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Comparison of Optical Contouring Methods

Optical contouring methods are still not competitive with stereophotogrammetric methods.

Abstract: *In the last few years several direct optical contouring schemes have been proposed and demonstrated. An effort is made in this paper to identify some of their characteristics and evaluate their performance as it relates to their application in close-range photogrammetry. It is shown that, even though these systems exhibit potential and promise, further development in technique is necessary before they can become competitive to stereo-photogrammetric systems.*

Introduction

The idea of generating contours of constant elevation as a means of geometrically measuring a close-range object has fascinated many investigators, and over the last few years this has resulted in numerous optical contouring techniques. A large number of these techniques are based on theoretical propositions; however, many of them have also been experimentally demonstrated. Each of them claims to offer unique advantages over similar methods. The applicability and the advantages offered by specific methods depend on the nature of the measuring problem and hence it is very difficult to objectively compare these methods. The intent of this paper is to evaluate and identify the performance characteristics of some of the direct optical contouring techniques reported in the literature. It is hoped that such a comparison will permit one to derive qualitatively the advantages of one technique over the other under any given situation. Most of the direct optical contouring schemes are applicable to only small objects since all of them require artificial illumination, coherent or incoherent, of the object scene. Examples of such objects are machined parts, human body organs, biological specimens, etc.

The various types of optical contouring methods that have been proposed and demonstrated are too many to be covered in this paper. Hence only a selected number of the contouring methods are considered in this evaluation. The different methods considered are (1) Moiré contouring methods, (2) contouring with holographic interferometry, (3) contour generation with optical processing of stereo photographs, and (4) contouring from holographic images. The last of the above methods is not a direct optical contouring method; however, it is included in this evaluation because it represents a novel solution to the contouring problem. The brief descriptions of the various methods are included only to provide continuity.

MOIRÉ CONTOURING

Moiré techniques of generating elevation contours on opaque objects had been demonstrated over a decade ago.[1-3]. In its simplest form it consists of an amplitude grating such as a Ronchi ruling placed close to the object, as shown in Figure 1. The combination is illuminated by a quasi-point source at an angle θ to the normal of the grating surface. The observation is made along the normal direction. The moiré pattern between the projected shadow on the object and the grating represents an instantaneous display of elevation contours. The contour interval has a value given by $dh = d/\tan\theta$ where d represents the period of the grating.

During the past several years several modifications to this basic method have been proposed and demonstrated. Some of the significant and modifications are listed in this paper, and the reader is referred to the references for additional information. The contrast of the moiré fringes obtained by the simple system described above greatly depends on the contrast of the grating and the projected shadow, the distance between the object surface and the grating, and the nature of the illumination[4]. One of the simplest of ways to improve all these parameters is by forming the shadows on the object through a projection system. The shadows on the object can be formed by either projecting the image of a Ronchi ruling on the object or by interfering two coherent plane waves on the object. The shadow on the object in turn is imaged on to another Ronchi grating and the resulting moiré fringes once again represent elevation contours.

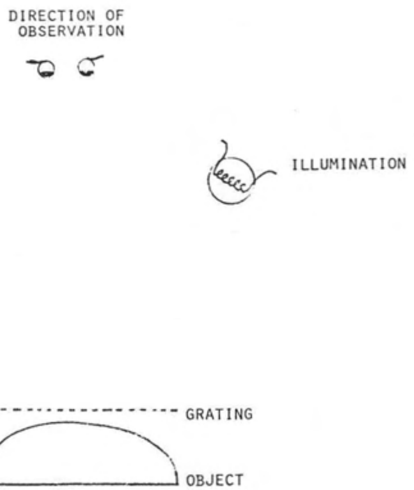

FIG. 1. Moiré contouring.

The carrier frequency patterns due to the grating and the shadow often interfere with the observation of the contour fringes by introducing noise terms. This can be avoided by first recording the shadow pattern on the object and then processing the record subsequently using an optical system shown in Figure 2. The interfering plane waves behind the record provide the demodulating reference pattern. The contour fringes, which represent low spatial frequency information, are spatially filtered using the low pass filter from other noise terms.

