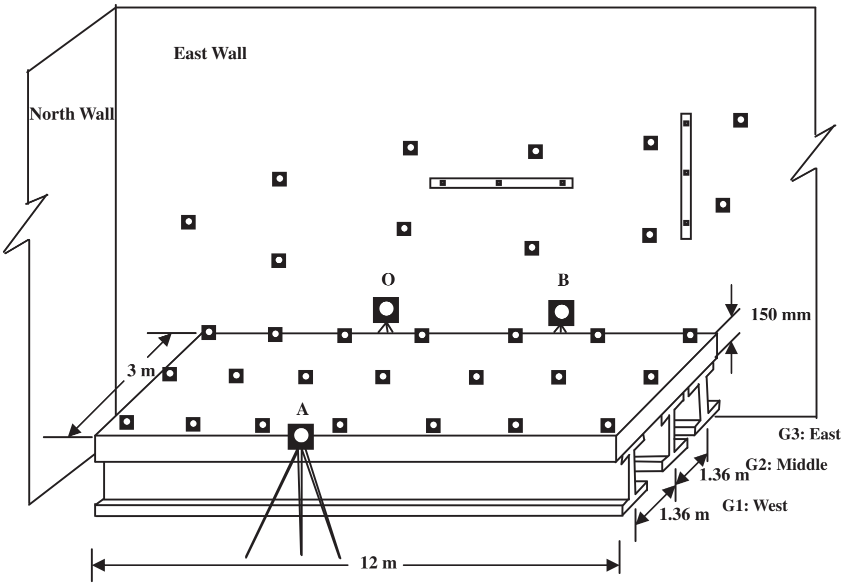


**Fig. 1.** Target layout for laboratory study.

**Fig. 2.** Target layout for the field study.

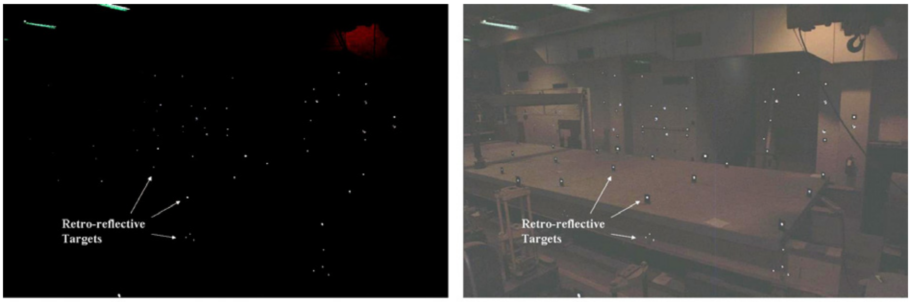
calibration techniques. Kodak DCS professional digital cameras were found to be one of the more popular series being used. The more recent Kodak DCS Pro SLR camera series use Complementary Metal Oxide Semiconductor (CMOS) instead of CCD sensors; CMOS sensors were previously used only for low level digital cameras [4]. With the improvement of its properties, the CMOS sensor is now employed in high-end cameras at a much lower price than those with CCD sensors. The main difference between a CCD and a CMOS sensor is that the former processes image pixels in sequence (pixel by pixel), while the latter processes pixels simultaneously. As a result, CMOS sensors provide higher speed at a lower price, and use much less space and energy.

In this study, a Kodak Pro SLR/n camera with a 36 × 24 mm, 13.85 million pixel CMOS sensor was evaluated in comparison to a Kodak DCS660 camera with a 27 × 18 mm, 6 million pixel CCD sensor. The Kodak DCS660 digital camera used is shown in Fig. 3a which was equipped with a Nikkor 20-mm f2.8D AF wide-angle lens. This camera has ISO ratings of 80–200, and a wide range of shutter speeds. A SUNPAK NE-1AF ring flash was used which provides uniformly distributed light for illuminating retro-reflective targets. The Kodak Pro SLR/n camera used has a wide ISO range from 160 to 1600. The same type of lens was also used for the DCS Pro SLR/n camera. Since the SUNPAK ring flash did not have a compatible adapter for the Kodak Pro SLR/n camera at the time of this study, a Nikon SB28DX speed light was used instead as shown in Fig. 3b.


