A novel camera localization system for extending three-dimensional Digital Image Correlation Measurement

Alessandro Sabato1, * Narasimha Reddy2, Sameer Khan2, and Christopher Niezrecki1

1 Department of Mechanical Engineering, University of Massachusetts Lowell, 1 University Avenue, Lowell, MA, USA 01852
2 Department of Computer Science, University of Massachusetts Lowell, 1 University Avenue, Lowell, MA, USA 01852

ABSTRACT

The monitoring of civil, mechanical, and aerospace structures is important especially as these systems approach or surpass their design life. Often, Structural Health Monitoring (SHM) relies on sensing techniques for condition assessment. Advancements achieved in camera technology and optical sensors have made three-dimensional (3D) Digital Image Correlation (DIC) a valid technique for extracting structural deformations and geometry profiles. Prior to making stereo-photogrammetry measurements, a calibration has to be performed to obtain the vision systems’ extrinsic and intrinsic parameters. It means that the position of the cameras relative to each other (i.e. separation distance, cameras angle, etc.) must be determined. Typically, cameras are placed on a rigid bar to prevent any relative motion between the cameras. This constraint limits the utility of the 3D-DIC technique, especially as it is applied to monitor large-sized structures and from various fields of view. In this preliminary study, the design of a multi-sensor system is proposed to extend 3D-DIC’s capability and allow for easier calibration and measurement. The suggested system relies on a MEMS-based Inertial Measurement Unit (IMU) and a 77 GHz radar sensor for measuring the orientation and relative distance of the stereo cameras. The feasibility of the proposed combined IMU-radar system is evaluated through laboratory tests, demonstrating its ability in determining the cameras position in space for performing accurate 3D-DIC calibration and measurements.

Keywords: Calibration, Digital Image Correlation, Inertial Measurement Unit, MEMS, Radar, Structural Health Monitoring.

1. INTRODUCTION

Civil, mechanical, and aerospace structures continue to routinely be used despite the fact that they are approaching or have already exceeded their design life. Therefore, the need to assess structural integrity is more important than ever and efficient and low-cost monitoring techniques are actively being sought. Recent developments in camera technology, optical sensors, and image-processing algorithms have made stereophotogrammetry and three-dimensional (3D) Digital Image Correlation (DIC) an appealing tool for Structural Health Monitoring (SHM) and Non-Destructive Inspection (NDI) of structures, as well as for dynamic testing. In particular, 3D-DIC has been shown to be an accurate method in providing quantitative information about full-field displacement, strain, and geometry profiles of a variety of structures from images acquired using a pair of synchronized stereo-cameras. Notable examples include monitoring of bridges [1], railroad tracks [2], wind turbine blades [3], and rotating machinery [4] among the other.

The fundamental principle of 3D-DIC relies on matching the same physical point between a reference state and the altered configuration [5]. Before performing stereo-photogrammetry measurements, the position of the cameras relative to each other and the distortions of the individual lenses must be determined [6]. Calibration is performed on the cameras’ useful measurement volume to obtain the radial distortion coefficient together with the extrinsic and intrinsic parameters for each vision system (see Figure 1a) [7]. The most straightforward technique used for calibration purposes only requires the camera(s) to observe a planar pattern shown at least two different orientations [8]. Calibration for a field of views up to ~2 meters are performed by taking several pictures of National Institute of Standards and Technology (NIST) - traceable calibration objects (e.g., panels or crosses) containing optical targets (i.e., dots) whose positions are previously well-known (see Figure 1b). This procedure creates calibrated measuring volumes that are approximately the same width as the calibration object. This information is required for computing the three elementary transformations needed for the pinhole camera model to obtain the 3D coordinate of any physical point using the triangulation theory [5, 9]. These include the conversion of global coordinates of a target object to the camera system coordinates, projection transformation into the retinal plane, and transformation into the sensor coordinate system in pixel units. Then a photogrammetry process known as bundle adjustment is used to establish the precise relationship.
between the two cameras. Once a system is calibrated, the relative position of the cameras must not be altered. Otherwise, measurement errors will occur. Therefore, the camera pairs are rigidly mounted to a stiff bar (generally no longer than 3 m in length) or are fixed on stable tripods. As the dimensions of the targeted object increases, a more complex procedure needs to be performed (i.e., large-area calibration). This operation is arduous as it involves the use of coded and uncoded targets that have to be placed on an area having dimensions comparable to that of the object to be tested (see Figure 1c). Moreover, calibration itself is time-consuming because the distance between several pairs of targets needs to be measured to be used as scale bars, and because each camera must be independently calibrated before acquiring the last picture with the two cameras placed in their final position for calculating the relative geometry of the stereo-vision system.

