A Hybrid Algorithm for Contour Thinning in Image Processing

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***Abstract*—Visual data processing is a rapidly expanding field, with image processing aimed at enhancing image features for object recognition. Typically, an initial captured image undergoes pre-processing, followed by segmentation. Segmentation results directly depend on the results of image processing stage. Precise contour separation of objects is crucial for effective segmentation; however, contouring methods often produce thick contour lines, leading to unnecessary information in the final image. Contour thinning algorithms address this issue, yet many existing algorithms lack real-time applicability and fail to deliver precise contour separation. The use of modern deep learning algorithms is considered inefficient due to the fact that they require large amounts of training data, a large number of computing resources, and are not adapted to work in real time. This highlights the need for advanced algorithms that meet real-time requirements and improve contour accuracy. In this research work, a hybrid algorithm for thinning image contours that has passed through image pre-processing steps is proposed, and it is compared with existing algorithms in terms of pixel matching and time criteria. Computational experiments demonstrate that the hybrid algorithm outperforms current options, making it a practical recommendation for real-time applications.**

***Index Terms*—contour detection, image processing, contrast enhancement, noise reduction, Sobel filter.**

I. INTRODUCTION

VISUAL data processing is rapidly advancing due to developments in image processing and recognition technologies. In image processing systems, after receiving a natural image, it is subjected to a pre-processing process. The preliminary processing of images is carried out in two main stages, that is, in the stages of image formation and its encoding (compression). Image formation is a procedure for obtaining an image in the form of discrete elements that form a matrix or contour in the memory of video processors. Depending on the type of image obtained, the encoding can be performed before or after segmentation. If the image contains several objects, then it is desirable to perform segmentation before encoding. In this case, the segmentation results depend on the output image formed in the image processing stage. This research work is dedicated to the stages of image processing, in which a hybrid algorithm for thinning image contours is proposed.

In technical vision systems, the image is filtered during the image processing stage, that is, hardware or software interference is attenuated and the discrete image is smoothed. Also, at this stage, the contours that store about 90% of the information about the image are separated. Contrast enhancement, noise reduction, binarization, contour separation, and thinning are commonly used in image processing. Algorithms for segmentation, formation of object features, and identification of informative features from the set of formed features are used to recognize objects in the image [1]. Interesting works on the formation of informative features are described in detail in the literature [2-11]. Segmentation is a very important stage of recognition, the result of which directly depends on the correct and accurate separation of contours at the stage of image processing.

Contouring is the process of identifying points where the brightness of a digital image changes sharply using certain mathematical methods, and the detected points usually represent curves. The resulting curves are called object boundaries or contours. A contour can be defined as the border of two different regions of an image. Contour detection significantly reduces the amount of data that needs to be processed and filters out invalid or irrelevant data, allowing the important information in the image to be extracted. The correct and complete extraction of contours when determining the object's boundaries in the image depends on the image, which is without various noises and distortions and has a normal level of contrast. Too much noise in the image causes false contours to appear, and not enough contrast prevents the contours from being captured clearly and completely. Eliminating these problems is one of the main goals of image processing.

As a result of contour separation and the application of binarization algorithms to it, the boundaries of objects can be formed in the form of thick lines. This increases the amount of data in the image that need to be processed. The thickness of the contour lines creates various problems in distinguishing objects, forming symbols for recognition, and expressing information about the object. In particular, in industrial inspection and medical imaging, it leads to an increase in invalid data and a decrease in necessary data. This occurs when fine details and edges in objects or shapes in images are not captured clearly. In image segmentation and recognition, the accurate definition of object boundaries is critical, and the application of contour thinning algorithms leads to the correct classification of image objects.

In medical imaging, thick contour lines can obscure image

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features or lead to misinterpretations, leading to patient misdiagnosis when delineating organs or tissues. Also, thin contours make it possible to segment objects such as tumors, vessels, or bones in medical diagnosis, and to estimate their size and volume more accurately.

In addition, in areas such as materials science or quality control, where precise measurements are required to evaluate the properties of the product or detect defects, the presence of thick contours adversely affects the performance of automated inspection systems. Although many algorithms for thinning object contour lines have been developed, most of them do not meet the requirements of real-time mode. Analysis of existing contour thinning algorithms shows that they have a number of important technical limitations. The Zhang-Suen algorithm, due to its high computational complexity, works slowly on large images and requires a lot of memory resources. The Hilditch algorithm can lead to contour breaks in complex geometric shapes. Although the K3M algorithm gives good results in preserving fine details in the image, the computational time is significantly higher. The Guo-Hall method, on the other hand, is observed to oversimplify contours in some cases. The Stentiford algorithm cannot preserve contour integrity in complex shapes. In addition, some algorithms tend to oversimplify or thin contours, which can lead to the loss of fine details in the shape of the object. Contour thinning algorithms usually involve complex rules or iterative procedures, which make them complicated to implement and maintain, especially when considering hardware or software optimization. In addition, in some cases, the contour thinning process can lead to inconsistent results when applied to slightly modified versions of the same image, which makes the algorithm unsuitable for applications that require high reliability. Therefore, it is necessary to improve existing algorithms and develop new ones to eliminate the mentioned shortcomings and obtain quick and accurate results.

This work studies popular and widely used contour thinning algorithms, and two new contour thinning algorithms based on them are proposed and tested in experimental studies.

