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用基于种子点的三维图像相关法测量连续大变形

肖振中[1,2,3*]，徐爱珠[1]，安顺泰[2]，唐正宗[3]
(1. 义安理工学院 光学与激光研究中心，新加坡 599489；
2. 南洋理工大学 机械与宇航工程学院，新加坡 639798；3. 西安交通大学 机械工程学院，陕西 西安 710049)

摘要：针对使用图像相关法测量物体发生的较大刚体旋转或变形容易失效的问题，提出了一种连续大变形的图像匹配方法。该方法首先利用相邻状态变形的连续性对种子点进行匹配，然后利用同一状态相邻点的变形连续性，通过种子点为其他点提供初值，并最终完成对所有点的匹配，从而在无需人工交互的情况下实现对大变形过程的高效测量。刚体旋转实验以及单向拉伸实验表明，对于 40°的刚体旋转位移场以及高达 113%的变形，测量结果良好，证明了本文方法的有效性。

关　键　词：三维图像相关法；种子点；连续大变形；数字相机；标定
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Measurement of large deformation by digital image correlation method based on seed points

XIAO Zhen-zhong[1,2,3*], Oichoo Chee[1], Anand Asundi[2], TANG Zheng-zong[3]

(1. *Ngee Ann Centre of Innovation, Ngee Ann Polytechnic, Singapore* 599489;
2. *School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore* 639798;
3. *School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an* 710049, *China*)
* *Corresponding author, E-mail: xiaoxice@hot.mail.com*

Abstract: To solve the problem of a large deformation measurement by using the Digital Image Correlation (DIC) method, a DIC method based on seed points is presented. After dividing subsets in the reference image, one point is chosen as the seed point and is matched firstly. According to the deformation continuity of adjacent stages of the image, an improved integer pixel search method is proposed to guarantee that the seed point can be matched successfully even in a large deformation situation. Once the seed point is matched, it can be used to calculate the initial correlation parameters of its four neighbor points according to the deformation continuity of neighbor points in one stage. The above progress repeats until all the points are matched. A rigid rotation experiment and a tensile test are carried out to verify the proposed method. Measurement results for 40° rotation and large deformation up to 113% confirm the validity of the method.

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Key words: 3D Digital Image Correlation(DIC); seed point; large deformation measurement; digital camera; calibration

1 Introduction

The Digital Image Correlation (DIC) method uses the random speckle pattern to match the corresponding points in the reference image and the deformed image. Traditionally, in order to track the location of a point in the deformed image, a square subset surrounding the point in the reference image is chosen and used as reference subset. A certain correlation coefficient is predefined to evaluate the similarity between the reference subset and the target subset. Then the corresponding point can be obtained by searching the maximum (or minimum) correlation coefficient in the deformed image[1].

The Newton-Raphson (NR) method[2] and the iterative least-squares (ILS)[3] method are the most commonly used algorithms. Compared to NR method, the ILS method is more brief and easy to implement, and is adopted in this paper. Both of the two methods are nonlinear optimization algorithms, and their convergences heavily rely on the initial values of the unknown correlation parameters[4]. Normally, a coarse search scheme pixel by pixel can be employed to get the initial value. However, the coarse search scheme fails when large rotation and/or large deformation occurs between the reference and target subsets. Some global optimization algorithms do not require initial values, such as genetic algorithms[5] and difference algorithm[6]. Yet these global algorithms are very time-consuming and are rarely adopted in practical use. A nested coarse-fine algorithm based on affine transformation is proposed[7] which can provide the initial value for each point through calculating the overall relative deformation of two images using three or more feature points. A technique can provide reliable initial value for the first calculation point by picking three corresponding points manually. The two methods need human interaction, and are somewhat cumbersome if the number of deformation images is large.

This paper proposes a new scheme of large deformation in the digital image correlation. After selecting calculation area and dividing subsets in the reference image, an arbitrary subset is used as a seed point and is matched firstly. An improved coarse search scheme which makes use of the deformation continuity of the adjacent states is proposed to provide the initial correlation parameters of the seed point. Using this method, the seed point can be matched successfully even in a large rotation and/or large deformation situation. After the seed point is matched, it can be used to calculate the initial values of its four neighbor points. The same procedure repeats until all the points are matched successfully. To a series of continuous deformation images, the proposed method can handle large deformation efficiently without initial manual operations.

