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Kalman filter based initial guess estimation for digital image correlation

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ABSTRACT

In applications digital image correlation based algorithms often present a basis for analysis of movement/deformation of bodies. The sequence of the obtained images is analyzed for this purpose. Especially, in cases when the body's movement/deformation between two successive images is significant, the initial guess can have a major influence on the execution speed of the algorithm. In the worst case it can even cause the divergence of the algorithm. This was the inspiration to develop a new and unique approach for an accurate and reliable determination of an initial guess for each image pixel. Kalman filter has been used for this purpose. It uses past measurements of observed variable(s) for calculations. Beside that it also incorporates state space model of the actual system. This is one of the most important advantages provided by Kalman filter. The determined initial guess by the proposed method is actually close to the true one and it enables fast convergence. Even more important property of this approach is the fact that it is not path-dependant because each image pixel, which is defined in ROI, is tracked through the sequence of images based on its own past measurements and general state space model. Consequently, the proposed method can be used to analyze tasks where discontinuities between image pixels are present. The applied method can be used to predict an initial guess where reference and deformed subsets are related by translational and rotational motion. The advantages mentioned above are verified with numerical and real experiments. The experimental validations are performed by NR (Newton–Raphson) approach which is the most widely used. Beside NR method the presented algorithm is applicable for other registration methods as well. It is used as an addition for calculation of initial guesses in a sequence of deformed images.

1. Introduction

Digital image correlation (DIC) is a powerful optical method for quantitative deformation measurement. It is widely accepted and commonly used in the field of experimental solid mechanics. Compared to some other non-contact optical methods, including both interferometric techniques and non-interferometric techniques, digital image correlation has some advantages. These are fast processing capability, full-field deformation measurement, avoidance of tedious phase information, interferometric fringe treatment and the possibility of the usage of natural light sources for illumination. The basic idea of DIC method is to reliably and accurately measure motion of each image pixel between two or more images, where each of them is recorded in a different state or by different camera with different orientation. The motion of the desired image pixel is determined based on matching or tracking of the same image pixel located between two different images or sequence of images. The result of DIC analysis is image motion of each image pixel, which can be further converted to the desired physical quantities, such as displacement or dimension information of the measured test object. In this case, the values of the camera parameters must be determined in advance.

Before the start of the DIC analysis, a region of interest (ROI) must be specified in the reference image. Image pixels are evenly placed into the desired region of interest, which usually has a rectangular shape but in some special cases irregular shapes can be used. In the conventional DIC analysis, the calculation starts with the top left image pixel in ROI and then proceeds to the right and downwards. The first step is the application of an algorithm with the accuracy of one pixel. In general, the sub-pixel methods are only used afterwards to get a more accurate displacement. The first step (one pixel accuracy) can be made by a simple searching scheme [1] within the deformed image. In the literature, various sub-pixel accuracy (sub-pixel registration) algorithms are known [2–4]. One of the best known approaches is the iterative spatial domain cross-correlation algorithm which uses Newton–Raphson (NR) [5] or improved NR method [6], where an approximation of

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the Hessian matrix is used. Some extensions and modifications of the NR algorithm together with its relation to other DIC algorithms are presented in [7]. One of the important comparative advantages of the NR methods is their ability to take the deformation of the subset into account, which means that they are insensitive to large strains or rotations of the deformed image [5,6]. It should be noted that when any of the mentioned DIC algorithms is used, an initial guess or initial value of the displacement or rotation angle is required as an initial condition in the correlation procedure. It has direct impact on the convergence characteristics of the applied algorithm and consequently its speed. In the conventional pointwise DIC approach, displacements and strains of the current image pixel are used as an initial guess for the next pixel. This assumption is possible to make when continuous deformation is assumed. Because in each step the initial guess depends on the current image pixel, pointwise DIC computation can be classified as path-dependent approach [8]. On the other hand, it is possible to estimate the initial guess for each pixel separately, but this approach is extremely time-consuming and the probability of mis-identification is relatively high, especially when a large rotational deformation is present in the deformed image. As described in [9–11], the pointwise DIC approach can provide erroneous results in the following cases. In many applications, the test objects contain discontinuous areas such as holes, cracks and other discontinuities, where assumption regarding continuous deformation is not valid. Because of that the transfer of initial guess for the next pixel will fail for some locations in the ROI. The failure of the transfer of initial guess can occur if discontinuous deformation occurs in deformed image or if a faulty data pixel occurs. It should be noted that if the initial guess for the next pixel is not appropriate, the result will affect the subsequent image pixel(s). This leads to the propagation of error.

