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MOIRE CONTOURGRAPH - AN ACCURACY ANALYSIS

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Abstract

The geometrical aspects of moiré fringe topography and its possible error sources are discussed. Experimental results obtained with the Moiré Contourgraph, designed for scoliosis detection and analysis, are presented. The accuracy of the geometrical information, offered by the moiré fringes, is analyzed by means of precise photogrammetric measurement of the test object.

Introduction

Moiré fringe topography is a simple optical method for spatial analysis of an object. The fringes represent the three-dimensional information in a similar way as contour lines used on topographical maps to describe the surface of the earth. They can be generated, for example, by superimposing a set of parallel lines over a similar, but slightly distorted, pattern such as obtained by projecting the original set of lines on a three-dimensional surface. A permanent record of the fringe pattern can be obtained by photography.

Moiré technology has been applied in various engineering and medical projects (Meadows et al., 1970) and there is an increasing interest to use it in scoliosis screening of school children and clinical analysis of spinal curvatures (Adair et al., 1977). A special instrument, the *Moiré Contourgraph*, has been developed for this type of application (Fig. 1). It consists of a screen, a light source and a camera. The person being examined is positioned behind the screen and a moiré pattern is generated by the screen and its shadow on the patient's back. When the screen is oriented parallel to the required part of the body, usually the lower back or the buttocks, a symmetrical contour pattern appears at both sides of the spine in the case of a normal back. An asymmetrical pattern can be an indication of spinal curvature, possibly caused by scoliosis. The moiré photograph can be analyzed in more detail by digitizing the moiré fringes.

Whatever use is made of the technique it is important that the various error sources that affect the geometry of the moiré photograph are analyzed, and that the accuracy of the derived geometrical information is evaluated. Standards for the geometrical quality and the optimum interval of the moiré fringes for scoliosis screening and analysis can then be set. This is of particular importance when more instruments for taking moiré photographs will become available and photographs taken at different institutions will have to be compared.

