Pattern Recognition 60 (2016) 949–970

Contents lists available at ScienceDirect

Pattern Recognition

journal homepage: www.elsevier.com/locate/pr

A survey on curvilinear object segmentation in multiple applications

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form
13 May 2016
Accepted 12 July 2016
Available online 14 July 2016

Keywords:
Image processing
Pattern recognition
Curvilinear objects
Segmentation
Survey
Review

ABSTRACT

Curvilinear object segmentation is a paramount step for many applications ranging from medical to aerial image processing. In particular, vessel segmentation in retinal images, detection of spiculated lesions in mammograms or extraction of airways in CT scans provide essential information to experts to evaluate, diagnose and propose a treatment. The significance of these applications has conducted important efforts to propose curvilinear object segmentation algorithms based on the most different techniques. The main objective of this review is to clearly present the similarities and differences between curvilinear structures in different applications and the different techniques used to segment them more effectively. To do so, we propose a general definition of curvilinear structures that encompasses the distinct models considered in the literature. In addition, we analyse and classify the mathematical techniques used to segment the curvilinear structures found across all considered applications, studying their strengths and weaknesses. In particular, we present the most relevant benchmarks related to curvilinear object segmentation as well as the best algorithms according to several performance measures. By doing so, it is acquired a wider point of view to extend the results from some fields to others, and to understand under which conditions some methodologies should be favoured over the rest of them.

1. Introduction

Several applications extract curvilinear objects from images with different purposes. Curvilinear objects can be roughly defined as thin, long, line-like regions with different intensities than their neighbouring pixels. Such structures are found in a wide variety of situations: vessels in medical imaging, roads in satellite imagery or fingerprints from specialized acquisition devices are just a few examples of them. Since these and other applications face very similar problems, the methods that employ them tend to be based on the same techniques. However, researchers usually focus on one or two applications, disregarding the results they could potentially achieve in other fields with their own techniques. Besides not being developed in all their potential, the same mathematical tools are rediscovered and fine-grained on many occasions.

There are a great number of published methods that deal with the segmentation of line-like objects, and some highly detailed reviews of them. However, all these reviews are focused on just one specific application. Although all of them compare and classify methods with respect to different taxonomies, there is no single study that unifies these fields to the best of our knowledge. Kirbas and Quek [1] studied and summarized techniques for vessel segmentation. More recently, a survey focused on retinal vessel segmentation was published by Fraz et al. [2]. Lesage et al. [3] presented a review of 3D vessel lumen segmentation techniques. Several methods aimed at performing airway tree segmentation in chest Computed Tomography (CT) scans were collected and compared in a study led by Lo [4]. Mena [5] published a qualitative survey of road extraction algorithms. A brief review in road pavement assessment algorithms was provided by Chambon and Moliard [6]. Other surveys on tightly related applications have also been presented, like palmprint line enhancement [7] or fingerprint classification [8]. In view of the lack of an in-depth, common analysis of these related techniques, the present survey is aimed at providing a cross-application comparison of the different strategies employed to segment curvilinear structures.

The methodology employed to study curvilinear structure segmentation has very important consequences in our study. Regarding the nature of the method, we have focused on *segmentation methods* to limit the field of work, which eases the comparison among methods and potentially empowers a more specific analysis. Segmentation methods are the ones whose input is a two- or three-dimensional image, and whose output is a binary mask indicating whether the pixel belongs to the curvilinear object or not. In contrast, enhancement methods, which may be seen as pixel-wise estimators of the belonging degree to a curvilinear object, are deliberately given a lower priority in this review. Besides, we do

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http://dx.doi.org/10.1016/j.patcog.2016.07.023
0031-3203/

not include algorithms concerned with edges or contours between different objects. With regard to the studied algorithms, we find a vast amount of published works along decades when considering several applications. To increase the coverage of the survey while retaining the most relevant results, we have selected a subset of them based on, in order of relevance, the following criteria: (a) their quantitative results in the most relevant benchmarks, (b) the number of incoming cites according to Google Scholar, (c) the year of their publication, and, (d) the singularity of the application or the mathematical approach used to segment, favouring methods that segment curvilinear objects in infrequent settings. These four criteria are considered jointly instead of as four independent scores. By doing so, we have selected papers that contribute to this review due to their successful approach, their high impact on the field or their originality.

The objective of this review is to clearly present the similarities and differences between curvilinear structures in different applications and how they are segmented more effectively. By doing so, we can potentially acquire a wider point of view to extend the results from some fields to others, and to understand under which conditions some methodologies should be favoured over the rest of them.

