Fast, Accurate and Fully Parallelizable Digital Image Correlation

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Abstract & Introduction

Digital image correlation (DIC) is a widely used optical metrology for surface deformation measurements [1]. DIC relies on nonlinear optimization method. Thus an initial guess is quite important due to its influence on the converge characteristics of the algorithm. In order to obtain a reliable, accurate initial guess, a reliability-guided digital image correlation (RG-DIC) method [2], which is able to intelligently obtain a reliable initial guess without using time-consuming integer-pixel registration, was proposed. However, the RG-DIC and its improved methods [2–4] are path-dependent and cannot be fully parallelized. Besides, it is highly possible that RG-DIC fails in the full-field analysis of deformation without manual intervention if the deformation fields contain large areas of discontinuous deformation. Feature-based initial guess [5–7] is highly robust while it is relatively time-consuming. Recently, path-independent algorithm [8], fast Fourier transform-based cross correlation (FFT-CC) algorithm, was proposed to estimate the initial guess. Complete parallelizability is the major advantage of the FFT-CC algorithm, while it is sensitive to small deformation. Wu et al proposed an efficient integer-pixel search scheme [9], but the parameters of this algorithm are set by the users empirically. In this technical note, a fully parallelizable DIC method is proposed. Different from RG-DIC method, the proposed method divides DIC algorithm into two parts: full-field initial guess estimation and sub-pixel registration. The proposed method has the following benefits: 1) providing a pre-knowledge of deformation fields; 2) saving computational time; 3) reducing error propagation; 4) integratability with well-established DIC algorithms; 5) fully parallelizability.

Keywords: digital image correlation; parallelizability; sub-pixel registration; inverse compositional Gauss Newton algorithm; initial guess;
In subset-based digital image correlation, each pixel of interest (POI) is tracked using a subset of pixels centered at the interrogated pixel. By mapping it with another most similar subset in the target image, the deformation vector of the POI can be obtained. At the same time, the deformation vectors of all the POIs in the subset can also be obtained. Usually, they are underused by the present DIC algorithm. The proposed method is to make full use of these redundant deformation vectors to obtain accurate, reliable initial guess. Fast, accurate and fully parallelizable DIC is expected to be realized.

For simplicity, a rectangular region of interest (ROI) without boundary pixels is selected in the reference image. A grid of tightly connected subsets with a size of \((2M + 1) \times (2M + 1)\) is selected as initial-guess estimation subsets (IES) to cover the ROI. Through a simple integer pixel searching process or other path-independent approaches [5–9], the initial guess of inverse compositional Gauss Newton (IC-GN) algorithm can be achieved [4]. The deformation vectors of the center point of IESs are obtained. Besides, the redundant and inaccurate deformation vectors of all the POIs in the IESs can be regarded as initial guesses of their actual deformation vectors.

Using first-order shape function for IES, the initial guess of the POI, denoted by \( \mathbf{p}_0 = [u_0^0, u_0^0, u_0^0, v_0^0, v_0^0, v_0^0] \), is computed from the deformation vector of the center of the IES where the POI is located, \( \mathbf{p}_{\text{CS}} \) (corresponding subset) = \([u_{\text{CS}}, u_{\text{CS},x}, u_{\text{CS},y}, v_{\text{CS},x}, v_{\text{CS},y}] \), as follows

\[
\begin{align*}
  u^0 &= u_{\text{CS}} + u_{\text{CS},x} \Delta x + u_{\text{CS},y} \Delta y, \\
  v^0 &= v_{\text{CS}} + v_{\text{CS},x} \Delta x + v_{\text{CS},y} \Delta y.
\end{align*}
\]

(1)

Using second-order shape function, the initial guess is computed from the deformation vector \( \mathbf{p}_{\text{CS}} \) (corresponding subset) = \([u_{\text{CS}}, u_{\text{CS},x}, u_{\text{CS},y}, u_{\text{CS},xx}, u_{\text{CS},xy}, u_{\text{CS},yy}, v_{\text{CS},x}, v_{\text{CS},y}, v_{\text{CS},xx}, v_{\text{CS},xy}, v_{\text{CS},yy}] \), as follows
where $\Delta x$ and $\Delta y$ are the distance between the POI and the center of the IES in $x$-axis and $y$-axis.

Using the initial guess calculated from Eq. (1) or Eq. (2), each of POI can get the desired deformation vector by using IC-GN algorithm with common used first-order shape function. Fig. 1 presents a flow chart of the proposed method.

