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PROJECTION COLOUR MOIRÉ TECHNIQUE FOR 3–D SURFACE RECONSTRUCTION

Daria PAVELEVA and Ákos ANTAL

Department of Mechatronics, Optics and Instrumentation Technology
Budapest University of Technology and Economics
pavelyeva@mom.bme.hu
tel.: 36 1 463 2412
fax: 36 1 463 3787

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Abstract

Moiré effect is an optical phenomenon that occurs in consequence of the coincidence of two periodical structures, gratings. Nowadays the moiré effect is used for contour generation of three–dimensional objects and measurements of deformation: strain analysis, linear or angular displacements and vibration analysis. Projection moiré method is a typical method for three–dimensional measurements. To find the absolute order of a fringe (z-coordinate of the object under research) one must define the difference in depth between two points by the moiré patterns. But to present day for extraction of an object's three–dimensional information several moiré patterns and image processing methods such as Fourier–transform method, temporal phase shifting technique were needed, since from one moiré image it's impossible to determine whether the object is concave or convex. It means that it was impossible to work with dynamic objects in real–time operation mode. Here we present colour moiré projection technique that resolves the arising problem of ambiguities in moiré patterns by application of only one moiré pattern. This method is based on application of colour rulings to gratings in projection moiré technique.

Keywords: Moiré phenomenon, problem of ambiguities, projection technique.

1. Introduction

Surface reconstruction is one of the most important topics in computer vision due to its wide field of application. Some examples of applications are range sensoring, industrial inspection of manufactured parts, object recognition and 3–D map building. There are several different techniques that can be used for optical three–dimensional measurements on object surfaces, such as interferometric, stereovision, coded structured light and moiré methods. These are based on both contact and non–contact procedures and present different sensitivities. Interferometry is an old technique to measure the deviation between two wave fields with a sensitivity of a fraction of the wavelength of the illumination source. Holography is an interference–based technique that represents a wave front reconstruction – a process by which the amplitude and phase variation across a wave front may be recorded and subsequently reproduced. Stereovision is based on imaging the scene from two or more points of view and then finding correspondences between the different images in order to triangulate the 3–D position. Coded structured light consists of replacing one of the two cameras by a device that projects a light pattern onto the measuring surface [1]. Moiré methods are based on moiré effect that occurs wherever a repetitive structure is overlaid with another structure and the line elements are nearly superimposed.

2. Theory

2.1. Moiré Phenomenon

The moiré phenomenon can be readily observed when superimposing two periodic or quasiperiodic structures. When the two structures have the same or slightly different line spacing and their lines are set approximately parallel, a new coarse pattern appears. This pattern is known as a moiré fringe pattern. The spacing and orientation of the moiré fringes depend on the spacing and orientation of the structures being overlapped whereas the visibility of fringes is related to the width of transparent or black lines with respect to the line spacing of the structures [2]. In *Fig. 1* moiré pattern caused by two straight–line gratings with different frequencies tilted with respect to one another is shown.

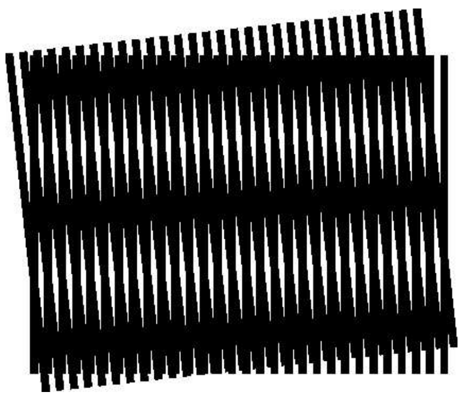


Fig. 1. Moiré pattern caused by two straight–line gratings with different frequencies tilted with respect to one another

2.2. Moiré Phenomenon Appearance

Superposition of periodic and/or quasiperiodic patterns in optics frequently results in striking spatial configurations commonly called moiré patterns. The spatial frequency of these new periodicities may be considerably lower than the original ones.

