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Rasterstereography: A Photogrammetric Method for Measurement of Body Surfaces

Although only a single camera and a projector with a raster diapositive are used, the standard photogrammetric procedures of calibration and model reconstruction can be employed with minimum modifications.

Abstract: *A stereophotogrammetric method referred to as rasterstereography is presented which is, to some extent, intermediate between common stereophotography and Moiré topography. The technical aspects of rasterstereographic image preparation using a camera and a projector with a raster diapositive are discussed in detail. It is shown that, by analogy with stereophotography, the standard photogrammetric procedures of calibration and model reconstruction can be used with minute modifications. A method of automatic processing of rasterstereographs is outlined.*

Introduction

Contact-free measurements of body surfaces are mainly performed using stereophotogrammetric techniques based on distance measurements by triangulation. The most familiar application is stereophotography (Figure 1a). Rasterstereography is quite similar to conventional stereophotography except that one of the two cameras is replaced by a projector with a raster diapositive. That is, the direction of the light rays of one of the two half images is reversed, and the pertinent half image is replaced by the raster diapositive (Figure 1b). The second half image is generated, as usual, by the camera and contains an image of the surface to be measured bearing the projected and distorted raster lines. Thus, the raster diapositive and the camera image still form some sort of a stereoscopic image pair, and all the well known photogrammetric techniques such as model reconstruction and calibration can be applied with minute modifications. However, because the whole of the three-dimensional information is now contained in a single image, only this one image has to be measured in the discrete raster points, and stereoscopic vision is not necessary. Due to this fact, identification of corresponding points in the image pair is possible in an objective and unique manner by a determination of the row and column numbers of the raster intersections, as opposed to stereophotography, where the correlation is commonly effected by stereoscopic vision in a stereocomparator. This is particularly important in the case of unstructured surfaces such as the human skin. In addition, due to the simple image pattern, an automatic processing of rasterstereographic images is relatively simple. This may be an important point, e.g., in medical screening investigations.

An early approach to obtaining three-dimensional surface measurements using the same basic principles is known as "Lichtschnittverfahren" (light sectioning technique; see, e.g., Joel (1974), Kiessling (1976)). In recent years similar methods were reported by several authors. Kováts (1974, 1978) used a projected grid for the morphometric study of breathing movements of the trunk. Renner *et al.* developed a method for the design of tissue compensators in radiation therapy which they called monoscopic quantitative photogrammetry (Irish and Renner, 1977; Renner, 1977; Renner *et al.*, 1977). They used a grid projected by a point shaped light source and an arbitrarily positioned

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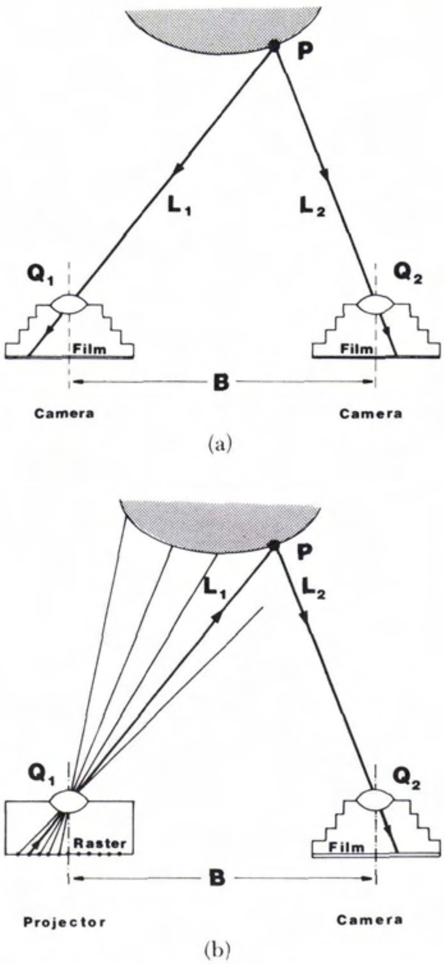


FIG. 1. (a) Stereophotography and (b) rasterstereography.

