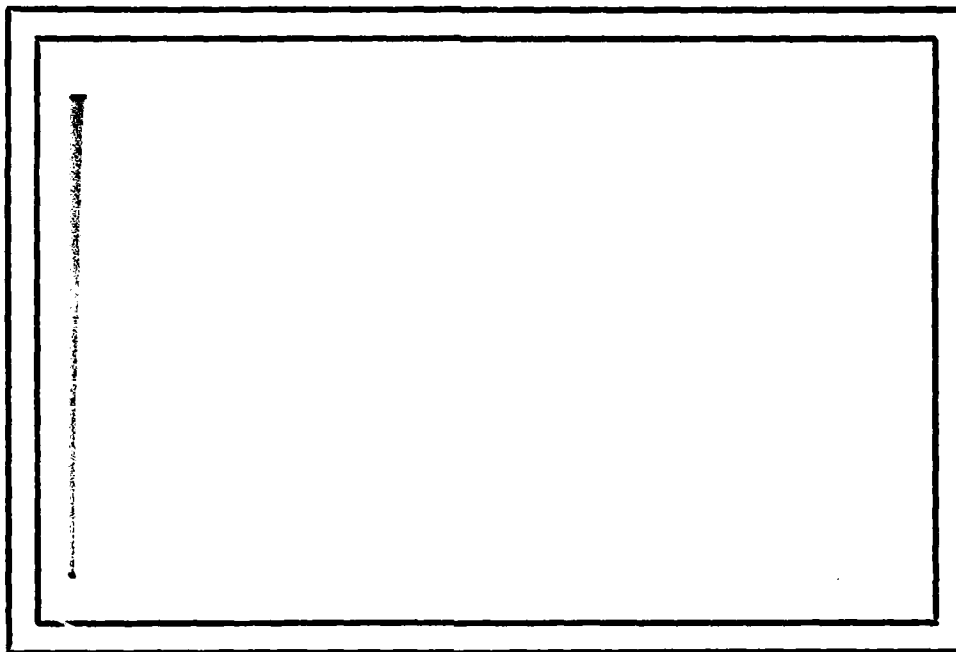


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- DARPA Order - 3206

A METHOD FOR LINKING PAIRS
OF COMPATIBLE LINEAR FEATURES

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ABSTRACT

A method of linking compatible straight edges is presented and discussed. The linking is based on information about the geometrical configuration of the edges, the similarity of the gray levels on their object sides, and the similarity of their object sides with the line joining their endpoints. Three figures of merit are defined for evaluating pairs of segments for possible linking. Examples are shown of applying the method to high resolution aerial photographs. Results indicate that cultural features such as roads and buildings can be extracted and that a significant reduction in the complexity of the image description can be obtained. This approach should be especially useful for defining the degrees of compatibility of pairs of edges in a relaxation scheme for classifying linear feature segments.

The support of the Defense Advanced Research Projects Agency and the U.S. Army Night Vision Laboratory under Contract DAAG-53-76C-0138 (DARPA Order 3206) is gratefully acknowledged, as is the help of Kathryn Riley in preparing this paper.

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1. Introduction

Cultural features often contrast with their surrounds, and are usually bounded by sharp, locally straight edges. As a preliminary step towards the recognition of such objects, the straight edges can be extracted [1,2] and clustered into compatible pairs (i.e. pairs of edges having compatible object sides that can be merged together). The clustering process is the subject of this report.

Line linking techniques have been studied since the early days of this field. The literature is too large to cite here in full. Partial surveys may be found in [3-6]. In general, clustering must take into account information from the picture in the regions around the edges. For example, a roof of a house usually has a uniform gray level and thus it is reasonable to expect that the object sides of the compatible pairs have similar gray levels. The process to be described here deals with lines extracted from an image together with information about the object side of each line (e.g., bright objects or dark objects with respect to the background scene).

The process accepts as input a set of ordered pairs of line endpoints, and the original gray level picture. It attempts to find pairs of lines that are geometrically compatible and that obey relations involving similarity of object side gray levels. The approach that we are taking here toward a global representation of the line segments in a picture begins with finding

potential linking segments between the ends of line segments in the picture, and measuring certain properties of the segments and the linking segment. Once we have found strong linking segments, our approach proceeds toward a global representation of the line segments by linking them together or merging them. The merging process begins by choosing a few lines closest to each end of a given line as candidates for merging. Then a figure of merit based on the similarity of the object side gray levels and angle between the lines is calculated for each pair. Three figures of merit are suggested, based on successively more knowledge about the scene.

This report suggests three figures of merit defining the mutual support of two linear features for merging. In what follows the compatibility conditions will be derived and then the figures of merit will be explained.

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2. Compatibility conditions

Each pair of lines should satisfy certain conditions in order to be accepted as a candidate compatible pair. In general these conditions are:

a) Similarity of gray level of a strip connecting their ends with respect to the gray level on the object side of the pair.

b) Similarity of gray level of strips on the object sides of the pair.

c) Conditions on the geometrical configuration of the pair of lines.

d) Conditions on the angle between the lines.

e) Object gray level measures.

In what follows each of the above measures will be discussed in more detail.

2.1 Similarity measures

Referring to Figure 1 the measure of similarity between line A and lines A_1, A_2, A_3 , etc. is defined as

$$S_{i1} = |g - g_i|$$

where g and g_i are the average gray levels along strips on the object sides of lines A and A_i , respectively. Similarly the measure of similarity between a linking line c_i and the pair of lines A, A_i is defined as

$$S_{i2} = |gc_i - g|$$

and

$$S_{i3} = |gc_i - g_i|$$

If S_{i1} , S_{i2} , and S_{i3} are small for a pair of lines, then that pair is compatible on the basis of similarity of the gray levels.

To define a figure of merit, a linear function as shown in

Figure 2 is defined for each measure of similarity. According to this linear function when the above differences are zero the figure of merit d_{ik} ($k=1,2,3$) is equal to 1 and when the difference is greater than the maximum allowable level of similarity d_{ik} is equal to zero. In other words

$$d_{i1} = \begin{cases} 0 & \text{if } S_{i1} > S_{\max} \\ 1 - S_{i1}/S_{\max} & \text{if } S_{i1} \leq S_{\max} \end{cases}$$

where S_{\max} is the maximum allowable similarity level.

Similarly for d_{i2} and d_{i3} we have

$$d_{ik} = \begin{cases} 0 & \text{if } S_{ik} > S_{\max} \\ 1 - S_{ik}/S_{\max} & \text{if } S_{ik} \leq S_{\max} \\ 1 & \text{if the distance between the end points} \\ & \text{is less than the width of the strip used} \\ & \text{for calculating the average gray level.} \end{cases}$$

for $k=2$ and 3 . In cases where the distance between the end points is less than the width of the strip used in calculating the average gray level, the calculation is not reliable (the number of points used in this calculation is too limited). In these cases since the distance is small the benefit of doubt is given and the value of the function is set equal to 1.

The total figure of merit due to similarity is defined as

$$D_i = d_{i1} + d_{i2} + d_{i3}$$

The maximum possible value for D_i is 3, and the lowest value is 0.

2.2 Geometrical measures

Geometrical conditions are important in making two lines compatible. Figures 3a and 3b show examples of geometrically compatible and incompatible pairs, respectively. The plus sign refers to the object side of the segment. It is clear that objects cannot be built with the lines shown in Figure 3b.

To differentiate between geometrically compatible and incompatible pairs certain constraints on the geometrical locations of the end points are necessary. Here we allow a large gap between the pairs if the lines of the pair are long, and vice versa. Having this in mind we will assume that the gap should be less than the other distances connecting the other ends of the pair of lines. Figure 4 shows examples of different orientations of pairs of lines. Referring to the object side and end conventions, the ratios of the distances are summarized as follows:

For case (a)

$$R_1 = a_2 b_1 / a_2 b_2 \quad R_2 = a_2 b_1 / a_1 b_1 \quad R_3 = a_2 b_1 / a_1 b_2$$

For case (b)

$$R_1 = a_1 b_1 / a_1 b_2 \quad R_2 = a_1 b_1 / a_2 b_2 \quad R_3 = a_1 b_1 / a_2 b_1$$

For case (c)

$$R_1 = a_1 b_2 / a_2 b_1 \quad R_2 = a_1 b_2 / a_2 b_2 \quad R_3 = a_1 b_2 / a_1 b_1$$

For case (d)

$$R_1 = a_2 b_2 / a_1 b_1 \quad R_2 = a_2 b_2 / a_2 b_1 \quad R_3 = a_2 b_2 / a_1 b_2$$

In order to calculate these ratios the ends and the sides of the lines should be consistently labeled (see [7]).

Assume that for each neighboring line (i) these ratios are called R_{ki} . Then the geometric measure for each ratio is defined as:

$$G_{ik} = \begin{cases} 1 & \text{if } R_{ki} < 1 \\ 0 & \text{if } R_{ki} \geq 1 \end{cases}$$

where $k=1,2,3$ and i is the label of the neighboring line.

The overall geometrical measure is defined to be

$$G_i = G_{i1} \cdot G_{i2} \cdot G_{i3}$$

According to this definition, if the geometrical requirements are satisfied $G_i=1$, otherwise $G_i=0$.

By examining these ratios it will be clear that the smaller the ratio the better will be the geometrical compatibility of the lines. Using this fact, another more restrictive definition for the geometrical measure can be obtained.

To define this geometrical measure, let

$$r_i = \begin{cases} \sum_{k=1}^3 R_{ki}/3 & \text{if } R_{ki} < 1 \\ 1 & \text{if } R_{ki} \geq 1 \end{cases}$$

for $k=1,2,3$

Figure 5 shows the suggested linear function. According to this figure, as the sum of these ratios decreases with respect to the minimum value $m=\min(r_i)$, the geometrical measure decreases too. The geometrical measure H_i is defined by

$$H_i = \begin{cases} 1-(r_i-m)/(1-m) & \text{if } r_i < 1 \\ 0 & \text{if } r_i = 1 \end{cases}$$

2.3 Angle function

The angle between geometrically compatible candidates is also an important factor in finding compatible pairs. First, the angle between the geometrically compatible candidates is calculated. Figure 6 shows examples of the calculation of angles between two geometrically compatible lines. In this figure θ_A and θ_B are the angles of lines A and B with respect to the horizontal axis. In this convention the angle between two collinear geometrically compatible lines is 180° . Referring to Figure 7, the angle between line A and compatible candidate A_i is designated by θ_i . As shown in this figure, the smaller the angle between compatible candidates, the stronger the degree of compatibility between the lines. To express this situation, a linear function is again proposed. Figure 8 shows the proposed angle function. This linear function is normalized with respect to the smallest angle θ_s between the lines in question. We assume that the angle between two compatible candidates cannot be less than θ_ℓ (usually 25°), and cannot be greater than $2\pi - \theta_\ell$. If θ_s is less than θ_ℓ the next greater angle will be used for θ_s . If no angle with the above condition is found the angle function is set equal to zero for all the compatible candidate lines. In summary, the linear angle function is defined as follows:

$$F(\theta_i) = \begin{cases} 0 & \text{if } \theta_i < \theta_\ell \text{ or } \theta_i > 2\pi - \theta_\ell \\ 1 - (\theta_i - \theta_s) / (2\pi - \theta_s) & \text{for } \theta_s \leq \theta_i \leq 2\pi - \theta_s \end{cases}$$

2.4 Object gray level function

The given object gray level or estimated object gray level can also be used in defining the figure of merit. This measure can be incorporated into the figure of merit in such a way as to yield a high value for the compatibility of object lines and a low value for non-object lines. The gray level average of the object can be automatically estimated as follows:

- 1) Calculate the average gray level in a strip on each side of each line segment.
- 2) Sort the line segments in decreasing order of length.
- 3) Select the longest $p\%$ of the lines (usually 5%).
- 4) Calculate the average gray levels of the brightest (or darkest) sides of the lines selected in step (3).

The average gray level calculated in this way can be accepted as a good estimate for the typical gray level of the objects. In a case where the scene is not illuminated uniformly, one can estimate the typical gray level average of $p\%$ of the longest lines if they are distributed geometrically in different locations on the scene.

If the differences between the estimated gray levels of the two lines in question and the average object side gray level is small, the two lines should reinforce each other to yield a high figure of merit. Otherwise, they should punish each other in order to yield a low figure of merit. A linear function is defined for this purpose, as shown in Figure 9.

In this figure g_e is the estimated gray level average and g_i is the gray level average of a small neighborhood along the object side of line i . S_{\max} is the maximum allowable level of similarity. In summary the gray level measure for each line is defined as follows:

$$f(g_i) = \begin{cases} 1 & \text{if } 0 \leq |g_e - g_i| \leq S_{\max} \\ 2 - |g_e - g_i| / S_{\max} & \text{if } S_{\max} < |g_e - g_i| < 2S_{\max} \\ 0 & \text{if } |g_e - g_i| > 2S_{\max} \end{cases}$$

Using the above definition for each line, the mutual gray level strength between line i and line j is defined as

$$F(g_{ij}) = f(g_i) \cdot f(g_j)$$

3. Figures of merit

Three figures of merit are defined. The first one uses the similarity and geometric measures and the angle function. The second uses the information used in the first one as well as the object mutual gray level strength. The first figure of merit is defined as

$$FM1 = \text{Max}(MS)$$

where the merging strength MS is defined as

$$MS = D_i F(\theta_i) G_i$$

Here i is the label of the neighboring line.

This definition simply multiplies the similarity measure and the angle function for the line in question and other neighboring lines and the binary function of the geometrical measure. The maximum value of the figure of merit is 3 when a neighboring line has the same object side gray level average as the linking line and the given line, and also makes the smallest angle with the given line.

The second figure of merit uses information about the given or estimated object gray level. This is again defined as

$$FM2 = \text{Max}(MS')$$

where the merging strength MS' is defined as:

$$MS' = D_i F(\theta_i) G_i F(g_{ji})$$

where j is the label of the given line and i is the label of the neighboring line. Here again the maximum value of the figure of merit is 3, when the conditions stated for the first definition are satisfied along with the condition that the differences

between the object side average gray levels of the given pair of lines and the estimated gray level are within the maximum level of similarity.

The third figure of merit is defined similarly to the first and the second figures of merit, except that the geometrical measure G_i is replaced by H_i .

