W. Frobin
E. Hierholzer
Orthopädische Universitätsklinik
Abteilung Biomechanik
D-4400 Münster, Federal Republic of Germany

Automatic Measurement of Body Surfaces Using Rasterstereography

Part II: Analysis of the rasterstereographic line pattern and three-dimensional surface reconstruction*

A complex analysis of the line pattern is necessary in order to determine absolute raster line numbers, which are required to convert the rasterstereograph into a conventional stereo image pair.

Introduction

In the preceding Part I of this work (Frobin and Hierholzer, 1983) the automatic scanning of line rasterstereographs was described. As a result of the image scan, x and y image coordinates of points on the raster line images ("raster line peaks") and of the control point images are obtained.

Abstract: *In the preceding Part I of this work the automatic scanning (including some preprocessing) of line rasterstereographs was described. In the present Part II the analysis of the rasterstereographic line pattern is presented. This analysis enables the conversion of a line rasterstereograph into an equivalent stereo image pair which is suitable for standard photogrammetric calibration and model reconstruction procedures. As a result a completely computerized three-dimensional measurement of body surfaces is obtained.*

The calibration and model reconstruction of a rasterstereograph is based on standard methods of stereophotogrammetry (Frobin and Hierholzer, 1981, 1982). However, in the case of rasterstereography the whole of the three-dimensional information is contained in a single image. In order to apply photogrammetric procedures, the rasterstereograph has to be converted into an equivalent stereo image pair. One of the two stereo half images is given by the rasterstereograph itself, which is produced by the camera of the rasterstereographic setup. The other half image is formed by the raster diapositive in the projector ("projector image").

We are now faced with the task of searching for corresponding points in this image pair. Only points lying on raster lines and control points are considered. Any raster line peak detected during the scanning of the camera image corresponds to a point on the appropriate line in the raster diapositive. For the photogrammetric evaluation, the x and y image coordinates of corresponding points have to be determined. In the camera image, the x and y coordinates of a raster line point are measured during image scan. In a line raster diapositive, one coordinate (y, normal to the raster lines) of the corresponding point is *a priori* known provided that the "absolute raster line number" is known. The other projector image coordinate (x, along the raster lines) is indeterminate and may only roughly be estimated from the geometry of the rasterstereographic setup. As pointed out in previous papers (Frobin and Hierholzer, 1981, 1982), only three of the four image pair coordinates must be known with high accuracy for photogrammetric model reconstruction.

* Part I of this article was published in the March 1983 issue.

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In essence, the search for a corresponding point in the raster diapositive is reduced to a determination of the absolute raster line number of any point measured in the camera image. This is effected by an analysis of the line pattern in the rasterstereograph. As already mentioned in Part I, the absolute raster line number is encoded in a unique pattern of light and heavy lines in the diapositive.

In principle, the absolute raster line numbers can be determined separately in any individual scan line, provided that an uninterrupted sequence of consecutive raster lines is hit by the sensor of the line scan camera. However, this is generally not the case, as demonstrated in Figure 1. A possible position of the camera sensor is indicated by the vertical solid line. Interruptions in the sequence of raster lines occur, e.g., in the case of regions with concave boundaries (waist region) and at the border line of different surfaces (shoulder region), as marked by arrows.

Thus, it is not sufficient to examine a one-dimensional section of the raster line system. The whole two-dimensional line pattern must be analyzed in order to correctly determine absolute raster line numbers. Our line pattern analysis consists of three basic steps:

- line search
- line sequence analysis
- line numeration

In the line search procedure the raster line peaks measured during image scan are reassembled to contiguous lines. In the line sequence analysis a topological order (i.e., a relative numeration) of the raster lines is established. According to this order and to the sequence of light and heavy lines, the line numeration in terms of absolute raster line numbers is performed.

For photogrammetric calibration, image pairs of

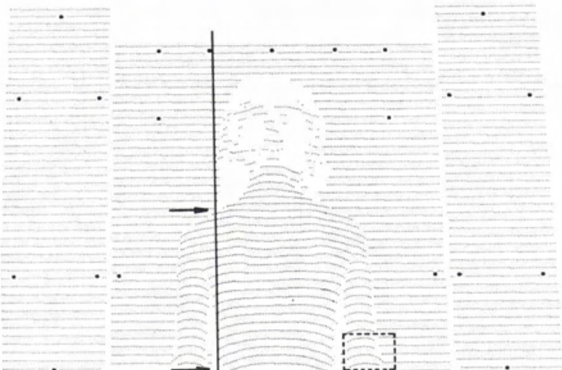

Fig. 1. Result of the image scan.

the control points are also needed. Because a control point generally does not coincide with a raster line, its corresponding projector image must be calculated by interpolation between the raster lines (Frobin and Hierholzer, 1982b). Thus, the positions of the control points relative to the raster line system must be determined in terms of "interpolated absolute raster line numbers."

As a final step, stereo image coordinates are calculated for each measured raster line point and for each control point. These image coordinates are then used as an input to the photogrammetric calibration and reconstruction programs.

