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Adaptive subset offset for systematic error reduction in incremental digital image correlation

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ABSTRACT

Digital image correlation (DIC) relies on a high correlation between the intensities in the reference image and the target image. When decorrelation occurs due to large deformation or viewpoint change, incremental DIC is utilized to update the reference image and use the correspondences in this renewed image as the reference points in subsequent DIC computation. As each updated reference point is derived from previous correlation, its location is generally of sub-pixel accuracy. Conventional subset which is centered at the point results in subset points at non-integer positions. Therefore, the acquisition of the intensities of the subset demands interpolation which is proved to introduce additional systematic error. We hereby present adaptive subset offset to slightly translate the subset so that all the subset points fall on integer positions. By this means, interpolation in the updated reference image is totally avoided regardless of the non-integer locations of the reference points. The translation is determined according to the decimal of the reference point location, and the maximum are half a pixel in each direction. Such small translation has no negative effect on the compatibility of the widely used shape functions, correlation functions and the optimization algorithms. The results of the simulation and the real-world experiments show that adaptive subset offset produces lower measurement error than the conventional method in incremental DIC when applied in both 2D-DIC and 3D-DIC.

1. Introduction

Digital image correlation (DIC) is a non-contact optical metrology which extracts full-field deformation by matching corresponding locations in the images recorded before and after the deformation of the specimen [1–5]. When DIC is combined with stereovision (also termed as 3D-DIC), three-dimensional shape and deformation can be measured as well [4,6–8]. In order to find the correspondence of a reference point in a target image, a square subset of $M \times M$ pixels centered at the point is selected, and the target position of the subset is obtained by maximizing the similarity of the intensity values involved. Usually, the reference points are sampled in a pre-defined region of interest (ROI) in the reference image. Integer pixel locations are selected for the sample points, so that the intensity values of the subset pixels can be directly obtained from the digital image. On the contrary, the correspondences of the subset pixels in the target image often fall on non-integer pixel locations. In this case, one requires interpolation (e.g. bicubic interpolation) to reconstruct the intensities, which would bring systematic error in the measured displacement [9,10].

Unfortunately, the reference points may also have non-integer locations. This phenomenon can be prevalently found in incremental DIC which is widely used in large deformation measurement and 3D-DIC [8,11,12]. For instance, a large deformation can cause severe decorrelation between the initial undeformed image and the deformed image. In this case, one needs to substitute the original reference image with an intermediate image so that it can be correlated with the images afterwards [11]. When the reference image is renewed, the reference points are also being updated by the corresponding positions in the selected image (see Fig. 1). As each of these correspondences is generally of sub-pixel accuracy, the pixels in the subset centered at the correspondence have non-integer positions as well. Therefore, additional interpolation is required to compute the intensity values in the updated reference image.

Another common application of incremental DIC is 3D-DIC, which involves correlation not only between the images before and after deformation but also between the images in the left and the right viewpoint. Without loss of generality, the reference points are sampled at integer positions in the left undeformed image. In order to measure the 3D displacement of a point, three DIC computations are needed to acquire the correspondence in the right undeformed image, the left deformed image and the right

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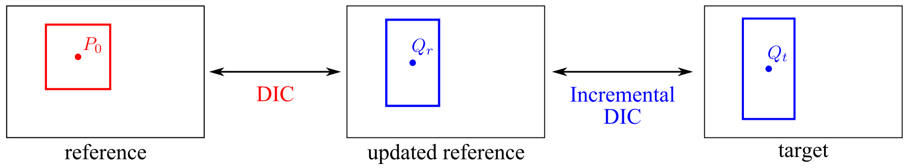

Fig. 1. Incremental DIC in 2D-DIC.

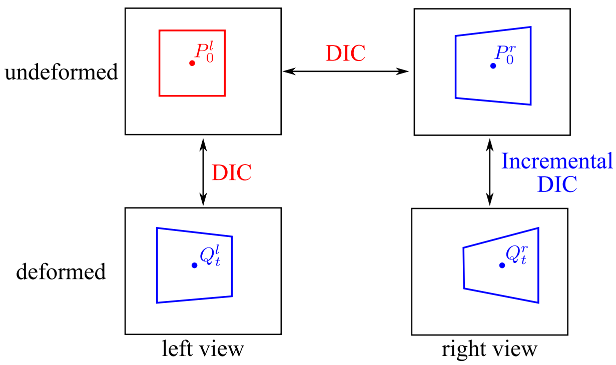

Fig. 2. Incremental DIC in 3D-DIC.

deformed image. As the image correlation is usually higher in the same view than the image correlation across the views, the last DIC computation involves incremental DIC which regards the previously matched position in the right undeformed image as the reference point (see Fig. 2). In this case, intensity interpolation is required in both the updated reference image and the target image.

