NON-CONTACTING MEASUREMENT TECHNOLOGY FOR COMPONENT SAFETY ASSESSEMENT

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1 Introduction

The ever increasing requirements for improved passenger safety in automobiles has led to a great number of improvements over the recent years. Active safety components like airbags or seatbelt tensioners in combination with crash sensors can be found in virtually every new car. Furthermore, passive safety has been greatly improved through optimization of the deformations of components or the complete car body in the event of a crash. These cost-effective optimizations are becoming more and more important as new materials and joining methods are being introduced into the automotive manufacturing industry. The Finite-Element Method (FEM) has proven an invaluable tool helping designers to understand and improve passive automotive safety. With the increased usage of FEM analysis has come an increased need for experimental model validation not satisfied by traditional measurement technology such as strain or clip gages or extensometers. The demand for accurate, time-resolved full-field deformation measurements has led to the development of new techniques for optical deformation measurement technology that is ideally suited for FEM model verification and the determination of material characteristics under quasi-static or dynamic loading conditions. In this article, we introduce an accurate non-contacting full-field measurement technology applicable to both two and three-dimensional measurement problems.

2 Digital Image Correlation

The digital image correlation technique was originally introduced in the early '80s by researchers from the University of South Carolina [1]. The idea behind the method is to infer the displacement of the material under test by tracking the deformation of a random speckle pattern applied to the component's surface in digital images acquired during the loading. Mathematically, this is accomplished by finding the region in a deformed image that maximizes the normalized cross-correlation score with regard to a small subset of the image taken while no load was applied. By repeating this process for a large number of subsets, full-field deformation data can be obtained.

More recently, the DIC method has been extended to use multiple cameras, permitting the measurement of three-dimensional shape as well as the measurement of the three-dimensional deformation [2]. The three-dimensional technique requires the use of at least two synchronized cameras acquiring images of the loaded specimen from different viewing angles. By determining corresponding image locations accross views from the different cameras and tracking the movement throughout the loading cycle, the shape and deformation can be reconstructed based on a simple camera calibration.

2.1 Measurement Setup

The experimental setup for the DIC method is comparatively simple and illustrated in Figure 1. For the case of two-dimensional measurements (only in-plane displacements on relatively flat specimens), only one camera is required. For three-dimensional measurements, two or more cameras are needed, as shown in the figure 1.

The DIC method does not require the use of lasers and the specimen can be illuminated by means of a white-light source. However, the specimen surface must have a fairly uniform random pattern, which can either be naturally occuring or applied to the specimen before the test. Among the many methods for pattern application are self-adhesive, pre-printed patterns, stamps and application of paint speckles with air-brushes, spray cans or brushes.

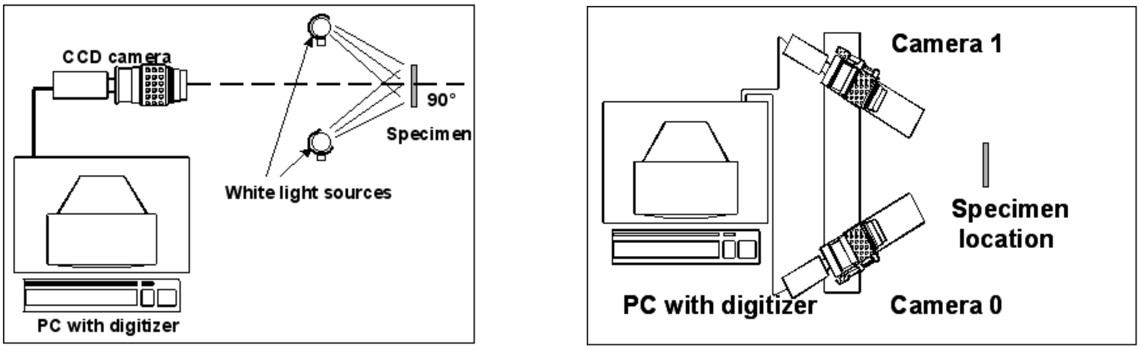

Figure 1: Setup for 2D and 3D-deformation measurement.

