XIV Congress of the International Society for Photogrammetry

Hamburg 1980

Commission V

Working Group 6

Invited Paper

E. Hierholzer, W. Frobin

Orthopädische Universitätsklinik Münster
Abteilung Biomechanik

METHODS OF EVALUATION AND ANALYSIS OF RASTERSTEREOGRAPHIC SURFACE MEASUREMENTS

Abstract

A modified close-range stereophotogrammetric method referred to as rasterstereography is presented. The advantages of this method, using a camera and a projector with a raster diapositive instead of two cameras, as compared to common stereophotography or Moiré topography, are discussed. A particular advantage is the possibility of an easy automatic image processing; the mathematical and physical aspects of such an evaluation method are outlined.

As an application to biostereometry the measurement and analysis of the human back shape is reported. The shape analysis is carried out in terms of invariant shape parameters such as the local curvature of the body surface. It is pointed out, that the mathematical structure of the rasterstereographic image data is particularly suited for the analysis, classification and comparison of the body shape.

Rasterstereography is a stereophotogrammetric technique for the three-dimensional measurement of body surfaces. It is quite similar to common 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 stereoscopic half images is reversed and the belonging half image is replaced by the raster diapositive (fig. 1). 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 of stereo image processing can be applied with minute modifications. However, because the whole 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 the 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. Thus an automatic processing of rasterstereographic images is relatively simple, which may be an important point for example in medical screening investigations.

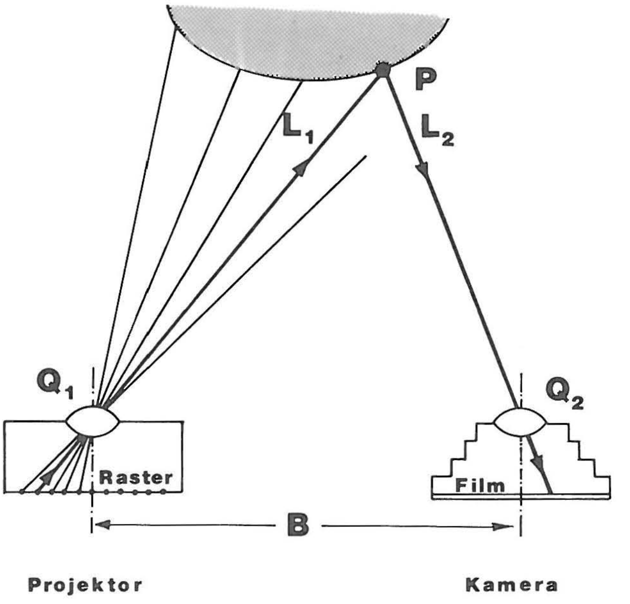


Fig. 1: Principle of rasterstereography

A complete evaluation and analysis of a rasterstereographic surface measurement consists of

1. *preparation of the rasterstereographic image*
2. *image data acquisition*
3. *calibration*
4. *reconstruction*
5. *surface data analysis.*

A simple setup for the *image preparation* consists of a camera, a projector and a system of control points (fig. 2). The arrangement resembles that of stereophotography and certain realizations of Moiré topography. The spacing of the raster lines depends on the desired resolution and on the curvature of the surface.

The *image data acquisition* may be carried out with a simple x/y-digitizer. Only the raster intersection points, characterized by their row and column numbers, need to be measured. Intermediate points can be calculated with sufficient accuracy by interpolation, provided that the density of the raster lines is adequate with respect to the curvature of the surface. For calibration purposes also the control point images have to be evaluated (fig. 3).

As already mentioned, an automatic image data acquisition is facilitated by the simple structure of rasterstereographic images. Fig. 4 shows the basic design of such an image processing device presently being developped. The apparatus consists of a light source, a computer controlled motor driven x/y-translation stage bearing the film, and a solid state sensor camera (either with a linear or a matrix sensor element).