Finally, one can define the probability of merging line j with line i as

$$P_{ji} = \text{Merging strength}/3$$

4. The algorithm

1) Read in the data for each line in the form (x_1, y_1, x_2, y_2) where (x_1, y_1) are the co-ordinates of the first end point and (x_2, y_2) are the co-ordinates of the second end point of the line.

2) For end "1" of each line, find the closest N neighboring end points. Record the labels of these lines. (N is taken as 3 in the program to keep computational time reasonable.)

3) Calculate the figure of merit and record it along with the corresponding ends, line label, and label of the compatible line. Mark this line and the compatible line so that they will not be processed again.

4) Choose the other end of the compatible line found in (3) and continue the process. If no compatible line is found go to (5).

5) Choose end "2" of the line started with and go to (2). If end "2" is already processed go to (6).

6) Continue the above process for the other line segments.

The compatible lines are chosen in a serial manner, that is once a compatible line is found the process jumps to the other end of the compatible line and continues the process. The algorithm can also be adapted to operate in a parallel fashion. The width of the strip used in calculation of the average gray level is 4 pixels. This value is selected for reasons involving the resolution of the scene.

5. Examples and discussion

The algorithm presented here performs well on several input data sets. The straight edges in the images were extracted using an iterative enhancement technique [2] and the resulting lines were used as input to the pairing program. Figure 10 shows one input image and the set of lines extracted from it is shown in Figure 11. Figure 12 shows the histogram of the first figure of merit. The maximum level of similarity is set to be 10 in calculation of the figure of merit; this is quite a tolerant value. Figures 13 to 16 show the result of line linking with different thresholds (2.3, 2.0, 1.3, 0.1) on the value of the figure of merit. In these figures, the lines that have at least one compatible pair within the threshold of the figure of merit are shown. It is clear that the process is rather stable. The best threshold is around 2 (probability of merging is equal to 0.7).

The effect of changing the maximum level of similarity has also been studied. When this level is changed to 12 or 15, the results are shown in Figures 17 to 26. The effect of increasing the maximum level of similarity is to modify the histogram of the figures of merit. Comparing the results, it is apparent that no major change results when the maximum level of similarity is changed. Figure 27 shows another image, and Figures 28 to 33 show the results of using the process on this scene.

Another series of experiments has been performed using the second figure of merit. Figure 34 shows the histogram of the second figure of merit for the first scene. The results of line linking using different thresholds are shown in Figures 35 to 38. It is seen that the second method of defining the figure of merit also has the property of cleaning the non-object lines (noisy lines). Figure 39 to 43 show the results for the second scene.

Examination of the output with different thresholds on the figure of merit shows that one can choose the lowest nonzero threshold without causing trouble.

A similar series of experiments has been performed using the third figure of merit. No major change has been observed and in most cases exactly similar results have been obtained.

The effect of increasing S_{\max} in the second figure of merit has also been studied. As we increase this level, the probability that non-object lines are linked is increased. The results of increasing S_{\max} to 12 and 15 are shown in Figures 44 to 54.

The linking algorithm in this paper can be criticized for taking too local a view in determining the best matches from the three closest neighbors only, although the program can consider more than three. It might happen that a pair of lines

that are mutually best partners should not, in fact, be linked. This problem can be overcome by increasing the number of closest neighbors in calculating the figure of merit. The results show that reliable merging can be obtained by considering three neighbors only. The results also suggest that one might use such algorithms to define the degrees of compatibility of the line segments in a relaxation scheme for classifying the line segments.

6. Extensions and conclusions

The following extensions that may improve the results of the linking process are suggested.

1) Include the distribution (e.g. standard deviation) of the object side gray level along the linking line in the figure of merit. There are rare cases in which the gray level along the object side of the linking line changes in such a way as to produce an average gray level similar to that of the pair, resulting from gray levels that are partly too high and partly too low and hence not actually similar.

2) The same as (1) but for the pair of lines themselves.

3) The linking line should not intersect other lines.

This paper has presented an algorithm for linking compatible linear features. The linking process is based on the degree of similarity of the gray levels of the object sides of the pairs and the linking lines, the angles between them, geometrical conditions, and also the estimated object gray level. The algorithm was evaluated using lines extracted from real images using an edge detection and enhancement process. The results were seen to be generally reasonable and the result of applying the process was a new image representation that was more useful for further processing than the initial edge image. This process should be especially useful for defining the degrees of compatibility of the line segments in a relaxation scheme for classifying the feature segments.

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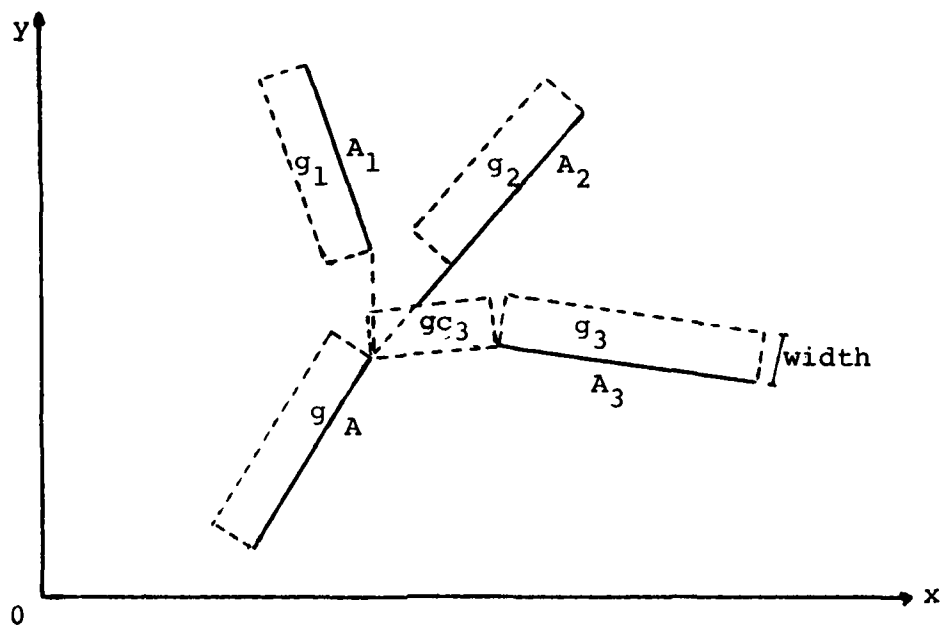


Figure 1. Gray level similarity along the lines and the linking line.

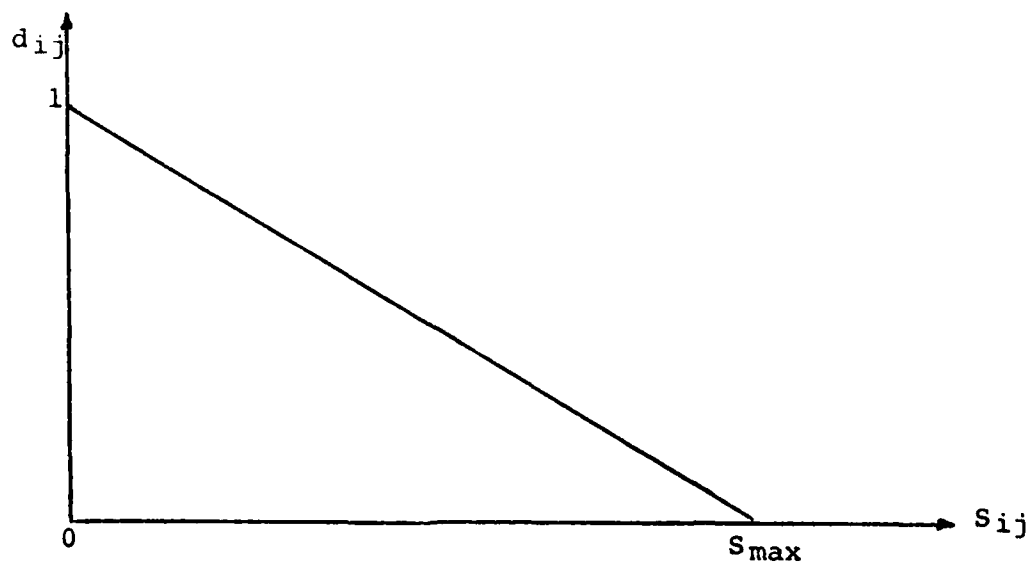


Figure 2. Linear function for calculation of similarity measures.

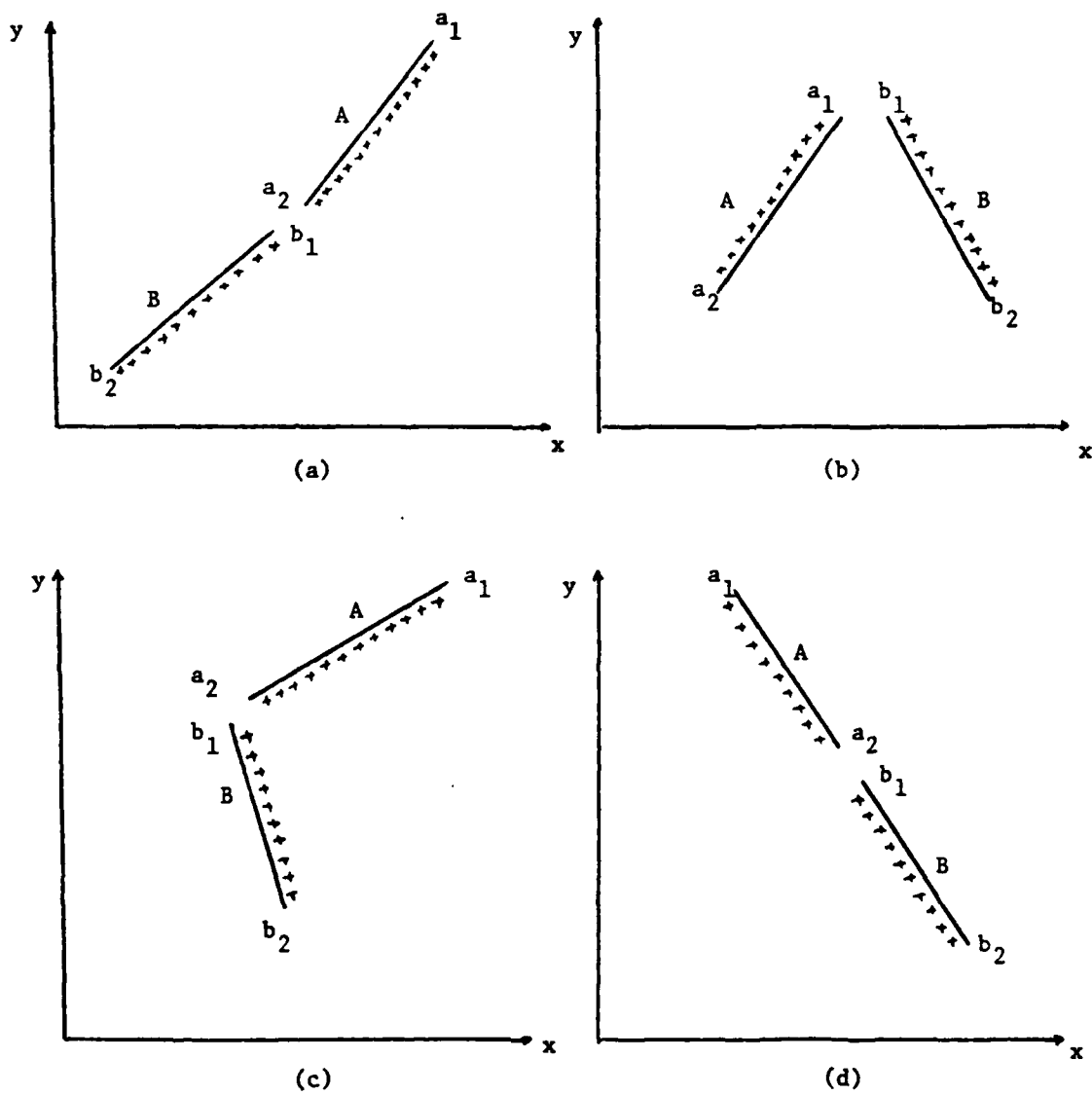


Figure 3a. Examples of geometrically compatible candidate pairs.

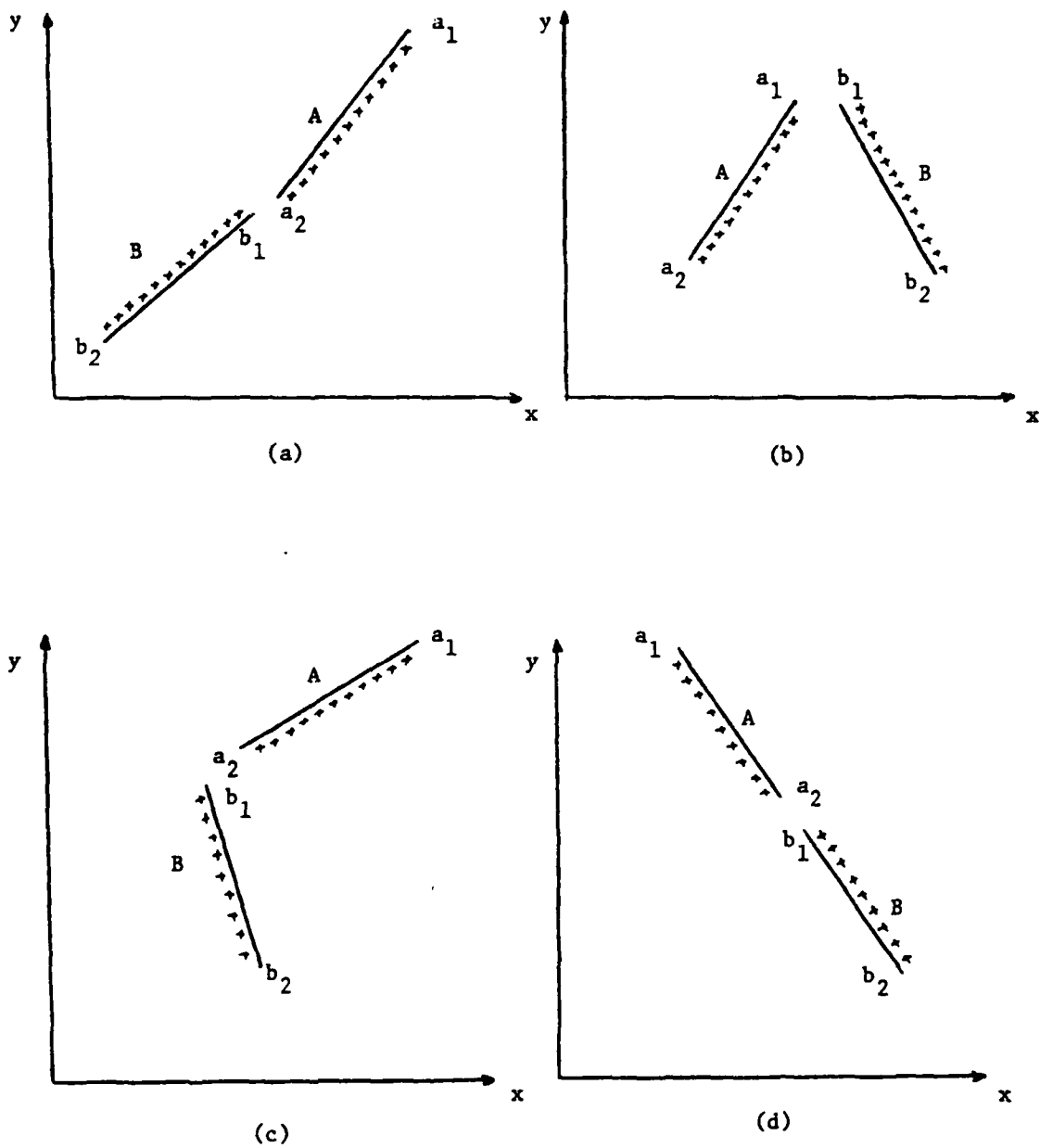


Figure 3b. Examples of geometrically incompatible candidate pairs.

