3D DEFORMATION MEASUREMENT USING STEREO-CORRELATION APPLIED TO EXPERIMENTAL MECHANICS

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Abstract

Optical methods that give displacement or strain fields are now emerging significantly in the mechanical sciences. In the Material Research laboratory at École des Mines d'Albi, we have developed a binocular stereovision system that can be used a) to measure the 3D shape of a static object or b) to measure the deformations of an object undergoing some 3D mechanical or thermal stress.
In this paper, we will focus on two current applications of the stereo-correlation method:
1. the measurement of local deformations on stamped sheet metal parts,
2. the measurement of 3D displacement and strain fields on an inflated elastomer membrane undergoing large elongations (>100%).

1 Introduction

Binocular stereovision is a technique for building a three dimensional description of a scene observed from two slightly different viewpoints.
As soon as two image points are matched, i.e. identified as corresponding to the same physical point, it is possible to compute the 3D coordinates of this physical point by triangulation, provided that the stereo rig has been calibrated beforehand.
The first method we proposed required that a predefined pattern be applied to the sheet metal surface before stamping [Orteu, 1997]. More recently, we have extended our work to the measurement of deformations on 3D unmarked objects (or marked with a random pattern, e.g. with spray paint, which is easier to apply to the surface than a gridded pattern), using a correlation-based stereovision technique [Garcia,1999].
This non-contact 3D measurement method is now used in our laboratory to measure the deformations of materials undergoing mechanical stress (i.e. stamped sheet metal parts or inflated elastomer membranes) or thermal stress (i.e. measurement of distortions in steels under heat treatment [Claudinon, 2000]).

2 The stereo-correlation technique

Binocular stereovision is a technique for building a three dimensional description of a scene observed from two slightly different viewpoints (see Figure 1 where P(X,Y,Z) is the 3D 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 3D coordinates of a physical 3D point by triangulation under 2 conditions:
1. the two image points p_1 and p_2 have to be matched, i.e. identified as corresponding to the same physical point P. This is called the *stereo-matching problem*.
2. the geometry of the stereo rig (i.e. the relative position and orientation of the two cameras) has to be known. This problem is solved by means of an *off-line camera calibration procedure*.