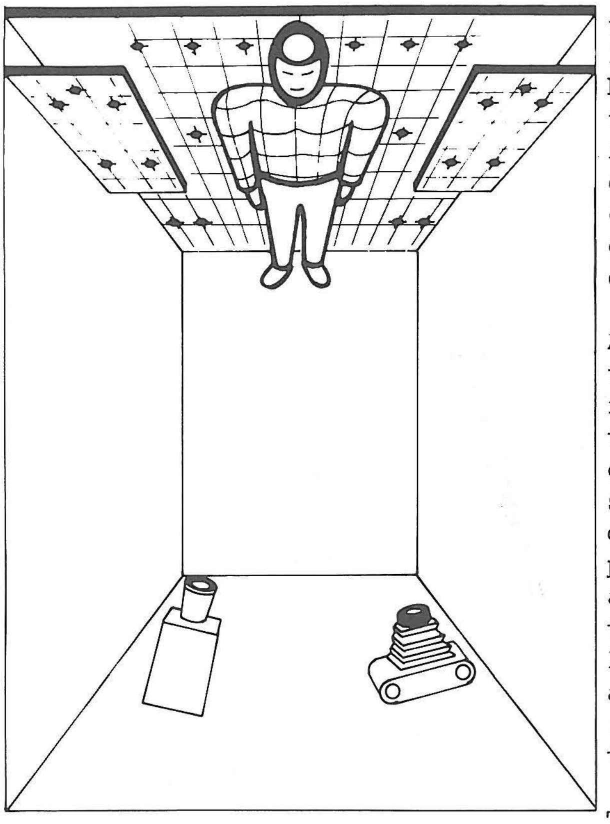


Fig. 2: Rasterstereographic setup

To compensate for the limited dynamic range of the solid state camera and to prevent saturation effects it is advantageous to control the intensity of the light source. The light level may be dynamically adjusted by the computer.

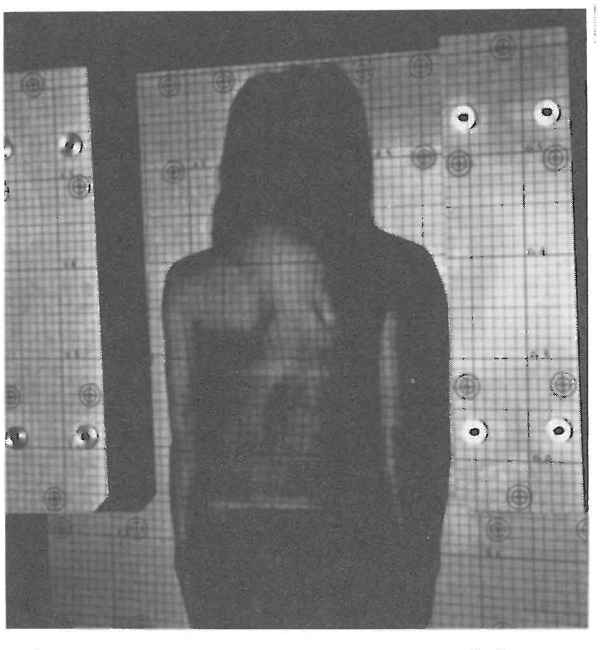


Fig. 3: Rasterstereographic camera image

The video camera output is fed into the computer via an analog digital converter interface. The computer discriminates the raster lines from background and carries out validity checks to ensure that the lines are correctly identified and measured; the checks may include a tentative reconstruction of surface points and a correlation with previously measured parts of the surface. Finally the computer advances the translation stage to the next position and starts a new camera cycle. The details of the measuring strategy depend on whether a linear or a matrix camera is used.

To simplify the automatic image processing a modification of the rasterstereographic method de-

