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High-efficiency and high-accuracy digital image correlation for three-dimensional measurement

Yue Gao, Teng Cheng*, Yong Su, Xiaohai Xu, Yong Zhang, Qingchuan Zhang*

CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei 230027, China

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A B S T R A C T

The computational efficiency and measurement accuracy of the digital image correlation (DIC) have become more and more important in recent years. For the three-dimensional DIC (3D-DIC), these issues are much more serious. First, there are two cameras employed which increases the computational amount several times. Second, because of the differences in view angles, the must-do stereo correspondence between the left and right images is equivalently a non-uniform deformation, and cannot be weakened by increasing the sampling frequency of digital cameras. This work mainly focuses on the efficiency and accuracy of 3D-DIC. The inverse compositional Gauss–Newton algorithm (IC-GN^2) with the second-order shape function is firstly proposed. Because it contains the second-order displacement gradient terms, the measurement accuracy for the non-uniform deformation thus can be improved significantly, which is typically one order higher than the first-order shape function combined with the IC-GN algorithm (IC-GN^1), and 2 times faster than the second-order shape function combined with the forward additive Gauss–Newton algorithm (FA-GN^2). Then, based on the features of the IC-GN^1 and IC-GN^2 algorithms, a high-efficiency and high-accuracy measurement strategy for 3D-DIC is proposed in the end.

1. Introduction

Digital image correlation (DIC) is a non-interferometric and non-contacting optical metrology for full-field shape, motion and deformation measurements. Since its invention in the early 1980s [1,2], numerous studies have been performed by the scholars over the world [3,4], and significant improvements, such as basic principle, registration accuracy, computational efficiency and application fields have been achieved. It has become the most popular and powerful technique in experiment mechanics, and has been widely applied in various scientific and industrial fields [5–11].

In recent years, research on DIC is mostly focused on the computational efficiency and measurement accuracy. For the topic of computational efficiency, there are always tens of thousands grid points must be analyzed even in a single deformed image. With the development of digital cameras, the number of grid points would keep increasing year by year. Moreover, there are usually tens of thousands of deformed images recorded in the measurements, such as in a dynamic testing or in a real-time motion tracking. The computational cost of DIC therefore is generally considered to be very huge. A lot of achievements have been done to improve the computational efficiency of DIC [12–15]. As a typical DIC method, the forward additive Gauss–Newton (FA-GN) algorithm combining with the robust Zero-mean Normalized Sum of Squared Differences (ZNSSD) criterion is commonly used [16–18]. However the Hessian matrix of this method must be calculated and inverted in each iteration. As an equivalent but more efficient strategy [19,20], the inverse compositional Gauss–Newton (IC-GN) algorithm combining with ZNSSD criterion has been estimated [21]. However, both the IC-GN and FA-GN algorithms are actually at the same level of accuracy, the sub-pixel registration algorithm remains a key issue, especially for the non-uniform deformation.

In general, the DIC method can be classified broadly as either two-dimensional DIC (2D-DIC) [22] or three-dimensional DIC (3D-DIC) [23]. 2D-DIC employs just a single camera. It is only valid for the in-plane deformation. The measurement accuracy is very susceptible to the out-of-plane displacement [24]. To overcome the limitations of 2D-DIC, 3D-DIC based on the principle of binocular stereovision has been developed. By employing two synchronized cameras, 3D-DIC can measure not only the 3D shape but also the three displacement components of specimen surfaces. Namely, both the in-plane and out-of-plane deformations can be determined simultaneously. Therefore, 3D-DIC is commonly considered to be more accurate and practical than 2D-DIC.

It is worthy to note that although there are many advantages, the issues about the computational efficiency and measurement

* Corresponding authors.
E-mail addresses: chteng@ustc.edu.cn (T. Cheng), zhangqc@ustc.edu.cn (Q. Zhang).

