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Vision System for Remote Strain/Deformation Measurement

Gregory L. Hovis, Ph.D. (Savannah River Technology Center)
Prof. William F. Ranson, Ph.D., (University of South Carolina)
Howard J. Reed, (Savannah River Technology Center)
Carl T. Etheredge, (University of Alabama)

Savannah River Site, Building 773-A, Aiken, SC/USA
e-mail: gregory.hovis@srs.gov
Tel: 1-803-725-1180

ABSTRACT

Machine vision metrology is ideally suited to the task of non-contact/non-intrusive deformation and strain measurement in a remote system. The objective of this work-in-progress is to develop a compact instrument for strain measurement consisting of a camera, image capture card, PC, software, and light source. The instrument is portable and useful in a variety of applications and environments. A digital camera with a microscopic lens is connected to an image capture card in a PC. Commercially available image processing software is used to control the image capture and image processing steps leading up to displacement/strain measurement. Image processing steps include filtering and edge/feature enhancement. Custom software is required to control/automate certain elements of the acquisition and processing. Images of a region on the surface of a specimen are acquired at hold points (during static tests) or at regular time intervals (during transients). Salient features in the image scene (microstructure, oxide deposits, etc.) are observed in subsequent images. The strain measurement algorithm characterizes relative motion of the salient features with individual displacement vectors yielding 2-D deformation equations. The set of deformation equations is solved simultaneously to yield unknown deformation gradient terms that are used to express 2-D strain. The overall concept, theory, and test results to date are presented herein.

1. Introduction

Under hazardous or difficult conditions, remote systems are used in a variety of ways. In production facilities, research environments, and for specialized tasks, remote systems play a key role in worker protection. The material presented herein describes an effort to package a non-contact/non-intrusive deformation and strain measurement instrument in a portable remote system. This work represents the application of theory first developed by Ranson and Hovis [1] which provides a method for measuring full-field two-dimensional strain by observing the motion of salient features on the surface of a specimen. This theory eliminates the need for artificial speckle patterns or light interference techniques, and thereby reduces the required equipment to a level suitable for packaging in a portable remote system.

The objective of task is to develop a compact instrument for strain measurement consisting only of a camera, image capture card, PC, software, and light source. The instrument is designed to be portable and useful in a variety of applications and environments. A digital camera with a microscopic lens is connected to an image capture card in a PC. Commercially available image processing software is used to control the image capture and image processing steps leading up to displacement/strain measurement. Image processing steps include filtering and edge/feature enhancement. Custom software is developed as part of this work which provides necessary image processing utilities to calculate strain via a centroidal tracking algorithm (see Hovis[2]). Images of a region on the surface of a specimen are acquired at hold points (during static tests) or at regular time intervals (during transients). Salient features in the image scene (microstructure, oxide deposits, etc.) are observed in subsequent images. The strain measurement algorithm characterizes relative motion of the salient features with individual displacement vectors yielding 2-D deformation equations. The set of deformation equations is solved simultaneously to yield unknown deformation gradient terms that are used to express 2-D strain.

This paper describes the development of a prototype instrument for visual strain measurement. Required equipment, measurement algorithm, and a theoretical basis are presented herein.

2. Instrument Features

The following sections give details on the equipment used for the visual strain measurement instrument. Equipment specifications will vary with metrology requirements. The equipment described is chosen to meet the objectives for development of a prototype instrument. The goal is to measure strain magnitudes representing the elastic region of common metal alloys (e.g. stainless steels, carbon steels, and aluminum alloys).