As stated earlier the contour interval is equal to the period of the projected shadow pattern when the angle of projection is 45°. Hence the resolution of the moiré contouring method depends on the spatial frequency of the projected shadow. For increased resolution, the projection and the imaging systems must be low f-number systems. This automatically limits the elevation range since, as the f-number of the optical system is lowered, the depth-of-focus becomes reduced drastically. This limitation can be overcome by modifying the manner of processing the photographic record. In this scheme a fringe pattern is projected on the surface under test by two coherent plane waves inclined at an angle ϕ. The projected pattern is then recorded on a photographic plate placed at the image plane of a recording lens. If θ is the projection angle, the intensity distribution on the object can be written as

$$I(x,y) = 1 + \cos \frac{2\pi}{d} (x + h(x) \tan\theta) \qquad (1)$$

where d is the fringe spacing given by $d = \lambda/\cos\phi$, λ being the wave length of illuminating radiation. The amplitude transmission of the photographic record is then given by

$$t(x,y) = k(1 + \cos \frac{2\pi}{d} (x + h(x) \tan\theta) \qquad (2)$$

where k is a constant of proportionality. The photographic plate is then bleached to convert the amplitude transparency to a phase transparency. The amplitude transmittence of the plate is now given by

$$t(x,y) = \exp i(a_0 \cos \frac{2\pi}{d} (x + h(x) \tan\theta)) \qquad (3)$$

where a_0 is a constant representing the amplitude of phase relief. Equation 3 can be written as

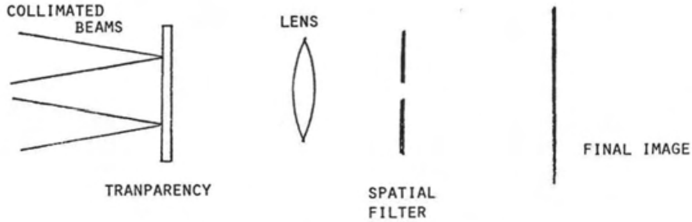

FIG. 2. Optical system for eliminating noise.

$$t(x,y) = \sum_{n:1}^{\infty} J_n(a_o) \exp i \frac{2\pi n}{d}(x + h(x)\tan\theta) \quad (4)$$

where $J_n(a_o)$ represents the Bessel function of order n. If the transparency is illuminated by a plane wave, the diffracted orders are represented by the corresponding terms of the series in Equation 4. The order of diffraction is represented by n. If two collimated beams illuminate the transparency in such a way that the nth order and the -nth order beams interfere with each other, the resulting fringe pattern can be shown to represent elevation contours. The contour spacing is given by

$$h(x) = \frac{d}{2n \tan\theta}$$

When $\theta = 45°$, the expression for the contour spacing becomes $d/2n$ instead of d as in the conventional case. Thus when $n = 5$ the sensitivity is increased by a factor of 10.

This method of contour generation offers many advantages over conventional techniques. Since the first recording is done with low spatial frequencies, the imaging system can operate at large f-numbers, thus increasing the depth-of-field. While the resolution is proportional to the f-number, the depth-of-field is proportional to the square of the f-number. There is no compromise on resolution of contour spacing since it can be increased independently at the processing stage.

CONTOURING WITH HOLOGRAPH INTERFEROMETRY

Elevation contour generation using holographic interferometry has been accomplished by the superposition of two holographic recordings on a single photographic plate. The holographic recordings differ in phase in such a way that the phase difference corresponding to every point on the object is proportional to the distance of the object point from the hologram. The interference between the two reconstructed images of the hologram produces a fringe pattern representing the elevation contours of the object. The different holographic contouring methods arise because of the various options available to change the phase between exposures as a function of elevation. The three significant methods that have been proposed and demonstrated are the multiple wavelength method, the multiple source method, and the multiple index method.

In the multiple wave-length method, the two exposures are made with two different wave lengths of light. The angle of the reference beam in each case is adjusted so as to make the two spatial carrier frequencies the same. With a collimated reference beam there is only a longitudional magnification due to change in wave length. The longitudinal magnification at every point in turn is proportional to its distance from the hologram. Hence upon reconstruction with a single wave length reference beam, the images have phase differences proportional to the differential longitudinal magnification. This phase difference gives rise to a contour fringe pattern. The contour interval is given by $dh = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$.