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accuracy in 3D-DIC are much more serious than 2D-DIC. Firstly, because there are two cameras employed, the computational amount of 3D-DIC is approximately three times heavier than 2D-DIC. Secondly, the angle of the two cameras usually ranges from 25° to 65° in the practical implementations of 3D-DIC. Due to the differences in view angles, the left and right images recorded at the same time have obvious differences, which cannot be eliminated by increasing the sampling frequency of digital cameras. For example, the deformation variation in a single subset (with the subset size of 49 pixels) is up to 1.4% when the angle between the left and right cameras is about 40° in typical. Therefore, the must-do stereo correspondence between the left and right images in 3D-DIC is equivalently a non-uniform deformation, and cannot be weakened.

In this work, the authors have focused on the efficiency and accuracy of 3D-DIC. After conclusion some typical DIC methods, including the widely used FA-GN algorithms with first-order and second-order shape function (FA-GN^1, FA-GN^2 [25,26]), and the high-efficiency IC-GN algorithm with first-order shape function (IC-GN^1), Section 3 presents a new IC-GN algorithm with second-order shape function (IC-GN^2) to achieve the high-accuracy measurement of the non-uniform deformation. Section 4 presents the theoretical and experimental validations of this proposed method. Based on the different features of the IC-GN^1 and IC-GN^2 algorithms, Section 5 presents a high-efficiency and high-accuracy strategy for 3D-DIC. Section 6 presents concluding remarks.

2. DIC method using FA-GN algorithm

Fig. 1 schematically shows a typical DIC method using the FA-GN algorithm, where $\mathbf{W}(x, y; \mathbf{p})$ is the shape function (or named warp function) with a parameter vector $\mathbf{p}$ to describe the position and shape of the target subset relative to the original square reference subset. The subscript 1 and 2 denote whether the first-order or second-order shape function is employed. The ZNSSD criterion is usually performed to evaluate the similarity between the reference and target subsets. In each iteration, the current estimate of the target subset is compared with the reference subset to solve for the parameter increment $\Delta\mathbf{p}$, which is subsequently added to the parameter vector $\mathbf{p}$ to update the current estimate (namely, $\mathbf{p}=\mathbf{p}+\Delta\mathbf{p}$). The ZNSSD criterion thus can be described as

$$C_{\mathrm{ZNSSD}}(\Delta\mathbf{p})=\sum_{y=-M}^{M}\sum_{x=-M}^{M}\left\{\frac{f(\mathbf{W}(x,y;0))-\bar{f}}{f_s}-\frac{g(\mathbf{W}(x,y;\mathbf{p}+\Delta\mathbf{p}))-\bar{g}}{g_s}\right\}^2 \quad (1)$$

$$\mathbf{H}=\sum_{y=-M}^{M}\sum_{x=-M}^{M}\left\{\left(\nabla g\frac{\partial\mathbf{W}}{\partial\mathbf{p}}\right)^T\left(\nabla g\frac{\partial\mathbf{W}}{\partial\mathbf{p}}\right)\right\} \quad (2)$$

where f and g denote the gray levels at the point (x,y) of the reference and target subsets, $\bar{f}$and $\bar{g}$ denote the mean intensity values of the reference and target subsets, $M$is the half width of the subset, $f_s=\sqrt{\sum_{y=-M}^{M}\sum_{x=-M}^{M}[f(x,y)-\bar{f}]^2}$ and $g_s=\sqrt{\sum_{y=-M}^{M}\sum_{x=-M}^{M}[g(x',y')-\bar{g}]^2}$, $\mathbf{H}$is the Hessian matrix.

The first-order and second-order shape functions can be described respectively as:

$$\mathbf{W_1}(x,y;\mathbf{p_1})=\begin{bmatrix}x'\\y'\end{bmatrix}=\begin{bmatrix}1+u_x & u_y & u\\ v_x & 1+v_y & v\end{bmatrix}\begin{bmatrix}x\\y\\1\end{bmatrix}$$
$$\mathbf{p_1}=(u,u_x,u_y,v,v_x,v_y)^T \quad (3)$$

$$\mathbf{W_2}(x,y;\mathbf{p_2})=\begin{bmatrix}x'\\y'\end{bmatrix}=\begin{bmatrix}\frac{1}{2}u_{xx} & u_{xy} & \frac{1}{2}u_{yy} & 1+u_x & u_y & u\\ \frac{1}{2}v_{xx} & v_{xy} & \frac{1}{2}v_{yy} & v_x & 1+v_y & v\end{bmatrix}\begin{bmatrix}x^2\\xy\\y^2\\x\\y\\1\end{bmatrix}$$
$$\mathbf{p_2}=(u,u_x,u_y,u_{xx},u_{xy},u_{yy},v,v_x,v_y,v_{xx},v_{xy},v_{yy})^T \quad (4)$$

