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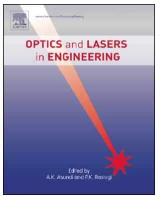

Path-independent digital image correlation with high accuracy, speed and robustness

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ABSTRACT

The initial guess transferring mechanism is widely used in iterative DIC algorithms and leads to path-dependence. Using the known deformation at a processed point to estimate the initial guess at its neighboring points could save considerable computation time, and a cogitatively-selected processing path contributes to the improved robustness. In this work, our experimental study demonstrates that a path-independent DIC method is capable to achieve high accuracy, efficiency and robustness in full-field measurement of deformation, by combining an inverse compositional Gauss–Newton (IC-GN) algorithm for sub-pixel registration with a fast Fourier transform-based cross correlation (FFT-CC) algorithm to estimate the initial guess. In the proposed DIC method, the determination of initial guess accelerated by well developed software library can be a negligible burden of computation. The path-independence also endows the DIC method with the ability to handle the images containing large discontinuity of deformation without manual intervention. Furthermore, the possible performance of the proposed path-independent DIC method on parallel computing device is estimated, which shows the feasibility of the development of real-time DIC with high-accuracy.

1. Introduction

Since Peters and Ranson introduced digital image correlation (DIC) to measure the displacement on solid surfaces in 1982 [1], this technique has been undergoing accelerating growth in the past three decades, and has become one of the most important and popular technologies in experimental mechanics for non-contact full-field measurements of shape, deformation and motion [2,3].

In the methodology study of DIC, three key issues have been investigated persistently and still remain as the major challenges nowadays, i.e., measurement accuracy, computation efficiency and robustness. To achieve high accuracy, various sub-pixel registration algorithms have been developed to reach accuracies ranging from 0.01 to 0.5 pixel, including the coarse-fine search method [1,4], the correlation coefficient curve-fitting method [5,6], the gradient-based method [7,8], and the iterative method represented by the Newton–Raphson (NR) algorithm [9,10]. However, the high accuracy of sub-pixel registration algorithms is at the price of high computation cost since most of these algorithms consist of an interpolation operation. In particular, the NR algorithm, though gives the best performance in accuracy and stability [11], is computationally expensive due to its nature of non-linear optimization. During each iteration step of the NR algorithm, the intensity and intensity gradient at sub-pixel locations in the target (deformed) image have to be reconstructed based on interpolation, accompanied with the re-evaluation of the inverse of the Hessian matrix. This problem becomes increasingly critical with the explosion of the number of the points of interest (POIs) to be processed by DIC, due to the rapid development and application of higher resolution digital cameras for image acquisition. To overcome it, an inverse compositional Gauss–Newton (IC-GN) algorithm [12,13] was introduced into DIC recently [2,14]. In contrast with the traditional forward additive NR algorithm which matches the affinely warped target image with the reference (undeformed) image iteratively, the IC-GN algorithm warps the reference image in a small range and then matches it with the warped target image, whereby the algorithm avoids the repeated calculation of intensity gradients and the inverse of the Hessian matrix during the iterations. The IC-GN algorithm has been proven to be mathematically equivalent to the classic forward additive algorithm [12,13], and shows similar accuracy and convergence criteria to the NR algorithm in experimental study [11,14,15].

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The robustness of DIC refers to its adaptability to handle complex deformation fields and its resistance to intensity variation and noise. In recent years, the strategies to enhance the robustness of DIC, e.g., the choice of the subset size [16,17], correlation criterion [18,19], and the processing path [20,21], have been studied extensively. Pan et al. [19] compared commonly used correlation criteria, and found the zero-mean normalized cross-correlation (ZNCC) criterion, zero-mean normalized sum of squared difference (ZNSSD) criterion and the parametric sum of squared difference (PSSD_{ab}) criterion (with two additional unknown parameters a and b) are insensitive to the variation of intensity before and after deformation.

The importance of processing path stems from a widely adopted approach to get the initial guess for iterative DIC algorithm. Based on the assumption of continuous deformation, the displacement and its gradient at a POI can be used to estimate the displacement at the neighboring POIs, supposing that they are close enough. Therefore, correct deformation information at a POI helps to provide reliable initial guess for the DIC calculation at its neighbors and avoid the time-consuming computation of initial guess at each POIs. On the other hand, unfortunately, error of calculation at a POI can be spread out through the same way. Inspired by the strategy used in phase unwrapping, Pan proposed a reliability-guided processing path scheme to prevent the spread of error [14,20,22]. This scheme starts from a pre-set seed POI, then processes the four POIs adjacent to the seed and weighs the reliability of these POIs according to their ZNCC values, afterwards inserts these POIs into a queue in a descending order of ZNCC values. The POI on the top of the queue is popped out as the new seed. Its adjacent POIs, if not processed, are correlated, weighed and inserted into the queue, followed by a re-ordering of the queue. By repeating this processing–weighing–queuing procedure, the processing path is guided to follow the direction towards the area with a good chance to get accurate DIC results. The cogitatively selected path can reduce the disturbance of area with poor quality of speckle pattern or subject to discontinuous deformation, as compared to a simple scanning path along rows or columns. Due to the aforementioned advantages, a DIC method combining ZNCC-based reliability-guided tracking with a ZNSSD-based IC-GN algorithm was expected to be a new standard approach [14].

