Unmanned aerial vehicle acquisition of three-dimensional digital image correlation measurements for structural health monitoring of bridges

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ABSTRACT

Civil engineering structures such as bridges, buildings, and tunnels continue to be used despite aging and deterioration well past their design life. In 2013, the American Society of Civil Engineers (ASCE) rated the state of the U.S. bridges as mediocre, despite the $12.8 billion USD annually invested. Traditional inspection and monitoring techniques may produce inconsistent results, are labor intensive and too time-consuming to be considered effective for large-scale monitoring. Therefore, new structural health monitoring systems must be developed that are automated, highly accurate, minimally invasive, and cost effective. Three-dimensional (3D) digital image correlation (DIC) systems possess the capability of extracting full-field strain, displacement, and geometry profiles. Furthermore, as this measurement technique is implemented within an Unmanned Aerial Vehicle (UAV) the capability to expedite the optical-based measurement process is increased as well as the infrastructure downtime being reduced. These resulting integrity maps of the structure of interest can be easily interpreted by trained personal. Within this paper, the feasibility of performing DIC measurements using a pair of cameras installed on a UAV is shown. Performance is validated with in-flight measurements. Also, full-field displacement monitoring, 3D measurement stitching, and 3D point-tracking techniques are employed in conjunction with 3D mapping and data management software. The results of these experiments show that the combination of autonomous flight with 3D DIC and other non-contact measurement systems provides a highly valuable and effective civil inspection platform.

Keywords: autonomous inspection, bridge, digital image correlation, infrastructure, photogrammetry, structural health monitoring, unmanned aerial vehicle

1. INTRODUCTION

The expected lifespan of bridges is approximately 50 years; nevertheless, the majority of the bridges are used despite the reality that they are past their intended design life. In particular, from a statistic released in 2013, the bridge’s national average age in the United States was 42 years, one-out-of-four of them was classified as functionally obsolete, and one-out-of-ten as structurally deficient [1]. Despite a structural deficiency that does not necessarily imply that the bridge is unsafe or likely to collapse, it typically requires maintenance, repair to remain in service, or replacement to address deterioration[2]. Although several efforts have been made to reduce the percentage of substandard bridges, estimations provided by the Federal Highway Administration (FHWA) demonstrate that $20.5 billion are still necessary annually to cut bridges’ structural backlog by 2028 [3].

According to the National Bridge Inspection Standards (NBIS) and Bridge Inspector's Reference Manual (BIRM) released by FHWA, road bridges are mandated to receive inspections every two years and the level of inspection depends on different parameters (e.g. material, structural type, etc.) [4]. In most cases assessment, decision-making, and repair are based on visual inspections. Though the measurement processes is fundamentally simple, it is highly subjective, focuses on the observation of very few details at a time (e.g. broken hardware, corrosion, etc.). Moreover, it requires specialized heavy machinery to access the area (e.g. ladder, inspection trucks, scaffolding, etc.), which interferes with traffic conditions, and allows detecting damages when they have already happened [5]. Furthermore, large-scale deformations and internal damage are also particularly difficult to diagnose. The latter problem is extremely important as concrete bridges are considered. This typology of structures is characterized by several deterioration phenomena, which are often coupled (e.g. carbonation, crystallization, salt and acid actions, creep, shrinkage, water penetration, etc.). All of the above are characterized by the formation of micro-cracking, macro-cracking, and spalling phenomena which can jeopardize the bridge’s health even before they become noticeable by visual inspection.

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For these reasons, the demand for bridges' structural monitoring has increased and novel, cost-effective assessing techniques are continuously sought. In the last few years, achievements made in cameras technology, optical sensors, and image-processing algorithms allowed the development of a new generation of non-contact measuring methods [6]. Three-dimensional (3D) Digital Image Correlation (DIC) has become a valuable asset for performing non-contact measurements and extracting surface strain, displacement and geometry profiles from images acquired through a synchronized pair of stereo cameras. To perform these measurements, a stochastic pattern and/or optical targets are applied to the surface of interest and the deformation and displacement of the pattern are tracked through a series of photographs to evaluate the corresponding displacement object of interest[7].