![Flow chart of the proposed method](image1)

Fig.1. Flow chart of the proposed method

To verify the feasibility and effectiveness of the proposed method, experiments with relatively complex deformation field are employed. In the process of initial guess estimation, first-order and second-order shape function are used for comparison purpose. Two IES sizes, $33 \times 33$ and $61 \times 61$ pixels, are investigated in the experiments. IC-GN algorithm with first-order shape function is used to optimize ZNSSD criterion [4] to obtain sub-pixel accuracy. The subset used in
IC-GN algorithm is $33 \times 33$ pixels and the grid step is 1 pixels. The convergence conditions are set to ensure that variations in the norm of the incremental deformation parameter are equal to or less than 0.001. It is worth noting that the subset used in initial guess estimation and IC-GN algorithm can be of different size. There are many works presenting subset selection methods [12] in the process of sub-pixel registration; however, further research is desirable to obtain the optimal selection of the IES. Moreover, it is not an obligation to select a grid of tightly connected subsets without overlap. Intuitively, these IESs can overlap but must cover all ROI. More works are needed to study on it.

![Image of Reference Image and Target Image](image)

**Fig. 2.** Reference image with ROI and target image

Fig. 2 shows the reference image with $1001 \times 401$ pixels ROI and target image used in the experiment. The grayscale images are obtained from the website of the Society for Experimental Mechanics (Digital Image Correlation Challenge) [10]. Fig. 3 shows the initial guess and their gradient components fields in $x$-axis, $y$-axis using first-order shape function with IES size $33 \times 33$ pixels, which provide a pre-knowledge of the deformation fields. Fig. 4 shows the deformation fields calculated by IC-GN algorithm. Table 1 shows the average iteration and calculation speed. From this table, the average iteration and calculation speed using the proposed method is faster
than that using simple integer-pixel registration. When IES size is 33, the average iteration using first-order IES is 0.4 less than that using second-order subset. When subset size is 61, the average iteration using first-order IES is still less than that using second-order subset but the values are closer to each other. Because a smaller subset with identical shape function is more suitable to represent a relatively complex deformation field, and the second-order shape function leads to bigger random error than first-order shape function [13]. It is easy to understand that second-order shape function can provide a more accurate initial guess for deformation field with relatively larger strains. Most importantly, for computational efficiency, the proposed method is able to be fully parallelized with negligible time taken by initial guess estimation. In this experiment, for example, there are only 403 and 136 calculation points which needed time-consuming integer-pixel registration as IES sizes are 33 and 61. Compared with the time spent on 401401 POIs analyzed in the experiment, the time spent on initial guess approaches to 0.

Fig.3. Initial guess $u$, $v$ fields and their gradient components $u_x$, $u_y$, $v_x$, $v_y$ fields estimated by the proposed method.
Fig. 4. Displacements $u$, $v$ fields and their gradient components $u_x$, $u_y$, $v_x$, $v_y$ fields calculated by IC-GN algorithm

| Initial-guess estimation subset size (pixels) | Simple integer-pixel registration | Average iteration/calculation speed of IC-GN algorithm (p/s) | the proposed initial guess method |
|---------------------------------------------|-----------------------------------|------------------------------------------------------------|----------------------------------|
| $33 \times 33$                             | 4.4396/1253                       | 3.7434/1415                                               | 4.1393/1324                      |
| $61 \times 61$                             | 4.1692/1267                       | 4.1865/1282                                               | 4.1865/1282                      |

A method used for initial guess estimation in DIC is proposed in this technical note. It is shown that this fully parallelizable method can provide an accurate initial guess without increment of consuming time. Different from the present RG-DIC method, which transfer the initial guess among consecutive calculation points, the proposed method divides full-field DIC algorithms into two parts: initial guess estimation and sub-pixel registration. The separate treatment for initial guess and sub-pixel registration has the following benefits. 1) Providing a pre-knowledge; for example, this method combined with discontinuous shape function can provide a pre-knowledge
of discontinuity locations to avoid wasting time spent on unnecessary usage of discontinuous shape function for deformation fields with unknown discontinuity [11]. 2) Saving computational time; for RG-DIC method, the initial guess is computed from the deformation vector of its neighbor point [4], which is obtained from sub-pixel registration algorithm with first-order shape function where subset size is always selected for the optimal sub-pixel accuracy [12]; however, the initial guess can be obtained using a more suitable subset size and shape function, which is able to reduce the computational time in the process of sub-pixel registration. 3) Reducing the influence of error propagation; the error propagation only limits in a restrictive IES in the proposed method, which is easy to be manually intervened. 4) Integratability with well-established DIC algorithm; as mentioned above, the proposed method is easy to combine with discontinuous shape function to provide a pre-knowledge for deformation analysis; moreover, combined with robust initial guess approach [5–10], the proposed method is expected to offer reliable initial guess for measuring full-field displacement of an object subjected to large rigid-body motion and deformation. 5) Fully parallelizability; the proposed method is path-independent and meets the essential requirement of parallel computing. Therefore, the proposed method is worthy of further study and should have more applications in various time-critical digital image displacement analysis.

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Table 1 Average iteration/calculation speed of IC-GN algorithm with first-order function