An autonomous unmanned aerial vehicle sensing system for structural health monitoring of bridges

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ABSTRACT

As civil infrastructure (i.e. bridges, railways, and tunnels) continues to age; the frequency and need to perform inspection more quickly on a broader scale increases. Traditional inspection and monitoring techniques (e.g., visual inspection, mechanical sounding, rebound hammer, cover meter, electrical potential measurements, ultrasound, and ground penetrating radar) may produce inconsistent results, require lane closure, are labor intensive and time-consuming. 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 have the merits of extracting full-field strain, deformation, and geometry profiles. These profiles can then be stitched together to generate a complete integrity map of the area of interest. Concurrently, unmanned aerial vehicles (UAVs) have emerged as valuable resources for positioning sensing equipment where it is either difficult to measure or poses a risk to human safety. UAVs have the capability to expedite the optical-based measurement process, offer increased accessibility, and reduce interference with local traffic. Within this work, an autonomous unmanned aerial vehicle in conjunction with 3D DIC was developed for monitoring bridges. The capabilities of the proposed system are demonstrated in both laboratory measurements and data collected from bridges currently in service. Potential measurement influences from platform instability, rotor vibration and positioning inaccuracy are also studied in a controlled environment. The results of these experiments show that the combination of autonomous flight with 3D DIC and other non-contact measurement systems provides a valuable and effective civil inspection platform.

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

1. INTRODUCTION

Bridges are typically designed to have a lifespan of approximately 50 years [1]. According to the American Society of Civil Engineers (ASCE), in 2013, the average age of the nation's 607,380 bridges was 42 years. This means that thousands of bridges are nearing or have exceeded their design life. As a result, 24.9% of the nation's bridges were classified as being functionally obsolete and 11% were classified as structurally deficient [2].

Visual inspection is still the primary method currently used to assess bridge health. Though the measurement processes is fundamentally simple, accessing critical areas beneath bridges often requires expensive equipment and interferes with traffic conditions. Additionally, there is significant variation between inspections performed by various personnel[3]. For example, small cracks will often go unseen, particularly if they track along existing features such as parting lines and the rate of expansion may not be properly estimated. Large scale deformations and internal damage are also particularly difficult to diagnose.

To improve the quality of bridge health monitoring data, more advanced measurement techniques have been implemented. Fixed hardware sensors such as strain gages, accelerometers, fiber optic sensors, and extensometers are becoming increasingly common in structural health monitoring [4, 5]. However, these devices often require power, implementation of data transmission methods, and only provide information for discrete points or along a line. Various

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non-contact measurement techniques such as GPR (ground penetrating radar), electro-optical airborne/satellite imagery, LiDAR (light detection and ranging), Thermal IR, Acoustics and InSAR (Interferometric Synthetic Aperture Radar) have been experiment with and each possess their own advantages and challenges [6].