Line Search

As a result of the image scan, the positions, widths, and heights of the raster line peaks in each scan line are known. The output of the image scan program is arranged such that, within each scan line, i.e., for fixed x image coordinate (translator position), the raster line peaks are ordered according to increasing y image coordinates. The scan lines, in turn, are ordered according to increasing x image coordinates. This ordering scheme is illustrated in Table 1.

The preambel contains the x image coordinate x_i (translator position) and the number of peaks N_i found in scan line i. The subsequent N_i data lines consist of the y image coordinates y_{ik}, widths w_{ik}, and heights h_{ik} of all peaks found in scan line i.

Because raster lines may begin or end in any scan line, the belonging of a peak to a specific raster line in the rasterstereograph may not directly be concluded from the peak data. For example, peak 1 in scan line 1 may or may not belong to the same raster line as peak 1 in scan line 2.

Therefore, the next task is to determine for each peak the raster line to which it belongs. That is, the peaks have to be reassembled to lines, and the lines have to be identified with respect to their original line number in the raster diapositive. However, to facilitate the procedure, the latter is deferred to the next steps of our evaluation.

Table 1. Primary Peak Data File

x_1, N_1	preambel	scan line 1
y_{11}, w_{11}, h_{11}	peak 1	scan line 1
y_{12}, w_{12}, h_{12}	peak 2	scan line 1
....	.	
....	.	
$y_{1N_1}, w_{1N_1}, h_{1N_1}$	*peak* N_1	scan line 1
x_2, N_2	preambel	scan line 2
y_{21}, w_{21}, h_{21}	peak 1	scan line 2
....	.	
....	.	
$y_{2N_2}, w_{2N_2}, h_{2N_2}$	peak N_2	scan line 2
....		
....		

Table 2. Classification of Raster Line Peaks

Peak Type	Abbreviation	Criterion
solitary	*s*	no *x* neighbor
beginning	*b*	right *x* neighbor only
end	*e*	left *x* neighbor only
internal	*i*	left and right *x* neighbor, weak bend
corner	*c*	left and right *x* neighbor, strong bend

As already mentioned in Part I of this work, the lines in a line rasterstereograph may neither branch out nor cross. Therefore, any raster line must have a unique beginning and a unique end. Any appearing branches and crossings must be erroneous, e.g., due to dust particles, etc. It will thus be possible to follow up any raster line in accordance with the translator steps of the image scan.

Any raster line peak may be classified according to its position within the pertaining raster line. Thus, we basically may distinguish five different peak types which are listed in Table 2.

In many applications one is concerned with surfaces which are, at least piecewise, smooth. Consequently, the raster lines are generally smooth, too, and corners may appear only in the case of surface edges or due to erroneous interconnections of virtually different raster lines. Depending on the application, such corners may either be classified in a separate class (c), or considered as a solitary peak (s) or as an internal peak (i). In our application—the measurement of the human body shape—sharp edges do not exist and all corner peaks are classified as solitary peaks.

It is evident that for the classification discussed above neighborhood relations between raster line peaks in several consecutive scan lines must be investigated. In order to classify a raster line peak in scan line i, we consider both adjacent scan lines $i - 1$ and $i + 1$ (Figure 2). According to the presence and position of neighbored peaks in the adjacent scan lines, five different types may be attributed to the raster line peaks in scan line i. The criteria used for this classification are listed in Table 2.

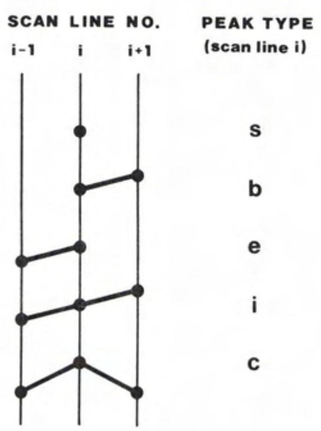

Fig. 2. Primary raster line peak classification.

The neighborhood of two raster line peaks in the scanning (x) direction is determined according to the following:

Definition 1:

Two raster line peaks are said to be x neighbored, if

(i) they are lying in consecutive scan lines i and $i + 1$

(ii) their y distance (first y difference) does not exceed a certain limit:

$$| y_{i+1,j} - y_{ik} | \leqq D_{\max}$$

(iii) there is no other peak in scan line $i + 1$ lying more closely to the peak at y_{ik} in scan line i, *and vice versa*.

Condition (ii) essentially prohibits false interconnections of different raster lines. $D_{\max}$ is dependent on the density and the maximum allowable slope of the raster lines in the camera image. Condition (iii) prohibits false branching and crossing of raster lines.

Because the scanning density (translator x step) is generally constant, it is sufficient to consider the y differences instead of true peak distances.

To distinguish corner peaks (type c) from internal peaks (type i), the peak positions in three consecutive scan lines must be considered (Figure 2). Assuming a constant scanning density, the bending angle of the raster line at scan line i is dependent on the second y difference according to the following:

Definition 2:

A peak in scan line i is called an internal raster line peak (type i), if

(iv) it has one right and one x left neighbor (conditions (ii) and (iii)).