3. DIC method using IC-GN algorithm

Note that the Hessian matrix in the FA-GN algorithm must be calculated and inverted in each iteration, which seriously reduces the computational efficiency. Therefore, as shown in Fig. 2, the IC-GN algorithm combined with ZNSSD criterion has been proposed. In each iteration, the incremental warp $\mathbf{W}(x,y;\Delta\mathbf{p})$ is firstly exerted to the reference subset rather than the target subset, and subsequently inverted and composed with the current estimate $\mathbf{W}(x,y;\mathbf{p})$ to update the target subset:

$$\mathbf{W}(x,y;\mathbf{p})=\mathbf{W}(x,y;\mathbf{p})\,\mathbf{W}^{-1}(x,y;\Delta\mathbf{p}). \quad (5)$$

The ZNSSD criterion thus can be described as

$$C_{\mathrm{ZNSSD}}(\Delta\mathbf{p})=\sum_{y=-M}^{M}\sum_{x=-M}^{M}\left\{\frac{f(\mathbf{W}(x,y;\Delta\mathbf{p}))-\bar{f}}{f_s}-\frac{g(\mathbf{W}(x,y;\mathbf{p}))-\bar{g}}{g_s}\right\}^2. \quad (6)$$

To solve this equation, a first-order Taylor expansion with respect to $\Delta\mathbf{p}$ can be performed. This yields:

$$C_{\mathrm{ZNSSD}}(\Delta\mathbf{p})=\sum_{y=-M}^{M}\sum_{x=-M}^{M}\left\{\frac{f(\mathbf{W}(x,y;0))+\nabla f(\partial\mathbf{W}/\partial\mathbf{p})\Delta\mathbf{p}-\bar{f}}{f_s}-\frac{g(\mathbf{W}(x,y;\mathbf{p}))-\bar{g}}{g_s}\right\}^2 \quad (7)$$

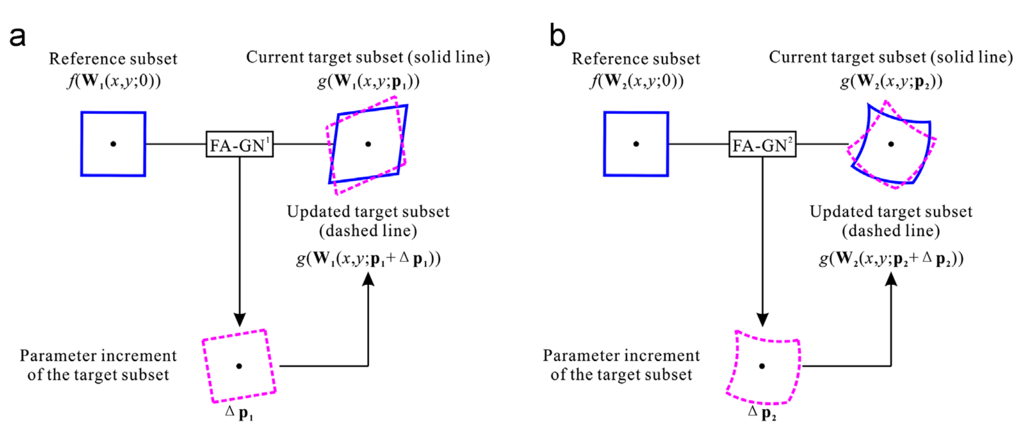

Fig. 1. Typical DIC method using the FA-GN algorithm with (a) the first-order shape function (FA-GN^1) and (b) the second-order shape function (FA-GN^2).