Jointly Contour and Curvature Estimation for Lightning Channel Segmentation

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Abstract. As a phenomenon of strong charge movement, the lightning channel is of great significance in meteorology research and lightning monitoring. This paper presents a novel method that jointly estimates the contour and curvature for precisely segmenting lightning channel for practical applications. First, the input images are preprocessed by the adaptive threshold method to highlight the brightness features of the flash channel. On this basis, a contour detection algorithm is designed to extract the edge contours of each object in the image. Moreover, a curvature calculation component is incorporated into the proposed method to obtain curvature information and further identify the real lightning channel. In addition, during the experimental research, we constructed a lightning dataset. This dataset includes real lightning images captured under different environmental conditions, collected from meteorological stations, scientific research institutes, the Internet, and other sources. The experimental results show that the proposed method has good performance in identifying lightning channels, which is important for a deep understanding of lightning phenomena, meteorological research, and environmental monitoring.

Keywords: lightning channel; adaptive thresholds; contour detection; curvature analysis

1 INTRODUCTION

Lightning activity is an integral component of meteorological research, which is closely related to meteorological phenomena such as thunderstorms and climate change[1][6][20]. The production and distribution of lightning have a certain impact on weather patterns and climate change, indicating thermal changes and humidity in the air. Lightning also has significant implications for human life and safety. Fire, equipment failure and personal danger caused by lightning strikes have always been one of the major threats to the safe operation of China's high-speed railways. According to incomplete statistics, the annual troubles of the railway electrical power systems caused by lightning strikes accounts for 40% to 70% of the total number of electricity failure, and the annual troubles of the railway signaling system due to lightning damages account for about 10% to 20%, which seriously affects traffic safety and transportation efficiency.

Modern weather radar and lightning location technology can capture the electromagnetic field change information of lightning and obtain the location information of lightning through the inversion algorithm of Maxwell equations[3][21]. However, due to the influence of surface transmission and other factors, the distance obtained by this method generally has several hundred meters error, so the location results are not applicable to the railway system. Therefore, this study selected lightning image data for analysis and processing, assist maintainers accurately know the lightning strike point and to investigate lightning faults. However, directly using these image data for analysis and application is often limited by the complexity and noise of the images. Therefore, segmentation of lightning images becomes a critical step for extracting effective information. By dividing the lightning image into segments, the lightning area in the image can be effectively separated from the background, extracting the characteristics and attributes of the target area for subsequent analysis and application.

However, for the traditional lightning channel recognition method is mainly based on threshold segmentation[7][8], a simple and effective image segmentation method that divides the image into different regions by comparing the pixels in the image according to their gray value with a preset threshold. In recent years, most methods have utilized adaptive thresholding to effectively separate lightning channels and background areas in lightning images with low background complexity. But this approach faces some challenges when dealing with images containing complex backgrounds such as trees, buildings, etc. These elements may interfere with the identification of lightning channels, thereby increasing the difficulty of extracting lightning image data. Therefore, this paper proposes a lightning image segmentation method based on contour detection and eigenvalue estimation to deal with the problems of traditional methods and provide more reliable technical support for lightning research and application. In the field of image processing and analysis, contour and feature extraction are commonly used techniques used to extract target regions of interest from images. This paper aims to explore the application of methods based on contour extraction and feature value estimation in lightning image processing. The contour extraction technology[2] can effectively identify the target area boundary in the image, so that the shape and position of lightning can be accurately captured and described. On this basis, the curvature analysis of lightning is added to identify the lightning channel by the bending degree of lightning and the noise.

Compared to conventional segmentation methods, this contour-based extraction and feature value estimation method exhibits significant advantages in lightning image processing. It can effectively extract and describe lightning targets in lightning images with complex backgrounds, providing a reliable basis for further analysis and research. This paper will combine with experimental results to verify the effectiveness and practicality of this method in lightning image processing, providing reference for the improvement of lightning monitoring and early warning systems.