(a) (b)

**Fig. 3.** Kodak DCS660 (a) and Pro SLR/n (b) cameras.

Camera settings need to be determined before starting the photography. The main settings include resolution, focal length, focus, aperture, shutter speed, white balance, picture quality, drive mode, ISO rating, flash intensity, and image formats. Higher aperture stop means a smaller opening for light to enter the camera lens, which requires longer light exposure and allows more objects being recorded in the image. For retro-reflective targets, high shutter speed should be used (e.g., 1/200 s) to provide high contrast between targets and the background (see Fig. 4a). Focal length should be fixed at infinity to bring more objects into focus. White balance adjusts the camera according to the type of light (such as daylight, fluorescent, or flash) to optimize exposure. Fig. 4 shows a typical photo taken with the Kodak DCS660 digital camera. The photo on the left (a) is the original with the actual exposure effect, and the one on the right (b) is the same picture but artificially enhanced for better view. In the original photograph (a), only retro-reflective targets are visible with the background completely dark, which provides a high contrast (signal/noise ratio). The major settings used for the Kodak DCS660 are 20 mm focal length, infinite focus, *f*/8 aperture stop, 1/200 s shutter speed, ISO 100, 1/16 flash intensity, and TIFF format. Similar settings were used for the Kodak Pro SLR/n camera. The measurements with the two types of cameras were taken under different calibrations as described in the following sections.



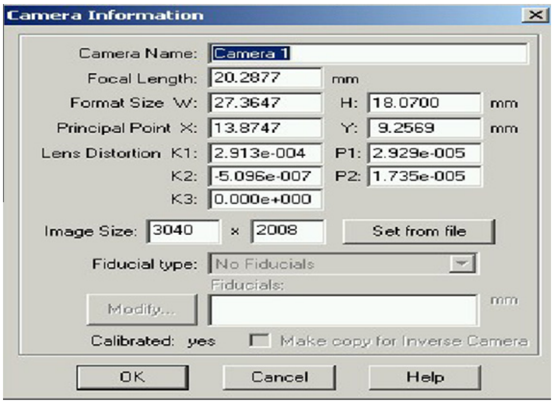
(a) Original photo (b) Artificially enhanced photo

**Fig. 4.** A typical photograph for the laboratory study.

### 3.2. Camera calibration

Camera calibration is critical for measurement quality in that lens distortion parameters are determined. If there are sufficient good quality targets in images from the actual measurement (25 according to Photomodeler [5]), separate camera calibration is not necessary. In this case, the same set of photographs can be used both for deflection measurement and for camera calibration, which is referred to as self-calibration. Otherwise, a separate calibration should be made.

In this study, two camera calibration methods are compared. The first method calibrated cameras through an artificial object image projected onto a flat surface. Photographs are taken around the image and targets on the image are marked and referenced to calculate the distortion parameters of the camera. The procedure described in Photomodeler User's Manual was followed for this type of calibration [5]. This calibration is referred to as classroom calibration in this paper since it was performed in a classroom setting. The second method was self-calibration which was expected to result in better accuracy since the real environment variables such as object size, brightness, temperature, humidity, camera-to-object distance, and surrounding obstacles are applied both in the calibration and the actual measurement. An example set of calibration parameters is shown in Fig. 5. In the calibration, the focal length, format and image sizes are calculated, the principal point is located, and the parameters on lens distortion calculations ($K$ and $P$ values) are measured.



Camera Name: Camera 1
Focal Length: 20.2877 mm
Format Size W: 27.3647 H: 18.0700 mm
Principal Point X: 13.8747 Y: 9.2569 mm
Lens Distortion K1: 2.913e-004 P1: 2.929e-005
K2: -5.096e-007 P2: 1.735e-005
K3: 0.000e+000
Image Size: 3040 x 2008
Fiducial type: No Fiducials
Fiducials: mm
Calibrated: yes ☐ Make copy for Inverse Camera

