Reconstruction of broken handwritten digits based on structural morphological features

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Received 18 March 1999; received in revised form 3 August 1999; accepted 25 August 1999

Abstract

In this paper, a new method of reconstructing broken handwritten digits is developed. The conditional dilation algorithm is used to bridge small gaps. Spurious segments introduced during extraction of digit fields are detected and deleted based on the morphological structural analyses of digit fields. A set of structural points of digits are detected along the outer contours of digits. The preselected broken points of the digits are determined based on the minimum distance between two structural points. The correction rules of the preselected broken points are based on the structural morphological analyses and the stroke extension. The reconstruction and recognition of handwritten internally broken digits are also discussed. Experimental results are given showing the effectiveness of the method. © 2000 Pattern Recognition Society. Published by Elsevier Science Ltd. All rights reserved.

Keywords: Broken handwritten digits; Morphological operation; Structural points; Character recognition

1. Introduction

Computerized recognition of handwritten digits has been studied for several decades. It has many practical applications, including reading postal codes and social bank checks. When handwritten digits contain broken strokes and spurious segments in their fields, it is difficult to recognize them using some digit recognition methods such as contour structural features and there are also other significant problems to overcome [1]. Broken handwritten digits are a result of segmentation and thresholding errors of noisy digits or, a result of the writing style or tools used. Some examples of broken handwritten digits are shown in Fig. 1. They are taken from the US National Institute of Science and Technology (NIST) database. In order to reconstruct the broken digits correctly, small gaps in the digits need to be bridged, spurious segments in digit fields need to be deleted, and broken points of digits need to be determined and then the missing links of broken digits need to be reformulated.

For the general stroke extension method of reconstructing broken digits, there is always a risk of forming links where none really exist, thereby creating an additional problem [2]. Another approach is to use variable-sized masks to increase the size of the link [2]. However, when using the above algorithm, if the distance between two points of a broken digit (with no link) is less than that between the other two points (with a link), a bad reconstruction of the broken digit will result.

In this paper, a new method of reconstructing broken handwritten digits is developed. In Section 2, the conditional dilation algorithm is described which bridges small gaps in broken digits, an efficient algorithm is introduced for smoothing, linearization and detection of the structural points of broken digits [3,4] is introduced, and spurious segments in digit fields are detected and deleted based on the morphological structural analysis of spurious segments. In Section 3, the preselected broken points of digits are determined based on the minimum distance between two upper block region points of a broken digit,
Fig. 1. Sample images of broken handwritten digits.

and some correction rules of the preselected broken points are discussed based on the structural morphological features. Sections 2 and 3 describe the major algorithms used in reconstructing a broken digit (demonstrated in Fig. 2). Processing is finished if only one block region (one outer contour) is detected. In Section 4, the reconstruction and recognition of internally broken digits are discussed when only one block region (one outer contour) is detected based on the analysis of morphological structures. Finally, in Section 5 the experimental results and a conclusion are given.

2. Preprocessing of broken digits

2.1. Conditional dilation

In many cases there may be small gaps in a broken digit. Dilation is a basic operation of morphological processing which can smooth the uncertain points and fill in small gaps in digit fields. The dilation process can be interpreted as follows:

\[ A \oplus B = \{ x | [(\hat{B})_x \cap A] \subseteq A \} \]

where \( A \) is the processed image, \( B \) is the structural element in dilation and \( x \) is the displacement [5]. However, there is a danger of forming links where none exist. Some examples of these are shown in Figs. 3(1) and (2), which show that the small gaps of the lower block region in Fig. 3(1) and the upper block region in Fig. 3(2) should not be linked. We therefore need to impose some conditions in the dilation operation to avoid such cases. Suppose the starting point is the upper left corner, then we have the following conditions:

Condition 1: If a candidate contour point is a convex point (in the direction of code 2), calculate the distances between it and other contour points whose y coordinate...
is less than candidate’s $y$ coordinate. If these distances are less than or equal to 3, then this candidate point and corresponding contour points found are the undilated points.

**Condition 2:** If a candidate contour point is a concave point (in the direction of code 6), calculate the distances between it and other contour points whose $y$ coordinate is greater than candidate’s $y$ coordinate. If these distances are less than or equal to 3, then this candidate point and corresponding contour points found are the undilated points.

