Close-range Photogrammetry for Accurate Deformation Distribution Measurement

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ABSTRACT: This paper introduces a methodology for improving the accuracy of deformation distribution measurement (DDM) using close-range photogrammetry. After reviewing various algorithms for 2D digital image correlation (DIC), zero-normalized cross-correlation (ZNCC) is selected for deformation measurement. The impact of several other factors on DIC measurement accuracy has been investigated, including the type of imaging sensors, the contrast and pattern of a specimen, and searching window size. Optimal option of these factors is proposed. The technique is utilized in the experiment of applying static loading on a replica of a concrete structural component used for Sydney Harbour Bridge. Test results presented in the paper include DIC measurements and validation data from conventional sensors.

1 INTRODUCTION

Measuring the deformation of structures subjected to various loading is an important and challenging task. Many instruments have been developed for surface deformation measurement, such as strain gauges, linear variable differential transformer (LVDT) and laser Doppler vibrometers (LDVs). In general they are reliable and accurate, but can only provide one dimensional measurement at one point, and require physical contact to tested structures. It is costly and inopportune to use them for deformation distribution measurement (DDM) that needs simultaneous 2D or 3D measurement at multiple locations. DDM can be used to analyse many aspects of structural behaviour (Gencturk et al. 2014), such as load transfer through contact surfaces, load path in structure components with complex geometry, and effect of boundary conditions. Better options are highly expected to combine measurement accuracy with cost efficiency, easy set-up process and measuring capability.

Various non-contact optical methods, including both interferometric and non-interferometric techniques, have been developed for DDM (Rastogi 2003). Close-range photogrammetry is non-interferometric optical technique that measures surface deformation by comparing the change of images of a specimen surface before and after deformation. It includes the grid method (Goldrein et al. 1995) and the digital image correlation (DIC) method. Both can measure multiple points, have less stringent requirement for experimental conditions, and are suitable for DDM.

The DIC method has been widely used as a powerful and flexible tool for the surface DDM in the field of experimental solid mechanics. In principle, DIC is an optical metrology based on image processing and numerical computing (Pan et al. 2009). It can directly provide deformation distribution and the strain of a structure surface by comparing the digital images captured in un-deformed (as the reference) and deformed states respectively on a specimen surface.

During last few decades, DIC has been extensively investigated and significantly improved for reducing computation complexity, achieving accurate DDM and expanding application range. To obtain reliable measurements, some requirements on the measuring system must be met (Sutton et al. 2000, Schreier 2003). For example, 2D DIC using one camera is limited to in-plane DDM of a planar object surface. It is not applicable for measuring a curved surface or when 3D deformation occurred after loading. 3D DIC method based on the principle of stereovision has to be applied.

Compared with interferometric optical techniques used for in-plane deformation measurement, DIC method has both advantages and disadvantages. Its advantages include: 1) simple experimental setup as only one fixed camera is needed to capture images, and the preparation of specimen surface is simple and even unnecessary if using the natural texture of a specimen surface; 2) robust measurement environment suitable for both laboratory and field applications; 3) with a wide range of measurement sensitivity and resolution for images captured by various digital image acquisition devices, such as scanning electron microscopes for nano-scale deformation measurement. However, DIC method also suffers some disadvantages; for example, its measurement accuracy depends heavily on the quality of imaging sensors and at present, is lower than that of interferometric techniques. As a result, it is not recommended as an effective tool for non-homogeneous small deformation measurement (Pan et al. 2009).

The development of digital imaging and computing technologies has made DIC feasible for DDM. However, in the application of this technique, there are still some issues need to be addressed.

This paper introduces the research of UTS on DDM using close-range photogrammetry, specifically 2D DIC. Zero-normalized cross-correlation (ZNCC), a popular DIC algorithm, is applied. The impact of several factors on the measurement accuracy has been investigated. The criteria for selecting optimal option of these factors have been proposed. This technique has been applied in an experiment on a replica of a concrete structural component used for Sydney Harbour Bridge.

A brief introduction of 2D DIC is given in Section 2. Investigation on the impact of some factors on the measurement accuracy is introduced in Section 3. Section 4 describes the experiment of applying loading on a replica of a concrete structural component, and presents the data processing results. Section 5 gives the summary and conclusions.