An example of this procedure is shown in Figure 2, where the procedure for obtaining a large-area calibration performed on the ~7m x 7m area shown in Figure 1c is summarized.

Figure 1. a) Visualization of a typical 3D-DIC camera system and calibrated measurement volume; b) example of calibration target recognition on a coded calibration cross having dimension of 1m x 1m; c) a very large wall mounted with optical targets being used for calibration of a ~7m x 7m area.

Figure 2. Schematic of a large-area calibration procedure using 14 coded and 42 un-coded targets over a calibration surface with dimensions approximately 7m x 7m: (a) calibration for the right camera requiring images taken from 12 different views of the target array; (b) calibration for the left camera requiring images taken from 12 different views of the target array calibration; (c) acquisition of the last images of the calibration panel array using both cameras in their final relative position.
Performing the calibration over this field of view requires: (1) fabrication of a calibration panel approximately the same size as the measurement test section (see Figure 1c), (2) manufacture of a very heavy and stiff calibration bar to mount the cameras, and (3) taking 25 separate camera images in various positions or orientations. Once the final picture is taken, the location of one camera concerning the other cannot change. Any change in cameras’ orientation or position will affect the calculated extrinsic parameters values and will result in errors in the estimation of the displacement and strain fields. The fabrication of the calibration panel, the camera bar, and the sensitivity of the cameras to relative motion make the current large-area calibration procedure difficult and not practical to perform SHM, NDI, and dynamic testing for larger-scale structures such as bridges, wind turbines, and tall buildings.

In this paper, the preliminary design of a novel wireless sensor board embedding a MEMS-based Inertial Measurement Unit (IMU) and a 77 GHz radar unit for determining the orientation and distance of cameras in space is presented. The design schematics, selected components, software adjustments, and the laboratory tests performed to evaluate the measurement accuracy are described. Each sensor is compared with its commercially available counterpart to determine whether or not it can be used to provide data for determining the seven degree-of-freedom (DOF) needed to identify the cameras relative position. If fully developed, the proposed system would enable to achieve easier measurements on large-scale engineering structures and infrastructure that require periodic inspections.

2. SENSOR BOARD DEVELOPMENT

To perform the calibration for stereo-photogrammetry, the relative distance between the cameras and their orientation needs to be determined whenever images are recorded. So far, all calibration techniques rely on self-calibration via both targeted planar arrays and targetless scenes [10, 11]. The proposed measurement system will streamline the calibration process by 1) enabling the determination of the cameras’ relative position for each image sample (eliminating the need for a camera bar and calibrated panel); 2) removing the need to perform the cumbersome calibration prior to testing; and 3) allowing the cameras to be movable during test, thereby opening the door for long-term monitoring (i.e., camera de-calibration is no longer an issue due to movement).

IMU sensors have been widely used for providing low-cost but accurate real-time navigation, guidance, and control of unmanned aerial vehicles focus on delivering reliable detection and localization to maintain a stable attitude and a correct heading direction during flight [12 - 14]. The use of IMU module for photogrammetry applications is still limited to few applications, mostly concerning the onboard georeferentiation of the captured images by a single UAV [15, 16] or the off-board georeferentiation using at least three points and an already calibrated camera [17]. On the other hand, radar units have often been used for determining the distance (or its change) between two objects in space for dynamics analyses [18], modal identification [19], and structural deflection [20]. A schematic diagram of the proposed sensor package is shown in Figure 3.

