Computerized Medical Imaging and Graphics 47 (2016) 1–15

Contents lists available at ScienceDirect

Computerized Medical Imaging and Graphics

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

Automatic tracking of vessel-like structures from a single starting point

Dário Augusto Borges Oliveira [a,b,*], Laura Leal-Taixé [e], Raul Queiroz Feitosa [b,d], Bodo Rosenhahn [c]

[a] Institute of Mathematics and Statistics, University of São Paulo, Brazil
[b] Electrical Engineering Department, Pontifical Catholic University of Rio de Janeiro, Brazil
[c] Institute for Information Processing, Leibniz University Hannover, Germany
[d] Electrical Engineering Department, Rio de Janeiro State University, Brazil
[e] Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland

ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 6 July 2015
Accepted 5 November 2015

Keywords:
Vascular network tracking
Linear Programming
Vessel characterization
Medical imaging

ABSTRACT

The identification of vascular networks is an important topic in the medical image analysis community. While most methods focus on single vessel tracking, the few solutions that exist for tracking complete vascular networks are usually computationally intensive and require a lot of user interaction. In this paper we present a method to track full vascular networks iteratively using a single starting point. Our approach is based on a cloud of sampling points distributed over concentric spherical layers. We also proposed a vessel model and a metric of how well a sample point fits this model. Then, we implement the network tracking as a min-cost flow problem, and propose a novel optimization scheme to iteratively track the vessel structure by inherently handling bifurcations and paths. The method was tested using both synthetic and real images. On the 9 different data-sets of synthetic blood vessels, we achieved maximum accuracies of more than 98%. We further use the synthetic data-set to analyze the sensibility of our method to parameter setting, showing the robustness of the proposed algorithm. For real images, we used coronary, carotid and pulmonary data to segment vascular structures and present the visual results. Still for real images, we present numerical and visual results for networks of nerve fibers in the olfactory system. Further visual results also show the potential of our approach for identifying vascular networks topologies. The presented method delivers good results for the several different datasets tested and have potential for segmenting vessel-like structures. Also, the topology information, inherently extracted, can be used for further analysis to computed aided diagnosis and surgical planning. Finally, the method's modular aspect holds potential for problem-oriented adjustments and improvements.

1. Introduction

The identification of vascular networks is a topic of general interest in medical image analysis and in particular for diagnosis of problems related to the vascular system such as cerebrovascular accidents or thrombosis. While efficient algorithms for single vessel tracking exist, the segmentation of complete vascular networks is still a challenge, mainly due to huge search space involved. Indeed, most solutions are only locally optimal, very computationally intensive or both.

We refer the interested reader to [12] for a detailed review of methods to tackle the vascular segmentation problem. Many of these works are based on a propagating structure emanating from a given starting point using different techniques such as level-sets [15,16] or minimal paths [4,25]. Other approaches are based on particle filters [5,13], Markov chain processes [11], statistical methods for tubular structures [24] and multiple hypothesis testing [6]. Recent works [23,22] have shown that global optimization can be reliable as it finds all the vessels of the structure jointly. In [23], authors find a set of vessel candidate points and then solve the k-minimum spanning tree (k-MST) problem to find the final structure, while in [22], the vessel detection model needs to be specifically trained for each type of data. The latter assumes a well behaved distribution of vessel points and a careful training.

In this paper we present a novel Linear Programming (LP) solution for tracking vascular networks through a fast iterative method that tracks each vessel branch independently and is able to handle bifurcations. Our approach does not impose any restrictions to

* Corresponding author at: Institute of Mathematics and Statistics, University of São Paulo, Brazil. Tel.: +55 21 999447901.
E-mail address: darioaugusto@gmail.com (D.A. Borges Oliveira).

