December 1974

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University of Pennsylvania

THE MOORE SCHOOL OF ELECTRICAL ENGINEERING

A GENERAL STRIP FINDER

Clayton Dane

A thesis submitted to the Faculty of The Moore School of Electrical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Engineering for graduate work in Computer and Information Sciences.

Philadelphia, Pennsylvania

December 1974
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December 1974

AUTHOR

FACULTY SUPERVISOR

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CHAPTER 1

INTRODUCTION

The main contribution of the work reported in this thesis is the extension of work done by R. Bajcsy and M. Tavakoli. A second, and less significant effort, is reported concerning the comparison of two biological images. The initial ideas for these investigations evolved during Dr. Bajcsy's "Vision Seminar" in the spring of 1974. Much of the implementation had to wait until the summer.

The smaller of the two investigations is a study of the feasibility of obtaining low level difference data. It involved the comparison of two biological images on a point by point basis. At the present time, this comparison is done for a few selected areas manually.

The main investigation involved the generalization of the road finder implemented by M. Tavakoli. The road is a special case of a strip-like structure. Other examples of specialized strips are blood vessels in biological images and tracks in bubble or spark chambers of high energy physics experiments. The road finder uses properties of the general strip; like connectivity, continuity of gray levels along the
length of the strip and the distinctive jump pattern associated with the width of the strip. In addition it uses specific information about roads. It makes assumptions about the maximum width, the rate of change of the width and the permitted change in direction. These additional assumptions permit quicker recognition of roads. However, they make the algorithm less suitable for finding other types of strips. The work reported here is an effort to avoid writing specific strip finders for each application. Admittedly, this general strip finder is a trade off between program development costs and problem run time costs. If large volumes of data sets are to be processed, then a specialized processor like the road finder should be developed.
CHAPTER 2

PREVIOUS WORK

A brief survey of the literature reveals interest in similar problems for many years. Edge finders and followers seem to have received more attention at first. However, line finders and followers appear to have a larger field of application. A strip finder would seem to be a nature extension to this work.

Roberts developed a primitive system of computer vision as early as 1963. It was heavily dependent on ideal data and unable to handle the noisy data of the real world effectively. His operator for detecting edges used only local information and produced a picture of edge points. These edge points were scanned and linked together to form lines. Pingle developed "A Program to Find Objects in a Picture" in 1966. The program used an edge detector to scan the picture and roughly locate an edge. After finding an edge, it stopped and examined the area in greater detail to locate the edge more precisely. The edge detector used a neighborhood of points as input. It
also estimated the direction of any edge detected. Using this information, a prediction about the edge's location some distance off was made. The algorithm then tried to verify the prediction.

Rosenfeld has been a constant contributor to the literature in the field of computer vision. He reported on some ideas in parallel processing edge detectors as early as 1969. The techniques seem to be aimed more at picture enhancement than at actual edge finding. He later gives a summary of some gradient operators for edge detection. Recently he reported on the "Detection of Step Edges in Noisy One-Dimensional Data".

Hueckel developed an operator for detecting edges in 1969. He used a larger neighborhood than Pingle or Roberts as input. Later improvements to the basic operator were reported in 1971 and 1973. He presents a strong mathematical basis for his operator.

Kelly developed an interesting means of edge detection in 1970. He used a traditional local edge detector and enhanced its operation by generating and using global information. First finding major edges in a reduced picture, the operator used this
information to guide it in the edge detection process of the full detail picture. In effect, the first pass looked at a defocused picture and the second pass looked at the focused picture.

Horn reported on a line finder developed for images containing polyhedra. A list of edge points were produced and a least squares fit was used on these lists in the line finding process. Martelli developed an edge detector which reduces the problem to finding an optimal path in a weighted graph.

Aharon Gill developed a corner-finder as part of his research into "Visual Feedback and Related Problems in Computer Controlled Hand Eye Coordination". He utilized ideas about both 'Gradient Followers' and 'Region Growers' in this finder. It computed an intensity histogram and threshold to distinguish regions. It located a boundary and followed it using a maze-solving type procedure. The operator also made use of as much prior information as soon as possible.