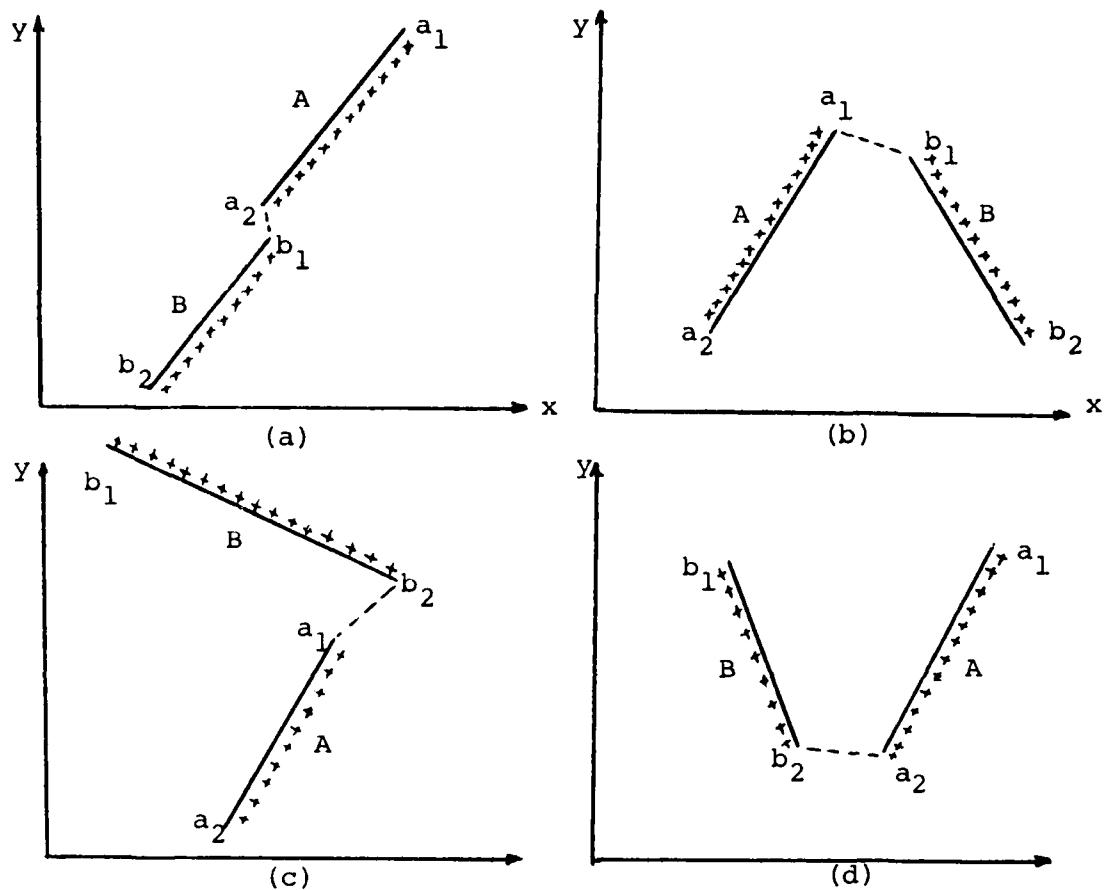


Figure 4. Examples of different orientations of geometrically compatible lines.

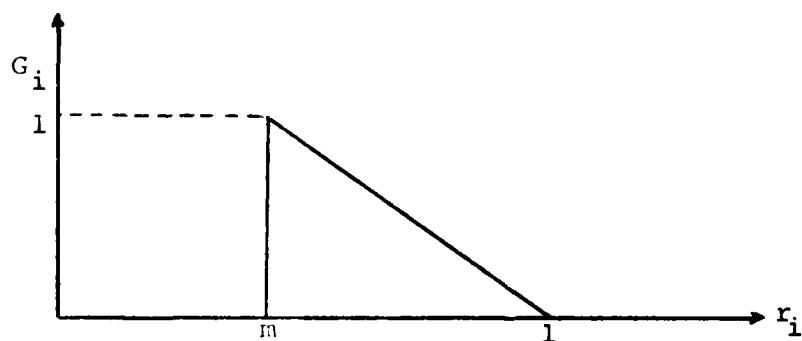
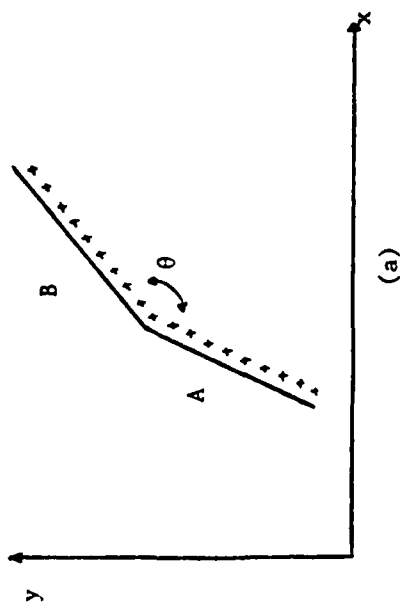
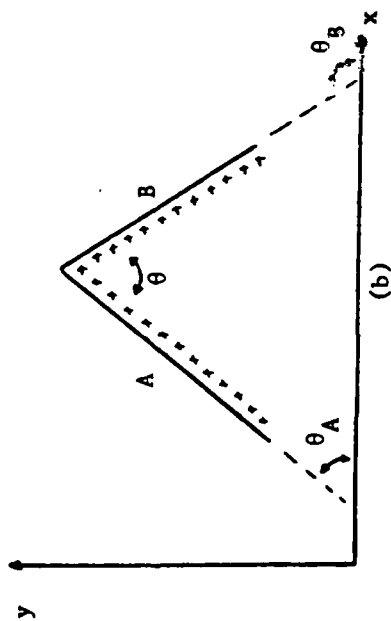


Figure 5. Linear function for calculation of the second geometrical measure.

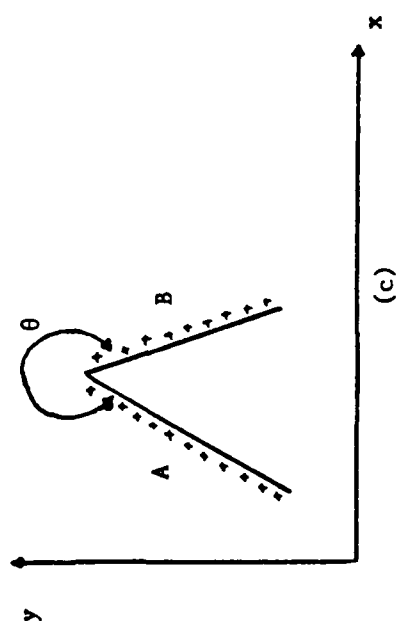


$$\theta = \pi + |\theta_A - \theta_B| \text{ if } \theta_B > \theta_A$$

$$\theta = \pi - |\theta_A - \theta_B| \text{ if } \theta_B \leq \theta_A$$



$$\theta = |\theta_A - \theta_B|$$



$$\theta = 2\pi - |\theta_A - \theta_B|$$

Figure 6. The angle between two lines in different orientations

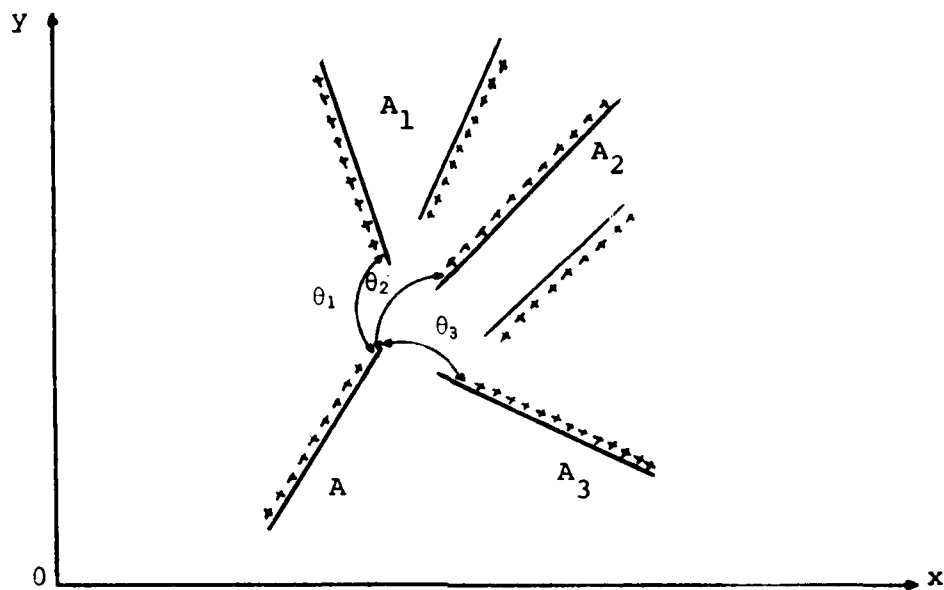


Figure 7. The angles between geometrically compatible pairs.

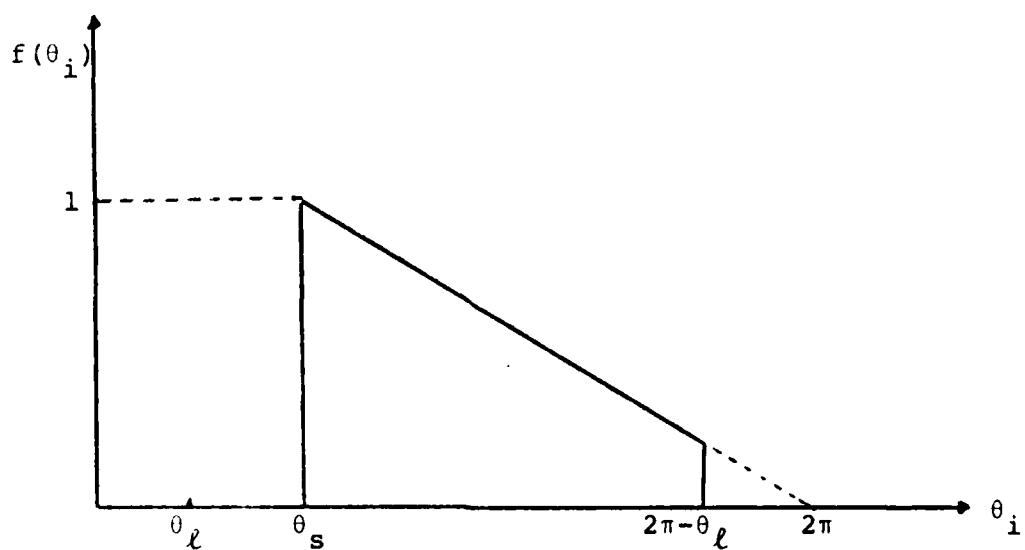


Figure 8. Linear function for calculation of angle function.

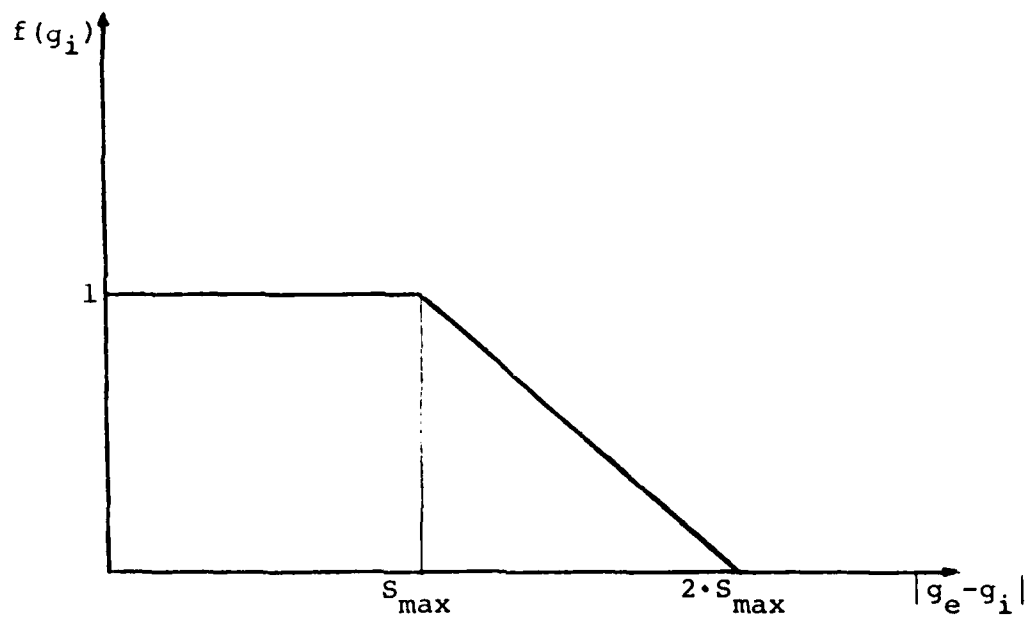


Figure 9. The function used for calculation of the gray level measure.