It is noteworthy to point out that any spatial path-dependent strategy has its inherent deficiency which limits the potential of DIC in further improvement of computation efficiency and robustness. Current DIC method is basically a block-by-block, or windowed processing technique, which is suitable for parallel computing. Enlightened by the recent progress in the general-purpose computing on graphics processing units (GPU), the computation speed of integer-pixel DIC algorithms is found to speed up for a couple of orders of magnitude when running the DIC program on commercially available GPU platforms [23–25]. However, the spatial path-dependent strategy based on sequential processing mechanism apparently does not meet the essential requirement of parallel computing, i.e., the operation performed in parallel processing unit should be independent.

In the aspect of robustness, even for an intelligent strategy like reliability-guided displacement tracing, there is high probability to fail in the full-field analysis of deformation without manual intervention if the images contain large areas of discontinuous deformation. For example, on the lateral surface of a composite laminate subjected to delamination, the boundary of spatial discontinuities can transverse the whole view field. In this case it is difficult to compute the full-field deformation using the path-dependent strategy unless multiple seed POIs are preliminarily set.

To replace the path-dependent DIC method with a path-independent one, a question emerges naturally: is the estimation of initial guess without the information transferred from neighboring POI unbearably expensive in computation? In this paper, we demonstrate that the time spent for the independent calculation of initial guess at each POI (with integer-pixel accuracy) can be reduced to a negligible level by using a fast Fourier transform-based cross-correlation (FFT-CC) algorithm with ZNCC criterion, which is accelerated by one of the fastest FFT software libraries (FFTW [26]). The initial guess obtained using the FFT-CC algorithm is able to make the ZNSSD-based IC-GN algorithm converge fast and reach sub-pixel accuracy. A systematic experimental study shows how the path-independent DIC can achieve improved efficiency and robustness without sacrifice of accuracy.

The rest of the paper is structured as follows. Sections 2 and 3 provide brief introductions of the FFT-CC algorithm for integer-pixel registration and the IC-GN algorithm for sub-pixel registration, respectively. A path-independent DIC method that combines these two algorithms is proposed in Section 4. In Section 5, the proposed method is verified using simulated speckle images and real experimental results. The paper is concluded in Section 6.

2. Fast Fourier transform-based cross correlation algorithm

2.1. Principle and implementation

Cross correlation method, first introduced by Yamaguchi to tracking the in-plane speckle displacement on solid surface [27,28], is a powerful technique in particle image velocimetry (PIV) to measure velocity field of flows [29–31]. By tracking the translation of the spherical tracer particles in fluids, which are like artificial speckles in the recorded images, the velocity distribution of flows can be determined. Cross correlation of function R and function T is defined mathematically as the integral of the product of $R^*(x)$ with $T(x)$

$$C_{CC}(\Delta x) = R \otimes T = \int_{-\infty}^{+\infty} R^*(x) T(x+\Delta x) dx, \tag{1}$$

where the symbol $\otimes$ denotes the operation of cross correlation, and the superscript $*$ indicates the complex conjugate. Δx is a shift of distance between the two functions, which can be determined by searching the peak of $C_{CC}(\Delta x)$. Suppose that a square subset includes N discrete pixels, and let R_i and T_i represent the grayscale values of the ith pixel in the reference subset (before deformation) and the target subset (after deformation), respectively. The discrete form of Eq. (1) combining with the ZNCC criterion can be written as

$$C_{ZNCC} = \frac{\sum_i \overline{R}_i \overline{T}_i}{\sqrt{\sum_i (\overline{R}_i)^2 \sum_i (\overline{T}_i)^2}}, \tag{2}$$

where $\overline{R}_i = R_i - R_m$ and $\overline{T}_i = T_i - T_m$, with R_m and T_m as the mean values of the intensity in the two subsets, i.e., $R_m = 1/N \sum_i R_i$ and $T_m = 1/N \sum_i T_i$. Notice that the superscript $*$ has been omitted here since R contains only real numbers and thus $R^*(x) = R(x)$.

The calculation of Eq. (2) can be simplified by introducing the operation in frequency domain. According to Fourier theory, the operation of cross correlation in space domain is equivalent to a simple product in frequency domain, i.e.,

$$R \otimes T = FT^{-1}\{[FT(R)]^* \cdot FT(T)\}, \tag{3}$$

where $FT(\cdot)$ and $FT^{-1}(\cdot)$ denote the Fourier transform and inverse Fourier transform, respectively.

Fig. 1 illustrates the flow chart of the ZNCC-based FFT-CC algorithm. At first, two matrices containing zero-mean normalized values, i.e., $[\overline{R}]$ and $[\overline{T}]$, are constructed as the reference subset and the target subset respectively. Fourier transform is then performed on the two matrices, yielding $FT([\overline{R}])$ and $FT([\overline{T}])$. By performing