**Fig. 5.** Kodak DCS660 camera calibration results.

One objective of this research is to explore how to perform self-calibration and to evaluate its accuracy. Self-calibration eliminates the need for a separate calibration and thus significantly save time and simplify the measurement. The evaluation with the two cameras was made by comparison with the dial gage measurements in the laboratory study. The absolute average difference (AAD) between the photogrammetric and dial gage measurements at nine locations is listed in Table 1; classroom- and self-calibration results are reported. It was observed that the two cameras provided a similar level of accuracy. The Kodak Pro SLR/n camera was more sensitive to camera calibration; that is, its accuracy improved more than that of the Kodak DCS660 after performing the self-calibration. The average AAD for the three load cases is 0.19 mm (0.008 in.) for the Kodak DCS660 camera and 0.25 mm (0.010 in.) for the Kodak Pro SLR/n camera based on the classroom calibration. The AAD reduced to 0.17 mm (0.007 in.) for the Kodak DCS660 and 0.15 mm (0.006 in.) for the Pro SLR/n after self-calibration. It was concluded that the two cameras provide the same level of measurement accuracy, and the self-calibration yields a better accuracy than the classroom calibration.

In the field test, an evaluation was first made from a repeatability test in which two sets of images were acquired before loading of the bridge. The time difference between the two sets of photographs was about 20 min. In such a short period of time, the effect of thermal deformation between the two sets of measurements was considered negligible; thus, the difference of the $Z$-coordinates (vertical direction) between the two sets of pre-loading measurements should theoretically be zero. This $Z$-coordinate difference is referred to here as the "virtual deflection"; a smaller "virtual deflection" indicates better measurement accuracy. Table 2 gives the range and AAD of the "virtual deflections" measured at 30 group 1 targets with the DCS660 and Pro SLR/n camera, respectively. The two cameras provided a similar level of accuracy, and camera self-calibration played a significant role in the accuracy of the field measurement. For both cameras, the average error reduced by half as a result of self-calibration.

The evaluation of the two cameras was also made in terms of the actual measured deflections under three truck

**Table 1**
Difference of deflections between dial gages and photogrammetry (lab study for camera).

| | Differences of photogrammetric deflections from dial gages | | | | | |
|---|---|---|---|---|---|---|
| | East loading case | | Middle loading case | | West loading case | |
| | DCS660 | Pro SLR | DCS660 | Pro SLR | DCS660 | Pro SLR |
| *Classroom-calibration* | | | | | | |
| High difference (mm) | 0.18 | 0.89 | 0.40 | 0.31 | 0.10 | 0.33 |
| Low difference (mm) | −0.40 | −0.41 | −0.06 | −0.29 | −0.47 | −0.48 |
| AAD (mm) | 0.22 | 0.38 | 0.22 | 0.17 | 0.14 | 0.20 |
| AAD (in.) | 0.009 | 0.015 | 0.009 | 0.007 | 0.006 | 0.008 |
| *Self-calibration* | | | | | | |
| High difference (mm) | 0.39 | 0.33 | −0.04 | 0.28 | 0.13 | 0.11 |
| Low difference (mm) | −0.37 | −0.31 | −0.24 | −0.11 | −0.55 | −0.39 |
| AAD (mm) | 0.25 | 0.19 | 0.12 | 0.12 | 0.14 | 0.15 |
| AAD (in.) | 0.009 | 0.007 | 0.005 | 0.005 | 0.006 | 0.006 |

**Table 2**
"Virtual deflections" measured with the Kodak DCS660 and Pro SLR camera (field study).

| Difference from zero | "Virtual deflection" | | | |
|---|---|---|---|---|
| | Classroom-calibration | | Self-calibration | |
| | (mm) | (in.) | (mm) | (in.) |
| *DCS660* | | | | |
| High difference | 1.33 | 0.052 | 0.80 | 0.031 |
| Low difference | 0.10 | 0.004 | −0.14 | −0.006 |
| AAD | 0.58 | 0.023 | 0.24 | 0.009 |
| *Pro SLR* | | | | |
| High difference | −0.24 | −0.009 | 0.06 | 0.002 |
| Low difference | −1.15 | −0.045 | −0.99 | −0.039 |
| AAD | 0.81 | 0.032 | 0.43 | 0.017 |

load cases (designated as the east, middle, and west load cases). The deflection measurements obtained with the two cameras agreed with each other very well; the differences were generally less than 1 mm (0.039 in.) between the two cameras. The photogrammetric measurements also agreed well with those obtained using a level rod; the differences were generally within 1 mm (0.039 in.) with a maximum difference of approximately 1.5 mm (0.059 in.).