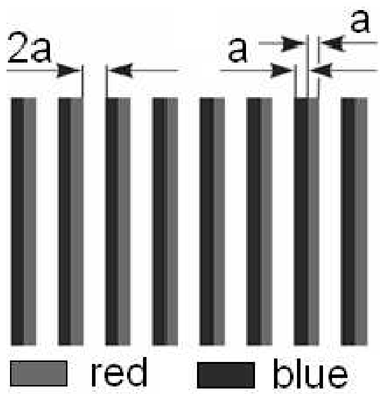


Fig. 2. Grating with two coloured bars

Therefore, they become pronounced at low contrasts. Composite patterns can be formed in different ways. For example, addition, subtraction, and multiplication, (three of the four basic rules of arithmetic) are easy to display by optical means. Pattern combinations according to any of these can be made, with corresponding composite configurations having different appearances [3]. Multiplicative superimposition of two structures is the most common method for generating moiré patterns.

2.3. *Moiré Topographical Methods*

Moiré topographical methods can be distinguished as: the basic grating–shadow, the grating–projection, the grating – TV and the synthetic grating methods. Shadow moiré is a contour mapping technique that involves positioning a grating close to an object and observing its shadow on the object through the grating. Thus, the basic grating–shadow method offers the best accuracy and the simplest arrangement because the projected grating and the master grating are identical: they have the highest degree of binding. Shadow moiré technique presents the disadvantage that the master grating has a similar size to the measured object. Projection moiré is a contour mapping technique that involves projection of a grating onto an object to produce a shadow grating that is observed through another grating. The projection–type methods offer a lower degree of binding between the phenomenon and the observering grating, larger object size, and more flexibility in adjusting the sensitivity, but there exist very rigid demands for the performance of the projection – and the master – grating. All methods where the master grating is generated by an electronic time varying signal or by a computational process offer the lowest degree of binding. This means complete independence of both gratings in amplitude and phase. The advantages are additional operations like detection, different types of superposition, and elevation detection. Their disadvantage is the limited accuracy of all opto–electronic devices [4, 5]. To cope with the above requirements, projection moiré has been chosen as the measuring method to be enhanced.

2.4. "Hill and valley" Problem Arising with Recognition of Three–dimensional Objects and Methods of its Solution

The arising problem of ambiguities (or "hill and valley" problem) in moiré patterns by reconstruction of surfaces in 3–D space consists in inability to differ valleys from hills with application of one traditional moiré pattern (one, that is generated by coincidence of two monochromatic gratings). Various techniques to evaluate phase data embedded in moiré fringe pattern have been demonstrated. These techniques can be essentially classified into two basic types: the phase shifting and the Fourier–transform type. Phase shifting techniques usually require four phase–shifted interference fringe patterns with consecutive $\frac{\pi}{2}$ phase difference [6]. Fourier transform methods can describe the phase change in relation to place, but these are not capable of providing satisfactory measurements in case of ambiguity.

2.5. Projection Colour Moiré Technique for Reconstruction of 3–D Surface

As it was mentioned above the problem of ambiguities could not be solved from one moiré pattern before, here we present colour projection moiré method for simple reconstruction of three–D surfaces from one moiré image. The proposed method is very simple, as long as no extra equipment (only colour camera) or complicated computations are added; the formulas of the new method are the same as by the traditional projection method. The main idea of our method was to distinguish hills from valleys by determination colours order in colour moiré pattern. Thus, we used two–coloured opaque bars in the gratings instead of black ones, the width of each transmittance bar is equal to the width of two–coloured opaque line red (R: 255, G: 0, B: 0) and blue (R: 0, G: 0, B: 255) colours were chosen for the bars (*Fig. 2*) [7].