2.2 Image Analysis

Though a large variety of DIC algorithms have been developed over the years [1,3,4,5,6], one particular method has established itself as the preferred method for deformation analysis due to it's capability to measure arbitrarily large rotations and strains in excess of 500%, as well as it's superior accuracy and efficient implementation. This algorithm [3,4] is based on an iterative solution process for finding the maximum of the cross-correlation coefficient in an n-dimensional parameter space. The parameter space is spanned by the parameters of a mapping function that transforms coordinates from the original image frame to coordinates in the deformed image and typically includes the mean displacement in the horizontal and vertical directions as well as the four gradients of the displacements with respect to the coordinate axes. Using this parameterization, an originally square neighborhood in the undeformed image can be mapped to a sheared, strained and rotated subset in a deformed image. This is illustrated in Figure 2. As the deformed coordinates will not fall onto the sampling grid of the image, accurate gray-value interpolation techniques are required to achieve optimal sub-pixel accuracy without bias [4].

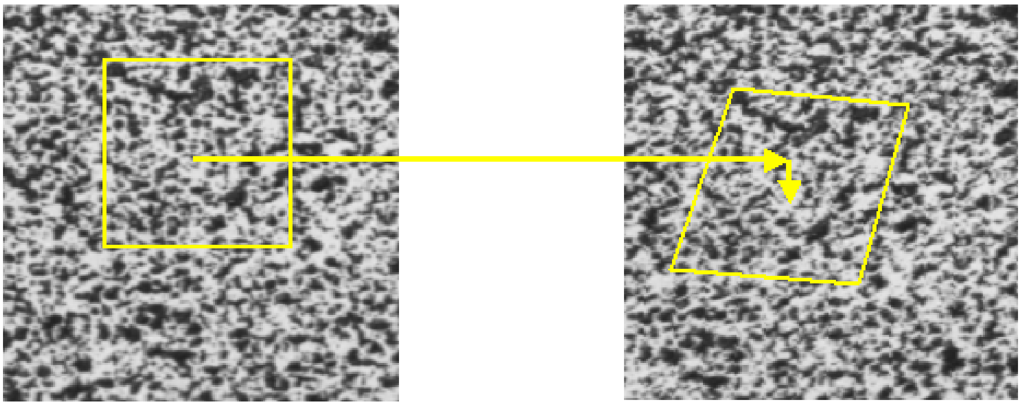

Figure 2: Undeformed and deformed image with subset. The mapping function permits the matching of square areas from the undeformed image to non-square areas in the deformed image.

For three-dimensional shape measurements, a similar algorithm is used. However, the mapping function is now based on the known calibration parameters of the cameras, and the sought parameters are the location and orientation of a segment of the surface assumed to be locally planar. For deformation measurements, additional parameters describing the orientation and position of the surface segment after deformation as well as parameters describing higher-order deformation terms are added to the mapping functions. This process can be interpreted as a projection/back projection approach, as illustrated in Figure 3.

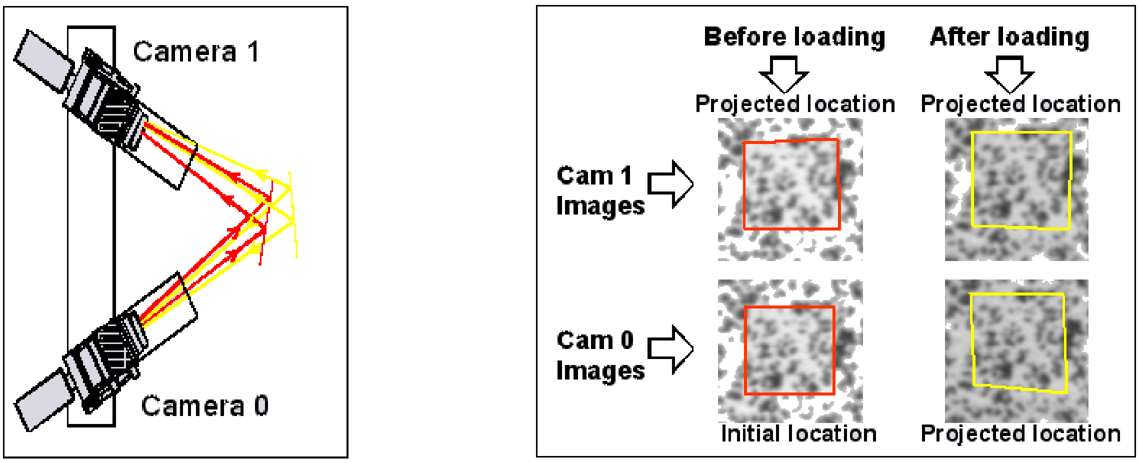

Figure 3: 3D measurement principle. Usage of projection and back projection method to determine the position and displacement of small segments of the surface.