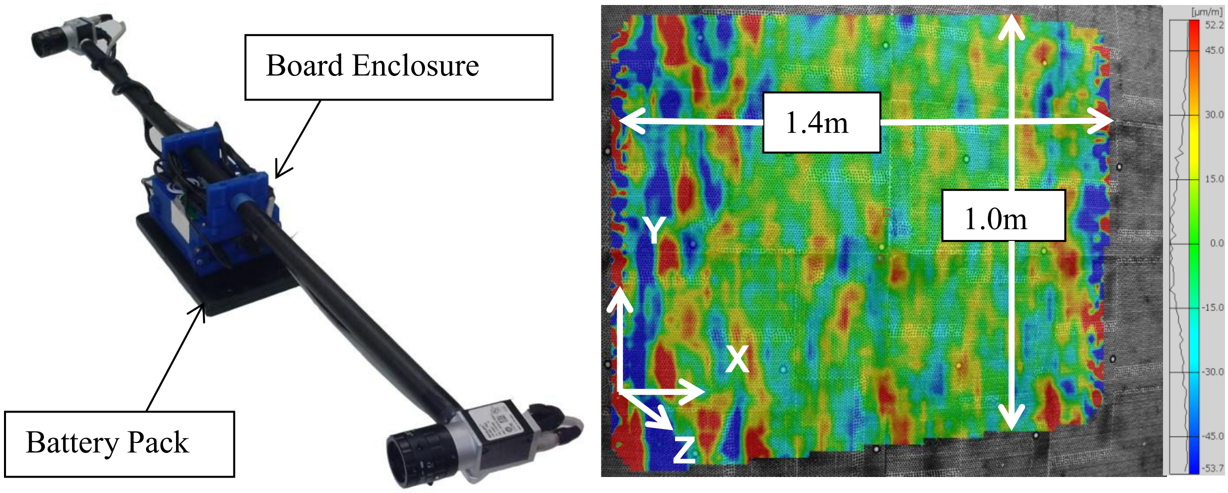
Three-dimensional digital image correlation (3D DIC) is a non-contact, full field, optical measuring technique capable of extracting surface strain, displacement and geometry profiles from images acquired through a synchronized stereo camera system. To perform these measurements, a stochastic pattern and/or optical targets are applied to the surface of interest. Subsequently, a series of photographs (stages) are taken by a synchronized pair of cameras as the surface deforms over time. In this work, GOM's software TRITOP and ARAMIS are utilized to calibrate the stereovision system and perform DIC to extract 3D information.

Previous work has demonstrated the capability of DIC to quantitatively assess bridge health [7-9]. On the other hand, unmanned aerial vehicles (UAVs) have emerged as valuable resources for positioning sensing equipment where it is either difficult to measure or poses risks to human safety. UAVs have the capability to expedite the optical-based measurement process for civil infrastructure [10, 11], offer increased accessibility, and reduce interference with local traffic. Additional work has demonstrated the feasibility of using processing algorithms to identify the position of target markers on bridges from UAV acquired images [10]. Within this work, an autonomous unmanned aerial vehicle in conjunction with 3D DIC was developed for monitoring bridges. This paper presents the preliminary results and description of the constructed UAV sensing platform and initial measurements used to demonstrate the feasibility to make DIC measurements in flight.

2. EXPERIMENTAL TEST SETUP

A stereoscopic camera system was created that could be flown on an InstantEye®Gen 4 Quadcopter. The system is capable of optically determining surface displacement and strain field as shown in Figure 1b. Remote operation of the stereovision payload is performed through an ad-hoc wireless network generated by a Minnowboard MAX dual-core single board computer (SBC) running a Linux Ubuntu 14.04 operating system. The pair of Basler acA1600-20 series cameras used employ Sony ICX274 charge coupled device (CCD) monochrome image sensors with a resolution of (1626 x 1236 pixels) and a pixel size of (4.4 x 4.4 µm). The cameras were fitted with 8.5 mm focal length lenses.

The cameras are positioned to have a 25 degree separation angle between the central line of sight and operate with a working distance of 1.75 m. In this configuration, the camera system is capable of measuring an area of 1.4 x 1.0 m. The remote camera system is shown in Figure 1b as configured for handheld measurements. An example of the noise floor for in-plane strain, as measured while the camera system and target are stationary is also shown. The measurement results for the mobile stereovision system under ideal conditions show a strain range of (-) 53.7 to (+) 52.2 µm/m. The expected noise floor for strain with the ARAMIS software with currently available stereovision systems is approximately +/- 50µm/m.



(a) (b)

Figure 1: Stereovision payload configured for off-UAV inspections (a) and noise floor for in-plane strain from a stationary measurement (b)

3. LABORATORY TESTS OF DIC DAMAGE DETECTION CAPABILITIES

Calibration of the new stereo camera system was validated by taking several pictures of a target object prior to inducing displacements and strains. The strain and displacement measured from the stationary system is referred to as the noise floor for the measurement and it generally indicates the minimum detectable measurement value achievable with the DIC system. Figure 2 shows a test fixture capable of displacing an aluminum patterned plate in 0.01mm increments along a lead screw attached to a dial indicator. The areas highlighted in green are the surfaces recognized by the DIC software and their position is recalculated at each stage. The locations of the white on black optical targets are also recalculated for at each stage with the purpose of defining a local coordinate system with an x-axis aligned with the axis of translation. This is exemplified in the results plotted in Figure 3. As it is possible to observe data recorded with the DIC system (green and red lines) are consistent with the well-known X-displacement provided to the structure (blue line). On the other hand, degradation in accuracy is observed as the payload is hand-held (red line) due to the manual repositioning of the cameras from their initial reference position. This implies that some measurement error can be expected as the cameras' position moves when flying.