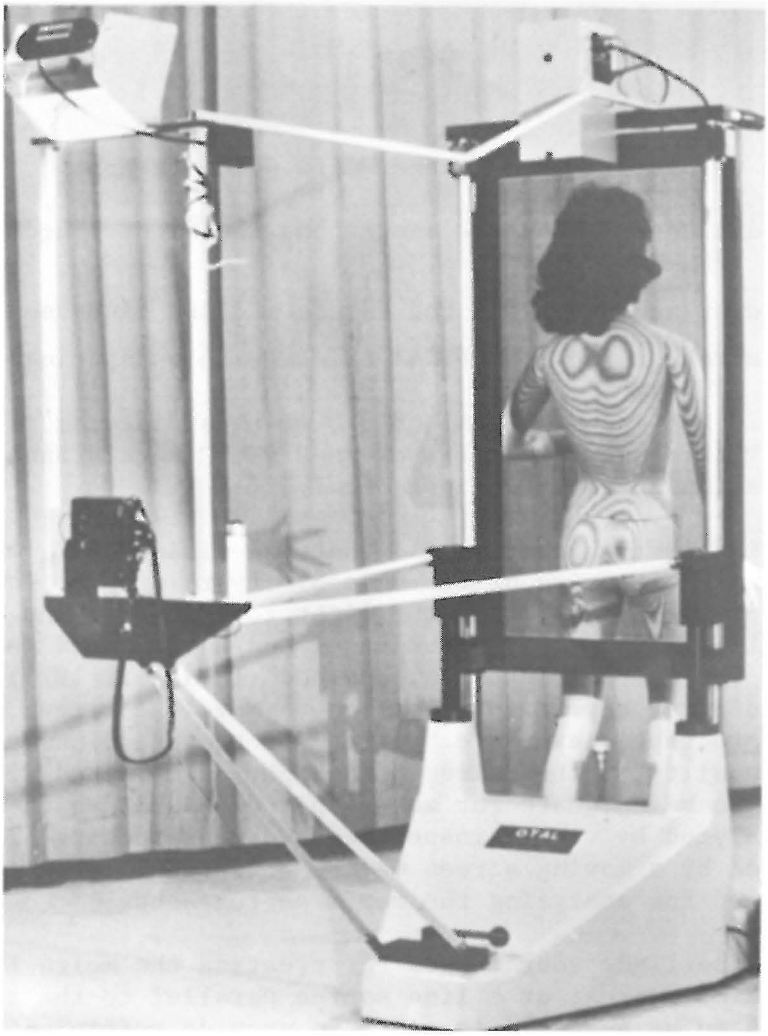

Figure 1

Moiré Contourgraph, Model MS-1 (moving screen)

The Moiré Contourgraph

In the Moiré Contourgraph the screen, the light source, and the camera have been combined in one rigid, mechanical system resulting in a high degree of repeatability and accuracy of the moiré pattern. It also offers the possibility of orienting the instrument with respect to the patient without affecting the relative positions of its components.

The light source is mounted above the camera and the illumination and the photo image are both symmetrical for the left and right side of the object. The moiré fringes generated by the instrument define a set of vertical planes parallel to the screen. The distances between these planes i.e. the fringe interval, depend on the positions of the various instrument components and on the thickness and spacing of the lines of the screen.

The distance $\Delta\ell_n$ from the n^{th} fringe to the screen is:

$$\Delta \ell_n = \frac{n\ell}{\frac{d}{s} - n} \qquad (1)$$

The following values are used in the Moiré Contourgraph:

for the distance ℓ from the camera and the light source to the screen: 1700 mm

for the distance d between the camera and the light source: 710 mm

for the screen interval s (line thickness plus spacing): 2 mm

This results in a fringe interval of 5.0 mm at a distance of 40 mm from the screen. The fringe interval increases with the distance from the screen (increasing n) as shown in Table I.

It is evident from equation (1) that the distance $\Delta \ell_n$ is not affected by the vertical positioning of the screen. By raising or lowering the screen along its vertical plane, the light zones behind the screen (fringes) will be more evenly illuminated and an improved photographic definition of the moiré fringes is obtained (Takasaki, 1975). The Moiré Contourgraph offers therefore the option to move the screen vertically during the photographic exposure. It should be noted, however, that the photographic quality of the moiré photograph, as obtained with a stationary screen, seems to be adequate for most applications in which the moiré images are analyzed by visual inspection and measurement. The improved quality offered by a moving screen may be beneficial, when automated devices are used for analyzing the moiré photographs.

Ideally, the light source used for creating the moiré fringe pattern should be a point source, or a line source parallel to the screen. A compromise has to be accepted in order to provide sufficient light for the photographic exposure (Drerup, 1977). For this purpose, a quartz cylindrical condensor, in conjunction with a photographic studio light, is provided in the Moiré Contourgraph with a moving screen (Fig. 1). The model with the stationary screen is equipped with a narrow slit in front of an electronic flash unit. The distance behind the screen over which well-defined moiré fringes are obtained covers approximately 50 cm for both types of illumination systems.

The instrument is supplied with a reference coordinate system, consisting of a horizontal and a vertical line near the plane of the screen. The origin of this coordinate system indicates the point where the optical axis of the camera intersects the plane of the screen. The coordinate system, which is clearly defined on the photographs, can be used in a digital analysis of the moiré pattern to correct for the perspective distortions caused by the central projective geometry of the photograph. The horizontal grid line offers the possibility to calculate the distances from the moiré fringes to the screen (Takasaki, 1973).