The main contributions of this research work to solving the problems of the image processing field are as follows:

- The hybrid contour refinement algorithm is built based on the well-known Zhang-Suen algorithm, which allows to solve the problem of object segmentation effectively;
- The proposed algorithm allows to significantly reduce the computational complexity associated with existing traditional contour refinement algorithms and makes it more suitable for real-time applications;
- The results of computational experiments show that the proposed algorithm can be used to improve the quality of image formation, especially in complex scenarios with various contours and edges;
- The algorithm can ensure the continuity of the contour line and form contours with a width of one pixel;
- The algorithm allows for the reduction of the time required for image processing.

The general organization of the research work consists of 8 sections, the first of which is presented in Section I, which describes in detail the purpose and relevance of the research work. Section II reviews the available literature on contour refinement and image formation approaches. Section III provides information on each of the image formation stages. Section IV provides descriptions and formulas of the contour refinement algorithms used in the work. Section V is the "Methodology" section, which describes the idea of conducting the research. Section VI provides information on the image set used for testing in the study and the reasons for choosing the image set. Section VII demonstrates the effectiveness of the algorithm through a series of tests and comparisons, that is, it presents the results of applying the proposed algorithm to contour refinement, including image samples and the values of the evaluation indicators. Section VIII is devoted to discussing the results of computational experiments, which describe the proposed algorithm's advantages and disadvantages compared to existing algorithms. Finally, Section IX summarizes the study's main findings and suggests potential directions for future work.

II. LITERATURE REVIEW

Contour refinement algorithms are mainly methods that accept binary images as input data and are divided into iterative and non-iterative types [12]. Iterative algorithms refine contours by examining each pixel step by step, while non-iterative algorithms use a distance calculation method. Although non-iterative methods are fast, they often have qualitative shortcomings. Therefore, many researchers have preferred to use iterative algorithms. For example, the Zhang-Suen [13], Guo-Hall [14], and Hilditch algorithms [15] can be cited as examples of iterative methods.

In a study aimed at comparing different algorithms [12], it was found that the Zhang-Suen algorithm requires minimal computational time. The Zhang-Suen and Guo-Hall algorithms were also considered in [16], and the Zhang-Suen algorithm was proven to be superior. However, various studies have shown that contour refinement algorithms have some limitations. For example, it has been noted that the Zhang-Suen algorithm is not very efficient in working with edge pixels [17]. Although morphological methods are distinguished by their speed, their results are strongly dependent on the preprocessing of the image [18]. Another drawback of the traditional Zhang-Suen algorithm is the lack of conditions for checking diagonal pixels. To solve this problem, a "bidiagonal" algorithm was proposed [19], in which diagonal pixels are added to the checking conditions. According to the results of the study, this new method showed better results in pixel analysis criteria than the Zhang-Suen algorithm.

In general, the Zhang-Suen algorithm is a method widely used in the field of contour refinement and is used as a basis for developing new algorithms. However, the limitations of this algorithm and other existing methods indicate the need for further improvement. The following sections will discuss in detail the existing algorithms used in the work and the proposed new approaches.

III. STEPS OF IMAGE PROCESSING

Usually, image processing is carried out at the stages of increasing image contrast, eliminating noise in the image, separating contour lines, and binarizing and thinning contours. Below is a summary of these efforts.

A. Increase Image Contrast

Image contrast can be increased by changing the brightness of each image element or by increasing its range. Nowadays, many effective algorithms of image contrast enhancement such as histogram equalization, contrast stretching and contrast-limited adaptive histogram equalization and morphological contrast enhancement algorithms have been developed [20-31]. When increasing image contrast, many researchers use a histogram equalization algorithm, and its main idea is to uniformly redistribute the intensity of the image in the range of gray levels. This algorithm is based on the following formulas:

$$p\left(r_k\right)=\frac{n_k}{n}, k=0,1,...,L-1 \tag{1}$$

$$s_k=T\left(r_k\right)=(L-1)\sum_{j=0}^{k}p\left(r_j\right)=(L-1)\sum_{j=0}^{k}\frac{n_j}{n} \tag{2}$$

where r_k- input luminance, s_k- output luminance, L- luminance range, n_j- number of bright pixels, n- total number of pixels.

Contrast Limited Adaptive Histogram Equalization (CLAHE) is an enhanced version of the standard Histogram Equalization (HE), designed to improve contrast in images, especially in regions with low contrast, while avoiding over-amplification of noise. CLAHE works by applying local contrast adjustments rather than a global one, making it useful for medical imaging, remote sensing, and other fields where detail enhancement in localized areas is crucial.

Steps of CLAHE:

Step 1. Convert Image to Grayscale (if necessary):

If the image is in color, convert it to grayscale, as CLAHE is often applied to grayscale images. In the case of color images, CLAHE can be applied to each channel separately in some implementations.

Step 2. Divide the Image into Non-overlapping Regions (Tiles or Blocks):

The image is split into smaller, equal-sized regions known as tiles or blocks. These tiles can have dimensions like 8x8 or 16x16 pixels, depending on the size of the input image.

Step 3. Apply Histogram Equalization to Each Tile:

For each tile, a local histogram of pixel intensity values is calculated. The histogram equalization technique is then applied within each tile, enhancing contrast locally by redistributing pixel intensities over the available intensity range.

Step 4. Clip the Histogram:

To prevent over-amplification of noise in flat or low-contrast areas, CLAHE limits the contrast enhancement by clipping the histogram at a predefined threshold (clip limit). This step reduces the influence of noise and avoids excessive contrast in homogeneous regions.

