Research progress of DSCM in sub-pixel level measurement

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Abstract. The digital speckle correlation method (DSCM) is a full-field and non-contact optical measurement method. This paper analyzes the research status of the sub-pixel algorithm in DSCM, and analyzes the research progress and data of the algorithm. The inverse compositional Gaussian-Newton algorithm (IC-GN) has obvious advantages. The conclusion is that the inverse compositional Gaussian-Newton algorithm has obvious comprehensive advantages over traditional sub-pixel algorithms in terms of measurement accuracy and computational speed.

1 Introduction

DSCM has the advantages of full field measurement, non-contact etc. [1], a non-contact optical measurement method that can measure material strain and deformation. Traditional research on DSCM, such as Newton iterative method, cross search method, mountain climbing method, etc., is now more popular in the research of intelligent algorithms, such as neural network algorithm, wavelet transform, adaptive genetic algorithm etc. [2][3]. The speed of intelligent algorithms is faster than the traditional algorithm, and the calculation accuracy is higher than the traditional algorithm. The traditional algorithms such as Newton-Simpson algorithm, fitting method, gradient method, interpolation method etc. The common problem is that the accuracy has not met the needs of the actual problems. Needed, the current mainstream algorithm is the IC-GN [4], which is more robust.

Pan Bing [5] studied the Newton-Simpson method, surface fitting method and gradient method. The Newton-Simpson method has the highest accuracy, but the calculation time is significantly slower than the other two. The team of Meng Libo [6] compared the interpolation method, the fitting method and the gradient method. The fitting method and the interpolation method have the same precision. The gradient method is more stable when the small displacement changes and the interpolation method has higher precision when the displacement is large. Lu Rongsheng [7] analyzed various forms of the fitting method and concluded that the quadric surface method works best. Liu Kaipei [8] analyzed and compared various forms of interpolation method, and obtained the bicubic spline interpolation has the best effect. At present, the optimal compositional algorithm forward compositional algorithm and IC-GN have the same precision, but the IC-GN has faster processing speed [9]. Lu Rongsheng [10] also proposed a fast IC-GN for single-point and full-field deformation measurements, which can be increased by 10% and 25%, respectively.

2 The Principle of DSCM

According to the DIC schematic diagram [11], for the two speckle patterns before and after the deformation, a seed calculation point $P$ is taken on the image before the deformation, and one $(2M+1)$
×(2M+1) is taken as the center of $P$. The square area $R$ is matched on the deformed image to obtain the target point $P'$ and the corresponding target area $R'$, which is the optimal matching point of the point $P$ in the deformed image. The displacement relationship is:

\[
\begin{align*}
  u &= x' - x \\
  v &= y' - y
\end{align*}
\]  

(1)

![Fig.1 DIC basic principle diagram](image)

In this paper, the following function is used as fitness function [12]. The expression is:

\[
C = \frac{\sum \sum (f - \bar{f})(g' - \bar{g})}{\sqrt{\sum \sum (f - \bar{f})^2} \sqrt{\sum \sum (g' - \bar{g})^2}}
\]  

(2)

Among them, the gray value of point $P$ is $f$; the gray value at point $P'$ is $g'$; the average gray level of $f$ is $\bar{f}$; $\bar{g}$ is the average gray of $g$. The larger the C value, the better the matching degree. And $C = 1$ means the perfect match.

3 The Principle of IC-GN

The inverse compositional algorithm [9][10] is inferred from the Newton-Gaussian algorithm. According to the relationship between $R$ and $R'$, the energy formula of the IC-GN algorithm is:

\[
E = \sum \left[ R \left( W \left( x, \Delta P \right) - R' \left( W \left( x, P \right) \right) \right) \right]^2
\]  

(3)

The coordinate shape variable is:

\[
W \left( x, P \right) = \begin{pmatrix}
  1 + u_x & u_y & u_x \\
  v_x & 1 + v_y & v_y
\end{pmatrix} \begin{pmatrix}
  x \\
  y \\
  1
\end{pmatrix}
\]  

(4)

Among them,

\[P = [u_x, u_y, u_v, v_x, v_y]^T\], the parameters $P$ of can be calculated by formula (1) and (2). Solving the formula (3) by iterative method:

\[
\Delta P = H^{-1} \sum \left[ \Lambda R \cdot \frac{\partial W}{\partial P} \cdot \left[ R \left( W \left( x, P \right) - R \left( x \right) \right) \right] \right]
\]  

(5)

$H$ is Hessian matrix, $H = \sum \left| \Lambda R \cdot J \right|^2 \cdot \left| \Lambda R \cdot J \right|$, $J$ is Jacobian matrix,
\[
J = \begin{bmatrix}
\left( \frac{\partial f}{\partial W} \cdot \frac{\partial W}{\partial W_{k}} \cdot \frac{\partial W_{k}}{\partial (\Delta R)} \right)_{1} \\
\vdots \\
\left( \frac{\partial f}{\partial W} \cdot \frac{\partial W}{\partial W_{k}} \cdot \frac{\partial W_{k}}{\partial (\Delta R)} \right)_{(2M+1)^{2}}
\end{bmatrix}
\]

In the iterative process, the Hessian matrix only needs to be calculated once. It does not need to calculate every iteration, which greatly saves the calculation time. It only needs to calculate the gray value at \( R' \) by interpolation or fitting.

### 4 Algorithm Analyses and Verification

In this paper, we use the computer simulates speckle, the image size is \( 256 \times 256 \), the speckle numbers are 1200, and the speckle particle size is between 2 and 4 pixels, as shown in Figure 2.

![Fig.2 The computer simulated speckle pattern](image)

In order to verify the algorithm, this paper uses the contrast form to verify the IC-GN algorithm, because the accuracy of fitting method and interpolation method is equivalent, Newton-Simpson's calculation time is too slow, so quadratic surface fitting, gradient method The IC-GN are compared and analyzed from two aspects: relative error and calculation speed.

Between 0 and 1 pixel, in steps of 0.1 pixel; between 1 and 10 pixels, in steps of 1 pixel, generate ten speckle patterns by translation, the matching sub-area size is 51x51, the sub-area window is shown in Figure 2, the relative error curves are shown in Figure 3 and Figure 4, respectively.

![Fig.3. Sub-pixel relative error curve](image)

![Fig.4. Integer pixel relative error curve](image)

It can be seen from the relative error curves of the three algorithms that the IC-GN has absolute
precision advantages, whether it is from sub-pixel displacement or integer pixel displacement, which satisfies the requirement of displacement measurement accuracy.

According to the calculation time of 20 times, the speed of IC-GN is about 11 times of the fitting method and about 7 times of the gradient method.

5 Conclusions

In this paper, the comparison of the algorithm shows that the inverse compositional Newton-Gauss algorithm has absolute advantages in measurement accuracy and calculation speed. Therefore, the inverse compositional Newton-Gaussian algorithm is the main direction of future research. The application in practical engineering and the continuous improvement of the Gauss-Newton method are the future trends.

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