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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

RGB-D Digital Image Correlation technique for crack assessment through homography-based movement compensation on drones

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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1. Introduction

The thesis addresses an RGB-D digital image correlation [1] approach for crack measurements with sensors mounted on a moving reference (ex. drone). The aim of the thesis is to develop an algorithm capable of compensating the movements of the drone through homographies [2], thus providing accurate displacement results. The RGB-D sensor is composed by an RGB or greyscale camera (Flir camera) and by a depth sensor (Time of Flight – Blaze 101).

The capabilities of the approach are firstly tested with a simulator and then in a real laboratory application, showing promising results.

2. Algorithm description

On the acquired in motion images, 2D DIC is performed. With the depth information coming from the Time of Flight (ToF) sensor, it is possible to build the centre subset point clouds (x_{3D}, y_{3D}, z_{3D}) for each frame, thanks to the pin-hole model (Eq.2.1):

$$\begin{cases} x_{3D} = (x_{pix} - c_x) * \frac{z_{3D}}{f_x} \\ y_{3D} = (y_{pix} - c_y) * \frac{z_{3D}}{f_y} \end{cases} \quad 2.1$$

Where:

- x_{pix} and y_{pix} are the coordinates of each centre subset coming from DIC software (respectively for x-coordinates and y-coordinates);
- f_x, f_y, c_x, c_y are the intrinsics parameters of the camera (f: focal length (in pixels), c: optical centre (in pixels));
- z_{3D} is the z coordinate of each centre subset coming from the depth sensor.

The movement compensation is performed on an approximately fixed part of the measurand, if present, or on the entire set of points to remove the average displacement and leave the deformations. It is always done between a defined frame (reference frame) and all the others, to report all the data to the same reference.

Three different solutions for the camera movement compensation are evaluated:

- homography estimation with calculation based on the realignement of 3D point clouds of the centre subsets (approach recalled 'H 3D');

The use of homographies limits the application to approximately plane surfaces of the object of interest. This choice is made to average the effects of noisy depth to the best fitting plane, since ToF sensors have a poor accuracy, of the order of magnitude of millimeters [3].

The calculation of the homography is done according to Eq.2.2:

$$H = K * \left(R - t * \frac{n}{d}\right) * inv(K) \qquad 2.2$$

where the parameters are:

-K is the intrinsic parameters matrix in the form presented here below:

$$K = \begin{bmatrix} f_x & 0 & 0 \\ 0 & f_y & 0 \\ c_x & c_y & 1 \end{bmatrix}$$

-R and t are the rotation matrix and the translation vector which bring the reference frame XYZ coincident with the successive frame X'Y'Z;

-n is the normal of the plane evaluated from the reference frame XYZ;

-d is the known term of the plane ax + by + cz + d = 0 evaluated from the reference frame XYZ;

The inverse of this homography is applied to 2D homogenous coordinates of the centre subsets of the successive frames to report data to the reference frame.

- homography estimation based on the realignment of 2D set of points of the centre subsets (approach recalled 'H 2D');

The estimation is based on the MSAC algorithm, that, with a minimization procedure, calculates the induced best-fitting homography between reference and moved views. This allows to minimize eventual issues related to an imperfection in the depth estimation, because it is performed on 2D homogenous coordinates of the centre subset points. At the same time, since the algorithm is based on a projective trasformation, some deformations effects can be confounded as projective effects by the minimization algorithm, thus causing their undesired compensation.

- rototranslation estimation from point clouds of the centre subsets (approach recalled 'PC 3D');

The direct application of the rototranslation to the point clouds allows to work with objects that aren't strictly planar and provide information also on the third coordinate (z), but the noise effects of the ToF can induce inaccurate results.

Knowing the centre subset point clouds in the space also allows to apply a final transformation to report these points perpendicular to the optical axis of the camera. In this way, the misalignment of the object with respect to the axis of the camera is corrected.

After the above mentioned compensations, actual displacements and deformations are retrieved.

The outputs of the algorithm in case of the presence of a fixed part and a moving one for the x displacement is represented in Figure 2.1. The same output is obtainable for y (and z in case of 'PC 3D').

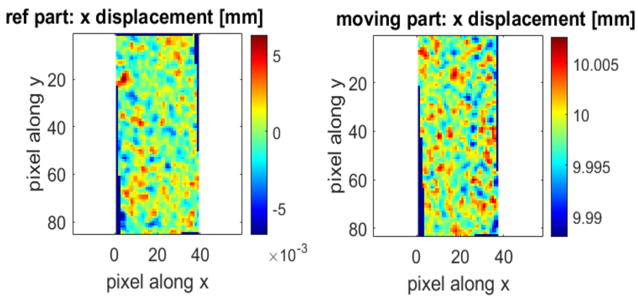

Figure 2.1: final output of the algorithm for reference and moving part

3. Algorithm testing methodology

In this paragraph the validation of the algorithm with the simulator and the experimental test are presented.