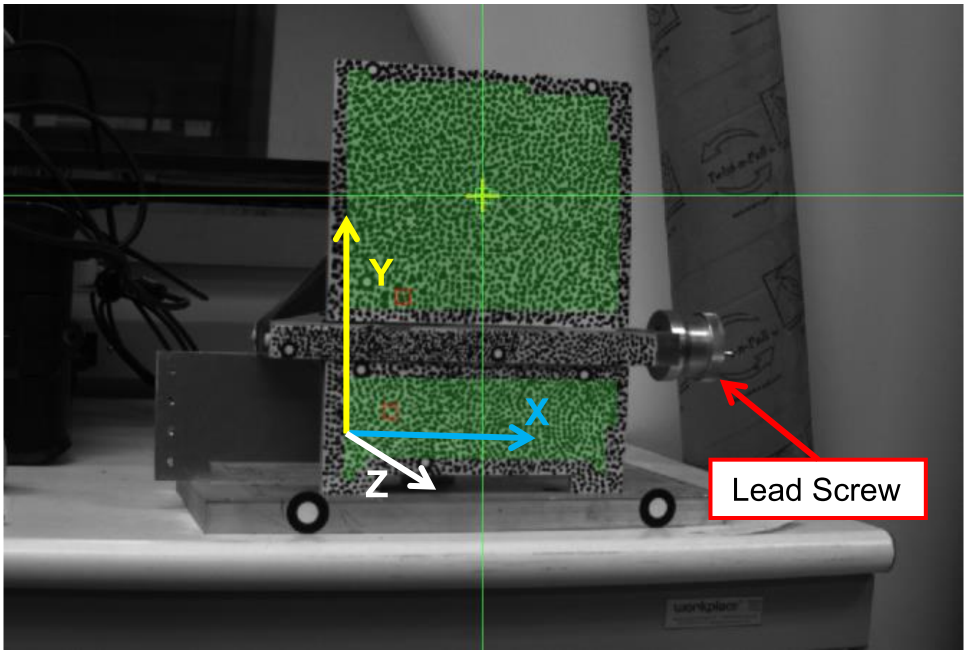


Figure 2: Experimental structure for inducing displacement

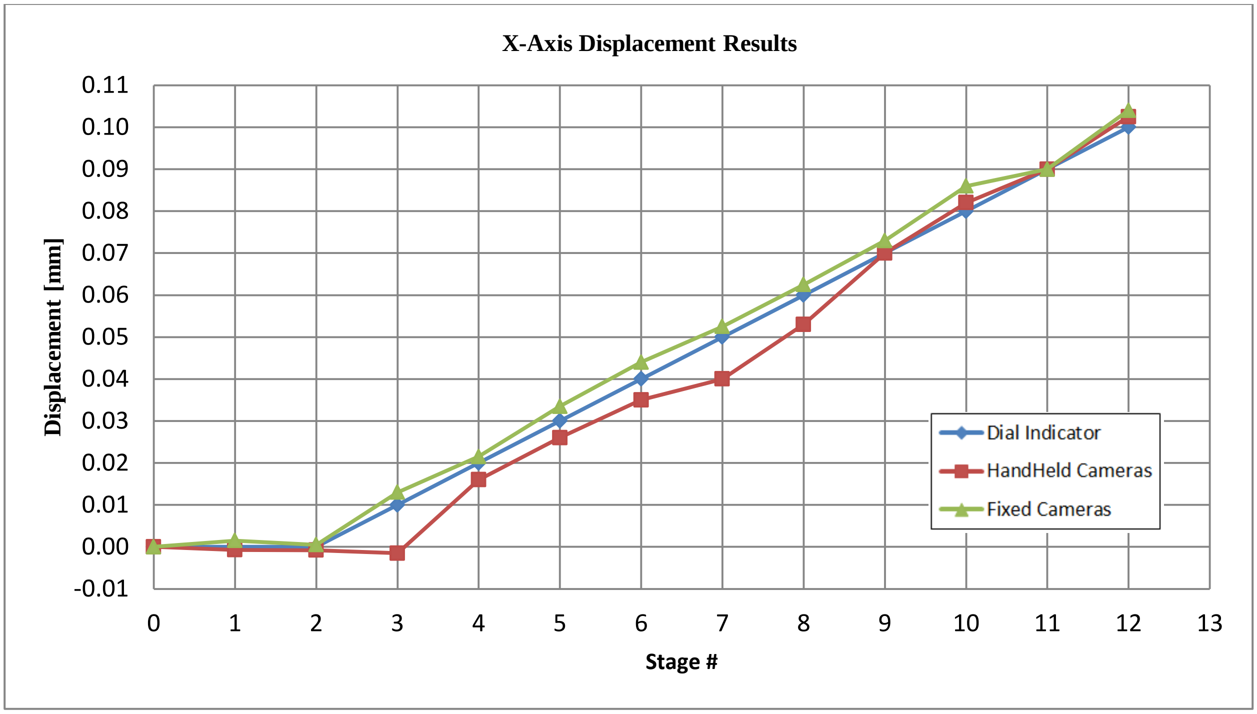


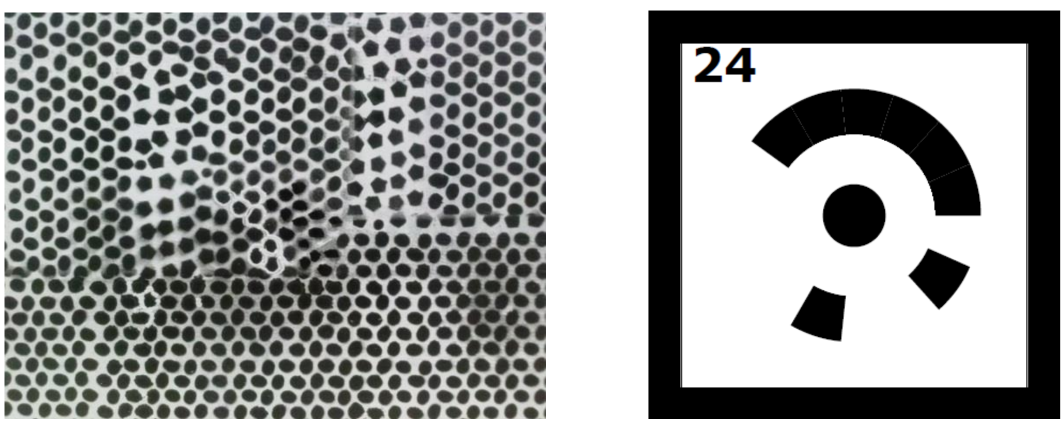
Figure 3: Comparison of displacement measurement results

4. BRIDGE MONITORING USING DIGITAL IMAGE CORRELATION (DIC)

The monitoring approach starts by making an initial measurement of an area of interest on a bridge (obtaining the reference surface geometry and pattern). The area is then measured again after a period of time to quantify changes. Any change to the area can be quantified by comparing the current measurement to the initial reference measurement. Seven areas of interest on two bridges in Lowell, Massachusetts were patterned in preparation for continuous monitoring using the aforementioned DIC UAV system. The locations were specifically chosen to provide a significant range of measurable deformation and a variety of geometries. This allowed us to choose the most appropriate patterning to suit the navigation capabilities of the UAV. Measurements were made at locations that included both non-visible and visible cracks, expansion joints, flat walls, columns, and bridge cap faces.