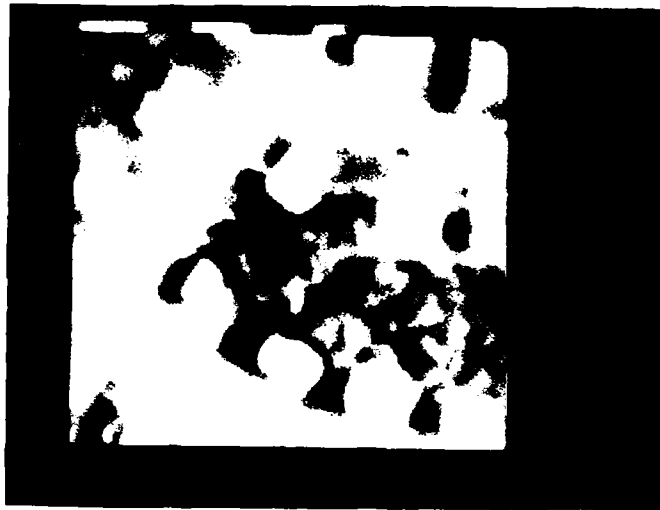


Figure 10. A suburban scene.



Figure 11. The extracted lines.

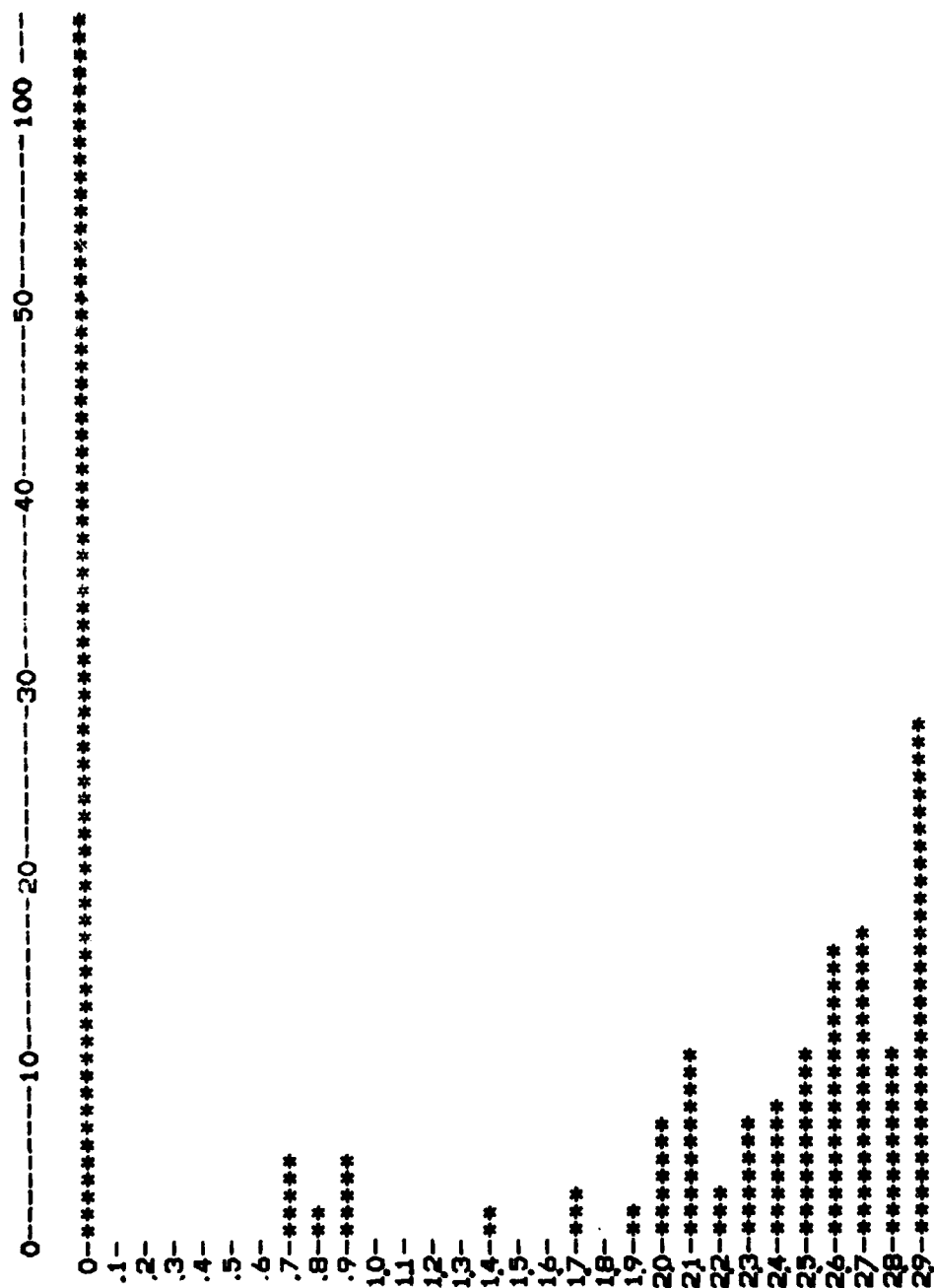


Figure 12. The histogram of the first figure of merit:
 $S_{\max} = 10$, suburban scene.

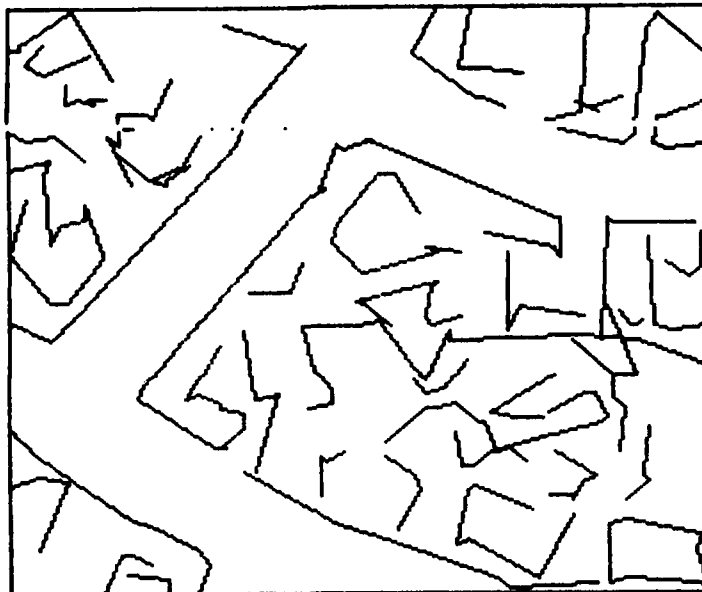


Figure 13. Line linking: $FM1=2.3$, $S_{max}=10$.

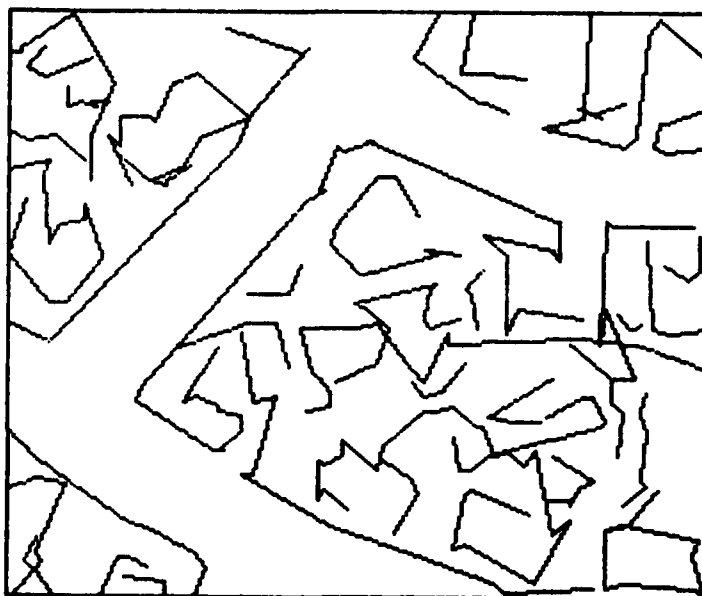


Figure 14. Line linking: $FM1=2.0$, $S_{max}=10$.

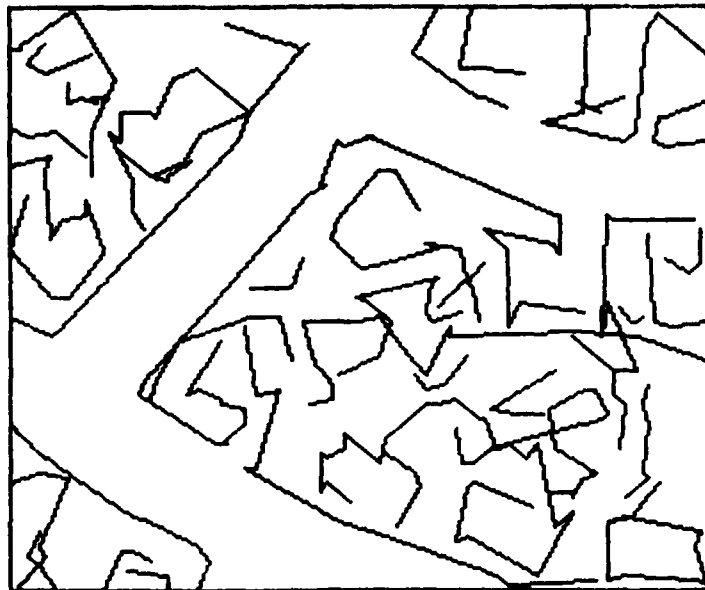


Figure 15. Line linking: $FMl=1.3$, $S_{max}=10$.

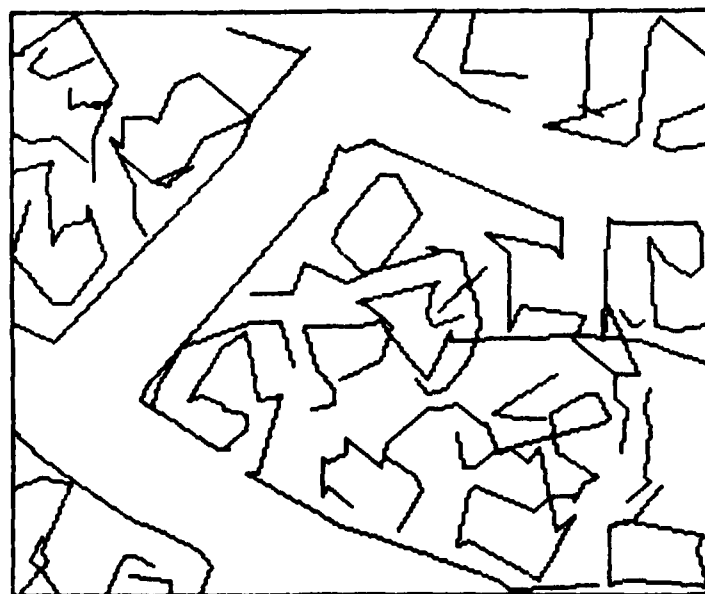


Figure 16. Line linking: $FMl=0.1$, $S_{max}=10$.

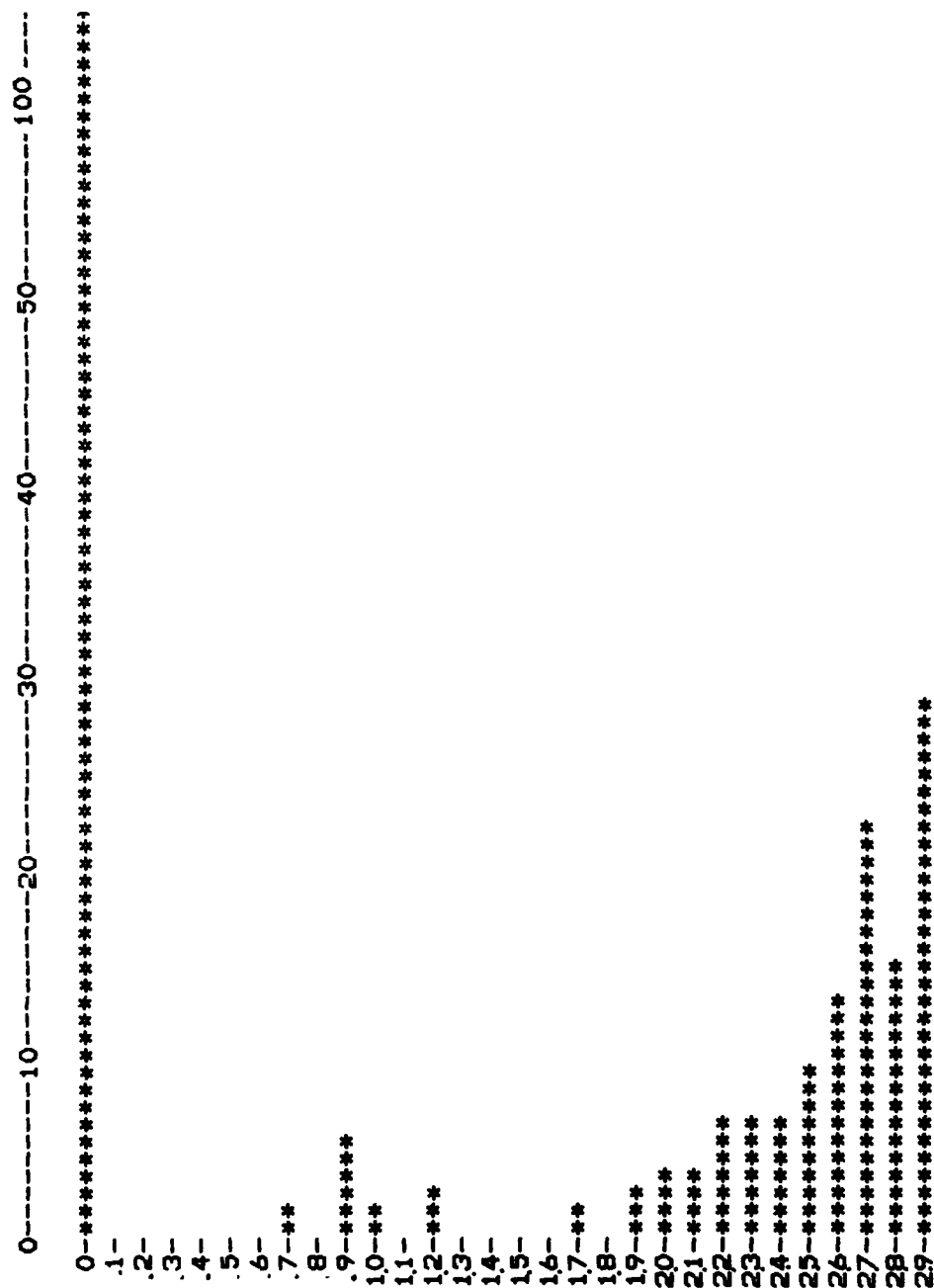


Figure 17. The histogram of the first figure of merit: $S_{\max}=12$, suburban scene.