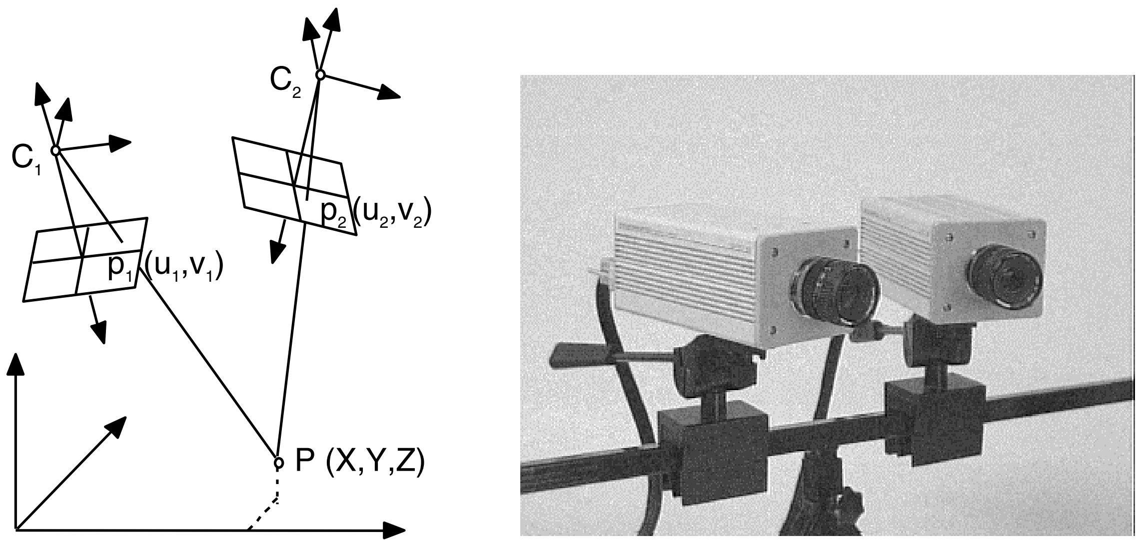

Figure 1: Binocular stereovision

2.1 Calibration of the stereovision sensor

An important task in 3D computer vision is camera calibration, specially when metric informations are required for applications involving accurate dimensional measurements. We have developed a flexible technique to easily calibrate a camera. Lens distortion is taken into account. The technique only requires the camera to observe a (quasi planar) pattern shown at a few different orientations. The motion of the pattern need not be known and the pattern itself can be imprecise.
This technique has been recently extended to the calibration of a stereovision sensor. Using a photogrammetry approach, the intrinsic parameters of each camera, the 3D points of the pattern and the relative position and orientation of the two cameras are computed all together using a nonlinear minimization technique. Our proposed technique is easy to use, flexible and gives accurate results [Garcia, 2000].

The calibration parameters will be used in the sequel at different stages:

a) the rectification of the stereo image pairs,
b) the correction of lens distortion,
c) the calculation of the 3D 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, if we look for its corresponding point p_2 in image 2 (this is the stereo-matching problem), it appears that p_2 belongs necessary to a straight line of image 2, entirely defined by the coordinates of p_1 and the relative geometry of the two cameras, called the *epipolar line* associated to p_1 [Ayache, 1988][Loop, 1999].
This geometric constraint imposed by the imaging system, called *epipolar constraint*, is very important: thanks to it, during the stereo-matching phase, we can transform a two-dimensional search for correspondence into a one-dimensional one (along the epipolar line).

The epipolar lines form a bundle of lines going through an epipolar center E_2 which is the image of the optical center C_1 in camera 2.

In the particular case where the image planes are coplanar and parallel to the vector C_1C_2 defined by the optical centers, then the epipolar centers are rejected to infinity and the epipolar lines form a pencil of parallel lines. If in addition the image coordinate frames are judiciously defined, we get a particular configuration where the epipolar lines are parallel to the axes of the image coordinate frames. This ideal configuration enables efficient stereo-matching procedures since corresponding pixels are on the same row in both cameras.

In practice, it is impossible to get the ideal configuration of the cameras mechanically. Nevertheless, it is possible to apply to each image of the initial stereo pair a transformation, called *rectification*, to obtain a new pair of stereo images corresponding to a virtual stereo rig with perfectly aligned cameras [Loop, 1999].

The rectification procedure uses the calibration parameters computed in the off-line camera calibration phase. During the rectification, we also transform the real distorted images into ideal distortion-free images.

We may consider that after the image rectification procedure, we end up with a pair of images that corresponds to an ideal stereo rig of distortion free and perfectly aligned cameras. This will greatly simplify the stereo-matching phase.

2.3 Correlation-based 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 roughly be classified in two categories:

- *feature matching*. In this category, the algorithms first extract salient primitives from the images, such as edge segments or contours, and match them in the views being considered. The methods are fast because only a small subset of the image pixels are used, but may fail if the chosen primitives cannot be reliably detected in the images.
- *template matching*. In this category, 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 difference.

In [Orteu,1997], we proposed a method based on stereovision for measuring deformations in stamped 3D sheet metal parts. 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.

The stereo-correlation technique discussed in this paper falls into category 2.

Correlation scores are computed by comparing a fixed window in the first image to a shifting window in the second (see Figure 2). The second window is moved in the second image by integer increments along the corresponding image row (remember that the images have been rectified) and a curve of correlation scores is generated (see Figure 3).

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 within a minimum range (Δ).

