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# AN IMPROVED METHOD FOR SKELETONIZATION OF TWO-DIMENSIONAL REGIONS THAT TAKES INTO ACCOUNT BOUNDARY FEATURES

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The problem of two-dimensional area skeletonization that takes into account boundary features is considered. A modification of Zhang-Suen parallel thinning algorithm is proposed. The modification utilizes boundary tracking for boundary features detection. Skeletons that were obtained by means of the proposed method were found to be persistent to region rotation. The method was utilized for dactyl images skeletonization and processing.

Keywords - skeletonization, thinning, dactyl recognition

Розглядається задача скелетонізації двовимірної області із врахуванням особливостей контуру. Пропонується модифікація методу скелетонізації Чжана-Суна, яка використовує попередній обхід контуру для визначення його особливих пікселів. З використанням нового методу отримано скелети, стійкі до повороту області. Метод застосовано для скелетонізації зображень кисті руки в дактильній абетці.

# Ключові слова - скелетонізація, потоншення, розпізнавання дактилю

## Introduction

The topological skeleton of a two-dimensional region plays an important role in object representation and recognition. Skeleton-based models are successfully used for solving handwriting analysis [1], flexible object comparison [2], detection of pedestrians [3] tasks. The models can also be utilized to identify elements of a sign language and determine the position of the human body [4] as well.

The main property of the skeleton is the preservation of the original object's shape and topological structure. However, skeletonization algorithms are sensitive to noise and the object boundary deformation what can seriously influence the skeletonization result.

The skeleton of a closed two-dimensional region is a set of all points of the region, each of which has at least two closest points equidistant to the region boundary of the region [5]. The skeleton can be represented as a set of segments. There are two classes of skeleton construction methods. The former utilizes a set of polygons to represent a region boundary and the latter utilizes a raster representation of a region.

Methods based on a raster representation are called the skeletonization or thinning methods. The skeleton obtained is represented as a plurality of pixels and can be considered the approximation of a twodimensional skeleton of a region. It should be obtained one pixel thick and must be connected if the processed region is connected.

Methods based on a polygon representation provide stable skeletonization results, but the known implementations [6, 7] perform slowlier in the case of non-convex regions with holes. They sometimes lead to incorrect results due to the imprecision of floating-point arithmetic.

In contrast, methods that work with a raster representation are guaranteed to complete in a finite number of steps and do not involve any floating-point computations. One of the well-known methods for region skeletonization is the Zhang-Suen digital image parallel thinning algorithm [8]. The algorithm works well for thinning binary images and is easy to run in parallel computing environment, using multi-core CPU or GPU. For small bitmap images of up to 640x480 pixels in scale, the Zhang-Suen algorithm is approximately two times faster than a well-known Felkel-Obdrzhalek skeletonization algorithm implemented by Roger James for the Library Virtual Terrain Project (VTP). The disadvantage of the

known skeletonization methods is that these methods cannot distinguish between small variations of a boundary and a significant change in it. This is due to the fact that these methods are using a small neighbourhood of processed pixels. As a result, the constructed skeletons vary considerably when the two-dimensional region is rotated in relation to the coordinate system (Fig. 1). For some figures, the skeletons do not reproduce the figures' corners and are shifted to their centres (Fig. 2).



Fig. 1 The Zhang-Suen algorithm thinning result depending of the region rotation



Fig. 2. The Zhang-Suen algorithm does not take into account the visible corners of figures

The study of different skeletonization algorithms [9, 10, 11, 12] has shown that there are no reliable and fast methods that can solve the above mentioned problems.

#### Statement of the problem

The skeleton-based pattern recognition methods require the development of a fast and reliable region skeletonization method. The obtained two-dimensional skeleton of the region should be persistent to rotations and small shape deformations.

A two-dimensional image can be represented as a matrix  $M = \{m_{ij}\}_{h \times w}$ ,  $1 \le i \le h, 1 \le j \le w$ , where h, w are the height and width of the matrix, respectively,  $m_{ij} \in \{0,1\}$  are the elements of the matrix. The area is defined by the matrix elements equal to one. Let  $m_{ij}$  denote a pixel with coordinates (i, j).

The boundary of the region is assumed to be a plurality of pixels that are adjacent vertically or horizontally to the pixels that lie outside of the region.

The boundaries that occur in pattern recognition problems usually contain visible corners, that can be associated with some certain characteristics of a form, and a large number of irregularities induced by noise and considered insignificant (Fig. 3).



Fig. 3. Small, insignificant irregularities(left) and important angle(right)

Let special boundary pixels be the pixels that are the vertices of all well-visible corners. This definition is fuzzy, but such pixels should remain "special" when rotating the area.

This paper presents a method for determining special boundary pixels and a skeleton construction method providing for the preservation of all special pixels at the vertices and ensuring the skeleton persistence to area rotation.

