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Automatic Measurement of Body Surfaces Using Rasterstereography

Part I: Image Scan and Control Point Measurement*

The images are scanned and digitized, and digital image processing techniques are employed.

Introduction

Rasterstereography is a close-range photogrammetric method for three-dimensional measurement of body surfaces. It greatly resembles conventional stereophotography; however, one of the two cameras is replaced by a projector with a raster diapositive. Thus, the three-dimensional information is contained in the distortion of the projected raster lines in a single image. A detailed description of rasterstereography and its photogrammetric evaluation is given elsewhere (Frobin and Hierholzer, 1981; Frobin and Hierholzer, 1982).

Abstract: *Rasterstereography (using a projected grid) is a method for three-dimensional measurement of body surfaces. If a line raster is employed, the image structure of a rasterstereograph becomes particularly simple and is well suited for an automatic evaluation. In Part I of this work the automatic data acquisition including some preprocessing, i.e., image scanning, primary data reduction, and control point measurement, is described.*

In the subsequent Part II the image data evaluation, i.e., analysis of the rasterstereographic line pattern, is presented. As a result, a stereo image pair is obtained which is suitable for the usual photogrammetric calibration and model reconstruction.

Rasterstereography is particularly suited for the measurement of smooth and structureless surfaces of irregular shape, which often occur in biostereometrics. For example, the measurement of the human trunk shape for detection of deformations of the spinal column has gained increasing interest in recent years. Other examples are measurements of the foot sole or of articular surfaces. In such applications, especially in the case of medical screening investigations, a fast and easy image evaluation is essential. In this view, the simple structure of rasterstereographic images is very appropriate to an evaluation by hand as well as by automatic image processing. Because a rasterstereograph contains only well defined lines (and, eventually, control points), automatic processing is relatively uncomplicated, as compared to other methods of surface measurement such as stereophotography or moiré topography.

In the present work a method for automatic evaluation of rasterstereographs of the human back is presented. Although some special arrangements have been made for this application, the general method may well be adopted to other

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* Part II of this article will be published in a subsequent issue.

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tasks provided that proper modifications are applied.

The evaluation procedure presented here is restricted to rasterstereographs produced by a line raster. In general, any type of a raster, e.g., cross rasters, line rasters, or even point rasters, may be employed in rasterstereography. A line raster, however, seems to be the most favorable one, if automatic image processing is desired. The principle of line rasterstereography and some basic elements of an automatic evaluation have been published in a previous paper (Frobin and Hierholzer, 1981).

Any method of image processing consists of the basic steps of image data acquisition and data analysis. The data acquisition is, to a great extent, dependent on the technical equipment used for image scanning. Our method of image data acquisition, including some preprocessing, is described in the present Part I of this work. The image data analysis—consisting basically of a line pattern analysis in the case of rasterstereographs—is essentially independent of the particular type of data acquisition. It is presented in the subsequent Part II of this work.

LINE RASTERSTEREOGRAPHY

In Figure 1 a line rasterstereograph of the human back is shown. Based on the symmetry of the human body, we are using a perpendicular stereo base, and the raster lines are oriented horizontally. The raster is projected onto the body surface as well as onto "control planes" containing self-luminous control points. The control points are arranged in two planes. On the rasterstereograph they appear as small bright circles. In order to alleviate the evaluation procedure, the control points are surrounded by circular areas of black velvet. Thus, no intersection of raster lines with control points may occur.

FIG. 1. Line rasterstereograph with control points.

As pointed out in a previous paper (Frobin and Hierholzer, 1981), the raster lines must be individually identified for a three-dimensional surface reconstruction. This is effected by a unique pattern of light and heavy lines, as shown in Figure 1. Using a certain fixed origin, heavy lines are located, e.g., at 0, ±5, ±15, ±25 raster units in the diapositive plane. Thus, any line may be identified by its "absolute raster line number."

There are a number of features inherent in line rasterstereography which greatly facilitate automatic image evaluation or, more specifically, what is called image segmentation in digital image processing. In addition, in the present application some foreknowledge of the expected image structures may be used to further alleviate the procedure.