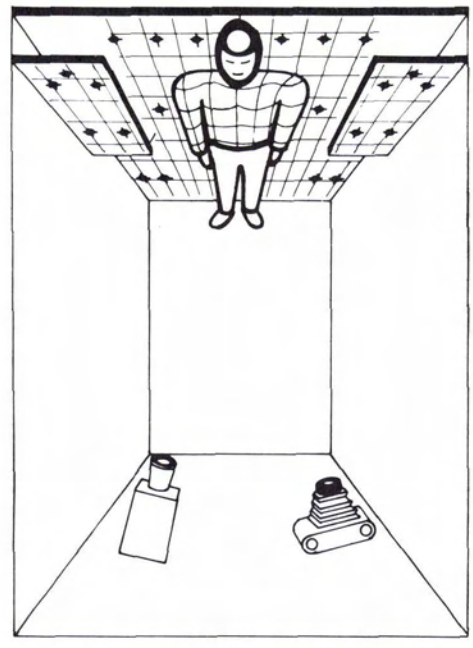


FIG. 2. Basic arrangement for rasterstereography.

non-metric camera. The concept of rasterstereography presented here resulted from discussions concerning improvements of Moiré topography, which is another "monoscopic" technique for three-dimensional surface measurements (Takasaki, 1974; Miles and Speight, 1975; Drerup, 1977), and which is likewise based on triangulation. First results obtained with the rasterstereographic method presented here were published by Frobin and Hierholzer (1978).

In the present paper the physical and technical aspects of the preparation and processing of rasterstereographs are discussed. Likewise, the concept of an automatic image data acquisition system presently being developed is illustrated. The image data evaluation consists of the calibration of the rasterstereographic apparatus, the three-dimensional model reconstruction, and the shape analysis as described elsewhere (Frobin and Hierholzer, 1982; Hierholzer and Frobin, 1980).

PRACTICAL USE OF RASTERSTEREOGRAPHY

Rasterstereography can be employed in any close-range stereophotogrammetric problem where objects with clearly defined surfaces of sufficient size are to be measured. The range of applications of rasterstereography is equivalent to that of Moiré topography. A number of possible applications is quoted in the paper of Irish and Renner (1977). The practical realization of a rasterstereographic system depends on the geometry of the objects to be measured and on the needs of accuracy.

The basic design of a rasterstereographic setup suitable, e.g., for determining the human trunk shape is shown in Figure 2. It consists of a projector with a raster diapositive, a camera, and a system of control points.

Several modifications of this basic design are possible with regard to the overall geometry, the type of the raster diapositive, and the control point distribution.

The overall geometry has to be chosen in accordance with the object size and the desired resolution; i.e., the same rules as in conventional stereophotography have to be observed. However, as stopping down the projector lens is generally not possible, the orientation of the camera and projector axes relative to the stereo base must be chosen with regard to their different depth of field. As a rule of thumb, their maximum inclination (relative to the normal case of photogrammetry) must be inversely proportional to their entrance pupils. If short exposure times and consequently