As studies [9,10] show that intensity interpolation causes systematic error in the measurement result of DIC, additional interpolation for the reference intensity values is undesirable. We hereby propose adaptive subset offset to entirely avoid reference intensity interpolation even in the presence of non-integer location of a reference point. According to the decimal of the position of each reference point, the local subset is slightly translated up to half a pixel in both directions, so that the pixels in the translated subset always fall on integer locations. After the offset, no interpolation is needed to compute the reference intensities, although the reference point may have sub-pixel location. In addition, as the translation is relatively small compared to the subset size, popular shape functions, correlation criteria and iterative optimization can still be effectively used.

The rest of the paper is organized as follows. The basic principle of incremental DIC is described in Section 2. The proposed adaptive subset offset is detailed in Section 3. In Section 4, the proposed method is compared with traditional subset selection on simulated experiments. In Section 5, a real-world experiment of out-of-plane displacement measurement is adopted for validation. Finally, Section 6 gives the conclusion.

2. Incremental digital image correlation

2.1. Digital image correlation

Digital image correlation matches the corresponding locations in a reference image and a target image by maximizing the correlation of the intensity values in the two images. The most widely used correlation function is zero-mean normalized cross correlation (ZNCC) because of its robustness to change in image brightness and contrast [4,5,13]. Zero-mean normalized sum of squared difference (ZNSSD) is an alternative, expressed in a quadratic form which enables efficient optimization using iterative algorithms [14]:

$$C_{ZNSSD}(\mathbf{p}) = \sum_{\Omega}\left[\frac{F(x,y)-F_m}{\sqrt{\sum_{\Omega}[F(x,y)-F_m]^2}} - \frac{G(x',y')-G_m}{\sqrt{\sum_{\Omega}[G(x',y')-G_m]^2}}\right]^2 \quad (1)$$

where Ω is the set of points in the square subset centered at (x,y). $F(x,y)$ and $G(x',y')$ are the intensity values at corresponding locations in the two images. F_m and G_m are the mean intensity in the two subsets. As the images are digital, if any coordinate is non-integer, interpolation, e.g. bicubic interpolation [15–17], is required to estimate the intensity at sub-pixel locations.

The deformation parameter $\mathbf{p}$ encodes the information that we wish to acquire through the optimization. The parameter characterizes a shape function, which expresses the correspondences between the reference image and the target image. First-order shape function is the most popular due to its simplicity [15]:

$$\begin{cases} x' = x + u + u_x\Delta x + u_y\Delta y \\ y' = y + v + v_x\Delta x + v_y\Delta y \end{cases} \quad (2)$$

where $\Delta x = x - x_0$, $\Delta y = y - y_0$, and the deformation parameter $\mathbf{p} = (u, v, u_x, u_y, v_x, v_y)$.

Second-order shape function [18] is commonly used to approximate non-linear deformation, e.g. the image transformation between a pair of stereo images:

$$\begin{cases} x' = x + u + u_x\Delta x + u_y\Delta y + \frac{1}{2}u_{xx}\Delta x^2 + u_{xy}\Delta x\Delta y + \frac{1}{2}u_{yy}\Delta y^2 \\ y' = y + v + v_x\Delta x + v_y\Delta y + \frac{1}{2}v_{xx}\Delta x^2 + v_{xy}\Delta x\Delta y + \frac{1}{2}v_{yy}\Delta y^2 \end{cases} \quad (3)$$

where $(u_{xx}, u_{xy}, u_{yy}, v_{xx}, v_{xy}, v_{yy})$ are the additional second-order deformation parameters.

Because the correlation function is highly non-convex, iterative algorithm (e.g. Newton–Raphson or Levenberg–Marquardt) is often adopted to solve the optimization [15,19–21]. The algorithm starts from a reasonable initial guess of the deformation parameter, and then iteratively refines it until the optimal solution is reached [22–24].

2.2. Incremental digital image correlation

DIC relies on a high correlation between the intensity values of the corresponding positions in the two images involved. This assumption may be violated in some situations. For instance, when the specimen undergoes a large deformation, severe decorrelation can occur between the undeformed reference image and the deformed image [11]. DIC computation between these two images does not produce desirable displacement field. In this case, an intermediate image during the deformation is selected as the updated reference image in the correlation with the deformed image. The final displacement in the deformed image is the sum of the correlation result and the displacement in the updated reference image (see Fig. 1).

3D-DIC is another common situation where incremental DIC is applied. Two cameras are used to simultaneously record the deformation, and correspondences in all the captured images need to be recovered. Because of the difference in viewpoint and camera configuration, the correlation between images from different