To reconstruct the body surface in three dimensions a line rasterstereograph has to be segmented into the following structures:

(i) Raster lines projected onto the surface to be measured.
In the general case of a curved and tilted surface these lines are curved and their direction differs from that of the original raster lines.
In the case of the back surface of a standing subject (Figure 1) the lines are more or less horizontal and their slope generally does not exceed an angle of about ±45°.

(ii) Raster lines projected onto the control planes.
These lines are straight, horizontal, and parallel to each other, if the standard geometry of rasterstereography is chosen. In the standard case the control planes are normal to a plane defined by the (intersecting) optical axes of the camera and the projector.

(iii) Control points.
The shape and size of the control points should be chosen such that they can easily be distinguished from dust particles, short line segments, and so on. We are using circles with a diameter of about twice the width of the heavy raster lines.

An important feature of line rasterstereographs is that the raster line images can neither branch nor intersect. If any branches appear, these must be due to false interconnections of different raster lines, which have to be cut in the evaluation procedure.

To separate the raster line systems (i) and (ii), some foreknowledge of the surface to be measured must be employed. It is, however, difficult to analyze a rasterstereograph of an object consisting only of planes parallel to the control planes.

The procedure of calibration and model reconstruction for line rasterstereographs has been discussed in a previous paper (Frobin and Hierholzer, 1982). For this procedure the x and y image coordinates of any point of the raster line system (i) must be measured. In addition, the absolute raster line numbers must be determined from the pattern of light and heavy lines.

Of line system (ii), in principle only the portions surrounding the control points are needed. However, to safely establish absolute line numbers also for system (ii), the whole system must be measured, too.

Of the control points, the x and y image coordinates of their centers are to be measured. In addition, the location within the line system (ii) of each control point must be known in terms of (interpolated) absolute raster line numbers (for more details see Frobin and Hierholzer, 1982).

To extract these data from a line rasterstereograph, the image is disassembled into a matrix of pixels each of which is associated with a gray value, as is usual in digital image processing. Due to the particular structure of line rasterstereographs, our procedure of image segmentation and data processing is somewhat different from the methods generally reported in literature. It must be noted that, in addition to an error-free pattern recognition, a measurement with photogrammetric accuracy is absolutely required in order to obtain a useful surface reconstruction.

The whole procedure of automatic surface measurement consists of the following steps:

(1) Rasterstereographic record
(2) Image scan
(3) Control point measurement
(4) Raster line pattern analysis
(5) Calculation of true image coordinates
(6) Calibration
(7) Reconstruction

Steps (1), (6), and (7) have already been described in previous papers (Frobin and Hierholzer, 1981; Frobin and Hierholzer, 1982). In the next sections, steps (2) and (3) are discussed in detail. Steps (4) and (5) are presented in the subsequent Part II of this work.

IMAGE SCAN

A short description of our method of image scanning has already been given by Frobin and Hierholzer (1981). As a consequence of the accuracy required, a conventional analog video camera with its large and irregular distortions is not very well suited for this purpose. On the other hand, solid state matrix cameras are available at present with insufficient resolution only, and they are expensive. Thus, we decided to use a solid state camera with a linear sensor which is oriented in the direction of the y image coordinate, and to scan the image in the x direction using a motor driven translator (Figure 2). This arrangement is, to some extent, equivalent to a matrix camera.

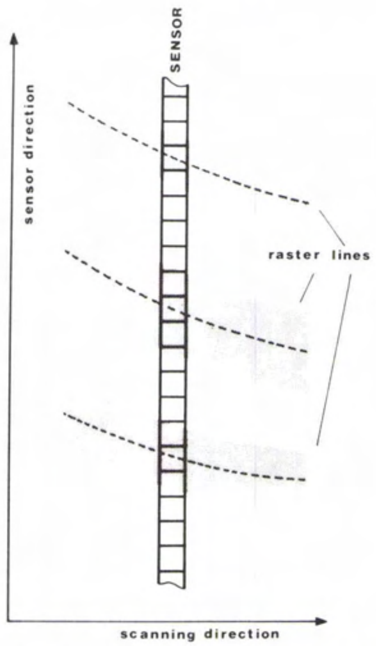

FIG. 2. Scanning of a line rasterstereograph using a linear sensor.

We are using an LC 100 line scan camera with 1024 sensor elements (manufactured by Reticon) and an EK 8b translator with an MS 12 motor control unit (manufactured by Märzhäuser, Wetzlar, Germany).