Our key contributions are summarized as follows:

1) Compared with the existing traditional thresholding methods, this paper proposes a novel method based on contour detection that can accurately extract the edge information in an image for the segmentation of the lightning channel. The proposed method can effectively deal with the complex background and noise in images, improving the accuracy of the segmentation results.
2) A curvature estimation component is further incorporated into the proposed model, which can more accurately measure the morphological features of the lightning channel by estimating the curvature of the lightning shape. This effectively filters out contours that do not match the shape of the lightning channel and captures subtle changes in the lightning shape, thus improving the quality of the segmentation results.
3) Our team utilizes radar, cameras, or other sensor devices to capture lightning images and compile them into a lightning dataset. The dataset covers a wide range of classical environments, various types of lightning activity, including intra-cloud lightning, cloud-to-ground lightning and cloud-to-cloud lightning, single lightning channels, and multi-branch lightning channels, ensuring the diversity and representativeness of the dataset. Furthermore, the lightning data undergo annotation and validation processes to identify characteristics such as the location and morphology of lightning channels. Moreover, this dataset contains nearly four hundred lightning images, and we will publicly release the dataset once it is complete.

2 RELATED WORK

Adaptive Thresholds. In previous studies of lightning channel recognition, the majority of segmentation tasks have been accomplished through thresholding, evolving from initial global threshold segmentation to adaptive threshold segmentation[4]. Compared to global thresholding, adaptive thresholding can dynamically adjust the threshold value based on the local features of the image, thereby better segmenting the lightning channel region[9]. However, adaptive threshold segmentation also has its limitations and is currently only applicable to lightning images with simple backgrounds. For instance, it can more accurately extract the lightning channel when there is significant brightness contrast between the lightning and the background in the image. However, for lightning images with more complex backgrounds, such as those with numerous buildings and strong light interference, the extraction performance is poorer. Therefore, threshold processing[13][14] is somewhat limited in the lightning channel recognition task in complex images.

Contour Detection. In the process of lightning channel recognition, traditional threshold segmentation methods are sometimes ineffective in extracting the structure of lightning channels. To address this issue, this paper proposes a method that combines contour detection with threshold segmentation, enabling complete extraction of lightning channels by analyzing their contour structures[28][29] . This method facilitates recognizing lightning channels in complex backgrounds and handling multiple branching structures of lightning channels [12]. The specific implementation steps are as follows. Contour decomposition: decomposing complex contours into simpler sub-contours[19]. Contour grouping: combining neighboring sub-contours to form a complete object contour. Conic line approximation: using polygons, spline curves or other mathematical models. Contour Matching: matching extracted contours with templates or known contours to identify objects. Branching Analysis: detecting branch points and branches in a contour using a skeleton extraction algorithm. By combining these techniques, complex contours can be efficiently processed, and a more complete lightning channel can be extracted from the image[27]. Contour detection of lightning can extract lightning channels more efficiently than threshold segmentation.

Curvature. For the detected contours, this paper incorporates lightning features, treating lightning as a surface or manifold. By measuring the curvature of lightning [16][17] , its degree of bending is determined to distinguish lightning from non-lightning features. Curvature estimation can further refine the segmentation results of lightning images. By measuring the curvature of the lightning shape, the true morphology of the lightning channel can be identified more accurately, so that contours that do not match the shape of the lightning channel can be eliminated and the accuracy of segmentation can be improved. Lightning channels usually present a curved shape, and curvature estimation is based on this feature to distinguish lightning from non-lightning features (e.g., noise, background objects, etc.) in the image. By setting an appropriate curvature threshold, the noise that does not match the lightning shape feature can be effectively filtered out, improving the accuracy and reliability of segmentation. Curvature estimation not only identifies the main curved part of the lightning channel, but also captures the subtle changes in the lightning channel, such as small changes in the bending angle, and subtle extensions of lightning branches. The capture of these subtle information is of great significance for the comprehensive and accurate description of the morphological characteristics of lightning.

3 PROPOSED METHOD

3.1 Problem Definition

Currently, for lightning channel recognition, traditional threshold segmentation methods[15] can achieve complete segmentation to a certain extent. However, this requires preprocessing of the images to ensure that the main content retained is the lightning channel. For images with complex backgrounds, the effectiveness of early preprocessing is not ideal. This paper utilizes contour detection and feature analysis methods to process the segmented images, analyzing the shape and curvature characteristics of the lightning contours to extract the lightning channels more accurately.

3.2 Overall Architecture

Figure 1 shows the overall architecture based on contour detection and feature extraction, which mainly includes three parts, segmentation preprocessing, traversal contour, and curvature feature extraction of the contour, to extract the lightning channel. (1) Preprocessing: the image is converted into a grayscale image, and the edge detection algorithm is applied to detect the edges in the image. Use morphological manipulation (e.g. corrosion and expansion) or non-maximum suppression. (2) Contour detection: using the connectivity algorithm, the separated edges are connected into a connected contour to generate a contour representation containing the contour pixel coordinates or parametric equation. The contour can be represented as polygons, spline curves or other mathematical models[25][26]. Confines are filtered by area and perimeter, while removing noisy or unrelated contours. (3) Curvature feature extraction: lightning usually presents a branching form, extending from the cloud to the ground or other places in the clouds. These branching forms are determined by the movement path of the charge in the atmosphere, and sometimes have tree, network, and other structures, which belong to the slender, thin, and polygonal shape. By measuring the bending degree of the traversed contour, it is more accurate to identify the lightning channel than the simple contour detection.

