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PERICONTOUROGRAPHY

Abstract: Surfaces having tubular character, such as human limbs, may be geometrically defined in terms of shadow moire fringes based on a surrounding cylinder as datum. In pericontourography such fringes, formed in the usual way, are recorded through a narrow focal plane aperture on a moving film as the observed surface is rotated about an arbitrary axis parallel to the slit-aperture. A plane development is thus formed of the datum cylinder tangential to the reference grid complete with shadow moire fringes automatically superimposed and fortuitously filtered of high frequency grid-images. This plane development may be digitised. Alternatively, the fringes may be detected directly in the instantaneous slit-aperture by an electronic linear scanning array of light-sensitive elements giving digital outputs at each of a series of angular positions. Data so obtained may serve as input to processes of replication by the POLYHEDRAL NC method of automatic machining.

Introduction

The impetus for the development of pericontourography came from a need to measure the natural surfaces of artefacts and human anatomy requiring economical physical replication. Such surfaces have been and are still being defined for medical purposes by short-range, conventional stereo photogrammetry. When a terraced contour model of the human skull is needed, for instance, as a prelude to major cranial reconstruction, the excellent accuracy of stereo photogrammetry and the time and cost involved in producing a model from two photographs per view may be well justified. The authors have themselves developed and applied such conventional methods. (Ref. 1.).

Apart from the finite object-distance and ability to control the location of the observed surface in short range stereo photogrammetry, the method resembles aerial photogrammetry in that the observed field is approximately normal to the line of sight and the total contour interval is usually a small fraction of the flying height. The datum for contours is usually a horizontal plane normal to the vertical, being the tangential plane to a localised area of the earth's surface.

A relatively small artefact or anatomical surface whose extreme dimensions may be of the order of one fifth to one tenth of the "flying height" is likely to exhibit extremely closely spaced, even unresolvable, contours if viewed by two cameras centred about a single line of sight. Thus for "tubular" surfaces, such as human limbs or the trunk of the human body, it is usual to produce contour maps by conventional photogrammetry with respect to several related datum planes ranged round the surface, with contours overlapping. Kratky (Ref. 2) has described such a method in which

two metric cameras observed a model of a human knee, directly from the front and via mirrors, in two directions at the back. Takasaki, using moire photography (Ref. 3), has observed the human trunk directly from the front and simultaneously from the back. The projected contours near the side of the body being poorly resolved in projection.

This problem of mapping "tubular" surfaces, in which the outer normal of the surface is generally a radial direction with respect to an axis which the "tubular" surface surrounds, was recognized in ancient times by Dibutades, the Greek, when he reproduced the human form by silhouetting envelopes (Ref. 1). The principle he used of observing the surface in many radial directions with respect to an axis has been extended in pericontourography to an infinite number of directions, giving not a series of envelopes but a continuous assembly of strip contour maps.

In addition to multiple, virtually-continuous viewing, in pericontourography we also employ shadow moire fringe formation as a sufficiently accurate alternative to conventional stereo photogrammetry. The method still employs the principle of parallax but produces contours directly and instantaneously, saving the time and cost of interpretation of two ordinary photographs. Thus we have coupled the well known principles of periphery photography and shadow moire fringe formation and, as will be shown, have fortuitously benefited from automatic filtering of the conventional, unfiltered shadow moire contourograph.

The Shadow Moire Method

This method, by now well known, was first applied in 1964 by the principal author (Ref. 4) to the mapping of significantly curved surfaces at Pennsylvania State University. That application represented an extension of the method as used there for stress analysis by Theocaris (Ref. 5). At that time the author used a beam of collimated light which made interpretation of the observed fringes simple but limited the field to that of the lenses or mirrors available for collimation.

From about 1969 others (Refs. 6, 7, 8) developed the central perspective version of shadow moire fringe formation which was not limited by aperture but required perspective corrections to the observed contours. This is easily achieved by digitisation of contours and computed correction of coordinates.

A full account of the authors' development of pericontourography is given in Reference 9. Figure 1 herewith taken from Reference 9 shows how typical and conventional fringes are formed. A linear light source illuminates a grid or grating of alternatively opaque and transparent "bars" of which shadows are cast on the object of interest placed behind the grid. A camera, preferably with its principal axis normal to the grid-plane, views the shadows and the grid bars simultaneously and interference fringes are imaged on the plate. As shown in Reference 9 each fringe can be labelled with a contour level beneath the grid-plane as datum. These fringes are not in the locations at which true contours of the surface would project orthogonally onto the grid-plane but correction for that perspective distortion is easily effected in later processing of digitised data.