2 Large deformation measurement scheme

2.1 The principle of digital image correlation method

The digital image correlation method uses the random speckle pattern to match the corresponding points precisely on two digital images. As shown in Fig. 1, the left image is a reference image, and the right one is a deformed image. In the reference image, a square reference subset of $(2M+1)\times(2M+1)$ pixel centered at point (x, y) is picked. The matching procedure is to find the corresponding subset centered at point $(x',$

y') in the target image which has the maximum similarity with the reference subset. Then the two center points (x, y) and (x', y') are a couple of corresponding points of the two images. Obviously, the relative relationship of gray level in the reference image does not change in the target image, so any point (x_i, y_i) in the reference subset can be mapped to a point (x_i', y_i') in the target image according to a mapping function. The first-order mapping function is used in our algorithm, which allows translation, rotation, shear, normal strains and their combinations of the subset:

$$\begin{aligned} x_i' &= x_0 + \Delta x + u + u_x \Delta x + u_y \Delta y \\ y_i' &= y_0 + \Delta y + v + v_x \Delta x + v_y \Delta y \end{aligned} \quad . \tag{1}$$

where Δx, Δy are the distances from the subset center to points (x_i, y_i); u and v are the displacement components of the reference subset center in x and y directions; u_x, u_y, v_x, v_y are the first-order displacement gradients of the reference subset.

As mentioned before, in order to get the initial value for the ILS algorithm, the coarse search scheme pixel by pixel is usually used to find the initial value of displacement component (u, v), and the initial value of correlation parameters is set to $p = [u, 0, 0, v, 0, 0, 0, 1]$. But the coarse search scheme does not work when large rotation and/or large deformation happens. To overcome this problem, an improved search scheme is proposed in the following section which makes use of the deformation continuity of the adjacent states.

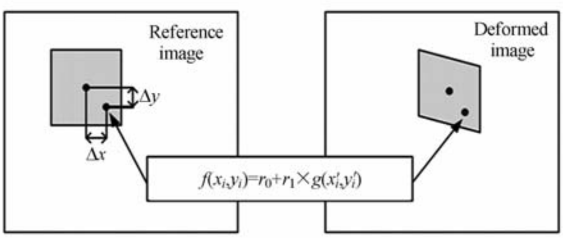
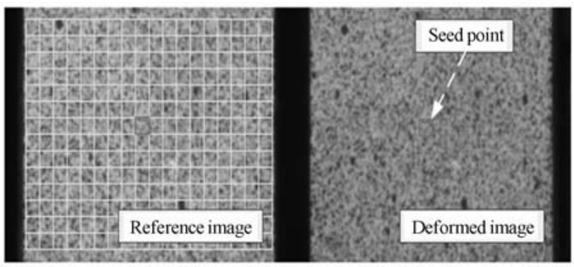


Fig. 1　Basic principle of digital image correlation

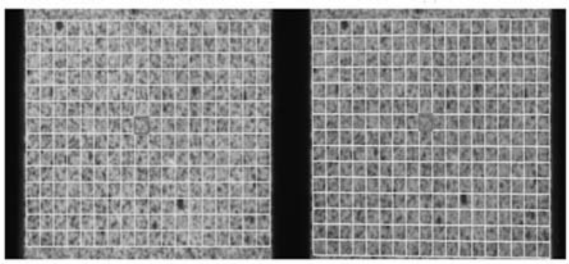
2.2　Image correlation method based on seed point

Before correlation calculation, the calculation area is specified and divided into subsets as shown in Fig. 2 (a), and each white square subset represents a point. However, the coarse search scheme is quite time-consuming and only displacement component is considered which may decrease the convergence speed of ILS algorithm, so the whole match procedure will be quite inefficient if the initial value of each point is provided through the coarse search scheme.