2.1 Hardware

A Dell 333MHz Pentium II with 128Mb RAM is the computing platform used in the prototype instrument. Images are taken with a Kodak scientific camera (Model ES1.0/10bit). The camera has a 1028X1024 square pixel arrangement, 10 bits per pixel, and is capable of acquiring images at 30 frames per second. Camera images are collected using a Matrox Pulsar frame grabber. It should be noted that this card is a “single tap” model (i.e. it has a single 16-bit interface). Therefore with this combination of camera and card, images can only be acquired at 15 frames per second. For the prototype strain measurement device, this is a sufficient image capture rate. A microscopic lens was chosen to view a region size suitable for strain measurement on the order of 0.5 to 15 thousands of an inch per inch (.0013 to 0.038 cm per cm). The lens has variable magnification of 7x to 45x. The actual region size represented by the 1028x1024 pixel array is 9.5 to 65 thousands of an inch (0.024 to 0.166 cm).

2.2 Measurement Technique

The strain measurement algorithm presented is unique in that motion of salient features on the surface of the specimen is observed during a strain-inducing event. Salient features might be material texture, machining marks, oxide deposits, or finishing/polishing marks. This method eliminates the need for artificial patterns, interferometry, or holography.

An example of the types of images being acquired is shown below. Figure 1a shows a gray scale digital image of bead blasted aluminum. This image was taken at ~40x magnification and the field of view is ~0.020 inches (~0.051cm). Figure 1b is the same image after simple feature enhancement. Figure 1b provides the basis for the theory. Deformation equations are formulated using the naturally occurring isolated dark regions in the enhanced image. The positions of the dark regions, termed "items of interest," are tracked from one image to another to measure strain using a centroidal tracking algorithm (discussed below).

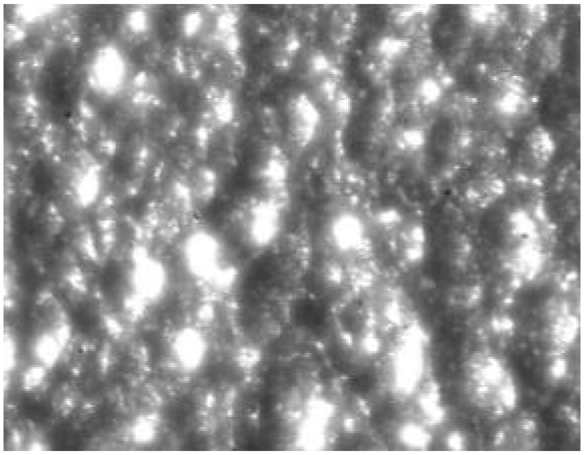

Figure 1a. Gray scale image.

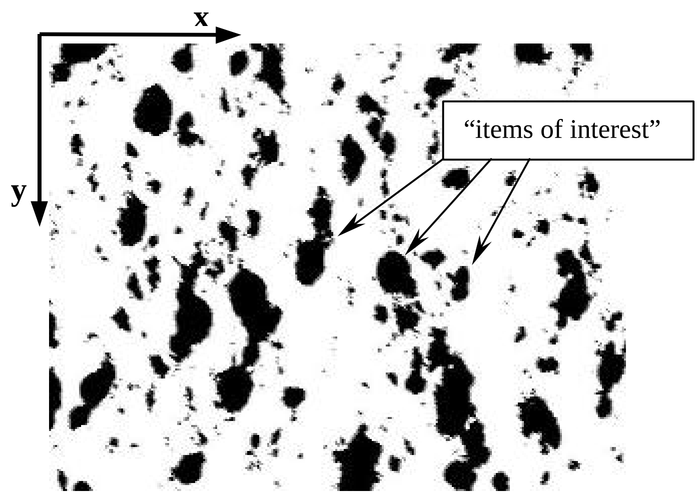

Figure 1b. Gray scale image after feature enhancement.

