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A LASER AND VIDEO-BASED DISPLACEMENT TRANSDUCER FOR THE MONITORING OF BRIDGE DEFLECTIONS

Nicholas Brown[1], Thomas Schumacher
Portland State University
Portland, OR

Miguel Vicente
Associate Professor
Department of Civil Engineering
University of Burgos, c/ Villadiego, s/n 09001
Burgos, Spain

ABSTRACT

Deflection measurements on bridges, especially with regards to long-term bridge monitoring, continues to be a challenge with current technological capabilities. Material degradation and changes in the mechanical properties due to aging (for example, creep and shrinkage in concrete bridges) directly impact the vertical deflections exhibited by a structure. This presentation discusses a novel laser and video-based displacement transducer (LVBDT) to monitor displacements and rotations in structures remotely. In contrast to other video-based approaches, the sensor is located at the measurement location on the structure. Ongoing laboratory tests include sensor configuration under both static and dynamic displacements to determine the applicability, accuracy, and limitations of the sensor. Sensor configuration, sensing approach and methodology, and preliminary laboratory testing results will be presented and discussed in this paper. Essential for field implementation, the results demonstrate the sensing approach to be robust, accurate, reliable, and inexpensive.

Keywords: structural health monitoring, laser, video, displacement

1. INTRODUCTION

Historically, visual inspection has been the primary method of structural condition assessment. Visual degradation of materials, cracking, large displacements, etc. are visual cues for structural deficiencies in a structure. Unfortunately, these rely on the subjective judgement of the inspector, and require structural deficiencies to be severe enough to be seen with the naked eye (or assistive tools). With the rapid evolution of digital sensors over the last decade, alternative monitoring solutions have been researched and developed that seek to identify structural deficiencies continuously before they become extreme.

With regards to bridges, vertical deflection monitoring may be one of the most desired and crucial variables associated with structural health since it directly correlates with the serviceability of the structure. Long-term effects such as creep, shrinkage, and prestressing losses in prestressed/post-tensioned structures directly impact vertical deflection. The same observations can be made with regards to the effects of environmental processes on a structure (corrosion, carbonation, overall structural aging, etc.).

Although highly useful, long-term monitoring of vertical deflections on bridges has proven to be challenging due to the shortcomings of current measurement technologies. In addition to the harsh environmental conditions often surrounding bridges, the scale of the structure often makes such measurements more difficult. The currently available technologies to measure displacements such as linear variable differential transducers (LVDT) or potentiometers, GPS-based systems, accelerometers, laser distance meters, either require the sensor to be connected to a fixed reference, are of low resolution, are unable to measure slowly-varying displacements, or are expensive, respectively. Thus, a cost-effective and reliable solution for monitoring long - term and potentially slowly-varying displacements on bridges is needed.

More recently, video-based sensors have emerged as a potential alternative to fill this need. Advancements in video camera technology have resulted in widespread availability and lowered costs. In addition, video/image processing software has also become widely available. Although these sensor advancements are promising, there are drawbacks that need further development before it can be considered a reliable method of data collection. An initial problem with video-based sensors was with resolution. However, this has become less of an issue with the rapid advancement of camera technology over the last several years. With the increase in camera resolution comes the problem of file size and processing time. Large file sizes and long-term monitoring requirements necessitate the need for ways to store large amounts of data. In addition, video/image

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[1] Contact author: nibrown@pdx.edu

processing software must be capable of processing these large files quickly (common video cameras record video at 30-60 frames per second).

Most video-based sensor solutions to date have placed the camera sensor at a fixed location off-structure. The camera sensor is then pointed at an area of interest on the structure and data is collected. Our proposed sensor approach instead places the camera sensor on the structure at the point of interest. A set of lasers is placed at a fixed location off-structure and then focused on a translucent panel attached to the camera sensor. Any deflections experienced by the structure are then directly experienced by the camera sensor. The movement of the sensor directly corresponds to movement of the laser dot location on the translucent panel (recorded direction of laser movement being in the opposite direction of the movement experienced by the sensor). An added benefit of this approach is that the sensor is less sensitive to rotational effects placed on the sensor itself.

In the following sections, the proposed laser and video-based displacement transducer (LVBDT) is described in detail. Two laboratory-based experiments aimed at identifying accuracy, repeatability, and applicability in an array of lighting conditions are presented and the results are discussed.

2. SENSING APPROACH

2.1 Components and Equipment

The proposed laser and video-based displacement transducer is comprised of two main components: the fixed part and the movable part. Figure 1 provides a general overview of the components of the LVBDT. The fixed part (Figure 1 (a)) is placed at an immovable location where it remains fixed for the entire duration of planned monitoring. It is comprised of two laser emitters secured to a fixed support. For the purposes of this research, the laser emitters produce green laser dots when focused on the translucent panel of the movable part of the sensor.