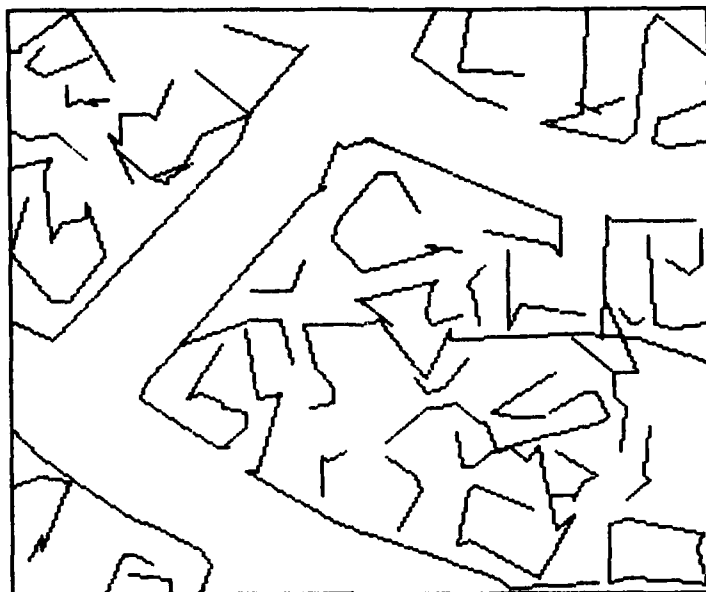


Figure 18. Line linking: $FMl=2.3$, $S_{max}=12$.

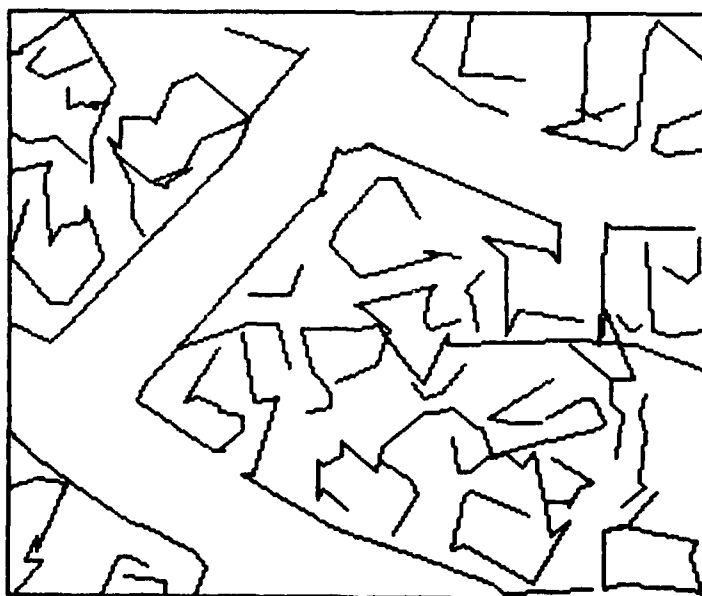


Figure 19. Line linking: $FMl=2.0$, $S_{max}=12$.

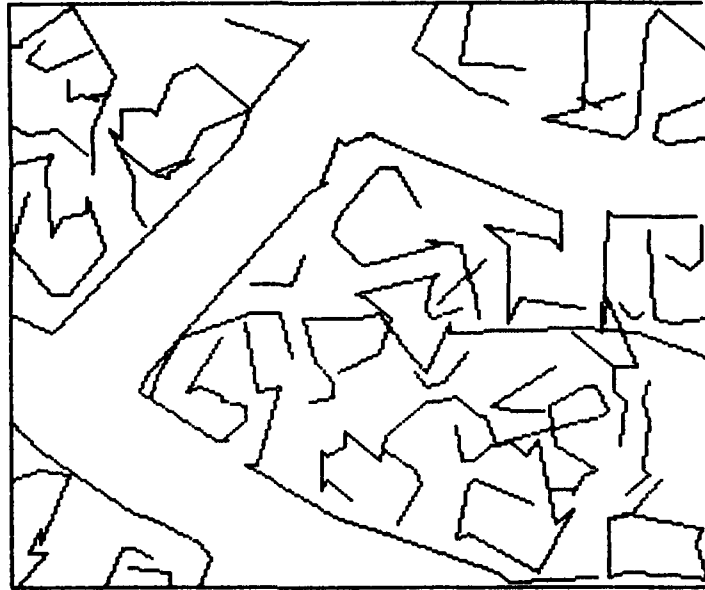


Figure 20. Line linking: $FMl=1.3$, $S_{max}=12$.



Figure 21. Line linking: $FMl=0.1$, $S_{max}=12$.

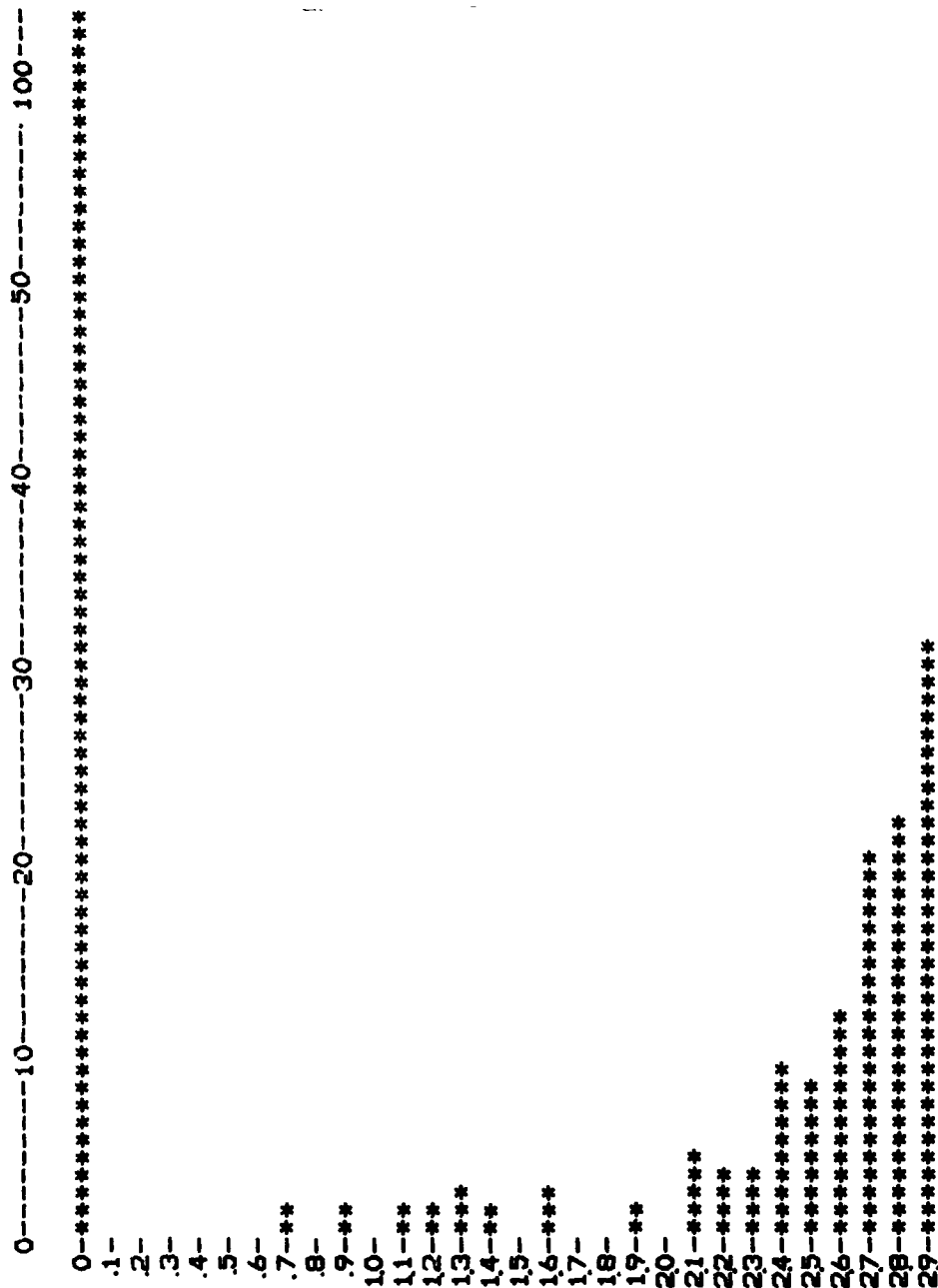


Figure 22. The histogram of the first figure of merit:
 $S_{\max}=15$, suburban scene.

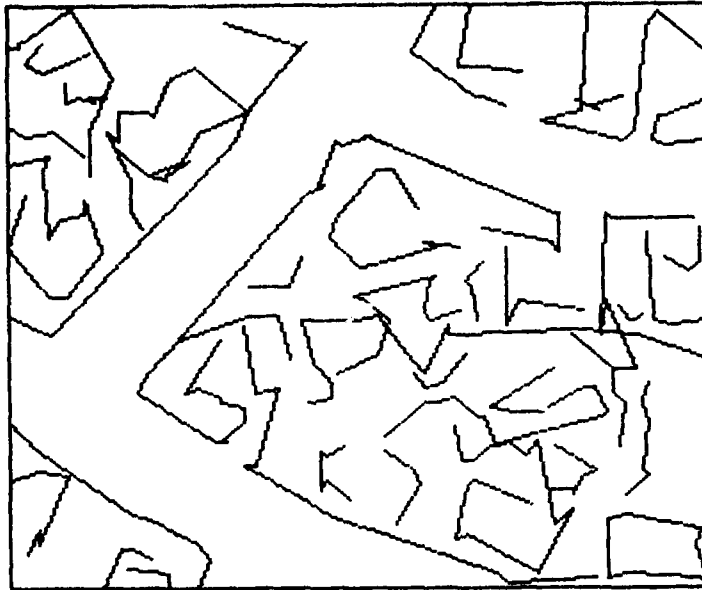


Figure 23. Line linking: $FMl=2.3$, $S_{max}=15$.

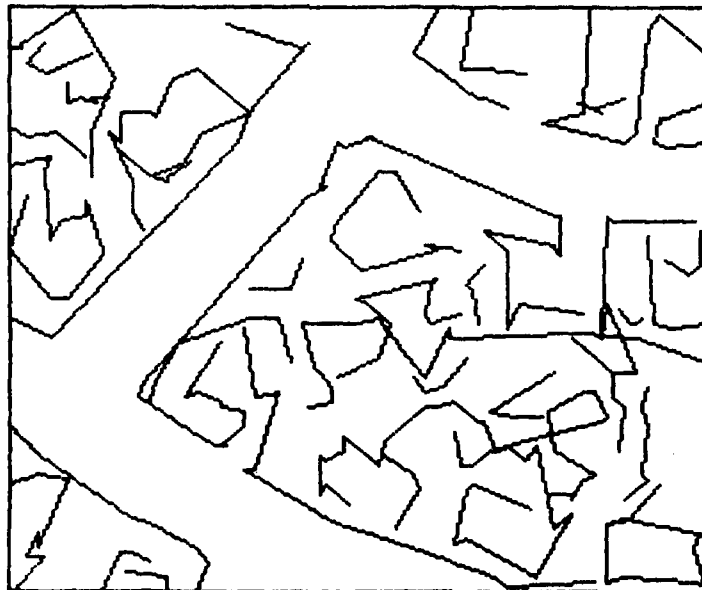


Figure 24. Line linking: $FMl=2.0$, $S_{max}=15$.

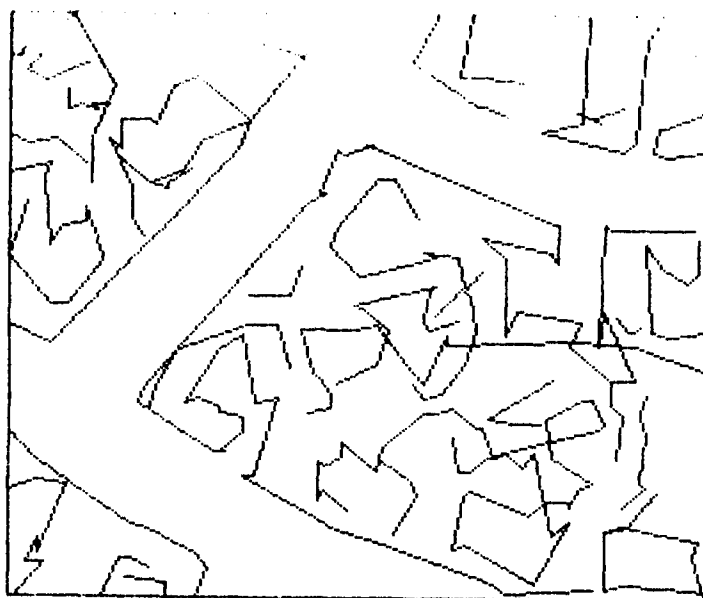


Figure 25. Line linking: $FMl=1.3$, $S_{max}=15$.

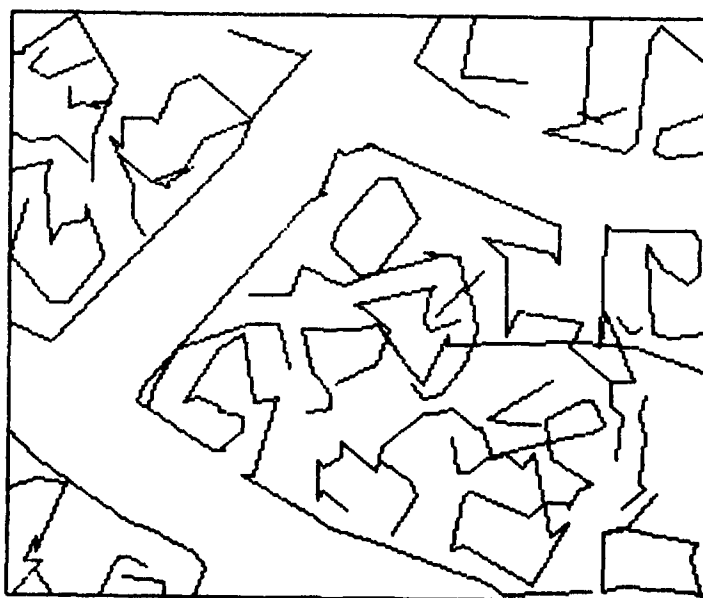


Figure 26. Line linking: $FMl=0.1$, $S_{max}=15$.