Based on the above conditions, the undilated points as shown in Figs. 3(1) and (2) can be found. The dilation operation with the above constraining conditions (c) can be represented as follows:

$$A \oplus B = \{x|[\hat{B}]_c \cap A \subseteq A\},$$  \hspace{1cm} (2)

where “$c$” represents the conditions. The processed results of the original sample images in Figs. 3(1)–(4) are shown in Figs. 3(5)–(8) based on the above conditional dilation definition. It can be seen that there is no false
link in Figs. 3(5) and (6), and small gaps between two block regions of the broken digit in Figs. 3(3) and (4) are linked as shown in Figs. 3(7) and (8).

2.2. Contour smoothing, linearization and detection of structural points

The \( k \)th contour of a binary image is represented as

\[
C_k = \{ c_0, c_1, \ldots, c_{i-1}, c_i \},
\]

where \( C_k \) is the direction chain code set of contour \( k \), and \( i \) is the index of the contour pixels. The difference code is defined as

\[
d_i = c_{i+1} - c_i.
\]

In the smoothed contour, \(|d_i|\) equals 0 or 1 [3,4]. Based on the algorithm for the linearization of a smoothed contour [3], a smoothed contour can be converted to a set of lines. Suppose that a linearized line which consists of ordered pixels or its direction chain code set is

\[
\{ c_i^{ln} \} \quad (i = 0, \ldots, (n_l^n - 1)),
\]

where \( l_n \) is the \( ln \)th line of a smoothed contour and \( n_l^n \) is the number of points of the \( ln \)th line. A linearized line consists of ordered pixels which have the following property [3]: if

\[
d_{ij} = c_i^{ln}[j] - c_i^{ln}[j] \quad (i = 0, \ldots, k - 1), (j = 0, \ldots, k - 1),
\]

then

\[
|d_{ij}| \leq 1 \quad (i = 0, \ldots, k - 1), (j = 0, \ldots, k - 1).
\]

Therefore a linearized line only contains two elements whose direction codes meet the above equation.

For the description and recognition of a shape, we need to make use of reliable structural and geometrical information [3,6]. The definition of different structural feature points is based on the pattern models shown in Fig. 4, and 16 different characters in these figures are used to represent these structural points [3]. They are the upper convex point “^

\[
\text{Upper Convex Point (a)}
\]

\[
\text{Upper Valley Point (m)}
\]

\[
\text{Lower Convex Point (s)}
\]

\[
\text{Lower Valley Point (v)}
\]

\[
\text{Left Convex Point (l)}
\]

\[
\text{Left valley Point (f)}
\]

\[
\text{Right Convex Point (i)}
\]

\[
\text{Right Valley Point (l)}
\]

\[
\text{Convex Point of the Code 5 (F)}
\]

\[
\text{Valley Point of the Code 5 (f)}
\]

\[
\text{Convex Point of the Code 1 (O)}
\]

\[
\text{Valley Point of the Code 1 (o)}
\]

\[
\text{Convex Point of the Code 7 (S)}
\]

\[
\text{Valley Point of the Code 7 (s)}
\]

\[
\text{Convex Point of the Code 3 (T)}
\]

\[
\text{Valley Point of the Code 3 (t)}
\]

\[
\text{Convex Point of the Code 3 (T)}
\]

\[
\text{Valley Point of the Code 3 (t)}
\]

Fig. 4. The pattern models and representations of different structural points.
different chain code directions along the contour of a binary image. They can therefore be used to represent the morphological structure of a contour region [3,6]. Some original images are shown in Figs. 1(7), (3), (8), 12(1), 1(10), and (5), respectively. They are dilated with the constraining conditions, then their contours are followed and linearized, and then their structural points are extracted (as shown in Fig. 5). For visibility some structural points are marked with larger characters in Fig. 5.