In 1973, Grape reported on a line finder which used Hueckel's edge detecting operator. The results of the edge detector were transformed into a list of
vectors that represented the direction and magnitude of the "Local Intensity Discontinuity". Horn's lists were built on the basis of proximity of points. Grape's lists were built on the basis of edge-pairs and not proximity. O'Gorma and Clowes reported on a finder using the collinearity of feature points. The method appears similar to Grape's method. They are both extensions of the Hough transformation described by Duda and Hart.

These basic finders and followers are used in many applications. They include character recognition, fingerprint analysis, map making and biological image analysis.
CHAPTER 3

THE ALGORITHM

A DEFINITIONS

A strip in visual terms may be considered a long narrow area that is differentiated from its background. There are generally two long edges of interest and the area is relatively homogeneous. How does this general description relate to properties one finds in digitized data? This is the starting point for the algorithm.

The primary property used to detect possible strips is the presence of a pair of complementing edges. This property is characterized in the data by a pattern of relatively high intensity values followed by low values, followed finally by high values again. The shape and size of this pattern may vary with the size and direction of the cross section, but the basic pattern is always there. It may be distorted when two strips meet. However, it remains the basic evidence for the suggestion that a strip is present.
NOTE

There is the assumption that the strip will have a lower intensity value than the background. In reality, it is possible that the strip may have a higher value. This case may be handled by an inverting process. The algorithm is limited to searching for one or the other, but not both at the same time.
More must be said about the edges. When looking at data, one sees a great difference in the type of edges. A sharp edge will have a single jump between two points. A less distinct edge will have this jump spread out over several points. This gradient of intensity can vary greatly. One must establish a threshold to separate the background from the strip. This threshold, or minimum jump in intensity, is required to distinguish between noise and the true strips.

A second property is that the intensity values are locally stable. This property is a result of the strips relative homogeneous nature. Cross sections located near each other will have similar intensity values at corresponding parts. There are many reasons why it is only locally stable. If the strip passes through an area where the illumination changes, one will find a change in the intensity of the strip also. As the strips width changes, it's intensity may vary. For example, in biological images an increase in the width of blood vessels means an increase in diameter. This also means an increase in the depth of the blood vessels which results in a 'darker' image.
The properties discussed so far relate to the physics of the strip's detection. Now it is time to classify the strip by geometric properties. A strip is long and therefore has a minimum acceptable length. Things not meeting this requirement might be considered spots or points or just noise. Likewise there is a minimum acceptable width. These parameters are not enough since a strip of width five is acceptable if its length is fifty. However, it is not if its length is only six. A length to width ratio helps resolve such seeming conflicts.

Another useful geometric property is the variation in width. The most restrictive case would be a strip of fixed width. A less restrictive case is where the strip's width is permitted to increase or decrease in a monotonic fashion. The least restrictive case is a strip whose width varies freely.
B INPUT

The input to the algorithm is the quantized values obtained by sampling the image intensity at 64 x 64 points. There are 64 quantization cells or gray levels. The area represented by one point is approximately a square. When the original data does not meet these criteria, it must be transformed by a preprocessor. The sample data used here had to undergo such preprocessing.

The user must also provide certain parameters about the strips that are to be found. The parameters the algorithm needs are

width

width to length ratio

range of acceptable gray levels

search grid density factor
The program refines the raw intensity data into a higher level data base. This data base has a structure made up of four basic elements which are the point, the strip, the junction, and the joint.

The Point

The point describes a location in the raw data and associates it with a group of points and a strip. It marks significant parts of the strip, for example, the end points.

The Strip

The strip is defined by a group of points, an average width, a length, a type of width restriction, junction associations, the number of segments and average slope. The type of width is

1 if the width is constant

2 if the width is monotonic increasing

-2 if the width is monotonic decreasing

3 if the width varies freely
A segment is part of a strip between two points. A strip may contain one or more segments.

The Junction

A junction is formed whenever three or more strips come together at one location. There are special cases where a junction may be formed when only two strips meet. The junction's location and a list of associated strips are kept for each junction.