Error Sources in Moiré Topography

a. Instrumental Errors

The geometrical quality of a moiré photograph depends on the accuracy with which the various components of the instrument, i.e. the camera, the

Table I

DISTANCES FROM FRINGES TO SCREEN AND FRINGE INTERVALS FOR THE MOIRÉ CONTOURGRAPH

Fringe No.	Distance Fringe To Screen	Fringe Interval	Fringe No.	Distance Fringe To Screen	Fringe Interval
1	4.8 mm		21	106.9 mm	
		4.8 mm			5.4 mm
2	9.6		22	112.3	
		4.9			5.5
3	14.5		23	117.8	
		4.9			5.5
4	19.4		24	123.3	
		4.9			5.5
5	24.3		25	128.8	
		4.9			5.5
6	29.2		26	134.3	
		5.0			5.6
7	34.2		27	139.9	
		5.0			5.6
8	39.2		28	145.6	
		5.0			5.7
9	44.2		29	151.2	
		5.1			5.7
10	49.3		30	156.9	
		5.1			5.7
11	54.4		31	162.7	
		5.1			5.8
12	59.5		32	168.4	
		5.1			5.8
13	64.6		33	174.2	
		5.2			5.8
14	69.8		34	180.1	
		5.2			5.9
15	75.0		35	185.9	
		5.2			5.9
16	80.2		36	191.8	
		5.3			6.0
17	85.5		37	197.8	
		5.3			6.0
18	90.8		38	203.8	
		5.3			6.0
19	96.1		39	209.8	
		5.4			6.1
20	101.5		40	215.9	
		5.4			

light source, and the screen, are aligned and the distances between them are defined. Other possible error sources are imperfections of the screen, and camera distortions.

The effect of errors in the distances between the light source, the camera and the screen, and variations of the screen interval can be evaluated by differentiating equation (1) and applying the law of error propagation. The following expression is obtained for the rms (root mean square) error $m_{\Delta\ell_n}$ of the distance of the n^{th} fringe to the screen in terms of the rms errors m_ℓ, m_d, and m_s in the distances ℓ and d and the screen interval s, respectively:

$$m^2_{\Delta\ell_n} = \frac{(ns)^2}{(d - ns)^2} m^2_\ell + \frac{(n\ell s)^2}{(d - ns)^4} m^2_d + \frac{(n\ell d)^2}{(d - ns)^4} m^2_s \tag{2}$$

The rms error $m_{\Delta\ell_n}$ increases with the distance to the screen, i.e., with an increasing fringe sequential number n. For a distance of approximately 20 cm (n = 40) behind the screen, the following expression is obtained for the parameters used in the Moiré Contourgraph,

$$m^2_{\Delta\ell} = 0.016\, m^2_\ell + 0.117\, m^2_d + 14800\, m^2_s \tag{3}$$

Accepting $m_{\Delta\ell_n} = 2.5$ mm (half a fringe interval) over a distance of 20 cm from the screen, the inaccuracies of the instrument parameters must not exceed the following rms values:

distance of camera and light source to the screen,	$m_\ell \leq 11$ mm
distance between camera and light source,	$m_d \leq 4$ mm
screen interval,	$m_s \leq 0.012$ mm

For a distance of 40 cm from the screen (n = 80) the tolerances are approximately half of the above rms values.

In the above analysis, it is assumed that the light source and the camera lens are at equal distances from the screen. A difference in these distances will result in a slight tilt of the planes defined by the moiré fringes and will also affect the effective vertical distance between the light source and the camera lens. In order to maintain the previously derived tolerance m_d for a distance of 20 cm from the screen, the distances from the light source and the camera to the screen should not differ more than 6 mm (rms value). The effect of this error on the verticality of the planes defined by the moiré fringes can be neglected.

Although a 35 mm camera of good quality will in most cases be satisfactory for scoliosis screening and analysis, certain limitations in the accuracy of these cameras, particularly as far as lens distortion and film flatness are concerned, will have to be accepted. A test on the accuracy of the Contax camera supplied with NRC's Moiré Contourgraph will be described under the experimental results.

