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Experimental Stress Analysis

Improved precision of stereometric measurement of relief's surface by means of structured light enhanced photometric stereo method

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Abstract: Photometry is an interesting method for 3D measurement of surfaces with relief. It utilizes a relationship between depth of shadow determined intensity of light and surface normal orientation towards source of light. Advantage of methods incorporating this principle is their independence on distance between measured object and the measuring apparatus and scalable sensitivity suitable for relatively flat surfaces. On the other hand, there is a drawback as the photometric methods yield results up to an unknown multiplicative factor. One way how to overcome this limitation is to simultaneously describe the measured surface by means of another optical method. Among the "candidates", the structured light projection is the most promising one for a simple implementation. The presentation of the possibility to integrate these two methods in unified system is main topic of this contribution.

Keywords: Optical methods, Strain measurement

1. Introduction

Flat specimens with surface relief represent significant portion of bodies studied by mechanics and also by other scientific disciplines. Investigation and documentation of surface evolution is the task best suited for optical methods. It is well known that out of plane deformations are measured with a lower precision than in plane deformations by many experimental methods. Out of plane deformation measurement carried out by optical methods is also affected by the distance between measured object and camera.

Popularity of optical methods for measurement of deformed shape of the object is implied by many advantages associated with their working principles: the data (image) is acquired at once, the method is non-contact and therefore does not interfere with the experiment, the data is obtained in the full-field form, it means that in one measurement, a dense array of measured points is recorded and in digital form ready for consequent computer processing.

Although it is possible to sort the methods available by popularity expressed in numbers of papers published, it is generally accepted truth that none of the method can be used in every situation. Usage limits are implied by experimental setup and environmental conditions, the range of measured features, the size of the object, etc. Therefore it is useful to keep diversity of methods wide and develop them further.

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2. Coded photometry stereo method

2.1. Principle of the method

Among optical methods used infrequently photometry stereo methods, also often called "shape-from-shading" methods can be named (see refs. [1-2] for more details). These methods utilize the relation between detected light intensity from given point on the specimen surface and angle between normal of the surface facet at this point and direction of illuminating light. Provided, the vector of light illumination is known, field of surface normal can be deduced from the surface image containing the light intensity information. Then, in the process of integration, the information on normals in transformed into topography information. Once the field of normals is known, it is straightforward to reconstruct the surface. The method [3] utilizing wavelet transformation was used, because of its simplicity and availability of open source code. As there are three unknowns – slopes in two perpendicular directions and color of the surface's facet, actually three independent measurements of light intensity have to be performed. This condition is easily met with a set of three different illumination setting. Combining data from the three images, all unknowns can be determined.

Switching between the light sources and taking shots by camera would render such a method virtually useless for dynamical testing unless some modification is carried out. The modification allows acquisition of the three images at the same time. Acquiring and storing three independent images in one is made possible by taking advantage of the wavelength selectivity of red-green-blue (RGB) Bayer filter in front of the camera chip. The idea is that by using three different colours of illuminating light sources corresponding to the filter colours, three independent images are coded in one (Coded Photometrical Stereo).

2.2. Coded Photometrical Stereo

Coded Photometric Stereo (CPS) is the enhanced PS method utilizing Red-Green-Blue (RGB) lights coding [4]. Monochromatic RGB light positioned around the observed area produce directional illumination. Three different scenes are encoded in one composite image and then decoded using standard RGB colour channels of the digital camera. Out of plane displacement is measured by CPS using these scenes.

Reconstructed topography is known up to a multiplicative factor and that is why the so called dimension calibration must be carried out to determine the factor. It can be done by one point mechanical measurement of the elevation differences between two points of the studied surface or it is necessary to have some calibration object of known height/depth connected with the surface. The results of the CPS method are demonstrated in Fig. 1. White cone of known dimensions is inserted into the scene for height calibration.

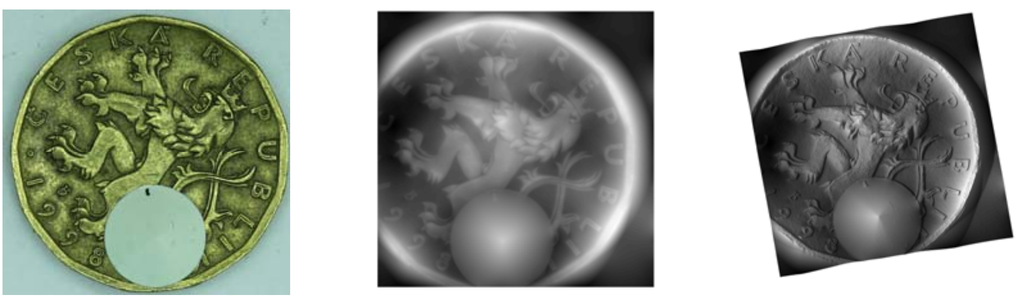

Fig. 1. Example of application of CPS method for topography of coin surface reconstruction. Image on the left shows original coin appearance, surface heights are coded in grey level in the middle image. The image on the right visualizes axonometric view on the coin surface. It can be easily seen that surface roughness is exaggerated using this method.

An issue of CPS method is that it properly represents specimen's surface locally, but on longer ranges, the results are rather inconsistent and have to be complemented with other method.

3. Fringe projection method

3.1. Principle of the method

The fringe projection method belongs to the structured light optical methods family [5, 6]. Using DLP data projector patterned light is slantingly projected onto the specimen and digital camera mounted above the specimen is used to record the pattern. Irregularities of the pattern can be used for determination of specimen's topography. Fig. 2 schematically explains the experimental setup, measuring principle (left) and fringe pattern projected on specimen (right). Fringes discontinuity reflects discontinuity in heights of the surface and also "hills" and "valleys" are noticeable in curved pattern of fringes.