http://dx.doi.org/10.1016/j.compmedimag.2015.11.002
0895-6111/

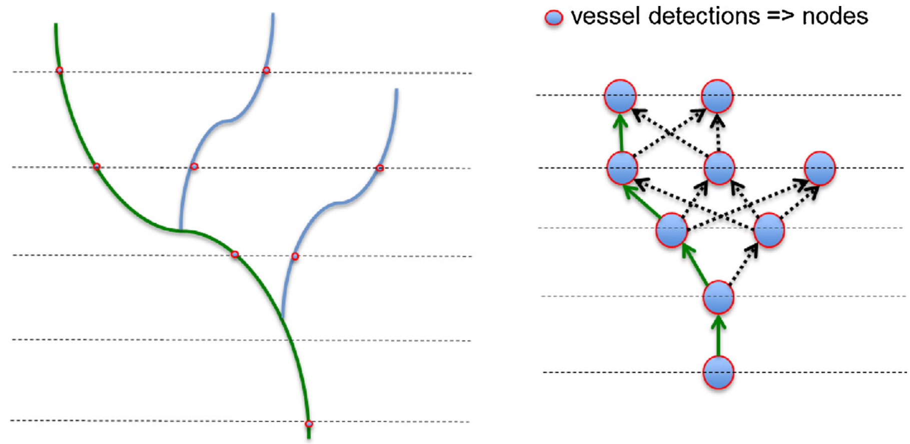

Fig. 1. Modeling a vascular network in a graph using a single direction. On the left side there is a model representing a vascular network with an identified green branch; on the right side its respective graph with green edges indicating the green branch path, and dashed edges representing other path possibilities.

the form of vessels offshoots. It relies on two simple assumptions: vessels are nearly cylindrical, having circular or elliptic cross sections, and present a tree like structure. Contrary to most methods proposed thus far, it only requires one starting point to track a full vessel network with arbitrary form.

1.1. Motivation and graph modeling

The use of directed graphs to segment tree-like structures (such as vascular networks) is somewhat intuitive. Considering vessel point detections as graph nodes, a vascular network can be structured as a directed graph, which allows the segmentation of its branches through the analysis of graph paths, as depicted in Fig. 1.

Not very intuitive is the problem of using directed graphs to represent vascular structures in images with voxels distributed uniformly in a given direction, such as CT scans. Vessels usually change direction continuously and hardly follow the direction of a single axis. Since directed graphs consist of nodes organized in interconnected layers following a certain direction, this behavior is problematic. The use of a single axis to define the directed graph levels, would lead to the impossibility of segmenting vessels whose direction goes in favor of the axis at some point, but against it later. In other words, the directed graph modeling does not allow a path passing through a sequence of levels N and $N+1$ to return to any node on level N. Fig. 2 depicts the problem. The yellow branch cannot be entirely represented since it crosses some planes more than once.

This paper proposes a way to overcome this difficulty through the use of multiple graphs, each one modeling a portion of the vascular network that conforms the implied sequential spatial arrangement of vessel detection. These local graphs are created iteratively and their nodes are associated to spatial positions expressed in a convenient coordinate system, as illustrated in Fig. 3. This approach provides, at least locally, a model in which the problem described in Fig. 2 does not occur, so that the modeling through directed graphs becomes effective. The proposed sampling model is formally defined in Section 2.2.

Our contribution is three-fold:

- Oriented conical sampling method using vessel point detections to allow tracking of each vessel along its axis.
- New formulation of the vascular network tracking problem as a min-cost flow problem to track local vascular structures from a single seed point while dealing with bifurcations.
- Novel optimization scheme that iteratively tracks the full vascular network and guarantee anatomical vascular properties.

Our paper is structured as the following: in Section 2 we explain in detail our method, in Section 3 we show and discuss the results, and in Section 4 we present our conclusions.

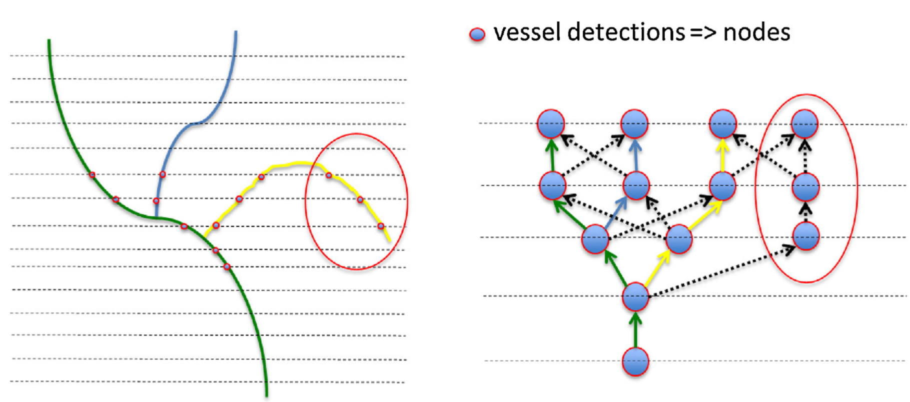

Fig. 2. Issues of modeling a vascular network as a graph using a single direction (some edges were hidden to improve understanding). The model on the left side has its green and blue branches correctly modeled in the graph represented on the right side. The yellow path, though, is incorrectly represented – as the red line points out – due to directed graph representation issues. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)