![Diagram of the proposed sensor board](image)

Figure 3. Flow diagram of the proposed sensor board embedded on a Microcontroller Unit to be installed on a set of cameras.
To realize the sensor package, primarily off-the-shelf components have been used and integrated on a MCU Raspberry Pi 3 Model B developed by Raspberry Pi Foundation [21]. The IMU is an ICM-20948 sensor produced by InvenSense [22]. It is a low power 9-axis motion tracking device (suited for smartphones, tablets, wearable sensors, and Internet of Things applications) embedding 3-axis gyroscope, 3-axis accelerometer, and 3-axis compass. The sensor is installed on an evaluation board EVICM-20948 commercialized by InvenSense [23] for connecting the sensor itself with a daughterboard BRD_CARRIER [24] used for programming and controlling the operations. An MCU STM32F411RE manufactured by STMicroelectronics [25] is used for interfacing the IMU sensor to a laptop computer for data streaming. This interface provides very reliable access to the component, through MotionLink software or C/C++ codes using customized libraries (e.g., Workbench). This whole setup includes an interface for the IMU itself, and a NUCLEO board, all powered individually, using USB Cables. No external power supply is required since the system can be powered using the ± 5V power supplied by any computer’s Universal Serial Bus (USB) port. The radar unit is a 77 GHz sensor RS3400W/04 developed by SiversIMA [26], which is interfaced to a laptop for data streaming using a Controller Board - CO1000A/01 provided by the same company [27]. The radar setup involves the usage of an external 12V power supply and a ± 5V input for powering the Controller Board. A standard gain pyramidal horn antenna was used to collect the backscattered signals. A detail of the various components used is shown in Table 1.

Table 1. Used components and primary functions.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Purpose</th>
<th>Image</th>
<th>Equipment</th>
<th>Purpose</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICM-20948</td>
<td>Sensing of roll, pitch, and yaw angles</td>
<td></td>
<td>RS3400W/04</td>
<td>Distance measurement</td>
<td></td>
</tr>
<tr>
<td>EVICM-20948</td>
<td>Sensor board with embedded IMU sensor</td>
<td></td>
<td>CO1000A/01</td>
<td>Interface radar sensor with computer for data streaming</td>
<td></td>
</tr>
<tr>
<td>BRD_CARRIER</td>
<td>Testing of the EVICM-20948</td>
<td></td>
<td>Antenna</td>
<td>Signal reception</td>
<td></td>
</tr>
<tr>
<td>STM32F411RE</td>
<td>Interface sensor board to computer for data streaming</td>
<td></td>
<td>Raspberry Pi 3</td>
<td>IMU and radar sensors data acquisition and synchronization</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Model B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both IMU and radar have been programmed using suitable codes. In particular, the IMU relies on an ad-hoc Python library that allows the BRD_CARRIER to setup the EVICM-20948 (e.g., sampling frequency, dynamic range, number of sensors active) and receives the sampled data before transmitting them to a laptop via the STM32F411RE. The radar employs a set of customized Python codes for enabling measurements, data recording, and data streaming through an RS232 to USB interface. Details about those codes are here omitted for the sake of brevity.

3. EXPERIMENTAL SETUP

Several laboratory tests were performed to evaluate the performance of the proposed systems. The first set aimed to demonstrate that radar accuracy in measuring distance relevant to 3D-DIC applications is comparable with the precision of traditionally used measurement systems. The second one was performed to evaluate IMU consistency in measuring angles. The experiments referred to a stationary signal acquisition of the data recorded using the 77 GHz unit and a direct comparison with traditional length measurement devices, while the second set of tests employed a back-to-back comparison with an inclinometer embedded in a cellphone. A detailed description of the performed experiments is provided in the following sections.