(v) its second y difference does not exceed a certain limit:

$$| y_{i+1,j} - 2y_{ik} + y_{i-1,1} | \leqq A_{\max}$$

If condition (iv), but not (v), is fulfilled, the peak is called a corner (type c).

Depending on the treatment of corner peaks, the above classification of the raster line peaks may or may not be sufficient. If smooth surfaces such as the human body are considered, no real corners may appear in a raster line. Any such peaks must then be reclassified as solitary peaks. As a consequence of this, beginning or end peaks neighbored to a corner in the adjacent scan lines must eventually be reclassified as solitary peaks, too. In addition, depending on the configuration, neighbored internal peaks may be reclassified as beginning, end, or solitary peaks.

The final classification is performed in two steps. In a first step the peaks are classified according to the five types described above using three consecutive scan lines (small letters). As a result, for a peak in scan line i there are altogether 17 possible configurations of primary classifications in three consecutive scan lines $i - 1$, i, and $i + 1$, as listed in Table 3.

Evidently, for the final classification of a peak in scan line i, a total of five consecutive scan lines ($i - 2$, $i - 1$, i, $i + 1$, $i + 2$) must be considered.

If any corner occurs, the final classification (capital letters) differs from the primary one (small letters). Because all corners are reclassified as solitary peaks, there are only four different final types of raster line peaks (B, E, I, S).

If corners are considered to be valid parts of the raster lines, the simple classification according to Figure 2 and Table 2 is sufficient.

As noted earlier, any valid raster line must have a unique beginning and a unique end. Hence, if a beginning peak (Type B) is detected, a new raster line has been found in the image. Using the definition of x neighborhood given above (Definition 1), the raster line may be followed up scan line by scan line across the image until an end peak (type E) is detected. By that, all raster lines contained in the rasterstereograph may be detected.

TABLE 3. FINAL PEAK CLASSIFICATION FOR SMOOTH SURFACES

Primary Classification in Scan Line $i - 1$	i	$i + 1$	Final Classification in Scan Line i
	s		*S*
	b	*e*	*B*
	b	*i*	*B*
	b	*c*	*S*
b	*e*		*E*
i	*e*		*E*
c	*e*		*S*
b	*i*	*e*	*I*
b	*i*	*i*	*I*
b	*i*	*c*	*E*
i	*i*	*e*	*I*
i	*i*	*i*	*I*
i	*i*	*c*	*E*
c	*i*	*e*	*B*
c	*i*	*i*	*B*
c	*i*	*c*	*S*
(any)	*c*	(any)	*S*

For the purpose of identification, any detected raster line is provided with a preliminary raster line number. Every time a peak of type B is found, a new raster line number is "opened." Any peak in the sequence of scan lines belonging to this same raster line (according to the x neighborhood criterium) is labeled with the preliminary raster line number. The raster line number is "closed" if a peak of type E is detected.

As an illustrative example, in Figure 3 the result of the peak classification and line search procedure is shown for an enlarged detail of Figure 1 (dashed rectangle). Peaks belonging to the same raster line are connected by a dash. According to the detection of their beginning (B), the raster lines are equipped with preliminary raster line numbers in ascending order. For example, at scan line 0 the beginning of three raster lines (1, 2, 3) is discovered. They are numbered in accordance with their y coordinates. The next raster line (4) beginning is found at scan line 1, raster lines 5 and 6 are found at scan line 15, and so on.

In Figure 3 a complete peak classification is given only for raster lines 1 and 8. At scan line 17 a corner (c) is detected. Taking into account the peaks in scan lines 15 to 19, the corner is later reclassified as a solitary peak (S) and the direct neighbors are changed from internal (i) to end (E) and beginning peaks (B), respectively. Thus, a wrong interconnection of raster line 1 with raster line 8 is avoided.

However, a false interconnection with a small bending angle cannot be discovered at this stage of the evaluation procedure. Such an interconnection may be cut off in the line sequence analysis (next section).

As a result of the line search, any peak in the original scanning output (Table 1) is provided with two additional data, namely the peak type t_{ik} (B, I, E, etc.) and a preliminary number n_{ik} of the raster line to which it belongs. The format of the extended data file is shown in Table 4.

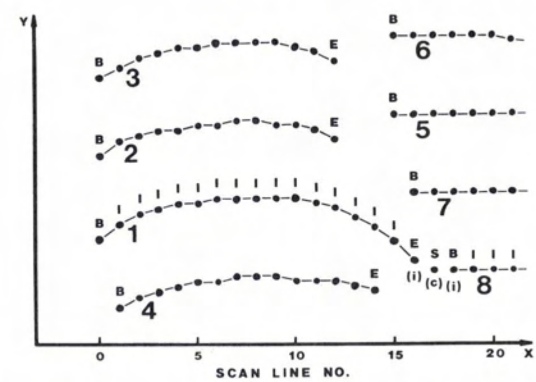

FIG. 3. Result of peak classification and line search for an enlarged detail of Figure 1 (dashed rectangle).