To speed up the matching procedure, an image correlation method based on seed point is introduced here. As is shown in Fig. 2 (a), after the calculation area is divided into subset, an arbitrary subset is used as the seed point (black square subset) in the reference image and is matched firstly. The initial correlation parameter of the seed point is obtained by the proposed improved coarse search scheme, and then optimized by the ILS method.



(a) Seed point is matched



(b) All points are matched

Fig. 2　Calculate correlation parameters using a seed point

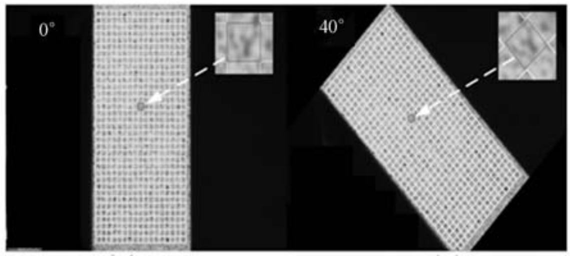
The improved coarse search scheme guarantees that the seed point can be matched successfully even in a large rotation or large deformation situation. After the seed point is matched, considering the deformation continuity of neighbor points, the seed point is then used to calculate the initial values of correlation parameters of its four neighbor points (left, right, up, down). An estimation of the location of the neighbor point in deformed image can be obtained according to Eq. (1), which can be used to solve the initial values of u and v directly. The initial values of the rest of correlation parameters are set according to the seed point. Then the ILS algorithm is used to refine the correlation parameter of the neighbor points. Once the four neighbor points are matched successfully, they can act as seed points for their neighbor points. The procedure repeats until all the points are matched, as shown in Fig. 2 (b). Because the deformation parameters of neighbor points are very close, the initial value of ILS algorithm can be provided with high accuracy. Additionally, because only one seed point is needed, the computing time of coarse search scheme can be ignored and the total time of correlation is much reduced.

3 Experiments and result analysis

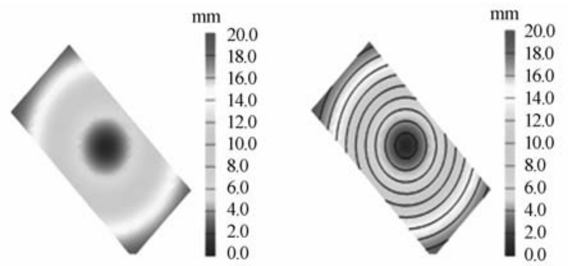
A rotation experiment and a tensile experiment are carried out to verify the proposed method.

3.1 The rotation experiment with variant angles

The original image is shown in Fig. 3(a) as the reference image. By rotating the image around its center counter-clockwise by 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, respectively, and eight continuous deformed images are generated. After dividing subsets in the reference image, an arbitrary subset is used as the seed point (black square subset) and matched in all the eight deformed images. If traditional coarse search scheme is employed, the seed point can only be matched successfully in the first deformed image (under 5° rotation), but failed in the other images. Yet if the improved coarse search scheme is applied, the seed point can be matched successfully in all the eight images. After the seed point is matched, the correlation spreads out from the seed point according to the method illustrated in section 2, and all the points are matched. Fig. 3 (b) is the correlation result of the image after 40° rotation. After all the points are matched, the displacement field can then be obtained directly. Fig. 3 (c) is the displacement magnitude distribution color map of deformed image after 40° rotation, and Fig. 3 (d) is the same color



(a) Reference image before rotation　(b) Deformed image after 40° rotation



(c) and (d) Displacement magnitude distribution of deformed image after 40° rotation without and with isolines

Fig. 3　Rotation experiments with variant angles

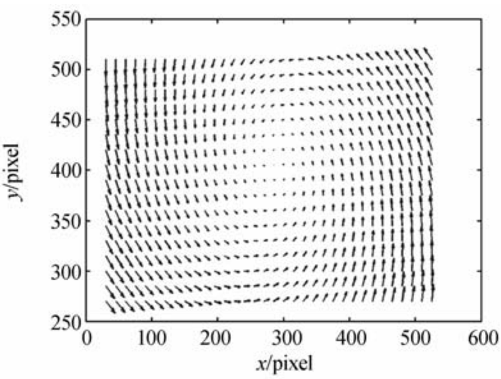


Fig. 4　Displacement vector of 40° rotation

map with isolines on it. Fig. 4 is the corresponding displacement vector field. As can be seen from the figures, the measurement results meet the pre-imposed deformation. In fact, even rotations larger than 40° can also be calculated using this method, as long as the neighbor stages do not change too much.