Figure 27. A portion of Lorton Reformatory.

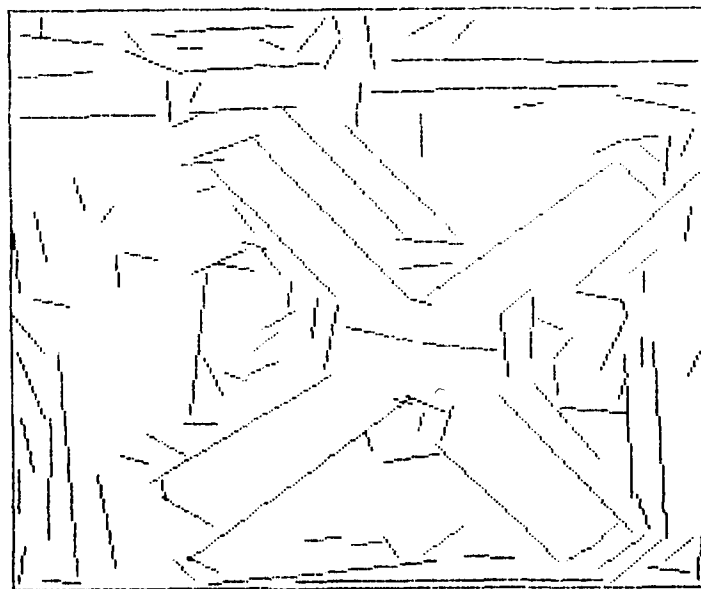


Figure 28. The extracted lines.

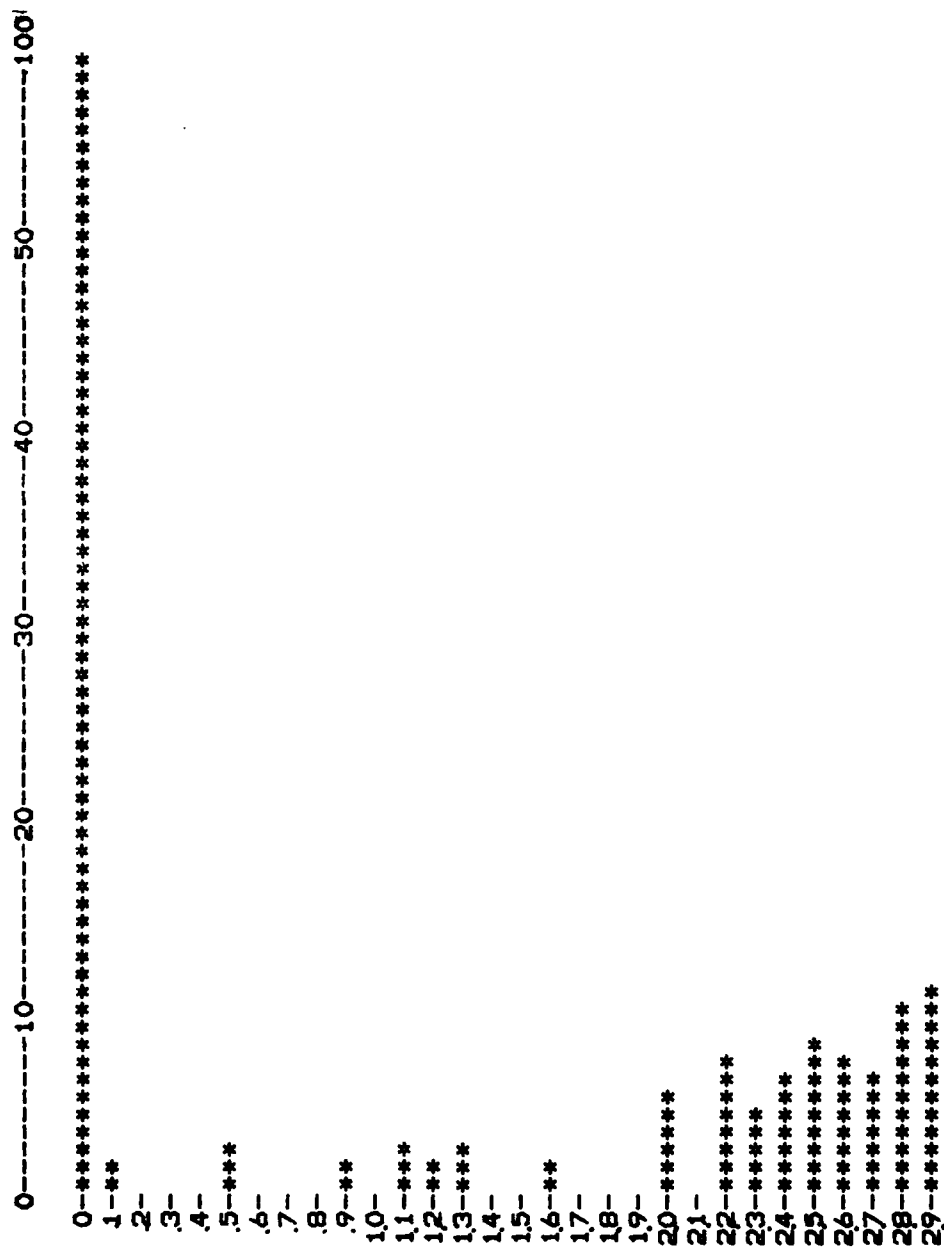


Figure 2 . The histogram of the first figure of merit:
 $S_{\max}=10$, Lorton scene.

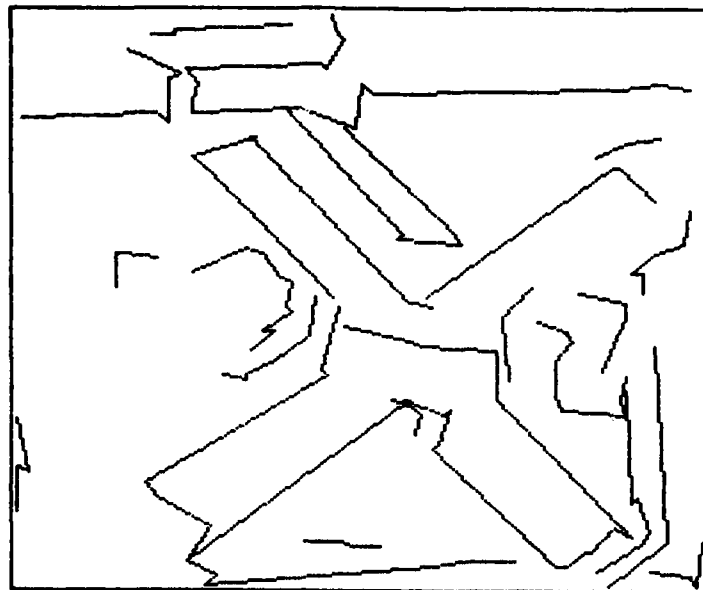


Figure 30. Line linking: $FM1=2.3$, $S_{max}=10$.

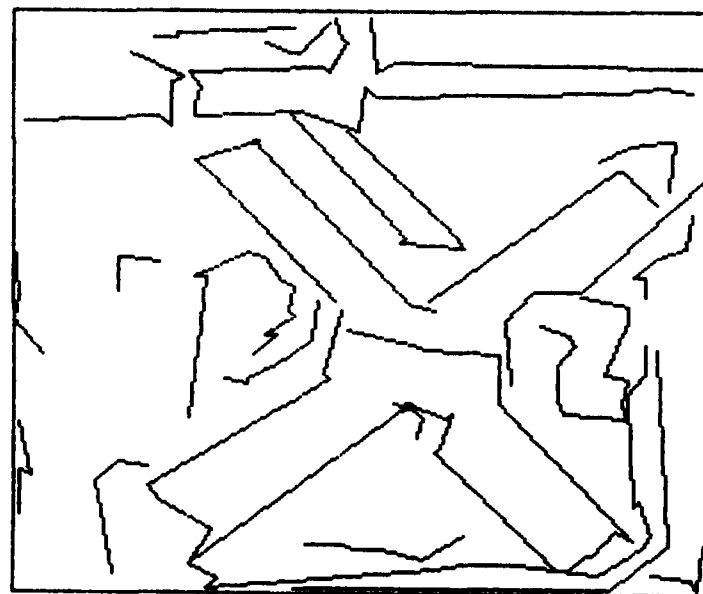


Figure 31. Line linking: $FM1=2.0$, $S_{max}=10$.

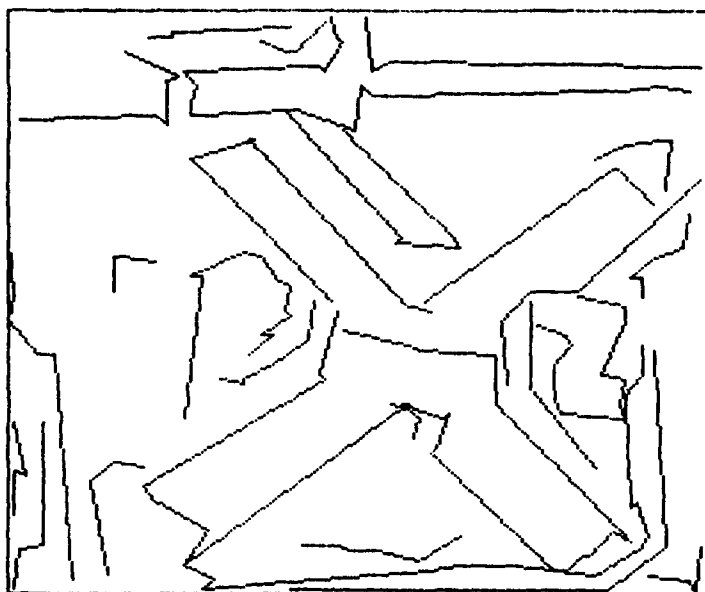


Figure 32. Line linking: $FMl=1.3$, $S_{max}=10$.

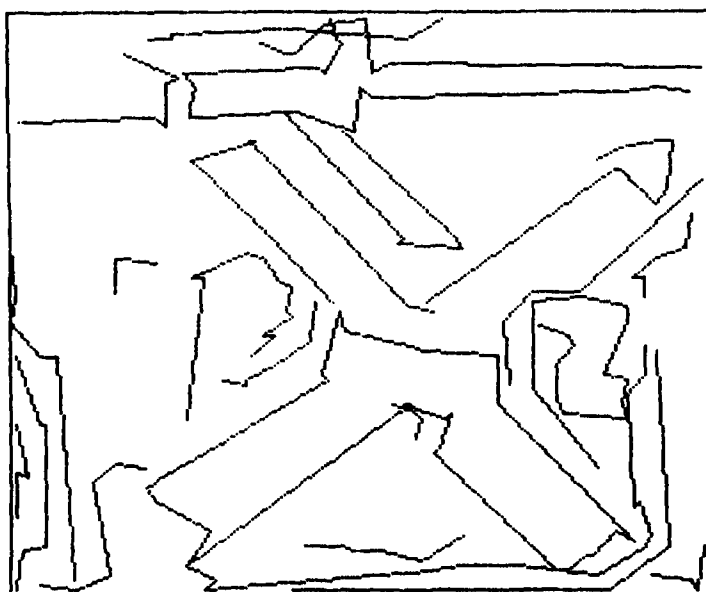


Figure 33. Line linking: $FMl=0.1$, $S_{max}=10$.

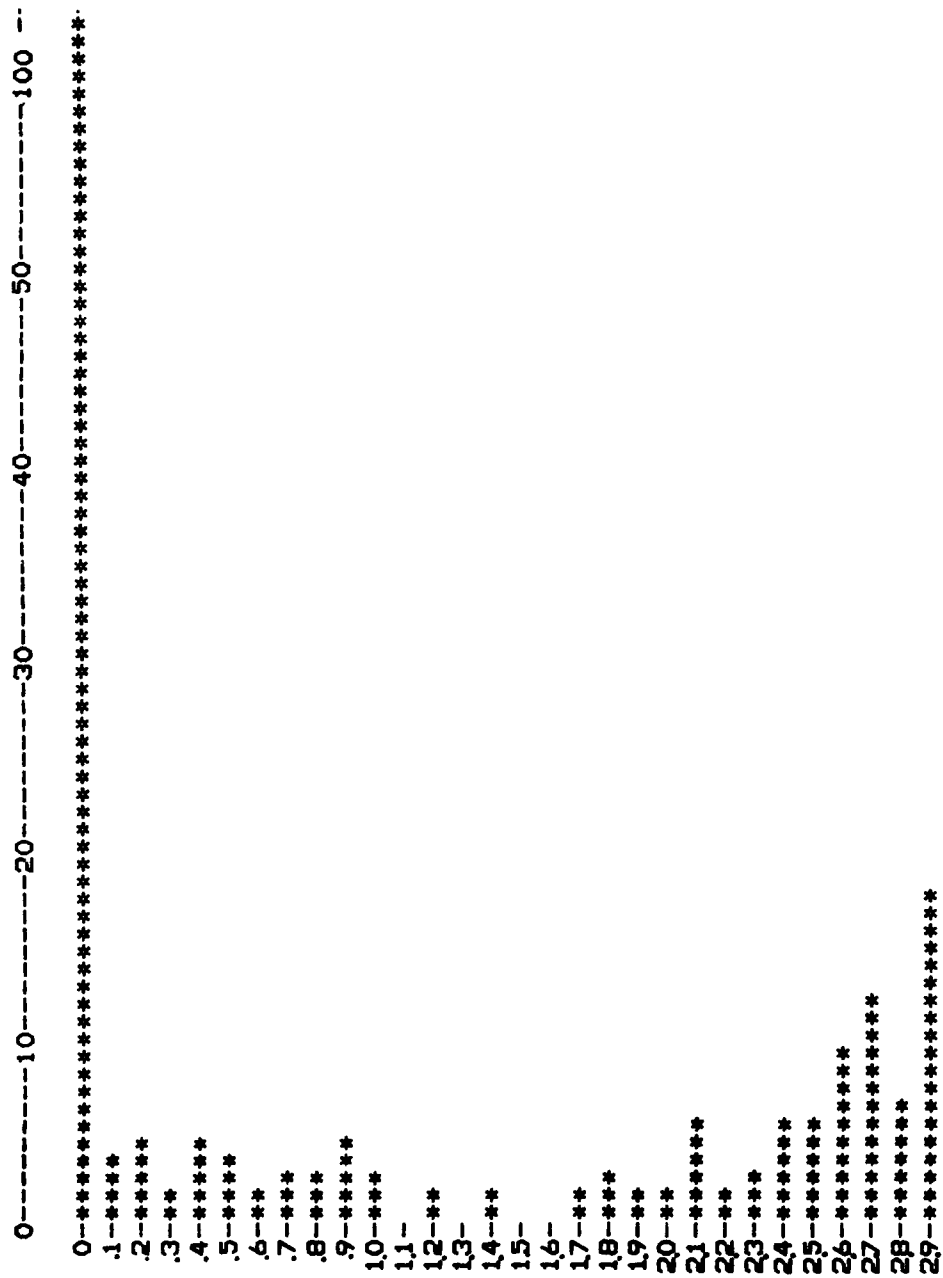


Figure 34. Histogram of the second figure of merit:
 $S_{\max}=10$, suburban scene.

