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Proposed Standardization Effort: Digital-Image Correlation for Mechanical Testing*

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ABSTRACT

We propose a standardization effort on digital-image correlation, to collect and document the available methods for assessing image quality, for analyzing the images to derive displacement and strain values, and for determining the measurement uncertainties. These quantitative measurement methods are needed to guide the practitioners in decisions regarding specimen surface treatment, apparatus and procedures for acquiring images, analysis methods, and reporting of results. The purpose of this presentation is to notify researchers and practitioners of this standardization effort and to invite participation. This presentation also briefly describes the scope of this standardization effort, factors affecting image quality, digital-image correlation, evaluation of results derived from digital-image correlation procedures, and reporting suggestions.

INTRODUCTION

Digital-image correlation techniques were first developed and applied to calculate displacement and strain fields from surface images of deformed specimens at the University of South Carolina in the early 1980s [1-4]. Today, the techniques are widely used for displacement and strain measurements in a variety of materials and engineering applications. Numerous organizations offer services using the techniques and/or sell software that performs digital-image correlation. The reasons for the widespread usage of the techniques for the majority of applications are: (1) the technology for acquisition and analysis of digital images is now widely available; (2) white light (coherent light is not necessary) is used for surface images of specimens; (3) the techniques provide full-field measurements. More importantly, if properly applied, the techniques appear to provide accurate results.

With increasing interest in microscale mechanical testing [5,6], imaging techniques are the only practical choice for specimens that are too small to be instrumented with electrical-resistance strain gages or mechanical extensometers. Hence, now is an opportune time for a standardization effort on digital-image correlation, to collect and document the available methods for assessing image quality, for analyzing the images to derive displacement and strain values, and for determining the measurement uncertainties. These quantitative measurement methods are needed to guide the practitioners in decisions regarding specimen surface treatment, apparatus and procedures for acquiring images, analysis methods, and presentation of results.

The purpose of this presentation is to notify researchers and practitioners in the field of this standardization effort and to invite participation. The terminology to be used in this effort will follow those terms described in the "Standard Guide for Evaluating Non-contacting Optical Strain Measurement Systems" [7]. Additional relevant terms will be added to the list when they are considered to be necessary.

SCOPE

For an application of digital-image correlation to a mechanical test, the two required components are digital images of the object at different deformation levels of interest and a digital-image correlation procedure to convert the encoded deformation information on the images into values of displacement and strain. This standardization effort is primarily concerned with the variables that affect the quality of the images that contain the basic data, and the digital-image correlation procedures that produce the derived data. Various ASTM standards provide guidance for specimen design and mechanical loading [8].

The proposed scope of the present effort is digital-image correlation of plan-view images for measurement of in-plane deformation. Images will include those acquired during common mechanical tests and microscale testing. Left to complementary efforts are, for example, three-dimensional techniques using multiple cameras, speckle-interferometric techniques utilizing optical gratings, and moiré techniques.

FACTORS AFFECTING IMAGE QUALITIES

In this section, we briefly describe and discuss some of the variables that influence the qualities of images, which in turn affect the accuracy of the derived data after digital-image correlation. These variables can be introduced in specimen preparation, in apparatus setup, or during mechanical testing.

Some of the variables include image characteristics such as brightness and contrast, sharpness, feature (or speckle) size and its distribution, feature shape, and feature density. For digital-image correlation, the images should have a proper balance between brightness and contrast with random distinct features, which are usually generated manually. For instance, a metallic specimen with an untreated reflective surface will not be desirable.

Although some algorithms can accommodate different average brightness of images, a significant change in brightness or contrast from one image to the other may introduce errors in the derived data. This typically occurs in imaging by optical microscopy with vertical illumination, when the test specimen rotates about the loading axis during deformation and produces out-of-plane displacements. This violates one of the requirements in applying the two-dimensional digital-image correlation technique: the recording camera needs to be set and maintained perpendicular to the object surface during deformation. Variation of lighting source intensity or relative position with respect to the object surface also changes the brightness and contrast from image to image. This phenomenon of variable brightness and contrast also frequently occurs in images taken in the scanning electron microscope (SEM). In this regard, the use of methods such as normalized cross-correlation, which accounts for overall changes in brightness within each subset, needs to be considered in assessing these effects.