2.3. Detection and deletion of spurious segments in digit fields

The spurious segments are unavoidably introduced during extraction of numeral fields from images of forms and coupons which contain the digits. Based on statistical analyses of broken handwritten digits (taken from 50,000 samples) which contain spurious segments in their fields, the ratio of occurrence of digit 1 is 46%, the ratio of spurious segment height being greater than their width is 93%, and most spurious segments distribute at one of four corners in a field, and this ratio is about 95%. For any candidate broken digit, there are at least two block regions. The block region for the one which has the biggest contour length is called the main part of the digit field, and the other block regions are the adjunctive parts. The spurious segment contour is always the adjunctive part of a digit field. Generally, if the adjunctive part of a digit field extends up or down, there are no crossing points between its extension lines and the main part of the digit field. Based on the above morphological structural analyses, it is possible to detect if an adjunctive part of a digit field is a spurious segment of it. It can be determined if the main part of a digit field is the shape of digit 1 based on structural points it contains. That is, if the main part of a digit field is the shape of digit 1, then there are no structural points “m”, “S”, “$”, and “t” on its contour [6,7].

(1) Rule 1 for detecting spurious segments.

If the main part of a digit field is the shape of digit 1, the height of the adjunctive part is greater than its width, and there are no crossing points between the up or down extension lines of the adjunctive part and the main part, then this adjunctive part of a digit field is a spurious segment. An exception to this is, that if the adjunctive part is on the left of the main part, and it is not at upper-left or lower-left corner, then the adjunctive part is not a spurious segment.

(2) Rule 2 for detecting spurious segments.

If the main part of a digit field is (a) not the shape of digit 1, (b) the height of the adjunctive part is greater than its width, (c) the adjunctive part is at one of four corners in the digit field and (d) there are no crossing points between the up or down extension lines of the adjunctive part and the main part, then this adjunctive part of the digit field is a spurious segment.

Based on the above rules, spurious segments can be found and deleted. For example, for the original image as shown in Fig. 6(1), its main part can be found, and its contour does not contain points “m”, “S”, “$”, and “t” (as shown in Fig. 6(3)). Therefore its main part is digit 1. Its adjunctive part extension is shown in Fig. 6(5). Based on the above Rule 1, its adjunctive part is a spurious segment of this digit field, and its separation result can be seen in Fig. 6(1). Similarly, the spurious segment of sample 2 in Fig. 6 can be determined and deleted based on the above Rule 2. For sample 3 of Fig. 7, as there are crossing points between the extension lines of its adjunctive part and its main part, its adjunctive part is not a spurious part based on the above Rule 2. Other examples are shown in Fig. 8.

3. Broken points preselection and correction

The dilation operation with the conditional conditions can only link small gaps in the broken digits. A method for linking big gaps is developed, which combines morphological structure features with stroke extending.

3.1. Preselection of broken points

A broken digit contains at least one missing link between two block regions. The broken points (points “∧”, “∨”, “[”, “>”, and “<”) are the terminal points of the missing link between two block regions of the broken digit. If these broken points can be determined, then the missing link of the broken digit can be reconstructed. In most cases, broken points are the structural points of each block region, and the distance between two broken points which are in different block regions respectively, is minimal as the morphological structure of the broken digits is analysed. Based on the above description, therefore, broken points can be preselected as follows:

1. Find the upper-most point “∧”, the lower-most point “∨”, the leftmost point “[” and the rightmost point “]” in each block region.

2. Calculate the distance between the two points found in Step 1 by the above processing step. Because there are four distances between one point in one block region and four points in another block region, sixteen distances between two block regions can be determined.

3. Preselect broken points between which minimum distance can be determined.

Based on Step 1, the processed result is shown in Fig. 9. Based on Steps 2 and 3, the preselected broken points are shown in Fig. 10. In Figs. 9 and 10, for visibility the region points found and the preselected broken points are marked with large characters. It can be seen that the
Fig. 5. The structural points of the sample images.
Fig. 6. Detecting and deleting spurious segments of two samples.

preselected broken points in Figs. 10(1) and (2) are correct.

3.2. Correction of preselected broken points

In most cases, the preselected broken points are correct. However, some false selection of broken points may occur especially if the distance between the two preselected broken points is large. For example the distance between the two preselected broken points of Figs. 10(3) and (6) is large compared to the height of the whole digit, therefore their preselected broken points are false. For Fig. 10(4) the preselected broken points are also false. For Fig. 10(5), only one pair of broken points is selected, but
in fact there is another pair of broken points. In such cases it is necessary to correct the preselected broken points. The correction rules are based on extending the two neighboring lines of the preselected broken points and on the morphological structural analyses of the broken digits in each case.