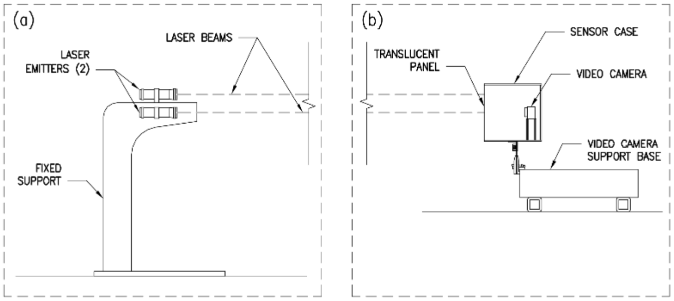

FIGURE 1: ILLUSTRATION OF LASER AND VIDEO-BASED DISPLACEMENT TRANSDUCER (LVBDT) IN LABORATORY TEST SETUP: (a) FIXED PART, (b) MOVABLE PART.

The movable part of the sensor (Figure 1(b)) is comprised of three main elements: a translucent panel, a series of (8) red LED diodes, and a video camera. The translucent panel was made of medium-weight plain white paper stock, measuring 100 mm width by 150 mm height. The panel was fastened securely to the sensor box to ensure the panel remained planar and orthogonal to the video camera. The red LED diodes were used to provide a reference coordinate system for calculating displacement and rotation of the sensor during testing. The video camera used during this research was a GoPro Hero 3-Black Edition. Image resolution used during data collection was 3000 x 4000 pixels and images were recorded in the RGB color space. The video camera was fixed to the inside of the sensor box via a 3D printed bracket attached to the box. The video camera location was chosen so that the recorded image captured the entire translucent panel and as little area beyond the panel as possible.

2.2 Sensing Methodology

The laser emitters project a set of two green dots onto the translucent panel of the sensor. The location of the green dots with respect to the red dots is recorded by the camera and stored for processing. During processing, images are extracted from the video camera and imported into MATLAB for video/image-based analysis. Color thresholding procedures were used to isolate the green and red dots. Once isolated, additional pixel information within the image was removed to improve processing times. The location of the centroid of each dot was then calculated and recorded using built-in MATLAB functions for each image frame. During laboratory testing, a digital caliper was attached to the base of the sensor, creating a means to verify results, and to assist in creating pixel-to-displacement conversion functions.

The first laboratory experiment was used to calibrate the sensor and test the accuracy of the sensor at measurement distances of 3.05, 7.62, 15.2, and 30.5 m. At each location, the sensor was moved vertically in approximately 8 mm increments until the lasers were at the extreme end of the translucent panel, then the sensor was moved vertically in the opposite direction, first by 4 mm, then subsequently in 8 mm increments so that measurements were taken at approximately 4 mm increments across the face of the translucent panel. This process was repeated for each measurement distance. To calibrate the sensor, the red dot locations were identified in the initial extracted image. These locations were compared with the known locations of the red LED diodes in the assigned cartesian coordinate system. An array of distances measured between each of the eight points were constructed and compared with the data taken from the extracted image. These results were then analyzed and averaged to determine a pixel-to-mm calibration constant.

The second laboratory experiment aimed to gather data on the applicability of the sensor under different lighting conditions. The sensor was set up as before, with the laser device being placed at a measurement distance of 7.62 m. Three recordings were taken under normal indoor lighting conditions. A bright fluorescent lamp was then placed close to the sensor so that the translucent panel was completely illuminated. Again, three recordings were taken. Next, the lamp was oriented so that one laser on the panel was illuminated, and the other was experiencing normal indoor lighting conditions. For the final condition, all lights in the laboratory were turned off, and recordings were taken.

3. RESULTS AND DISCUSSION

Processing results from the first laboratory experiment provided a calibration constant between 16.0 and 18.5 pixel/mm for each of the (8) red LED diodes analyzed. The average calibration constant used throughout the remainder of the laboratory tests was 17.48 pixel/mm. Figure 2 shows correlation plots for each of the four fixed distances, comparing the recorded caliper reading (measured in mm) and the calculated centroid of one green dot in the vertical axis (measured in pixels). The first-order polynomial-curve fit function passing through the set of data points at each measurement distance is shown as well. The near linear nature of the curve fit functions corresponds to a constant conversion factor, which was expected.