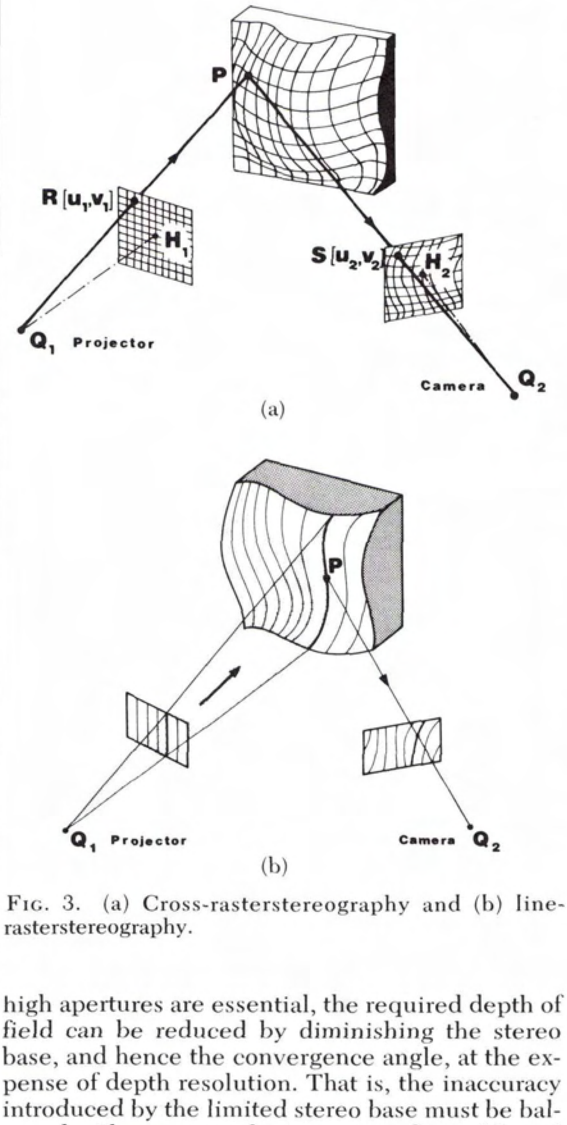


FIG. 3. (a) Cross-rasterstereography and (b) line-rasterstereography.

high apertures are essential, the required depth of field can be reduced by diminishing the stereo base, and hence the convergence angle, at the expense of depth resolution. That is, the inaccuracy introduced by the limited stereo base must be balanced with respect to the inaccuracy due to blurred images. For essentially planar objects the situation can be improved by using the Scheimpflug principle for the alignment of the raster diapositive relative to the projector lens.

There are two basic types of raster diapositives which can be used in rasterstereography: cross rasters and line rasters. In cross-rasterstereography (Figure 3a) a regular square raster is employed. Only the raster intersections are evaluated for the reconstruction of surface points, although (at least in principle) any point could be measured (possibly by interpolation). Provisions must be made in order to identify uniquely the raster intersections by row and column numbers, e.g., by allocating numbers to the raster lines or by a unique pattern of heavy and light raster lines. If the dimensions of the raster diapositive are known, the position u_1, v_1 of any raster intersection R can be calculated from the row and column numbers. The image coordinates u_2, v_2 of the corresponding point S in the camera image are directly measured with an x/y digitizer of any type. R and S are considered as a stereo image pair of P which is suitable for the known photogrammetric procedures.

Although the evaluation scheme is very simple in the case of cross-rasterstereography, it is not very well suited for automatic image processing unless very complicated and time-consuming pattern recognition algorithms are employed. However, as there is some redundancy in a cross-rasterstereographic image, a considerable simplification of the image structure can be achieved by using a line raster. Then a unique reconstruction of any surface point is still possible (Figure 3b), although with a little loss of accuracy. Again the raster lines must be uniquely identified, either by line numbers or by an appropriate pattern of light and heavy lines. Any point on a raster line may be evaluated in the camera image (for mathematical details, see Frobin and Hierholzer (1981)).

A system of properly distributed control points is necessary for the calibration of the arrangement, i.e., the determination of the interior and exterior orientation of the camera and the projector. From theoretical considerations it is evident that the control points must not all lie in a plane. In addition, in order that the system of equations employed in the calibration procedure be well-conditioned, the control points should be distributed as uniformly as possible over the whole volume of interest. Furthermore, the calibration procedure described by Frobin and Hierholzer (1981) requires that the control points be fixed on planes on which the raster lines can be projected. Thus, at least two control planes are needed which may, for the sake of simplicity, be parallel. The three-dimensional coordinates of the control points must be known. However, when using the bundle method of photogrammetry, an absolute accuracy of the a priori control point coordinates is not necessary.

If the geometry of the rasterstereographic setup is not fixed, the calibration has to be performed individually for each record. If the camera and the projector are fixed in their positions, only one initial calibration of the apparatus is required. However, then at least two fiducial marks must be recorded in the camera image. These fiducial marks must be fixed with respect to the camera (film plane).