Also, the orientation of the camera will affect the geometry of the moiré pattern, and ideally, the image plane should be parallel to the screen. An incorrect camera orientation will result in an overall image displacement and image distortions. In particular, distortions resulting in image asymmetry should be avoided. For the distance between the camera and screen in the Moiré Contourgraph a non-parallelism of 1° for the camera image plane and the screen results in a maximum asymmetric image deformation of 4 mm near the corners of the screen.

b. Distortions Due to Central Projective Geometry

Each fringe represents a different distance from the camera and is recorded on the photograph at a slightly different scale. This results in radial image displacements, which for the Moiré Contourgraph may amount to ±15 mm for a patient's back assuming a variation of 100 mm in the distance from the back to the screen. These image displacements can be corrected. It should be pointed out, however, that they have little effect on the symmetry of the moiré pattern if the patient is positioned with the midline near the camera optical axis. These distortions can therefore be neglected in a screening program where the moiré photographs are primarily used to detect asymmetry of the left and right side of the midline.

Experimental Results

a. Testing Procedure

The accuracy of the geometrical information offered by the Moiré Contourgraph was evaluated for the back of a tailor's mannequin. The surface area used in the test was approximately 700 mm in height, 300 mm in width, with a maximum depth difference of 100 mm, representing the dimensions of the back of an average-sized adult. The centre of the test surface was located near the optical axis of the camera.

The Moiré Contourgraph was equipped with a Contax single lens reflex 35 mm camera with a Zeiss lens (f = 50 mm) for recording the moiré pattern. Immediately after the moiré photograph was taken, the mannequin was photographed with two simultaneously operated Hasselblad photogrammetric cameras, installed 600 mm apart at both sides of the Contax camera. The photographs made with the photogrammetric cameras were used to provide precise three-dimensional information in the test surface, needed for the accuracy analysis of the moiré photographs.

For evaluating the image errors, such as caused by lens distortion and lack of flatness of the film in the Contax camera, a total of 40 control targets were provided. The targets were located in a plane near the screen along four vertical lines of ten targets each. Behind the mannequin, additional control points were provided for photogrammetric purposes. The precise locations of all the targets were surveyed and defined in a co-ordinate system parallel to the screen of the Moiré Contourgraph.

b. Camera Distortions

The image coordinates of the forty targets were measured on the 35 mm Contax negatives using a photogrammetric comparator, and transformed to the known values by linear conformal coordinate transformation. The root mean square coordinate error, determined from the residuals, was 1.8 mm, or 60 μm at the image scale. An analysis of the errors for the individual control points indicated that the orientation of the camera with respect to the control targets and the screen did not contribute by any significant amount to the above error. The determined rms error is therefore a result of the combined effect of lens distortion and lack of film flatness. It may be considered to be typical for this type of camera, which is not designed for precise photogrammetric measurements.

c. Accuracy of Moiré Fringes

The stereophotographs taken with the Hasselblad cameras were used to plot the contour lines of the test surface on a photogrammetric plotter. The contour lines, which represent a set of vertical planes parallel to the screen, were plotted at the computed distances between the moiré fringes and the screen (Table I). Figure 2 shows the photogrammetrically compiled contour lines superimposed on the moiré photograph. Fringe no. 12, at the average distance between the mannequin's back and the screen, was used for the scaling of the moiré photograph to the photogrammetric contour lines. It can be seen that generally a satisfactory agreement is obtained between the white bands of the moiré pattern and the photogrammetric contour lines. It should be noted, however, that the moiré photograph is affected by distortions caused by its central perspective geometry, which accounts for some of the discrepancies. These distortions increase with the distance from the principal point of the photograph and with the surface depth with respect to fringe no. 12. Thus, the buttocks indicate the largest discrepancies in the example in Figure 2.

