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3D Structure of Positive Corona Streamer Reconstruction Using Stereo Photography and Computer Algorithms

***Abstract**. 3D structure of corona streamer was measured using stereo photography method. To enhance and speed-up the image processing computer algorithms were developed for automatic reconstruction of 3D structure of streamers.*

***Streszczenie.** W niniejszym artykule przedstawiono metodę rekonstrukcji struktury przestrzennej strimera wyładowania koronowego. Dzięki zastosowaniu opracowanych algorytmów komputerowych możliwe było zautomatyzowanie procesu odtwarzania struktury strimera z wykonanych metodą stereofotografii obrazów. (**Rekonstrukcja struktury 3D strimera dodatniego stałoprądowego wyładowania koronowego za pomocą stereografii wspomaganej algorytmami komputerowymi**).*

Keywords: corona streamer, 3D reconstruction, stereo photography, local methods.
Słowa kluczowe: strimery wyładowania koronowego, stereo fotografia, metody lokalne.

Introduction

Positive streamers are widely used in the field of air pollution control such as NOx or SOx removal and VOCs decomposition based on plasma chemical reactions. Although the streamers have been studied for many years, they are still not fully understood due to their complex nature. One of such unexplored issue in streamer research is the breakup of single channels, called streamer branching. Streamer branching is commonly seen in experiments [1,2]. Multiple streamer branching actually determines the gas volume that is crossed by streamers and consecutively chemically activated for plasma processing purposes. However, up to now, only the conditions of the first branching event have been resolved in microscopic models. On the other hand, the distribution of branching lengths and angles is an ingredient of models for the complete branching tree on larger scales [3]. Therefore, there is a need for experimental data of streamer branching lengths and angles. For imaging of streamer discharges digital cameras (CCD cameras) or intensified cameras (ICCD) are used. The result of the imaging is two dimensional (2D) representations of what is actually a three-dimensional (3D) phenomenon. These 2D representations can be difficult in the interpretation and measurements of i.e. branching angles can lead to false conclusions. For this purpose, we have implemented a stereo photography method which makes it possible to image streamer discharges in 3D. The stereographical method we used is commonly used for imaging sparks [4], flames [5], dusty plasmas [6] and pulsed streamers [7]. However, in previous experiments (including our own research [8]) reconstruction of 3D structure was done manually what is difficult and time consuming. The limited number of images which are possible to obtain in that way reduce significantly the value of experimental data. To increase the statistics we decided to develop computer algorithms for automatic reconstruction of 3D structure of streamers.

Computer algorithms

To reconstruct the 3D streamer structure several numerical methods were applied and compared.

3D streamer reconstruction methods

We can divide 3D reconstruction methods into 2 groups: global and local approaches which is related to global and local error minimization. In the first approach the 3D discharge model is created and subsequently modified to stereo photography matching using particle simulations or evolutionary searching methods [9]. The comprehensive description of global methods used for 3D streamer reconstruction problem can be found in [10]. In the local approach broadly described in this article in the first step two 2D models are created separately for each of projection photography. In the second step 3D model is built based on 2D projection models. The first step can be divided into image preprocessing stage and lines (curves) + nodes detection which can be named as vectorization stage. The modular structure showed in Fig. 1 provides the possibilities of different methods compositions.