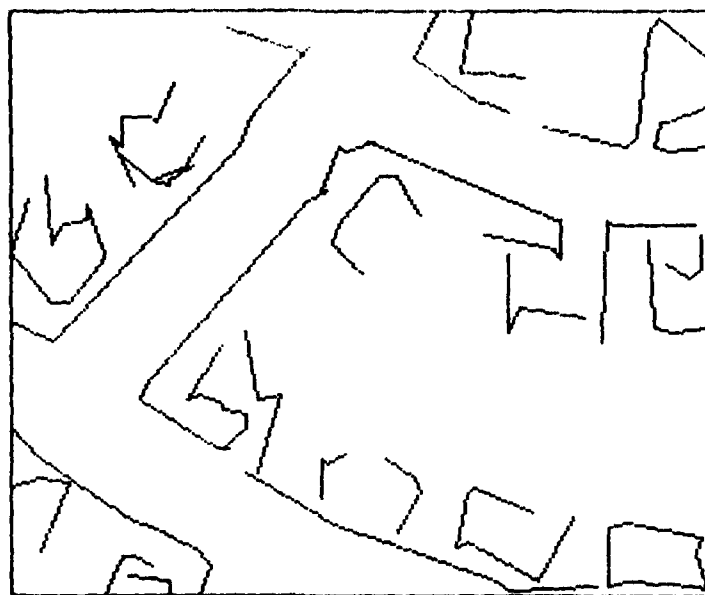


Figure 35. Line linking: $FM2=2.3$, $S_{max}=10$.

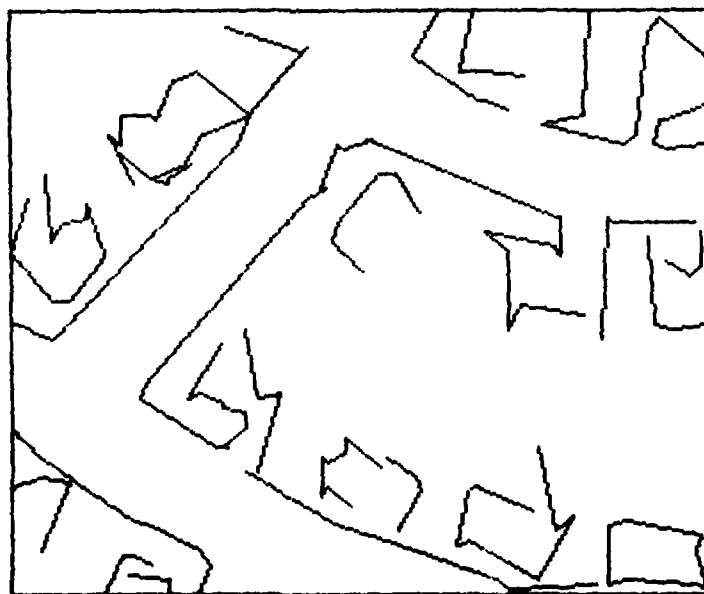


Figure 36. Line linking: $FM2=2.0$, $S_{max}=10$.



Figure 37. Line linking: $FM2=1.3$, $S_{max}=10$.



Figure 38. Line linking: $FM2=0.1$, $S_{max}=10$.



Figure 39. Histogram of the second figure of merit:
 $S_{\max}=10$, Lorton scene.

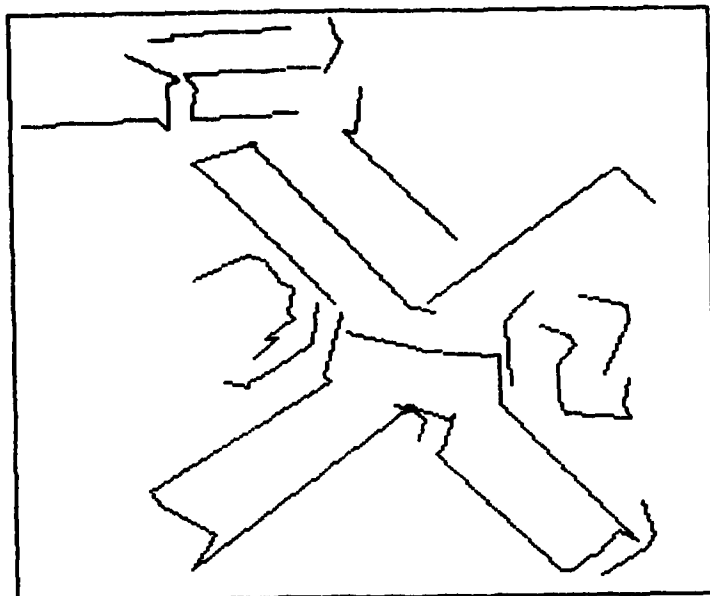


Figure 40. Line linking: $FM2=2.3$, $S_{max}=10$.

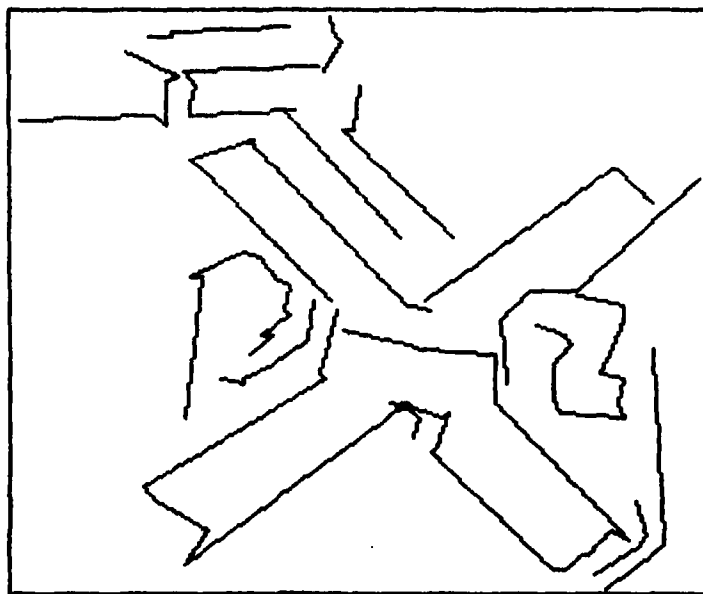


Figure 41. Line linking: $FM2=2.0$, $S_{max}=10$.

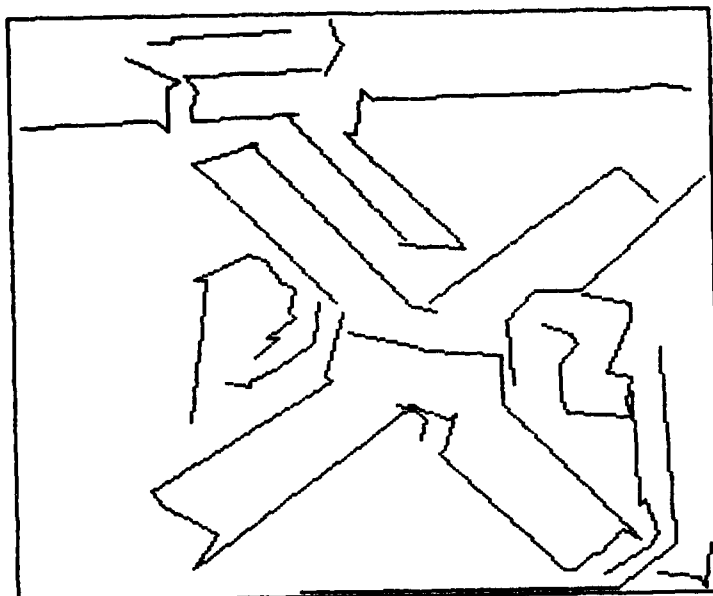


Figure 42. Line linking: $FM2=1.3$, $S_{max}=10$.

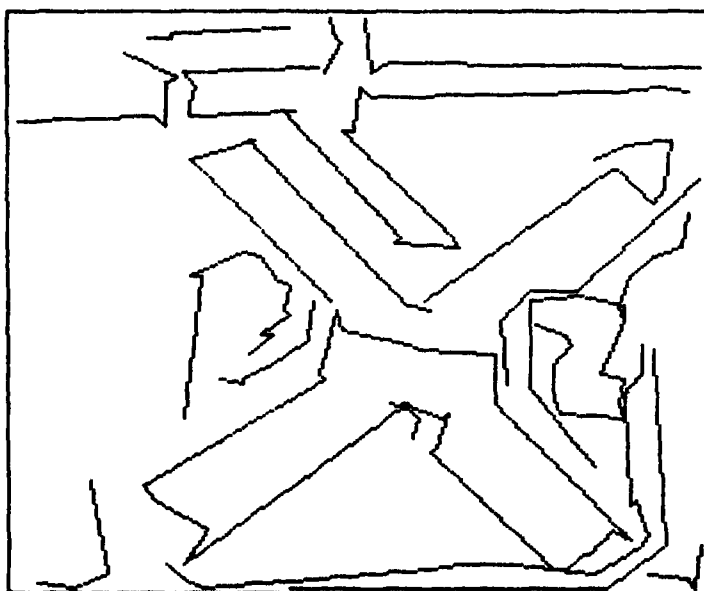


Figure 43. Line linking: $FM2=0.1$, $S_{max}=10$.

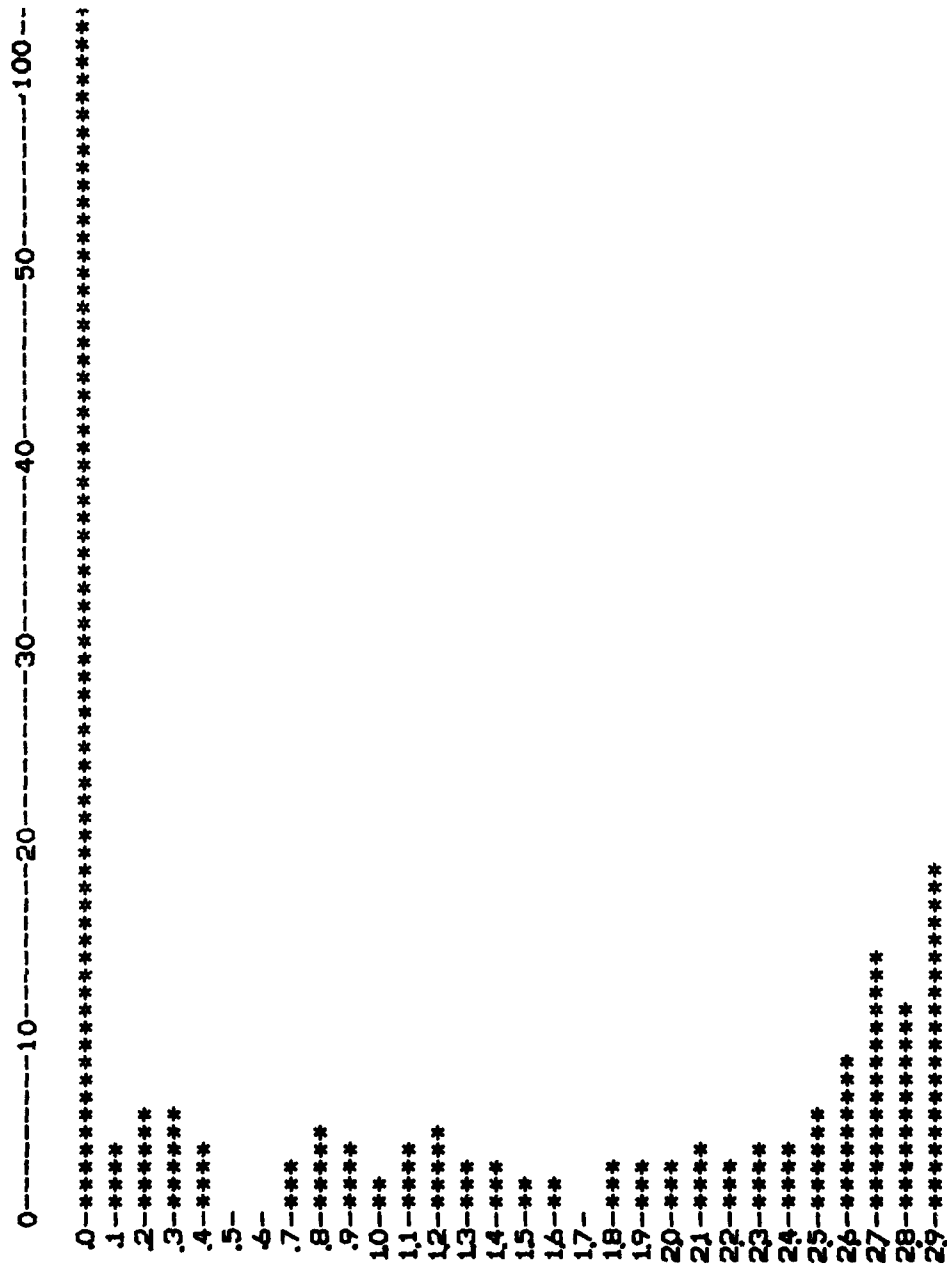


Figure 44. The histogram of the second figure of merit:
 $S_{\max}=12$, suburban scene.