Often, paints or inks are used to generate random features on the specimen surface to facilitate the subsequent digital-image correlation processing. Usually, the desirable size and density of the features are chosen based on consideration of the pixel size of the recording camera, such as 3x3 or 4x4 pixels in size. Unfortunately, there are cases where manual surface treatment is not feasible, such as microscale specimens. In these cases, surface features such as microstructure, material inhomogeneity, or even surface contamination of the specimen can provide useful features.

There is also a question of how much strain or rigid-body motion (especially rotation) is acceptable between the images being processed. That is, how often must images be acquired during a continuous deformation experiment for a given strain rate. Too large a strain between images might cause the digital-image correlation scheme to be unable to find a correlation between the images, producing so-called de-correlation, and thus fail to produce accurate results.

To address the issues raised above, we are soliciting input and discussion from researchers and practitioners in the field of all the variables that might influence the qualities of images, and of the methods for quantitatively assessing the effects that these variables may have on the accuracy of the derived displacement and strain values. Discussions of the effects of some variables can be found in references [9-12].

DIGITAL-IMAGE CORRELATION PROCEDURES

A variety of image-processing approaches have been used in various digital-image correlation procedures to derive displacements and strains from a pair of initial and subsequently deformed images [2,4,5,9,10,13]. Recently, two extensive review articles have been published [14,15] outlining a range of applications that have been addressed using both 2D and 3D digital-image correlation. Although different approaches and procedures have their advantages and disadvantages, it is not the intent of this standardization effort to rank the merits of each individual approach or procedure. Rather, the present effort is to collect and document the parameters and quantities that are defined and used in various approaches and procedures for digital-image processing and then to assess the effects of these variables on the accuracy of the derived values of displacement and strain.

The approaches used in the digital-image correlation can be categorized as: (1) Fourier-type techniques, which use intensity frequency of the images; and (2) amplitude techniques, which directly use the intensity amplitude of the images. Different subset sizes of the images, different interpolation functions, and different optimization schemes have been used in both approaches to achieve desirable results. Most of the digital-image correlation papers listed in the references have reported errors associated with the analyses. It is time to systematically collect these error-assessment methods and to critically evaluate and document the errors associated with different approaches, interpolation functions, and optimization schemes.

The study described in reference [12] is a good example of a systematic assessment of the errors associated with various experimental variables. Example results are given in Figs. 1 and 2, for bilinear and bicubic pixel interpolation, respectively. Figure 1 shows the dependence of errors on sensor size Δx, which is the reciprocal of the one-dimensional total sampling points of the sensor. It shows that errors decrease with decreasing Δx from 0.2 to 0.05, which corresponds to increasing sampling frequency. Further decrease in Δx to 0.01 increases the errors. This is attributed to quantization errors, which are reduced when a higher quantization level is used (8 bits versus 12 bits in the study). The largest errors occur at the interpolation values, which are reduced if the interpolation function is changed from bilinear interpolation to bicubic interpolation. This result is shown in Fig. 2.

Recently, Schreier and Sutton [16] have shown that cyclic errors, similar in form to those shown in Fig 1, can be directly attributed to the method of interpolation used when analyzing images in digital-image correlation. Most importantly, their work suggests that by using sophisticated interpolation and image analysis methods, it is theoretically possible to achieve (a) point-to-point displacement accuracy on the order of 0.001 pixels and (b) point to point strain accuracy of a few microstrain.