In order to determine if preselected broken points which are similar to those shown in Fig. 10(3) are real broken points, it is necessary to analyze their extending lines. That is, if there are crossing points between the extending lines related to the preselected broken points “∧” on the lower block region and “∨” on the upper block region, then these preselected broken points are real selected broken points. Otherwise, other points “∧” on the lower block region are selected as new candidate broken points. Which point “∧” on the lower block region is the real selected broken point depends on its extending result. The extending lines which are related to
Fig. 9. The region points of the sample images.
Fig. 10. The preselected broken points of the sample images.
the preselected broken point “∧” are its two neighboring
to the rate of the two elements of each extended
related to the preselected broken point “∧” of the upper block region is similar to
the case described above except that the extension direction is upwards.
Based on the above analyses and description, the fol-
the case described above except that the extension direc-
point equals that of the broken point

digit be \( h_{ud} \) and compare it to the distance between the
preselected broken points in order to determine whether it is large or small.

**Correction rule 1.** If the preselected broken points are
points “∧” of the upper block region and “∧” of the
lower block region, and the distance between two
preselected broken points is greater than a quarter of \( h_{ud} \),
then the correction procedure is as follows:

1. Two neighboring lines of the preselected broken
point “∧” are extended downwards until the \( y \) coordinate
of the extension point equals that of each broken
point “∧” of the lower block region.

2. Two neighboring lines of the preselected broken
point “∧” are extended upwards until the \( y \) coordinate
of the extension point equals that of the broken point “∧”
of the upper block region.

3. If there are crossing points between the extending
lines (by step 2) of one point “∧” on the lower region and
the extending lines (by step 1) of point “∧”, then this
point “∧” and point “∧” are the selected broken points.

Based on Step 1, the down-extensions of the stroke in
the sample image in Fig. 11(1) is represented by charac-
ters “∧”. Based on Step 2, the up-extensions of the stroke
of the sample image in Fig. 11(1) is represented by charac-
ters “∧”. Based on Step 3 the left point “∧” on the lower
block can be found (as shown in Fig. 11(2)), and it is a
newly selected broken point. Based on the selected
broken points of the broken digit, the missing link of
the stroke can be created (as shown in Fig. 11(3)). The
reconstructed digit is shown in Fig. 11(4).

For the sample image in Fig. 12(1), the minimum
distance between the two block regions of the broken
digit is between the leftmost point “[” of the upper block
region and the uppermost point “∧” of the lower block
region. The preselected broken points are shown in Fig.
10(4). It is clear that these preselected broken points are
false. When we analyze the contour morphological struc-
ture of handwritten digits, we find that generally there are
two points “S” in the series of structural points of digits
3 and 7 (having a line overlap the vertical part of numeral
7) [3,6]. This means that there are two curves in the
convex direction of code 7 along the left lateral of the
digit. Therefore, if the morphological structure of the
outer contour of the upper block region belongs the
above case, then that the preselected broken points are
leftmost “[” of the upper block region and the upper-
most point “∧” of the lower block region is therefore
unreasonable. Based on the above analyses we can de-
scribe the correction rule of those cases which are similar
to Fig. 10(4).

**Correction rule 2.** If the broken points are the leftmost
point “[” of the upper block region and the uppermost
point “∧” of the lower block region, then the correction
procedure is as follows:

1. Determine whether there are two points “S” in the
series of structural points on the outer contour of
the upper region.

2. If Step 1 is true, then the lowermost point “∧” of
the upper region is selected as a new broken point and
the rightmost point “)” is selected as another broken
point instead of the preselected points.

For example, the sample image in Fig. 5(4) demon-
strates that there are two points “S” in the series of
structural points on the outer contour of the upper
region. Therefore, based on Correction rule 2, the preselec-
ted broken points are corrected as point “∧” of the
upper block region and point “)” of the lower block
region as shown in Fig. 12(2). Based on the selected
broken points of the broken digit, the missing link of
the stroke can be created as shown in Fig. 12(3). The recon-
structed digit is shown in Fig. 12(4).