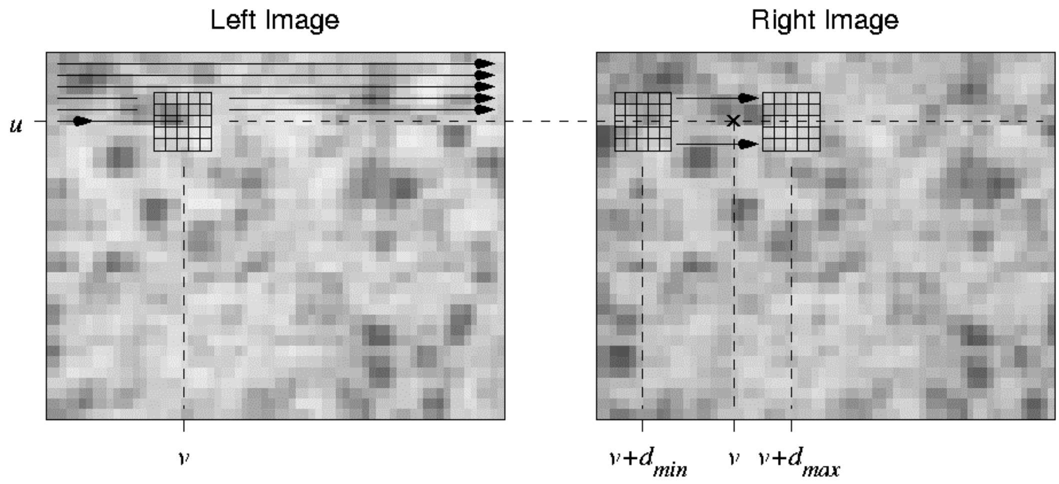

Figure 2: Correlation-based stereo-matching

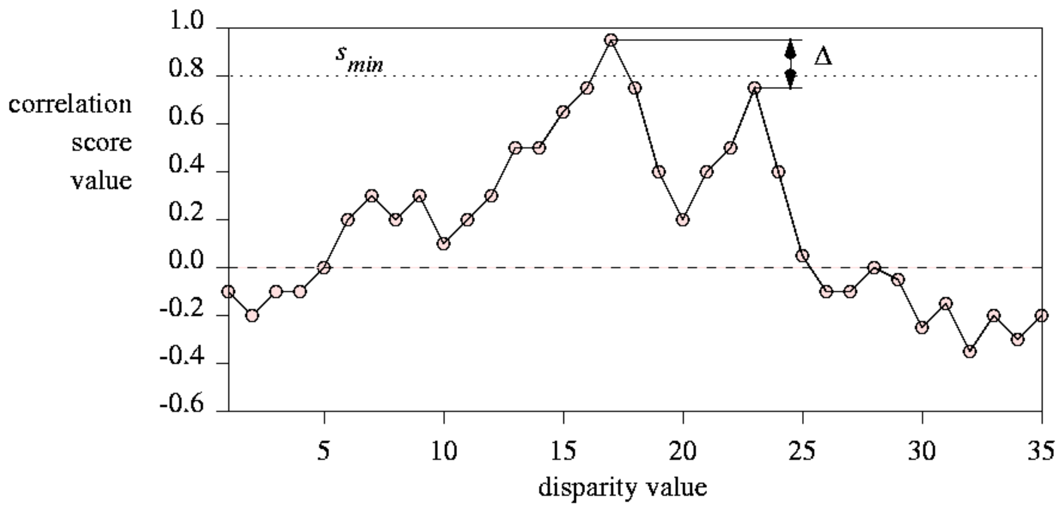

Figure 3: Curve of correlation scores

According to Figure 2, the reader may think that the fixed and shifting windows in the two images to be correlated have constant size and shape (rectangle). That is not true because a small surface element that is viewed as a square of pixels in the left image can be seen in the right image as a distorted square. So, we calculate the correlation between the fixed left window (a rectangle) and the shifting right window (a distorted rectangle). For more details see [Garcia, 1999].

As mentioned above, it is well known that the correlation technique is efficient on textured objects. Before stamping, it only takes a few seconds to mark the part to be measured with a random pattern of spray paint (see Figures 4 and 5).

2.4 3D reconstruction

Using the calibration parameters of each camera and given a stereo matched pair (provided by the stereo-matching phase), the calculation of the 3D position of a scene point from its stereo projections can be obtained by triangulation [Orteu,1997].

As an example of 3D reconstruction obtained by the stereo-correlation technique, we show in the sequel the 3D digitizing of a stamped sheet metal part.