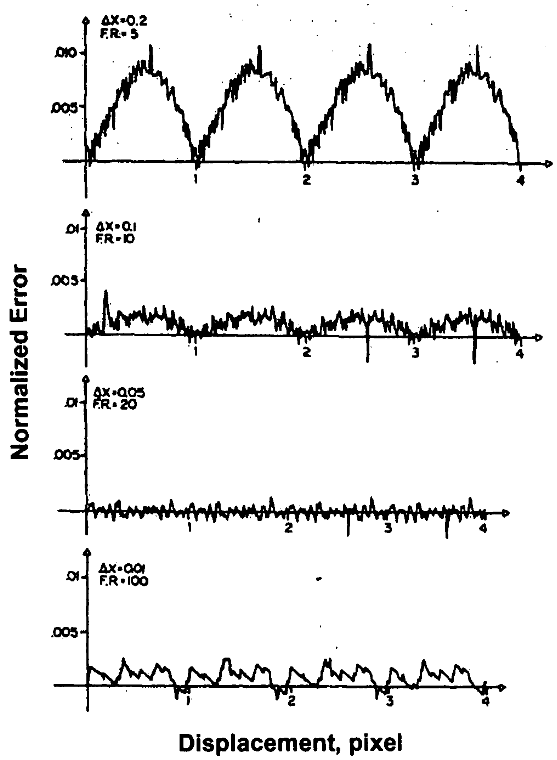

Figure 1. Normalized errors in estimated centerpoint translation of a damped sinusoid versus actual translation in pixels for an 8-bit digitizer and bilinear intensity interpolation. Δx is the total sensor size or sample size, and F.R. is the frequency ratio.

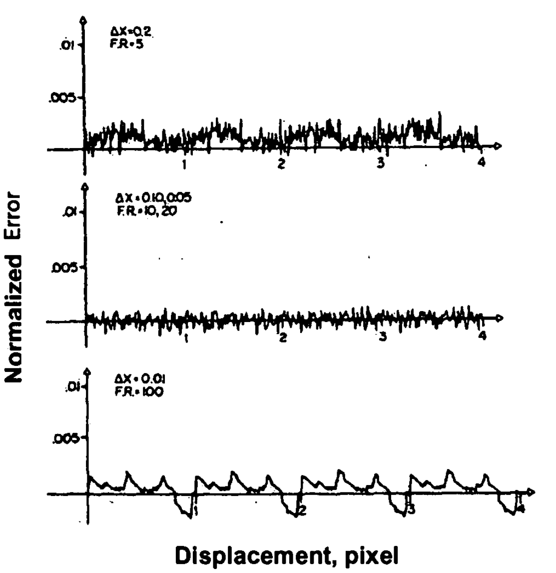

Figure 2. Normalized errors in estimated centerpoint translation for an 8-bit digitizer and bicubic intensity interpolation. Results for Δx = 0.10 and Δx = 0.05 are similar. Δx is the total sensor size or sample size, and F.R. is the frequency ratio.

EVALUATION OF RESULTS DERIVED FROM DIGITAL-IMAGE CORRELATION PROCEDURES

Each software package for performing digital-image correlation must be evaluated to determine reliable estimates for accuracy of the resulting displacement and strain values. For this purpose, the guideline described in Section 5 of reference [7] is applicable.

We intend to distribute sets of images obtained with specimens that had strains and displacements measured during loading with standard measurement methods at various laboratories for interested users to process with their digital-image correlation package. The results of this round-robin exercise should provide some estimates of errors that are produced in each package. This might also provide some information regarding the sources of errors.

REPORTING SUGGESTIONS

For reporting the results of the digital-image-correlation analysis, one should include details of specimen preparation. If the specimen surface is treated to enhance features, the description of the materials and the preparation procedures used for the enhancement purpose should be reported.

The specifications of the recording camera and the frame grabber should be reported. If optical microscopes, SEM or other magnifying devices are used, their characteristics should be documented. The report should also include the description of the digital-image correlation procedures and how the strain values are calculated.

ACTION ITEMS

We will provide sets of images as mentioned in the previous section for a round-robin exercise. We are soliciting input and discussion from researchers and practitioners in the field of digital-image correlation and inviting interested parties to join this standardization effort. Interested parties can contact Dr. David T. Read at read@boulder.nist.gov or (303) 497-3853, or Professor Michael A. Sutton at sutton@sc.edu (803) 777-7158.

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