3.1 Evaluation of the accuracy of the 77 GHz radar sensor in measuring distances

To evaluate the accuracy of the radar, a back-to-back comparison has been performed with a tape measure and a laser displacement sensor model DLR130K, manufactured by Bosch. Both auxiliary systems have an accuracy of ± 1·10^{-3} m,
while radar systems can measure distance with a theoretical precision of half of their wavelength $\lambda$. For a 77GHz radar, $\lambda$ is equal to $3.896 \cdot 10^{-3}$ m; therefore, measurement accuracy of $\sim \pm 2 \cdot 10^{-3}$ m should be expected. Since the 77GHz sensor does not provide results in engineering units (e.g., length, L or time, T), a calibration procedure has been developed that allows matching the readings from the radar with those from a tape measure. Then, once a reliable calibration curve has been obtained, a comparison with the readings from the laser tape measure has been carried out to determine the average measurement error. Figure 4 shows the experimental setup used for determining the calibration curve and performing the comparison.

![Figure 4. Experimental setup for radar calibration: (a) deployment of the three different systems used for comparison; (b) side view of the three displacement sensors relative to the target object.](image)

As can be seen in Figure 4b, the three measurement systems have been placed on a four-wheel cart that was moved away from a target object consisting of a wood panel positioned perpendicular to the direction of propagation of the radar’s signal. The cart has been moved away from the target object with random increments and, for each of the positions used, a total of seven measurements have been recorded with the radar and the laser displacement sensor.

![Figure 5. Calibration curve and scale factor for determining distance compared to the radar’s readings.](image)

A significant number of measurements allowed for data averaging and statistical parameters determination (e.g., average and standard deviation, $\sigma$). The average of data measured using the radar for each position (in radar units) has been compared to the distances measured by the measuring tape. This procedure enabled the researchers to determine a curve that can be used for converting the radar readings into physical engineering units (i.e. meters). Figure 5 shows the calibration curve obtained for a measurement range from 1 to 8 m. For instance, as the radar is providing a reading of 75.6866 it corresponds to a distance of $1998 \cdot 10^{-3}$ m $\pm 1 \cdot 10^{-3}$ m measured using the tape measure.
As observed from Figure 5, the relation between the radar readings and the distance measured using the tape measure is linear, and the data correlation is excellent (i.e., \( R^2 = 0.999993 \)). To further validate the accuracy of the 77 GHz radar unit and the defined calibration curve, a back-to-back comparison with data recorded using the laser displacement sensor has been performed. The results of this experiment are summarized in Figure 6.

![Figure 6. Comparison of the distance measured using the laser tape measure and the 77 GHz radar.](image)

The difference between the two sets of data is on average equal to \(2.46 \times 10^{-3} \text{ m} \) (on the same order of magnitude of the theoretical accuracy of a 77 GHz radar system), with a maximum error equal to \(5.29 \times 10^{-3} \text{ m} \) recorded for a distance of 1.662 m. Error in the measurement may be attributed to the not perfect alignment of the cart to the target object resulting in an angle between the laser tape and the radar sensors. Further investigations are required to refine those findings.

### 3.2 Evaluation of the accuracy of the IMU sensor in measuring orientation

An IMU is an electronic device that can measure a body's, acceleration, angular rotation, and magnetic heading, using a combination of accelerometers, gyroscopes, and magnetometers. The accelerometer provides detection of gravity and can measure pitch and yaw. The gyroscope’s data provide a rate of rotation or relative motion, but not an absolute position (x, y, z). Therefore, the motion vectors can be integrated to estimate change from a known position, while the magnetometer can be used for detecting the change in magnetic field to determine rotation from North. The numerical relationship used for determining the roll, pitch, and yaw angle from the IMU reading are shown below:

\[
\theta_{\text{pitch}} = \tan^{-1} \left( \frac{\text{Acc}_x}{\sqrt{\text{Acc}_y^2 + \text{Acc}_z^2}} \right) \\
\theta_{\text{roll}} = \tan^{-1} \left( \frac{\text{Acc}_y}{\sqrt{\text{Acc}_x^2 + \text{Acc}_z^2}} \right) \\
\theta_{\text{yaw}} = \tan^{-1} \left( \frac{\text{Acc}_z}{\sqrt{\text{Acc}_x^2 + \text{Acc}_y^2}} \right)
\]

(Eq. 1)

(Eq. 2)

(Eq. 3)