The Joint

A joint is the means by which the list of associated strips for the junction is kept. It contains a pointer to a strip and a pointer to another joint.
SUMMARY OF BASIC DATA STRUCTURE ELEMENTS

POINT

1  Row coordinate
2  Column coordinate
3  Strip association
4  Pointer to other points
5  Local width

STRIP

1  Pointer to first point
2  Pointer to last point
3  Average width of strip
4  Length of strip
5  Type of width
6  Pointer to first point end junction
7  Pointer to last point end junction
8  Number of segments
9  Average slope

JUNCTION

1  Row coordinate
2  Column coordinate
3  Length of joint list
4  Pointer to first joint
5  Junction radius

JOINT

1  Pointer to associated strip
2  Pointer to next joint
A visual scene may be represented in the computer in many ways. One wants to represent the scene in a concise and meaningful manner. The eye will accept a graphic display of the data as a meaningful input. However, to communicate the information point by point for use by others is not convenient. The basic item of description, the point, does not convey a large amount of the total picture information. In this case, one point represents $1/(64 \times 64)$ of the total.

This algorithm translates the visual scene description from one representation into another one. It specifically takes a large amount of data with a low information content per basic unit of description and produces a smaller amount of data in a representation with a higher information content. The level of description has been raised by changing the representation. One is no longer concerned with individual points, but now one uses strips as the basic unit of description.
The description of the scene in the new representation is now much easier to communicate and use in a non-visual world. There is a price to be paid, however. The total amount of information has been selectively reduced. This fact has been long evidence by the observation "One picture is worth a thousand words."
Assume there is a searcher available that travels in a straight line and perpendicular to the strip's paired edges. Only local data is available to the searcher. As the edge of the strip is encountered, the searcher recognizes a change in the image intensity. This is followed by a section of similar intensity values. As the searcher crosses back into the background a second change of intensity occurs. This is a very accurate description of what one expects to find in picture data containing strips. However, the detection of one such pattern does not make a strip.

Assume further that one has the ability to start the search from any location and search in any direction. One may try to confirm a strips existence by searching in the same direction a short distance away from the initial pattern. If it is successful, then the known area of the possible strip has been expanded. The confirming evidence is established
using only the paired edge property. This procedure assumes that a strip is relatively straight and therefore it travels in a single direction. This is generally true in a local area, but it may not be valid globally for some fields of application.

The situation described above is ideal. The searcher always crosses the strip in a perpendicular direction. This is not always true in the real world because the strip's direction is not known in advance. The effect of the non-perpendicular crossings must be considered. Fortunately, the property for detecting a single edge is not effected. The only change is the apparent increase in the width of the strip. At crossing angles near ninety degrees, the apparent width is almost equal to the true width. At forty five degrees, the apparent width is about 1.41 times the true width. Finally, as the angle approaches zero degrees, the apparent width tends toward infinity. These observations are based on the geometry of the right triangle.

The procedure as described has several weaknesses. The paired edge property breaks down when two or more strips meet or intersect. At a typical Y junction, the procedure may stop or fail to detect one of the
strips depending on the amount of local width variation permitted. A second weakness is the assumption that strips are straight. Sharp turns cause the procedure to 'lose' the strip. How sharp the turn must be depends on the true width of the strip, the search/strip crossing angle and the maximum look ahead for the complementing edge of the strip once the initial edge is located. A turn of ninety or more degrees will lose the procedure regardless of the maximum look ahead or true width. Therefore, this procedure is good only for following strips locally. Pass one uses this procedure in conjunction with a global grid search.

The maximum look ahead is chosen to guarantee that strips with a search/strip crossing angle less than fifty degrees are detected. The global search procedure, searching in two perpendicular directions, will detect all strips. To combat the junction problem, the grid must be of appropriate size to assure that all strips are crossed at least once between all junctions. Too large a grid spacing and some strips may be lost. Too fine a grid and the processing time grows exponentially large.
The pass one output is a list of endpoints of possible strips. These local strip candidates are, by nature, small and are assumed to be straight and of constant width. Pass two attempts to combine them into larger structures. When several candidates fit together to form an enlarged structure, one has more confidence in saying it is a strip. The fitting together process assumes that if two endpoints are close enough, and the strips have similar direction, then they are part of the same strip. The cosine of the angle the two strips form is used as a measure of similar direction. A generalization of this assumption permits networks of strips to be formed. This lesser condition is if two or more endpoints are less than some distance from a point, then the strips are connected at that point. This is the basis for the processing in pass two.
CHAPTER 5

FIRST PASS

A THE PROCESS

A sequential method is used to extract the strips. A selected grid is traveled in search of preliminary indications of a strip. When the algorithm finds such an indication, it tries to confirm the strip's existence by enlarging it. The strip's enlargement is limited by the search grid size. If the strip is confirmed, it is recorded in a primary hit table.