3.1. Numerical simulator validation

The algorithm is tested in a developed simulation environment to assess the ideal capabilities of the approach. The simulator generates greyscale images, acquired with a virtual moving camera, and corresponding depth maps. The speckle image (an example is shown in Figure 3.1) is divided in a fixed part, used for the movement compensation, and a moving part on which the displacement is tested. The moving part position is imposed in the simulator. The displacement between fixed and moving part simulate the crack opening.

The algorithm is tested with 7 different reference images (where the moving part displacement is set to 0) with diverse rototranslation values to validate the realignment perpendicular to the optical axis of the camera. Moreover, a set of 40 images with controlled crack size (moving part displacement) and defined rototranslation are considered to study the camera movement compensation.

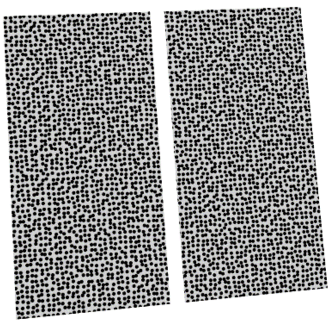

Figure 3.1: greyscale image obtained through the simulator

The results of the simulation tests are satisfying. The obtained uncertainty with all the 3 approaches for the camera movement compensation is, in average, below 2-3 hundredths of pixels, comparable with the intrinsic uncertainty of the standard DIC procedure [4]. This validates the proposed algorithm.

Moreover, the effects of the increase of the angles of rotations of the camera and of the increase of the crack size are assessed. An approximately linear trend for the average displacement value is present when the pitch and yaw angles increase but contained in a range comparable with the uncertainty of the measurement. Also, the standard deviation increases when the rotation is higher but not of a significant amount.

3.2. Experimental validation of the technique

After the simulator validation, an experiment is conducted to evaluate the approach in a real scenario as well as to understand the accuracy reachable with the sensors considered.
The laboratory experiment consists in the dynamical analysis of the crack displacement of a xps panel (shown in Figure 3.2). The pre-cracked panel, on which a speckle is painted, is cyclically loaded with a three point bending system. The RGB-D system is handheld to simulate the movements of the drone. Its results are compared to the data coming from a 3D DIC system that is considered as the ground truth.

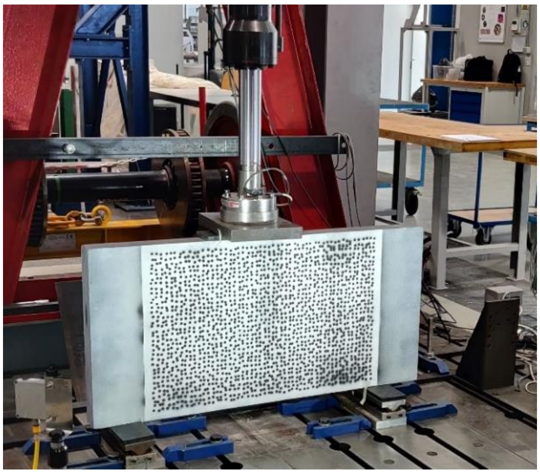

Figure 3.2: xps pre-cracked panel with painted speckle

The ‘PC 3D’ approach is discarded due to the fact that the accuracy of the Blaze is ±5 mm and because the panel is approximately flat.
The ‘H 2D’ and ‘H 3D’ approaches are tested against the DIC 3D. In correspondence of the crack two zones, one on the left and one on the right side of the crack are considered. The relative displacement between right and left is calculated

in the time. The derived time histories describing the crack opening are compared here below in Figure 3.3

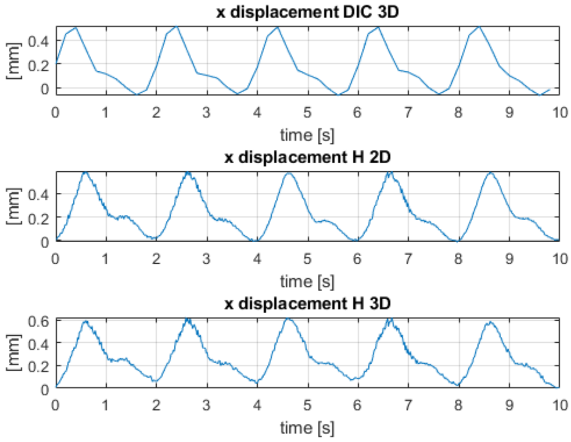

Figure 3.3: time histories retrieved with DIC 3D, H 2D and H 3D methods.