TABLE 4. EXTENDED PEAK DATA FILE

x_1, N_1	preambel	scan line 1
$y_{11}, w_{11}, h_{11}, t_{11}, n_{11}$	peak 1	scan line 1
$y_{12}, w_{12}, h_{12}, t_{12}, n_{12}$	peak 2	scan line 1
....	.	
....	.	
$y_{1N_1}, w_{1N_1}, h_{1N_1}, t_{1N_1}, n_{1N_1}$	peak N_1	scan line 1
x_2, N_2	preambel	scan line 2
$y_{21}, w_{21}, h_{21}, t_{21}, n_{21}$	peak 1	scan line 2
....	.	
....	.	
$y_{2N_2}, w_{2N_2}, h_2N_2, t_{2N_2}, n_{2N_2}$	peak N_2	scan line 2
....		
....		

The procedure described above may be regarded as a segmentation of the rasterstereograph into the raster lines, each of which is composed of a series of points (raster line peaks).

LINE SEQUENCE ANALYSIS

During the line search procedure, the raster line peaks are examined with respect to their neighborhood relations (x neighborhood). In the line sequence analysis the neighborhood of entire raster lines which have been found during line search is investigated. The method is, to some extent, similar to that of the preceding section, but—in consequence of the large number of topological line configurations—considerably more complicated.

From Figure 3 it is evident that, from the preliminary numbers of the raster lines, nothing can be concluded in regard to their neighborhood. In addition, consecutive raster line peaks within one and the same scan line may or may not belong to consecutive (i.e., neighbored) raster lines. For example, in scan line 1 (Figure 3) the first and second peak belong to neighbored raster lines (lines 4 and 1), whereas the first and second peak in scan line 16 (raster lines 1 and 7) do not. Thus, an intricate analysis of the topology of the raster line system is necessary.

To simplify the discussion, we start with some basic definitions. Obviously, the neighborhood of raster lines is related to the neighborhood of raster line peaks within one and the same scan line, i.e., in the direction of the y image coordinate. Thus, we may establish the following:

Definition 3:

Two raster line peaks are said to be y neighbored, if

(vi) they are lying in one and the same scan line
(vii) they immediately follow each other in the scan line (Table 1 and Table 4)

Because the peaks are ordered according to their y coordinates, the neighborhood is said to be directed. In the example mentioned above, the first two raster line peaks in scan line 1 as well as in scan line 16 are y neighbored.

With regard to entire raster lines, we establish another definition of neighborhood:

Definition 4:

Two raster lines are said to be neighbored, if

(viii) there is an interval in the x (scanning) direction extending over scan lines i through k, where the pertaining raster line peaks are y neighbored (according to Definition 3).

Neighbored raster lines are said to form a neighborhood interval. For example, in Figure 3 the raster lines 4 and 1 are neighbored in the interval from scan line 1 to scan line 14.

If a neighborhood interval is produced by two consecutive lines in the original raster diapositive, it generally corresponds to a stripe on the measured surface which lies between two projected raster lines. There may be other invalid neighborhood intervals which do not correspond to real surface stripes. It is the aim of the line sequence analysis to order the measured raster lines according to valid neighborhood intervals.

Neighborhood intervals are investigated by examining the extended peak data file (Table 4) which contains the peak type and the preliminary raster line number. If the beginning of a raster line (peak type B) is detected in a scan line, then the presence of a y neighbored raster line peak (Definition 3) is tested. If a y neighbored peak is found, then a new neighborhood interval is opened. The neighborhood interval is continued in successive scan lines until the end of one of the two participating raster lines (peak type E) is encountered.

For example, in Figure 3 a neighborhood interval consisting of raster lines 1 and 2 is opened in scan line 0. At the same time, another interval is opened

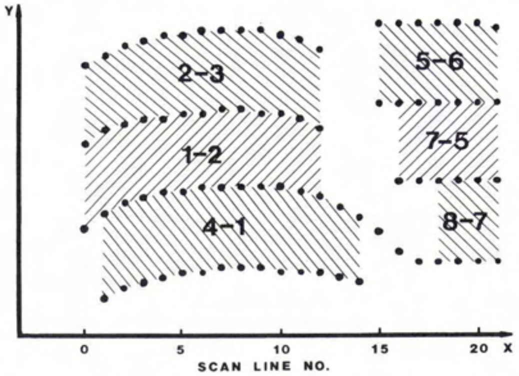

FIG. 4. Valid neighborhood intervals of Figure 3.

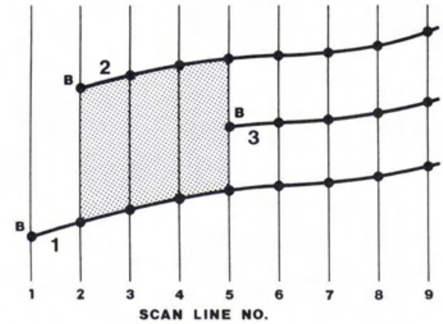

FIG. 5. Example of an invalid neighborhood interval.

for raster lines 2 and 3. In scan line 1 a new interval is opened for raster lines 4 and 1. These intervals are continued up to scan line 12, where intervals 1–2 and 2–3 are closed. Interval 4–1 ends at scan line 14. In Figure 4 the neighborhood intervals of the raster lines of Figure 3 are indicated by the shaded areas.