3 Examples

For FEM analysis, the accurate knowledge of material properties such as the Young's modulus and the yield strength is critical to successfull modelling. Such parameters are not always available and have to be measured, particularly in new materials or functionally graded materials as found in and around weld joints. Using digital image correlation has a particular advantage when locally varying material properties have to be measured, as the modulus and the yield strength for different regions can be measured in a single tension test. This is illustrated in the following example. A 3.18mm thick by 9.53mm wide steel tensile coupon was machined from an arc-welded butt-joint. A speckle pattern was applied to the specimen by first spraying a white coat of latex paint and then applying Xerox toner powder to create a contrasting pattern. Images before and after deformation of the sample are shown in Figure 4. A series of images was acquired and the load for each image was recorded. Using a digital image correlation analysis software [7], the strain for each load level was determined from the images. The resulting stress-strain curve for the material in the weld nugget, several locations in the heat-affected zone (HAZ) as well as the base material are shown in Figure 5. Due to the full-field capability of the optical measurement technique, the locally varying material behaviour can be characterized in a single tension test.

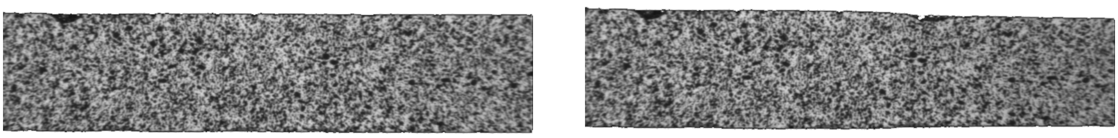

Figure 4: Two deformation states of a 9,53mm wide steel tensile coupon. The left image is the original undeformed state of the sample.

Figure 5: Stress-strain curves for base, HAZ and nugget of arc-welded steel.

For test conditions where the specimen is either non-planar, or the deformation is not pre-dominantly in-plane, the specimen shape and deformation can be measured using a two-camera setup. An example of such a measurement system is shown in Figure 6. The two cameras are mounted on a rigid aluminum bar to avoid relative motion of the cameras. As opposed to two-dimensional systems, where camera calibration is simply the determination of a scale factor, three-dimensional systems have to be calibrated. Commonly, a pin-hole camera model with Seidel lens distortions is used. The calibration process involves the acquisition of a series of images of a calibration target in different orientations (rotations around all three axes). Two example images are shown in Figure 7. From the images of the calibration target, calibration parameters for the two cameras as well as their relative orientation can be determined fully-automatically [8]. Once the system is calibrated, images of the specimen undergoing deformation are acquired. Figure 8 shows the two images acquired by the left and right camera for the example of a 6.35mm diameter metal fastener at the end of the loading cycle close to failure. Using digital image correlation software [9], the shape of the deformed fastener as well as the strains were calculated and are shown in Figure 9. One can see the pronounced necking toward the bottom of the specimen. This example is part of an on-going research project to determine the effects of high-speed impacts on material behaviour.

Figure 6: Setup for 3D measurement.

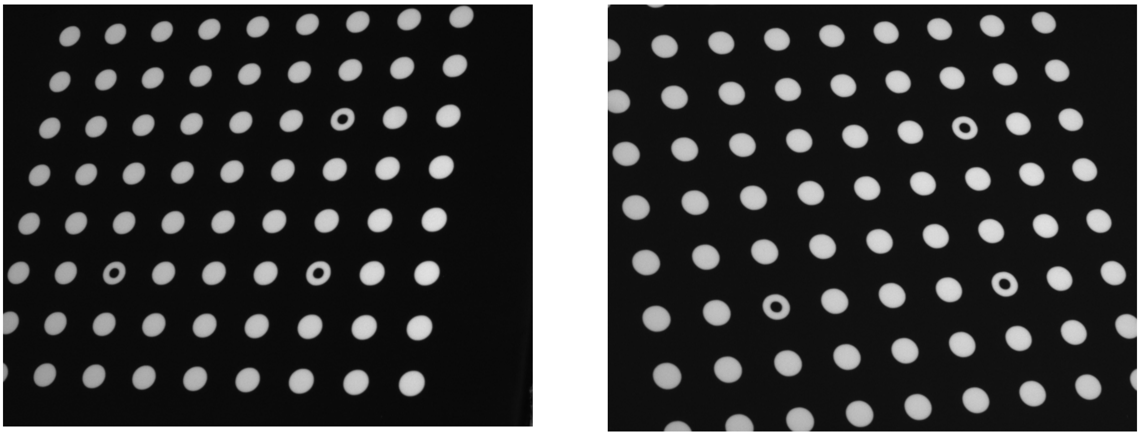

Figure 7: Example images of the calibration pattern taken from camera 1 and camera 2.