Motivated by these two potential contributions, our goals are: (I) to select applications of curvilinear structure segmentation and study how the curvilinear objects present in them are modelled; (II) to propose a general and broad definition that encompasses the curvilinear objects that are found in all the selected fields of interest; (III) to summarize the mathematical techniques used to segment the curvilinear structures found across all considered applications; and (IV) to study the strengths and weaknesses of these techniques according to the type of curvilinear objects and to the final objective that the segmentation contributes to fulfill.

The structure of the rest of this survey is as follows. We introduce the models of curvilinear objects according to each application in Section 2, where we also extract the common denominator of such models, addressing thus Goals (I) and (II). In Section 3, which is aimed at facing Goal (III), the selected methods are described and classified according to the mathematical tool with which curvilinear objects are segmented. A comparison of the results provided by different methods is given in Section 4, along with a discussion concerning which methods can be compared and how to do such comparison, addressing thus the Goal (IV). Finally, Section 5 concludes with a discussion, unifying the analysis scattered over the previous sections.

2. Description of curvilinear structures

This section establishes the foundations of a coherent study of the different mathematical techniques used to segment curvilinear structures. To do so, we should establish which objects can be considered curvilinear structures, which is accomplished by studying different applications, the algorithms that address them and their explicit and implicit models. We firstly introduce a *Model for Curvilinear Structures*, which covers the common characteristics that share all curvilinear objects as we understand them. Besides, we present a series of applications that contain curvilinear structures, focusing on the most widely studied.

2.1. Model for curvilinear structures

Our model for curvilinear structures has been obtained as the common denominator of the explicit and implicit models considered in the selected literature.

When dealing with image segmentation, a model can be thought of as a collection of high-level features that define the object of interest, discriminating it from the rest of the image. These features must be translated into a series of constraints such that, broadly speaking, a pixel will be tagged as belonging to the object if it fulfills such constraints. Depending on their nature, such constraints will be classified, in accordance with the literature [3,6,9], as either geometric, when the restriction involves the spatial relations among the pixels, or photometric, in which the intensity value of pixels are taken into account.

That said, we define a *Curvilinear Structure* as a region of pixels within one image that fulfills the following geometric (**G**) and photometric (**P**) characteristics:

G1. Its pixels should be “mostly” connected.
G2. The region should be “thin” across a “long” path.
G3. The variation of width along the region should be “smooth”.
G4. It should have a specific structure. That is, the overall shape of the whole segmentation seen as a binary mask. It can be a binary tree-like structure, a series of unconnected segments, a grid, etc.
G5. It should have a specific local curvature profile. This covers the behaviour of the bends that the tubular object may have. For instance, some objects may be mostly straight, others can admit soft bends and others may be highly tortuous.
G6. It should present a specific amount of bifurcations. We define a bifurcation as a three-branch joint. That is, a position of the curvilinear object where exactly three distinct branches collide.
G7. It should present a specific amount of intersections. An intersection, as we understand it, is a joint with four or more branches.
P1. Its pixels should have “significantly different” intensities compared to its neighbouring background. In multivariate images, different channels may conceive independent information, capturing some of them more information than others
P2. The variation of pixel intensities along the main direction should be “smooth”.
P3. Its cross-section profile – the intensity values transverse to the main direction – should follow a specific distribution. In 2D images it is represented as a one-dimensional function, whereas 3D imaging has a cross section whose domain is a two-dimensional area. For example, a flat profile, also referred to as a bar-like profile, assigns a single value to each point in the cross-section.

A pixel is considered to belong to a curvilinear structure if it belongs to a region fulfilling the constraints **G1**–**G7** and **P1**–**P3**. While the constraints **G1**–**G3** remain stable among the different applications, the features **G4**–**G7** and **P1**–**P3** should be further specified to improve the model for the curvilinear structures of interest. This helps to discriminate curvilinear objects from other structures, the background texture or noise in each particular application. Tables 1 and 2 detail such features for the applications considered in this review.

We highlight that curvilinear, one-pixel width segments are intentionally included in our definition. However, this definition does not include contours or edges, since these regions do not fulfill **P1**: their intensity is similar to either one of the two regions they divide. We remark that we are not concerned with the limits between two objects, but with one tubular-shaped object placed in the foreground of a uniform or non-uniform background.

We also highlight the subjective nature of our definition, which is explicit by containing some vague words such as “mostly”, and “thin’. These vague concepts should be accurately established in each specific situation. This lack of formality is unavoidable: there are pixels that some experts may flag differently than others. Such vagueness is deliberately incorporated into our general definition.

The meaning of the aforementioned vague concepts can be illustrated with the curvilinear structures found in Figs. 1–5. For