As already noted, the conventional pointwise DIC approach has some limitations which can lead to the erroneous calculation of the initial guess for the next image pixel. For this reason other techniques are needed to achieve a reliable initial guess of deformation for each calculated pixel. In [1] a coarse-fine search scheme is presented, where the initial guess of the deformation is calculated based on an affine transformation. This search scheme can be described as follows. First, the affine parameter should be calculated based on manual selection of three or more image pixels with distinct features in the reference image (x_i, y_i) $(i = 1, 2, \dots, n)$ and their corresponding locations (x'_i, y'_i) $(i = 1, 2, \dots, n)$ in the deformed image. Second, the location of each image pixel in ROI is then evaluated based on the calculated affine parameters. In the final step, a coarse-fine search is applied around evaluated location to obtain exact displacement. Slightly different technique from [1] is presented in [12] where initial guess of the deformation for the first pixel is obtained based on affine parameters. It is calculated by selecting three or more pixels in the reference subset and their corresponding locations in the deformed subset. Then based on the assumption of a continuous deformation of a solid object, the result of the first pixel serves as the initial guess for the next pixel.

In the literature, beside conventional pointwise DIC approach, reliability-guided digital image correlation (RGDIC) method is known as well. It was proposed by Pan [9]. It can be used for reliable image deformation measurement. The basic idea of the RGDIC can be described as follows. Before tracking in ROI is performed, the zero-mean normalized cross correlation (ZNCC) coefficients for a seed pixel and neighboring pixels around it are calculated. Neighboring pixels with the highest correlation coefficient in a queue will be processed first. This means that calculation path is actually in the most reliable direction. This makes it possible to avoid the error propagation completely, which is not true in the case of the conventional DIC method. It should be noted that the computed deformation parameters of the removed points are used as an initial guess for its neighbors. However, such an assumption is not always the optimal one, especially if a large in-plane rotation in ROI is present.

In the case of large in-plane rotation, neighboring points could have quite different displacements and consequently the conventional DIC approach might produce substantial initialization error. This problem was addressed in [13], where an elegant solution based on relating adjacent deformations by using analytical functions is proposed. It seems that the only difficulty of the transfer scheme is how to obtain a valid starting point to initiate the transfer and it is discussed more thoroughly in [14–16].

Quite different from pointwise algorithms are continuum or global methods based on B-spline function and finite element formulation as indicated in Refs. [17,18], respectively. In both of them, displacement and displacement gradients are changing continuously during calculation of image pixels. In general, continuum methods are much more complicated and computationally extensive compared to conventional pointwise or subset-based DIC methods.

In this paper, a novel method for initial guess calculation for each pixel in the sequence of deformed images is presented. The method is applicable on a wide set of registration methods [10] (coarse-fine search, peak-finding, iterative spatial domain cross-correlation, spatial-gradient, etc.). Its main goal is to overcome the limitation of the conventional DIC method. Initial guess of each pixel in the next deformed image is calculated based on a Kalman filter. In general, a Kalman filter is used to predict location (x'_i, y'_i) and rotation θ of each pixel from current to the next deformed image and it is then used as an initial guess for correlation analysis in the next image. The calculated initial guess for each pixel based on a Kalman filter depends on the previously calculated image pixels and the choice of a system model, which should be known in advance. The influence of each one depends on the covariance of the noise in the system model, which is defined as a linear state space model. The predicted initial guess is calculated for each pixel separately and for every new image the current state is updated. This means that proposed method is not path-dependent and erroneous results which might occur in conventional pointwise DIC are not possible here. Thus the proposed method is insensitive to a discontinuous area in the deformed image. It should be noted that implementation of the Kalman filter is simple and its execution is extremely fast compared to the other methods. It is applicable for other registration methods [19,20] as well.

To verify the performance of the proposed method for initial guess calculation, numerical and real experiments are also presented. In our experiments, rotation angle θ of each subset in deformed image is calculated within frameworks for small and large deformation theory. The results of both approaches are compared as well. As described in [6], when small deformation theory is used, the rigid body rotation θ in deformed subset can be accurately calculated if it is smaller than 10° $(\theta \le 10^\circ)$ compared to reference subset. On the other hand, if rigid body rotation θ is larger than 10°, it is recommended to use large deformation theory. The very similar conclusion is presented in our paper. The results clearly demonstrate the robustness and effectiveness of the novel method for calculation of the initial guess of each image pixel.

2. Principles of digital image correlation and Kalman filtering

2.1. Basic principles of digital image correlation

After digital images of the object surface before and after deformation are obtained, DIC method can be used to calculate the movement of each image pixel. If full-field deformation is