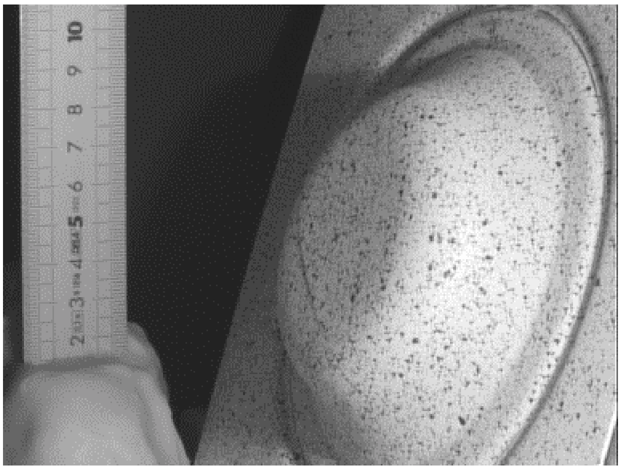

Figure 4: The stamped sheet metal part to be digitally reconstructed

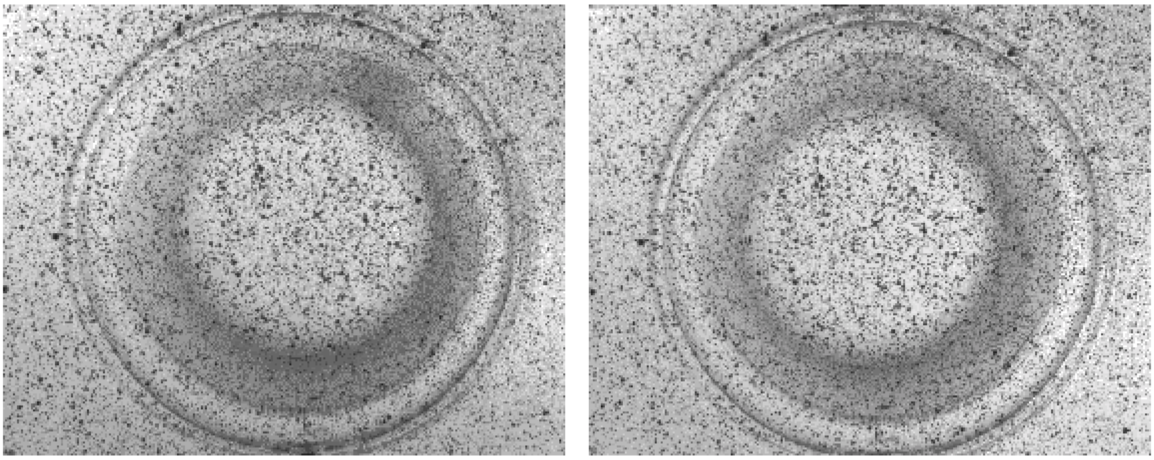

Figure 5: The pair of stereo images taken with the stereo rig

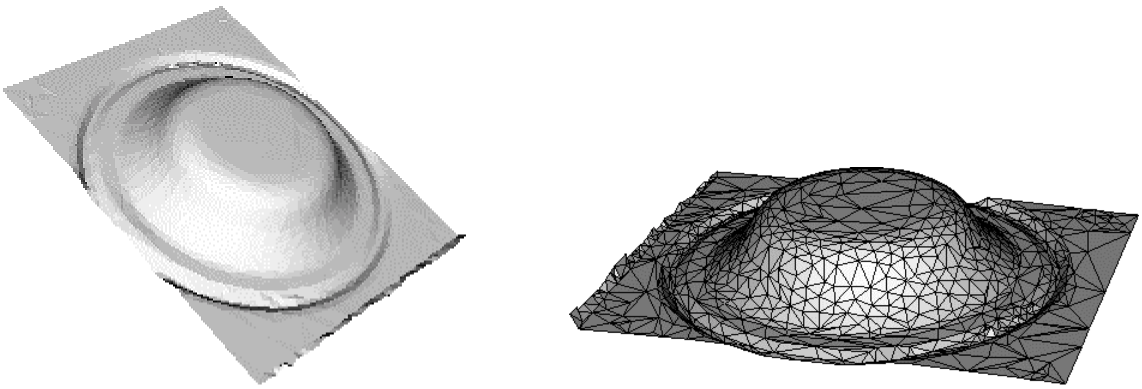

Figure 6: 3D reconstruction of the stamped sheet metal part

The stereo-correlation technique gives a dense 3D reconstruction (almost all the pixels of the stereo images can be matched). The stereo rig we use is made up of two high resolution digital cameras with 1280 x 1024 pixels each. This allows us to calculate 1.3 million 3D data points from one pair of stereo images. We can compute a triangular mesh from the 3D data points resulting from the 3D reconstructions (see Figure 6).
This is used a) to reduce the large amount of 3D data available, for real-time visualization purposes, or b) to compute the deformation field from two 3D reconstructions (see next section).