The a centroidal tracking algorithm, first presented by Hovis[2], determines the positions of items of interest by finding their centroids with respect to an 2-D Cartesian coordinate system as shown in Figure 1b. An item of interest is defined by any closed surface consisting of discrete connected elements (or pixels). Example items of interest are pointed out in Figure 1b. Centroid location is obtained using equations 1-3 below.

$$X_c = \Sigma[x_i \Delta a_i]/A \qquad (2.2.1)$$

$$Y_c = \Sigma[y_i \Delta a_i]/A \qquad (2.2.2)$$

$$A = \Sigma[\Delta a_i] \qquad (2.2.3)$$

The centroid location is defined by the coordinate (X_c, Y_c). The coordinates (x_i, y_i) locate individual pixels in the item of interest. Pixel area, Δa_i=1 pixel, so the total area, A, of an item of interest is simply the sum of number of pixels in the item.

This algorithm necessitates two fundamental requirements on acquired images used in making strain calculations: (1) The image acquisition and/or processing must isolate useful items of interest represented by groupings of distinct isolated connected pixels. (2) In order to measure deformation, the features must be initially in the image scene, and they must not leave the image scene in subsequent images (i.e. deformation cannot be greater than the viewable region size established by the camera and lens).

Centroids of items of interest are obtained for initial and subsequent images. Strain is measured by writing 2-D deformation equations (or mapping functions) that mathematically characterize the movement of the items. The theoretical basis is described below.

2.3 Theoretical Basis

In this section the theoretical problem is formulated as follows: Given the positions of points in a reference configuration and the corresponding points in a deformed configuration, determine the change in the distance between two points by a transition from the first to the second. The question is geometrical in nature and neither the causes that give rise to the deformation nor the law according to which the body resists it are of any importance in the analysis. Since the analysis is purely geometrical, measurements are referred to as strain measurements.

Centroidal coordinates P and Q, which define the location of a small region of two distinct features of an image, are shown in figure 2a.

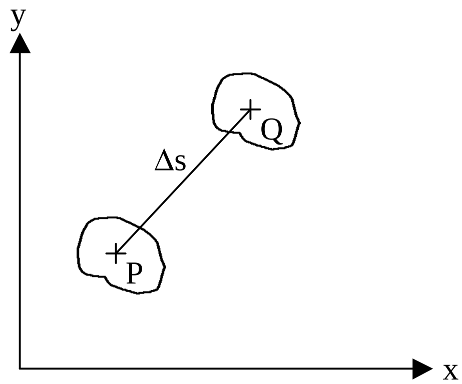

Figure 2a. Two distinct features in image scene.

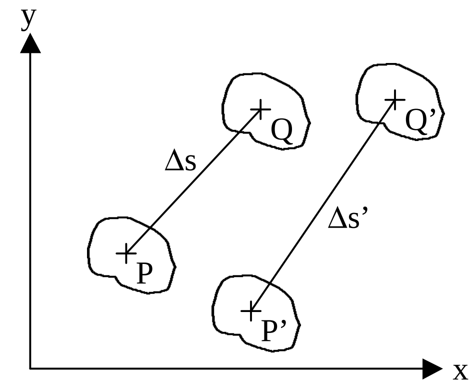

Figure 2b. Features before and after deformation.

As a result of the deforming process, points P and Q are displaced to the deformed points P' and Q' respectively (Figure 2b). If the area that defines the centroidal coordinates P and Q is sufficiently small, then points P and Q are mapped uniquely in to the centroids P' and Q'. Thus the distances Δs and $\Delta s'$ determine the change in length and orientation of the relative change in positions P and Q.

Introduce the notation:

$$E_{PQ} = \frac{\Delta s' - \Delta s}{\Delta s} \qquad (2.3.1)$$

E_{PQ} is the relative change in distance between the points P and Q produced by the deformation. This quantity is called the relative elongation at the point P in the direction of Q, which is the usual definition of engineering strain. This quantity can be expressed in terms of the strain components ε_{ij} (as developed through the theory of continuum mechanics [3]). This relationship is expressed in the form,

$$E_{PQ} (1+1/2\, E_{PQ}) = l^2\varepsilon_{xx} + m^2\varepsilon_{yy} + n^2\varepsilon_{zz} + lm\varepsilon_{xy} + ln\varepsilon_{xz} + mn\varepsilon_{yz} \qquad (2.3.2)$$

where direction cosines l,m, and n determine the orientation of E_{PQ}. For surface measurements where the outer normal forms on the coordinate axes, then the expression takes the form:

$$E_{PQ}\,(1+1/2\;E_{PQ}) = l^2\varepsilon_{xx} + m^2\varepsilon_{yy} + lm\varepsilon_{xy} \qquad (2.3.3)$$