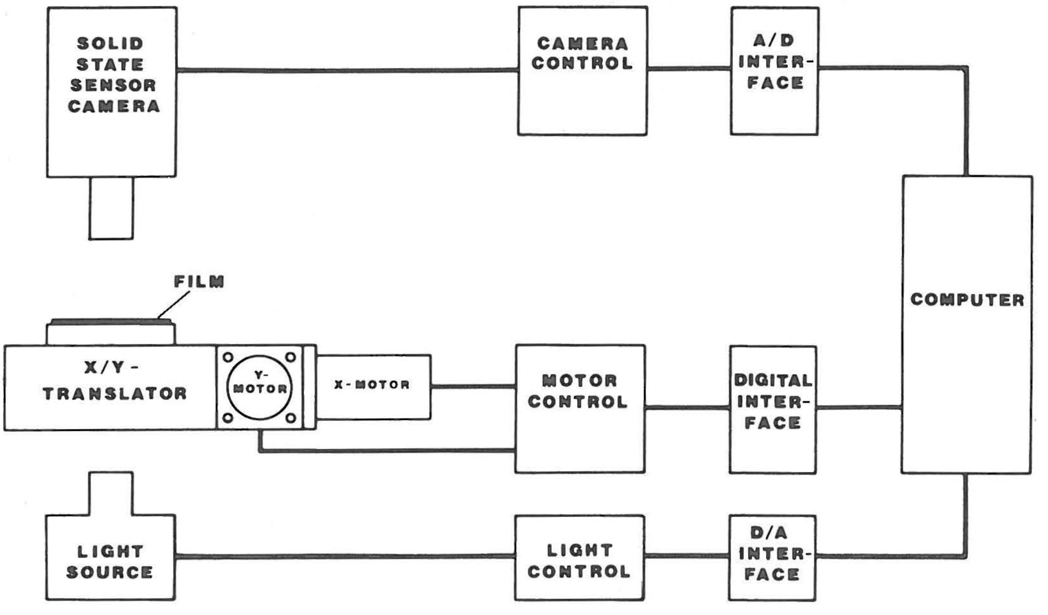


Fig. 4: Automatic evaluation of rasterstereographic images

scribed above may be employed. If, instead of a cross raster, a line raster is used, a unique three-dimensional reconstruction of the surface points is still possible (fig. 5). In this case the computing expense for the identification and measurement of the raster lines is heavily reduced.

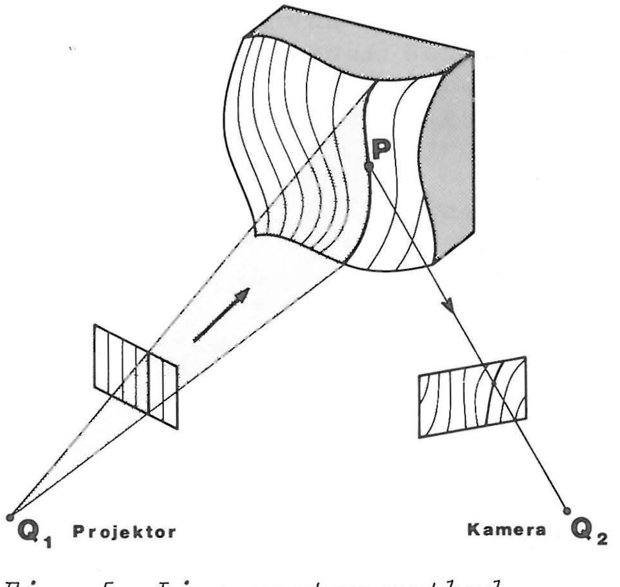


Fig. 5: Line raster method

The *calibration* procedure consists in the determination of the interior and exterior orientation of the camera and the projector with respect to the coordinate system of the control points. As the projector may be considered as a reversed camera, the known procedures of stereophotogrammetry can be employed. However, whereas the camera images of the control points can be measured on the film (either by hand or automatically), there is no real projector image of the control point distribution. Therefore we suppose the control points to be imaged into the raster diapositive plane by the projector lens in a fictitious backward imaging. The fictitious control point images can be calculated from data measured solely in the camera image, possibly by interpolation between the raster lines.

The camera image and the calculated fictitious projector image form a stereo image pair of the control point distribution suitable for the standard photogrammetric calibration procedures.

As the coordinates of the control points could not be measured with very high precision in three dimensions, we employed the photogrammetric bundle method for the determination of the camera and projector orientation as well as for the correction of the control point coordinates.

The *reconstruction* of the surface may be carried out either simultaneously with the calibration using the bundle method, or separately; the latter procedure has the advantage of saving computing time, with a little loss of accuracy.

It should be pointed out, that the same calibration and reconstruction algorithms can be used for the cross raster method as well as for the line raster method. This is possible, if weight factors for the image coordinates are introduced in the bundle method. In the case of the cross raster method equal weight factors have to be employed for both image coordinates. However, in the case of a line raster the image coordinates in the direction of the raster lines are virtually indeterminate. Therefore, a weight factor of (approximately) zero has to be introduced in this coordinate direction.