Step 5. Interpolate Between Neighboring Tiles:

After local histogram equalization, the enhanced tiles are combined back into a single image. To avoid visible boundaries between tiles, bilinear interpolation is used, smoothing the transitions between neighboring regions.

Step 6. Merge the Result (if in color):

If CLAHE was applied to individual channels of a color image, the enhanced channels are merged back to form the final enhanced image.

B. Noise Reducing

Usually naturally captured images are not free of noises and they are improved based on noise reduction filters. However, denoising in digital images is very difficult without prior knowledge of the noise model. In this case, it is natural for researchers to have some questions. In particular, questions such as what types of noise are modeled in images and which ones cannot be removed from the image make the research of noise models a necessity. In the literature, there are mainly 7 types of noise in the image. There are also reports that image-denoising filters have been researched in many literatures [32-36]. In particular, it was noted by the authors of [37] that Gaussian, BM3D, NLM, and TV filters provide good results in eliminating Gaussian noise in the image. Among them, the BM3D filter is a popular algorithm for removing Gaussian noise. It is a noise reduction method based on applying a filter to local image slices in the transformation domain. This noise reduction method is implemented in the following four steps.

- identifying image fragments similar to a given image fragment and grouping them in a 3D block;
- 3D linear transformation of a 3D block;
- reduction of transformation spectrum coefficients;
- implement inverse 3D transformation;

The process of identifying a similar block is as follows:

$$\rho(p)=\{Q:d(P,Q)\leqslant\tau^{hard}\}, \tag{3}$$

where P denotes the patch of the image cycle with the size $k^{hard}\times k^{hard}, d(P,Q)-$ the Euclidean distance between the blocks.

Median, Weiner and adaptive median filters are effective in reducing salt-and-pepper noise. Salt-and-pepper noise is common in images, and the median filter is widely used to remove it. This filter is implemented as follows:

$$\widehat{f}\left(x,y\right)=median\left\{g\left(s,t\right)\right\}, \tag{4}$$

where $(s,t)\in S_{xy},\widehat{f}\left(x,y\right)$- is the image formed after applying the filter, x,y- spatial coordinates, S_{xy}- is a set of coordinates of the rectangular area of the image centered at the point (x,y).

The de-noised image is passed to the next step, the object contour extraction step, as an improved input image.

C. Extracting Object Contour Lines

Separation of object contours in the image is one of the main steps in image processing, the results of which determine the results of further classification. The advantages of this approach are that it reduces computational and algorithmic complexity by considering only contours, and image analysis methods based on contour models are invariant to transformations such as translation, rotation, and scaling. This, in turn, ensures that object boundaries are captured more accurately.

At the moment, many contour separation approaches have been developed [38-43]. Examples include gradient classical [44], statistical [45], active contour [46], anisotropic [47], fuzzy set [48], and machine learning [49] methods. Among the mentioned methods, gradient methods are widely used in contour separation because they make calculations easy to perform.

Gradient methods are divided into two categories according to the use of first- and second-order derivatives. Methods based on the first-order derivative include Sobel, Prewitt, Scharr, Roberts, Kayalli, Orhei contour separation methods [50]. Among these methods, the Sobel filter is famous for its good separation of outer thick lines of objects in the image. In the Sobel filter, the brightness gradient at each point of the image and its value $mag\left(\nabla T\right)$ is calculated, that is:

$$S_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, S_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \tag{5}$$

$$\frac{\partial T}{\partial x} = S_x \otimes T; \frac{\partial T}{\partial y} = S_y \otimes T \tag{6}$$

$$\nabla T = \left[\frac{\partial T}{\partial x}; \frac{\partial T}{\partial y}\right] \tag{7}$$

D. Binarization

As a result of the application of contour separation algorithms, gray images are created. In subsequent processing, the image is subjected to a binarization step to facilitate calculations, and the methods of this image binarization are detailed in works [51-53]. Binarization is the process of converting an image into a monochrome or binary image. Suppose $f_{ij}-$ gray image, $t-$ threshold and b_0, b_1- -binary value are given. Based on the given threshold value, the binary image $g_{ij}-$ is formed as follows:

$$g_{ij} = \begin{cases} b_0, & if \quad f_{ij} \le t, \\ b_1, & if \quad f_{ij} > t \end{cases} \tag{8}$$

E. Contour Thinning

Contour thinning is the process of reducing the width of contour lines in a binary image to one pixel, which allows you to reduce the processing time of the image and optimize the amount of data to be transmitted. Morphological methods for contour thinning [18], the Zhang-Suen method [13], and its various modifications [54] are effective methods that are widely used in practice. These methods are based on the principle of preserving the structure of objects in the image. Therefore, in this study, the above methods of contour thinning were studied, experiments were conducted on them, and a comparative analysis was performed with the proposed new method.