3.2 The tensile deformation test

During the tensile test, the drawing speed is set to 10 mm/min, and the camera frame rate is set to 1 frame/s. There are 102 stages collected throughout the experiment in all. Because the 45# steel has very good toughness, necking happens at the end of the test. The deformation at the necking place is very large, including both rotation and stretching. Fig. 5 (a-d) shows images of four stages and their correlation results. By dividing subsets in the reference image, and choosing an arbitrary subset as the seed point (the black square subset) and match it firstly, as shown in Fig. 5 (a). As can be seen in Fig. 5 (d), quite large deformation happens to the seed point. If the traditional coarse scheme is used, only the first 30 stages can be matched successfully. However, if the improved coarse scheme is used, all the 102 stages can be matched successfully. Here, we deliberately choose a point with larger deformation (at the necking place) as the seed point to test the proposed method. Of course, we can also choose a point with little deformation as the seed point. In that case, the difficulty of matching is reduced and the traditional coarse search method can work in more than 30 stages, but still unable to calculate all the stages.

After all the stages are matched, their displacement fields can be obtained directly. Fig. 5 (e-h) illustrates the displacement fields of the four stages. The displacement becomes larger along the tensile direction, which agrees with the actual displacement distribution. The strain of different stages is calculated using the method presented in section 2 (D). The major strains and minor strains of the four stages are displayed in Fig. 5 (i-l) and Fig. 5 (m-p), respectively.

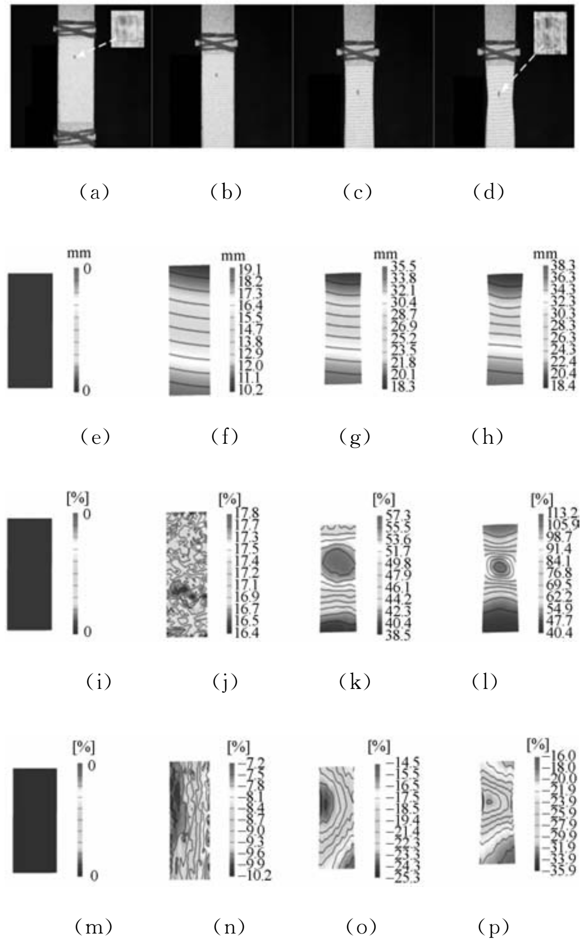


Fig. 5 Images and correlation results of (a) Reference stage (b) 50th stage (c) 90th stage (d) 102th stage. Displacement field of (e) the reference stage, (f) the 50th stage, (g) the 90th stage and (h) the 102th stage. Major strain field of (i) the reference stage, (j) the 50th stage, (k) the 90th stage and (l) the 102th stage. Minor strain field of (m) the reference stage, (n) the 50th stage, (o) the 90th stage and (p) the 102th stage.