In this paper, a novel approach that combines the use of unmanned aerial vehicle (UAV) and 3D-DIC to perform remote monitoring of concrete bridges' cracks is described. Results of long term monitoring activities performed on two concrete bridges still in service show that the proposed system can measure the relative displacement across cracked surfaces with a resolution of 10^{-5} m and with the same accuracy of currently employed measurement techniques. This is extremely important as measurement noise and uncertainty are critical for defect detection and good sets of data are extremely important for selecting the best remediation activity [8, 9]. The paper is organized as follows: Section II presents a review of bridges' inspection techniques together with an overview of DIC applications and UAV state-of-the-art for engineering related operations. The results of the long-term monitoring of two areas located on a concrete bridge currently in-service are discussed in Section III. Here, the performance of the 3D-DIC UAV system in performing full-field displacement monitoring and 3D point-tracking are described. Finally, conclusions are drawn and future work is briefly outlined in Section IV. This paper represents the first attempt to perform bridge assessment using UAV and DIC technologies combined together for performing long-term monitoring of areas difficult to access.

2. RELATED WORKS

To improve the quality of bridges health monitoring data, more advanced measurement techniques have been implemented in the last decades. In this section a summary review of these systems is presented in three parts. The first is a brief overview of some of the existing methods used for assessing the state of bridges. The second part focuses on the use of DIC systems for SHM purposes; while, the latter summarizes the use of UAVs for civil and mechanical engineering related operations.

As stated before, visual inspection is still the main method used to evaluate a bridge's health. Nevertheless, some important characteristics such as the expansion rate of sub-millimeter cracks may not be properly estimated, or they can go unseen [10]. Over time, bridge's health monitoring systems have become increasingly sophisticated and accurate. Accelerometers are extremely common for structural health monitoring (SHM) and are used for evaluating changes in dynamic properties (e.g. shifts in natural frequencies, vibration amplitude increases, vibration transmissivity variations, etc.) that could represent status change in the stability of the infrastructure [11]. Also, fiber optic sensors, due to their immunity to Electro Magnetic Interference (EMI) have proven to be valid sensing alternatives for monitoring civil structures [12]. Nevertheless, their deployment over large-areas can be extremely cumbersome because of their wire-based connections, cost, and dimensions. For these reasons, several researchers developed monitoring systems using MEMS-based Wireless Sensor Networks (WSNs) [13]. Nevertheless, many times these sensors are not durable enough to be embedded in a structure and perform measurements for years after its construction (when failures are more likely to happen). Recent technological developments have made several new techniques available for bridge SHM. More efficient and accurate imaging techniques (e.g. radiography and infrared thermography) were developed for performing evaluation of concrete structures [14, 15]. Other non-contact techniques like Ground Penetrating Radar (GPR), Light Detection And Ranging (LiDAR), Acoustics Emissions (AE), and Interferometric Synthetic Aperture Radar (InSAR) have been experimented and each possesses their own advantages and challenges [16, 17]. Still, the practical challenges faced by the user for in-situ investigations make many of these systems not suited for large-scale monitoring; moreover, many of them limit the information obtained to measurement at only a few discrete points.

Recently, a great deal of attention has been aroused by the opportunity to measure displacement, strain, and dynamic parameters of a structure using optical techniques and digital cameras. An example of optically based technique is 3D-DIC. The basic principle of DIC is to match the same physical point between a reference image and several deformed stages based on gray-scale variations of continuous patterns. Thus, to perform DIC measurements, a stochastic pattern made of black and white dots or optical targets is applied to the targeted surface. Then, the relative position of each dot is tracked as the surface deforms over time. In each of the measuring areas, a set of unique correlation point (i.e. facets) is defined. The center of each facet is a measurement point that can be thought of as a displacement sensor. The position of these facets is tracked through each of the successive acquired images and the 3D coordinates of the entire area of interest are calculated with sub-pixel accuracy [7]. DIC has the potential to perform non-contact, full-field inspection over a wide range of civil and mechanical engineering systems such as wind turbine blades, rotating machineries, bridges, railroad tracks, and composite materials [18 - 21]. The results shown in these studies have proven that this technology allows for obtaining full-field measurements with accuracy comparable to that of traditionally employed sensors (e.g. accelerometers, strain gages) and reduces the installation downtime.