2 2D DIGITAL IMAGE CORRELATION

2.1 *Fundamentals of 2D DIC*

The basic principle of 2D DIC is the matching of the same points (or pixels) between two images before and after deformation, as illustrated in Figure 1. In order to compute the displacements of point P, a square subset of (2M+1)×(2M+1) pixels centred at point P(x_0, y_0) from a reference image is chosen and used to track the corresponding point P'(x'_0, y'_0) in a deformed image in a searching area (yellow square).

The point P and P' are related by a displacement function. If the motion of the object relative to the camera is parallel to camera image plane, the relationship between two points can be expressed as the equation 1 (Russell and Sutton 1989).

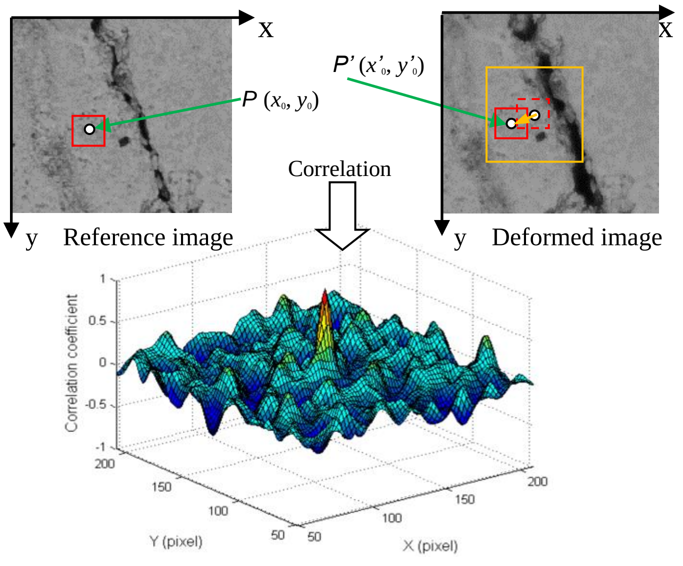

Figure 1. Principle of detecting deformation with DIC

$$x_i' = x_i + u(x_i, y_j) \qquad (i, j = -M{:}M) \tag{1}$$
$$y_j' = y_j + v(x_i, y_j)$$

where *i* and *j* are the pixel (or sub-pixel) numbers, *x* and *y* are the coordinates of the pixel in the reference and deformed images respectively, *u*(*x*,*y*) and *v*(*x*,*y*) are the displacement functions.

In most cases, the first-order displacement function is used in the equation (1) that can model the translation, rotation, shear and normal strains of a subset

$$u(x_i, y_j) = u + u_x\,\Delta x + u_y\,\Delta y \tag{2}$$
$$v(x_i, y_j) = v + v_x\,\Delta x + v_y\,\Delta y$$

where $\Delta x = x_i - x_0$, $\Delta y = y_j - y_0$; *u*, *v* are the directional displacement components of the reference subset centre P on x and y; u_x, u_y, v_x, v_y are the first-order displacement gradients of the reference subset.

A correlation function must be defined to evaluate the similarity degree between the reference subset and the deformed subset. The matching procedure is searching a position with the peak correlation coefficient. Once the peak point is detected, P', the centre position of the deformed subset is determined. The differences in the positions of the two subset centres yield the in-plane displacement vector at point P, as illustrated in Figure 1.

The most popular correlation function include the zero-normalized cross-correlation (ZNCC) and zero-normalized sum of squared differences (ZNSSD) (Pan et al. 2007). They are invariant to a linear transformation in grey intensity, thus theoretically unaffected by changes in illumination. The correlation coefficient of ZNCC is C_{ZNCC}:

$$C_{ZNCC} = \sum_{i=-M}^{M} \sum_{j=-M}^{M} \frac{\left[f(x_i, y_j) - f_m\right] \times \left[g(x'_i, y'_j) - g_m\right]}{Df \times Dg} \tag{3}$$

where *f* and *g* are the matrixes of the reference and deformed images in grey levels between 0 and 1, as detailed in (Pan et al. 2009). Ideally the value of C_{ZNCC} at the peak point should be 1 and the shape near the peak point is very sharp for achieving high precision DDM.

2.2 *2D DIC implementation*

The implementation of 2D DIC method, in general, comprises the following three steps: 1) specimen and experimental preparations; 2) recording the images of the planar specimen surface during the test; 3) processing the acquired images using to obtain the desired displacement and strain information.

The speckle pattern on the planar specimen surface can be the natural texture or artificially painted. The camera is placed with its optical axis normal to the specimen surface, imaging the specimen surface in onto its sensor plane.