The perfect synchronization between the 3D DIC system and the RGB-D one was not possible. To compare more precisely the results, the normalized cross correlation between the two approaches with the 3D DIC time histories is performed. The cross correlation peak retrieval allows to realign the time histories.

Visually, the superimposition of the time histories is satisfying. The RMS error is calculated (Eq. 3.1) on the realigned graphs (Figure 3.4) to compare the two approaches (results shown in Table 3.1).

$$RMS_{error} = \sqrt{\frac{\sum_i (x(H)_i - x(3D\ DIC)_i)^2}{n-1}} \quad 3.1$$

	H 3D	H 2D
RMS error	0.038 mm	0.032 mm

Table 3.1: RMS error for H 3D and H 2D

'H 2D' seems to perform slightly better than 'H 3D' in terms of Root Mean Square value. This is not so significant to define the best technique since the calculation is valid only locally, in correspondence of the crack. Moreover, the values are very small and similar, comparable with the uncertainty of the measurement approach.

Considering all the displacement field of the panel, it is possible to see that qualitatively (according to Figure 3.5) the 'H 3D' approach behaves far better than the 'H 2D' one. The homography calculation on 2D points loses information in different parts of the panel. The deformations effects are confounded as projective movements of the camera by the minimization algorithm. The application of the derived homography causes their undesired compensation.

Concluding that, in the experimental scenario, with the addition of non perfectly planar object and of the deformations of the panel, the 'H 3D' approach results more robust compared to the 'H 2D' one. The calculation of the homography passing through 3D point clouds data allows to

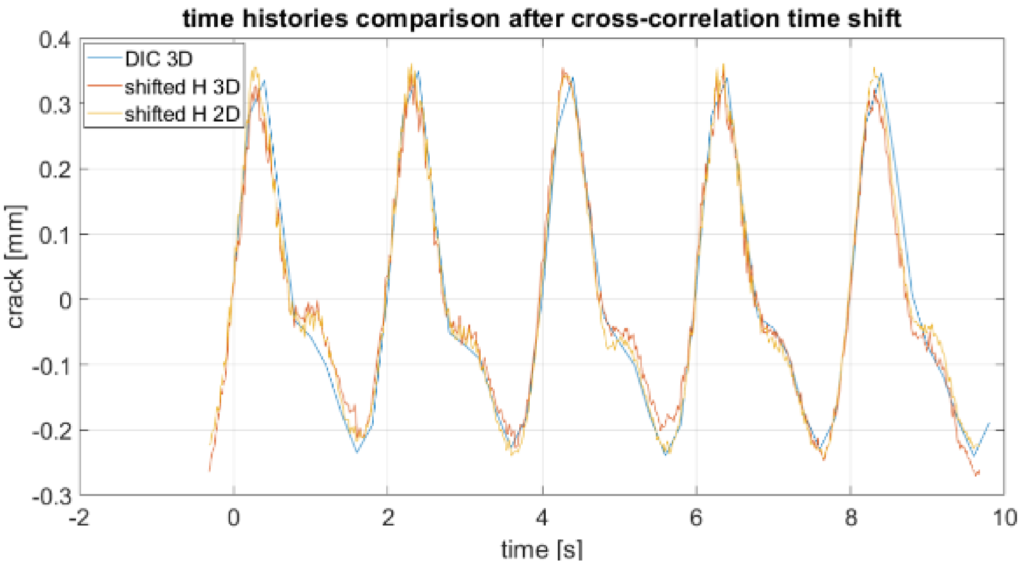

Figure 3.4: graph with the realignement of the time histories for the three different methods (DIC 3D, H 2D and H 3D)

avoid the 2D problem of confounding deformations and shape effects as projective effects by the 2D minimization algorithm. At the same time, the actual degree of uncertainty associated to ToF sensors does not permit to work directly with rototranslation applied to point clouds of centre subset points ('PC 3D'). The use of homography with the plane assumption minimizes the effects of ToF noise, providing accurate results.