UAVs are small-sized aircraft, which can fly autonomously, controlled remotely by computers or trained personnel. Initially developed for military operations, in the last years several they found applications in civil scenarios as well. Among them, flora and fauna monitoring, environmental disaster management, and heritage documentation [22 - 24]. Currently, UAVs have emerged as valuable resources for positioning sensing equipment where it is either difficult to measure or poses risks to human safety, have proved the capability to expedite the measurement process for civil infrastructure by offering increased accessibility and reducing interference with local traffic [25]. Cameras are among the most common devices installed on a UAV and the civil engineering applications using these systems are rising. For instance, UAV and photogrammetry-based inspections were employed for examining locally linear civil engineering structures (e.g. oil-gas pipelines, roads) [26], and for generating accurate rendering of structural details to support condition assessment[27]. The most recent findings have shown that the accuracy of these systems is on the order of 0.5 mm and that the major cracks on a structure can be easily detected and quantified. A detailed review of developed UAVs and their applications in civil engineering can be found in [28]. What is sure is that several improvements have been achieved in the utilization of UAVs for performing inspections on civil engineering structures. It is to be expected that advancements in image sensor technology will allow for increasingly accurate results to be obtained.

3. EXPERIMENTAL SETUP AND ANALYSIS OF THE RESULTS

In this paper, the results of DIC measurements performed using a pair of cameras installed on a UAV payload are discussed. It should be noted that it is the first attempt to perform bridge assessment using UAV and DIC technologies combined together. The approach may speed up the inspection process, track the relative motion of part of the bridge, and be used to perform long-term monitoring of areas difficult to access. This section offers an overview of the design specifications of the combined 3D-DIC UAV system and the results of two monitoring activities performed over a currently in service, 56 years old, concrete bridge in Lowell, MA. In particular two different locations in correspondence of two expansion joints on the bridge's abutment walls are monitored using different DIC techniques (i.e. 3D point-tracking and 3D full-field measurements).

3.1 3D-DIC UAV platform specifications

The DIC sensor system design is based on the specifications of the selected UAV: the InstantEye Gen4 heavy lift variant developed by Physical Science, Inc. (PSI) having a theoretical payload limit of 2.25 kg. The DIC system selected consists of a pair of 2 Megapixels acA1600-20um digital cameras manufactured by Basler employing a $(7.16 \times 5.44)\cdot 10^{-3}$ m interline progressive charge coupled device (CCD) monochrome image sensors with a resolution of 1626 x 1236 pixels and a pixel size of $(4.4 \times 4.4)\cdot 10^{-6}$ m. The cameras were fitted with 8.5 mm focal length lenses manufactured by Edmund Optics Ltd. The 3D-DIC system was positioned to have a working distance of 1.75 meter and a cameras separation distance of 0.707 m, which resulted in a 25° separation angle between the cameras' central line of sight. The decision to use this working distance depends on the fact that the developed DIC payload was intended to work in parallel with a synthetic aperture radar (SAR) sensor module having an ideal working distance of 1.75 m [29]. In this configuration, the stereo-photogrammetry system was capable of measuring an area of 1.414 x 1.075 m. Furthermore, the payload is equipped with a Minnowboard-MAX, runs a Linux-based OS, and uses on an ad-hoc Wi-Fi network for connection with a remote laptop. This feature allows an operator to remotely control the two cameras for adjusting the camera parameters and taking the pictures. Figures 1 and 2 show the InstantEye Gen4 heavy lift variant quad-copter and the customized 3D-DIC payload used in the tests described in this research.