This pass may be characterized as optimistic. It is designed to nominate all strips and maybe some candidates which are not truly strips. It depends on later passes to detect and reject the false strips.
B SUMMARY OF ROUTINES

FIND - Low level hi-low-hi (HLH) pattern recognizer

MRK - Mark HLH pattern in map array

SCAN - Executive for pass one conducting strip search

SLIM - Calculates look aside length for search

SSEA - Performs secondary search

SUMMARY OF ROUTINE RELATIONS

SCAN  
   |   FIND
   |   MRK
   |   SSEA  
   |       |   SLIM
   |       |   FIND
   |       |   MRK
C INPUT

The input to pass one is an array of intensity values representing a picture to be searched for strips. The user must specify several parameters to control the algorithm. It uses a minimum change of intensity value to detect significant edges. To limit some of the local search times, a maximum width of the expected strips parameter is used. Some areas of the picture will not want to be searched because they are too light or dark. A pair of numbers are input to bound the range of intensity values a strip must fall within. The size and area of the picture to be searched are specified by row and column limits. The grid size is controlled by the row and column increments.

D THE OUTPUT

The results of this pass are an array and a table. The array is similar in size to the input array of intensities. The output is a quasi-binary array that maps the results of the Find routine. A zero indicates no evidence of a strip was found. A
non-zero value indicates evidence of a strip was found. More specifically the value indicates which type of search was responsible for locating the indication. This map array was used to produce the pass one results. The following value relationships hold

<table>
<thead>
<tr>
<th>value</th>
<th>search</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Primary vertical</td>
</tr>
<tr>
<td>2</td>
<td>Secondary vertical</td>
</tr>
<tr>
<td>3</td>
<td>Primary horizontal</td>
</tr>
<tr>
<td>4</td>
<td>Secondary horizontal</td>
</tr>
</tbody>
</table>

The table is a set of strips described by ten numbers. It contains row and column coordinates of the four corners and the average intensity change of the edges at the ends of the strip segment.
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Row number of upper corner at end one</td>
</tr>
<tr>
<td>2</td>
<td>Column number of upper corner at end one</td>
</tr>
<tr>
<td>3</td>
<td>Row number of lower corner at end one</td>
</tr>
<tr>
<td>4</td>
<td>Column number of lower corner at end one</td>
</tr>
<tr>
<td>5</td>
<td>Average intensity change of edges at end one</td>
</tr>
<tr>
<td>6</td>
<td>Row number of the upper point at end two</td>
</tr>
<tr>
<td>7</td>
<td>Column number of the upper point at end two</td>
</tr>
<tr>
<td>8</td>
<td>Row number of the lower point at end two</td>
</tr>
<tr>
<td>9</td>
<td>Column number of the lower point at end two</td>
</tr>
<tr>
<td>10</td>
<td>Average intensity change of edges at end two</td>
</tr>
</tbody>
</table>
E ROUTINE DESCRIPTION

The FIND Routine

This routine is a very low level operator. It scans a line of data looking for a hi-low-hi pattern. This operation is the basic one used to detect a strip. The transition from hi to low or low to hi is controlled by a parameter which defines the minimum acceptable difference in intensity for this transition. Once the hi-low pattern is found, the maximum width of the strip is limited by an input parameter. In general, the search for the pattern is limited explicitly by boundary and incremental values and implicitly by two parameters which bound the range of acceptable raw data intensities. The pattern may also be checked for intensity continuity with other patterns previously found. When a pattern is found, its beginning and ending coordinates are reported along with the average value of the intensity change transitions. This routine has the capability to search in eight possible directions. However, only four directions are used currently.
The SSEA Routine

This routine conducts the follow up search for the continuation of a strip. After the SCAN routine finds an initial hi-low-hi pattern, SSEA attempts to follow and enlarge this into a strip within the local grid area. SSEA marks a 'map' with the location of the strip and also reports its coordinates in tabular form. It uses the routine FIND as a basic operator. It can search in only the four directions dictated by the SCAN routine.

The SCAN Routine

This routine builds from the raw intensity data a 'map' of strips and a table of their locations. The input parameters determine the area to be searched and the density of the primary search grid. They also determine the minimum jump threshold and bounds on the raw data values to be used by the routine FIND.