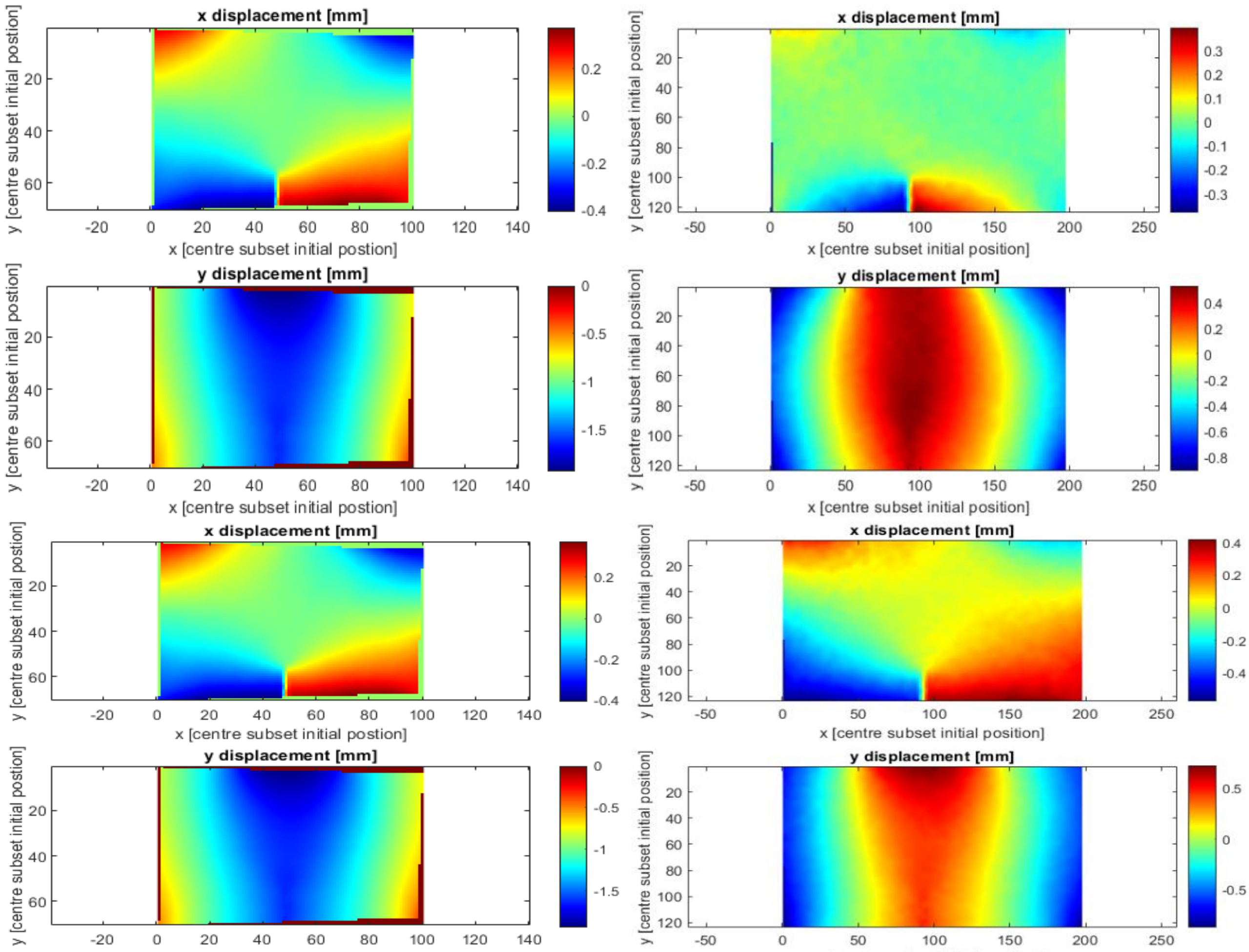

Figure 3.5: Final output with data from DIC 3D on the left part and from H 2D and H 3D respectively on the upper right (2 plots, one for x and one for y) and bottom right part (2 plots, one for x and one for y)

Conclusions

RGB-D digital image correlation with sensors mounted on a drone is an innovative technique that allows crack assessments on critical places (for example bridge decks), not easily reachable by men. The RGB-D sensor is suitable for drone transportation compared to a 3D DIC system, as well as much less expensive.

The implemented algorithm demonstrated to effectively compensate the drone movements, providing accurate information in the simulation environment.

In the laboratory experiment both the compensation with homographies from 3D rototranslation and from 2D centre subset points reconstructed accurately the local time history of the crack. The RMS error was contained below 0.04 mm against the ground truth 3D DIC in the two cases.

Instead, considering the entire deformation field of the panel, the approach based on the realignment with homographies calculated starting from the rototranslation of 3D centre subset point clouds was better. The calculation of the homographies on the 2D data brought a problem to the surface. In a real application the effects of deformations and not perfectly planar objects can be confounded as projective effects by the minimization algorithm, thus causing their undesired compensation. Working with a depth sensor and with point clouds allow to avoid this mistake.

4. References

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