# The proposed solution

The 2-dimensional region processing is performed in two stages. The special boundary pixels search is performed in the first stage. The skeleton of the region is built in the second stage. The special pixels found before are used in this stage.

Because there is no strict mathematical definition of a special boundary pixel, let us introduce a heuristic function whose value will indicate whether a pixel of the boundary generates a visible angle or not. A variety of methods for evaluating discrete curvature can be used to construct such a function [13]. Among the indexes that can be quickly evaluated there is the angle constructed from a current pixel to pixels of the boundary, taken at an equal number of steps (Fig. 4). The number of steps that is best suited to solve a particular problem class depends on the processed area size and possible irregularities. A larger number of steps are used to ignore bigger contour irregularities.

The special boundary pixels can be determined by a small value of the angle  $\varphi$ . We introduced a search criterion for such kind of boundary pixels:

- 1) angle  $\varphi$  must be less than a threshold value  $\Phi$ ;
- 2) angle  $\varphi$  must be an external corner of the boundary;
- 3) in the *s* pixels neighbourhood, there should be no boundary pixel with a smaller value of angle  $\varphi$ ;
- 4) pixel must reside on a locally convex part of the boundary (fig. 5).

The introduced 3 and 4 criteria are the further development of a well-known corner detector described by Rosenfeld and Azriel [14]. These criteria are introduced to make it possible to use the skeletonization method described below.

In order to find the special boundary pixels, the clockwise boundary tracking procedure is used. The value of  $\cos(\varphi)$  is calculated over the boundary. The larger  $\cos(\varphi)$ , the sharper the corresponding angle.

In case the processed region is not connected, it is necessary to process the boundaries of all its connected parts.



Fig. 4. Angle  $\varphi$  with a vertex in pixel K of the boundary, built to pixels L and M taken through s = 8 pixels of the boundary



Рис. 5. Локально опуклі (К, М) та локально вгнута (L) частини контуру

Now an algorithm for identifying the special boundary pixels (AISBP) is formulated. The algorithm takes a matrix M as an input and returns the set of special boundary pixels  $V = \{(i_k, j_k)\}$ . The algorithm comprises the following steps:

**Initialization.** Set  $V = \emptyset$ .

**Step 1.** Search for the pixels not belonging to any boundary found before using a condition  $(m_{ij} = 1) \land (j = 1 \lor m_{i,j-1} = 0)$ . The search is done sequentially for all pairs  $1 \le i \le h, 1 \le j \le w$ . The algorithm stops when there are no more such pixels.

**Step 2.** Trace the boundary, starting with the pixel (i, j), and create a list  $C = \langle c_k \rangle, c_k = (i_k, j_k), k = \overline{0, n-1}$ , where *n* is the length of the list.

Step 3. Trace the boundary and evaluate 
$$G_1(k)$$
,  $G_s(k)$ , and  $F(k)$  functions:  
 $G_1(k) = [(c_k - c_{k-1 \mod n}) \times (c_{k+1 \mod n} - c_k)]_z$   
 $G_s(k) = [(c_k - c_{k-s \mod n}) \times (c_{k+s \mod n} - c_k)]_z$   
 $F(k) = \begin{cases} 0, if G_1(k) < 0 \lor G_s(k) < 0 \\ \frac{(c_{k-s \mod n} - c_k) \cdot (c_{k+s \mod n} - c_k)}{\|c_{k-s \mod n} - c_k\|}, if G_1(k) \ge 0 \land G_s(k) \ge 0 \end{cases}$ 

for  $k = \overline{0, n-1}$ . The function  $G_s(k)$  value is a z-component of a cross product of two-dimensional vectors  $(c_k - c_{k-s \mod n})$  and  $(c_{k+s \mod n} - c_k)$  complemented with a zero. Its value shows whether a corresponding angle  $\varphi$  is an external angle (fig. 6). If  $G_s(k) < 0$ , then the angle is internal. In this case, the value of F(k) is set to zero. If  $G_1(k) < 0$ , then the pixel  $c_k$  lies on a locally concave part of the boundary. If  $G_1(k) \ge 0 \land G_s(k) \ge 0$ , then the angle is external, and a value of function F(k) is the cosine of angle  $\varphi$  built from the pixel to the boundary points that lie through *s* points before and after the pixel  $c_k$ , where *s* is the parameter of the algorithm. The parameter *s* sets the amount of pixels of the boundary to skip.



Fig. 6. Geometrical meaning of function F(k). In this example s = 10.

**Step 4.** Search for "good" local maximums of the function F(k). The maximum is considered to be "good", if a pixel  $(i_k, j_k)$  is a locally convex pixel of the boundary, the value of F(k) is larger than the threshold value  $\cos \Phi$  and also is equal or larger than the value of F(k) in the s-pixel neighbourhood of the pixel  $(i_k, j_k)$ . In case when there are more than one equal maximum of F(k) in the s-pixel neighbourhood, the first of them in the tracking direction is selected. As an alternative, one can select a maximum that is a median among other in the neighbourhood.