Figure 1. InstantEye Gen4 heavy lift variant developed by Physical Science, Inc. (PSI).

Figure 2. Payload mount for installing the stereovision system and the computer board.

At this stage of development, a trained pilot remotely controls the UAV. This means that the UAV is operated independently from the DIC sensor payload. For this study, the UAV operator would position and maintain the vehicle relative to the patterned areas of interest as instructed by the DIC payload operator by using the feedback of the sonar based optical vertical position hold module shown in Figure 3. A camera installed underneath the payload allows the operator to see the surface the UAV is flying over, while an ultrasonic rangefinder is used for stabilizing the system during the hovering phases. Once the DIC operator is satisfied with the positioning of the UAV, images can be acquired and the aircraft would be repositioned to the next local inspection area.

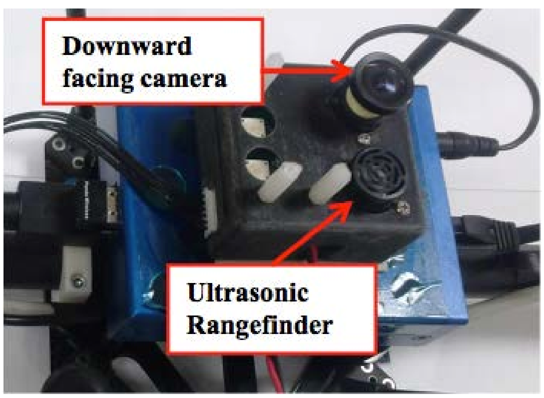

Figure 3. Sonar based optical vertical position hold module.

For being considered a potential replacement for human inspection, the accuracy of the system must surpass or at least match that of visual inspection (i.e. approximately 10^{-4} m). The potential accuracy of the system for in-plane displacement is estimated at $1/100^{th}$ of the effective pixel size [30]. For a camera resolution of 1626 pixel, a FOV width of 1.4 m, and a focal lens of 8.5 mm, the stereovision system is expected to generate an accuracy of $\pm 1 \cdot 10^{-5}$ m for ideal measurement conditions.

3.2 Results of the bridges monitoring field tests

The 3D-DIC UAV system has been widely evaluated by performing in-situ measurements and long-term monitoring on an in-service bridge in the city of Lowell, MA. In particular, the results presented in this paper refer to the tests performed on the Lincoln Street-Lowell Connector concrete cast-in-place bridge shown in Figure 4. The investigations presented in this work have focused on the monitoring of two areas located in correspondence of the two expansion joints on the bridge's abutment walls right below the bridge's superstructure. Prior to performing the DIC measurements, a stochastic pattern with black dots having a diameter of $5 \cdot 10^{-3}$ m was applied to the surfaces of interest. Also, a number of optical targets were applied to the opposite edges of the joints for performing point-tracking measurements.

Figure 4. Lincoln Street-Lowell Connector Bridge inspected using the 3D-DIC UAV system.

The first area examined is located on the left side of the bridge as shown in Figure 4, nearly 5 meters away from the road level. This area is difficult to access without proper equipment and this characteristic makes even more evident the utility of performing optically based measurements with the support of UAV technologies. As can be observed from Figure 5, the area of interest is located across the expansion joint and it also possesses two large (~2-5mm) horizontal cracks.

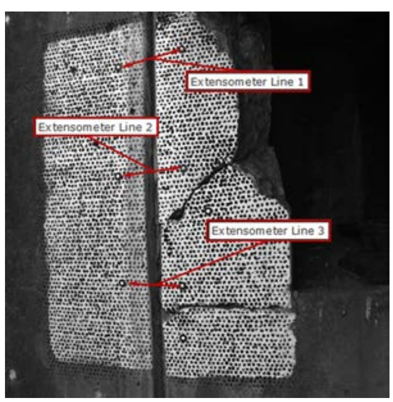

Figure 5. Monitoring area and extensometer locations across the expansion joint.