Based on the lab and field results, it is concluded that the Kodak DCS660 and Pro SLR cameras provide similar levels of accuracy for deflection measurement. The CMOS sensor used in the Pro SLR was found to be more sensitive to camera calibration. Both the CCD and CMOS cameras provided better measurement quality with self-calibration, especially for the field measurement. The CCD sensor results in same accuracy with the CMOS sensor of a much higher resolution.

## 4. Camera placement and orientation

A basic principle governing camera placement and orientation is that the best accuracy is attained if the angle between the optical axes of the cameras is close to a right angle (90°). As illustrated in Fig. 6, a right intersecting angle gives the minimum area of uncertainty [6]. To increase the reliability of measurement, a third shot from a second plane perpendicular to the plane of the first two shots (*XY* plane) is advantageous, as shown in Fig. 7; this third shot can come either from the *XZ* or from *YZ* plane.

A bridge is generally a long structure which cannot be covered in a single image. In this case, the bridge can be divided into several basic units and each unit can be covered by image shots described in Fig. 7. Consequently, both the lab and field bridge were divided into two basic units for purposes of photogrammetric measurement. Three camera placement options were considered, as illustrated in Fig. 8 for the field bridge. Option 1 used one row of five camera stations (shots in *XY* plane); option 2 added another row of camera stations at the same elevation as option 1, but on the other side of the bridge (the third shot from *YZ* plane); and option 3 added one row on the same side of the bridge, but at different height (the third shot also from *YZ* plane). Due to space limitations, only options 1 and 3 were used in the laboratory study. In option 1 there was one row of five elevated stations and in option 3 there were five elevated and five ground camera stations; each row provided nine image shots. In the field study, the three options shown in Fig. 8 were used. Double-sided targets are required in option 2.

Table 3 compares the test results from the lab study between options 1 and 3 for three load cases. The differences from the gage readings were compared and improvements were observed in the measurement accuracy from option 1 to option 3 for all three load cases. The AAD reduced from 0.57 mm (0.022 in.) for option 1 to 0.38 mm (0.015 in.) for option 3 for the east load case; from 0.27 mm (0.011 in.) to 0.17 mm (0.007 in.) for the middle load case; and from 0.63 mm (0.025 in.) to 0.20 mm (0.008 in.) for the west load case. These results indicate that option 3 provided more accurate and consistent measurements than option 1.

Table 4 lists the results from the field bridge repeatability test; while Table 5 gives the results from the actual deflection measurement for the west load case (results from other load cases were similar). It was observed that options 2 and 3 provided similar measurement accuracy and consistency, while the results from option 1 were not as consistent as the other two options. Measurement errors in options 2 and 3 are generally about 0.5 mm (0.02 in.) and within 1 mm (0.04 in.) as shown in Tables 4 and 5, while that of option 1 could be as high as 2–3 mm (0.08–0.12 in.). As a result, either option 2 or 3 is recommended for bridge deflection measurement.