IV. CONTOUR THINNING ALGORITHMS

When solving some practical problems, it is required to obtain not the contour of the object in the image, but a thin curve of it with a thickness of one pixel. This curve is called the object skeleton. The process of creating a skeleton from a binary image is called contour refinement. The problem of thinning contour lines is as follows:

Suppose that $I(x, y)-$ is a binary image, and $S(I)-$ is a skeleton image formed by thinning the contour lines of I image. The main task here is to determine a set of pixels that meet the following conditions:

- $S(I)-$ must preserve the topological structure of objects, that is, the shape, number, and combination of objects. This means that it is required that the removed pixel does not change the number of connected components;
- After scaling, each object must be represented by a line of one-pixel width;

Additional conditions are usually applied to preserve the structural properties of the image. In particular, the number of transitions from 0 to 1 (or from 1 to 0) in the neighborhood of pixel 8 must be equal to 1 to preserve the structure of the lines. Also, to avoid accidental line breaks, a pixel needs to be deleted only if it has at least two neighbors belonging to the object. That is, this process can be understood based on the consideration of the pixel $p = I(x, y)$ which is part of the object. Let $p = 1$, it is a white pixel in the binary image and surrounded by its local neighbors. Each p_i can be part of the object or part of the background. This pixel p_i has at least two neighboring pixels belonging to the object (that is, at least two $p_i = 1$ among the pixels $p_1, p_2, p_3, ..., p_8$) are removed. Also, this process can be expressed algorithmically as follows for each p pixel belonging to an object in the image $I(x, y)$:

Step 1. The number of neighbors belonging to an object is $B(p)$:

$$B(p) = p_1 + p_2 + p_3 + ... + p_8 \tag{9}$$

Step 2. If $B(p) \geqslant 2$, then p pixels are candidates for removal.

If $B(p) < 2$, then p pixels should not be removed.

In general, contour thinning can be described as an iterative process that can be represented by logical operations on the neighbors of image pixels that satisfy the structure-preserving conditions described above. Below is a brief description of common contour thinning algorithms.

A. Morphological Operator based Algorithm

A contour thinning algorithm based on morphological operators reduces the thickness of object contour lines in binary images to the minimum possible level, usually one pixel. The following basic morphological operators are used in contour thinning:

$$Erosion : X\Theta B = \{x : B_x \subseteq X\} = \bigcap_{b\in B} X_b \tag{10}$$

$$Dilation : X \oplus B = \{x + b : x \in X, b \in B\} = \bigcap_{b\in B} X_b \tag{11}$$

$$Opening : X_B = (X\Theta B) \oplus B \overset{\triangle}{=} X \circ B \tag{12}$$

$$Closing : X^B = (X \oplus B)\,\Theta B \triangleq X \bullet B \tag{13}$$

where erosion is equal to the intersection of sets and dilation is equal to the union of sets, where B is the structuring element and X is the given image.

B. Zhang-Suen Algorithm

It is one of the classic approaches to solving the problem of contour line thinning in binary images and is popular among causal thinning algorithms due to its simplicity and ability to preserve the topology of object contours. The algorithm works based on iterative parallel thinning on a 3×3 mask, and it deletes p_1 pixel in the center of the mask as a result of checking the specified conditions using two iterations (Figure 1).

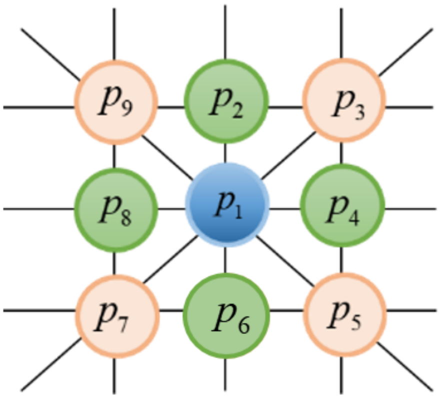


Fig. 1. 3×3 mask for Zhang-Suen algorithm

The first iteration of the algorithm consists of the following steps:

a) $2 \leqslant B(p_1) \leqslant 6$; b) $A(p_1) = 1$;

c) $p_2 \vee p_4 \vee p_6 = 0$; d) $p_4 \vee p_6 \vee p_8 = 0$

where $B\left(p_1\right)$ - is the foreground pixels number in the 3×3 mask, that is the number of white pixels, $A\left(p_1\right)$ - is the number of pixels p_1) transitioned from 0 to 1 among 8 neighbors.

The second iteration of the algorithm consists of the following steps:

a) $2 \leqslant B(p_1) \leqslant 6$; b) $A(p_1) = 1$;

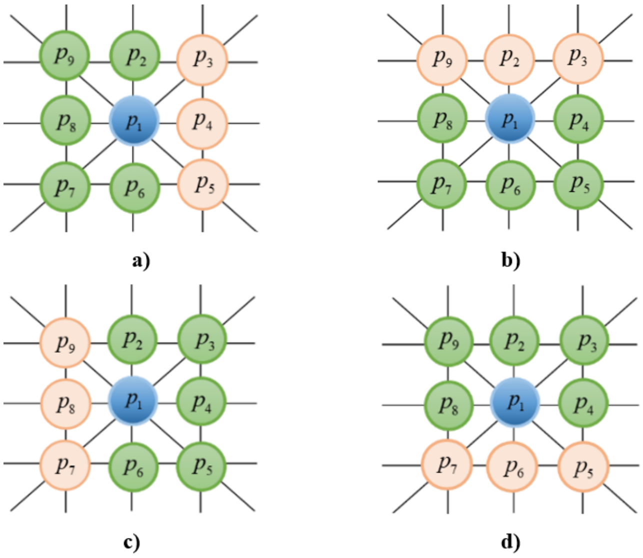
c) $p_2 \vee p_4 \vee p_8 = 0$; d) $p_2 \vee p_6 \vee p_8 = 0$

A pixel satisfying the above conditions p_1 is determined for deletion. In this way, these conditions are checked for all pixels of the image, and as a result of the appropriate action, an image with thinner contours is formed. The Zhang-Suen algorithm has some advantages, including that the algorithm's result is invariant to image rotation and rotation. Also, the algorithm is used in various real-time applications due to its low computational complexity and ease of implementation.