In the multiple source method, the hologram is recorded using a single wave length. Multiple object beams are used to project a set of fringe surfaces whose normals are roughly parallel to the direction of observation. The contour interval is given by $dh = \lambda/2 \sin \theta/2$ where θ is the angle between the two object beams.

In the multiple index method, the index-of-refraction of the medium surrounding the object is changed to provide the phase difference between exposures. This may be accomplished by immersing the object in liquids or gases of differing indices. The expression for the contour interval is given by $dh = \lambda/2\, dn$ where dn is the change in refractive index.

In all the holographic techniques, it is possible to make appropriate changes to make contour generation a real-time process. Some form of photographic recording technique must be employed to record the contour fringe pattern, since it is localized on or near the surface of the object or the image of the object.

Contour Generation with Optical Processing of Stereo-Photographs

In the last few years several coherent optical processing systems for generating instantaneous contours and profiles from stereo-pairs have been proposed and demonstrated. All these systems depend on optical correlation for the detection of conjugate images. In a pair of vertical stereo-photographs, the height information is stored in the form of x-parallax differences. The locus of all the points having the same x-parallax difference hence represents a contour on the photo coordinates. These contours are known as perspective contours and, based on the geometry of the stereo-pairs, the data can be reduced to represent orthoscopic contours either optically or digitally. These methods are different from conventional photogrammetric systems since a direct visual display of contour or profile information is possible. A few of the systems that have been reported in the literature are the positive-negative system[6], the scatter plate system[7], the image filter system[8], the matched filter profile generation system, and the interferometric contouring systems[10,11]. In most of these systems, a superposition of a stereo-pair of transparencies gives rise to a band representing points of conjugate image coincidence. For a pair of vertical photographs this band represents a contour. One of the transparencies is translated along the x-direction to generate contours of different elevations. Detailed descriptions of each of these methods, even briefly, is beyond the scope of this paper. A good review of these systems as they relate to close-range photogrammetry can be found in the references[12].

Contouring from Holographic Images

The reconstructed holographic images at unity magnification exhibit extreme degrees of metric fidelity[13]. The application of photogrammetric pointing methods as well as auto focusing methods have resulted in powerful techniques of measurement for close-range objects. This technique can not be classified as a direct optical contouring method but however is included in this evaluation because of its novel approach to the measurement problem.

The geometric fidelity is dependent greatly on the similarity of the recording and reconstructon geometries of the hologram. Considerable work has been done with regard to the geometric fidelity of holographic reconstructed images and the results are well documented elsewhere[13,14]. In the pointing approach, a self-illuminated dot attached to an *XYZ* coordinate measuring device and placed in the virtual image space is used as a measuring mark. During measurement the floating dot is brought in coincidence with the image point of interest and its coordinates are directly read from the coordinate measuring device. By maintaining the apparent contact of the dot with the surface, a contour is generated during translation in a single plane.

In the auto focus system the real image rather than the virtual image is used for measurement. A sinusoidal pattern is projected on the surface while recording the hologram. The detection of the contrast of this pattern in the real image space permits an unambiguous determination of the location of the focused image surface. An image dissector attached to an *XYZ* measuring device and used in the detection of the contrast permits automatic and quick data reduction.

The overall system can be either simple or very complex depending upon the resolution, speed, and sophistication of the data required. Spatial and depth resolutions of 25 to 50 micrometers have been experimentally demonstrated using these systems.

Evaluation of the Contouring Methods

The factors that must be considered in evaluating the performance characteristics of the various contouring systems are (a) resolution and range, (b) the signal-to-noise ratio, (c) metric accuracy and reliability, (d) the spatial resolution, and (e) the complexity of the system to meet the overall metric accuracy. Inherently the optical contouring systems offer speed and simplicity of configuration. These two main characteristics account for the widespread interest in optical contouring systems.