Ideally the estimated motion of each image point multiplying the magnification of the imaging system (in units of mm/pixel) accurately equal that of the actual physical point on the specimen surface, with the condition that out-of-plane motion during the loading is small enough to be neglected. Normally, the out-of-plane motion can be alleviated by placing the camera far from the specimen.

After recording the images of the specimen surface before and after deformation, DIC is applied to compute the motion of selected points by comparing the images in different test states. The region of interest in the reference image should be specified at first, which is further divided into evenly spaced grids. The displacement at each point of the grids is computed to obtain the DDM.

The integer displacements with one pixel accuracy can readily be computed due to the discrete nature of the digital image. To further improve measurement accuracy, an algorithm for sub-pixel accuracy should be applied. Therefore, the implementation of DIC generally comprises two steps to achieve sub-pixel accuracy. An integer-pixel displacement of 1 pixel resolution needs to be provided before conducting the sub-pixel displacement measurement.

The estimation of integer-pixel displacements can be obtained by applying a simple searching algorithm either in spatial domain or in frequency domain (Zhang et al. 2006) . Various sub-pixel measurement algorithms then can be applied for precise DDM.

3 2D DIC ACCURACY ANALYSES

As an experimental measurement method, 2D DIC suffers various error sources, which can be listed into two categories (Pan et al. 2009). Firstly, the errors related to specimen, loading and imaging process which include *speckle pattern*, *imaging quality*, *noises during image acquisition and digitization*, *non-parallel* between a sensor plane and a specimen surface and *out-of-plane displacement*. Secondly, the errors related to the correlation algorithm include *subset size*, *correlation function*, *sub-pixel measurement algorithm*, *displacement function* and *interpolation scheme.*

Estimation of the errors related to different error sources is important to find ways to improve the measurement accuracy of 2D DIC. Here some error sources are analysed, including D measurement algorithm, imaging quality and subset size etc.

3.1 *2D DIC algorithms*

Many sub-pixel measurement algorithms have been proposed in the literature. They can be classified in several types which have different performance in the aspects of accuracy, reliability and computing cost. In estimating integer-pixel displacement, a specified searching area is searched with 1 pixel step to find the point with maximum cross-correlation coefficient. The *coarse–fine search algorithm* is straightforward to change the search step into 0.1 pixels or 0.01 pixels to achieve a sub-pixel accuracy of 0.1 or 0.01 pixels respectively. The grey level at sub-pixel locations must be constructed in advance using certain interpolation scheme, which generally costs long computation time (Pan et al. 2006).

Peak-finding algorithms refer to a type of algorithms for detecting the peak position of a local discrete correlation coefficient matrix (3×3 or 5×5 pixels typically) around the pixel with maximum correlation coefficient after the integer-pixel displacement searching scheme. Both interpolation and least-squares fitting algorithms can be used to estimate the peak position of the approximated curve surface as the sub-pixel displacement. The implementation of peak-finding techniques for sub-pixel displacement measurement is simple, and can be done very fast. However, peak-finding algorithms do not consider the shape change of the deformed subset, and just compute the approximated peak rather than the actual peak of correlation coefficient; as a consequence, the accuracy is decreased (Pan et al. 2009).

Iterative spatial domain cross-correlation algorithm can handle the relative deformation (shape change) between the reference and deformed subsets, which make a nonlinear correlation function with respect to the desired mapping parameters vector. If first-order displacement function is used as the equation (2), then the desired mapping parameters vector is $\boldsymbol{p} = (u, u_x, u_y, v, v_x, v_y)^T$. Newton–Raphson (NR) algorithm is applied to obtain efficient and accurate solution, written as

$$p = p_0 - \nabla C(p_0)/\nabla\nabla C(p_0) \tag{4}$$

where p_0 is the initial guess of the solution, which can be provided by a integer-pixel displacements; p is the next iterative approximation solution; $\nabla C(p_0)$ is the gradient of correlation criteria and $\nabla\nabla C(p_0)$ is the second order derivation of correlation criteria, commonly called Hessian matrix. According to the approach proposed by Argyriou and Vlachos (1998), an approximation can be made to the Hessian matrix that can significantly simplify the calculation process of equation (4) without affecting the calculation accuracy.