Distortions caused by the central perspective geometry of the moiré photograph were corrected by tracing the moiré fringes in a photogrammetric plotting instrument and applying a scale correction for each fringe. The results are shown in Figure 3 together with the photogrammetrically plotted

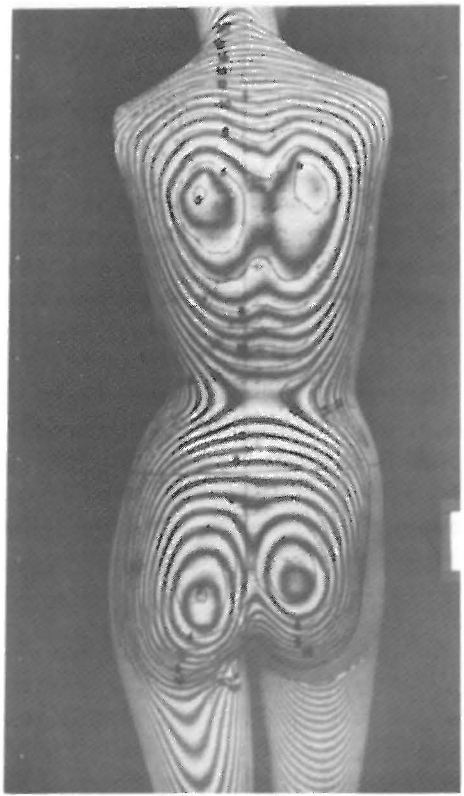

Figure 2

Comparison of photogrammetric contours with moiré fringes

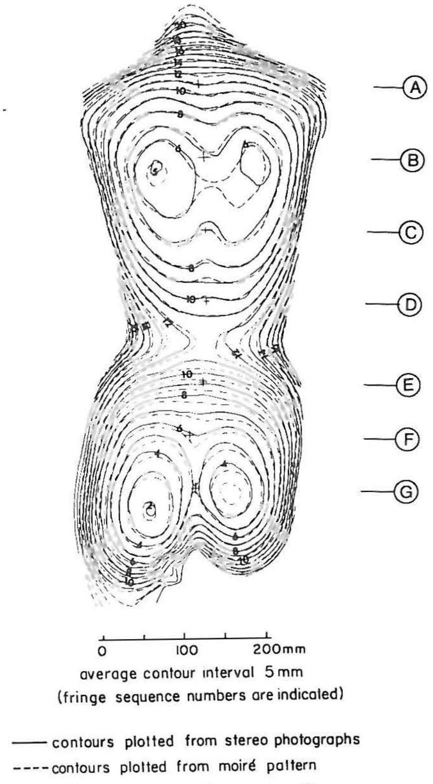

Figure 3

Comparison of photogrammetric contours with corrected moiré contours

contours from the Hasselblad photographs. An improvement can be noted, in comparison with Figure 2, particularly in the area near the buttocks.

The fringe pattern in Figure 2 and the corrected fringe pattern in Figure 3 were used in an accuracy analysis using the stereophotographs, taken with the Hasselblad camera. The distances from the fringes to the screen were measured photogrammetrically and compared with the theoretical values in Table I. The following rms values were calculated from the residuals:

- 2.0 mm, for moiré fringes scaled to fringe no. 12
- 1.4 mm, for moiré fringes corrected for differential scale changes.

It should be noted that the above rms errors include possible inaccuracies in the photogrammetric measurements.

d. Profiles Derived from Moiré Fringes

The moiré pattern can be used to derive profiles representing cross sections of the photographed surface. In deriving these profiles it should be realized that, due to the central perspective geometry of the moiré photograph, horizontal and vertical cross sections through the test surface generally are not represented by straight lines on the photograph. It is, however, possible to apply corrections similar to those for the correction of contour lines.

Seven horizontal profiles through reference marks on the mannequin's back were accurately plotted from the Hasselblad photographs on a photogrammetric plotter. Similar profile data were then derived from the moiré fringe pattern by two different methods. First, the intersections of the fringes with horizontal lines, drawn on the moiré photograph, were measured and the distances between a fringe and the screen used to construct the profiles. Image distortions, caused by the central perspective geometry of the moiré photograph were ignored in this method. The results are shown in Figure 4 together with the photogrammetrically plotted profiles. The depth scale is twice the scale along the profile axis, resulting in a depth exaggeration of the plotted profiles. The profiles derived from the moiré fringe pattern were scaled to the photogrammetric profiles for the average distance of the test surface to the screen (fringe no. 12).