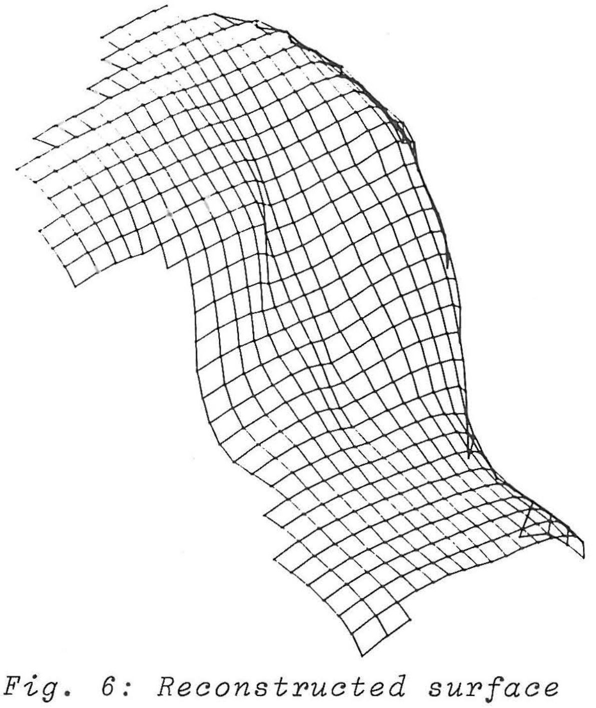


Fig. 6: Reconstructed surface

Once the reconstruction of the surface is accomplished (see fig. 6), the surface points are known by their x, y and z coordinates and by their row and column numbers in the raster. Thus the points may be ordered and neighbour points to any given point may easily be located. In the case of the line raster method only column numbers exist, but row numbers can then be established by calculation. This ordering scheme is favourable for the subsequent data analysis, as will become clear later on.

Before the data analysis is discussed in more detail, a comparison shall be made between rasterstereography, stereophotography and Moiré topography. All three methods are based on a distance measurement by triangulation; it can therefore be shown, that under similar geometrical conditions the depth resolution of these methods is similar, too. Of couse, rasterstereography and Moiré topography are limited to the close range. The main advantages of rasterstereography over stereophotography were already mentioned at the beginning. On the other hand, there are many analogies between rasterstereography and Moiré topography, especially in the case of the line raster method. However, in rasterstereography the whole procedure of image data processing (calibration, reconstruction) is executed by a computer. In Moiré topography the "reconstruction", that is, the generation of contour lines, is effected by a superposition of a second grid; this procedure is sometimes referred to as optical computing. An exact calibration such as in stereophotogrammetry is difficult to achieve for a Moiré apparatus.

As a result of optical computing a Moiré topogram directly yields contour lines (generally not equally spaced). However, care must be taken in interpreting such a topogram. The contour lines are lines of constant z (distance to a reference plane) and are thus coordinate dependent. In many cases, particularly in biostereometrics, one is interested in shape rather than in coordinate values. But the coordinate dependent information visualized in the Moiré topogram is not easily and directly related to shape parameters. To extract true shape parameters the Moiré topogram has to be digitized and processed by a computer. An automatic image data acquisition seems to be more difficult for Moiré topograms than for rasterstereographies.

To illustrate these considerations, contour lines on a patient's back are shown in figs. 7 and 8 for two reference planes tilted by 10°. Although the shape remained the same the contour pattern is strongly influenced. These pictures were actually calculated from rasterstereographies using a Monte Carlo method.