The line scan camera and the translator are connected to a DEC PDP 11/45 computer by means of an AR 11 analog interface without any additional control electronics (Figure 3). The arrangement has been somewhat simplified as compared to our first design, outlined by Frobin and Hierholzer (1981). Computer control of the light source proved to be unnecessary. However, it is useful to compensate for the uneven light distribution across the light source aperture. This may be effected by a simple shading filter composed of stripes of neutral density gelatine filters.

The optical design of the scanning device is shown schematically in Figure 4. As a light source,

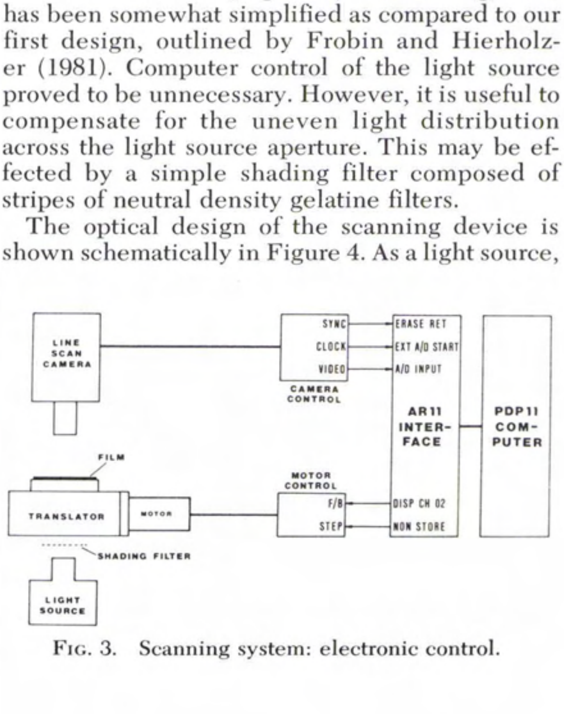

FIG. 3. Scanning system: electronic control.

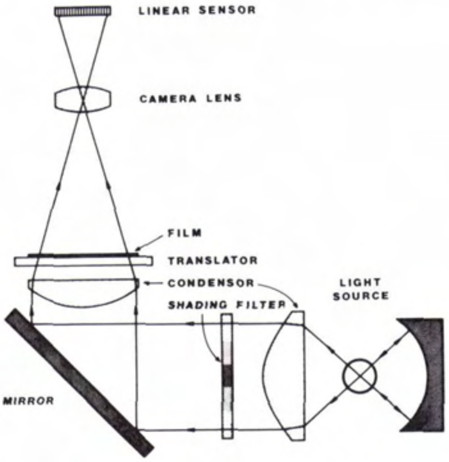

FIG. 4. Scanning system: optical design.

we are using a standard slide projector without projection lens (Leitz Prado Universal 250 W), where one of the two condensor lenses has been moved immediately under the film plane. The camera lens is a standard bellows macro lens (Asahi Pentax Bellows *f*:4/100 mm).

The control logic of the AR 11 interface (originally intended for graphic display control) is used to synchronize the camera electronics with the computer program (Figures 3 and 5). Once the camera readout subroutine is entered, the computer waits for the low-high transition of the camera *synchronization signal* (SYNC) *indicating* the beginning of a new camera cycle. The SYNC signal is sensed by a control input of the interface (ERASE RET, originally for display control). After the beginning of the camera cycle, an analog-digital conversion is initiated by the camera clock signal (CLOCK) which is connected to the external A/D start input (EXT A/D START) of the interface. The video signal of the first sensor element (pixel) is then digitized and stored in a memory location. The computer then waits for the second clock pulse to digitize the second pixel signal, which is stored in the next memory location, and so on. The subroutine exits after digitization of the last pixel signal.

If the LC 100 camera runs at its slowest speed, the clock signal has a frequency of 25 kHz. This is well below the limit of the AR 11 throughput (35 kHz for single channel operation). However, because all 1024 pixels must be digitized successively within a single camera cycle, the computer must not be interrupted during this period of time. Hence, a CPU latency of about 40 ms occurs during each camera readout, which may cause problems in multi-user operating systems. In this case, a better solution would be the use of double-buffering or direct memory access (DMA) which, however, requires additional electronic overhead.