Patterning of the target areas was performed by painting; templates were created using custom 0.014” thick polyethylene terephthalate (PET, Mylar®) stencils. Defined patterns were cut using an Epilog 60-watt laser cutter to allow a semi-regular black-on-white dot pattern to be applied. An example is shown in Figure 4a. The stencils were adhered to the bridge surface using 3M Spray Mount™ repositionable adhesive and were re-used throughout the patterning process. Customized stencils offer several advantages including a specified pixel/dot size, controlled irregularities in patterns to assist with location identification, and application of optical targets within the patterning process. A thickness of 0.014” proved to be highly robust and adhered adequately to imperfect concrete surfaces; however a reduced thickness PET or single use, adhesive-backed decal type stencil would be recommended for highly deteriorated areas such as where surface spalling has occurred.

The pattern was generated to produce dots approximately 5-7 pixels in diameter which is the recommended size for strain measurement using GOM Aramis DIC software. In addition to the high contrast pattern, larger dot targets and coded optical targets were applied to the areas of interest (see Figure 4b). These reference points are used within the Aramis software to assist with stage stitching and create local coordinate systems. The coded targets and their high contrast edges are utilized by the UAV’s visual position control and navigation system.



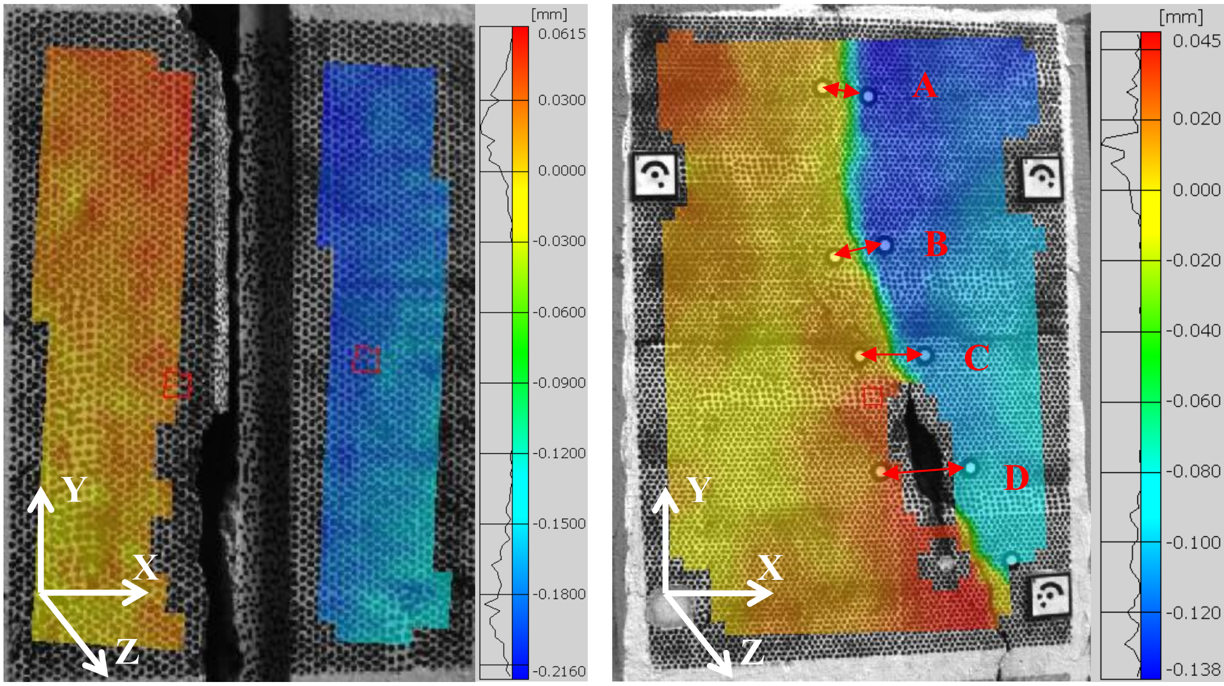
(a) (b)

Figure 4: Example of an applied pattern used for field inspections (a) and coded optical target (b)

4.1 Field Displacement Data from Handheld DIC Measurements

In preparation for UAV inspections, handheld measurements were performed using the remotely operated stereovision payload. Full-field X-direction displacement data obtained from an expansion joint and nearby crack on November 30th 2015 compared to measurements made on February 17th 2016 is shown in Figure 5. Both areas show a clear indication of contraction, with maximum relative displacement values of 0.2775 and 0.183 mm for the joint and crack, respectively.