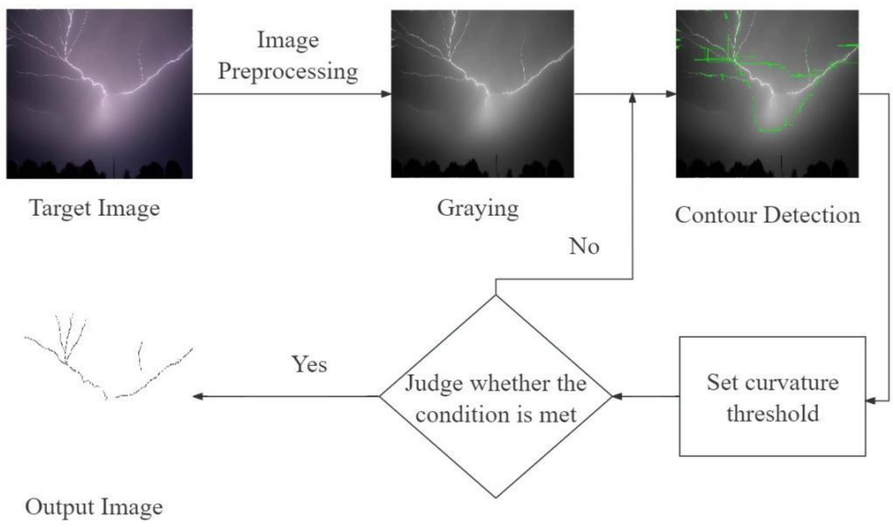

Fig. 1. Flowchart of lightning channel identification

3.3 Jointly Contour and Curvature Estimation Method

Preprocessing: For images intended for lightning channel extraction, preprocessing is typically necessary to mitigate background interference. Common preprocessing methods often involve contrast adjustment. In lightning images, background elements and structures typically exhibit lower luminance and darker hues compared to lightning discharges, hence background interference can be addressed through techniques such as contrast adjustment and image enhancement. Nevertheless, the efficacy of contrast adjustment methods may be limited by the visual luminance disparity between lightning and the surrounding environment, particularly when lightning channels occupy a small portion of the image. Therefore, initial processing primarily employs adaptive threshold segmentation and Gaussian denoising techniques. Subsequently, the lightning image is converted from the RGB color space to grayscale for further analysis.

The segmented images only are 0 and 1. The adaptive threshold segmentation formula is as follows:

$$T(x, y) = C * m(x, y) + k \tag{1}$$

Where T(x,y) is the threshold at pixel (x,y) and m(x,y) is the statistical characteristics of the pixel values within the window around pixel (x,y), such as mean or variance. C and k are parameters of the algorithm, which are used to control the way in which the threshold is calculated.

Contour Detection: Contour detection is a fundamental task in image processing and computer vision aimed at identifying and extracting the boundaries of objects in an image. In the context of lightning segmentation, The contour detection algorithm is able to accurately identify edge contours in lightning images that accurately represent the boundaries of the lightning. By extracting these boundaries, the lightning can be separated from the complex background, providing an accurate data base for subsequent analyses.

Based on the pre-processing, there is still some noise not removed. The contour in the image is extracted by using the level set method, which mainly represents and embeds the curve or surface using the zero level set of a high-dimensional function (usually a signed distance function), thus transforming the curve evolution problem into a partial differential equation solving problem[22][23]. Firstly, a high-dimensional signed distance function $\varphi(x, y, t) = 0$is constructed to represent the initial contour, and its zero-level set is the initial contour to be detected. Define a velocity function F that depends on the data items, curvature and control the evolution of the signed distance function φ according to the following partial differential equation.

$$\frac{\partial \varphi}{\partial t} + F|\nabla \varphi| = 0 \tag{2}$$

Where φ is a signed distance function and F is a velocity function dependent on data items, curvature, etc. The method describes the contour evolution process.

Contour usually refers to the boundary between an object and the background, contour detection can help to analyze the shape, size and location in an image[24]. Based on the image of the lightning, width and area factor can be extracted to approximate the area of the lightning channel.