In Figure 6 a camera readout of a line rasterstereograph is partially shown. The video signal contains peaks (resulting from raster lines and control points) and background noise. We chose our recording geometry such that the peak widths of light raster lines, heavy raster lines, and control points (central width) are approximately related as 1:2:4. These are effective widths as measured in the rasterstereograph. In order to compensate for line broadening in the imaging process, the original line widths in the raster diapositive have an increased ratio of 1:4 (light lines to heavy lines). Peaks 3, 4, and 5 in Figure 6 are light raster lines, peaks 1 and 6 are heavy lines, and peak 2 is a control point.

After each camera readout cycle, the translator is advanced one step in the x direction. In order to disassemble the image into square pixels, the step width should be fixed and equal to the sensor element spacing (converted into the film plane). The AR 11 interface control logic can also be used to control the translator motion. One digital output of the AR 11 (DISP CH 02) is used to preselect the direction of motion (forward/backward, or $+x/-x$) and another one (NON STORE) produces the starting pulse for the stepper motor control unit.

As a result of a complete scan, the image is disassembled into a gray matrix of, e.g., 1024 by 1024 pixels of 10 bits each. In general, it will be impractical to completely measure and store this

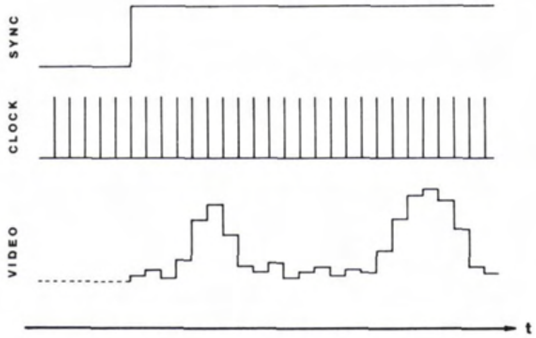

FIG. 5. Timing diagram of the line scan camera.

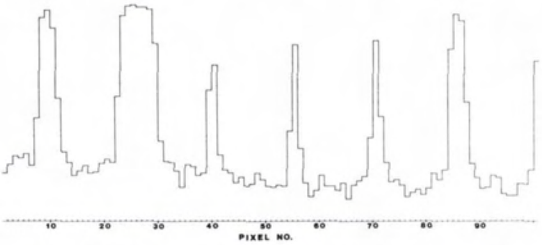

FIG. 6. Video signal of a line rasterstereograph.

large amount of data in a first step, and to analyze the image structures in a separate procedure. An early data reduction is mandatory.

We accomplished the data reduction by two different measures. First, it proved that, due to the relatively smooth shape of the raster lines (Figure 1), the sampling density along the raster lines (x direction) may be less by a factor of about four than at right angles to the lines (y direction). Thus, we utilize only every fourth column of the gray matrix. Second, in a preliminary procedure we analyze any camera readout (column of the gray matrix) immediately. As a result of this preprocessing, which is discussed below in more detail, only the position, width, and height of any valid peak in the video signal have to be stored. This may be considered as a first step in image segmentation: Separation of the information from background, thereby reducing the amount of data by a factor of about 10 to 20. In the subsequent analysis the raster line peaks of all camera readouts have to be reassembled to raster lines. This procedure will be discussed in detail in Part II of this work.

Using a reduced sampling density, the control points cannot be measured with sufficient accuracy. Thus, in a first scan only the raster lines and the approximate positions of the control points are measured. In a second scan, small windows around the control points are measured with full density. This is discussed in the overnext section. Of course, the reduced sampling density of the first scan must be high enough to hit every control point at least once in its central region in order to distinguish it from a heavy raster line.

Two remarks are necessary with respect to the image coordinates which are finally calculated from the image data and which are needed for the photogrammetric calibration and reconstruction procedure.

First, in most cases the resolution of a line scan camera with 1024 or even 2048 sensor elements is insufficient. However, by interpolation between the signals of adjacent pixels, the position of the maximum of a raster line peak, i.e., the line center, may be calculated up to a fraction of a pixel width. This is discussed in more detail in the next section. Similarly, the center of a control point can be calculated with relatively high accuracy (see overnext section).