3 3D displacements and deformations measurement

From the pair of stereo images taken before stress, we can compute the 3D reconstruction of the part before it is deformed. From the pair of stereo images taken after stress, we can compute the 3D reconstruction of the deformed part.
In addition, by matching the two images taken by the left camera (or the right one) before and after stress (this is called *temporal matching*), we can compute the 3D displacement corresponding to each image point (see Figure 7).

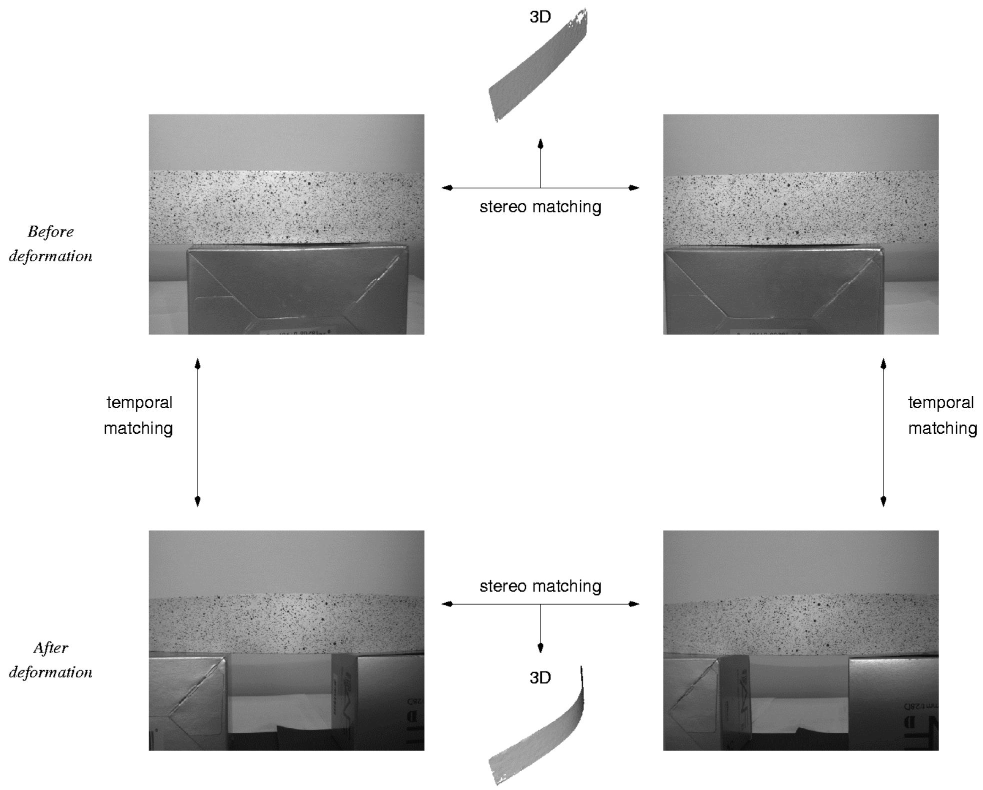

Figure 7: 3D displacement field computation

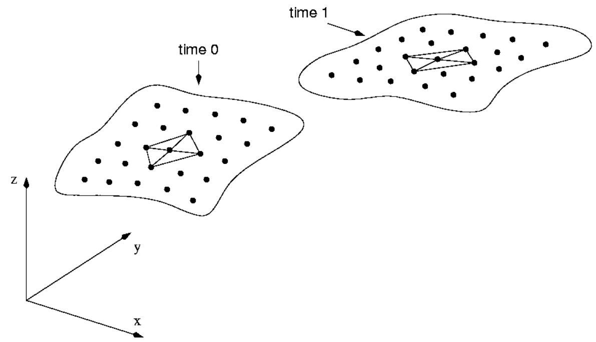

Figure 8: 3D deformation field computation

In [Orteu, 1997], we computed the deformation field by analyzing the initial and final configuration of an array of points marked on the surface. Each square element of the grid pattern is divided into triangular sub-elements. The principal strains in each element are determined by comparing the undeformed and deformed triangles as proposed in [Sowerby, 1986].