The usual procedure in continuum mechanics is to calculate the relative elongation at a point P from the quantities ε_{ij} which are expressible in terms of displacements which characterize the deformation. However in this experimental technique strain components are calculated from relative elongations from measured data. This technique makes no small strain assumptions and represents the most general experimental technique for direct strain measurements. Furthermore equation 2.3.1 can be redefined in a manner to reflect the deformed distances as a reference, and then this technique becomes applicable to fluid measurements.

Unknowns in equation 2.3.3 are ε_{xx}, ε_{yy}, and ε_{xy}, therefore a minimum of four features must be selected in order to calculate the strain components.

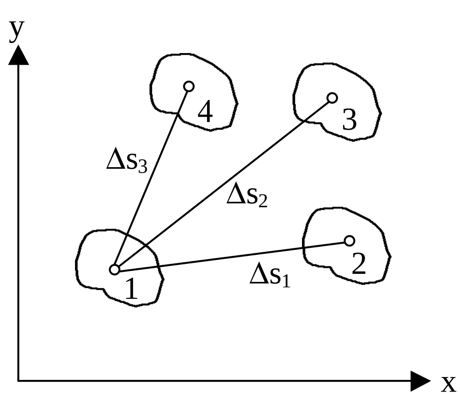

Figure 3a. Line segments connecting image features.

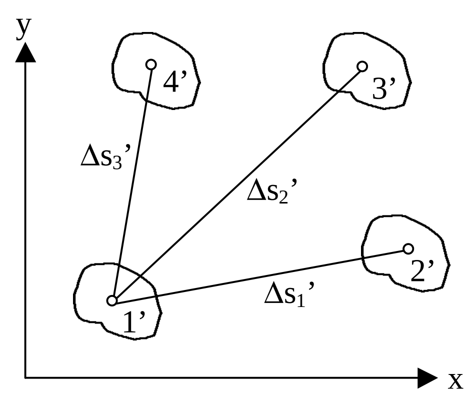

Figure 3b. Line segments after deformation.

Figure 3a identifies four features and three line segments Δs_1, Δs_2, and Δs_3 along with the orientations which determine the direction cosines for each line. Corresponding line segments $\Delta s_1'$, $\Delta s_2'$, and $\Delta s_3'$ from the deformed image are calculated using measured data as shown in Figure 3b. Equation 2.3.1 is then used for each line segment as input to equations 2.3.3. These four image features are the minimum data to calculate ε_{xx}, ε_{yy}, and ε_{xy}. Accuracy is increased by overdeterming the equations by selecting more than four image features.

2.4 Software

Custom Windows® software has been developed using Microsoft Visual C++® to carry-out the measurement technique and calculate strain on the basis of the theory above. This software loads pairs of images, performs necessary feature enhancement, and overlays the images to give a visual representation of deformation. Presently a manual method is used to indicate corresponding pairs of features. Full automation of the measurement algorithm is a planned enhancement to the image analysis software.

REFERENCES

1. Ranson, W.F. and Hovis, G.L., "*Machine Vision Applications in Micro-Mechanics*," Society for Experimental Mechanics Spring Conference, Cambridge Mass., May 1989.
2. Hovis, G.L., "*Centroidal Tracking Algorithm for Deformation Measurements Using Gray Scale Digital Images*," Doctoral dissertation, University of South Carolina, May 1989.
3. Frederick, D. and Chang, T.S., "*Continuum Mechanics,*" Scientific Publishers, Inc., Cambridge, Mass., 1972