The photographic plate bearing the fringes so formed may or may not also bear images of the bars of the grid. If the spatial frequency of the fringes is much greater than that of the bars and the latter are so close as to be beyond resolution by eye or camera-lens, the fringes will appear in excellent contrast. Otherwise the fringes may not be perceived easily.

In 1966 Haas and Loof (Ref. 10) described a method for filtering out the bar-images by diffraction. Allen et al. (Ref. 6) have described a dynamic method of spatial filtering which merely requires the grid to be translated in its own plane in a direction normal to the bars during photographic exposure.

The explanation of the disappearance in Allen's method of the bar-images only in an otherwise unaffected photograph lies in Fourier transform analysis of light passing through a periodic aperture. A layman's explanation might be as follows. Periodically in time one bar replaces another so nothing has changed in fringe formation. But the moving bars will all be blurred (into a uniform background) just as a moving object is blurred in an ordinary, long exposure photograph. So the fringe images remain stationary during bar translation and the bars are blurred out into uniformity. The result is a photograph of well contrasted black and white fringes.

In addition to filtering, such fringes can be further contrasted, particularly in regions of low slope where they may become broad and diffuse, by a degree of under development of photographic negatives or prints. Peaks of fringes may also be better defined by the method of Equidensitometry of Lau and Krug (Ref. 11).

Periphery Photography

The art and practice of photographing tubular objects by periphery photography is also well known. The principal author used the R.E. (Shell) Periphery Camera in 1965-6 and in 1972 as described in Reference 4 and such cameras were used for scientific purposes by the Caterpillar Tractor Company in U.S.A. in 1947.

Figure 2 herewith from Reference 9 shows the elements of such a camera. The object, the shoe-last of the deformed foot of a war veteran, is placed on a rotary table. A camera with a focal plane aperture and a movable plate holder views the last. If the object and plate are stationary the slit will admit to the plate an image of a narrow rectangular field-element of the object with the long direction parallel with the axis of the rotary table. If now the table is caused to rotate at constant speed whilst the plate holder translates in phase at constant speed, successive images of adjacent field-elements will be automatically assembled as a continuous "unwrapped" image of the object on the plate. The image distance from the lens is constant; the object distance is variable as in ordinary photography.

If now a grid is added as shown in Figure 2 together with a light source, the camera will image a long vertical slice of the conventional shadow moire contourograph of the surface as formed in Figure 1. Next, let the table rotate and the film translate in phase, each at constant speed. The

grid being stationary, is now translating relative to the last-surface as required for spatial filtering. Successive images of central vertical slices of the field are being formed and recorded continuously on the photographic plate. Every slice-image will be traversed by a series of shadow moire fringes, each representing elements of contours of known depth below or behind the grid plane. As rotation proceeds, such fringe elements associate on the plate to form the continuous fringe-images, each of an identifiable contour level below the grid plane. Fortuitously, images of the grid bars will be absent due to the inherent filtering capacity of the method.

The resultant photographic image for the last is as in Figure 3 from Reference 9. This represents a transformed contour map of this "tubular" surface in which contours represent points of the surface whose radial depth below the surrounding reference cylinder tangential to the grid-plane is constant. Thus if we regard the last as a generalised doubly curved surface like the earth itself, the horizontal lines on this photograph are developed, or, rather, projected curves of latitude and vertical lines, projected curves of longitude. In some senses this optical and photographic image is analogous to and resembles, but is not identical with, a Mercator's projection of the earth. It is certainly a transformation of a plane grid shadow moire contourograph to another plane representing the development of a circular reference cylinder.

Optical Projection

The shadow moire method depends upon effective projection of a grid onto a diffusing (non reflecting) surface and the subsequent simultaneous imaging in a focal plane of the distorted shadows of the grid and the undistorted grid itself. As described above, a physical grid is placed near the object. The quality of the shadows (with respect to edge-contrast) is affected by the finite area of the light source and by diffraction, as Ronchi grids tend to become diffraction gratings.

These problems are discussed by the principal author in Reference 4 where the existence of Fresnel planes of image formation of the grid is explained. The fact that good grid-shadows and hence moire fringes are not always formed on surfaces when the distance of surface elements from the grid is a large multiple of the grid-pitch lies in such explanations. Thus to map anatomical surfaces of relatively high curvatures an appropriately coarse grid of perhaps 4 mm pitch might be needed and the gap between grid and surface may be of the order of several centimeters.