The beginning, continuation, and end of a neighborhood interval is controlled by the peak type (*B*, *I*, *E*) taken from the extended peak data file (Table 4). Of course, only peaks bearing the same preliminary raster line numbers are taken into account. Solitary peaks (*S*) are discarded.

Using the simple scheme outlined above, an error-free evaluation is possible only for plain raster line configurations. Several precautions must be made in order not to establish invalid neighborhood intervals. For example, in Figure 3 no valid interval should be opened at scan line 15 between raster lines 1 and 5, or at scan line 16 between raster lines 1 and 7.

To eliminate these and other cases of invalid neighborhood intervals, we established a number of validity conditions. The detailed procedure is rather intricate and may only roughly be outlined here. In addition, certain details are somewhat dependent on the application and on the geometry of the rasterstereographic recording and scanning system. Appropriate modifications must be applied if necessary.

As already mentioned, the neighborhood between two raster line peaks is directed. The same holds for entire raster lines, because they neither branch nor cross each other. Thus, any raster line participating in a neighborhood interval may be a "source" or a "sink" of the neighborhood relation. We note that, according to the geometric structure of a rasterstereograph, a raster line may be a source or sink of only one neighborhood relation at a time, i.e., at the same scan line (a raster line may, however, have different neighbors at different scan lines).

For example, in Figure 5 a neighborhood interval is opened between raster lines 1 (source) and 2 (sink) at scan line 2. At scan line 5 new intervals are opened between raster lines 1 and 3 and between 3 and 2. Raster line 1 would now become a double source which, however, is not possible. Therefore, the neighborhood interval 1–2 is forced to close at scan line 4. Subsequently, it is marked invalid (shaded area).

By this procedure, a correct ordering of raster lines and surface stripes is achieved even if intermediate raster lines emerge (e.g., in the case of concave surface outlines). Similar measures are taken for other invalid intervals occurring, e.g., at the end of raster lines.

During the follow-up of a neighborhood interval across the rasterstereograph, a number of parameters is calculated which characterize the neighborhood and the participating raster line sections. These data include

(i) beginning x_b and end x_e of the neighborhood interval (in terms of scan line numbers or x coordinates),
(ii) mean y coordinate y_m,
(iii) standard deviations σ_1 and σ_2 of the participating raster lines from a straight line,
(iv) mean slopes a_1 and a_2 of the raster lines,
(v) mean distance d_{12} of the raster lines,
(vi) standard deviation σ_{12} of d_{12}, and
(vii) mean ratio q_{12} of the raster line widths (instead of the line width the peak area, i.e., the raster line width times peak height may be employed).

To calculate the parameters (ii) to (vii), only the raster line peaks within the neighborhood interval (i.e., the raster line section between x_b and x_e) are taken into account, even if the raster line extends over its limits. By this procedure false interconnections between different raster lines are automatically cut in most cases.

Every time a (valid or invalid) neighborhood interval is closed, the interval data are entered into a neighborhood table using the format of Table 5. Invalid intervals are marked with an asterisk.

The line sequence analysis may now be per-

TABLE 5. NEIGHBORHOOD TABLE OF FIGURE 3

Neighborhood Interval No.	Validity Flag	Source Raster Line	Sink Raster Line	x interval		Interval and Raster Line Parameters							
				Begin	End	y_m	σ_1	σ_2	a_1	a_2	d_{12}	σ_{12}	q_{12}
1		1	2	0	12	...	...	...	...	...	...	...	...
2		2	3	0	12	...	...	...	...	...	...	...	...
3		4	1	1	14	...	...	...	...	...	...	...	...
4	*	1	5	15	16	...	...	...	...	...	...	...	...
5		5	6	15	21	...	...	...	...	...	...	...	...
6	*	1	7	16	16	...	...	...	...	...	...	...	...
7		7	5	16	21	...	...	...	...	...	...	...	...
8		8	7	18	21	...	...	...	...	...	...	...	...

formed using the data contained in the first columns of Table 5. Any valid neighborhood interval corresponds to a surface stripe limited by two consecutive raster lines (with a certain overlap in the x direction). The whole surface may be built up from adjacent stripes having a common raster line (and an x overlap). For example, intervals 1 and 2 in Table 5 are adjacent because the sink of interval 1 (raster line 2) is the source of interval 2. The common x interval (overlap) extends from scan line 0 to scan line 12.