In some cases, it is possible that there are two missing
links. For example, the sample image in Fig. 5(5) demon-
strates such a case. Its original image is shown in
Fig. 1(10) and its region points and preselected broken
points are shown in Figs. 9(5) and 10(5), respectively. In
this case we can use morphological structure information
to determine if there are two missing links between the
two block regions. If the structural points on the outer
contour of the upper region follow a structural series:
“[” → “]” → “[” → “S” → “)” → “(” → “)”, then it is
the morphological description of a broken digit 8. In this
case, there are two missing links. Therefore, we can de-
scribe the following correction rule

**Correction rule 3.** If the preselected broken points are
points “∧” of the upper block region and “∧” of the
lower block region, and the distance between the two
preselected broken points is less than a quarter of \( h_{ud} \),
then the correction procedure is as follows:

1. Determine whether there is one series of structural
points, “[” → “]” → “[” → “S” → “)” → “(” → “)”, on
the outer contour of the upper block region.

2. If Step 1 is true and there are two points “∧” of
the lower contour of the lower region, then the left point “∧”
of the upper region and the uppermost point “∧” of the lower
region consists of one pair of broken points. Another pair
Fig. 11. An example of the correction rule 1.

The selected broken points of the broken digit can be found based on Step 2 of Correction rule 3, as shown in Fig. 13(2). Based on the selected broken points of the broken digit, two missing links of the stroke can be created as shown in Fig. 13(3). The reconstructed digit is shown in Fig. 13(4).

Similarly, for the other cases of unreasonable preselected broken points corresponding correction rules can be
set up. Based on these correction rules, broken points can be determined, missing links of the broken digits can be created, and these digits can be reconstructed. Based on our method, the sample images of Fig. 1 can be reconstructed, and some results of reconstructed digits are shown in Fig. 14. The reconstructed result of the sample image in Fig. 1(11) is shown in Fig. 14(7). For this case, the correction rule used is similar to Correction rule 3. The difference is that the determination of structural morphology only operates in the lower block region.

Based on the above procedures the broken digits can be reconstructed until there is only one block region for these broken digits. Two multi-broken digits are shown in Fig. 15. The original image shown in Fig. 15(1) has
three broken components. Based on the above algorithms the first link shown in Fig. 15(2) can be found. When the above algorithms are applied again, the second link shown in Fig. 15(3) can be found. The final reconstructed digit is shown in Fig. 15(4). The original image of another sample that has four broken components is shown in Fig. 15(5). Based on our algorithms, the first, second and third links can be found, and the results are shown in Figs. 15(6)–(8), respectively. The final reconstructed digit is shown in Fig. 15(9).
4. The reconstruction and recognition of internally broken digits

If a digit only consists of one block region (one outer contour), it is possible that it may be broken internally. Some examples are shown in Fig. 16. It is clear that these digits are mainly broken digits 0, 2, 4, 6, 8, and 9. An internally broken morphological structure is usually caused by broken inter contour. In some cases, a digit is broken internally broken because of writing styles. Such examples are shown in Figs. 16(5), (14), (17), and (21).

The reconstruction of internally broken digits can be done based on morphological structure. If we can distinguish between different structures in Fig. 16, we can recognize these broken digits and reconstruct them. The structural points can be used to describe morphological structures [6,8] as they represent convex or concave changes in a direction chain code [3]. The shape description of internally broken digits can be represented by...
a series of ordered structural points and their geometrical locations. The algorithm for reconstruction and recognition of internally broken digits is described below:

**Case 1.** The model in Fig. 16(22) is a broken digit 0 which includes a lower cut. A practical sample is shown in Fig. 17, in which the original image is shown in Fig. 17(1). After the digit is processed by algorithms described in Section 2 (conditional dilation), we obtain the result shown in Fig. 17(2). The image of Fig. 17(2) is processed by algorithm described in Section 2 (contour smoothing, linearization and detection of structural points), and the result is shown in Fig. 17(3). The image of Fig. 17(2) is thinned by a improved thinning algorithm,\(^1\) and the result is shown in Fig. 17(3), where character “e” represents end point of thinned line, and “j” is its junction point. The recognition of the image in Fig. 17(3) is based on following conditions.