The edge of shadows can be degraded by umbra and penumbra effects of "point" light sources of finite dimensions. Also the backscatter from light fringes formed on human flesh can illuminate and thus degrade the sharp edges of dark fringes.

The fringes are broad and diffuse in areas of small slope so that a fringe "centre", the peak of the intensity variation, is not always obvious or easily determined, particularly where the fringe interval is varying normal to the fringe direction. Thus fringe sharpening as mentioned above or use of equidensitometry (Ref. 11) may be desirable before interpretation and digitisation.

The idea of projecting a miniature plane-grid from an image plane onto a curved surface and then reimaging this projection onto a reference grid similar to the original has been suggested and tried by others. Apparatus for executing this technique is commercially available in Japan. The moire fringes are formed in the second image plane which may be photographed. The advantage of this method is, of course, that no large physical grid need be arranged near the observed surface.

The authors commenced work using remote projection of grids in association with pericontourography. Regretably this work was terminated when their projecting equipment and records were stolen from a display exhibit at a conference. Yet one elementary basic demonstration has survived to make the point and this is reproduced in Figure 4. On the left is an original coarse grating. On the right is its appearance when projected onto a tetrahedron. Below, by superposition, embryonic shadow moire fringes appear. They are not easily seen because the fringe spacing is of a similar order to the grid pitch. Also the thinning of the shadow compared with the grid-bar width due to the large slope of model exhibits another problem of fringe formation - an interfering narrow and broad bar do not form as clear a fringe as a shadow and bar of comparable width. This is why the horizontal fringes are not readily recognisable though theoretically present.

Image Detection

Shadow moire fringes have usually been recorded photographically but, clearly, video methods (as developed extensively by Prof. J. Butters and colleagues at Loughborough University, for instance,) can be used.

In Reference 9 by the present authors, the digitisation of shadow moire contours and the use of such data to derive a set of orthogonal profiles of a surface as in Figure 5 prior to its replication by machining is explained. That method called for the random digitisation of contours followed by a surface fit using parabolic interpolation and the assumption of relatively small departures from a cylindrical datum.

For routine application to many similar cases it would be desirable to record the fringe locations in each of a finite yet relatively large number of image slits in pericontourography. A scanning array of detectors supported by processing circuitry is currently being mounted behind the focal plane aperture of Figure 1. As the rotary table turns at a relatively low speed the array will be activated periodically and, at high speed, will detect the existence or non existence of a dark fringe at set of many locations along the aperture which is imaging a curve of longitude of the surface. This on-off, yes-no data will be fed into a PDP 11-34 computer storage as a set of coordinates of random surface points. There are problems of identifying fringes and detecting peaks and valleys which lead to a single fringe crossing the aperture twice at one observation. But when these problems of "tagging" are resolved, the observation of a surface by pericontourography will be rendered automatic right through to the intermediate production of a Calcomp perspective graphics plot like Figure 5 and on to the Polyhedral NC machining program by which the item might be replicated. The authors are aware that video type cameras which could achieve the same ends are available commercially to those who can afford them.

Replication

The impetus for the development of pericontourography was the need for economical and repetitive replication of tubular anatomical surfaces. The principal author's method, POLYHEDRAL NC, is described fully in Reference 12 and its application in other papers listed in that reference. The special feature of this method is its ability to machine automatically surfaces having an extreme range of curvature such as might be observed on a human face. Here features range from a "crease" between the lips to a deep-set eye socket and a forehead of relatively low curvature. All can be embraced in one automatic treatment by POLYHEDRAL NC.

For replication of surfaces mapped with reference to a datum cylinder as in pericontourography (rather than a datum plane) a special version (cylindrical) of POLYHEDRAL NC has been produced.

Conclusion

Pericontourography enables accessible tubular surfaces to be mapped rapidly and automatically in terms of contours with respect to a surrounding cylindrical datum. Contours appear in the primary recording. By immediate digital detection of fringes in the recording aperture the prospect of replication of complex surfaces by numerical control machining almost simultaneously with observation is in prospect.