Because we are dealing with directed neighborhood relations, we arrive at a directed sequence of adjacent surface stripes. Such a directed sequence is established by a path through the neighborhood table. This may be represented by a topological graph the elements of which are the neighborhood intervals. Depending on the position within the line sequence graph, the intervals may be divided into start, internal, and end intervals. In addition, because a neighborhood interval may be adjacent to several other intervals (in different x ranges), the graph may contain branches or crossings denoted as nodes. Depending on the neighborhood direction, a node may be a forward node, a backward node, or both. This is visualized in Figure 6. In Figure 6a a sequence of neighborhood intervals (surface stripes) is shown. The corresponding line sequence graph is shown in Figure 6b. In this graph, the nodal neighborhood intervals are represented by small circles, whereas internal intervals are indicated by short lines. The neighborhood relations are represented by directed lines.

To construct a complete line sequence graph, all start, end, and nodal intervals must be determined from the neighborhood table (Table 5).

A start interval is an interval the source raster line of which is not the sink of another interval. For example, neighborhood interval 3 in Table 5 is a start interval because its source (raster line 4) does not appear in the sink column of the table. Similarly, an end interval has a sink raster line which does not occur in the source column (e.g., interval 2). A forward node of multiplicity $n > 1$ has a sink which occurs n times in the source column, and the reverse holds for a backward node. Any other neighborhood interval is denoted as internal.

Once the start, end, node, and internal intervals are determined from the neighborhood table, segments of the line sequence graph, consisting of plain unbranched sections between consecutive nodes or start/end intervals, are constructed. For example, the graph in Figure 6b consists of four segments.

After having built up all segments, the complete graph may be constructed by joining the appropriate segments at their ends (nodes). Again, the preliminary raster line numbers of Table 5 (source and sink line numbers) are used to decide which segments have to be joined at a node. As a result, we obtain a topological description of the raster line

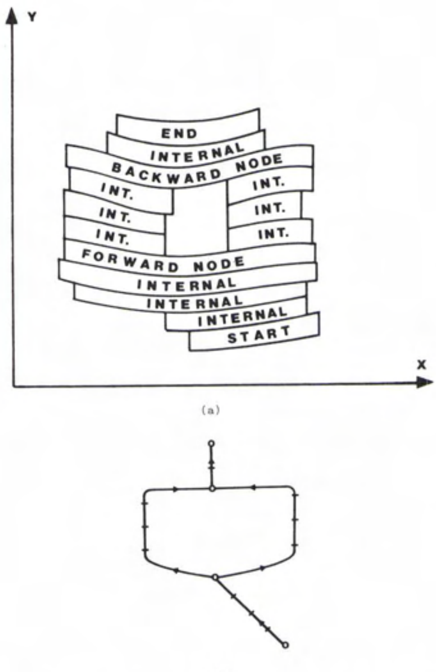

FIG. 6(a). Adjacent neighborhood intervals. (b) Line sequence graph of Figure 6a.

system (generally consisting of several separated graphs). For example, the rasterstereograph (Figure 1) is represented by the line sequence graphs shown in Figure 7 (somewhat simplified; internal intervals within the segments are partially represented by numbers instead of short lines). Due to interruptions of the raster lines in the surroundings of the control points, the topology of the graphs is rather complicated.

An important measure has been taken to separate the graphs pertaining to the control planes from those of the patient's body surface. In the last columns of Table 5 several characteristic parameters of the neighborhood intervals are listed. Testing these parameters enables a distinction to be made between straight horizontal lines on the control planes and curved lines on the patient's body. The straightness may be determined from σ_1 and σ_2. Their mean slope and parallelity is given by a_1, a_2, and σ_{12} (variance of their mean distance d_{12}).

Thus, the neighborhood intervals may be divided into those which are bounded by two straight raster lines (*S*-*S*), by two curved raster lines (*C*-*C*), and mixed types (*S*-*C* and *C*-*S*). In the line sequence analysis the mixed types are generally discarded in order to separate straight line graphs from those belonging to curved raster lines. In fact, the *S*-*C* and *C*-*S* intervals do not correspond to a real surface stripe, but occur at the boundaries of the body surface to be measured. In Figure 7 the graphs containing straight or curved lines are marked with *S* or *C*, respectively.

As a result of the line sequence analysis, the measured raster lines or, more exactly, the surface stripes between two consecutive raster lines are brought into a correct sequential order. This is essential for establishing absolute raster line numbers, which will be discussed in the next section.

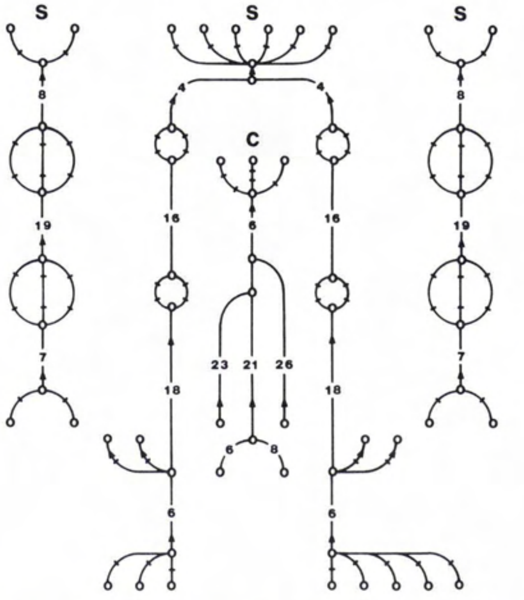

FIG. 7. Line sequence graph of Figure 1 (simplified). S = straight line graphs (control planes). C = curved line graphs (body surface). Intermediate (internal) neighborhood intervals are indicated by dashes or numbers.