Such choice of maximums guarantees a local convexity of the boundary in the special boundary pixels, and the angle is the sharpest angle in its neighbourhood. The parameter *s* controls the casting-out of the boundary roughness caused by the noisiness and inaccuracy of image thresholding methods.

**Step 5.** Mark the pixels of the boundary C by values  $m[i_k, j_k] = 2$  and proceed to the step 1.

Step 6. Return the set of the special boundary pixels.

The overall complexity of the AISBP algorithm is  $O(w \cdot h)$  because the algorithm has to visit all pixels of matrix M one time and trace each boundary, the total length of all boundaries does not exceed the total number of all matrix elements. The AISBP algorithm is executed once before the application of the Zhang-Suen thinning algorithm.

After the special boundary pixels are determined, the Zhang-Suen thinning algorithm is executed while taking into account these pixels. There are two approaches to implement the algorithm:

1) modification of the algorithm steps;

2) change of region shape to preserve the special boundary pixels.

Because the first method slows down the algorithm, the second approach is more suitable for realtime applications such as a hand shape recognition problem. In order to preserve the special boundary points, two pixels were added to the processed region. They preserve the algorithm from removing these pixels from a resulting skeleton. These pixels were added in such a way, that they touched the boundary only in one pixel (fig. 7). There was such a possibility because the special pixels were selected at the locally convex areas of the boundary.



Fig. 7. Addition of pixels to the object area corner (on the left) and side (on the right). The added pixels are shown in black. The special pixel is marked with a dot.

All processed images made it possible to make such changes to the two-dimensional region without making changes to the image topology. After making alteration to the area, the original Zhang-Suen algorithm was used.

#### **Experimental results**

The developed algorithm was tested on two image sets. The first set contained geometrical figures and the second consisted of hand shapes from the Ukrainian sign language alphabet.

More accurate result was achieved by means of the implemented modification that utilizes the AISBP algorithm when comparing to the Zhang-Suen thinning algorithm (fig. 7) and rotated shapes (fig. 8).



Fig. 7. Skeletons of geometrical figures obtained by the Zhang-Suen thinning algorithm (on the left) and implemented modification that utilizes AISBP (on the right)



Fig. 8. Skeletons of triangles rotated to different angles obtained with the Zhang-Suen algorithm (on the left) and implemented modification that utilizes AISBP (on the right)

In order to test the implemented algorithm on the Ukrainian sign language recognition problem, 40 frames with different hand shapes were selected. These frames contained all static hand shapes that correspond to dactyl letters and several frames for letters ' $\Lambda$ ', ' $\epsilon$ ', ' $\Lambda$ ', ' $\beta$ ' shown in dynamics. A few frames for letter 'P' where selected because a hand shape changes a lot depending on the gap between the index and nameless fingers.

The skin colour segmentation algorithm was applied to determine a hand shape region by means of a neural network [15]. The obtained two-dimensional regions where thinned with the aim of further comparison and processing.

A comparison of the skeletons obtained by means of the Zhang-Suen thinning algorithm showed that in 7 cases out of 40 the obtained skeletons were subject to a considerable change depending on the rotation angle. The example of such change is shown on fig. 9. A considerable change was observed for the letters ' $\ddot{H}$ ', 'K', ' $\Pi$ ', 'C', 'T', ' $\Psi$ ', 'b'. A result resistant to rotation was obtained for 38 hand shapes out of 40 by means of the modified Zhang-Suen thinning algorithm that utilizes AICSP with parameters  $\Phi = 65^{\circ}$  and s = 10. A significant change to the skeleton due to rotation was observed only in two hand shapes out of 40 (dactyl letters 'Й' and 'Ь'). The method parameters where tuned by using the Video Recognition Toolkit.



Fig. 9. Skeletonization result by means of the Zhang-Suen thinning method (on the left) and with the implemented modification that utilizes AICSP (on the right)

The performance of the algorithm was evaluated on a computer with a quad-core processor Intel Core-i5 3.1 GHz. It takes 77 ms to obtain skeletons for 40 frames 180x136 pixels in size with the modified algorithm that utilizes AISBP and 73 ms with the Zhang-Suen algorithm. The skeletonization time of one frame was less than 2 ms that is sufficient for real-time applications such as sign language recognition software.

### Conclusions

The Zhang-Suen thinning algorithm was improved by adding a procedure that identifies special boundary points. A stable to rotation result was obtained by means of the developed algorithm. The method performed well on basic geometrical figures and hand shapes from the Ukrainian Sign Language dactyl alphabet.

The study of the skeletons obtained showed that these skeletons do not correspond to fingers because the thresholded region does not contain any information about a hand illumination that is necessary for locating the fingers. The developments of methods, taking into account the illumination factors will be the subject for further researches.

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