3-D computer vision in experimental mechanics

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Abstract

Optical methods that give displacement or strain fields are now widely used in experimental mechanics. Some of the methods can only measure in plane displacements/strains on planar specimens and some of them can give both in plane and out of plane displacement/strain fields on any kind of specimen (planar or not). In the present paper, the stereovision technique that uses two cameras to measure 3 D displacement/strain fields on any 3 D object is presented. Additionally, a quite inclusive list of references on applications of stereovision (and 3 D DIC) to experimental mechanics is given at the end of the paper.

Keywords: Stereovision; Stereo-correlation; 3-D digital image correlation (3D-DIC); Shape measurement; Displacement/strain measurement; Experimental mechanics

1. Introduction

Full-field optical techniques for displacement or strain measurements are now widely used in experimental mechanics. The main techniques are photoelasticity, geometric moiré, moiré interferometry, holographic interferometry, speckle interferometry (ESPI), the grid method and digital image correlation (DIC) [1–9]. It should be noted that some of these techniques can only measure in-plane displacements/strains on planar specimens and some of them can give both in-plane and out-of-plane displacement/strain fields on any kind of specimen (planar or not). Due to its (apparent) simplicity and versatility, the DIC method is probably one of the most commonly used methods, and many applications can be found in the literature[1] [10–45]. When it is used with a single camera (classical DIC), the DIC method can only give in-plane displacement/strain fields on planar objects. By using two cameras (stereovision), the 3-D displacement field and the surface strain field of any 3-D object can be measured. Using stereovision in conjunction with DIC leads to a so-called digital image stereo-correlation technique (DISC), also called 3-D DIC. In this paper, the stereovision (and 3-D DIC) technique developed at the Research Center on Tools, Materials and Forming Processes (CROMeP) at École des Mines d'Albi is presented.

2. Stereovision for 3-D shape and 3-D displacement/strain measurement

Binocular stereovision is a technique for recovering the 3-D structure of a scene from two different viewpoints (see Fig. 1 where $P(X, Y, Z)$ is the 3-D point to be measured, $p_1(u_1, v_1)$ and $p_2(u_2, v_2)$ are its stereo projections in the images, C_1 and C_2 are the optical centers of the two cameras).

From a pair of images, it is possible to compute the 3-D coordinates of a physical 3-D point by triangulation assuming that:

1. The geometry of the stereo rig (i.e. the relative position and orientation of the two cameras) is known. This problem is solved by an off-line camera calibration procedure.

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[1] To date, the author has noted more than 350 journal papers dealing with DIC-based measurements in experimental mechanics. The reference list can be provided upon request.

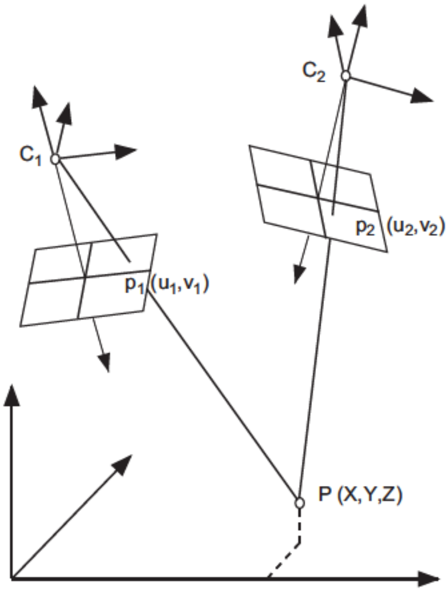

Fig. 1. Binocular stereovision.

2. The two image points p_1 and p_2 are matched, i.e. identified as corresponding to the same physical point P. This is called the stereo-matching problem.

2.1. Calibration of the stereovision sensor

Camera calibration is an important task in 3-D computer vision, particularly when metric data are required for applications involving accurate dimensional measurements.

Calibrating a camera involves determining its intrinsic parameters (generally, the two coordinates in the image frame of the intersection of the optical axis with the image plane, the two scale factors along the vertical and horizontal axes of the image frame, and, if need be, the lens distortion parameters) and its position and orientation with respect to an arbitrary world reference frame [46]. Calibrating a stereovision sensor made up of two cameras involves determining the intrinsic parameters of each camera and the relative position and orientation between the two cameras (see Fig. 2). These calibration data are required to compute, by triangulation, the 3-D coordinates of a point corresponding to matched pixels on the two images.