Second, to accurately convert the primary data into true image coordinates, the scanning apparatus must be carefully calibrated. The calibration procedure is, to some extent, similar to single camera calibration in photogrammetry. In essence, the scale factor of the imaging system (film plane to sensor plane) and the angular position (tilt) of the film plane relative to the optical axis must be determined. We shall, however, not go into details of this calibration.

PEAK DETECTION AND ANALYSIS

As already shown in Figure 6, a readout of the line scan camera contains a number of peaks originating from raster lines and control points. In the primary analysis immediately following the camera readout, these peaks are discriminated against background, and their position (y coordinate along the sensor direction), width, and height are calculated.

Different criteria may be used to detect a peak in the video signal. In the present application the best choice appeared to be a combination of peak height and slope criteria. We define a valid peak as a sequence of a positive and a negative edge of sufficient height and slope. The peak position is then given by a point halfway between the points of steepest slope of both edges. The basic parameters for detecting a valid peak are visualized in Figure 7.

An edge is detected by testing the first deriva-

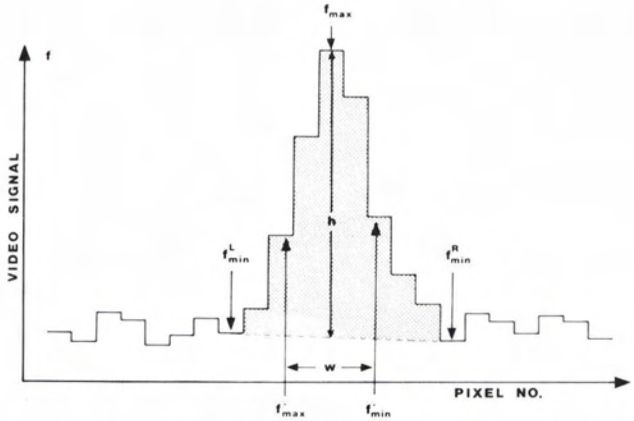

Fig. 7. Parameters for video signal peak detection.

tive of the signal. In the case of a digitized video signal the first difference quotient or (using the pixel width as a length unit) simply the first central difference

$$f'_{i+1/2} = f_{i+1} - f_i$$

of the signals f_{i+1} and f_i of pixels $i+1$ and i plays the role of the first derivative. In Figure 8 a peak and its first difference quotient are displayed. A local maximum $f'_{\max}$ or minimum $f'_{\min}$ in the difference quotient (slope) indicates a positive or negative edge in the original signal. If the absolute value of $f'_{\max}$ or $f'_{\min}$ exceeds a certain threshold, a valid edge is detected. The location of the edge is given by the point of steepest slope.

The height of the edge is determined by searching for the extremal values of the video signal f to the left and to the right of the point of steepest slope. That is, for a positive edge the left minimum, $f^L_{\min}$ in Fig. 7, and the right maximum $f_{\max}$ is searched. Similarly, for a negative edge the left maximum $f_{\max}$ and the right minimum $f^R_{\min}$ is searched. The edge height is then defined by

$$h^+ = f_{\max} - f^L_{\min}$$

and

$$h^- = f_{\max} - f^R_{\min},$$

respectively. An edge is discarded if its height is less than a preselected threshold.

A valid peak is then given by a sequence of a positive and a negative valid edge. Any unpaired edge, e.g., at the margin of the image field, is discarded. The peak position is defined as midway between the extrema in the difference quotient f'. The peak width w (Figure 7) is defined as the distance of these points. The peak height h is the mean value of the edge heights h^+ and h^-.

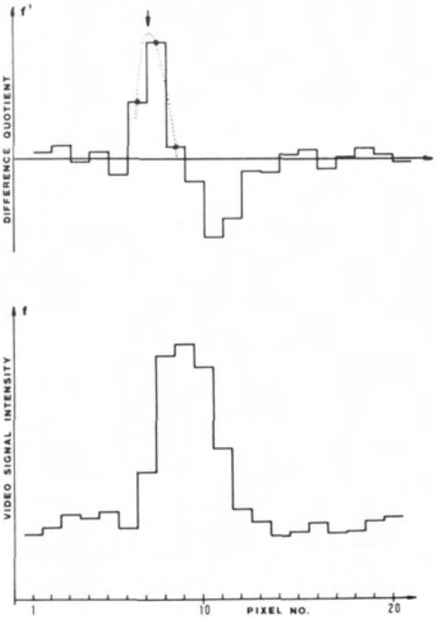

FIG. 8. Video signal peak and its first difference quotient.