This research focuses on demonstrating the efficiency of the 3D-DIC UAV system in measuring the displacement of the joint. Therefore, data was collected by measuring the changes in relative position between optical targets placed across the expansion joint only. The center of each optical target is a measurement point that can be thought of as the edge of an extensometer. The position of these points is tracked through each of the successive acquired images and their 3D coordinates are calculated with sub-pixel accuracy. Flight inspections of the joint widths were performed on three dates (May 11th, 2016; June 23rd, 2016; and October 18th, 2016) in a setup similar to that shown in Figure 6. Figure 7 shows the averaged extensometer displacement results from multiple 3D point tracking measurements. In particular, five snapshots for each of the individual measurements performed were taken to allow data averaging during post-processing analyses and to verify measurement repeatability. The results presented in Figure 7, show the displacement of the joint calculated as the average of the displacements characterizing the three extensometers during each of the individual measurements performed. Moreover, the error bars shown in the same figure represent the standard deviation range for five measurements taken at each of the three extensometer lines. Analyzing the trend of the displacement plotted in Figure 7, it is possible to observe a contraction in the joint during the transition from spring to summer followed by an expansion during the transition from summer into fall. It is assumed that these displacements result from the thermal expansion and contraction of the concrete abutments.

Figure 6. UAV inspection being performed at the expansion joint on the bridge's abutment wall on June 23, 2016.

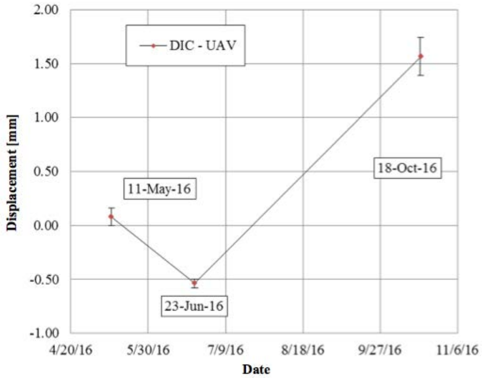

Figure 7. Averaged extensometer displacement results from multiple 3D point tracking measurements. Monitoring period May 11, 2016 to October 18, 2016.

The second area investigated is located on the right side of the bridge as shown in Figure 4, nearly 2 meters away from the road level. Due to the accessibility of this location, a total of nine inspections were performed over a period of 285 days. Three of the inspections utilized the UAV (as shown in Figure 8) while the additional six were performed with the payload being held by an inspector and powered by an external battery pack. As usual, for each of the measurements performed included five snapshots that were taken and results averaged. To further validate the accuracy of the measurements performed using the proposed 3D-DIC system, a back-to-back comparison with measurements acquired from parallel brackets fixed to the surface using a 0.001in. graduation dial caliper has been performed and compared to the discrete displacements recorded from the UAV inspections. Figure 9 shows the portion of the joint investigated with the extensometer lines used for calculating the relative motion of the two edges. It should be noticed that the parallel brackets were placed nearly 0.3 m away from the upper edge of the target area shown in Figure 9.

Figure 8. UAV inspection being performed at the expansion joint on the bridge's right abutment wall on June 23, 2016.

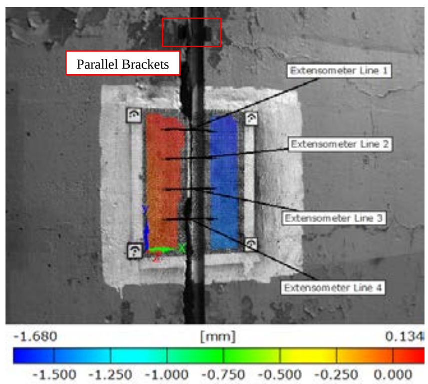

Figure 9. Full-field X-displacement (horizontal) contour plot and extensometer locations across the expansion joint. Monitoring period January 7, 2016 to October 18, 2016.