This routine conducts the primary search and upon finding a hit, it calls SSEA to verify and enlarge the strip. After the secondary search is completed, SCAN resumes the primary search. The user specifies which grid path is to be searched first, either horizontal
or vertical. The program performs best when the direction of the first path is perpendicular to the general direction of the expected strips.
TYPICAL PASS ONE PROCESSES

ORIGINAL DATA
AND
PART OF THE PRIMARY SEARCH GRID

FIGURE 5-1
SECONDARY SEARCH STRATEGY

FIGURE 5-3

REPRESENTATION OF PASS ONE TABLE RESULTS

FIGURE 5-4
A  Analog representation of the intensity along the search path
B  Calls to FIND
C  Hi-low Edge Search
D  Low-Hi Edge Search
E  Strips detected

EVENTS
1  Starting location of FIND on first call
2  Hi-low edge of strip detected
3  Low-hi edge of strip detected and starting location of FIND on second call
4  First return from FIND
5  Hi-low edge of strip detected
6  Low-hi edge of strip detected
7  Second return from FIND

THE FIND ROUTINE AT WORK

FIGURE 5-2
A THE PROCESS

Each strip candidate is compared to the existing strip network. If the network connects to the center of the candidate, it is split and added as two strips and a junction. If the network connects near the ends, it is added to the network as an extension of a strip. If the candidate does not appear to connect to the network, and it meets the requirements of a strip, it is entered as an independent strip. If it does not meet the requirements, it is placed in the rejection table.

There are times when a strip seems to connect to the network in a manner which is geometrically illogical. For example, both ends of a new strip are close enough to a point in the network to be connected there. This is generally not possible because the local following properties of pass one indicate that it can not track sharp turns. The algorithm
recognizes some of these situations; junctions the network point in question and places the strip candidate in the rejection table.

B SUMMARY OF ROUTINES

CORD  - Compute center line coordinates of strip
COMP  - Look for a connection between an end point and existing high level data (HLD)
CONEK - Add a strip to the existing HLD
DIST  - Compute distance between two points
DOAD  - Update HLD for dependent strips
ILOC  - Determine if a junction is required
LOC   - Compute junction location
NSTRIP- Add a strip to the HLD
SEPS  - Split a new strip if required
SLOPE - Compute average slope
STRUCT- Pass two executive
WALK  - Trace out points of a specific strip
WCOMP - Classify strips according to width
WIDTH - Compute strip width
SUMMARY OF ROUTINE RELATIONS

STRUCT
  CCORD
    WIDTH
    DIST
  SEPS
    WIDTH
    DIST
    LOC
  CONEK
    COMP
      WIDTH
      DIST
      ILOC
    NSTRIP
    DOAD
      LOC
      WALK
    NSTRIP

WCOMP
SLOPE
The input to pass two is the table output from pass one. Pass two does not use the map array in its processing. In addition to the table, there are several parameters.

Pass two uses a minimum length to width ratio, the grid size of pass one, a maximum width and a width tolerance. A scale factor of ten is applied to the grid size, maximum width and the width tolerance. The width tolerance is the acceptable amount of variation in the width for a strip to be considered of constant width. These parameters effect how the algorithm functions. In addition, there are some parameters which determine the maximum size of various data areas.

The output of pass two is divided into two kinds of results. The first is the refined data which has a structure described in chapter three section c. This data was input to a display routine to produce the skeleton figures. The second is a rejection table of
strip segments which pass two could not handle by itself. The rejection table has the same format as the input table for pass two.

E ROUTINE DESCRIPTION

The CORD Routine

This routine converts the boundary points in the primary hit table of the SCAN routine into skeleton coordinate format. This format, which represents the strip by its center line, is used in constructing the higher level data base. The routine computes the coordinates of the end points of the center line, corrected widths for the end points based on the direction of the strip and a length. The data is represented in integer format. In order to reduce roundoff errors, a scale factor of ten is introduced by this routine.

The SEPS Routine

This routine looks at the points existing in the data base in relationship to a new strip being added. Using the LOC routines, it determines if any points
are close enough to require that a junction be inserted. If this is the case, the new strip is split at the appropriate location and processed as two independent strips.

The LOC Routines

These routines determine the perpendicular distance between the center line of a strip and a point. One of the routines is used like a predicate. The other routine returns the coordinates of the point on the strip where the distance is measured from.