The displacements are hypothesized to be the result of thermal contraction as there was a decrease in average temperature from 40 to 27 degrees Fahrenheit from November to February.



(a) (b)

Figure 5: X-axis displacement of (a) bridge abutment expansion joint and (b) nearby crack

If it is undesirable to fully pattern an area of interest, dot targets can be adhered to the surface and their position and displacement can be determined from one measurement to the next. The relative horizontal displacement between the targets identified in Figure 5 is shown in Table 1. With the exception of target pair (C), the displacement values obtained from the dot targets are in the range of values calculated from the pattern area. The discrepancy is possibly due to the fact that the position of the dot targets is calculated differently than the facets which make up the full field geometry profile.

Table 1: Point to point displacement of the targets shown in Figure 5 in the x-direction of measurements made on November 30th 2015 compared to measurements made on February 17th 2016

Target Pair	ΔX [mm]
A	-0.151
B	-0.112
C	-0.190
D	-0.113

5. INTEGRATION OF DIC SENSOR SYSTEM WITH UAV PLATFORM

A UAV must be capable of waypoint navigation and localization in a GPS denied environments in order to perform autonomous inspections of bridges. To provide positioning information of the vehicle and sensors, the civil inspection UAV platform under development by Physical Science Inc. (PSI) will augment its GPS+IMU (Inertial Measurement

Unit) fusion position estimation algorithm with vision-aided estimation. This is similar to the simultaneous localization and mapping (SLAM) payload that PSI uses to provide autonomous localization in GPS denied environments. An example of previous data is shown in Figure 6. The calibrated HD cameras will use visual features extracted from the target (bridge) to provide enhanced position estimation using state of the art photogrammetry and SLAM algorithms. To achieve this, the UAV will need to make a calibrated "map" of the target area. The calibration is initiated by placing a set of coded targets (see Figure 4b) at known (measurable) locations over the target. PSI's UAV then uses this information and the proprietary algorithms developed by PSI for SLAM, to define visual features on the target (bridge face).