Curvature Estimation: According to the method of contour detection and segmentation, most of the lightning channels can be extracted. However, this study also incorporates lightning feature estimation, that is, further extracting lightning channels based on the curvature of lightning. Lightning channels typically manifest as curved lines, and appropriate curvature thresholds can be estimated by examining the curvature curve at a certain point[10][11]. That is, better identification of lightning channels can be achieved through appropriate curvature. The calculation of curvature can be achieved by solving the inverse of the curve tangent direction vector. Equations (3) to (7) are applicable to most discrete spaces [30] . Figure 2 illustrates the parameters required for measuring the curvature of lightning images[5]. Assuming there are n pixels, the curve length is the sum of all lightning image pixels p_k, and the total curvature computation is the sum of absolute values of all angles represented in radians.

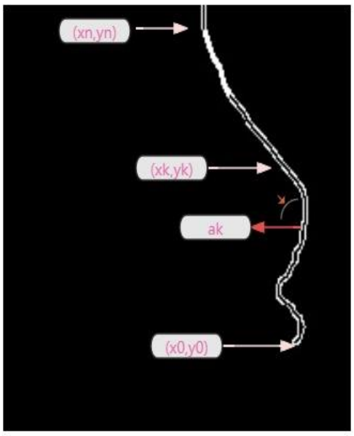

Fig. 2. Parameters required for the curvature measurement on the lightning image

$$\text{Distance Factor(DF)} = \frac{\text{Arc length}}{\text{Chord length}} = \frac{(\sum_{k=1}^{n} p_k)-1}{\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}} \tag{3}$$

Where p_k is the lightning image pixel, n denotes the total number of pixels in the picture, and DF denotes the distance factor, which is obtained from the length of the curve over the length of the chord.

$$\tau_1 = \frac{\text{Arc length}}{\text{Chord length}} - 1 = \frac{(\sum_{k=1}^{n} p_k)-1}{\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}} - 1 \tag{4}$$

$$\tau_2 = Total\ curvature = \sum_{k=1}^{n} |\alpha_k| \tag{5}$$

$$\tau_3 = Total\ square\ curvature = (\sum_{k=1}^{n} |\alpha_k|)^2 \tag{6}$$

$$\tau_4 = \frac{Total\ curvature}{Arc\ length} = \frac{\sum_{k=1}^{n} |\alpha_k|}{((\sum_{k=1}^{n} p_k)-1)} \tag{7}$$

The above τ_1, τ_2, τ_3, τ_4 are correlation values of curvature, which are measured by factors such as total curvature and curvature squared for lightning.

4 EXPERIMENTS

4.1 Datasets

This section presents the experimental results of methods based on threshold segmentation, curvature and profile detection. The purpose of the experiment was to verify the effectiveness and feasibility of the method in extracting lightning targets and analyzing lightning morphology. We will describe the experimental design, the dataset, and the results analysis.

The experimental data in this paper come from the digital images of lightning channels of high-speed cameras obtained by our research team. Lightning images from various typical environments are selected in Fig. 3, which can be roughly classified into three types of images. The first is a single lightning channel image with a simple background that usually contains only one major lightning discharge channel. The second is a multi-branch lightning channel image, in a specific environment, the lightning channel may bifurcate to form multiple branches. The third type is the lightning image with bright clouds and light interference, and when the background complexity is high, such as the lightning passage image above the city. Because the light is similar to the lightning light, the noise such as light cannot be completely filtered by threshold segmentation, and the extraction result is the lightning image with noise.

(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 3. (a~i) shows some of the lightning channel images used in this experiment.

In order to evaluate the performance and validity of the lightning classification model, we conducted a series of tests. This section describes our testing methodology and evaluation metrics. The main goal is to verify the applicability of the model in different scenarios so as to comprehensively assess its performance. In this paper, we use the intersection and merger ratio to evaluate the segmentation results. The intersection ratio is a measure of how much the segmented object or region overlaps with the real object or region. The formula for calculating the intersection ratio is as follows:

$$\mathrm{IOU}(X, Y) = \frac{\mathrm{Area(x)} \cap \mathrm{Area(y)}}{\mathrm{Area(x)} \cup \mathrm{Area(y)}} \tag{8}$$

4.2 Comparison with the Other Methods

In order to fully evaluate the performance and advantages of the lightning segmentation model, we compare the present method with several common segmentation methods as well as deep learning model[18] in Table 1.