An original and flexible technique has been developed to easily calibrate a camera or a stereovision sensor. Lens distortion is taken into account. The technique only requires the camera to observe a (planar) pattern shown at a few different orientations (typically between 10 and 20). The motion of the pattern need not be known and the pattern itself can be imprecise (i.e. its geometry need not be known accurately). Using a photogrammetric bundle adjustment approach [47], the intrinsic parameters of each camera (including the distortion parameters), the 3-D points of the pattern and the relative position and orientation between the two cameras are estimated all together. The technique is easy to use, flexible and leads to a highly accurate calibration [48,49].

Fig. 2. The stereo rig used in our lab.

The calibration parameters will be used throughout this paper at different stages for:

- the rectification of the pairs of stereo images;
- the correction of lens distortion;
- the calculation of the 3-D position of a scene point from its stereo projections by triangulation.

2.2. Rectification of the pair of stereo images

Given a point p_1 in image 1, its corresponding point p_2 in image 2, called stereo-correspondant (this is the stereo-matching problem discussed in Section 2.3) appears to be always lying along a line of image 2 entirely defined by the coordinates of p_1, the relative position/orientation of the two cameras and their intrinsic parameters: this is the so-called epipolar line associated to p_1 [50,51] (see Fig. 3). This geometric constraint inherent to any stereo imaging system, called the *epipolar constraint*, is very interesting since it simplifies the search for the stereo-correspondant of a given point from a 2-D search across the entire image to a 1-D search along its epipolar line.

In the particular case where the cameras are perfectly aligned, the epipolar lines are parallel to the image rows (see Fig. 4): this ideal configuration simplifies the search for correspondence since corresponding pixels are on the same row in both images. In this configuration, the difference between the column coordinates of two matched points is called "disparity".

In practice, the mechanical alignment of the cameras is very difficult to obtain. Nevertheless, the problem can be solved at the processing level by applying a transformation (plane-to-plane homography[2]) to each image of the initial

[2] A plane-to-plane homography is a bijective projective transformation mapping pairs of points between planes [51,52].

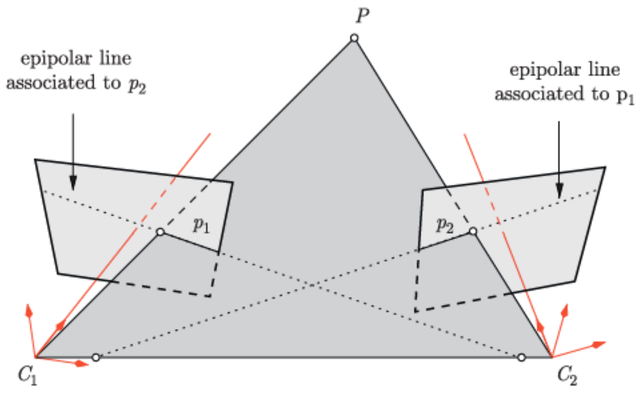

Fig. 3. The camera optical centers C_1 and C_2, the 3-D point P and its images p_1 and p_2 lie in a common plane. This plane intersects each image plane in an epipolar line.

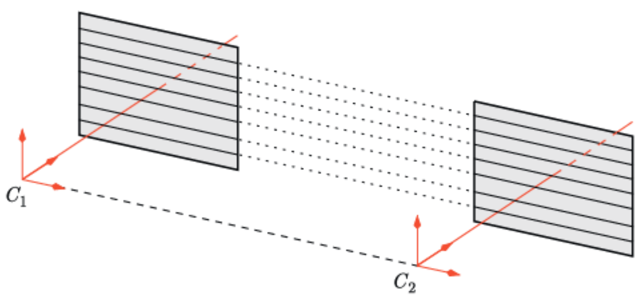

Fig. 4. A rectified stereovision sensor: the epipolar lines are parallel to the image rows.

stereo pair to obtain a new pair of stereo images corresponding to a virtual stereo rig with perfectly aligned cameras [50,51]. This rectification procedure uses the calibration parameters computed in the off-line camera calibration phase. Notice that during the rectification, the real distorted images (due to optical lens distortion) are also transformed into ideal distortion-free images.