In the second method, the profiles were derived from the moiré fringe pattern with necessary corrections for image displacements caused by the central perspective geometry; the profiles, derived from the moiré pattern, represent horizontal cross sections in this case. The profiles derived from the corrected moiré pattern are shown in Figure 5 together with the photogrammetrically plotted profiles.

It can be seen in Figure 4 that the discrepancies between the photogrammetric profiles and those derived from the uncorrected moiré pattern increase with the distance from the principal point of the moiré photograph, which is located between the centres of profiles C and D. The largest discrepancies of up to 5 mm occur in profiles A and G at the top and bottom of the test surface. In the case where the profiles derived from the moiré photographs were corrected for the effects of the central perspective geometry by applying differential scale corrections, the discrepancies with the photogrammetric profiles are generally smaller (Figure 5). In this case, the maximum discrepancies were found to be approximately 3.5 mm.

As expected, these results agree with those obtained from the contours in part (c) of this chapter. In a normal error distribution, maximum errors usually are 2.5 to 3 times the rms error.

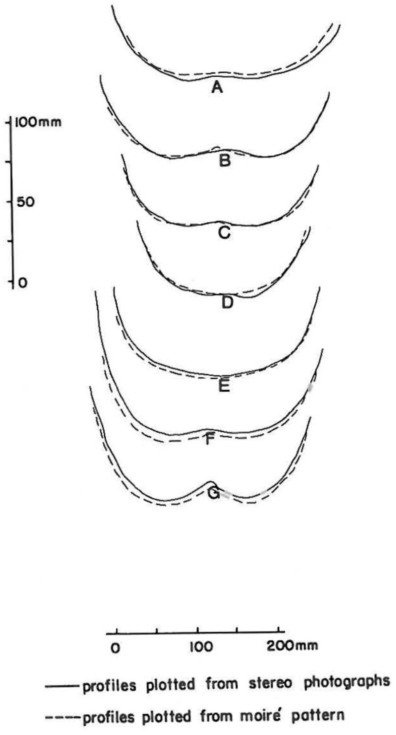

Figure 4

Comparison of photogrammetric profiles with profiles derived from moiré fringes.

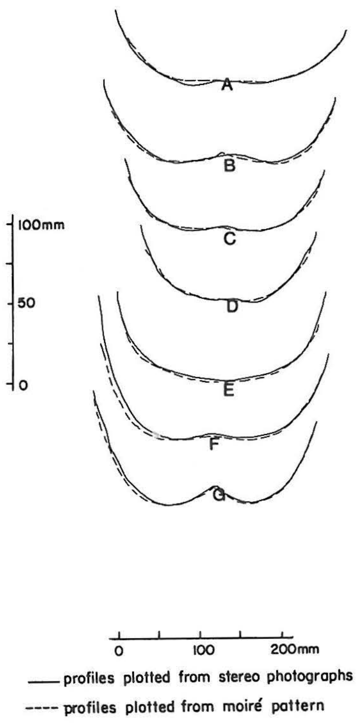

Figure 5

Comparison of photogrammetric profiles with profiles derived from corrected moiré fringes.

Conclusions

It can be generally concluded that an instrument such as the Moiré Contourgraph can offer geometrical information with an accuracy of 1 to 2 mm (rms value). Instrumental rigidity and a precise screen are essential to obtain this accuracy.

It was demonstrated that the accuracy of the results can be improved by applying corrections for the image distortions caused by the central projective geometry of the photograph. A coordinate reference system, defining the principal point of the photograph, should be provided in this case. Means also have to be provided to determine the average scale factor of the moiré photograph which, in the present experiments, was successfully accomplished by using the shadow of the horizontal reference line on the object and a known distance near the plane of the screen.

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