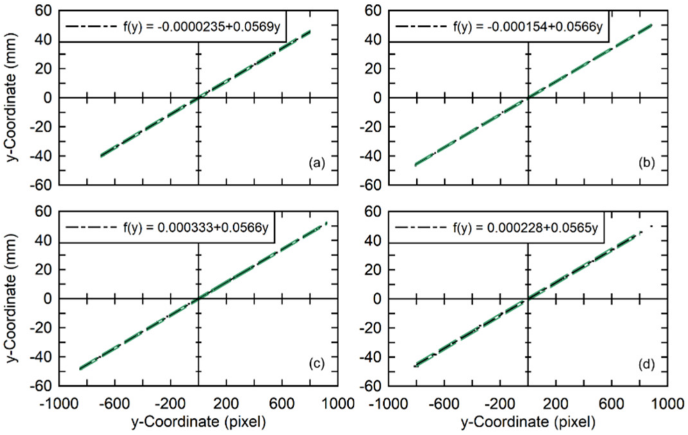

FIGURE 2: CORRELATION PLOTS FOR ALL MEASUREMENT DISTANCES WITH CURVE FIT FUNCTIONS: (a) 3.05 M, (b) 7.62 M, (c) 15.2 M, (d) 30.5 M. GREEN DASHED LINES REPRESENT 95% PREDICTION LIMITS.

Approximately 75 images were extracted from the first laboratory experiment for each measurement distance (i.e. 3.05, 7.62, 15.2, and 30.5 m). Green dot centroid locations were calculated for each image, converted to mm using the conversion constant, and compared to the caliper readings taken at the same time instant.

For each measurement distance, mean 95% prediction limits were calculated using the data obtained during processing. 95% prediction limits ranged from ± 0.8 mm to ± 1.15 mm. Figure 3 illustrates the mean 95% prediction limits versus measurement distance.

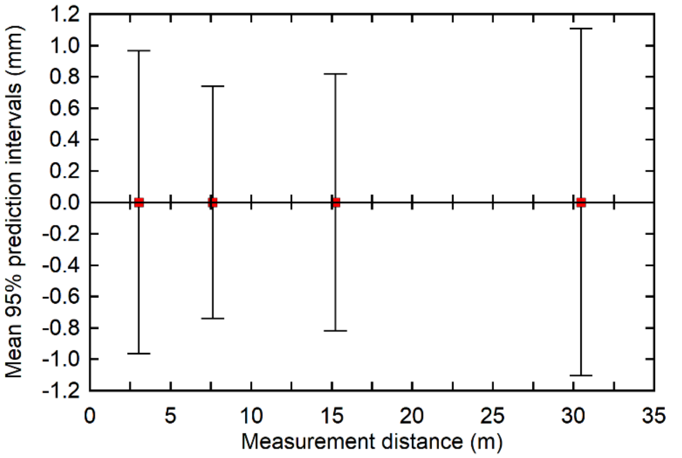

FIGURE 3: MEAN 95% PREDICTION LIMITS VERSUS MEASUREMENT DISTANCE.

Data recording and processing for the second laboratory experiment followed the same process as the first laboratory experiment using a measurement distance of 7.62 m. The two green laser dots were located at approximately the vertical center of the translucent panel. Three images were recorded for each of the lighting conditions. For each of the lighting conditions, the three images were processed and compared to determine the level of noise contained in the image data. Green dot centroid locations for each lighting condition varied from 0.28 pixel (0.016 mm) to 0.85 pixel (0.049 mm).

Next, calculated centroids for each green dot were compared between each of the lighting conditions to determine the sensitivity of the sensor to varied lighting conditions. Variations in centroid location between different lighting conditions (using normal indoor lighting as the control group) ranged from 0.34 pixel (0.019 mm) to 3.23 pixel (0.185 mm). The lighting condition having the smallest variance from the normal indoor lighting condition was the first partial shade configuration, varying by 0.34 pixel (0.019 mm). The lighting condition with the largest variance from the normal lighting condition was the full darkness configuration, varying by 3.23 pixel (0.185 mm).

4. CONCLUSION

With the rate of advancement in video-based technology and image processing software, it is likely that the accuracy, availability, and applicability of laser and video-based solutions will continue to improve.

Due to the direct correlation between vertical deflection and overall bridge condition, having a method of measuring vertical deflections on bridges is a high priority, specifically when it comes to tracking long-term changes in vertical deflections. Having a solution that is accurate, repeatable, and cost-effective in a wide variety of environmental conditions is crucial. Advances in video-based sensors and video processing offer promising results in the field of structural health monitoring.

Based on the results presented, a laser and video-based displacement transducer is a viable solution for the long-term monitoring of deflections of bridges (as well as other structures). Although further research and development is needed before this technology can be widely used in the field, initial results are promising.

The focus of these initial experiments was aimed at determining the accuracy of long-term deflection measurement in structures. Additional research should be performed to determine if the LVBDT could be used in determining short-term (dynamic) displacement measurements. Further research includes characterization of the sensor for capturing vibrations and evaluation of the sensor's performance for in-field measurements on a variety of structures and long-term under a variety of environmental conditions.

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PATENTS

A Spanish patent (patent no: ES-P201730410) has been submitted and is currently pending [4].

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