Research and Analysis on Key Techniques of Digital Speckle Correlation Method

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Abstract. The registration of speckle images plays a key role in many fields, such as: material mechanics; accident monitoring; geodetic survey; missile guidance. Speckle image is composed of a large number of random spots, that it is difficult to obtain obvious feature values through feature extraction. Digital speckle correlation method is to directly extract the surface displacement and deformation information of objects from digital images, so all kinds of digital images can be used as processing objects. However, when the target image quality is poor or has a large deformation, its registration accuracy is difficult to reach the sub-pixel level. In this paper, we will study and analyze the key technologies of existing digital speckle correlation methods.

1. Digital speckle correlation method

The Digital Speckle Correlation Method (DSCM), also known as the Digital Image Correlation Method (DICM), is a surface deformation measurement method for solid materials based on digital image processing [1,2,4]. It was first proposed in the 1980s by Japanese scientist I. Yamaguchi [3] and American scientists W.H.Peter and W.F.Ranson [4]. When I.Yamaguchi studied the small deformation of the surface of the object, the light intensity before and after the surface deformation of the object was compared, and the displacement of the object after deformation was derived by calculating the peak of the cross-correlation function. Peter and Ranson calculated the digital gray-scale field of the object before and after the deformation by the method of iterative method, that is, calculating the change of the correlation coefficient, and obtaining the maximum value of the correlation coefficient, and then obtaining the displacement deformation of the point to be measured. The key to digital speckle correlation technology lies in the correlation calculation, and the correlation calculation between the two speckle patterns before and after the deformation mainly depends on the computer operation. Therefore, some scholars have done a lot of research on how to improve the algorithm and improve the calculation accuracy and calculation speed. The key techniques of digital speckle correlation measurement methods [5] include correlation functions, correlation search algorithms, and sub-pixel registration algorithm.
2. Correlation functions
The gray level distribution of the image is the carrier of the displacement and deformation information of the object. The digital speckle correlation is the best matching degree for finding the gray distribution of the sub-area of the local area before and after the deformation. Therefore, it is necessary to establish a correlation function to characterize the similarity between image sub-regions before and after deformation in correlation analysis. The form of the correlation function is one of the key issues related to digital speckle. The correlation function should meet the following requirements [6]:

- Simplicity. Firstly, the correlation function should have a relatively simple mathematical expression. The parameters involved in the function expression can be obtained by simple means, and for different speckle patterns, these related parameters can be used, and the function of the relevant region should be guaranteed. The output value should be the highest value within a certain search range, and the function values of the relevant area and the unrelated area should be significantly different.
- Reliability. The speckle field is a random gray distribution, which itself determines the difference between the sub-areas of each speckle image. Due to the downsampling and anti-aliasing filtering of the image acquisition system, different target sub-areas and reference sub-areas There may be a certain degree of similarity between them, so there will be a certain misunderstanding rate in the relevant matching process. Therefore, the correlation function is required to have sufficient sensitivity to the small difference of the speckle pattern sub-region, thereby obtaining a large successful matching rate.
- Anti-interference. The image acquisition system in digital speckle correlation may have electronic noise when acquiring images, and at the same time, slight changes in the gray scale distribution of the speckle pattern before and after the deformation may be caused due to slight changes in illumination conditions. Therefore, the correlation function is required to maintain a stable and relatively accurate output when the grayscale changes slightly.
- High efficiency. The digital speckle correlation method requires a correlation matching search for multiple sub-areas, and the calculation amount of the correlation function determines the speed of the correlation matching. Therefore, the correlation function is required to have the least computation time.

The most commonly used correlation functions for digital speckle correlation methods are defined as follows:

- The normalized correlation function normalizes the correlation coefficient obtained by the direct correlation method by using the squared sum of the grays in the relevant image sub-region, so that the $C(u, v)$ value range is $[0, 1]$. Using the maximum value of the correlation function, the degree of matching between the reference image and the target image sub-region can be determined.

$$C(u, v) = \frac{\sum_{x=-M}^{M} \sum_{y=-M}^{M} [f(x, y)g(x+u, y+v)]}{\sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} f(x, y)^2} \sqrt{\sum_{x=-M}^{M} \sum_{y=-M}^{M} g(x+u, y+v)^2}}$$

Where in, $f(x, y)$, $g(x+u, y+v)$ are the gradation functions of the speckle map sub-region centered on the reference point and the target point; $u$ and $v$ are the displacement values of the horizontal and vertical directions thereof.

- The normalized covariance correlation function uses the gray mean squared difference in the relevant image sub-region to normalize the implementation of the covariance correlation function, let $C(u, v)$ have a value range of [-1,1]. When the two image sub-regions have the same feature, the correlation function value is 1; when completely inconsistent, the correlation function value is 0; when completely opposite, the correlation function value is -1.
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, the displacement value of the pixel search has important significance for the processing of speckle images. The integer-pixel search method includes point-by-point search method, mountain climbing method, cross search method, particle swarm algorithm, etc. [7]  

The point-by-point method, as the name implies, calculates the correlation coefficient with the point on the reference speckle image point by point on the deformed speckle image, and finds the point where the correlation coefficient is the largest. The point-by-point search method has a wide search range and high search accuracy, but it sacrifices computational efficiency and takes a long time.  

Mountain climbing is a method of searching for local optimization using heuristic methods. Mountain climbing is an improved method of depth-first search method, which generates feedback decisions through feedback information. The mountain climbing method avoids traversing the entire image and selects some nodes for calculation by heuristics, so as to improve the search efficiency. Since the algorithm is not a global search, the search result may fall into a local maximum or encounter a high ground phenomenon in the process of searching.  