LINE NUMERATION

In any topological graph constructed during the line sequence analysis, the surface stripes and their bounding raster lines are arranged in their natural order. In other words, any raster line is furnished with a relative ordinal number which is, except for an unknown offset, equivalent to the absolute raster line number needed for photogrammetric calibration and reconstruction.

The correctness of the relative numeration may be tested by comparing the numbers of intermediate (internal) neighborhood intervals in different segments between the same two nodes in the line sequence graph (Figure 7).

The absolute raster line number is determined from the sequence of light and heavy lines in the rasterstereograph. In the last column of Table 5 the mean ratio q_{12} of the widths (or peak areas) of the two raster line sections participating in the neighborhood interval is listed. Because in our case the line widths are approximately related as 1:2, we expect a sequence of ratios such as

$$\ldots 1, 1, 1/2, 2, 1, 1, 1 \ldots$$

where the figures 1/2, 2 are repeated every 10 (or 5) raster lines (see Figure 1 in Part I). The ratio of line widths, instead of the line width itself, is taken in order to be independent of the imaging scale.

The absolute raster line number is determined in a least-squares procedure.

For any line sequence graph of the rasterstereograph (Figure 7) the expected nominal sequence of ratios is compared with the measured one which is taken from the last column of Table 5. Then the position of the heavy raster lines in the nominal sequence is shifted by one raster unit (i.e., the figures 1/2, 2 are shifted by one position). The shifted nominal sequence is again compared with the measured one. The correct absolute numeration of the raster lines is obtained at the least-squares minimum.

Due to the location of heavy raster lines at 0, ± 5, ± 15, ± 25, ± 35 raster units in our raster diapositive, a unique least-squares minimum (and hence an unique absolute numeration) is obtained, if a sufficiently long sequence of raster lines containing the heavy zero line is examined. Otherwise, an absolute numeration is not possible. However, if at least one heavy raster line is contained in the line sequence, the absolute line number may be determined from the mean y coordinate y_m of the raster line (Table

5), provided that the geometry of the rasterstereographic setup is approximately known.

A better solution would be obtained by using a raster diapositive with an irregular (non-periodic) distribution of light and heavy lines (e.g., a random distribution or an overlay of two different periods of heavy lines, for instance every 9^{th} and every 10^{th} line).

As a result of the line numeration procedure, the two raster lines of any valid neighborhood interval in Table 5 are provided with their absolute line numbers. Thus, a look-up table converting the preliminary raster line numbers (columns 3 and 4 of Table 5) into absolute line numbers may be set up.

Calculation of Stereo Image Pairs and Model Reconstruction

The calculation of stereo image pairs suitable for the photogrammetric treatment is now straightforward. Again, the extended peak data file (Table 4) is used. The x and y camera image coordinates are directly calculated from this table using the scan line number (translator x position) and the listed y positions of the raster line peaks (some corrections must be applied according to the geometry of the scanning system).

The x and y projector image coordinates (raster diapositive plane) are calculated as follows: For any peak in Table 4, the peak type is examined first. Solitary peaks (S) are discarded. For a valid peak, the preliminary raster line number is converted into an absolute number by using the look-up table mentioned above (preliminary line numbers which are not contained in this table do not belong to useful raster lines). The y projector image coordinate is then directly calculated from the absolute raster line number and the line spacing of the raster diapositive.

As mentioned earlier, the x projector image coordinate need only roughly be estimated. We are using the x camera image coordinate multiplied by a fixed factor which is estimated from the imaging scales of the camera and the projector.

In some situations a modification of the above procedure is required. As shown in Figure 3, false interconnections of different raster lines (with different absolute line numbers) may occur. In the case of a sufficiently smooth interconnection this may not be detected in the line search procedure, due to the absence of a pronounced corner (c). Two virtually different raster lines are then supplied with one and the same preliminary raster line number (in Figure 3, line 8 would become a part of line 1). However, the resulting neighborhood intervals (1–2 and 8–7 in Figure 4) are nevertheless separated and extend over separate x ranges (provided that false interconnections do not occur in several consecutive raster lines).

In this case a correct absolute numeration of the raster lines is still possible. The look-up table must then be organized such that, for one and the same preliminary raster line number, different absolute numbers are attributed for different x ranges.

In general, only the raster lines belonging to the surface to be measured (curved raster lines in the case of the human body surface) are converted into stereo image pairs. The straight lines on the control planes are only partially utilized to calculate image pairs of the control points.

The treatment of the control points, although basically not difficult, is rather complicated and will only briefly be outlined here. The x and y camera image coordinates are calculated directly from the control point data file (similar to the procedure for the raster lines).