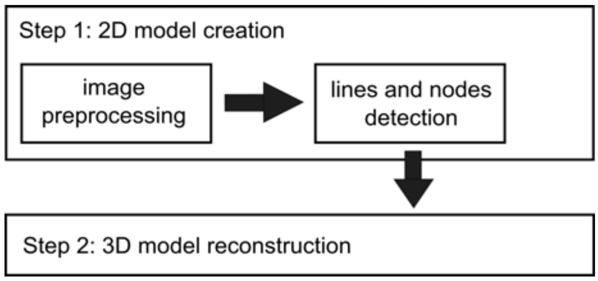

Fig.1. Modular structure of 3D stream reconstruction

The first step can be accomplished as full manual, semi automatic (interactive) or full automatic process. In the first case the user can draw lines and nodes by hand based on original images. In the second case the user can accept or correct the algorithmical suggestions. In the third case the process is the quickest but demands knowledge incorporation which is the most difficult challenge. The knowledge about physical phenomenon in the most simple approach can be represented by curve continuity and curvature limitation. In more advanced approach the learning based on manually obtained examples can be used to acquire human knowledge from manual and semi automatic methods to full automatic one. The decisions whether any point belongs to node or to a line can be treated as learning objectives. The problem arises from the fact that such tasks are always difficult for computer programs although easy for human, like face detection task. In this work we have concentrated on full automatic morphological and histogram based 2D model creation methods without learning as a first step of 3D model reconstruction.

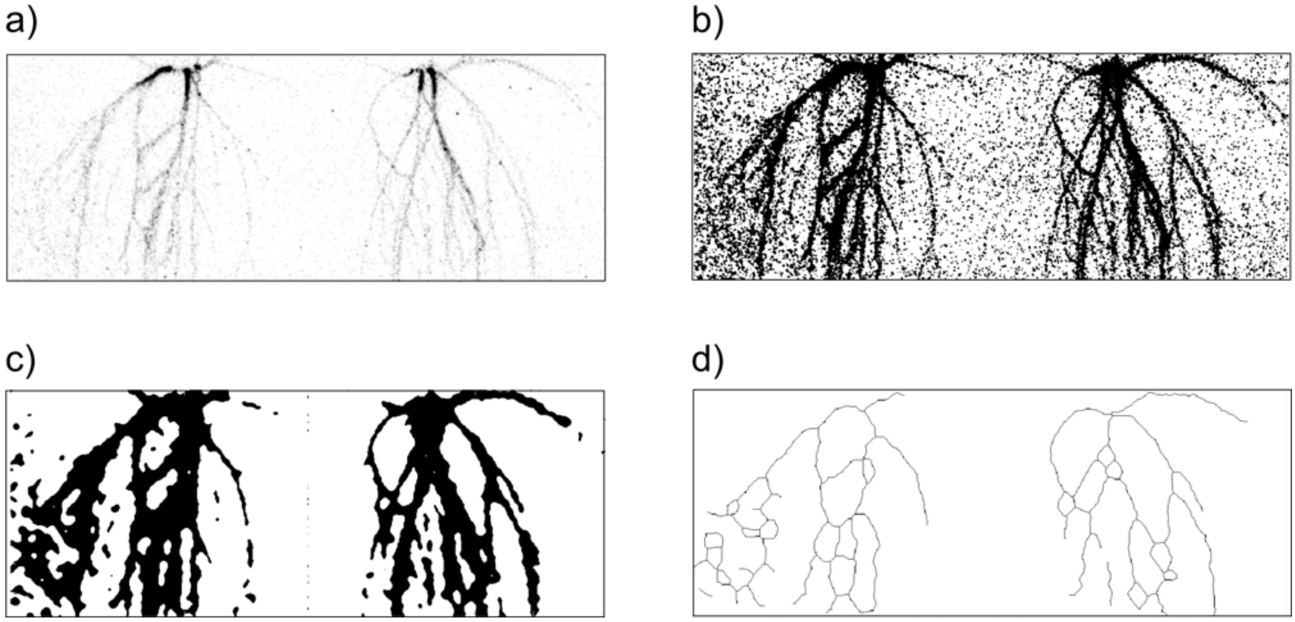

Fig.2. Morphological operations: a) original images, b) after binarization, c) after closing, d) after skeletonization with short curves reduction.