1. The following structural points exist as morphological structural feature vector of the image in Fig. 17(3):
   
   \[
   \text{“F”} \rightarrow \text{“I”} \rightarrow \text{“V”} \rightarrow \text{“D”} \rightarrow \text{“D”} \rightarrow \text{“$”} \rightarrow \text{“}]
   \]
   
   \[
   \rightarrow \text{“ V”} \rightarrow \text{“} ] \rightarrow \text{“ \&”}
   \]
2. Suppose the \( y \) coordinate of point "S" in the series selected by Step 1 is \( h_s \), and the height of this digit is \( h \), then \( h_s < h/4 \). That means the selected point "S" should be in the upper region.

If there is only one region (one outer contour) in an image and its outer contour meets the above two conditions, then the image belongs to the model shown in Fig. 16(22), and that is broken digit 0 which includes a lower cut. For this model the missing part can be found by extending lower outer contour points as shown in Fig. 17(4). The reconstructed image is shown in Fig. 17(5).

Case 2. The internally broken digit 6 which includes a lower cut is shown in Fig. 16(10). A real image is shown in Fig. 18. Its original image is shown in Fig. 18(1). The image of Fig. 18(1) is processed by algorithm described in Sections 2 and 3, and the missing part of the first reconstructed image is shown in Fig. 18(2). The boundary of the first reconstructed image is traced, linearized, and thinned. Also its structural points are detected, and shown in Fig. 18(3). The recognition of the image in Fig. 18(3) is based on following conditions.

1. The following structural points exist as morphological structural feature vector of the image in Fig. 18(3):

   \[ \text{"F"} \rightarrow \text{"["} \rightarrow \text{""} \rightarrow \text{"$"} \rightarrow \text{"["} \rightarrow \text{""} \rightarrow \text{"\^\"} \]

   \[ \rightarrow \text{"m"} \rightarrow \text{"("} \rightarrow \text{"\^\"}. \]

2. Suppose the \( y \) coordinate of the first point "\^\" in the series selected by Step 1 is \( h_{s1} \), and the height of this digit is \( h \), then \( h_{s1} > h(4/5) \). That means the first selected point "\^\" should be in the lower region.

3. The contour containing the last point "\^\" in the selected series of structural points is the last line of the outer contour.

If an image meets the above three conditions, the image belongs to the model of Fig. 16(10), and their broken points are two lower points "\^\". Based on the above algorithm we can find the broken points of the image in Fig. 18(3). The missing part found is shown in Fig. 18(4), and the final reconstructed image is shown in Fig. 18(5).

Case 3. Another reconstruction and recognition model of broken digit 8 which includes two cuts is shown in Fig. 16(13). A real sample is shown in Fig. 19. Its original image is shown in Fig. 19(1). The image of Fig. 19(1) is processed by algorithm described in Sections 2 and 3. The processed result of conditional dilation and found missing part between two upper regions are shown in Fig. 19(2). The first reconstructed result is shown in Fig. 19(4). It is processed by algorithm described in Section 2 (contour smoothing, linearization and detection of structural points), and the result is shown in Fig. 19(3). The recognition of the image in Fig. 19(3) is based on following conditions.

1. The following structural points exist as morphological structural feature vector of the image in Fig. 19(3):

   \[ \text{"["} \rightarrow \text{"("} \rightarrow \text{"$"} \rightarrow \text{"\"} \rightarrow \text{"\"} \rightarrow \text{"m"} \rightarrow \text{"\^\"}. \]

2. Suppose the \( y \) coordinate of the point "\^\" in the selected series by Step 1 is \( h_{m1} \), and the height of this digit
is $h$, then $h_m > h/4$. That means the selected point “m” should not be in the more upper region.

If an image meets the above two conditions, the image belongs to the model of Fig. 16(13). This model has two cuts. Therefore the final reconstructed result is shown in Fig. 19(5). Similarly, we can deal with other models in Fig. 16.

