Computerized Medical Imaging and Graphics 34 (2010) 213–227

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

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

Multi-scale retinal vessel segmentation using line tracking

Marios Vlachos*, Evangelos Dermatas

Department of Electrical Engineering and Computer Technology, University of Patras, Patras, Greece

ARTICLE INFO

Article history:
Received 1 June 2009
Received in revised form
24 September 2009
Accepted 25 September 2009

Keywords:
Multi-scale line tracking
Cross-sectional profile
Morphological reconstruction
Retinal images
Vessel segmentation

ABSTRACT

In this paper an algorithm for vessel segmentation and network extraction in retinal images is proposed. A new multi-scale line-tracking procedure is starting from a small group of pixels, derived from a brightness selection rule, and terminates when a cross-sectional profile condition becomes invalid. The multi-scale image map is derived after combining the individual image maps along scales, containing the pixels confidence to belong in a vessel. The initial vessel network is derived after map quantization of the multi-scale confidence matrix. Median filtering is applied in the initial vessel network, restoring disconnected vessel lines and eliminating noisy lines. Finally, post-processing removes erroneous areas using directional attributes of vessels and morphological reconstruction.

The experimental evaluation in the publicly available *DRIVE* database shows accurate extraction of vessels network. The average accuracy of 0.929 with 0.747 sensitivity and 0.955 specificity is very close to the manual segmentation rates obtained by the second observer. The proposed algorithm is compared also with widely used supervised and unsupervised methods and evaluated in noisy conditions, giving higher average sensitivity rate in the same range of specificity and accuracy, and showing robustness in the presence of additive Salt&Pepper or Gaussian white noise.

1. Introduction

The retina, a layer of membrane at the back of the eye, can be visualized as an image by the fundus camera. The retinal images, often noisy, poorly contrasted and non-uniformly illuminated suffer from brightness variations both along the same image and between different images.

Several supervised [1–3] and unsupervised [4–6] vessel segmentation methods have already been proposed and evaluated. Valuable applications has been presented [7,8] in the diagnosis of various eye and systemic diseases, such as diabetes, hypertension [9], and angiogenesis [10]. The most accurate supervised methods enhance their detection capabilities using several types of knowledge about the vessel network morphology.

An automated vessel location method in ocular fundus images is proposed using a novel cooperative synergy of local and global features to segment the vessel network [11]. Such a tool should be proved useful to eye care specialists for purposes of patient screening, treatment evaluation, and clinical studies. A method for rapid, automatic, robust, adaptive, and accurate tracing of retinal vasculature and analysis of intersections and crossovers is presented in [12] and is being applied to computer-assisted laser retinal surgery.

In a typical vessel segmentation method, after the initial estimation of a vessel network, fine tuning methods are used to improve the detection accuracy. In unsupervised segmentation, the vessel network is detected using pixel-based processing methods through spatial transformations or tracking operations. The tree-like geometry of the vessel network makes it a usable feature for registration between objects of a different nature. Vessel-like patterns are detected with respect to precise models. If a vessel is defined as a bright pattern, piece-wise connected and locally linear mathematical morphology operators are used to produce this type of description. In order to discriminate vessels from similar background patterns, a cross-curvature evaluation is performed. The vessels are separated out as they have a specific Gaussian-like profile whose curvature varies smoothly along the vessel.

The most popular pixel based segmentation methods include, two-dimensional matched filters [4,10], object classification and noise removal [13], continuous two-dimensional Morlet wavelet transformation at multiple scales [2], allowing noise filtering and vessel enhancement in a single step [1]. In [14], curvature evaluation is used to detect vessel-like patterns in a noisy environment. Computational models reduce noise and enhance the vessels network combining Naka-Rushton, cluster, hyperbole, median filters and skeleton processes. As a result, bifurcations and crossover pixels of retinal vessels are detected [15].

Several vessel detection algorithms are based on a four steps procedure: noise reduction, Gaussian-like profile enhancement,

* Corresponding author. Tel.: +30 2610996189.
E-mail address: mvlachos@george.wcl2.ee.upatras.gr (M. Vlachos).