In the present work, no regular grid is marked on the surface of the part but we can compute a triangular mesh from the 3D data points resulting from the 3D reconstructions (see Figure 8).

The deformation field can be computed by comparing each element of the undeformed and deformed meshes and by using the equations proposed in [Sowerby, 1986].

4 Application on stamped sheet metal parts

In order to validate our method of strain measurements, we decided to work with flat 50mm by 500mm sheet metal strips submitted to a tensile test and then bent (to give them a 3D shape).

For each sample, we carry out the following operations:

1. we mark the part with a random pattern, in a few seconds, with spray paint,
2. we take a pair of stereo images of the part (see Figure 9-a),
3. we submit the part to a tensile test (5%, 9% or 13% deformation) and then bend it,
4. we take a second pair of stereo images of the part (see Figure 9-b).

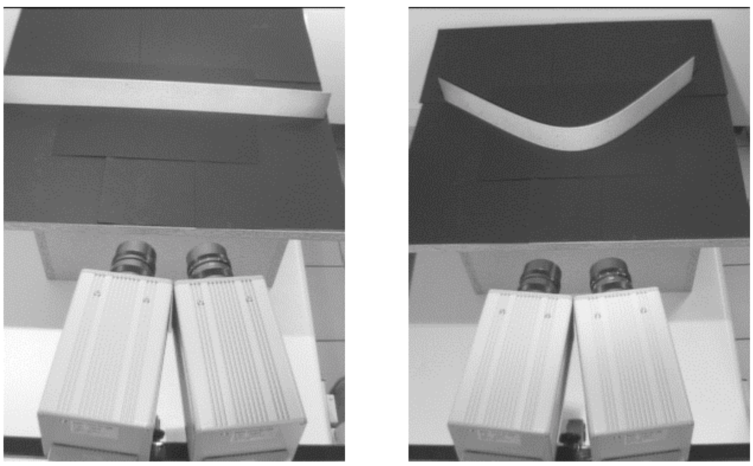

Figure 9: (a) a first stereo pair is taken before deformation and (b) a second stereo pair is taken after deformation

The strains can be displayed graphically in 3D (see Figure 10) or in the Forming Diagram (the most common tools used to study formability) where the major strain is plotted vertically and the minor strain horizontally (see Figure 11).