Spatial-gradient-based algorithms are based on the optical flow algorithm developed by Davis and Freeman (1998). Calculation using iteration least-squares is exempted from sub-pixel interpolation, so it has very fast computation speed. Because only the first-order spatial derivatives of the deformed image are required during calculation, thus, it is little simpler than the classic NR method. The spatial-gradient-based method is actually equivalent a variation of improved NR algorithm.

Some other algorithms have also been applied for 2D DIC. As a random search algorithm with robust global converge capability, the *genetic algorithm* is widely used to optimize the multi-dimensional nonlinear function. Although with extraordinary ability of global optimum, the genetic DIC method generally requires a high computing cost to find the global optimum of the correlation coefficient. Different to all the algorithms above, *Finite element method and*

B-spline algorithm belong to continuum method (or a global method), in which the surface deformation of the test object throughout the entire image area was represented by the B-spline function. These techniques ensure the displacement continuity and displacement gradients continuity among calculation points. However, these two methods seem not to provide higher displacement measurement accuracy than the NR algorithm (Pan et al. 2009).

Although so many algorithms can be used to achieve sub-pixel displacement, in the literature, two most widely used algorithms are iterative spatial domain cross-correlation and peak-finding, mainly due to their simplicity. After evaluating their measurement accuracy with controlled deformation, the iterative spatial domain cross correlation algorithm with higher accuracy, better stability and broader applicability. Therefore it is highly recommended for practical use (Pan et al. 2006).

3.2 *Imaging systems*

As the quality of DDM using DIC depends heavily on the imaging system, it is worth to investigate the DDM results using different imaging sensors. DIC processes grey images for DDM, so an ideal camera to capture images for it is a high resolution monochrome digital camera, which is expensive and rare to find in the market. On the contrary, colour digital cameras are very popular and low cost. Two types of colour digital camera have been tested.

Conventional colour digital cameras use Bayer filter mosaic above a photo sensor, as shown in the right side of Figure 2. Only partial RGB information is captured; interpolation is applied to fill in the missing part, inducing the inaccuracy in captured images.

Another type of colour digital camera (Sigma) uses a unique principle. RGB colours are captured with three layers of photodiodes in a direct image sensor, as shown in the left side of Figure 2. This vertical colour separation technology is similar to human cognition, and based on the fact that the penetration depth of light depends on its wavelength. The sensor is able to capture RGB information in every pixel and results in clearer image details (Sigma 2016).

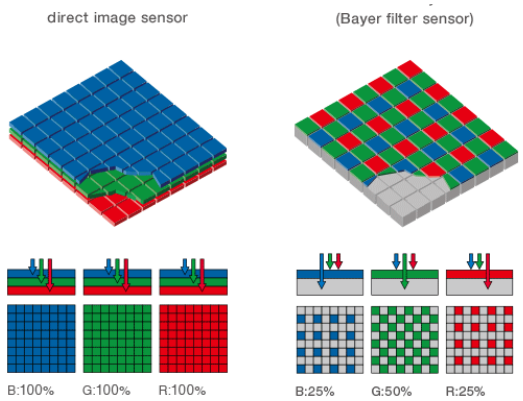

Figure 2. Two types of digital colour image sensor

Images captured with these two types of camera in our experiment are shown in Figure 3. Fine details is be obtained in the left image captured by a Sigma DP2 using the vertical colour separation technology, while the right image captured by a Nikon D7000 with Bayer filter mosaic and interpolation loses much detail with blurred edges. This will affect the accuracy of DDM using DIC method.


Figure 3. Images captured with two different types of digital camera, left with Sigma DP2 and right with Nikon D7000.

3.3 *Speckle pattern and contrast*

There are several criteria need to be considered to choose a good speckle for improving the accuracy of DIC (Jones 2014). The effect of the criteria on the accuracy of a 2D DIC method was evaluated using the standard test images provided by the Society for Experimental Mechanics (SEM) DIC Challenge (Board 2016). Obviously a good speckle should contain irregular fine patterns with high contrast and clear edges, as the image in Figure 4 provided for DIC Challenge (Board 2016).