Colour moiré phenomenon was generated by two methods: when reference and deformed grid patterns have the opposite order of two–coloured bars (*Fig. 3 a*), the uniform order of two–coloured bars in gratings (*Fig. 3 b*). In colour moiré pattern generated by superposition of two gratings with the opposite order of colour rulings moiré fringes with changing colour appear, what can give some extra information (as proved below) about the character of moiré fringes. When colour moiré pattern is generated by coincidence of gratings with the uniform order of colour bars then moiré fringes of permanent colour appear. This case is out of our interest, because it gives the same information as if we were operating with the traditional moiré pattern. Further in our work we operate with gratings coincident with opposite order of colour bars, so that the order of bars in deformed grating on the surface is RB, and the order of bars in the reference grating is BR. The orders

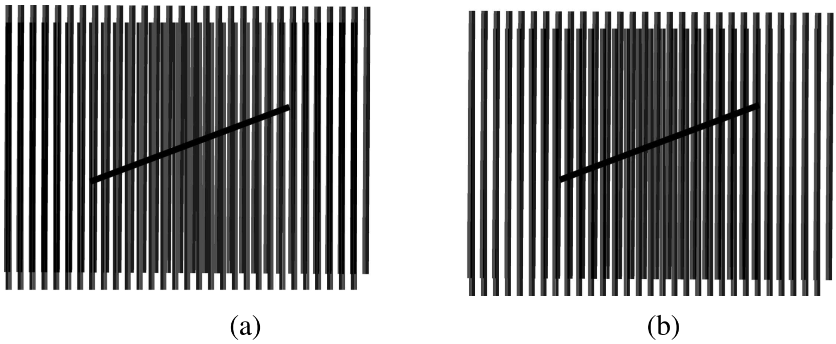


Fig. 3. Colour moiré pattern, when reference and deformed gratings have the: (a) opposite and (b) uniform order of two–coloured bars. Along the line the colour in moiré fringe for case (a) changing from orange to blue, (b) remains constant violet

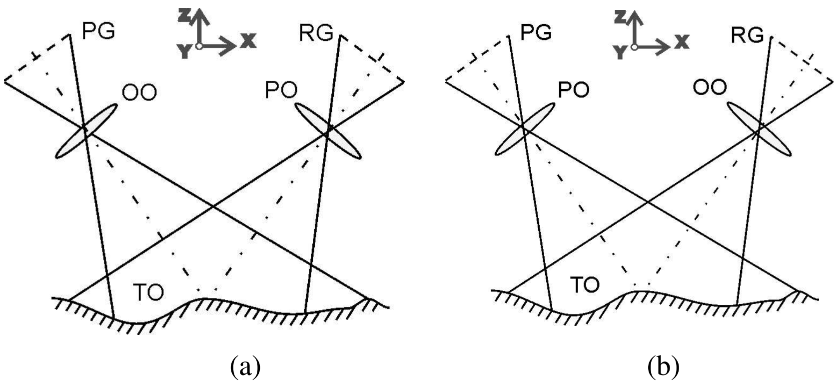


Fig. 4. Typical projection moiré configurations. PG – projection grating; PO – projection optics; TO – test object; OO – observation optics; RG – reference grating

of colour bars are presented in relation to X axes of XZY coordinate system (*Fig. 4*).

The typical projection moiré configurations are presented in *Fig. 4*. These types of projection equipment disposition are out of interest in the case of traditional projection moiré method. However, when colour gratings are used, it becomes very important, because one can correctly distinguish between concave and convex surface by colour order in moiré fringe, knowing projection moiré equipment disposition.

By various type of projection equipment location deformed colour rulings on the concave and convex regions have different center of curvature (*Fig. 5*) while looking at the object through observation optics, but without reference grating

(*Fig. 6*). The moiré colour patterns of the surface with convex and concave regions are shown in *Fig. 7*, where concave and convex parts of the test surface have the opposite order of colours in the moiré fringes of one colour moiré pattern.