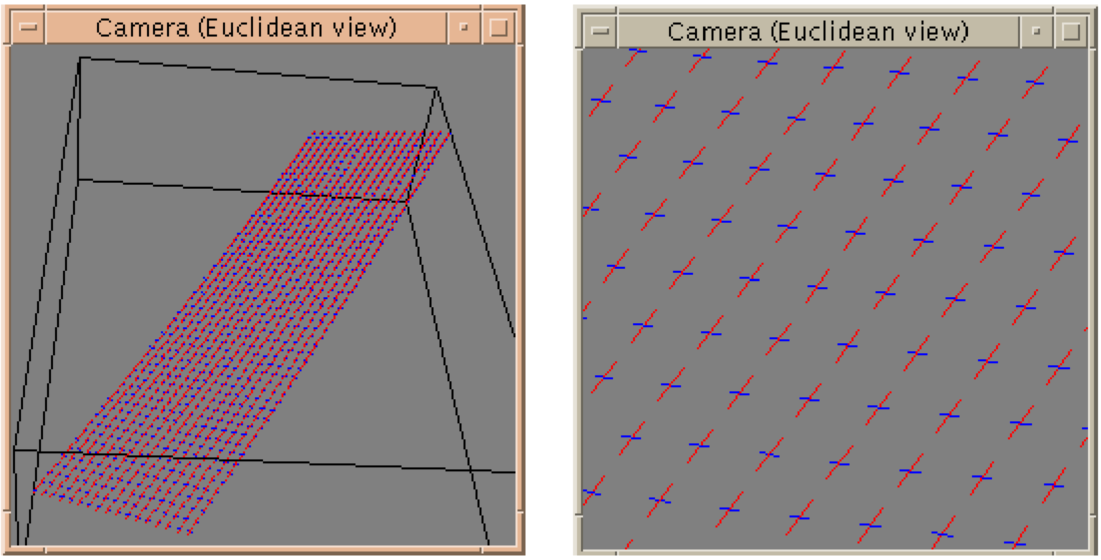

Figure 10: Strain field: (a) whole view and (b) zoom

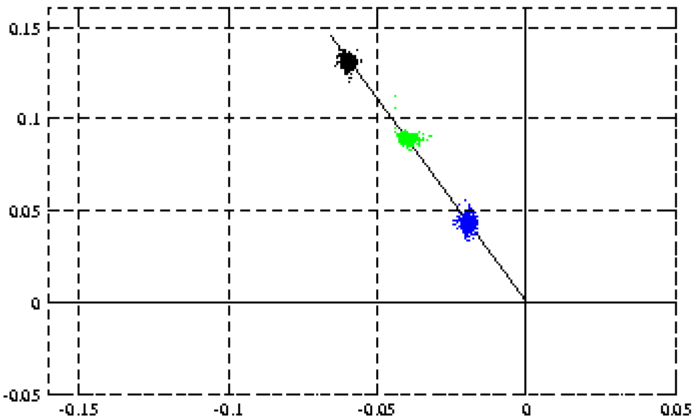

Figure 11: Principal strains in the two-dimensional strain space (Forming Diagram). The results for the 3 tensile tests at 4%, 9% and 13% are represented on the same diagram.

In order to evaluate the accuracy of the system, we have computed the deformation field for a non-deformed part. From 1800 nodal points in the meshes, we have obtained a standard deviation of 0.075%.

5 Application on an inflated elastomer membrane

F. Schmidt and al. [Schmidt, 1999] have developed at École des Mines d'Albi an experimental set up to study an elastomer rheological behaviour. In their work, the inflation of an elastomer membrane (see Figure 12) is recorded using a single CCD camera which allows the biaxial rheological properties of the elastomer to be determined.
We have recently proposed to measure the 3D displacement and strain fields of the elastomer membrane, by using our stereo-correlation method.

It should be noted that the correlation technique may fail if the deformation undergone by the part between two image acquisitions is too important. In the case of stamping, we can not observe the part during its deformation. We only have a pair of images of the undeformed blank and a pair of images of the deformed part. We have been able to measure up to 20% deformation.

With our experimental set up the elastomer membrane to be measured can be observed during its deformations (see Figure 12).
Thus, we can acquire a sequence of time-varying pairs of images with a sufficiently fast acquisition rate to guarantee a small deformation (<20%) between each image of the sequence.

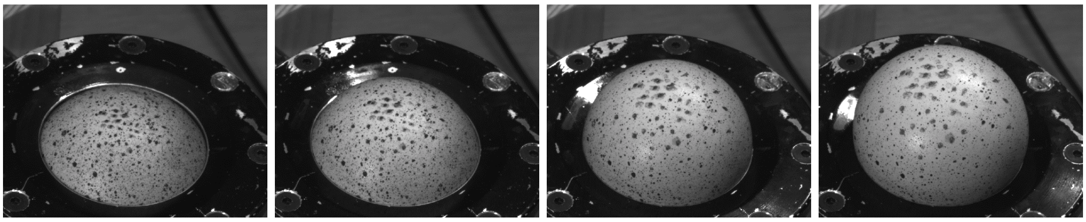

Figure 12: Four images from a sequence of six images

Figure 12 shows four images (number 1, 3, 5 and 6) from a sequence of six images acquired with the left camera of the stereo rig (another sequence of six images has been acquired with the right camera).
We have applied the temporal matching technique discussed in Section 3 to track a set of points distributed over a virtual grid.
In Figure 13, we show the 2D path followed by each point of the first row of the grid.
In Figure 14, we show the whole initial grid in the first image and the tracked grid in the last (sixth) image.