Using fiducial marks has the advantage that, e.g., in biostereometric applications, the subject is not handicapped by the relatively large control point system. In addition, if the fiducial marks are mounted at the camera, only the relative position

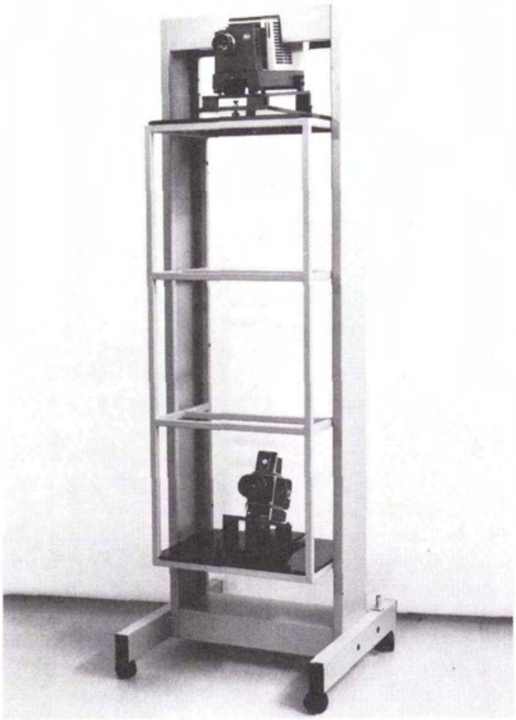


FIG. 4. Rasterstereographic camera set.

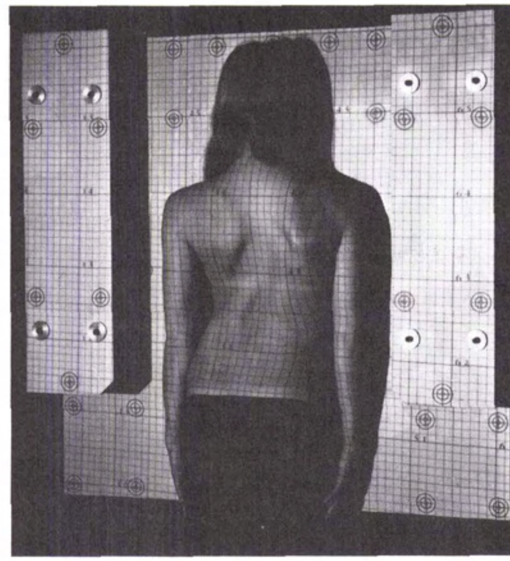


FIG. 5. Rasterstereographic camera image.

of the projector and the camera has to be maintained (including, of course, the focusing of the lenses). Thus, a relatively handy unit containing the projector and the camera can be constructed which can be moved around without losing its calibration and which indeed greatly resembles a terrestrial stereo camera setup (Figure 4).

The orientation of the stereo base may be of some importance in certain applications. For example, due to the symmetry of the human body, a vertical stereo base (Figure 4) should be more adequate for the standing position than the horizontal one shown in Figure 2. In the case of line rasterstereography, the raster lines must be aligned perpendicularly to the stereo base in order to obtain maximum accuracy of measurement. Also in the case of cross-rasterstereography the raster lines should preferably be oriented perpendicularly and parallel to the stereo base, although in principle any orientation is permitted.

The mathematical aspects of the calibration and reconstruction procedures are discussed in the paper of Frobin and Hierholzer (1981).

EXPERIMENTAL SETUP

Our first experimental setup was designed for the measurement of the human back shape in the case of spinal deformations such as scoliosis or kyphosis. The working distance was approximately 3 m with a stereo base of 1.25 m. The resulting depth resolution was about 0.5 mm. We used the cross raster method with a line density of 0.5 to 1 per centimetre at the object site. That is, the back surface was sampled every 1 to 2 cm.

We use a standard Hasselblad 500 ELM motor camera with a Zeiss Sonnar f:4/150 mm lens. The projector is a Leitz Prado Universal with a Colorplan f:2.5/90 mm lens and a 250 W lamp. The projector was slightly modified to fit a standard raster diapositive*. In our first experiments we used a positive cross raster (Heidenhain type 15a) with a 0.5-mm division. It was furnished with row and column numbers by mounting a film with small numbers in contact with the raster diapositive. The resulting camera image is shown in Figure 5.