Table 1. compares with other classical segmentation methods on the Lightning dataset

LIGHTNING SEGMENTATION METHOD	IOU METRIC
EDGE DETECTION METHOD	60.1%
GLOBAL THRESHOLD METHOD	73.4%
LOCAL THRESHOLD METHOD	77.7%
DEEP LEARNING MODEL（U2_NET）	83.0%
OUR METHOD	88.0%

The experimental results show that the IOU indicator for edge detection rate is 60.1%. In this experiment, using the edge detection method may not be able to correctly identify the lightning edges in some cases, such as for images with complex backgrounds or high noise interference. The edge detection accuracy of 60.1% indicates that there is still room for improvement of the current method in lightning segmentation, which requires further research and optimization.

Although the accuracy of the global thresholding method (73.4%) is higher than the traditional edge detection method (60.1%), it is still not very satisfactory. This may be due to the fact that global thresholding methods uniformly use a fixed threshold when processing images, which may not be adaptable enough to different image regions, resulting in some edges not being recognized correctly.

The local thresholding method has better adaptability compared to the global thresholding method and is able to dynamically adjust the threshold according to the local features of the image. This enables the method to better cope with brightness and contrast variations in different regions of the image, thereby improving the accuracy of lightning detection.

Local thresholding methods show high accuracy in lightning detection tasks because they can dynamically adjust the threshold according to the local features of the image. Lightning usually produces strong luminance changes in specific regions of the image, and local thresholding methods can better adapt to such local features to accurately detect lightning. Such localized luminosity variations can be captured efficiently by local thresholding methods. By employing different thresholds in different regions of the image, the local thresholding method can accurately identify these luminance changes and thus achieve effective lightning detection. Although local thresholding methods perform well in lightning detection, there may be local background noise in some images, which may affect the accuracy of detection. Therefore, for some complex image scenes, further optimization and improvement of the local thresholding method may be required to improve the robustness of the detection.

The accuracy of the deep learning model in the lightning detection experiment results is 83.0%, which indicates that the deep learning model achieves relatively high accuracy in the lightning detection task. By learning the lightning image data, the deep learning model is able to effectively capture the features of lightning and accurately distinguish it from the background. Despite the high accuracy rate achieved by the deep learning model, there is still room for further improvement. More lightning image data for training, as well as tuning of the model structure and parameters, may be needed to further improve the model's performance and generalization ability.

The accuracy of 88.0% indicates that our method is highly effective in capturing and identifying lightning. This may be due to the incorporation of methods such as contour detection and curvature estimation in the proposed method, which allows it to be better adapted to the lightning detection task. Due to the characteristics of lightning and the complexity of images, the lightning detection task is often affected by local features and background noise, while the proposed method can filter or suppress the background noise well. To improve the accuracy, the proposed method fuses multiple models. This fusion application allows the proposed method to capture and identify lightning more comprehensively, thus improving the accuracy. The next Figure 4 shows a schematic representation of several classical segmentation methods, as well as the lightning recognition results based on contour detection and curvature estimation presented in this chapter.

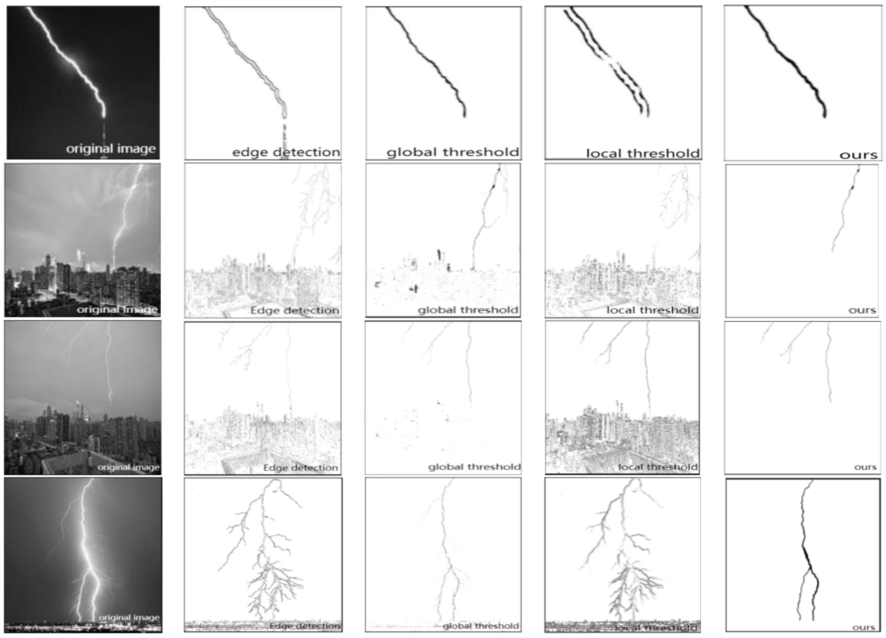

Fig. 4. Lightning channel identification results (From left to right, the original image, edge detection, global thresholding, local thresholding and our method)