As we can see in the figures, the strain throughout the specimen is almost uniform in the beginning of the test, but when necking happens, the strain at the necking position is much bigger than those of other positions and the major strain at the necking place in the last stage is up to 113%. The measurement results clearly demonstrate the robustness of the proposed method.

4 Conclusions

A large-deformation measurement scheme based on the digital image correlation method is presented in this paper. The correlation calculation starts with a seed point. An improved coarse search method is proposed to calculate the initial correlation parameters of the seed point to guarantee that the seed point can be matched successfully even in a large deformation situation. Once the seed point is matched, it can be used to calculate the initial correlation parameters of its neighbor points according to the deformation continuity. The procedure repeats until all the points are matched. Using this method, the correlation work of a series of images with large deformation can be finished automatically in high efficiency. A rigid rotation experiment and a tensile test are carried out to verify the proposed method. Measurement results of 40° rotation and large deformation up to 113% confirm the validity of the method.

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Authors' biographies:

XIAO Zhen-zhong, PhD, he is a research scientist in Ngee Ann Centre of Innovation and post-doctoral fellow in Nanyang Technological University, Singapore. He obtained BE, MS and PhD degrees from Xi'an Jiaotong University of China. His primary research work is related to 3D computer vision, photogrammetry and computational optics. E-mail: xiaoxice@hotmail.com

Oichoo Chee, she graduated from the University of Malaya, Malaysia. She has been working on multi-disciplinary projects to develop digital holography-based systems for material and life science applications. She is with Ngee Ann Polytechnic's Centre of Innovation for Photonics & Nanotechnology. Her teaching area is in electric circuit analysis and measurement. E-mail: coc@np.edu.sg

Anand Asundi, Professor, PhD, Members of SPIE, SEM, ASME, OSA, Chairman of OPSS. Editor of Optics and Lasers in Engineering, Director of Advanced Materials Research Centre, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His teaching area is solid mechanics and his research interests are in optical methods in mechanics including micro, nano and biomechanics, online structural health mornitoring and fiber optic bio-chemical sensors. He has organized numerous conferences and served on the Membership, Scholarship/Awards and Presidential Asian Advisory committees of SPIE and on the Board of Directors of SPIE. E-mail: anand. asundi@pmail. ntu. edu. sg

TANG Zheng-zong, is a PhD student in the School of Mechanical Engineering, Xi'an Jiaotong University in China. He obtained his MS degrees from Xi' an Jiaotong University and is working on photogrammetry and 3D deformation measurement for his PhD thesis. E-mail: nevret@gmail. com

●**下期预告**

Love 波传感器的性能分析与实验

苗　圃[1,2],李　锋[1],张　平[1],刘永顺[1,2],毕晓猛[1,2],吴一辉[1]

(1. 中国科学院 长春光学精密机械与物理研究所 应用光学国家重点实验室, 吉林 长春 130033;
2. 中国科学院 研究生院,北京 100049)

为了制作出具有高灵敏度的 Love 波传感器,本文分析了 Love 波在 ST-石英和二氧化硅薄膜分层结构中的传播特性,并对该分层结构进行了相关的理论推导和计算。首先,从该结构的声学动力学方程出发,分析求解了该分层结构的波动方程并得到了在该分层结构的色散关系式及结构中的位移表达式。然后在所得到的解析表达式的基础上进行了相应的波结构分析和特性曲线的绘制,并得到了 Love 波在该结构中的传播特性。最后应用 MEMS 工艺制作了由 ST-石英为基底、二氧化硅为波导层的 Love 波传感器,并通过电化学微电铸的方法进行了实验验证,对理论灵敏度与实验灵敏度之间不一致的原因进行了分析。分析结论指出了获得高质量传感器需要注意的参数。测试数据表明该传感器的质量灵敏度为 100 cm^2/g,最低检出限为 3.65 ng。实验结果证明该 Love 波传感器基本满足进行高灵敏度生化检测的要求。