To determine the accuracy of the IMU, the sensor has been rotated and therefore subjected to different values of the gravity acceleration for a given component vector, and readings have been used in a back-to-back comparison with an inclinometer application embedded in a cellphone. To facilitate the rotation, the IMU and cellphone have been attached to a rotation stage in a setup similar to that shown in Figure 7. During the test, the stage has been rotated with 10° increments from 60° to -60°. For each position, 30 seconds readings have been recorded to allow data averaging and significant statistical parameters evaluation. Ideally, only a single parameter (i.e., pitch or roll) at a time is supposed to change, with the other to remain stable within a tolerance of a few hundredths of a degree. Nevertheless, due to the setup used, changes in the other parameters were observed that might have affected the outcome of the experiments. Static acceleration data recorded have been used for calculating the values of pitch and roll using the equations (1 – 3) and are compared with the reading from the cellphone as summarized in Figures 8 and 9.
Figure 7. Experimental setup for IMU characterization: a) roll angle characterization setup and b) sensing axis of the IMU.

Figure 8. Comparison of pitch angles measured using the cellphone and the IMU sensor: a) Angle measured for different orientation of the translation stage and b) difference between the pitch (blue) and roll (red) angles between the IMU and the cellphone as the pitch angles are changed.

Figure 9. Comparison of pitch angles measured using the cellphone and the IMU sensor: a) Angle measured for different orientation of the translation stage and b) difference between the roll (blue) and pitch (red) angles between the IMU and the cellphone as the roll angles are changed.
Results plotted in Figure 8a and 9a show an excellent agreement between the IMU and cellphone data. From a more accurate analyses (see Figure 8b and 9b) it is observed that the difference between the two data sets is usually below 1°, but this difference increases as the non-dominant angle (i.e., roll for data reported in Figure 8 and pitch for data reported in Figure 9) rises. With reference to experiments summarized in Figure 8, the tests were performed to subject the IMU and the cellphone to increasing values of the roll angle. This means that as the roll angles increases with 10° steps, the value of the pitch angle should stay close to zero. As reported from data shown in Figure 8b, the pitch angle varies significantly as well and this may cause a larger difference between the roll angle values measured using the two systems. Increase in the roll angle from an ideal value of zero may be caused by (1) a non-perfect alignment of the experimental setup used, (2) the fact that the IMU and the cellphone are not perfectly co-located, and (3) error in the measurements performed by the cellphone. Similar conclusions can be drawn for the data shown in Figure 9. To finish, no information about the yaw angle has been determined at this time.

4. CONCLUSIONS

A novel sensor board prototype is proposed for measuring the seven degrees of freedom (i.e., the distance between the cameras, roll, pitch and yaw of camera #1, and roll, pitch, and yaw of camera #2) necessary for determining the extrinsic parameters of a set of paired cameras to be used for performing three-dimensional digital image correlation (3D-DIC). The system consists of an inertial measurement unit (IMU) and a 77 GHz radar unit embedded on a Raspberry Pi 3 microcontroller unit (MCU) board. In this study, the characterization of the two sensor units is introduced, and comparison with traditional measurement devices is presented to determine the accuracy of the proposed system.

A number of laboratory experiments have shown that the accuracy of the radar in measuring distances in a range from 1 to 8 meter is on average equal to $2.46 \times 10^{-3}$ m, while the IMU can detect change in the orientation with an accuracy of $\sim 1°$ when a back-to-back comparison with an inclinometer embedded in a smartphone is performed. An improved set of experiments has to be planned to better characterize the performance of the IMU and radar systems that can get rid of all the systematic errors that may have described the current version of the tests.

Nonetheless, results are extremely encouraging and may pave the road to further development of this research. The proposed system has the potential to transform the way existing small-scale photogrammetry and DIC measurements are made and will also enable quantitative analyses to be made at very-large-scale (>100 m) from multiple angles and positions. The proposed calibration system will also be insensitive to camera movement and therefore can be attached to a pair of unmanned aerial vehicles (UAVs) to enable measurement from multiple locations and fields of view. The use of the proposed system may allow the self-calibration of cameras as 3D-DIC analyses have to be performed eliminating the need for a rigid bar connection between the cameras, streamlining the calibration process, and extending the range of applicability that stereophotogrammetry and DIC can have.

REFERENCES