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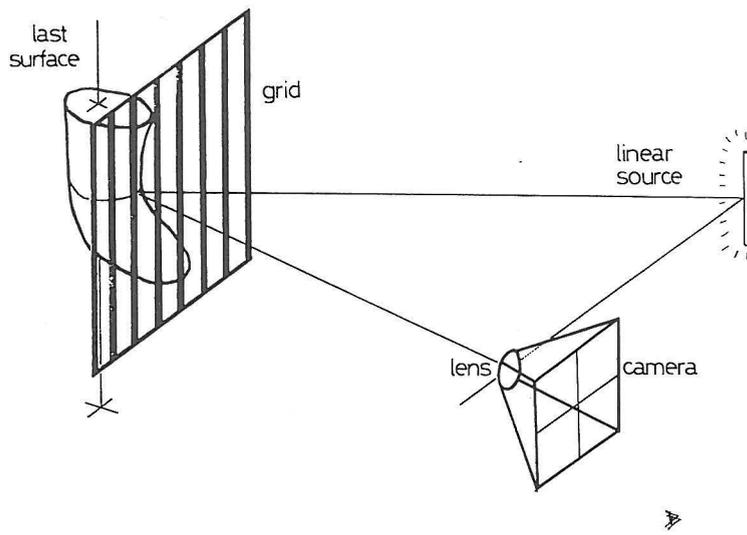