Despite its popularity, the Zhang-Suen method has some drawbacks. In the process of thinning, the connection violation due to the complete loss of square features makes the algorithm invalid from the connection point of view. In some cases, the thickness of the contour line resulting from the Zhang-Suen algorithm is greater than one pixel. This happens when checking diagonal line pixels. Therefore, in this research work, a new algorithm for contour thinning is proposed by developing this method.

C. Semicircular Algorithm

Existing shortcomings of the Zhang-Suen algorithm justify that this algorithm does not always give the expected result. This shows that it needs to be improved. In this research paper, a semicircular contour thinning algorithm based on the Zhang-Suen algorithm is proposed. The difference between the proposed algorithm and the Zhang-Suen algorithm is that the p_1 pixel is removed by checking not only three neighboring pixels from its eight neighbors but five neighboring pixels in the semicircle (Figure 2).



a) b) c) d)

Fig. 2. Cases checked in the semicircular algorithm of contour thinning: a) $p_2p_9p_8p_7p_6$, b) $p_8p_7p_6p_5p_4$, c) $p_6p_5p_4p_3p_2$, d) $p_4p_3p_2p_9p_8$

When the following conditions are met for p_1 pixels in the center of the 3×3 mask in the semicircular a) thinning algorithm, p_1 pixels are deleted:

The first iteration of the algorithm consists of the following steps:

a) $2 \leqslant B(p_1) \leqslant 6$; b) $A(p_1) = 1$;

c) $p_2 \vee p_4 \vee p_6 = 0$; d) $p_4 \vee p_6 \vee p_8 = 0$

The second iteration of the algorithm consists of the following steps:

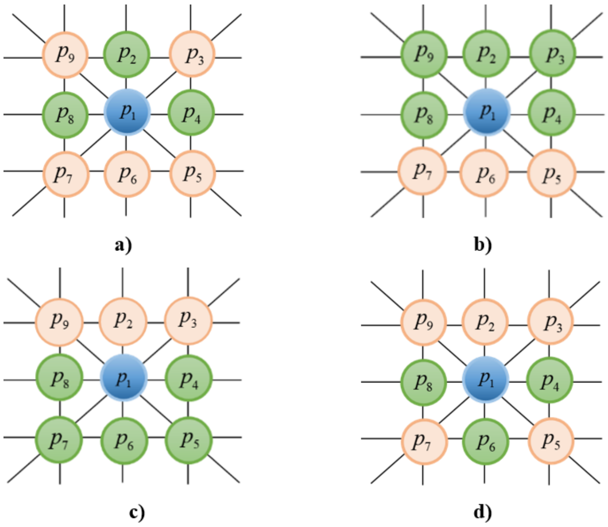
a) $2 \leqslant B(p_1) \leqslant 7$; b) $A(p_1) = 1$;

c) $p_2 \vee p_9 \vee p_8 \vee p_7 \vee p_6 = 0$; d) $p_8 \vee p_7 \vee p_6 \vee p_5 \vee p_4 = 0$

This process is repeated for all pixels of the given image, that is, the conditions of iterations 1, and 2 are checked. As a result of the algorithm, a new image with thinner contours is formed.

D. Semicircular Triangle Algorithm

A new hybrid algorithm was developed based on the combination of the steps of the first and second iterations of the Zhang-Suen and semicircular contour thinning algorithms. The difference between the proposed algorithm and the algorithms mentioned above is that it uses semicircular and triangular neighboring pixels when checking neighboring pixels of the p_1 pixel (Figure 3).



a) b) c) d)

Fig. 3. Checked cases of contour thinning in the semicircular triangle algorithm a) $p_2p_4p_8p_7p_6$, b) $p_4p_3p_2p_9p_8$, c) $p_8p_7p_6p_5p_4$, d) $p_4p_6p_8$

In the semicircular triangle algorithm, p_1 pixels are deleted when the following conditions are met for p_1 pixels in the center of the 3×3 mask:

The first iteration of the algorithm consists of the following steps:

a) $2 \leqslant B(p_1) \leqslant 6$; b) $A(p_1) = 1$;

c) $p_2 \vee p_4 \vee p_8 = 0$; d) $p_4 \vee p_3 \vee p_2 \vee p_9 \vee p_8 = 0$

The second iteration of the algorithm consists of the following steps:

a) $2 \leq B\left(p_1\right) \leq 7$; b) $A\left(p_1\right) = 1$;

c)$p_8 \vee p_7 \vee p_6 \vee p_5 \vee p_4$; d) $p_4 \vee p_6 \vee p_8$;

Due to the absence of adjustable parameters and the simplicity of the above hybrid algorithm, it can be easily implemented in any programming language.

V. METHODOLOGY

Suppose T_0 is a set of original images and a set of images T_0^k whose contours are separated by experts, T_f is a set of images with contours formed by applying certain filters of contour separation to the original image that has passed the stage of preprocessing, $u_i(i = \overline{1,4})$ contour thinning algorithm, let B be the image comparison criteria. $t_f \in T_f$ is a contour image formed based on contour separation filters, $t_0^k \in T_0^k$ is an image formed by experts, and the image obtained as a result of applying u_i algorithm to t_f image is defined as follows:

$$t_i = u_i(t_f), i = \overline{1,4} \tag{14}$$

where u_1 is a morphological operator, u_2 is a Zhang-Suen algorithm, u_3 is a semicircular and u_4 is a semicircular triangle algorithm.