Figure 8: Images of a metal fastener before loading (left) and close before failure.

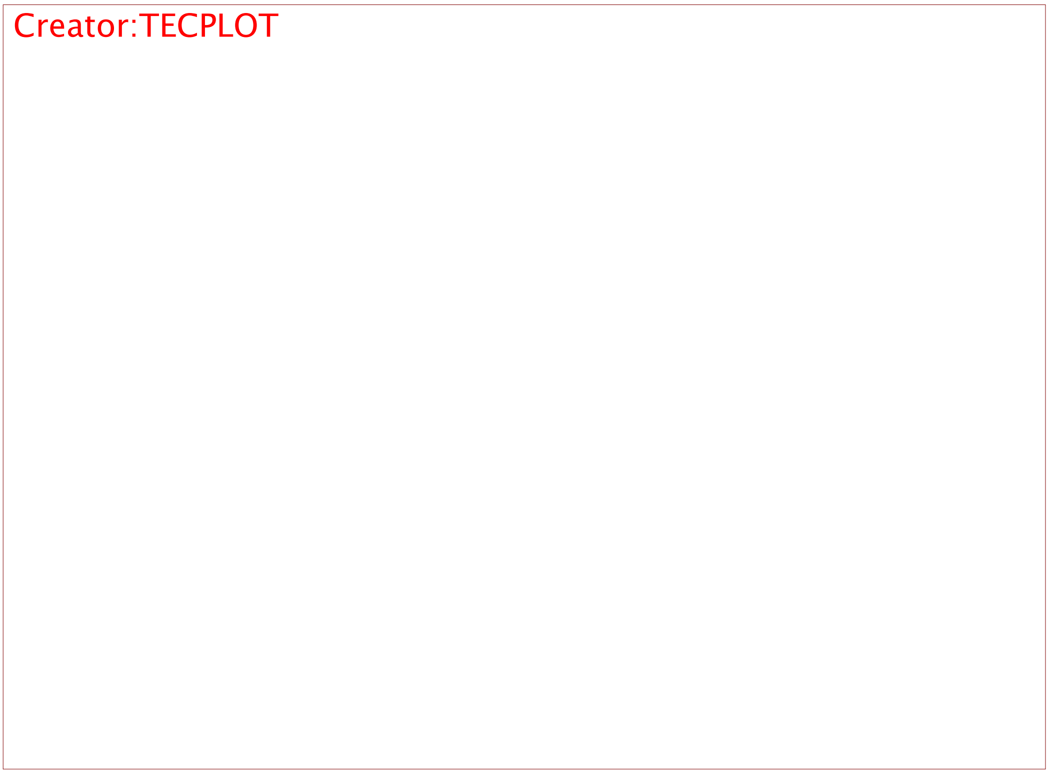

Figure 9: Result graph of the 3D-deformation measurement showing contour and strain of the sample.

4 Summary and Conclusion

In this paper, we have provided an overview of an accurate technology to measure non-contact and full-field displacement and strains. The simple and robust setup is well-suited to both laboratory and field conditions and minimal specimen preparation is required. The key points of the technology and analysis software are:

- Successfully used to make measurements on a range of specimen sizes from 0.50mm to 200mm
- Accuracy unaffected by large in-plane rotations or translations
- Accuracy up to +/-0.01 pixels in displacement
- Accuracy > 200 microstrain
- >500% strain can be measured
- Quasi-static to ultra-high speed events.

With the 3D technology full-field, three-dimensional displacement measurements can be achieved with:

- Curved or planar objects from <1mm to several meters in size
- Includes effects of perspective in image analysis
- Cameras can be calibrated and moved to test site
- Accuracy unaffected by large rotations or translations
- Strain levels in excess of 100% have been successfully measured
- Complex loading (combined tension/torsion, compression, pressurization etc.)

5 References

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