Although a positive raster is favorable for a directly interpretable documentation, it appears that a negative raster (e.g., Heidenhain type 15b) is more appropriate for automatic image processing. A further simplification of the automatic evaluation is achieved by using the line raster method. A suitable raster diapositive must, however, be manufactured separately. As it is difficult to recognize written numbers automatically, the line numbers may be determined from a unique pattern of heavy and light lines (see Figure 9). The most favorable design of such a line raster might be a random distribution of heavy and light lines.

The control point system shown in Figure 5 was made of white coated chip board. The control points are self-adhesive fitting marks as used for

* Manufacturer: Dr. Johannes Heidenhain, D-8225 Traunreut, Federal Republic of Germany.

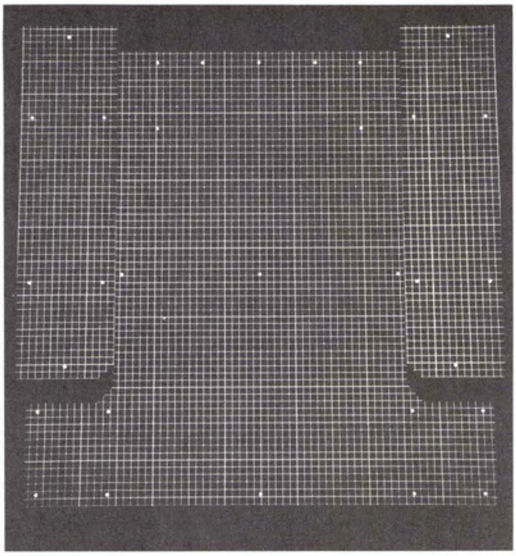


FIG. 6. Control point system with self-luminous control points and projected raster lines.

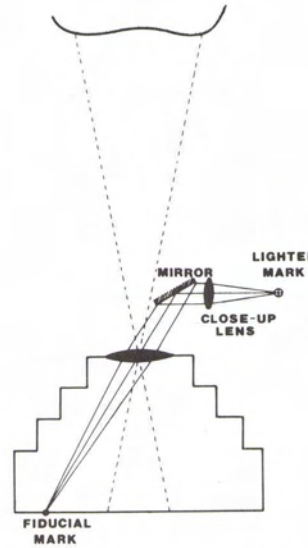


FIG. 7. Camera with lens mounted fiducial marks.

printed circuit design (manufactured by Bishop). They are mounted on two planes separated by a distance of 170 mm. The whole system is mounted on a steel frame. The a priori coordinates of the control points were measured with glass scales†, assuming that the boards are planar. The calibration procedure yielded control point corrections of the order of 0.2 mm for the in-plane errors (x and y) and 0.6 mm for the z error (normal to the planes).

If a negative raster is used, the control points are not sufficiently illuminated by the projector. Hence self-luminous control points must be used as shown in Figure 6. The diameter of the lighted area is 6 mm to give a well defined image on the film which is suitable for an automatic detection.

Using the optical equipment described above, an exposure time of 1/8 sec at an f stop number 16 of the camera lens was needed for an ASA 400 film (Ilford HP5) which had sufficient resolution. However, by employing Scheimpflug or shift lenses for both the camera and the projector, a considerable improvement in these figures should be possible if the use of nonstandard photographic equipment is accepted. A further improvement is possible by using a flashlight projector.

As mentioned in the previous chapter, a rasterstereographic apparatus with fixed geometry needs only one initial calibration, but fiducial marks must then be recorded in the camera image. The Hasselblad camera can be supplied with a reseau plate mounted in front of the film plane, and the reseau intersections can be used as fiducial marks. However, when using a negative raster diapositive, the reseau cannot easily be recognized. As shown in Figure 7, fiducial marks can be mirrored into the camera image using a supplementary lens. The whole system can be mounted in the filter thread of the camera lens without the need for any camera modification.