Currently, there are criteria for evaluating the results of contour separation algorithms such as MSE (Mean square error) [55], PSNR (Peak signal-to-noise ratio) [56], Recall [57], and F1-measure [58]. Taking into account the nature of the problem and the fact that the contours of the image are separated by experts, the pixel-by-pixel comparison criterion was used to evaluate the efficiency of the algorithms.

The efficiency of contour thinning algorithms is calculated based on the following formula:

$$b_i = \frac{|t_0^k \cap t_i|}{|t_{0^k}|} \cdot 100\%, i = \overline{1,4} \tag{15}$$

where $b_i \in B$, $|t_0^k|-$ is the number of contour image pixels, $|t_0^k \cap t_i|-$ is the number of pixels of intersection of t_0^k and t_i images.

In this approach, the greater the value calculated by the formula (14), then the algorithm corresponding to this value is considered effective, that is:

$$u_{opt} = \underset{i}{max}\{b_i\}, i = \overline{1,4} \tag{16}$$

VI. DATASETS

The BSDS500 (Berkeley Segmentation Dataset and Benchmark) image database is the most suitable database for experiments on the development and evaluation of algorithms for thinning contour lines in images. Because this image database has the following advantages:

- BSDS500 includes images with a variety of subjects and backgrounds, including natural scenes and everyday objects;
- BSDS500 contains not only images but also images with contours defined for each image by several experts. This allows for an objective evaluation of the effective separation of object contour lines with high accuracy;
- BSDS500 is the standard in the scientific community for contour line detection tasks, and most research results are based on this database.

The above-mentioned evidence allows us to recognize the BSDS500 image database as an ideal base for the development and evaluation of algorithms for thinning object contour lines.

VII. RESULTS

One of the reliable and effective methods of evaluating the contour thinning algorithm is the pixel comparison method. In the implementation of the calculation experiment, the original image and the images from the BSDS500 base, whose contours were formed by experts, were used. These images and information about them are available in full at www.kaggle.com. Below are examples of images from the BSDS500 image database.

Fig. 4. Samples from the BSDS500 image set (A- Original image, B- Ground truth image)

For computational experiments in this research work, 200 sample images were taken from the image set containing the above-mentioned BSDS500 contours expertly formed contour images. Sample images were first subjected to image processing steps.

The Sobel filter was used to separate the object contours in the images. Because the Sobel filter separates the thick outer line contours of the object in the image well [32]. By applying a Sobel filter to the image and binarizing, a contoured binary image with thick object contour lines was created. Zhang-Suen, morphological operator-based contour thinning, and semicircular, semicircular triangle algorithms are applied to the formed image. The following figure shows examples of the results of the application of the three algorithms mentioned above.

It can be seen from Figure 5 that the algorithm based on the morphological operator did not perform well for the image with object contours based on the Sobel filter. However, it is difficult to compare the results of the Zhang-Suen, semicircular and semicircular triangle algorithms with each other through subjective visual inspection. Therefore, the objective method calculated (15) pixel comparison criterion was used in the assessment.

In the comparison of contour thinning algorithms (15), the evaluation was carried out according to the evaluation criterion and the time criterion. In this case, the formula (15) was used to determine the extent to which the one pixel contours obtained as a result of the application of algorithms coincide with the contours of the image provided by the expert, and the time criterion was obtained because it is of great importance in the automation of image processing.

Table I presents the results of comparing contour thinning algorithms according to formula (15) and time criterion.

TABLE I
RESULTS OF COMPARISON OF CONTOUR THINNING ALGORITHMS (15) AND TIME CRITERION

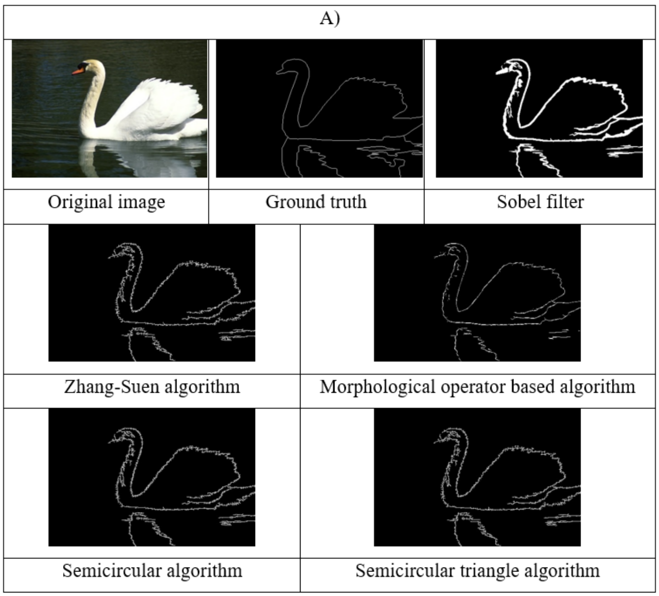
Algorithm	Match by pixel (average)	Time (average-seconds)
Morphological operator based algorithm	26.12%	0.063
Zhang-Suen	65.74%	22.24
Semicircular algorithm	63.69%	12.18
Semicircular triangle algorithm	68.97%	11.97

The BSDS500 database was used in the experimental research because its image contours were manually annotated by experts and it contains a diverse range of images, therefore testing was not conducted on other image databases. This is because there are very few databases available with expert-annotated contours besides BSDS500.