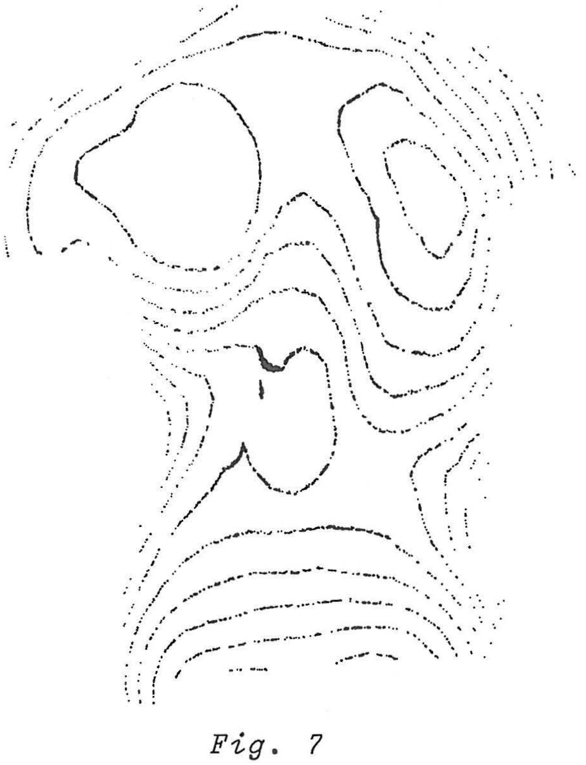


Fig. 7

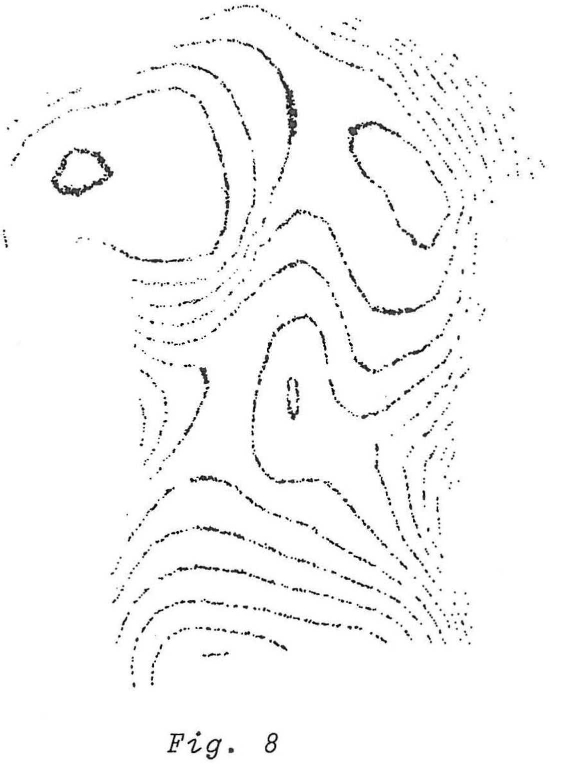


Fig. 8

Contour lines on a patient's back (reference planes tilted by 10°)

It is clear by intuition, that a description of shape can be achieved by those parameters, which are invariant under a three-dimensional translation and/or rotation of the surface as a whole. Consequently, the *surface data analysis* will in general consist in seeking for invariant shape parameters. In some cases also a comparison with a given standard shape may be adequate. Both procedures may be useful in biostereometrics.

There are two basic types of invariants: local and global ones. Global invariants are quantities like distance, angle, area or volume. The principal local invariant of a surface is its curvature. Both types of invariants may be calculated from rasterstereographies.

In recent years Kovâts (1) used a rasterstereographic technique to determine body volumes. Renner (2) employed a similar method for the computer design of tissue thickness compensators in radiation therapy.

Rasterstereography is particularly suited for a shape analysis using local invariants. For this purpose it is convenient to make use of the fact that by the projection of the raster lines a parametric representation of the surface is established in a natural way. That is, any surface point is associated with a row and column number (possibly by interpolation) and consequently with a coordinate pair in the raster diapositive plane. Therefore, the raster diapositive plane may be used as a parameter space in a two-parametric representation of the surface. Local invariants of surfaces are investigated in the best way by the methods of differential geometry, the equations of which are commonly expressed in parametric form. Due to the regular structure of the raster these relations may easily be accomodated for the evaluation of rasterstereographies. In contrast to this, difficulties arise if the equations of differential geometry should be applied to a random distribution of surface points.

From differential geometry it is known, that a surface may be characterized in any of its points by two local invariants, which may be calculated from the second derivatives of the coordinates with respect to the parameters. These invariants may be represented, for example, by the local curvature of the surface in two orthogonal directions. The appropriate formulae of differential geometry may - due to the discrete but regular structure of rasterstereographic measurements - easily be modified to construct an operator acting upon a 3 x 3 raster surrounding of a surface point to yield the aforesaid *principal* curvatures and directions.

In effect, the characterization of a surface by its curvatures is equivalent to an approximation to the second order in a 3 x 3 raster surrounding of any surface point. According to the limited number of second order surface types we can classify any surface point as planar, parabolic, elliptic or hyperbolic, corresponding to the local shape of the surface (fig. 9). In the case of a planar point (1st row of fig. 9) the surface is approximated by a plane with no curvature at all. In the parabolic case (2nd row) the surface is approximated by a cylinder, with one principal curvature (κ_2, last column) equal to zero; in an elliptic point both curvatures κ_1 and κ_2 are finite and of equal sign, whereas in the hyperbolic case the principal