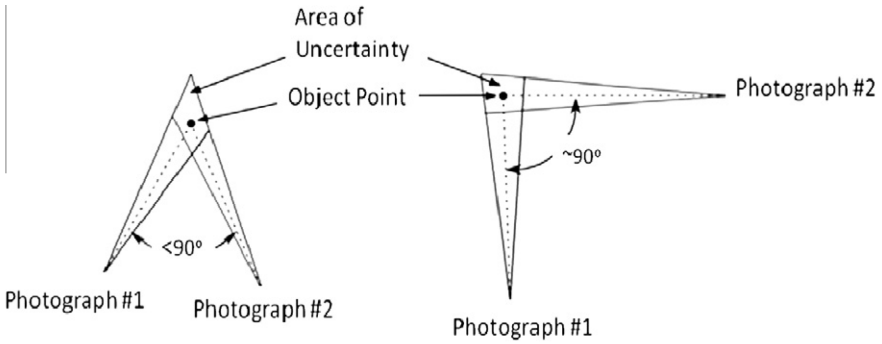


**Fig. 6.** Effect of camera shot angles [6].

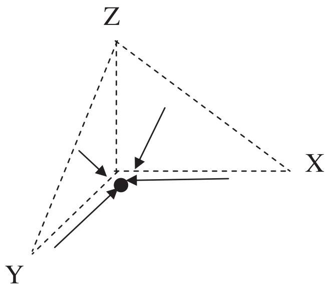


**Fig. 7.** Camera shot configuration.

## 5. Photogrammetry network control

The purpose of providing network control is to establish a measurement coordinate system and scale. Since bridge deflection is measured primarily in the vertical direction, a plumb vertical axis must be set up. The typical approach used a total station survey, by which stationary control points are placed around the object and surveyed to determine their 3-D coordinates [7,8]. Total station surveying is time-consuming and requires training for proper use; as a result, engineers generally need help from professional surveyors to perform such surveying and it takes about 1–2 h to complete for a typical bridge measurement [7]. To make the measurement more convenient to engineers, an alternative approach for establishing the network control was developed in this study. In this approach, designated as the refined distance constraint (RDC) approach, engineers can easily set three reference target points (O, A, and B in Figs. 1 and 2) to the same elevation with a level to define a horizontal plane, thus defining the plumb vertical direction. The object to image scale can subsequently established using scale bars. The RDC method takes only about 10–20 min to set up, thus significantly reducing the field work. In this study the RDC approach was compared with the conventional control point method and the results of the laboratory study are summarized in Table 6. It was observed that the RDC control method provided better or similar level of accuracy as the conventional control point method for all the three load cases. The AAD from dial gage readings provided by the RDC control method was about half of that of the control point method for the middle and west load cases.

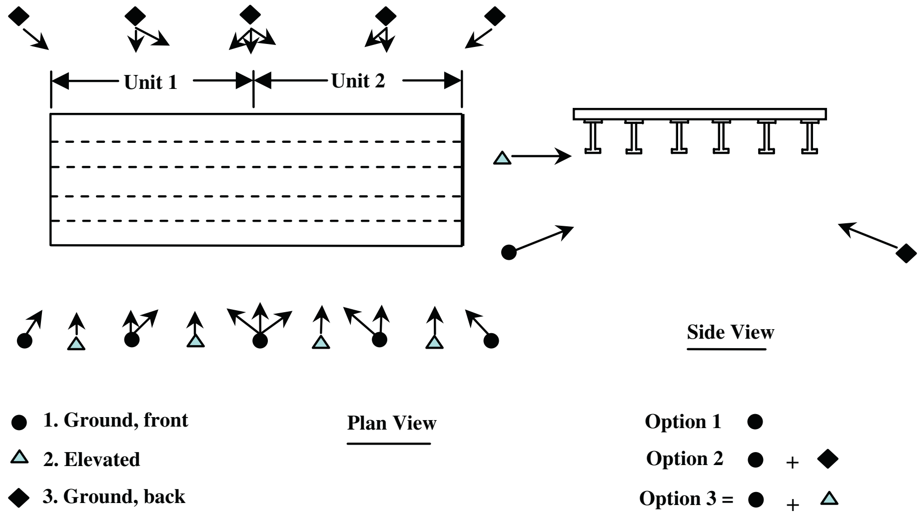


**Fig. 8.** Camera station placement and orientation options.

**Table 3**
Difference of deflections between dial gages and photogrammetry (camera station).

| Target name | Differences of photogrammetric deflections from dial gages | | | | | |
|---|---|---|---|---|---|---|
| | East loading case | | Middle loading case | | West loading case | |
| | Option 1 | Option 3 | Option 1 | Option 3 | Option 1 | Option 3 |
| High difference (mm) | 1.09 | 0.89 | 0.54 | 0.31 | 1.44 | 0.33 |
| Low difference (mm) | −0.62 | −0.41 | −0.47 | −0.29 | −0.82 | −0.48 |
| AAD (mm) | 0.57 | 0.38 | 0.27 | 0.17 | 0.63 | 0.20 |
| AAD (in.) | 0.022 | 0.015 | 0.011 | 0.007 | 0.025 | 0.008 |