The Cross search method is an improvement on the climbing method. The basic idea is to convert the two-dimensional search into two one-dimensional search after approaching the main peak. The search process is divided into two steps, first to find a small range of main peaks, and then find the peak point in the main peak region of the small range. But the process of finding the main peak area is particularly cumbersome, which greatly increases the search time.  

Particle Swarm Optimization (PSO)[8] has the characteristics of parallel computing, easy to understand and easy to implement. The basic idea of the algorithm is: assuming that there are a certain number of particles around the measured point, sending some particles to move in the measured area like a bird, recording the optimal search position of each particle and the global optimal position of all particles. That is, “individual extremum” and “global extremum”, each time the iteration is performed, the particle updates its position by tracking these two extreme values. Through such continuous iterative search, the particle is approached to the global optimal position and Finally reach the best value. In the search process, PSO makes full use of the sharing mechanism. Each particle dynamically adjusts its speed and position according to the individual and the flight experience of the population. However, the traditional PSO is easy to fall into the local optimum, and the search performance depends largely on the parameter setting, and the algorithm is prone to oscillations in the later stage.  

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Sub-pixel registration algorithm  

Since the speckle image is a discrete gray scale distribution in units of pixels, the displacement value that can be obtained by the correlation search can only be an integer multiple of the pixel. However,
the actual displacement is not necessarily the integer-pixel value, and the displacement accuracy of the integer-pixel is not enough in practical applications. Therefore, the sub-pixel displacement measurement algorithm is also one of the key techniques related to digital speckle correlation. Commonly used sub-pixel displacement algorithms are gray-scale interpolation, surface fitting, gradient-based search algorithm, and Newton-Raphson iterative method. [9]

Generally, the gray interpolation method has simple bilinear interpolation [10, 11]. In order to improve the accuracy, Lagrange interpolation and bicubic interpolation can be selected [11, 12] even five times spline interpolation [13]. This type of method is computationally intensive, and the effect is not satisfactory. Moreover, since the gray-scale field of the approximately continuous speckle image reconstructed by the gray-scale interpolation method is very different from the real situation, and the accuracy obtained by various noises is limited, the method is rarely used.

The surface fitting method is essentially a sub-pixel displacement method based on correlation coefficient interpolation fitting [14]. The basic idea of this method is: first find the nearest integer-pixel point \((x', y')\) closest to the sub-pixel point \((x, y)\), and interpolate the correlation coefficient of \((x', y')\) and other surrounding integer-pixels, then calculate the maximum value of the fitted surface to find the peak point, that is sub-pixel displacement.

Gradient-based search algorithm is a sub-pixel displacement search method based on gradation difference [14], this algorithm not only considers the gray difference of the image before and after the deformation, but also considers other similar characteristics between the two images, so the algorithm has higher accuracy. However, the gradient method is based on the gray level of the sub-area, in the actual measurement environment, uneven illumination or light intensity changes often occur, which leads to the gray value of the same point on the surface of the object. Changes occur before and after deformation, which will inevitably introduce computational errors.

The gradient method calculates the sub-pixel displacement based on the following two theoretical assumptions:

- Gray degree invariance hypothesis: the object is deformed, but the gray value of the surface pixel does not change.
- Sub-region rigid body motion hypothesis: When the object is slightly displaced, if the sub-region of the image is small enough, the displacement of each point in the image sub-region is approximately the same, and the motion of the image sub-region can be regarded as the translational motion of the rigid body.

The Newton-Raphson iterative method also considers the deformation of the template window, originally proposed by Burck et al. [9]. Compared with the coordinate rotation method, the method can reduce the calculation amount obviously, and can also obtain the displacement and strain information at the same time. But requires a more accurate initial value estimation. This method rejects the assumption that the image sub-region is strained to zero, and considers the presence of strain.

Recently, in order to improve the convergence characteristics of the Newton-Raphson iterative method and avoid the disadvantages of large computational complexity, some scholars have proposed other optimization calculation methods such as the Quisi-Newton method [15], Leveburg-Marquart method [11] and so on. However, although various measures are taken to improve the convergence speed, the method still takes a lot of computation time to find the local minimum, and Newton-Raphson and other methods can directly obtain displacement and strain information at the same time, but these methods obtained strain is heavily dependent on the local gray information of the image, as well as the influence of CCD noise, interpolation error, etc., the directly obtained strain has large fluctuations [16], so it is actually obtained by smoothing and differential processing of the displacement information. The strain is more accurate than the strain obtained directly.

5. Summary section

Through the algorithm research on these digital speckle correlation techniques. Correlation search algorithm is an important link to improve the efficiency and accuracy of digital speckle correlation,
however, the algorithm is less efficient in finding a single spot in the scattered map from a large range, and the displacement accuracy of the integer-pixel is far from enough in practical applications. Sub-pixel displacement measurement algorithms are also needed to improve image registration accuracy, as shown above, existing gray interpolation methods, surface fitting methods, gradient-based search algorithms, and Newton-Raphson iteration methods. The fitting accuracy of the interpolation and fitting methods is generally statistically reliable at around 0.1 pixels, but beyond this scale, for example, the fitting surface is interpolated to 0.01 pixels, and the registration accuracy cannot be verified by statistics. The gradient method will cause calculation errors due to uneven illumination or changes in light intensity. The Newton-Raphson method can directly obtain displacement and strain information at the same time, but the strain obtained by these methods is heavily dependent on the local gray information of the image, as well as the influence of CCD noise, interpolation error, etc., the directly obtained strain has large fluctuations.

At present, how to improve measurement accuracy and search speed is still a hot spot in the future of digital speckle correlation methods. In addition, how to improve the adaptability of the algorithm is also a problem to be considered.

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