5. Experimental results and conclusions

A new and efficient method of reconstructing broken handwritten digits has been developed using the conditional dilation method, the morphological structural analyses and the stroke extension method. Small gaps in broken digits can be linked based on the algorithm of the conditional dilation. An efficient algorithm for smoothing, linearization and detection of the structural points of broken digits makes the morphological structural analyses of broken digits possible. All image data are taken from the NIST database. It consists of 2100 forms completed by participants in the US census, scanned at 300-dotin. resolution and they are processed into separated binary images [9]. Some images have spurious segments because they do not fall within the area expected to be occupied by the digits. The spurious segments of digit fields can be determined and deleted based on the morphological structural analyses and the segment extension analyses of digit fields. There are sixteen cases of broken points between the upper and lower regions of the broken digits based on the minimum distance between two structural points. For each case, two broken points are preselected. In most of cases these preselected broken points are correct. However, in some cases the preselected broken points need to be corrected. The correction rules are based on the morphological structural analyses and the stroke extension of the broken digits. In order to set up models for these correction rules, 210 sample images taken from the database of NIST are used. There are 150,000 binary handwritten digits in the database of NIST. It contains about 2600 broken handwritten digits. For these broken digits, the rate of correctly reconstructed broken digits is 96%. When the method of digit recognition uses contour feature vector [10], the broken handwritten digits cannot be recognized. Therefore, in this case our reconstruction algorithm is useful. If the recognition algorithm is optimized nearest-neighbor classifier (ONNC) [11,12], the recognition rate is 98.1% without any reconstruction of broken digits, and 99.6% after reconstruction of broken digits. Incorrect reconstruction of the broken digits for the test images is caused by some special new structures not considered in our methods. However, we can generally add new procedures for special cases to enhance the reconstruction performance. If the recognition algorithm is optimized nearest-neighbor classifier (ONNC) [11,12] (neural networks) on a Sun Sparc 2 workstation, the average time of recognizing one handwritten digit is 0.02 s. If our reconstruction method is used, the average time of recognizing one broken handwritten digit is 0.23 s. Therefore, though recognition rate is improved, total recognition time is increased after using our reconstruction algorithm.
However, it is acceptable because the number of broken digits only is a little part of handwritten digits.

The newly developed algorithm is efficient because useful morphological structural analyses and stroke extension of the broken digits can be used to identify the broken points, make the missing link between two block regions, and determine and delete spurious segments of digit field. The method of linking broken digits with variable sized masks [2] cannot be used to link digits with large gaps, as shown in Figs. 1(4) and (5) and (8), and neither can it deal with the question of the spurious segments of a digit field. Also, if a digit is broken, there is at least one gap. However, if there is a gap, it is possible that it is part of the normal structure of the digit and in this case should not be linked. After a mask size is selected, it is still possible for both true and normal gaps to be linked. If a large-sized mask is selected for a large gap, then the reconstructed broken digit will be distorted [2]. If the general stroke extension method is used, it is difficult to select the threshold of the extending link length. If this threshold is small, then a big gap such as those of the sample images in Figs. 1(4) and (5) and (8) cannot be linked. If it is large, then it is possible that normal gaps of the broken digits are linked incorrectly. Such an example is shown in Fig. 12(1). The new method developed in this paper is more efficient because it makes links based not only on the stroke extension but also on the morphological structure of the broken digits. Therefore, based on this method both small and large true gaps of broken digits are linked, but the normal gaps of broken digits are not.

Although the developed algorithms are used to reconstruct broken handwritten digits, they can also be used to reconstruct broken handwritten letters if we can analyze morphological structures of the broken characters. Also, conditional dilation and finding broken points based on the minimum distance between two upper regions can be used for construction of broken characters. Some samples are shown in Fig. 20. The original images of handwritten characters “F” and “k” are shown in Figs. 20(1) and (2), respectively. After they are processed by conditional dilation, the results are shown in Figs. 20(6) and (7). Two other original images of handwritten characters “g” and “e” are shown in Figs. 20(3) and (6), respectively. The links can be found in Figs. 20(4) and (9), respectively, based our algorithms. The final reconstructed images are shown in Figs. 20(5) and (10). We can see that the method can work well with handwritten letters as well.

Acknowledgements

This work is supported by the Australia Research Council.

References


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