0895-6111/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compmedimag.2009.09.006

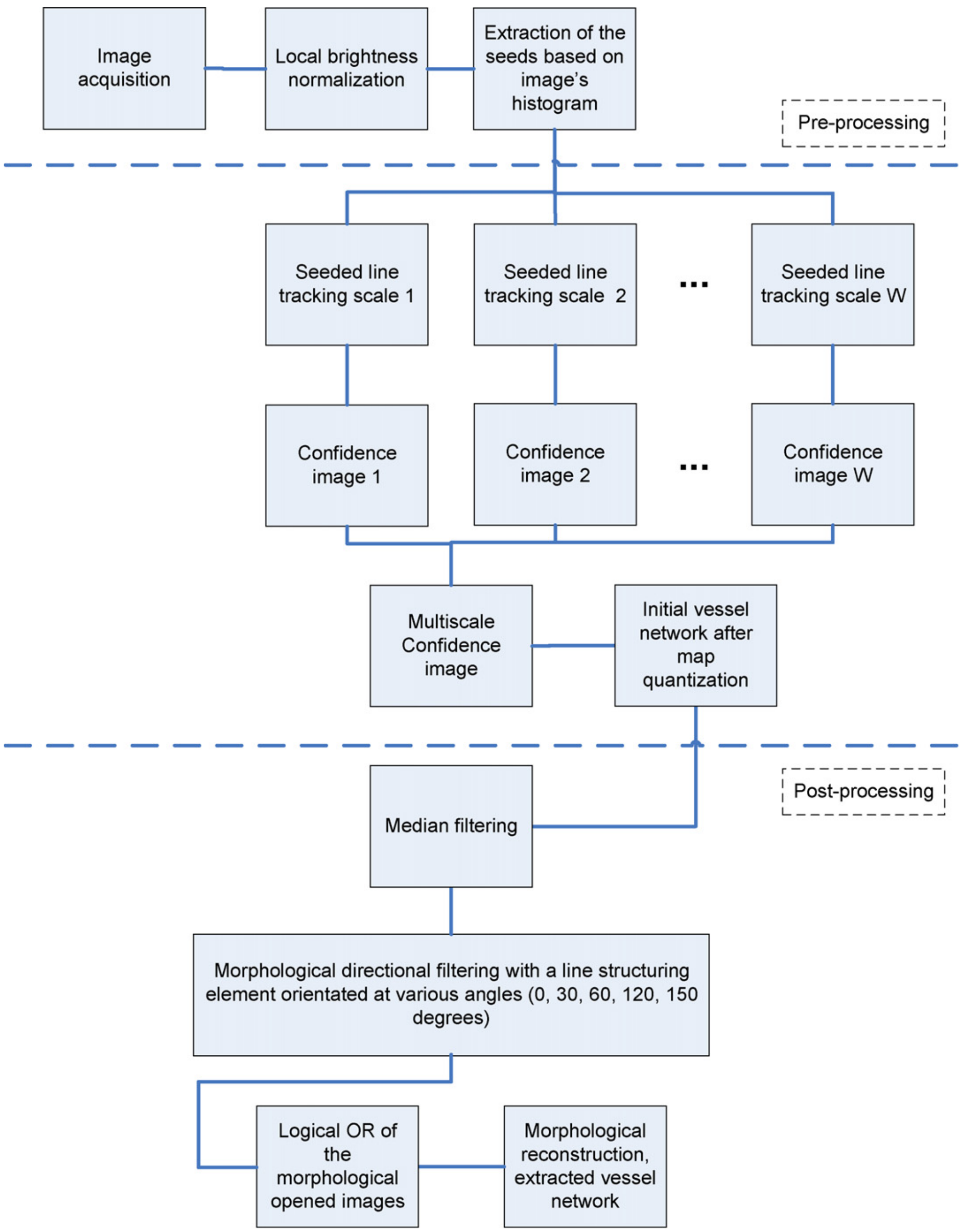

Fig. 1. Flowchart of the seeded multi-scale line-tracking algorithm (*MSLTA*).

cross-curvature evaluation and linear filtering. Based on the analysis of gradient orientation, where circular and linear structures are detected, a robust and efficient method for detection of anatomical features is used in low contrast and non-uniformly illuminated retinal images [9]. A multi-scale approach is employed to detect various sizes of features, especially blood vessels with varying diameters.

A second-order derivative Gaussian matched filter is used to locate the center point and width of a vessel in its cross-sectional profile [5]. In addition, the extended Kalman filter is employed for the optimal linear estimation of the next possible location of blood vessel segment and a simple branching detection strategy is implemented checking the bifurcation in the vessel network during tracking. In a similar approach, the fitness of estimating vessel profiles with Gaussian function is evaluated and an amplitude-modified second-order Gaussian filter is proposed for the detection and measurement of vessels [16].

Even in case of robust vessel segmentation, post-processing methods are used to remove false detected vessels, improving further the detection accuracy. The most important methods include mathematical morphology transformation [1], length filtering and vascular intersection detection [6], vessel detection based on piecewise linearity and anti-parallel edges [17] or detection of morphological similarities between image ridges and vessel centerlines [3]. The ridges are used to partition the original image into patches by composing primitives in the form of line elements. Each image pixel is assigned to the closest line element using a feature vector and the nearest neighbor classifier [3]. In angiograms, branching and bifurcation regions of typical vessel trees are detected decreas-