The COMP Routine

This routine looks at an end point of a new strip and determines if it fits into the existing geometric structure. There are three ways a new end point may fit in. It may be close enough to an existing junction to be associate with that junction. It may be near the end point of an existing strip, so the new strip may be added on as a continuation of the old one. Or lastly, the point may lie near the center line of an existing strip and a new junction is formed. The COMP routine decides how the new point will be processed.
The DOAD Routine

Once it has been decided how both end points of a new strip will be processed, the DOAD routine does the actual processing. Like COMP, this routine deals with three different cases and the routine is divided similarly. The information generated by COMP on how to process the end points is passed indirectly to DOAD after some extra information is added.

The CONEK Routine

This routine attempts to attach a new strip to the data base. It looks at both end points of the strip using COMP. It will add the strip to the data base if it can be connected and tell DOAD how to handle the process.

The SLOPE Routine

This routine computes the average slope of the strips after the network is complete. The slope is represented as an integer value using a scale factor of ten.
The STRUCT Routine

This routine asks CONEK to attach new strips to the existing data base if it can. If a strip can not be connected, it may try to rotate the center line ninety degrees. If this fails, STRUCT decides if the strip is large enough to stand alone.

The WCOMP Routine

After all the modifications to the HLD have been made, WCOMP examines each strip to determine its average width and width type. This is the last process before final output because modifying the network structure of the HLD effects this data. It is easier to compute it once at the end than to constantly update it during the modification process.
PASS TWO BUILDS THE NETWORK

FIGURE 6-1
RESULTS

Three test cases were chosen to evaluate the strip finder. Two cases used the same original intensity matrix as input but different minimum jump values for the edges. The third case used a different intensity matrix for input data. In all three cases, the data represented the brain of rats. The strip finder's job was to locate blood vessels. The noise level of the data is about one unit in sixty-four. That is to say, an intensity value of 32 in the matrix may have a true value as low as 31 or as high as 33. The table summary of input and output statistics used for each run are presented.

Pass One

The first major problem with pass one relates to the definition of strip. A strip is a long, narrow region. The pass one program has no concept of junction. Likewise, when there are many junctions and strips in a small area, strips become so interrupted
with junctions that part of the strip may look like a spot. The program does not know about special spots that connect junctions. Such spots are found in all the medical data used. For example, the upper large vessel is connected to a smaller parallel vessel in the middle of case A and B. For junctions, the program may function like the example given earlier if condition are right. The performance of the program depends to some extent on the primary search grid. The size and location of the grid should have as little effect on the performance as possible.

A second problem area is concerned with the use or lack of use of previous information. When the strip finder is trying to extent a strip segment, it uses information about point intensities to guide it. Given the same intensity data, strip searches from two different directions may find two different strip contours for the same strip. This fact is evidenced when two strip segments meet and have two different widths at the meeting location. This mis-match of widths is increased if one end of the segment was detected by the primary search. The primary search has no prior knowledge of the strip to guide it.
A third problem area appears when the noise level approaches the minimum intensity change at an edge. This is the situation for case B, where the noise is plus or minus one and the edge value is two. The local edge boundaries are very susceptible to location errors. One can never completely solve the noise masking problem. However, a better solution is needed here. A related problem is the rapid change of intensity in the strip that occurs sometime. This will cause the local width of the segment to change abruptly. The program has no means at present to effectively deal with these problems.

Pass Two

One encounters a problem immediately in pass two. At the beginning, the results of pass one are transformed from an area description format into a center line description format. Pass one generates information about strip segments and describes them as quadrilateral areas by entering the location of the four corners in a table. This table is the information pass two works on. The information about local width variations is saved in the map array only. It is not organized effectively and is not available to the pass
two program. The small grid size minimizes this lose of information at the expense of added effort to piece additional segments together. In addition, small grid size increases the difficulty of handling junctions correctly. The program was designed to deal with relatively long strips and occasional junctions at well spaced intervals.