† Manufacturer: A Messerli AG, CH-8152 Glattbrugg, Switzerland.

IMAGE PROCESSING

As mentioned at the beginning, the raster diapositive and the camera image are considered as an image pair quite similar to the case of stereophotography. Consequently, the image data evaluation consists in the determination of "left" and "right" image coordinages of those surface points onto which the raster intersections or raster lines are projected. The image coordinates in the raster diapositive are calculated from the row and column numbers of the raster lines and the known dimensions of the diapositive. The coordinates in the camera image are measured with an x/y digitizer.

In our first experiments with cross-rasterstereography, we measured the raster intersections by hand using a camera image enlarged on X-ray duplicating film. A monoscopically used stereocomparator, which was connected on-line to a computer (DEC PDP 11/45), served as a digitizer. A preprocessing program converted the row and column numbers and the comparator coordinates into image pair coordinates suitable for the standard photogrammetric programs. A separate procedure was necessary for the control points, the data of which were likewise converted into image pairs by interpolation between the raster lines (Frobin and Hierholzer, 1981).

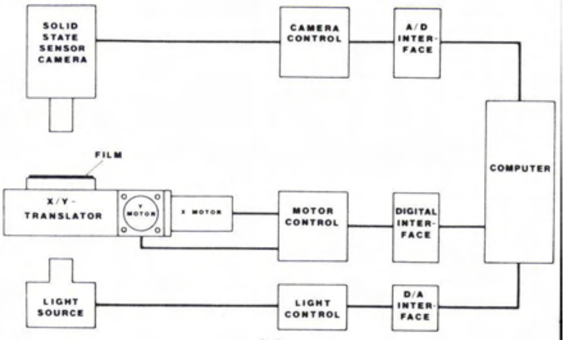
The preprocessing programs include corrections for the distortion of the projector and camera lenses. The distortion was calculated using data supplied by the lens manufacturers. Alternatively, the lens distortion may be determined using the self-calibrating bundle adjustment. If the camera image is enlarged before digitization, the lens distortion of the enlarging device must be taken into account in the form of a resultant distortion of the camera plus the enlarger. As most simple digitizers have a resolution in the order of 0.1 to 0.2 mm, an enlargement of the original negative is necessary to obtain a sufficient accuracy in calibration and model reconstruction.

Although the evaluation of a rasterstereographic image is evidently quite easy, the measurement with a digitizer requires a considerable amount of care and attention because the correct association of row and column numbers (or line numbers in the case of line-rasterstereography) to the measured image point is crucial in the calibration and reconstruction procedure. Thus, a reliable measurement by hand of large objects is relatively hard work, and an automatic image processing might be very desirable.

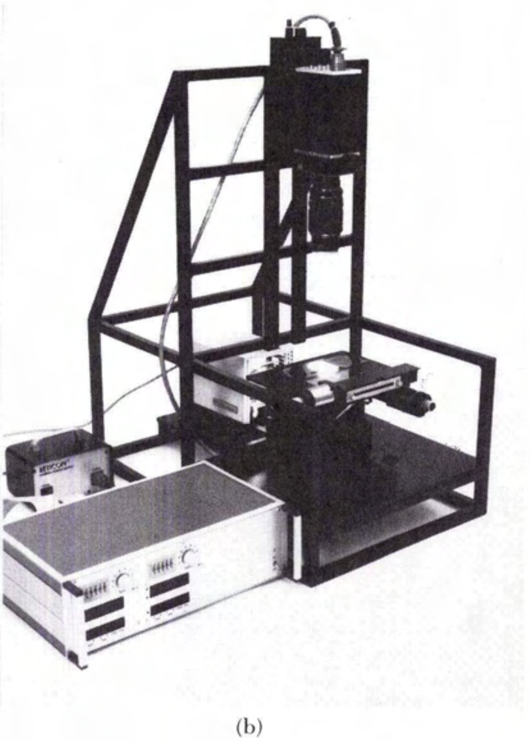
As was pointed out earlier, the method of line-rasterstereography is particularly suitable for an automatic evaluation. Furthermore, the raster lines on the film are most easily detected if a negative raster is used, that is, if light lines are projected onto the surface. Disturbing image structures are then largely absent. In Figure 8 our automatic image processing apparatus is shown. The device consists of a light source, a computer controlled motor driven *x/y* translator bearing the film, and a solid state sensor camera. In the case of line-rasterstereography, a linear camera is used. The linear sensor array is oriented approximately perpendicular to the raster lines (*x* direction), and the film is scanned moving the translator perpendicular to the direction of the sensor array (*y* direction). The other translation direction is not used in this case.