4.3 Ablation Study

To understand the internal mechanism of the lightning segmentation model and to improve its performance effectively, a series of ablation experiments are performed in this paper. These experiments aim to systematically analyze the impact of individual components or design choices in the model, thus exploring their contribution to segmentation accuracy and robustness. By comparing these experimental effects, we hope to reveal the key factors of the lightning segmentation model to provide strong support for further research and application. To this end, a series of experimental combinations are designed in this paper, each adjusted or eliminated for a key factor in the model, while keeping the other conditions constant. Figure 5 shows the comparison diagram of the ablation experiment.

In this paper, we first identified the key factors requiring ablation, including threshold segmentation, contour detection, curvature estimation algorithm, etc. Then, for each key factor, the corresponding experimental combinations are designed, including control and experimental groups. In the control group, the original design of the model was kept unchanged as a comparison group. In the experimental group, specific factors were adjusted or eliminated to observe their effects on segmentation performance.

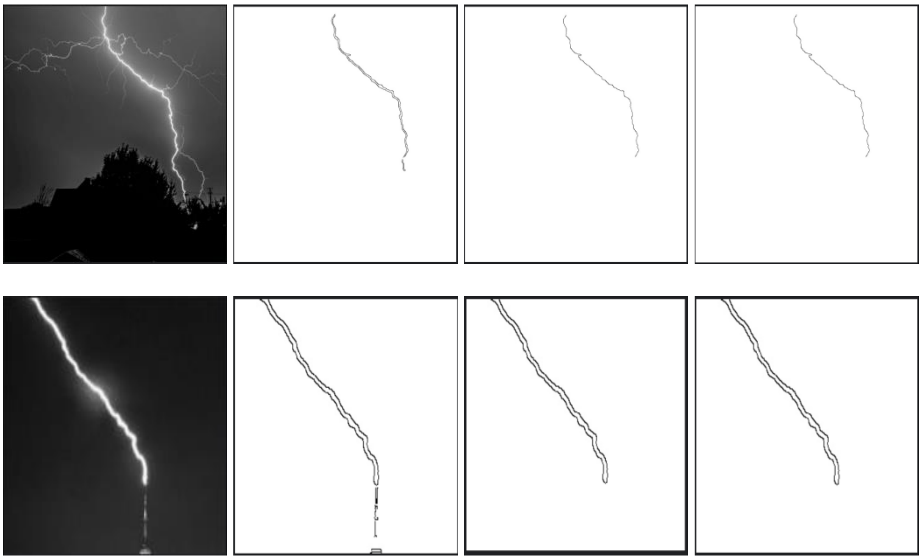

Fig. 5. Comparison of the ablation experiments (From left to right this shows the original image, the removal of contour detection, the removal of curvature estimation, and our Method)

In order to assess the importance of each component of the method based on threshold segmentation, curvature and contour detection in lightning image processing. We will use objective metrics to evaluate the effectiveness of the ablation experiments, as shown in Table 2 below, which will help us to quantify the role of each component in the overall system.

Table 2. IOU indicators for individual components in ablation experiments

ABLATION EXPERIMENT	IOU METRIC
REMOVE CONTOUR DETECTION	68.4%
REMOVE CURVATURE ESTIMATION	86.9%
OUR METHOD	88.0%

The results of the ablation experiments show that in the absence of the threshold segmentation step, the entire processing flow's almost impossible to proceed. This further validates the importance of thresholding in lightning image processing, which functions to separate the target region and reduce the effects of background noise.

Contour detection contributes more to the final processing results. The lack of contour detection module decreases the accuracy of the system to 68.4%, which indicates that contour detection plays a crucial role in the whole system. This may imply that the system relies on contour information in identifying and locating targets, and the absence of this step significantly affects the performance of the system. When faced with complex environments, threshold segmentation cannot completely filter out all background noise, which can bias the final result. Contour detection can analyze and describe the shape of the target object. By calculating the perimeter area and other shape features of the target object, the background noise is further filtered out to avoid the lightning image from being confused with the background or other objects. At the same time, contour detection has an impact on the subsequent curvature estimation.