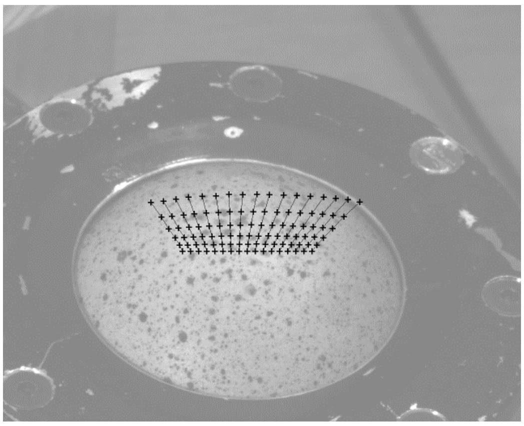

Figure 13: A line of points has been tracked along the six images – The result is superimposed on the first image

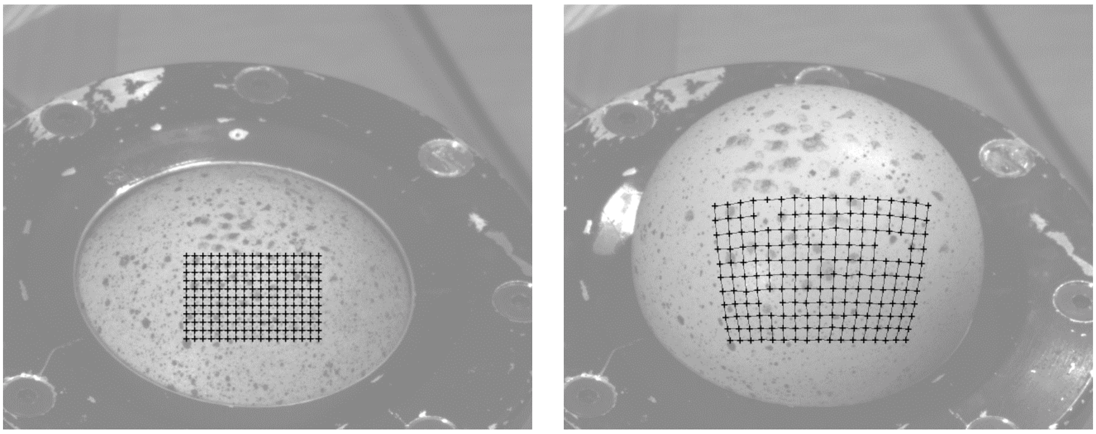

Figure 14: Temporal matching of a virtual grid between the first and the last image

Using the technique described in Figure 7, we can compute the 3D reconstruction corresponding to each view of the elastomer membrane and then the 3D displacement and strain fields (see Figure 15).

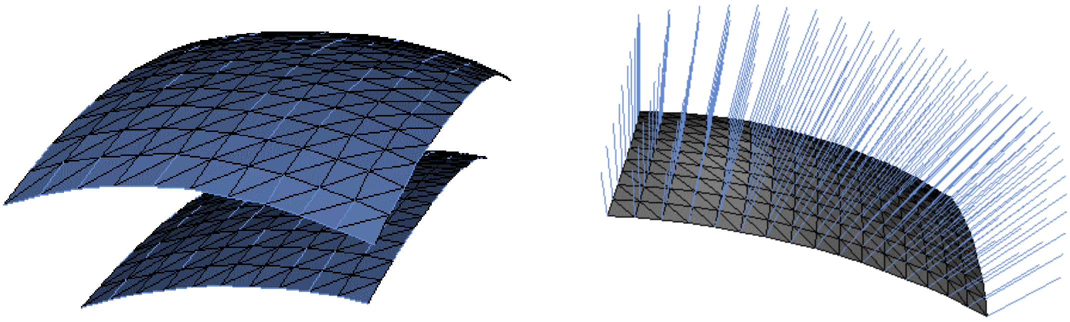

Figure 15: 3D reconstruction of the elastomer membrane (#1 and #4) and 3D displacement field

6 Conclusions

We have presented a binocular correlation-based stereovision technique that can be used a) to measure the 3D shape of a static object or b) to measure the deformations of an object undergoing some 3D mechanical or thermal stress.

The main advantages of this technique are:

- no regular grid needs to be applied to the part; we only have to mark it with a random pattern which can be done *in a few seconds* with spray paint
- a single pair of stereo images enables the 3D shape of the deformed part to be computed. We get a *dense 3D reconstruction* made up of more than 1.3 million 3D data points.
- the meshes used to compute the local deformations are generated *at the post-processing level* from the dense 3D reconstructions provided by the stereo-correlation algorithm. We can generate meshes of any size and in particular small ones to take into account large deformation gradients.

References

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