As a light source we use a Leitz Prado Universal projector (without projection lens). The translator (type EK 8b with control unit MS 12) was manufactured by Märzhäuser (Wetzlar/Germany). The camera is a Reticon LC 100 with 1024 sensor elements.

Using a 1024 element array and the geometrical conditions described in the preceding paragraph, a depth resolution of 2 to 3 mm is achieved. There are several possible methods of improving this figure: (1) A sensor with more elements may be used (image sensors with 2048 elements are available), (2) the film may be scanned in several strips (using the x direction of the translator), (3) if several sensor elements are hit by one and the same raster line, the center of gravity of the line may be calculated by interpolation using the appropriate sensor signals, or (4) the film may be shifted parallel to the sensor array (*x* direction) *n* times by 1/*n* of the sensor element spacing. From the resulting *n* sensor readouts, the line centers can be calculated using a digital deconvolution algorithm.



(a)



(b)

FIG. 8. Automatic processing of rasterstereographs: (a) principle, (b) apparatus.

If interpolation procedures (3) and (4) are employed, care must be taken in order not to exceed the dynamic range of the sensor elements. It may thus be necessary to control the intensity of the light source. In the arrangement of Figure 8a, the light level can be adjusted dynamically by the computer.

The video camera output is fed into the computer by means of an analog digital converter interface (we are using a Digital Equipment AR

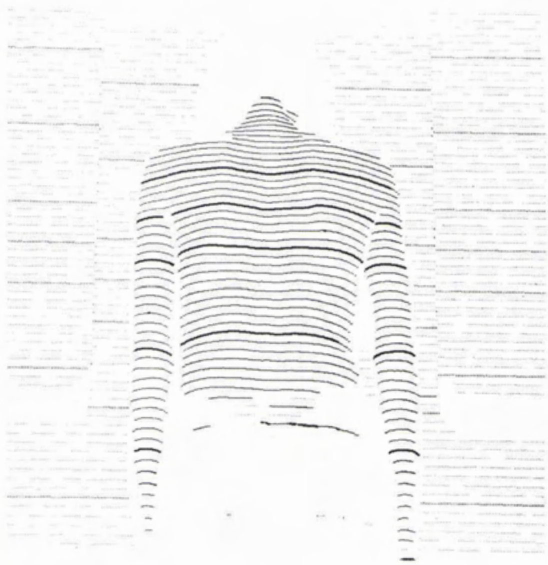
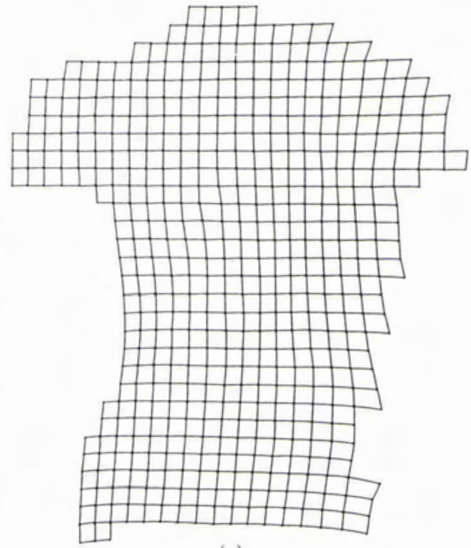
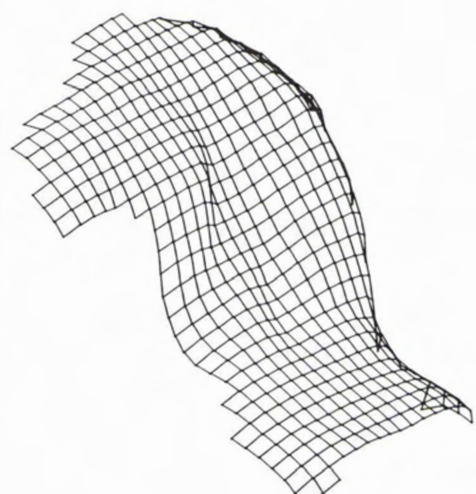