Curvature estimation also plays an important role in the system, and although its absence leads to a decrease in accuracy, the effect is relatively small. The accuracy of the system when curvature estimation is missing is 86.9%, which is an improvement over the accuracy when contour detection is missing, but still significantly lower than the accuracy of the original method. This may mean that curvature estimation plays a slightly lesser role in the system than contour detection.

The accuracy of the original method is 88.0%, indicating that the system has high accuracy in the intact state. Contour detection and curvature estimation, although contributing to the system performance, are not the only decisive factors. Based on the experimental results, the focus of optimizing the system performance should be on improving the accuracy of contour detection and curvature estimation. At the same time, other components should be further optimized to improve the overall performance of the system.

5 CONCLUSION

In this paper, we propose a lightning recognition segmentation algorithm based on contour detection and curvature value estimation, which processes and analyzes lightning images. It fuses classical segmentation methods with contour detection and curvature estimation to extract lightning images under different environmental conditions. With the results obtained experimentally, the proposed method can effectively segment the lightning target, identify the lightning region, and accurately separate the background noise. By analyzing the curvature and profile, we successfully extracted the morphological features of the lightning target. Compared with conventional methods, the methods in this study showed high adaptability and stability in handling lightning images of different kinds and background conditions. Deep learning has shown strong potential in the field of image segmentation. Future work will explore the reliability of the method when applied to complex railway sites and improve recognition by combining lightning recognition and feature recognition algorithms. Traditional preprocessing steps (e.g., threshold segmentation, contour detection, curvature estimation, etc.) are fused into deep learning models to achieve a more automated and end-to-end flash image segmentation process.

6 REFERENCES

[1]. GOH H H, SIM S yi, SHAARI J, et al. A Review of Lightning Protection System - Risk A ssessment and Application[J/OL]. Indonesian Journal of Electrical Engineering and Com

puter Science, 2019, 8(1): 221. http://dx.doi.org/10.11591/ijeecs.v8.i1.pp221-229. DOI:10.11591/ijeecs. v8. i1. pp221-229.

[2]. NAZARKEVYCH M, KOSTIAK M, OLEKSIV N, et al. A YOLO-based Method for Object Contour Detection and Recognition in Video Sequences[J].

[3]. LOPEZ G V, OREJUDOS J, DELLAGAS A A. ULAT: Deployment of Dense and Nationwide Lightning Detection Network for Weather Forecasting in the Philippines[C/OL]//2022 IEEE Global Humanitarian Technology Conference (GHTC), Santa Clara, CA, USA. 2022. http://dx.doi.org/10.1109/ghtc55712.2022.9911055. DOI:10.1109/ghtc55712.2022.9911055.

[4]. LEI Q, ZHONG J, WANG C, et al. Adaptive Thresholding based on Multi-task Learning for Refining Binary Medical Image Segmentation[J].

[5]. OROZCO-GOMEZ D, BOLANOS F, HERRERA-MURCIA J, et al. A classification model for lightning images without branches based on the tortuosity metric[J].

[6]. ZHANG Yijun, ZHOU Xiuji. Review and Progress of Lightning Research. Journal of Applied Meteorology, 2006, 17(6): 829-834.

[7]. YANG Xinyi, LU Weitao, YANG Jun, et al. Application of Three Threshold Methods in Flash Channel Image Recognition. Journal of Applied Meteorology, 2004, 4(4): 427-435.

[8]. Fangyan N, Mengzhu L, Pingfeng Z. Multilevel thresholding with divergence measure and improved particle swarm optimization algorithm for crack image segmentation [J]. Scientific Reports, 2024, 14 (1): 7642-7642.

[9]. Yang B, Liu W, Lu S, et al. Feature Extraction of Lubricating Oil Debris Signal Based on Segmentation Entropy with an Adaptive Threshold [J]. Sensors, 2024, 24 (5):

[10]. Sokhangou F, Sorelli L, Chouinard L, et al. Detecting Multiple Damages in UHPFRC Beams through Modal Curvature Analysis. [J]. Sensors (Basel, Switzerland), 2024, 24 (3)

[11]. Guoxu C, Ruirui L, Li C, et al. Geological structure identification of coalbed methane reservoir based on trend surface and curvature analysis algorithms [J]. Earth Science Informatics, 2024, 17 (2): 1345-1358.