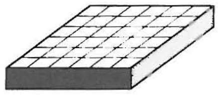
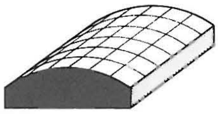
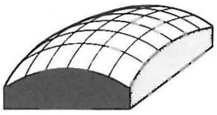
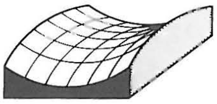
FLÄCHENFORM	BEISPIEL	KLASSE	KRÜMMUNGSMASS GAUSS K	MITTL. H	HAUPTKR. κ_1	κ_2
	EBENE	PLANAR	O	O	O	O
	ZYLINDER	PARA-BOLISCH	O	+(−)	+(−)	O
	KUGEL	ELLIP-TISCH	+	+(−)	+(−)	+(−)
	SATTEL	HYPER-BOLISCH	−	$-\infty \ldots +\infty$	−(+)	+(−)

Fig. 9: Classification of surface points by curvature (see text for explanations)

curvatures are of opposite sign (3rd and 4th row). A useful classification may also be obtained by the

Gaussian curvature $K = \kappa_1 \cdot \kappa_2$, and by the

mean curvature $H = (\kappa_1 + \kappa_2)/2$,

as displayed in columns 4 and 5 of fig. 9.

As an application the curvature analysis of the back shape of patients with spinal deformations such as scoliosis or kyphosis shall be performed. It is hoped, that from these studies conclusions can be made for diagnosis and therapy with reduced use of dangerous techniques such as radiography. As it is difficult to position a patient, especially in the case of deformations, in a unique and reproducible manner, the use of invariant properties is particularly important.

In fig. 10 the principal directions are represented by little crosses with the length of the crossbars proportional to the magnitude of the principal curvatures (the sign of the curvature could be displayed by different colours). Differently from the coordinate profiles (see figs. 7 and 8) the lines of constant curvature (principal, mean, or Gaussian) yield no satisfactory visualization of the surface curvature. However, if the surface is divided into different regions belonging to different ranges of curvature, these regions may be distinguished by different textures (fig. 11, mean curvature; fig. 12, Gaussian curvature), or by different colours.

It appears, that such a curvature analysis can be utilized to detect small asymmetries of the patient's back shape, which could possibly be related to spinal deformations in an early stage. Again it should be emphasized, that these data represent intrinsic shape properties of the back surface not related to any more or less artificial or arbitrary choice of a coordinate system, as it is the case e.g. for the profiles (figs. 7 and 8).

Although it might be difficult to establish definite relations between spinal deformations and the curvature of the back surface, it seems to be imperative to employ invariant quantities like the curvature to arrive at a reliable and significant shape analysis.

As already mentioned, a shape analysis may also be performed by comparison with a standard shape. Problems may then result from the necessity to relate a point in the test surface to each point in the surface to be analysed. Again it proves that a two-parametric representation as given by the rasterstereographic image evaluation is very appropriate to solve this question.

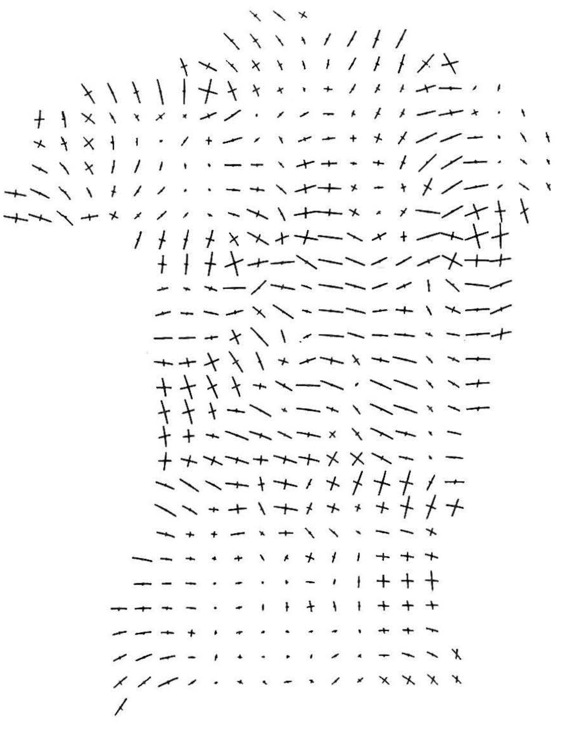


Fig. 10: Principal curvatures and principal directions

Fig. 11: Mean curvature

Fig. 12: Gaussian curvature

References: (1) *Kováts, F., Proceedings of the Symposium on Biostereometrics, Washington 1974*

(2) *Renner, W.D., Photogr. Eng. Remote Sensing, Vol. 43, No. 5, May 1977 pp. 581-591*