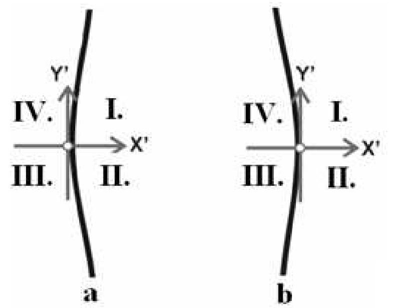


Fig. 5. The center of curvature is situated for projected line: (a) in I. or II square of $Y'X'$ relative coordinate system, (b) in III. or IV square of $Y'X'$ relative coordinate system. Axis Y' is a tangent of deformed line and axis X' is a normal to it

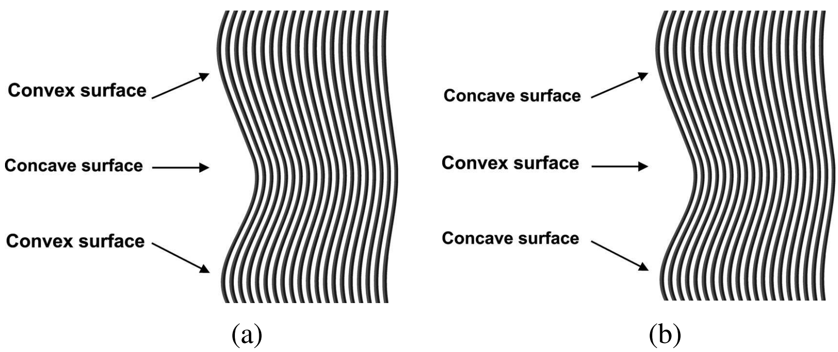


Fig. 6. Deformed projection grating in the test object with concave and convex parts by looking at the object through an observation optics, but without reference grating in case of (a) and (b) projection equipment dispositions. The order of colours in grating is RB for both (a) and (b) cases

Thus, formation of opposite fringe colour order for surfaces with "hills and valleys" can be explained by different centers of curvature of deformed colour bars in the object on convex and concave regions. After extracting the information about "hills and valleys" on the test surface one can convert the colour moiré image into a gray scale moiré pattern. The moiré fringes give us the information about x and y coordinates of the measuring object; knowing the parameters of the gratings and the equipment we can find z_N coordinates (height) by application of the traditional equations and this way reconstruct the surface. An expression for the distance of the Nth contouring from the reference plane is

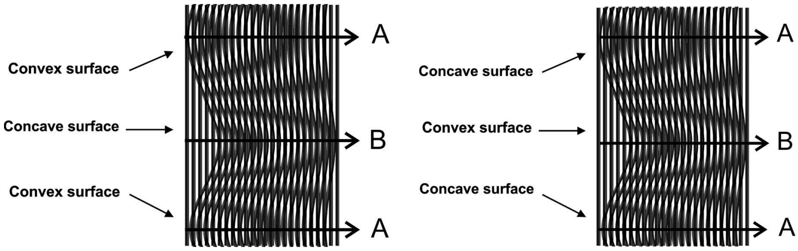
$$z_N = \frac{NldM_G}{b - NdM_G} = \frac{Nld_r}{b - Nd_r}$$

where z_N is the distance of the Nth contouring plane from the reference plane, d is the period of projection and detection gratings, b is the separation distance between optical axes, l is the distance of the join of entrance pupils from the reference plane, M_G is the magnification of the projection, and d_r is the period of the projected grid in the reference plan [2]. To resume we would like to pay once more attention to the simplicity of the purposed method, since it needs no extra or complicated computations, it is quick and cheap, because of just one colour camera is needed. The actual problems to be under investigation in projection colour moiré method are colour grating spatial frequency amplification and selection of colours for grating bars.