The image rectification procedure results in a pair of images that corresponds to an ideal stereo rig of distortion free and perfectly aligned cameras. This greatly simplifies the stereo-matching phase.

It should be noted that, *in practice, neither the rectified images nor the undistorted images are computed.* In fact, the computed rectification homographies and the distortion parameters are used directly in the expression of the correlation function to work on the raw images. This new approach can achieve the highest matching accuracy by avoiding the pixel interpolations involved in the distortion correction and rectification of the images (see [49,53] for more details).

2.3. Stereo-matching

The main difficulty in stereovision is to establish correspondences between pairs of images. Over the years, numerous algorithms for image matching have been proposed. They can be classified into two categories:

1. *Feature matching*: The algorithms first extract salient primitives from the images, such as edge segments or contours, and match them in the views being considered. These methods are fast because only a small subset of the image pixels is used but usually give few matches (sparse disparity maps).
2. *Template matching*: The algorithms attempt to correlate the grey levels of image patches in the views being considered, assuming that they present some similarity. The underlying assumption appears to be a valid one for relatively textured areas and for image pairs with small differences. These methods can give dense disparity maps.

In [54], a method based on stereovision for measuring strains in stamped 3-D sheet metal parts was proposed. This method falls into category 1 as it requires that a predefined pattern (a grid of squares) be applied to the sheet surface before stamping. Each image of the stereo pair is processed independently in order to locate the grid intersections. The grid intersections are extracted in such a way as to allow an automatic matching between the two images, provided that the operator matches manually a single pair of points.

A stereo-correlation technique that falls into category 2 has also been developed (and is presented below). With this technique, a regular grid need not be applied to the object and the meshes used to compute the local strains are generated at the post-processing level (meshes of any size can be generated, and in particular small ones to take into account the large strain gradients).

Correlation scores are computed by measuring the similarity of a fixed window in the first image to a shifting window in the second (see Fig. 5). The second window is moved into the second image by integer increments along the corresponding image row (remember that a "rectified space" is being worked with) and a curve of correlation scores is generated (see Fig. 6). The correct matching corresponds to the highest peak provided that this peak is greater than a threshold ($S_{\min}$). Note that a match is not accepted if the highest and the second highest peaks are

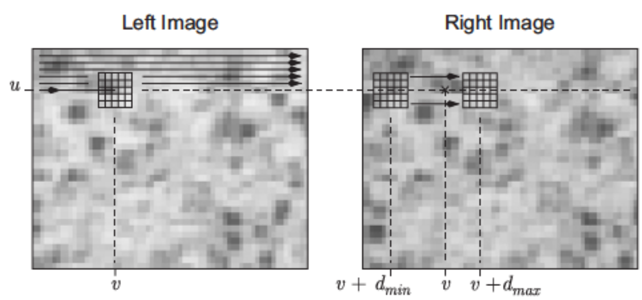

Fig. 5. Correlation-based stereo-matching.

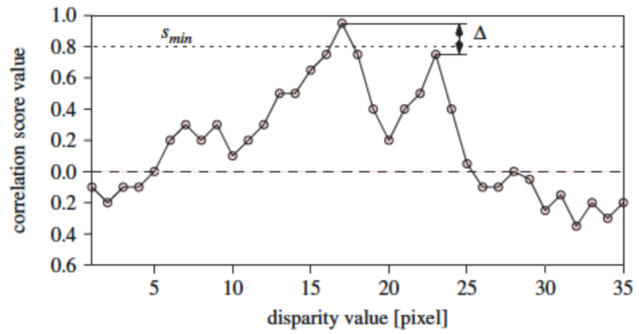

Fig. 6. Curve of correlation scores.

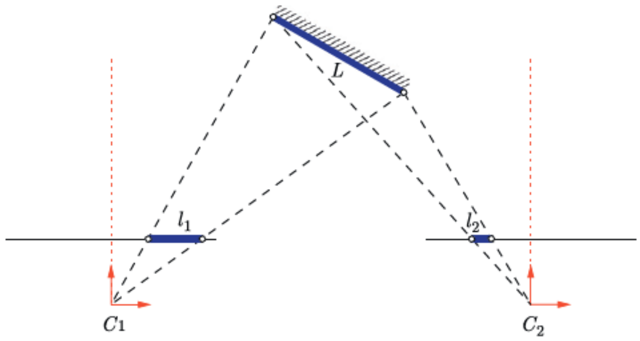

Fig. 7. Projective deformation: the segment of length L in space is projected to a segment of length l_1 in the left image and to a segment of length $l_2 \neq l_1$ in the right image.

within a minimum range (Δ). By the definition, corresponding points have coordinates (u, v) and $(u, v + d)$ in left and right rectified images, and d, the distance in pixels, is the disparity (see Fig. 5).