Figure 1 - Elements of Shadow Moire Fringe Formation

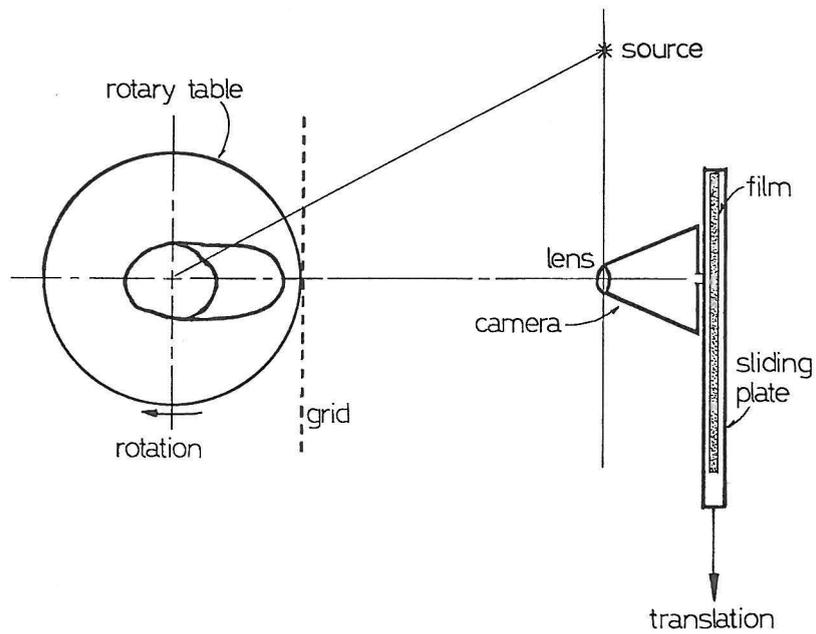


Figure 2 - Elements of Pericontourgraphy

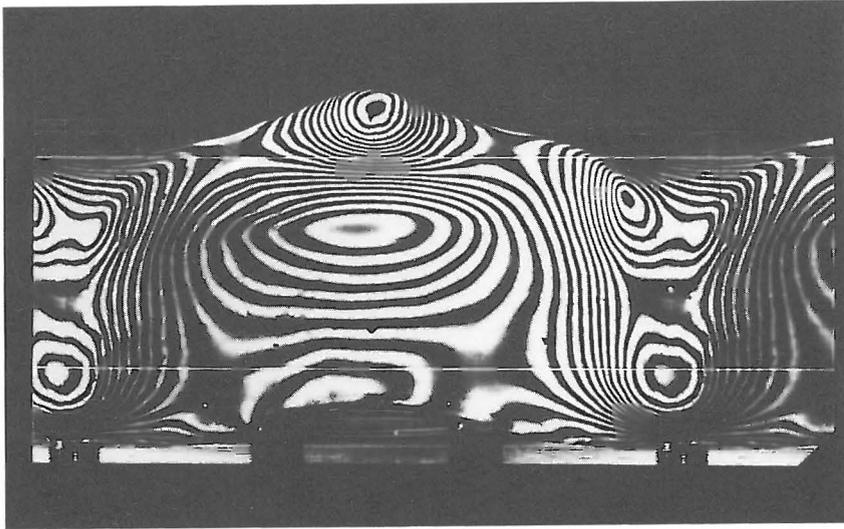


Figure 3 - Pericontourograph of a Foot-last

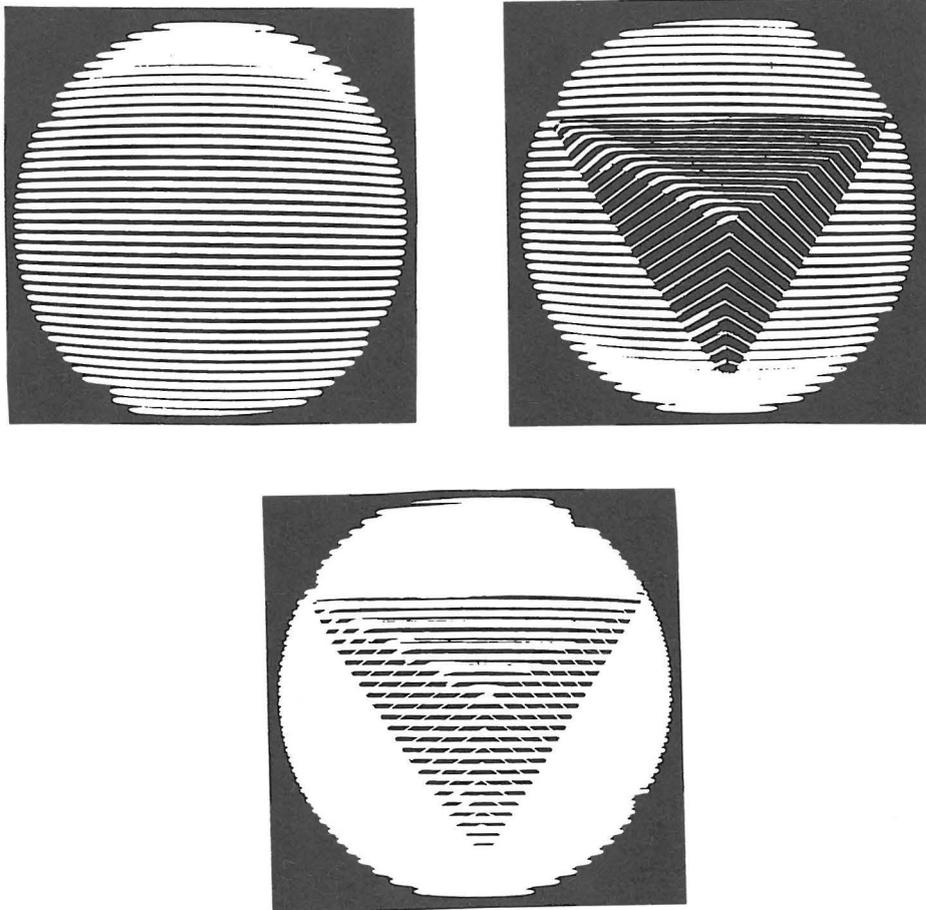


Figure 4 - Projected Grids and their Moires

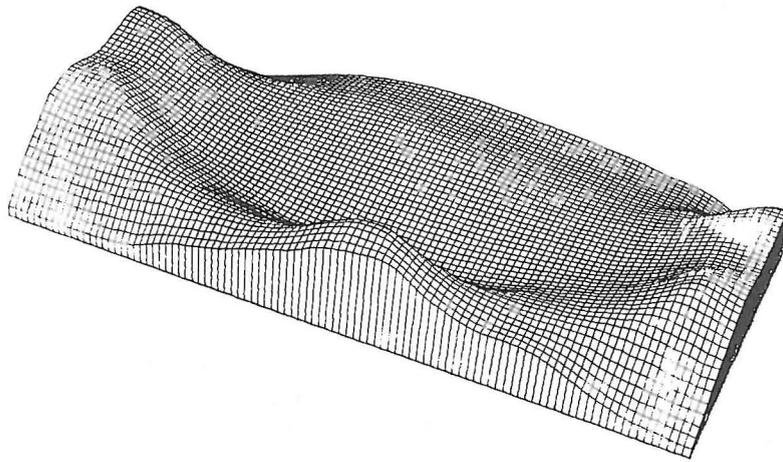


Figure 5 - Calcomp plot of profiles of surface shown in Figure 3.