3. Experiments

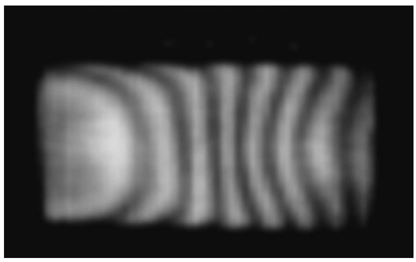
In experimental part we present practical results of colour moiré projection method application for reconstruction of 3–D surface with concave and convex parts. During experiments the effectiveness of application colour rulings to gratings for resolving the problem of ambiguity in moiré images was studied. Colour gratings were disposed with opposite order of colour bars in the gratings. Both colour gratings were taken with spatial frequency of 1 line/mm so, that the width of each opaque bar was 0, 25 mm and the width of the transparent bars was 0.5 mm. The colours for opaque lines were chosen red (R:255; G:0; B:0) and blue (R:0; G:0; B: 255). CorelDraw 12 program was used for generation of the gratings; colours were obtained by application of a laser printer (Osé 700); CMOS digital camera Canon D350 was applied for moiré patterns catching. Camera and projector were disposed like in *Fig. 4 b*; the distance between the equipments was 800 mm. We assumed that the examined object represents an ideal white object, camera transforms the colours precisely, white rulings of grating are spectral neutral colour, colour rulings confirm to theoretical colours, spectrum of the projector source of light is permanent. During the experiments spectral properties of optical systems were not taken into consideration.

In the experiments the object with concave and convex regions was tested and its colour moiré pattern was cached. Along the curvature radius of the moiré fringe in the direction from the center of curvature to the deformed moiré line the order of colours will be opposite for convex and concave parts of the object (*Fig. 8 a*). In *Fig. 8 b* the graphs illustrate the red green blue components of the data that we obtained by sampling along the curvature radius of the moiré fringe of convex and concave object parts. DAC, digital-to-analog converter is the measurement unit of the colour coordinates, and it can take any integer value between 0 and 255. From

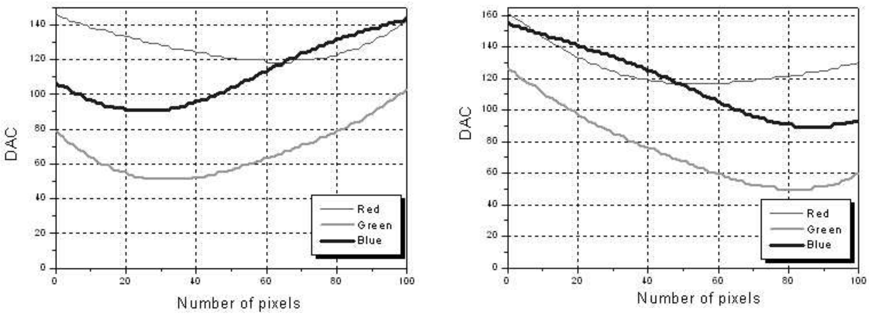


(a) (b)

Fig. 7. Difference in colour fringe order of concave and convex surfaces of the test object in one moiré fringe pattern in case of (a) and (b) projection equipment dispositions. For both cases along the line A colour in moiré fringes changes from blue to orange and along the line B from orange to blue



(a)



(b)

Fig. 8. Colour moiré pattern of the object with convex and concave regions (a); the graphs illustrate the red green blue components of the data that we obtained by sampling along the curvature radius of the moiré fringe of convex and concave object parts. DAC digital–to analog converter is the measurement unit of the colour coordinates, and it can take any integer value between 0 and 255 (b)

Fig. 8 b one can see that the graphs differ from each other by the opposite order of lines of colours for convex and concave parts of the measuring object.

4. Conclusions

In conclusion, we have presented a colour moiré projection method for 3–D surface reconstruction. The proposed method is very simple because just one moiré pattern is needed and complicated computations are not applied for contour generation of three–dimensional objects. In the experimental part of the work we reconstructed the real surface from colour moiré pattern by application of our method. Thus, colour moiré projection method should find many applications in the field of surface definition of the real objects.

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