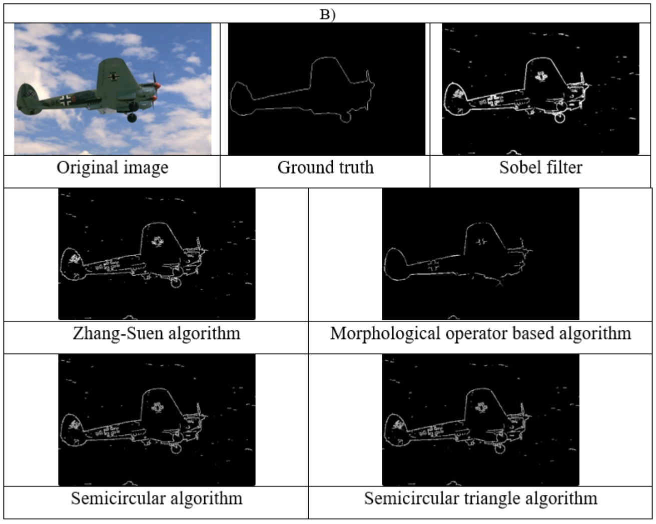
Table II shows the results of the comparison of contour thinning algorithms on 200 images in the BSDS500 database.

In the table above, the number of pixels in the columns indicates the number of pixels that make up the contour in Ground Truth (GT) Images and images generated by applying algorithms. It helps to understand how well the algorithm is suited to GT. Those given in Table II represent:

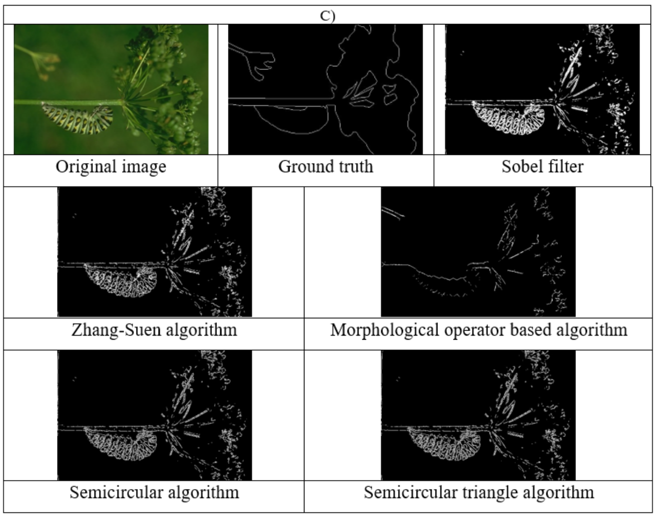
A)


Original image
Ground truth
Sobel filter
Zhang-Suen algorithm
Morphological operator based algorithm
Semicircular algorithm
Semicircular triangle algorithm

B)


Original image
Ground truth
Sobel filter
Zhang-Suen algorithm
Morphological operator based algorithm
Semicircular algorithm
Semicircular triangle algorithm

C)


Original image
Ground truth
Sobel filter
Zhang-Suen algorithm
Morphological operator based algorithm
Semicircular algorithm
Semicircular triangle algorithm

- Number of Contour Pixels in GT: 456,880 white pixels in expert-annotated contour images, serving as the reference or ”gold standard”;
- Number of Contour Pixels Identified by Each Algorithm. That is, total white pixels in the output images from

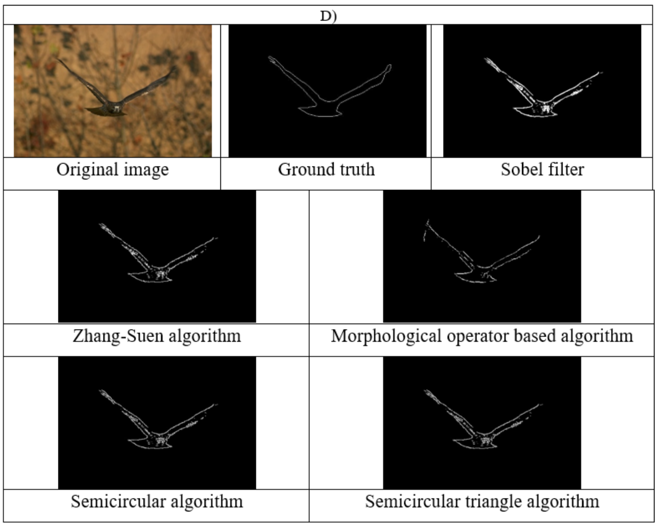


Fig. 5. Sample images from applying contour thinning algorithms (A-D)

TABLE II
RESULTS OF COMPARISON OF CONTOUR THINNING ALGORITHMS IN TERMS OF THE NUMBER OF CONTOUR-FORMING PIXELS IN THE BSDS500 IMAGE DATABASE

Number of images	Contour pixel count in Ground truth images versus thinning algorithm results				
	Ground truth image	Morphological operator based algorithm	Zhang-Suen algorithm	Semicircular algorithm	Semicircular triangle algorithm
200	456880	123357	287834	283266	352247

contour thinning algorithms:

1) Morphological operator-based thinning algorithm: Identified only 123,357 contour pixels, the lowest among all algorithms. This significant deviation (over 73% fewer pixels than GT) highlights that morphological thinning overly simplifies the contours, often losing finer details.
2) Zhang-Suen Algorithm: Identified 287,834 contour pixels, an improvement over the morphological operator but still significantly lower than the GT. The Zhang-Suen algorithm's reliance on only three neighboring pixels for thinning results in moderate contour simplification, but it still misses critical details.
3) Semi-Circular Algorithm: Identified 283,266 contour pixels, slightly fewer than the Zhang-Suen algorithm. While more robust in preserving contours, its semi-circular neighborhood leads to some oversights in preserving detailed sections, resulting in pixel counts close to Zhang-Suen's output.
4) Semi-Circular Triangle Algorithm: Identified 325,247 contour pixels, the highest among all algorithms. This count is closer to the GT, showing the hybrid method's efficiency in preserving contour details by combining semi-circular and triangular neighborhood analysis.

Comparing the efficiency of the algorithms by calculating the total number of white pixels in the one-pixel contour images separated by an expert in the BSDS500 image base and the number of white pixels in the resulting images of the four contour thinning algorithms presented in the research paper, it was found that the hybrid algorithm on the image base performed better than other algorithms. That is, the proposed Semicircular triangle algorithm showed an improvement of 8% compared to the result of using the Zhang-Suen algorithm, 9% compared to the Semicircular algorithm, and 44% compared to the morphological operator-based algorithm.

According to the obtained results, it can be seen that the contour thinning algorithm is superior to other algorithms in terms of pixel compatibility and time criterion. The algorithm based on the morphological operator provides fast results in terms of time. However, the object cannot completely capture the contour lines. That is, in this case, the requirement to fill the contour lines of the object requires additional computing resources and leads to the loss of important information. This, in turn, does not correspond to the requirements of perfect performance of the tasks to be solved.

Although Zhang-Suen and semicircular algorithms have high computational complexity, they perform well in contour thinning to create a one-pixel contour image. Based on the experiments, it can be said that the proposed algorithm is effective compared to other algorithms presented in the work.

VIII. DISCUSSION

The results of this study confirmed some of the information presented in the literature. In particular, it was reported in [54] that the Zhang-Suen algorithm is not always effective in forming one-pixel contour lines. Algorithms based on morphological operators are fast in terms of time, but the preprocessing of images depends on steps [18]. It was pointed out in [59] that repeated application of contour thinning algorithms causes contour lines to disappear completely. From the above, the question arises, how to eliminate the stated problems? As an answer to this question, a hybrid algorithm was proposed in this paper.

Contour thinning is usually performed after image processing steps, that is, contrast enhancement, noise reduction, contour separation, and binarization. Therefore, image noise levels are not discussed. Also, as a limitation of the algorithm proposed in this work, these algorithms depend on the results of contour separation, and the contours resulting from these algorithms require smoothing.

Despite the above-mentioned limitations of the proposed hybrid algorithm, the use of this algorithm in image processing processes serves to improve accuracy and efficiency to a certain extent. Also, by integrating them with emerging technologies, realistic visualization can be realized.

The algorithm proposed in this work can be integrated into all systems or software packages used for image processing. It includes handwritten image processing and medical image analysis systems. When solving these problems, it is possible to accurately identify objects in images and reduce the speed of image processing.

In applications in medical imaging, contour thinning algorithms can be adapted to aid in the detection and analysis of abnormalities in medical examinations such as X-rays, magnetic resonance imaging, or computed tomography.

IX. CONCLUSION

In this research work, the issue of thinning contour lines of images with thick line contours, which is one of the main problems that arise in the image processing stage of image preprocessing, was studied in detail. In this case, the Sobel filter, which is considered popular for separating image object contours, was used. As a result, Zhang-Suen algorithms based on morphological operators were studied for thinning thick contour lines, and a new algorithm was formed by selecting the sequence of checked pixels in a 3x3 mask in a semicircular form in the first and second iterations of the Zhang-Suen algorithm. Then, a new hybrid algorithm was formulated based on Zhang-Suen and semicircular algorithms. Extensive experiments have been conducted to evaluate the performance of the proposed hybrid contour thinning algorithm. In addition, the proposed algorithm was compared with Zhang-Suen and morphological operator-based algorithms for pixel matching and time criterion. In this research work, the BSDS500 image set with expertly formed contour images was used for computational experiments, and the following results can be summarized:

- Although the algorithm based on the morphological operator is the fastest in terms of time in contour thinning, it does not fully cover the contour lines of the object. This object requires additional resources to fill contour lines;
- the shortcomings of the Zhang-Suen algorithm were recognized and based on this algorithm, a semicircular algorithm for contour thinning was formed;
- based on computational experiments, it was shown that the semicircular triangle algorithm is effective both in terms of pixel matching and time criteria;
- as a result of experiments conducted on images with various subjects and backgrounds in the BM3D database, the average processing speed of the algorithm was 12 seconds, which fully meets the requirements for working in real-time mode;
- the proposed semicircular triangle algorithm of contour thinning was recommended for use as an alternative algorithm to the Zhang-Suen algorithm.

In this research work, an improved hybrid algorithm of contour thinning, which allows for reducing computational costs for automatic object detection systems operating in real-time, was recommended for practical use.

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