Morphological method

The main advantages of morphology usage for image preprocessing stage is their generality, speed, and easy nodes detection. It seems that the simplest approach to image preprocessing is to use the well known image processing methods like morphological operations to obtain a skeleton of an image. The example sequence of operations with example parameter values and on example couple of images were showed in Fig. 2.

a)

0	0	0
	1	
1	1	1

b)

	0	0
1	1	0
	1	

Fig.3. Structural elements for thinning operation

The binarization operation (Fig. 2b) changes each image into monochromatic one using chosen threshold value. The morphological closing operation (Fig. 2c) at next step is used for empty areas closing and to cancel the noise spots which are placed rather out of streamer channels. The operation is composed with dilation and erosion and was repeated several times. In this example the dilation determined each pixel value as ,,1" if more than 3 pixel values from 3x3 adjacent pixels were equal to 1. The erosion worked in the same way but the threshold was equal 7. The skeletonization process (Fig. 2d) is used to obtain the net composed of thin curves which helps to find single curves and nodes. In presented example the thinning algorithm with two structural elements showed at Fig. 3 was chosen from several other methods. Each pixel value on an image was fixed to zero if its 3x3 adjacent pixels matches first structural element (Fig. 3a) (empty squares can be matched to any value) and next after whole image transformation, the second structural element (Fig. 3b) is treated in the same way. Then, this two transformations was repeated for rotated structural elements by 90, 180, and 270 degrees. Simultaneously, during nodes and curves detection stage, the reduction of short curves takes place. The reduction decision is based on the observation if the short curve to be eventually removed belongs to streamer channel or to noise spot.

As can be seen in Fig. 2d the number of nodes and its vertical position are quite different in each projection which makes the 3D stream model reconstruction a difficult task. Other drawbacks of standard morphological operations in discharge 3D streamer reconstruction can be listed as following:

- limited number of node branches ,
- information loss related to binarization operation,
- branch leaving related to discontinuity of stream channel image,
- difficulties with distinguishing branching nodes from line crosses.

Therefore, all operations should be chosen in proper order and with proper parameter values to make 2D models most reliable to human expert e.g. each model should be consistent with human expert knowledge. We can reach high level of consistency using learning system in which several morphological operations with different threshold values are tested using human expert subjective estimation or any consistency criterion between two images.

Another approach to increase object detection quality is connected with direct expert knowledge incorporation by using dedicated image preprocessing methods prepared specially for streamer channel modelling. Histogram based object detection method is considered as an example of such approach.

Histogram based method

For each analysed pixel, histogram based on circular area is calculated. In a simple version each pixel which belongs to area was classified to one histogram bar related to particular angle. The weighted average pixel intensity value for each considered angle was calculated. The weight value is inversely proportional to distance between analysed pixel and considered pixel circular area e.g. when distance is higher the weight is lower. Fig. 4 presents example diagram after normalization and smoothing. Each branch can be detected as peak in the diagram, each straight line can be detected as two peaks shifted by the distance of about 180 degrees. Appearing of more than two peaks (see Fig. 4) suggests the node existence. The learning decision system can be used to classify histogram features using human expert decision. The peaks can be observed in different scales in many area diameters or by distance weights manipulation, providing much information for learning system purposes.

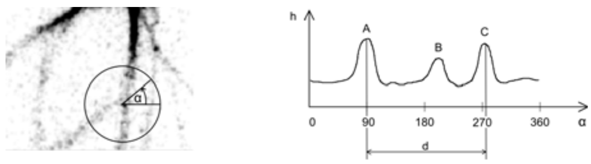

Fig.4. Histogram-based nodes and lines detection : weighted pixel intensity related to direction angle diagram and diagram calculation area

Conclusions

Two methods of image preprocessing and object detection were presented as a local method component. Local methods help to overcome high computational complexity related to global ones by direct application of real streamer features during 2D models creation and simple nodes matching algorithm.

The morphological operations help to detect nodes and curves quickly but not so precisely. Histogram based method is specially prepared for 3D streamer model reconstruction. The main difference between considered methods is due to knowledge incorporation method. In morphological method the parameter optimization techniques can be used based on human expert subjective estimation or any consistency criterion between two images. In histogram based method the knowledge is directly included with optional histogram features interpretation learned from human expert decision examples.

During initial experiments the histogram based method seemed to be more accurate but the way of knowledge incorporation makes this method less general than morphological. Moreover, the knowledge used for preparing algorithms may be uncertain or incomplete because physical phenomenon is under investigation.

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