For the long-term monitoring of this expansion joint area, full-field data were generated. When full-field data are collected, any pair of points may be selected to create an optical extensometer. Figure 9 also shows the full-field in-plane X-displacement of the two edges of the crack. As can be observed, the right side of the joint is moving to the left (i.e. negative displacements in the scale bar plotted), while the left side of the crack has little to no movement (i.e. slightly positive displacements in the scale bar plotted). Overall, the crack width is contracting. For this reason, the same area has been monitored for nearly 10 months to determine the ability of the proposed 3D-DIC UAV system in characterizing the activity of the joint over time. Figure 10 shows the change in the length of the four considered extensometer lines over time and the associated error evaluated as the average of the five images recorded in each measurement. The monitoring period to which the plot refers to has been performed between January, 7th and October, 18th 2016. The results show that the crack tends to contract through the whole winter period and the spring, while an opposite trend is shown in the warmest months. The average difference between the displacements measured using 3D-DIC and what was measured with dial calipers is 0.17 mm (relative error = 17.12 %). However it is also noted that this difference is on the same order of magnitude of the accuracy characterizing visual inspection (i.e. 10^{-4} m); thus, the measurement system is still highly capable of achieving a level of accuracy relevant to infrastructure monitoring.

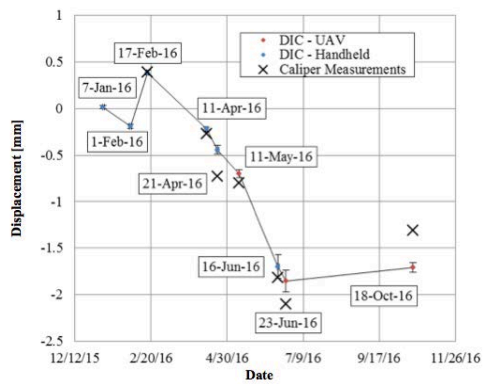

Figure 10. Averaged extensometer displacement results from 3D DIC measurements and comparison with caliper measurements. Monitoring period January 7, 2016 to October 18, 2016.

4. CONCLUSIONS

The objective of this research was to develop, demonstrate, and quantify the capabilities of an UAV equipped with a payload installing a 3D-DIC sensor package to be used for the monitoring of concrete bridges' cracks and expansion joints. Experimental results obtained from the monitoring activities of two area of interest on a currently in-service concrete cast-in-place bridge in the city of Lowell, MA have demonstrated the system's ability to monitor the displacement of joints at full field and at discrete points while being flown (operated remotely) and positioned by hand. In particular, the performance of the proposed 3D-DIC UAV proves its accuracy in measuring the evolution of displacements characterizing the expansion and the contraction of a joint with an accuracy comparable with that obtained with a dial caliper. Also, the results have shown that the system outperforms the accuracy that can be obtained when visual inspection techniques are employed. This research contributes to the overarching goal of developing a SHM system that can accurately monitor the condition of bridges, provide quantifiable measurement results, and minimize the interference with infrastructure functionality. The non-contact aspect of the optical measurement approach lends itself to automated recordings and allows for more frequent and cost-effective measurements of bridge conditions. Further development of this system may include methods to overcome the substantial challenge of positioning and localization in GPS denied environments, in stitching the point cloud data sets for scanning large areas of interest (e.g. complete walls, columns, etc.), and in determining other challenges associated with performing measurements from UAVs (e.g. effect of lighting, drone unwanted oscillations, etc.). It is expected that a fully developed system would be able to monitor relative movement over the entire area of a bridge in a few hours and increase the inspection frequency helping to improve infrastructure safety while enabling condition based maintenance and reducing the downtime associated with inspections. Though this paper is primarily focused on bridge inspection, the technology has potential to be applied to a variety of industrial and civil structures.

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