To calculate the x and y projector image coordinates of the control points, an interpolation procedure is necessary. For this purpose, all raster line peaks in a rectangular window around each control point are collected from the extended peak data file (Table 4). Only peaks belonging to straight lines on the control planes are considered. From the look-up table the absolute raster line numbers of the straight lines may be determined. From the y position of the control point and from the straight line segments in the window, an "interpolated absolute raster line number," i.e., the y projector image coordinate of the control point, is calculated (for more details, see Frobin and Hierholzer, 1982, Part II). The x projector image coordinate is estimated as in the case of the raster lines.

The calibration and model reconstruction may now be performed as usual in stereophotogrammetry. In Figure 8 the back surface reconstructed from the rasterstereograph (Figure 1 in Part I) is displayed in perspective view. With regard to the original scan data (Figure 1), this figure is simplified and purged by omitting the control planes and also some dispersed raster line fragments which cannot be identified by their absolute raster line number. In addition, short raster lines and short neighborhood intervals (i.e., intervals with only short x overlap) have been discarded.

Summary

The automatic evaluation of line rasterstereographs consists of two basic steps: image scan and line pattern analysis. The latter is necessary in order to determine absolute raster line numbers, which are required to convert the rasterstereograph into a conventional stereo image pair. Because absolute raster line numbers cannot be determined during the image scan (described in part I of this work), a complex analysis of the line pattern is necessary.

The line pattern analysis is organized in a hierarchical manner. In the first step the raster line peaks measured in the image scan procedure (Table 1) are reassembled to raster lines by examining neighbor-

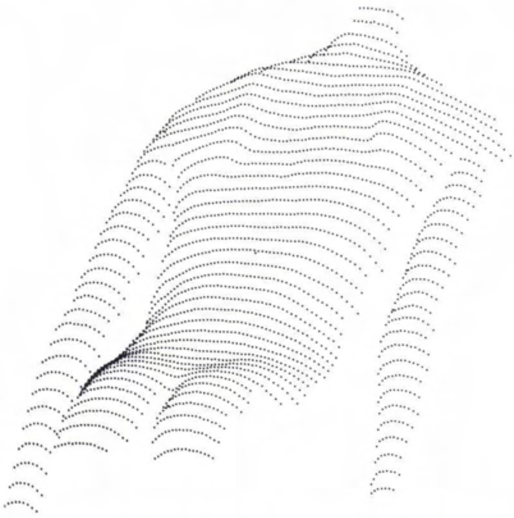

FIG. 8. Reconstructed body surface of Figure 1.

hood relations between raster line peaks in consecutive scan lines ("x neighborhood"). Any discovered raster line is identified by a preliminary raster line number (Table 4).

On the next hierarchical level, pairs of neighbored raster lines ("y neighborhood") are searched in the assembly of raster lines. Any such pair of lines is said to form a neighborhood interval which eventually corresponds to a real stripe on the measured body surface (bounded by two consecutive raster lines). Some characteristic parameters of the neighborhood interval and of the participating raster lines are calculated for identification purposes (Table 5).

On the next higher level, sequences of adjacent neighborhood intervals are assembled to segments which in turn are combined to line sequence graphs (Figures 6 and 7). Any line sequence graph represents a complete self-contained surface portion in the rasterstereograph (body surface, control planes). By comparing the sequence of raster line widths within each graph to that of the original raster diapositive, an absolute numeration of the raster lines is obtained. Using absolute raster line numbers, the rasterstereograph can immediately be converted into an equivalent stereo image pair.

It is a peculiarity of a hierarchical analysis that decisions, which cannot be made at one level, are deferred to the next higher level. It might then sometimes be useful to go back to a lower level and to reevaluate the data using some knowledge obtained at the higher level. Such a procedure is, however, rather circumstantial. If some preknowledge about the position and shape of the surfaces to be measured is introduced into the evaluation procedure, the vast majority of rasterstereographs may be evaluated without problems.

The computing time needed for the complete evaluation of a rasterstereograph is largely dependent on the surface size and the sampling density. In our application a computing time of 30 to 40 minutes on a DEC PDP 11/45 was needed. This time might still be reduced by optimization of the programs. Very large time savings (by a factor of 3 to 4) may be achieved by using a fixed rasterstereographic recording system. In this case, the calibration is performed separately and the control point system need not be recorded in the rasterstereograph (Frobin and Hierholzer, 1981). Hereby, the amount of image data to be processed is greatly reduced.

ACKNOWLEDGMENT

This work has been supported financially by the Deutsche Forschungsgemeinschaft.

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(Received 1 May 1982; accepted 16 May 1983)

Geosat Committee

The Geosat Committee will hold its final open Board of Directors meeting for 1983 on 4 November at 9:00 AM in Superior Oil's 24th Floor Exploration Conference Room, First City National Bank Building, 1001 Main Street, Houston, Texas. All persons interested in improving satellite remote sensing for geological applications are invited to attend.

For further information please contact

Ms. D. G. Park, Administrator
The Geosat Committee, Inc.
153 Kearny Street, Suite 209
San Francisco, CA 94108
Tele. (415) 981-6265