A script of Matlab commands performing various tasks necessary for interpretation and quantization of data was developed to obtain topography data from the image of projected patterns. The script is capable of semiautomatic image processing involving the following steps: input image adjustment and filtration, fringes identification and numbering, binary image operations like skeletonization, determination of depth from fringe displacement in discrete points and subsequently topography interpolation to the subset convex hull. Finally, results are visualized.

3.2. Comparison of CPS and Fringe Projection method

Fringe projection method keeps consistency of results in the whole area of image. On the other hand, to the contrary to the CPS, resulting surface data lack fine details and also do not contain information on surface texture. The projection angle can be altered in order to tune sensibility of the method to the specimen's topography.

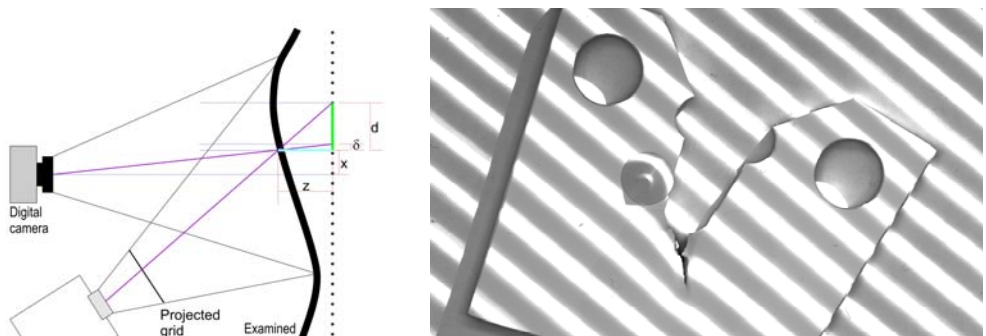

Fig. 2. Schematic drawing of fringe projection method (left) and image of fringe pattern projected on deformed specimen (right)

4. Combined approach

It was shown in previous chapters that both of the discussed optical methods offered some advantages and disadvantages. The goal is to combine their results together accentuating the benefits, i.e. keep global shape of the specimen as a result of fringe projection and enhance its crucial details by CPS.

This goal can be reached using various transmission functions that pick up the region of correct surface details from CPS data and complement it with the surface as calculated from fringe projection method.

Fig. 3 demonstrates results of the approach. As can be seen by comparison of reconstructed topographies, the result from CPS reproduces fine details of the surface well, but somehow distorts their proportions, while the topography derived from fringe projection estimates properly global trends and shape of the specimen but lacks the details resolution. Combined results, presented in the bottom section of the figure, then preserve the overall correctness and enhance it with details.

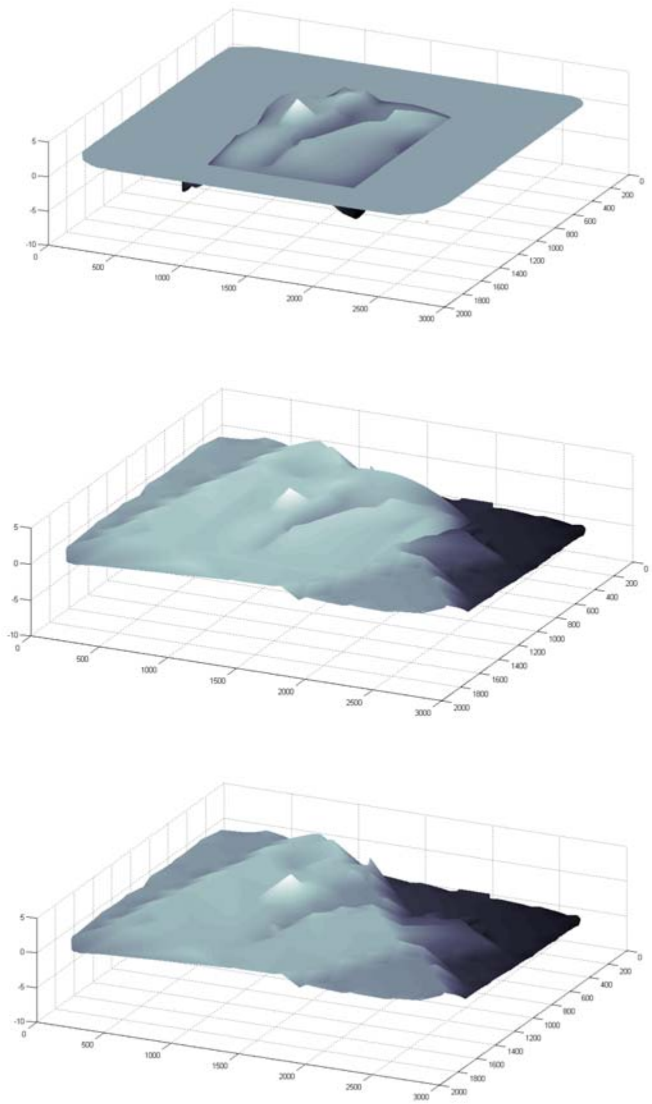

Fig. 3. Axonometric comparison of out of plane displacement field of CT specimen as calculated from CPS method only (top), fringe projection only (middle) and combined methods (bottom). Vertical axis is in different scale for easier demonstration of surface topography features.

5. Conclusions

The combination of methods seems a promising technique for precision improvement. At the present time, laboratory prototype is being tested on the basis of working principle optimization. The next step is further automation of the combination procedure and development simplified and miniaturized version of illumination system.

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