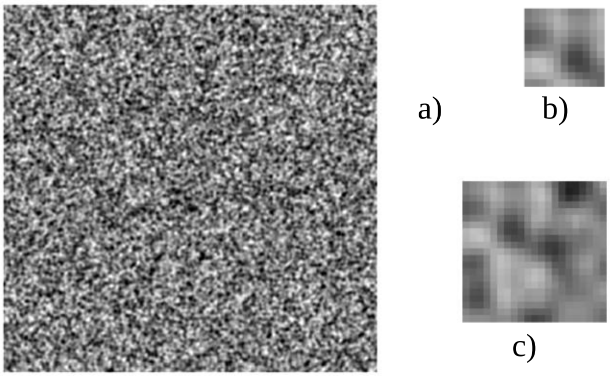

Figure 4. a) A good speckle. b) Representative subset with size 11 pixels. c) Representative subset with size 21 pixels

The natural specimen surface can be used for DIC if it has adequate details and contrast. Otherwise artificially painted surface with optimal pattern should be used. More detailed test results for the images of specimen can be found elsewhere (Jones 2014).

3.4 *Subset size selection*

A proper subset size should be selected for the DIC method. The size should be large enough to let it contain adequate variation in grey levels thus can be uniquely identified in deformed images, at the same time should be small enough to let the deformation within a subset can be precisely modelled with a displacement function for efficient processing.

There are several factors need to be considered when applying this principle for practical applications. The subset size is largely decided by speckle pattern, the resolution of an imaging sensor, and the area of the deformation to be measured. The size is normally set between 11 and 31 pixels (i.e. M given in Section 2.1 is set between 5 and 15). Figures 4 b) and 4 c) are the representative subsets in 4 a) with size 11 and 21 pixels respectively. A subset with larger size has better variation in grey levels.

4 EXPERIMENT DESCRIPTION

4.1 *Experiment setup*

An experiment has been conducted by applying loading on a replica of a concrete structural component used for Sydney Harbour Bridge. As shown in Figure 5, the concrete slab was fixed at one end and controlled hydraulic press was placed at the other end on a circular load plate. Six LVDTs were placed at different locations against the slab surface to measure the displacement during the loading. Many strain gauges were also attached on the slab.

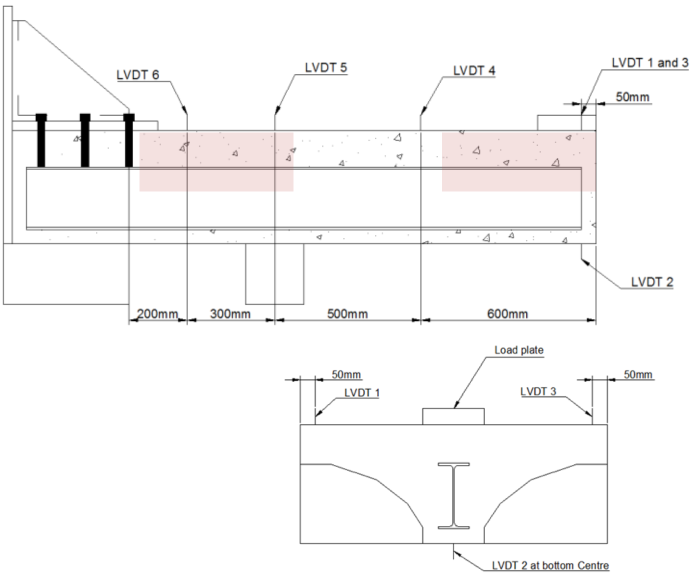

Figure 5. A replica of a concrete structural component used for Sydney Harbour Bridge

Two regions on one side of the slab are captured with two types of digital colour cameras. A Sigma DP2 camera was located at the middle section of the slab where LVDT5 and LVDT6 ware positioned. A Nikon camera was place at the end section where LVDT1 and LVDT3 were positioned. The cameras were adjusted to let them have best view angle and take pictures with minimal distortion, and fixed on tripods and set to automatic exposure with a fixed interval (15 seconds) to avoid undesired movement and to eliminate the operation errors. LED lights ware used to illuminate the regions to be measured. Artificial prints, designed as square patterns with sharp edges and high contrast, ware attached to the concrete surface.

The captured images were first converted to grey-scale, which DIC processing is required. The region of interest in the reference image was then selected based on its location and the quality of the surface for DDM with DIC. A MATLAB software package for DIC (Jones 2015) was applied to process the images captured by the fixed cameras at different times during experiment.

4.2 *Experimental results*

2D DIC measured deformation results from images captured with a Sigma DP2 camera are plotted in Figure 6. The vertical axis is the displacement in pixels and the horizontal axis is number of images used for DIC. The size of the subset selected for 2D DIC is 21 pixels. Measurements from multiple subsets are used to provide statistic information about the measurements. “Average”, “Min” and “Max” in the figure indicate mean, minimum and maximum, respectively. The figure shows that mean, minimum and maximum are very close, which suggests that DIC measurements are reliable and accurate.