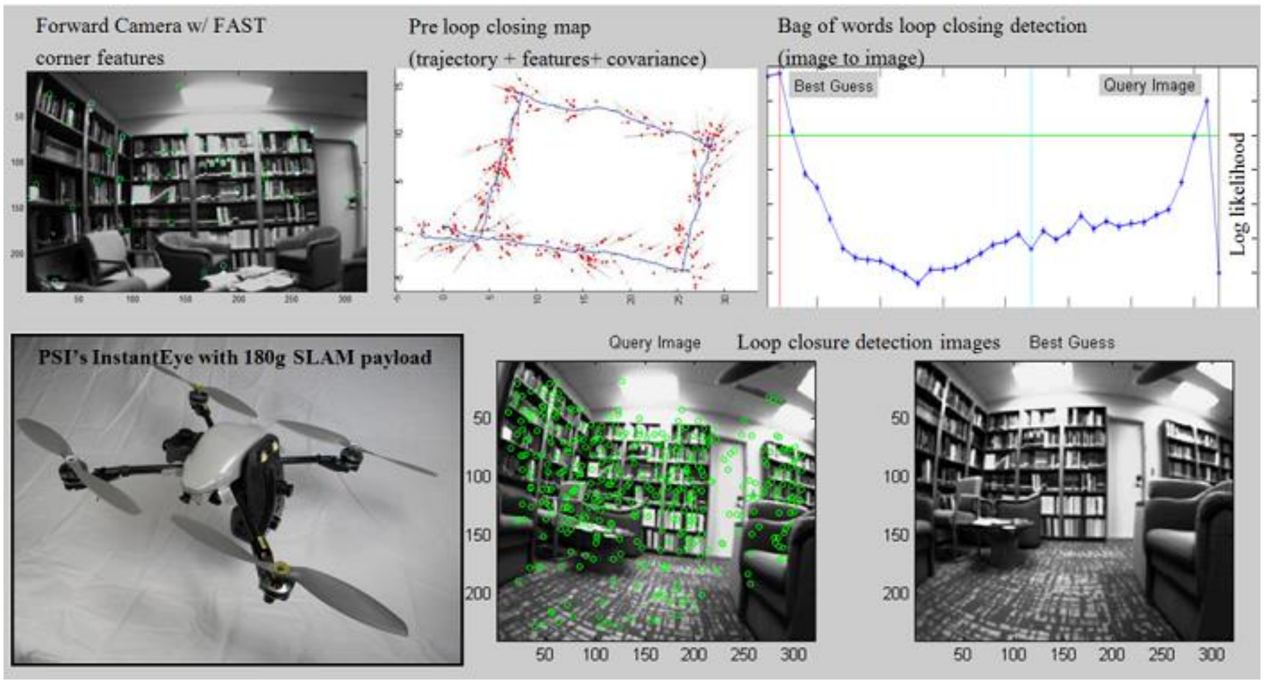


Figure 6: Results from monocular SLAM payload flown on PSI InstantEye at the moment of loop closing detection [12]

An indoor flight test was performed with the stereovision payload attached to the PSI InstantEye Mk2 Gen4 Medium Lift Variant (see Figure 7) and noise floor measurements were taken of a pre-patterned foam board to ensure all systems were functioning properly. The noise floor results for the in-flight measurement are shown in Figure 8. Results show a displacement range of (-) 0.217 to (+) 0.515 mm (see Figure 8). These values are expected to improve as the UAV's SLAM sensor payload is implemented into the current generation InstantEye UAV and measurements are made closer to the working distance that the cameras are positioned and calibrated to measure from.