FIG. 9. Automatically scanned line rasterstereograph.



(a)



(b)

FIG. 10. Reconstructed model of the back surface.

11, which meets the speed requirements of the Reticon camera). The computer discriminates the raster lines from background and carries out validity checks to ensure that the lines are correctly identified and measured. The raster line data, including line position, width, and intensity, are then stored on a magnetic disk. Finally, the computer advances the translator to the next position and starts a new camera cycle. In a separate procedure the line pattern of the stored image is analyzed and the correct numbering of the lines is established. In the next step the three-dimensional surface reconstruction can be carried out. The details of the image evaluation strategy are the subject of studies still in progress.

In Figure 9 a computer plot of an automatically scanned line raster image is shown.

Independent of whether the image data acquisition is performed by hand or automatically, the preprocessed data are fed into the standard photogrammetric calibration and reconstruction programs. As a result we obtain a table of the x, y, and z coordinates of all measured surface points. For the subsequent data analysis and representation, it is favorable to arrange the surface points according to their row and column numbers (or line numbers in the case of line-rasterstereography). In Figure 10, a graphic representation of the reconstructed surface (Figure 5) is shown in different angular positions. Methods of a more extensive surface data evaluation, including the calculation of profiles and a shape analysis by the surface curvature, are reported elsewhere (Hierholzer and Frobin, 1980).

Conclusion

Rasterstereography is a simple and versatile method for the measurement of body surfaces at close range. In a number of applications, particularly in biostereometrics, it seems to be superior to conventional stereophotography or Moiré topography. Its main advantages are the simplicity of the manual or automatic image processing without the need for stereoscopic vision, and the plain and regular structure of the resulting data. Furthermore, depending on the desired accuracy, standard off-the-shelf photographic and optical equipment can be used for rasterstereographic image preparation. Due to the similarity to stereophotography, the standard calibration and reconstruction procedures developed for stereophotogrammetry may be employed for the evaluation of rasterstereographs.

Some remarks seem to be appropriate with respect to Moiré topography. As mentioned earlier the ranges of application of Moiré topography and rasterstereography are essentially the same. However, while a Moiré topogram directly yields a contour map of the body surface, a computer evaluation of rasterstereographs is necessary in any case. Nevertheless, an image digitization and a computer evaluation is required even in the case of a Moiré topogram, if a true shape analysis of any type shall be performed. It must be kept in mind that the Moiré contour lines represent coordinate dependent data, from which the intrinsic shape properties can be extracted in general only with a considerable amount of computation (for a detailed discussion, see Hierholzer and Frobin (1980)). Thus, it appears that only in very special applications can a Moiré topogram be evaluated simply by inspection rather than by using a computer. In addition, in these cases a reliable visual evaluation is possible only by well-trained persons. Furthermore, an interpretation of a Moiré topogram in terms of (nearly) equidistant parallel contour planes is possible only for special geometries of the Moiré apparatus which must be carefully maintained. In contrast to that, an arbitrary geometry can be chosen in the case of rasterstereography. From these points of view it seems not to be a real disadvantage of rasterstereography to depend on a computer evaluation.

For an extensive discussion of the advantages, applications, and further developments of rasterstereography, we refer to the paper of Irish and Renner (1977). In our opinion the real benefits of rasterstereography will come out in connection with automatic image processing. Thus, the future applications of this technique will largely profit from the development of hardware and software tools for digital image processing and pattern recognition.

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