For a photogrammetric evaluation of the rasterstereograph, an accurate localization of the peaks is crucial. Using the procedure described above, a position accuracy of one pixel width is available. As discussed in the preceding section, this is not sufficient in many applications. However, the position accuracy may be improved considerably, if the basic peak detection procedure is supplemented by an interpolation algorithm.

We proceed in the following way. If an edge, i.e., a local extremum $f'_{i+1/2}$ in the difference quotient is detected, a second order parabola is fitted through the extremum and its left and right neighbours $f'_{i-1/2}$ and $f'_{i+3/2}$, respectively (dashed curve in Figure 8). The location of the extremum of the parabola is considered to be the interpolated point of steepest slope. The peak position, width, and height are calculated in exactly the same manner as above.

From the results obtained with a 1024 element camera, we conclude that the position resolution is increased by a factor of 5 to 10 if such an interpolation algorithm is employed. The absolute accuracy is, of course, somewhat lower and depends on the constancy and uniformity of the sensor element sensitivity. The absolute accuracy may, for example, be increased by a careful calibration of each individual sensor element. Such a method has been reported by Röhler (1979).

The procedure of noise discrimination and peak analysis presented here is based on the special nature of the video signal as a step function. Because each pixel signal results actually from an integration over a small area of the image, the information and noise it contains is band-limited. In consequence of this, the first derivative (difference) is limited in amplitude and is, thus, suited for a threshold criterium. This is not the case, for instance, for a signal with virtually unlimited frequency bandwidth. In such a signal, high frequency noise may cause high peaks in the first derivative, which may not be attributed to real edges. Thus, it may even be difficult to use a high resolution camera for peak detection, unless some sort of spatial integration or smoothing (i.e., bandwidth reduction) is performed. A better solution would be to use a low resolution camera and to shift the camera in the sensor direction by a fraction of a pixel width after each camera readout. The image structures may then be calculated with increased accuracy using a digital deconvolution algorithm.

An important condition for the validity of the interpolation procedure discussed above is that the peaks extend over several sensor elements, as shown in Figures 6, 7, and 8. Evidently, the accuracy of peak localization increases with increasing number of contributing sensor elements, provided that the peak shape is known and constant (e.g., Gaussian, trapezoidal, or simply symmetric).

As a result of the peak analysis, each camera readout is reduced to a number of peaks the positions, widths, and heights of which have to be stored for subsequent analysis. Most of the peaks result from light and heavy raster lines. The data of these peaks are processed in the line pattern analysis which is presented in Part II of this work. If, however, a peak width exceeding a certain limit is detected, a possible location of a control point is found.

In Figure 9 a plot of all peaks and control point locations detected during the image scan is shown. The peaks are represented by dots whereas the (possible) control point locations are indicated by little squares. In the next section the exact measurement and identification of the control points is discussed.

Control Point Measurement

Due to the low sampling density during image scan, the control points can only roughly be localized. Therefore, at the end of the scan the translator is returned to its origin and any of the predetermined control point locations is scanned separately with full sampling density. That is, a partial gray matrix is measured in the surroundings of any control point location. For example, in the case of our rasterstereographic system the control point images have a diameter of about 0.3 mm on the film (see Figure 1). A window of 1 × 1 mm^2 (equivalent to about 20 by 20 pixels) was chosen for fine measurement around each control point location (Figure 10).

The gray matrix of each control point window must now be analyzed as to whether or not it contains a valid control point. In addition, the accurate position of the control point center must be calculated. Invalid control point locations are caused by broad peaks generated, e.g., by dust particles or heavy raster lines which are heavily inclined or broadened due to high inclination of the body surface. Furthermore, there may be control points which are partially hidden or cut off and which are, therefore, unsuitable for calibration.