This leads to a second problem area. When a junction is formed by pass one and the strips are transformed into the skeleton like center line format, the end points at the junction do not correspond exactly. They may vary up to the width of the widest strip at the junction. Typically, it may be two or three units of distance. The strip finder has the ability to resolve two parallel strips whose center lines differ by two units. The program has trouble sometime distinguishing between two closely spaced parallel strips and a junction. A third problem area involves the piecing together of the strip segments detected by different scans. As the search/strip crossing angle increases, the quadrilateral representing the strip is distorted. When two segments from different scans meet, the supposedly matching end points may vary greatly. This situation
is aggravated by the fact that in pass one, the scan which detected the second strip may have terminated prematurely before good contact was made. This premature termination occurs when the second search locates only one corner of the first strip. Pass two may just fail to connect them correctly or it may try to connect them geometrically wrong. In the second case, the program may discard the strips completely.

Interpreting the Graphic Results

The figures labeled 'Original Data' are generated directly from the point intensity matrix. A natural representation of the data is used. Dark areas in the original photographs appear as dark areas in the figures. The dark areas produce low positive numbers. The lowest possible value, or darkest area, produces zero as its intensity value. The dark areas are produced by over-printing several characters. The light areas in the original photographs produce high intensity values and appear as light areas. The brightest area possible produces an intensity value of sixty three. The blank is used to represent the lightest areas in the matrix.
The figures labeled 'Pass One Results' use the numeric code convention described in chapter five, section D. The figures labeled 'Pass Two Results' use the character '*' to represent the strips and the character '%' to represent the junctions. The print routine which produces the figures does not extend those strips connected to junctions. The result is a gap between the strip and its junction. In order to present a better graphic display, the strips have been extented by hand.

The statistic labeled 'Scan' refers to the direction of the initial scan of the primary grid. In these cases, the 'v' represents the vertical scan.
Table of Input Statistics

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<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
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<tr>
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<tr>
<td>Vertical</td>
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<tr>
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### Table of Output Statistics

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<tr>
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</table>
CASE B

ORIGINAL DATA

FIGURE 7-4
CASE A

PASS ONE RESULTS

FIGURE 7-2
CASE A

PASS TWO RESULTS

FIGURE 7-3
CASE B

PASS ONE RESULTS

FIGURE 7-5
Case C

Original Data

Figure 7-7
CASE C
PASS TWO RESULTS
FIGURE 7-9
Chapter 8

CONCLUSIONS

Pass One

The dependence of the pass one performance on the primary grid should be eliminated. This goal demands several changes in design and operation philosophies of the strip finder. A more accurate data structure to describe the output of pass one is required. A structure similar to the current final one seems more acceptable. Part of the data base could be built dynamically by pass one as the strip's paired edges are being detected. The equivalent of the current strip segments could be built at intervals and connected to preliminary strip nodes. The grid size could be reduced and the secondary search range extended without limit. The disadvantage of increased processing time for pass two is no longer a problem since pass one will have already linked some segments together. The reduced grid size would also insure fewer missed strips. The direction of the secondary
search could be modified during the search based on the direction of the last connected segment's direction. The detection of paired edges would be improved by the addition of information in two areas. To take advantage of the contrast/width relationship, the range of look ahead for the second edge of the pair could be computed on the basis of the contrast of the first edge. Secondly, the user could specify an acceptable tolerance for local width variation. It might take the form of a percentage of current width.

Pass Two

The importance of good input can not be over emphasized. The changes to pass one will help assure more accurate input to pass two. However, if it is to continue to work with skeleton like data, then a more reliable method of reduction is required.

While pass one may be more informed about the shape of strips and junctions, it remains pass two's job to develop the network using global information. Pass two will need more geometric information to handle medical data. The rejected strip segments should be reprocessed after all the data has been processed once. Some of these rejected segments may
now fit into the network.

General

No matter how good the strip finder is, there will always be situations that confuse it. Trouble areas could be localized and looked at in greater detail. Like a zoom camera and Kelly's silhouette finder, the strip finder's value could be increased greatly by the ability to see things in greater or lesser detail.
CHAPTER 9

A LOW LEVEL DIFFERENCE OPERATOR

This operator does a point by point comparison of two images. Two biological images were used at the request of the Medical School. They hoped to obtain two results from this operation. First, the elimination of the manual process currently being used to compare intensities. Secondly, it was hoped that texture patterns might be found in the difference data.

THE DATA

Two negatives of rat brain tissue under different experimental conditions were obtained from the Medical School. The negatives were sent to a local commercial laboratory where prints were made. These prints were digitized here at the Moore School. The full frame of $480 \times 256$ intensity points was not used. Two smaller areas or windows of interest were selected. The first window was $256 \times 192$ intensity points. The second and

-51-
smaller window was 92 x 64 intensity points.