[12]. Tiejun H, Huaen L, Zhendong Q, et al. Research on Weakly Supervised Pavement Crack Segmentation Based on Defect Location by Generative Adversarial Network and Target Re-optimization [J]. Construction and Building Materials, 2024, 411 134668-.

[13]. Xie Z, Wu J, Tang W, et al. Advancing image segmentation with DBO-Otsu: Addressing rubber tree diseases through enhanced threshold techniques. [J]. PloS one, 2024, 19 (3) : e0297284-e0297284.

[14]. Cai Z, Li G, Zhang J, et al. Using an Artificial Physarum polycephalum Colony for Threshold Image Segmentation [J]. Applied Sciences, 2023, 13 (21):

[15]. Alsahafi S Y, Elshora S D, Mohamed R E, et al. Multilevel Threshold Segmentation of Skin Lesions in Color Images Using Coronavirus Optimization Algorithm [J]. Diagnostics, 2023, 13 (18):

[16]. MohammadReza S, Kost E, Hamid S, et al. Curvature analysis of perisylvian epilepsy. [J]. Acta neurologica Belgica, 2023, 123 (6): 2303-2313.

[17]. M. L H, P. D M, A. N C, et al. "Three-Dimensional Assessment of Frontal Bossing and Temporal Pinching in Patients with Sagittal Craniosynostosis using Curvature Analysis." [J]. Plastic & Reconstructive Surgery, 2023,

[18]. Zheng Q, Dongdong W, Xiangbo S, et al. Lightning Identification Method Based on Deep Learning [J]. Atmosphere, 2022, 13 (12): 2112-2112.

[19]. Zhao L, Zhu R. Research on Image Contour Edge Analysis Based on Canny Edge Detector [J]. Academic Journal of Computing & Information Science, 2022, 5.0 (1.0):

[20]. Abhay S, Dongxia L, Chen X, et al. Lightning Nowcasting with an Algorithm of Thunderstorm Tracking Based on Lightning Location Data over the Beijing Area [J]. Advances in Atmospheric Sciences, 2022, 39 (1): 178-188.
[21]. Bao J, Wang X, Zheng Y, et al. Lightning Performance Evaluation of Transmission Line Based on Data-Driven Lightning Identification, Tracking, and Analysis [J]. IEEE Transactions on Electromagnetic Compatibility, 2020, PP (99): 1-12.
[22]. Wang G, Baets B. Contour detection based on anisotropic edge strength and hierarchical superpixel contrast [J]. Signal, Image and Video Processing, 2019, 13 (8): 1657-1665.
[23]. Zhang Z, Wang H, Yu G, et al. Research on Four-Point Air Bending Process and Contour Detection Method for JCO Forming Process of LSAW Pipes [J]. Metals, 2019, 9 (8): 859-859.
[24]. Li C, Chau T V, Xie H, et al. Recent advances in mechanics of fracking and new results on 2D simulation of crack branching in anisotropic gas or oil shale [J]. Acta Mechanica, 2018, 229 (2): 975-992.
[25]. HIUCHI A, OGAWA T. Contour Detection Methods Using Random Forest for Augmented Reality [J]. D - Abstracts of IEICE TRANSACTIONS on Information and Systems (Japanese Edition), 2015, J98-D (9): 1201-1211.
[26]. Xerox Corporation: Patent Issued for Automated Contour Detection Methods, Systems and Processor-Readable Media [J]. Journal of Engineering, 2015,
[27]. H H, M A. Fractographic aspects of crack branching instability using a phase-field model. [J]. Physical review. E, Statistical, nonlinear, and soft matter physics, 2013, 88 (6): 060401.
[28]. Zeng C, Li Y, Yang K, et al. Contour detection based on a non-classical receptive field model with butterfly-shaped inhibition subregions [J]. Neurocomputing, 2010, 74 (10): 1527-1534.
[29]. LIU B. Long-Distance Recognition of Crack Width in Building Wall Based on Binocular Vision[C/OL]//2021 3rd International Conference on Artificial Intelligence and Advanced Manufacture. 2021.http://dx.doi.org/10.1145/3495018.3495513.DOI:10.1145/3495018.3495513.
[30]. KALITZEOS A A, LIP G Y H, HEITMAR R. Retinal vessel tortuosity measures and their applications[J/OL]. Experimental Eye Research, 2013, 106: 40-46. http://dx.doi.org/10.1016/j.exer.2012.10.015. DOI: 10.1016/j.exer.2012.10.015.