**Table 4**
"Virtual deflections" measured for different camera station placement options.

| | "Virtual deflection" | | | | | |
|---|---|---|---|---|---|---|
| | Option 1 | | Option 2 | | Option 3 | |
| | (mm) | (in.) | (mm) | (in.) | (mm) | (in.) |
| High difference | 1.01 | 0.040 | 0.54 | 0.021 | 0.80 | 0.012 |
| Low difference | −0.47 | −0.019 | −0.50 | −0.020 | −0.14 | −0.011 |
| AAD | 0.62 | 0.024 | 0.84 | 0.033 | 0.24 | 0.009 |

**Table 5**
Difference of deflections between level reading and photogrammetry (west load case).

| | Difference from level reading | | | | | |
|---|---|---|---|---|---|---|
| | Option 1 | | Option 2 | | Option 3 | |
| | (mm) | (in.) | (mm) | (in.) | (mm) | (in.) |
| High difference | 2.83 | 0.111 | 0.62 | 0.024 | 1.11 | 0.044 |
| Low difference | −3.10 | −0.122 | −0.68 | −0.027 | 0.01 | 0.001 |
| AAD | 1.18 | 0.046 | 0.29 | 0.011 | 0.54 | 0.021 |

In the field study, the average measurement error indicated by the AAD in the repeatability test was found to be 0.24 mm (0.009 in.) for both the RDC and control point method. In the truck load test, the deflections agreed well between the RDC approach, the control point method, and the level readings. As shown in Table 7, the differences from the level readings were within 1.5 mm (0.06 in.) and the AAD was about 0.5 mm (0.02 in.) on average for both the RDC and control point methods. Both the laboratory and field test results confirmed that the RDC method provided similar measurement accuracy as the conventional control point approach. The reader can refer to Jiang and Jauregui [7] for detailed information on the RDC control method.

## 6. Conclusion

The photogrammetric bridge deflection measurement system proposed in this paper consists of a Kodak CCD or

**Table 6**
Difference of deflections between dial gages and photogrammetry (network control).

| | Differences of photogrammetric deflections from level reading | | | | | |
|---|---|---|---|---|---|---|
| | East loading case | | Middle loading case | | West loading case | |
| | RDC method | Control point method | RDC method | Control point method | RDC method | Control point method |
| High difference (mm) | 0.39 | −0.03 | 0.28 | −0.31 | 0.11 | −0.11 |
| Low difference (mm) | −0.37 | −0.49 | −0.11 | −0.58 | −0.39 | −0.64 |
| AAD (mm) | 0.25 | 0.29 | 0.12 | 0.46 | 0.15 | 0.33 |
| AAD (in.) | 0.009 | 0.011 | 0.005 | 0.018 | 0.006 | 0.013 |

**Table 7**
Difference of deflections between level reading and photogrammetry (network control).

| | Differences of photogrammetric deflections from level reading | | | | | |
|---|---|---|---|---|---|---|
| | East loading case | | Middle loading case | | West loading case | |
| | RDC method | Control point method | RDC method | Control point method | RDC method | Control point method |
| High difference (mm) | 0.78 | 1.17 | 1.40 | 1.44 | 1.11 | 1.39 |
| Low difference (mm) | −1.47 | −1.01 | −0.49 | −0.68 | 0.01 | 0.01 |
| AAD (mm) | 0.33 | 0.44 | 0.38 | 0.46 | 0.54 | 0.66 |
| AAD (in.) | 0.013 | 0.017 | 0.015 | 0.018 | 0.021 | 0.026 |

CMOS high-end digital camera, retro-reflective targets, RDC network control method, and camera placement options from two elevations on one side of a bridge, or from one elevation but from both sides of the bridge if the elevated solutions are difficult to implement. Self-calibration proved to provide higher measurement accuracy and the CMOS sensor is more sensitive to camera calibration. Double-sided targets must be used if images are taken from both sides of the bridge, which provides a convenient camera station layout since no lifting equipment is required. The RDC network control method developed in this study provides an effective approach to establish a reference system; the accuracy provided by the RDC method is comparable to that of the conventional control point method while significantly reducing the field work. Based on the laboratory and field results through comparisons with dial gage and differential level measurements, respectively, the system proposed yielded differences within 1 mm (0.04 in.) from the gage measurement and within 2 mm (0.08 in.) from the level readings. Engineers can easily apply the system without a need for special training or assistance from a professional surveyor. The system provides an option for engineers to apply close-range photogrammetry with high measurement accuracy, low cost, and application convenience.

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