Fig. 5 presents a gross simplification of stereo-matching process: matching windows are assumed to be square and of the same size. In practice, due to local surface non-planarity as well as projective distortion, a square window is most likely matched with a non-square one as shown in Fig. 7. So, the correlation between the fixed left window (a rectangle) and the shifting right window (a distorted rectangle) is calculated. The optimal shape of the correlation window in the right image is computed according to the local orientation and curvature of the surface. In Fig. 6, the disparity is an integer value but in reality a subpixel correlation-based stereo-matching algorithm has been developed so the disparity is a real value. For more details see [49,53].

As mentioned above, it is well known that the correlation technique is efficient on textured objects. When an object does not present a suitable random, contrasted texture, one may apply a thin coating of high-contrast particles such as from spray painting [11], toner powder, ink, lithography, etc.

2.4. 3-D reconstruction

Using the calibration parameters of each camera and the rectifying homographies, a classical triangulation method [55] can be used to compute the 3-D position of a scene point corresponding to a stereo pair of image points (see Fig. 1), assuming that their distortion have been corrected. By repeating this operation for a large number of stereo matched pairs the 3-D shape of an object can be obtained.

2.5. 3-D displacement measurement

Using the stereovision technique, the shape variation of an object can be measured by analyzing a sequence of pair of stereo images. Nevertheless, in experimental mechanics, we are generally interested in the surface strain field, that can be obtained by tracking the displacement of some points at the surface of an object undergoing some mechanical or thermal stress.

As already mentioned, much work has been done on 2-D displacement/strain measurement, using a single camera, on gridded objects or using correlation-based techniques. These methods can give only the in-plane strains.

The stereovision technique allows measurement of the 3-D displacement field of an object undergoing 3-D deformation.

From the pair of stereo images taken at time t_0, the 3-D shape of the object at time t_0 can be computed. From the pair of stereo images taken at time t_1, the 3-D shape of the object at time t_1 can be computed. In addition, by matching the two images taken by the left camera (or the right one) at time t_0 and t_1 (this is called temporal matching or tracking), the 3-D displacement corresponding to each image point can be computed (see Fig. 8).

The temporal matching problem is similar to the classical 2-D displacement measurement problem. It is important to note that, in this case, the epipolar constraint cannot be used since two time-varying images taken by a single camera are being dealt with. Depending on whether the object is marked with a grid or not the temporal matching problem can be tackled using feature matching techniques or a correlation-based algorithm. When 3-D displacement fields are measured by 3-D DIC, stereo-correlation (i.e. stereovision + correlation-based stereo-matching), that gives 3-D information, and pixel tracking by correlation (DIC) in the sequence of stereo images are used in conjunction. In order to achieve better accuracy an improved method (combining temporal tracking and

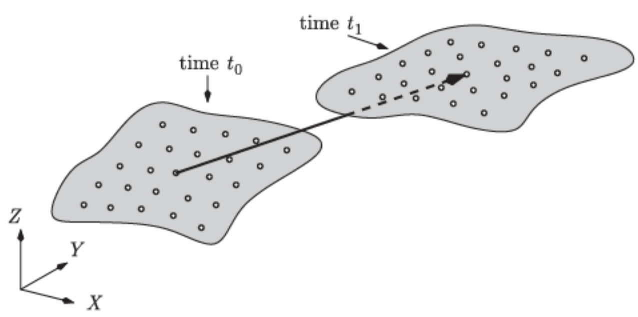

Fig. 8. 3-D displacement field computation.

stereo-correlation) has been proposed that operates simultaneously on the two pairs of stereo images [53].