Moiré contouring techniques are capable of high resolution, but only at the expense of reduced range. Without resorting to exotic optics in the imaging systems, it is possible to obtain contour intervals of about 25 micrometers easily. The elevation range for this resolution in conventional moiré contouring is about 2 to 3 mm. It is possible to increase this elevation range by at least an order of magnitude by adopting the phase transparency method. However, the instability of the photographic emulsion during bleaching might cause concern regarding the metric fidelity of the contours obtained. The signal-to-noise ratio of the moiré contour patterns depends on the contrast of the grating and the projected shadow and hence it is difficult to achieve a good signal-to-noise ratio at very high resolution. In order to improve the contrast of the contours it is sometimes necessary to paint the surface with a suitable structure. The variation in the thickness layer of the paint often introduces error in measurement. The metric accuracy and reliability are determined by the geometrical imaging characteristics of the recording optical system used. The contours produced localize on or near the object surface. In order to reduce the data, the contours must be recorded on a photographic film. As explained later in this section, this requirement poses a serious problem in achieving the desired metric accuracy. The overall systems used in moiré contouring are very simple compared to photogrammetric systems.

In all contouring methods based on holographic interferometry, the range and resolution are limited by the availability of suitable laser sources. In the multiple index method the problem of handling the object limits the size. Contour intervals of 1 to 2 micrometers have been obtained experimentally using holographic contouring methods. The signal-to-noise ratios associated with double-exposure holography govern the signal-to-noise performance of these contour systems. The speckle associated with diffuse holographic images usually causes serious noise problems whenever a high density of contours is encountered. Surface preparation such as painting improves the contrast of the fringes obtained. The metric accuracy of the holographic images along with the superposed contours can be very high if suitable precautions are taken during the holographic recording procedure. However, since the contours exist in three dimensional space, considerable effort is needed to maintain the same accuracy during the data reduction procedure. This point is discussed later in this section. Holographic systems are far more complex and are not often applicable to large objects. Because of the extreme stability requirements for holographic recording, these systems are practical only under research environments.

Optical processing of stereo-pairs permits the automation of the stereo-compilation process and in every other respect its performance characteristics are similar to conventional stereo-photogrammetric systems. The resolution in parallax measurement, which in turn determines the ultimate resolution, not only depends upon photogrammetric parameters such as base-to-height ratio but also depends on the image structure. The width of the contours obtained is inversely proportional to the spatial frequency content in the image. The contrast and the brightness of the contours depend on the perfect matching of the conjugate image points. The signal-to-noise performance of these systems degrade markedly under conditions of large base-to-height ratios and imagery involving large slopes. From the arguments presented above, it is clear that the stereo-transparencies have to be either vertical or rectified to be vertical. Since the contours relate to the photo coordinates rather than to the model space, the contours are perspective in nature. However, since the controls for the stereo-pair are known, they can be reduced easily to orthoscopic form either optically in real time or digitally. Since the performance of these systems depends greatly on the image structure, desired high frequency patterns such as speckles can be superimposed on the object to improve contrast and the resolution of the output. Moiré contouring can be considered as an example of this approach.

Contouring from holographic images effectively combines the advantages offered by holography with the measurement characteristics of photogrammetry. The resolution of these systems is determined either by the pointing accuracies or by the depth-of-focus of the auto focus system. Coherent speckle associated with the diffuse surfaces is the main source of noise in the system. Since the measurement is made in the model space, the data reduction involved becomes minimal. Problems arising from the environmental requirements for holographic recording are the main sources of inconvenience.

Most of the investigations relating to the generation of elevation contours have not addressed the problem of data reduction once the contours are generated. Once the record of the contours is made on a two dimensional photographic film, the contours become perspective. Each contour must be individually adjusted for magnification to provide the correct representation of the object. Also there is no way of identifying a contour representing a hill from a corresponding one representing a valley. The three-dimensional appearance of the object aids in discrimination during visual display, but this information is lost in the record. Alternative methods of data extraction are necessary before holographic interferometric and moiré techniques can provide very reliable and accurate metric information.

Conclusion

In this paper some of the direct optical contouring methods are evaluated with regard to their performance characteristics. At the outset optical contouring schemes seem to offer major advantages in close-range applications; however, care must be taken in assessing the metric accuracy of the contours generated. Optical contouring systems provide a powerful means of obtaining quick but qualitative information of close-range objects. The problems associated with data reduction represent the major roadblock to the widespread use of their potential.

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