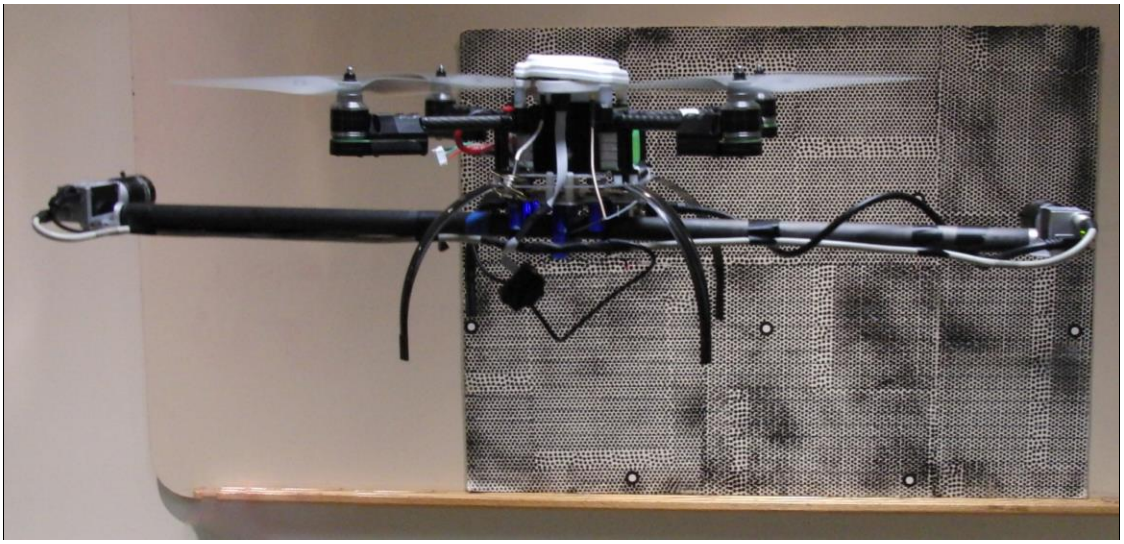


Figure 7: Physical Science Inc. InstantEye Mk2 Gen4 with Stereovision payload

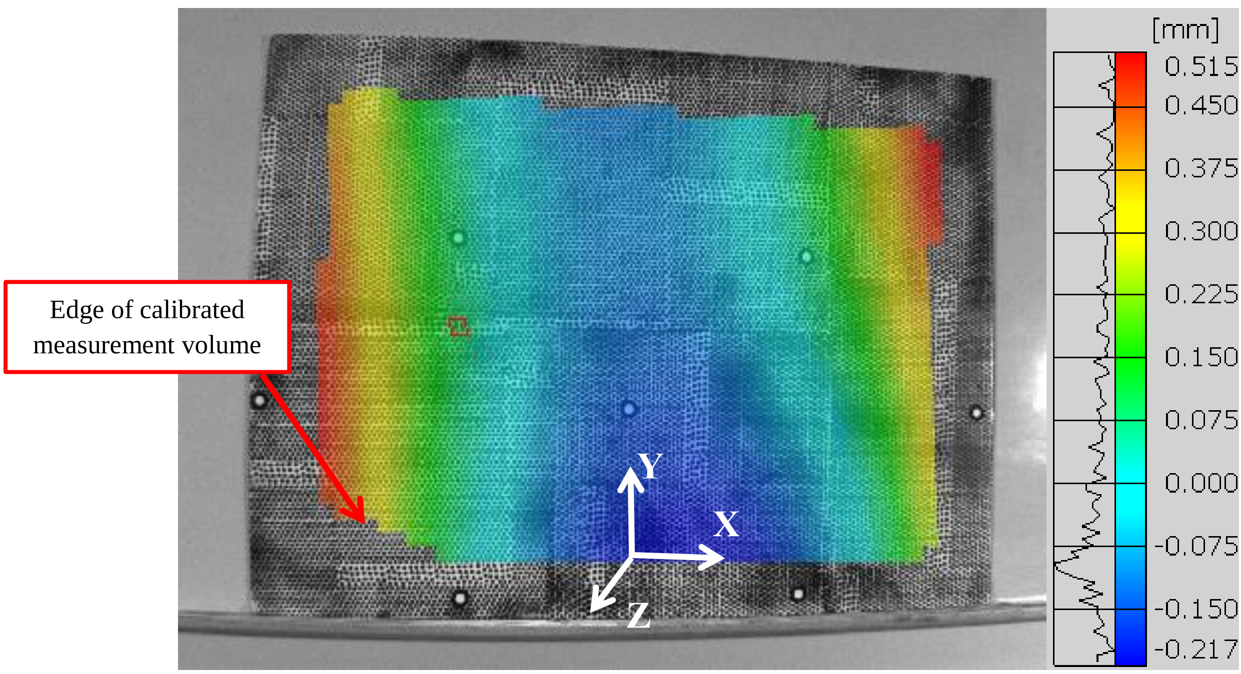


Figure 8: X-axis displacement noise floor from in-flight DIC measurement

6. CONCLUSIONS

The lightweight remotely operated stereovision system has proven to be capable of acquiring useful data for digital image correlation measurements in a handheld environment. The system has additionally demonstrated its ability to monitor the displacement of joints and cracks at full field and at discrete points while being positioned by hand and operated remotely. Methods to overcome the substantial challenge of positioning and localization in GPS denied environments were discussed. Preliminary 3D DIC data acquired from a UAV platform is presented. DIC data from fully autonomous flight test in without GPS guidance remains to be performed. The results of this paper show that 3D DIC has great potential for integration with UAV systems. Future work will focus on identifying noise induced through rotor vibration and determining other challenges associated with performing measurements from UAV's. Methods of managing and interpreting the substantial amounts of data that would potentially be extracted from a completely autonomous inspecting will also be investigated. 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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