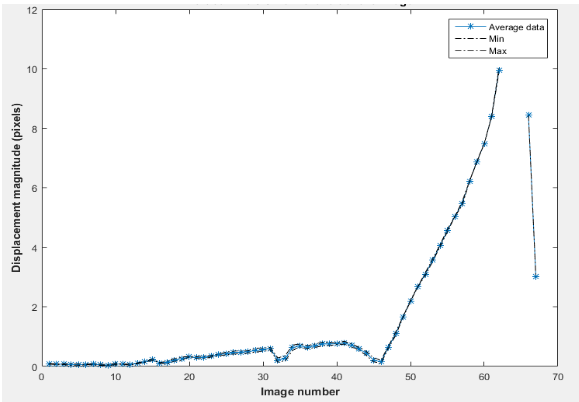

Figure 6. Displacement measurements using 2D DIC

It should be noted that DIC measurement quality changes with different types of speckle. Three types of speckle have been tested, as shown in Figure 7. The result from the printed pattern is the best. The one from natural concrete surface is inferior and the one from the scale mark are the worst, mainly due to its least intensity variation in the vertical direction.

Figure 7. Three types of specimen surface: printed pattern, concrete surface and scale mark

Table 1 gives 2D DIC results from difference types of specimen surface. The average displacement measurements from the printed pattern and natural concrete surface are close, but very different to the one from the scale mark. Measurement STD from the printed pattern is the smallest.

Table 1. Results from difference types of specimen surface

vertical displacement (in pixel)	horizontal line subsets		vertical line subsets	
	AVG	STD	AVG	STD
printed pattern	-1.81	0.012	-1.65	0.016
concrete surface	-1.78	0.035	-1.65	0.024
scale mark	-0.85	0.065	-1.45	0.089

The deformations measured with LVDT sensors at corresponding locations are used as the references for that measured with DIC. Figure 8 shows the comparison of the results from LVDT6 and DIC. It indicates that deformation measured by 2D DIC is closely matching that by the LVDT 6, though their magnitudes have some difference. This is mainly due to location difference between the LVDT and the region selected for DIC. Time synchronization in the experiment for the two measuring systems could also be further improved.

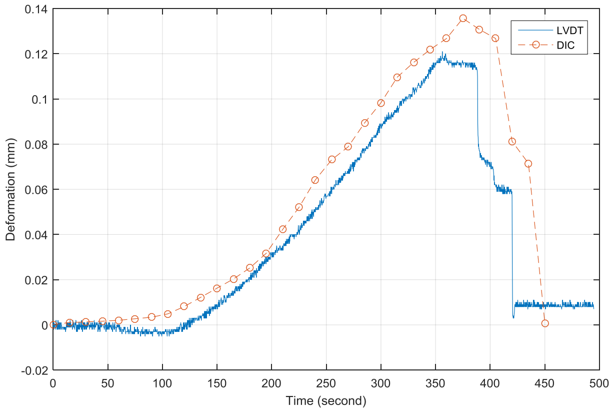

Figure 8. Comparison of the results from LVDT6 and 2D DIC

5 SUMMARY AND CONCLUSIONS

In this paper, the influence of several factors affecting DIC measurement accuracy have been analysed, and the optimal options for these factors have been proposed. The accuracy of DIC method is evaluated by comparing it with the measurements obtained from LVDTs in the experiment.

Experimental results show that DIC can give reasonably accurate displacement measurement with both the printed pattern and natural concrete surface. Printed pattern has very high measurement consistency. It is due to the pattern giving very clear intensity contrast that increased the recognition in the correlation process. Concrete surface itself contains natural texture, which lacks sharp edges and contrast. But it can still be used to measure the deformation with certain accuracy and consistency.

Unlike Sigma camera, the Nikon camera loses much detail with blurred edges; therefore the advantage of sharp edged pattern lost its functionality for DIC. 2D DIC displacement measurement from Sigma camera images for printed patterns with sharp edges and high contrast is comparable to the measurement from LVDTs. Its consistency and accuracy can be further improved by using more suitable patterns. The desired pattern should have clear edges, high contrast and contain proper patterns. The pattern should be neither too large to lose sensitivity nor too small when compared to image pixel size.

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