2.6. 3-D strain computation

In [54], the strain field was computed by analyzing the initial and final configuration of an array of points marked on the surface. Each square element of the grid pattern was divided into triangular sub-elements. The principal strains in each element were determined by comparing the undeformed and deformed triangles. With 3-D DIC, no regular grid is marked on the surface of the object but the 3-D mesh resulting from the 3-D reconstruction of a Delaunay triangular mesh defined in an image can be computed (sparse reconstruction, see Fig. 9). The strain field can be computed by using each 3-D triangular element of the meshes before and after the deformation. A finite-element software can be used for these computations. In our laboratory, the software Abaqus™ is often used for these computations. A 3-D triangular mesh is generated from the 3-D points and Abaqus™ computes the strain values from the 3-D displacements imposed at the nodes of the mesh [56].

2.7. Accuracy

The accuracy of 3-D reconstruction depends on many factors:

- the quality of the cameras and their resolution;
- the configuration of the two cameras (distance between the two cameras, angle between their optical axis, etc.) which governs the triangulation accuracy;
- the accuracy of the stereovision sensor calibration;
- the accuracy of the matched features in the images.

The accuracy of the matched features depends on the type of extracted feature. In [54] gridded objects were used and the grid intersection extraction accuracy was 1/30 pixel. In [49] it has been shown that the DIC technique leads to an accuracy better than 1/100 pixel.

Using high resolution digital cameras with 1024×1024 pixels each, the 3-D reconstruction relative accuracy in object space (the accuracy of coordinate determination divided by the size of the object) achieved using stereo-correlation under controlled laboratory conditions is about 1/50 000 (see [49] for a more detailed discussion on 3-D reconstruction accuracy).

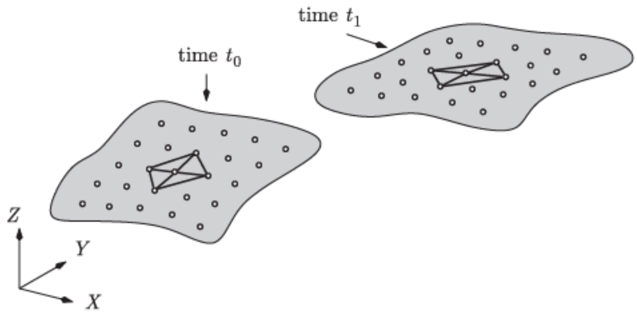

Fig. 9. 3-D strain field computation.

The strains are computed by numerical derivation from the displacements measured at several points distributed over a mesh. The strain at each point of the mesh is computed using neighboring points (see Fig. 9). The accuracy of the strain computation depends on many factors: the discrete derivation scheme used (shape of the integration domain) [57], the accuracy of the displacement measurement, and the computation basis (mesh element spacing). The method proposed can reach an accuracy of 0.05% (500 μstrain) on the computed strains with triangular elements measuring 50 pixels.

For example, using the integration domain shown in Fig. 9 (four neighboring points) and the discrete derivation scheme described in [57], the uncertainty for a 2-D strain computation can be evaluated using the following relation:

$$\Delta\varepsilon = \frac{\Delta d}{\sqrt{2}\,\Delta x},$$

where $\Delta\varepsilon$ is the uncertainty on strain computation, Δd the uncertainty on displacement measurement and Δx the computation basis for the discrete derivation.

For example, with Δd equal to 1/100 pixel and a derivation basis Δx equal to 14 pixels, the uncertainty on strain measurement $\Delta\varepsilon$ is equal to 0.05%. An uncertainty 10 times lower (0.005%) can be achieved by taking a derivation basis 10 times larger (140 pixels) but the result has much less local significance, which can be a problem with heterogeneous materials.

3. Conclusion

Stereovision (and 3-D DIC) has proven to be a powerful non-contact technique for measuring 3-D displacement/strain fields on any 3-D object and is now widely used for industrial applications. Several commercial software are available [163–166]. The technique is very versatile and can be used for a large scale of experimental mechanics problems: it can be applied at micro or macro scale (small or large structures), it can measure both small (a few hundred of microstrains) and large strains (>200%), it can be used for high-speed dynamic tests by using high-speed cameras, etc.

During the talk,[3] several examples of application will be presented (sheet metal forming, polymer forming, refractory concrete or composite structures mechanical behavior characterization, bio-mechanics, high-speed impact tests, etc.). Additionally, a quite inclusive list of references on applications of stereovision (and 3-D DIC) to experimental mechanics is given at the end of this paper [58–162].

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