THE OBJECTIVE

The main problem is the correct alignment of data. The computing of the actual differences is trivial. There are several factors causing the problems in this case. They are:

1 Experimental conditions

2 Photographic processing

3 Digitization processing

The experimental conditions involve physiological differences like the shifting in the shape of the jelly like cortex between pictures. The photographic process of developing and printing the pictures introduces rotational and translational shifts. Over or under development also effects the overall gray level and contrast of each picture. In general, the digitization introduces the same kinds of problems as the photographic processing.

The problems discussed above are concerned with shifts greater than the resolution of the data. It is highly likely that the optimal shift is not an
integer. There is always an inherent uncertainty that the points used to compute the difference do not represent the exact area in both pictures. In addition, local noise is reflected directly in the difference data. Therefore, the results of the point by point operation must not be taken as absolute.

THE METHOD

Rotational Shifts

There is no simple technique to correct for rotational. Most mathematical methods for approximating functions are based on the assumption of continuity. However, a picture function is highly discontinuous. A technique using such a method would seriously degrade the information content of the picture. No attempt was made at this time to have the computer correct for rotational shifts. Careful preprocessing and the use of small windows was to minimize the effects of rotational shifts.

Translational Shifts

The translational shifts are easily handled without degrading the information content of the pictures. A match routine was written which uses a
distinct mark which stands out from the background to align the data. The match routine looks at an area of 49 x 31 data points. The mark should be completely within this area and no larger than 31 x 23. Row and column sums for the pictures are computed. Each set of sums form a profile.

Two profiles are compared and an error value is computed. This process is repeated several times using different offset displacement values. The displacement value yielding the lowest error value is accepted as the best fit. If S1 is the vector of sums for picture 1, S2 is the vector of sums for picture 2, and I is the displacement, then the error value is

$$
er (I, N) = \sqrt{\sum_{j=1}^{N} \frac{(S1(j) - S2(j+I))^2}{N}}$$

The comparison is done separately for both row and column profiles and the results are returned as the program's estimate of the displacement parameters.

Shift In Gray Level Values

Since there was little control over gray levels during preprocessing, the absolute gray level values were abandoned in favor of relative gray level
differences. The mean and standard deviation of the resulting differences was also computed. All were taken into account to produce the two complementary results pictures.

RESULTS

The comparison of the larger window picture proved unsuccessful because of rotational shifts. Locally within the larger window, the matching process performed well. However, as the distance from the alignment mark increased, the poorer the alignment became. A smaller window of interest was chosen and the difference results proved satisfactory.

Both of the original goals were not achieved. Firstly, no operational procedures were developed to process images on a large scale. Secondly, the particular digitization of the image proved to be a very poor one to be used for texture analysis.

The basic unit of a text pattern is the text element. In order to recognize the texture, one must be able to 'see' the texture element. Since the area of interest in the data was represented by about 150 intensity points, no reliable conclusions could be
drawn about texture because the relatively large area each intensity point represents. An area of interest should be choosen and the pictures re-digitized at a greater magnification.

CONCLUSIONS

It was finally agreed by all concerned that a higher level difference operator was needed to provide more reliable and meaningful results. This higher level operator would first identify the geometry of the vein structure in the sample tissue and isolate areas of interest. The average gray levels over these areas of interest would then be compared. The problem of data alignment is no longer critical. Only gray level shifts remain as an obstacle. However, by including a test strip of known gray levels in each picture, this problem is also now under control. The computer with its great speed can now make the relatively simple correction for this problem.
Interpreting the Graphic Displays

The two figures labeled "Rat's Brain Sample" are to be interpreted the same way the original data of chapter seven is. The figures labeled "Difference Data" must be interpreted differently. For the "Positive" figure, large positive differences are represented by dark areas. Zero or negative differences are represented by light areas. For the "Negative" figure, large negative differences are represented by dark areas and zero or positive differences are represented by light areas.
RAT'S BRAIN SAMPLE ONE

FIGURE 9-1
DIFFERENCE RESULTS
(POSITIVE)

FIGURE 9-3
DIFFERENCE RESULTS
(NEGATIVE)

FIGURE 9-4
CHAPTER 10

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