In the first step of our analysis all pixels in a control point window are divided into "black" background pixels and "white" pixels (which may or may not belong to a valid control point). This is effected by using a threshold criterium determined, for instance, from the mean gray value in the window. Depending on the window size, "white" pixels may not only belong to a control point but also to residuals of raster lines (Figure 10). Thus, the "white" pixels must further be divided into valid control point pixels and invalid other pixels.

If the control point windows are chosen correctly, the valid control point pixels form a circular area completely isolated from the window boundaries. On the other hand, the raster line fragments intersect with the window boundaries. Thus, any "white" boundary pixel must belong to a raster line and is marked invalid. In the next step any other "white" pixel adjacent to an invalid "white" pixel is marked invalid, too. This process is called erosion in digital image processing. At the end of the erosion procedure any "white" pixel belonging to a raster line fragment has been eliminated.

To ensure that an isolated "white" area within the window is a valid control point, a simple size and shape analysis is performed. For this purpose the zeroth, first, and second moments of the intensity distribution of the "white" area are calculated.

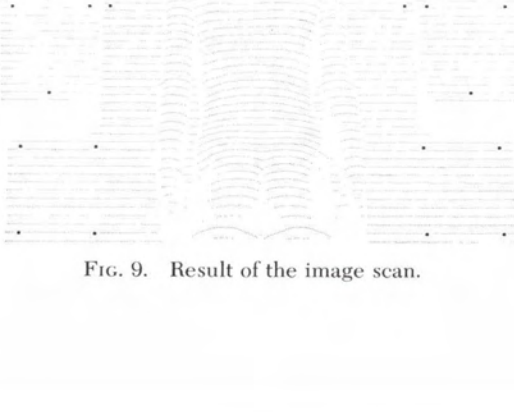

FIG. 9. Result of the image scan.

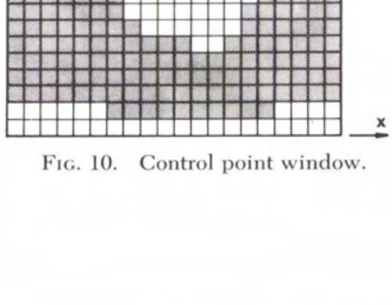

FIG. 10. Control point window.

The zeroth moment, or weight, is simply the area weighted with the intensity distribution. For a valid control point the weight must lie between certain limits.

The first moment has two components, namely, the coordinates of the center of gravity of the control point (relative to the lower left corner of the window). If these coordinates are added to those of the window corner, the accurate image coordinates of the control point are obtained.

The second central moment (corresponding to the moment of inertia of the intensity distribution, relative to the center of gravity) has four components, two of which are equal; i.e.,

$$\mathbf{M}_2 = \begin{bmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \end{bmatrix}$$

with $M_{yx} = M_{xy}$

The eigenvalues of this matrix are related to the half axes a and b of an ellipse which is best fitted to the intensity distribution of the "white" area. Thus, the ratio a/b, which should be equal to 1, is a measure for the circular shape of the control point. It must, however, be noted that any distribution with a fourfold point symmetry has also a ratio $a/b = 1$, for example, a square control point.

Using these criteria, a structure within a control point window is classified as a valid control point only if

- it does not touch the window boundaries,
- its intensity and size are within certain limits, and
- its shape is approximately circular.

For the photogrammetric calibration using control points with *a priori* known three-dimensional coordinates, any control point found in the rasterstereograph must be individually identified, e.g., by consecutive numbers. In general, an automatic identification is difficult unless individually shaped or marked control points are used. This is impractical in the case of a large number of control points. If identical control points are used, they may be identified only from their image coordinates which, however, depend on the orientation elements to be determined.

For this reason we chose a semi-automatic interactive procedure. In a first step, each control point is individually provided with its number by the operator. After "learning" this assignment, the program is able to automatically determine the control point numbers as long as the geometry of the rasterstereographic recording system remains approximately the same.

CONCLUSION

The automatic processing of line rasterstereographs consists of two basic steps: Image data acquisition and data analysis. In the present Part I of this work the image data acquisition, consisting of the image scan and some preprocessing, is discussed. As a result, raw data of the raster lines and of the control points are obtained. In the subsequent Part II the analysis of the line pattern of a rasterstereograph is described. This analysis is necessary before the final data processing using photogrammetric calibration and model reconstruction may be performed.

ACKNOWLEDGMENT

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