Figure 45. Line linking: $FM2=2.3$, $S_{max}=12$.

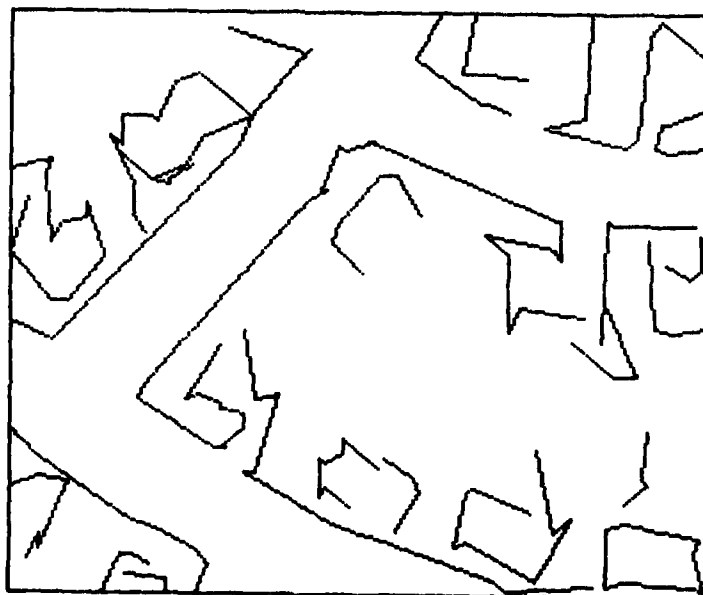


Figure 46. Line linking: $FM2=2.0$, $S_{max}=12$.

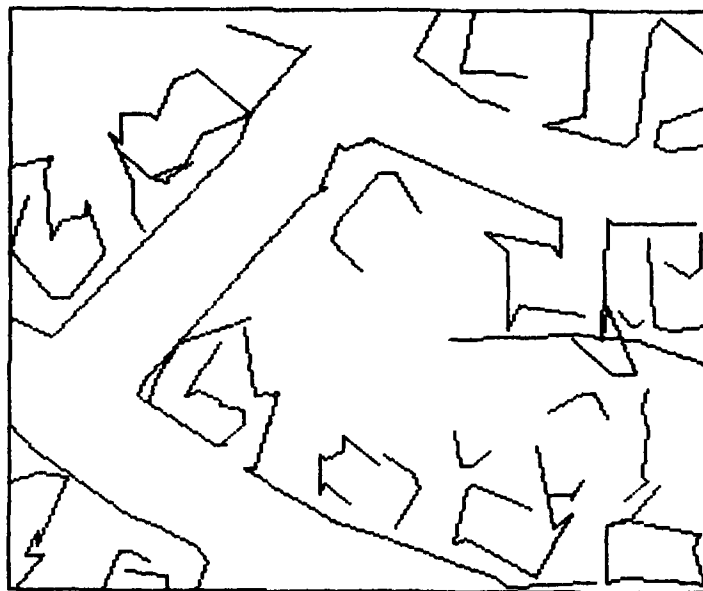


Figure 47. Line linking: $FM2=1.3$, $S_{max}=12$.



Figure 48. Line linking: $FM2=0.1$, $S_{max}=12$.

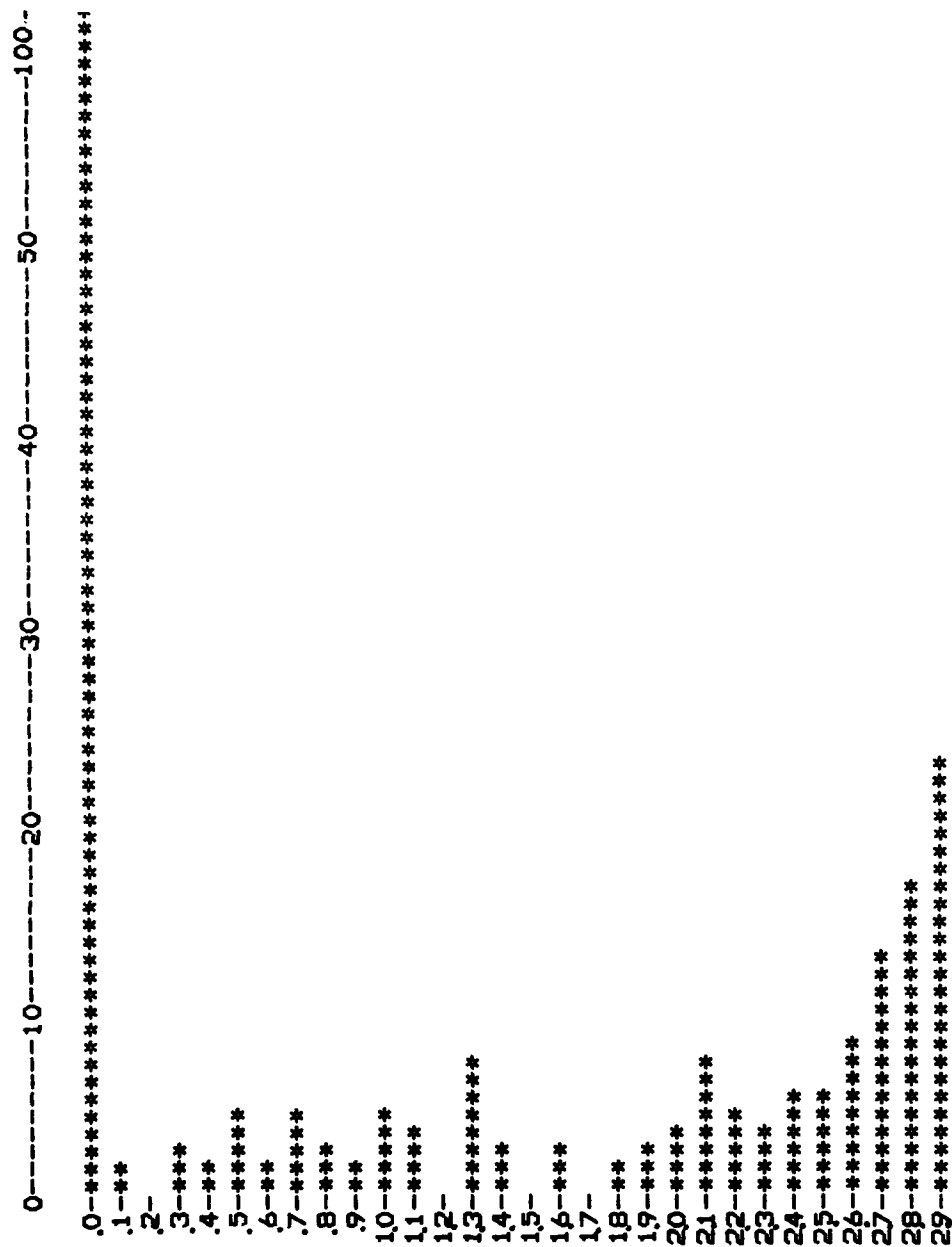


Figure 49. The histogram of the second figure of merit:
 $S_{\max}=15$, suburban scene.

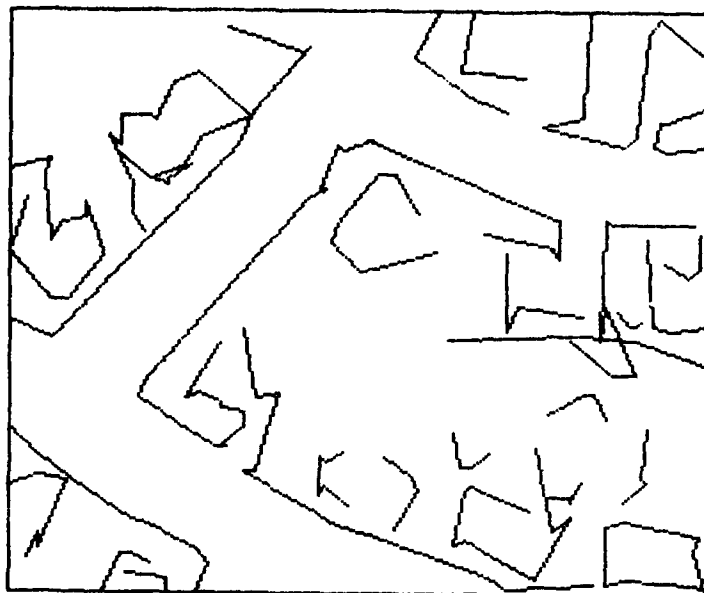


Figure 50. Line linking: $FM2=2.3$, $S_{max}=15$.

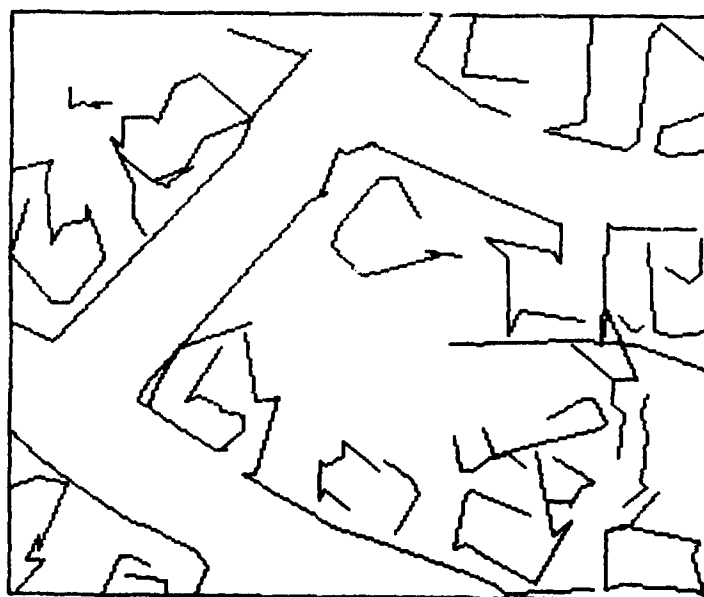


Figure 51. Line linking: $FM2=2.0$, $S_{max}=15$.

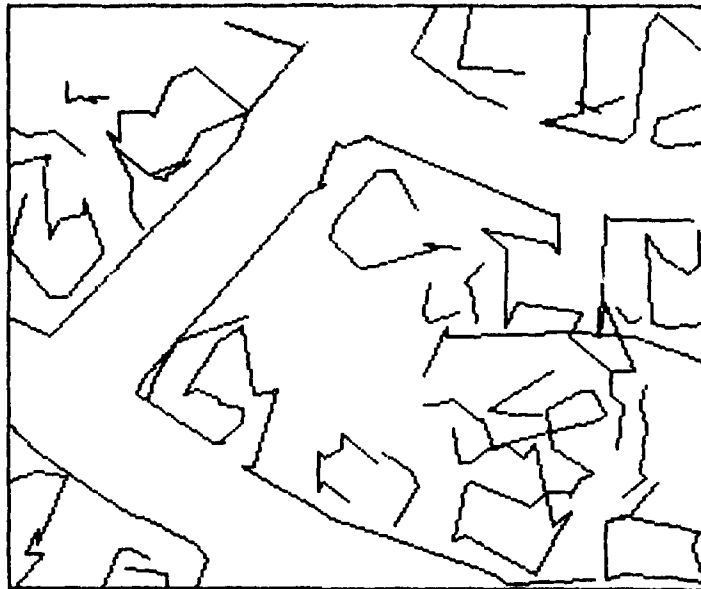


Figure 52. Line linking: $FM2=1.3$, $S_{max}=15$.

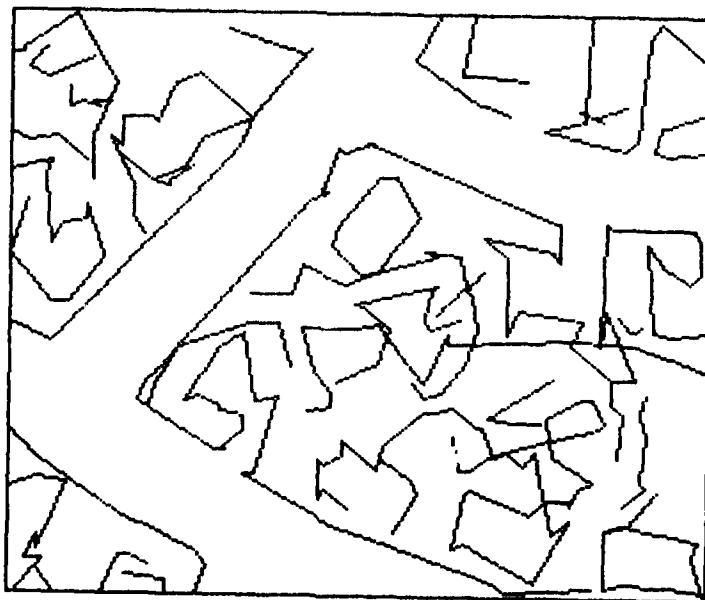


Figure 53. Line linking: $FM2=0.1$, $S_{max}=15$.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A 209517	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A METHOD FOR LINKING PAIRS OF COMPATIBLE LINEAR FEATURES		5. TYPE OF REPORT & PERIOD COVERED Technical
7. AUTHOR(s) Mohamad Tavakoli Azriel Rosenfeld		6. PERFORMING ORG. REPORT NUMBER TR-930
9. PERFORMING ORGANIZATION NAME AND ADDRESS Computer Vision Laboratory, Computer Science Center, University of Maryland, College Park, MD 20742		8. CONTRACT OR GRANT NUMBER(s) DAAG-53-76C-0138
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Night Vision Laboratory Ft. Belvoir, VA 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
12. REPORT DATE August 1980		13. NUMBER OF PAGES 55
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		18a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Image processing Pattern recognition Edge detection Linear features		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A method of linking compatible straight edges is presented and dis- cussed. The linking is based on information about the geometrical configuration of the edges, the similarity of the gray levels on their object sides, and the similarity of their object sides with the line joining their endpoints. Three figures of merit are defined for evaluating pairs of segments for possible linking. Examples are shown of applying the method to high resolution aerial photographs. Results indicate that cultural features such as roads and buildings		

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can be extracted and that a significant reduction in the complexity of the image description can be obtained. This approach should be especially useful for defining the degrees of compatibility of pairs of edges in a relaxation scheme for classifying linear feature segments.

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