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Retinal blood vessel segmentation using fully convolutional network with transfer learning

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ABSTRACT

Since the retinal blood vessel has been acknowledged as an indispensable element in both ophthalmological and cardiovascular disease diagnosis, the accurate segmentation of the retinal vessel tree has become the prerequisite step for automated or computer-aided diagnosis systems. In this paper, a supervised method is presented based on a pre-trained fully convolutional network through transfer learning. This proposed method has simplified the typical retinal vessel segmentation problem from full-size image segmentation to regional vessel element recognition and result merging. Meanwhile, additional unsupervised image post-processing techniques are applied to this proposed method so as to refine the final result. Extensive experiments have been conducted on DRIVE, STARE, CHASE_DB1 and HRF databases, and the accuracy of the cross-database test on these four databases is state-of-the-art, which also presents the high robustness of the proposed approach. This successful result has not only contributed to the area of automated retinal blood vessel segmentation but also supports the effectiveness of transfer learning when applying deep learning technique to medical imaging.

1. Introduction

The retinal vasculature has been acknowledged as an indispensable element in both ophthalmological and cardiovascular disease diagnosis such as glaucoma and diabetic retinopathy. The attributes of retinal blood vessels including length, width, tortuosity, branching pattern, and angles will contribute to the diagnostic result. However, manual segmentation of retinal blood vessels, although possible, is a time consuming and repetitive work, and it also requires professional skills. To assist ophthalmologists with this complex and tedious work, the demand for the fast automated analysis of the retinal vessel images arises.

However, to fully automate the analysis and practice in real medical situations is a harsh task. First, the diagnosis of the retinal related diseases requires extremely high accuracy of vessel extraction, because even the tiny thinnest vessel may contribute to the differential diagnosis list. Second, real medical situations demand extraordinary robustness, because unlike experimenting with certain databases and with a limited number of retinal images, more unfamiliar cases will come up at any time. A robust method is expected to maintain the high accuracy of vessel segmentation in all circumstances. In fact, only a small portion of the related supervised works have conducted the cross-database test and every work which has done cross-database test has encountered more or less a decrease in accuracy compared with their single-database test.

In an attempt to provide a highly accurate and robust automatic retinal blood vessel segmentation approach, this paper, therefore, proposes an innovative supervised method to extract retinal vessels using deep learning techniques. More specifically, the proposed method has applied the fully convolutional network, which is usually used to perform semantic segmentation task, with transfer learning.

Deep learning is an improvement of artificial neural networks, consisting of more layers that permit higher levels of feature abstraction and improved predictions from data (LeCun et al., 2015). Especially, the convolutional neural network has proven to be a powerful tool for various of computer vision tasks such as image classification and segmentation. Recently, medical image analysis groups across the world are quickly entering this field and applying convolutional neural networks and other deep learning methodologies to a wide variety of applications, and extraordinary results are emerging continuously (Greenspan et al., 2016).

The fully convolutional network, proposed by the computer vision group of the University of California, Berkeley (Shelhamer et al., 2017), is derived from the convolutional neural network, which, in theory, is normally comprised of one or more convolutional layers (often with a subsampling step) and then followed by one or more fully connected layers as in a standard multilayer neural network. The major feature that makes a fully convolutional network different from the

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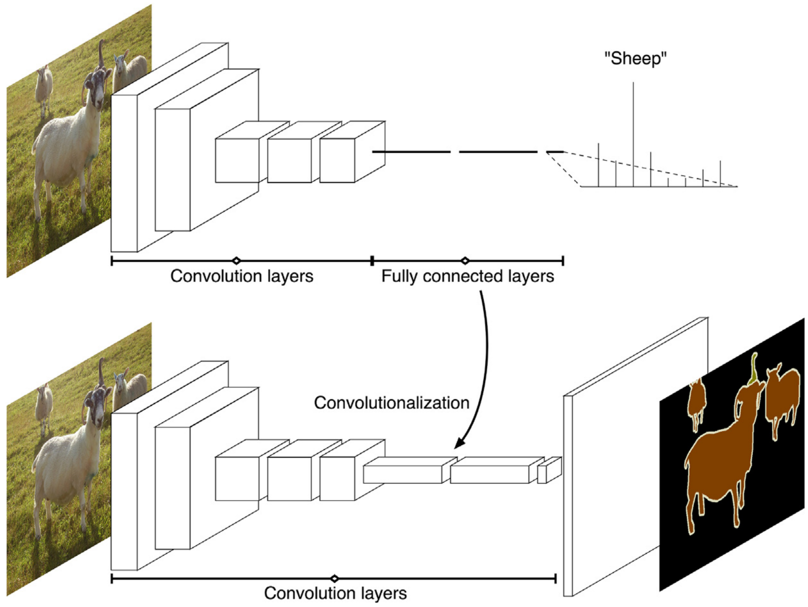

Fig. 1. By transforming the fully connected layers into convolutional convolution layers, the fully convolutional network can make dense predictions for per-pixel tasks like semantic segmentation.

convolutional neural network is the transformation of all fully connected layers into convolution layers (see Fig. 1), through which, a fully convolutional network is able to operate on an input of any size, and produces an output of corresponding spatial dimensions. In this case, some classification networks, such as the AlexNet (Krizhevsky et al., 2012), can be used for the end-to-end, pixels-to-pixels for semantic segmentation, instead of outputting the classification prediction scores.

In the work of Shelhamer et al. (2017), the fully convolutional version of AlexNet excels all the other state-of-the-art works without further machinery, which is therefore applied in the proposed work along with the transfer learning methodology.

Transfer learning is the perfect solution when there have insufficient publicly available datasets for training the network from scratch. Usually, training a convolutional neural network requires large numbers of labeled training data, which is somehow very difficult to realize in the medical domain where the expert annotation is expensive and the diseases are rare. For a task such like the retinal blood vessel segmentation, the total number of the retinal color images from all the four databases is 133, which is far away from the training requirement of the fully convolutional network. However, with transfer learning, the convolutional neural network models pre-trained from natural image dataset, such as ImageNet (Russakovsky et al., 2015), can be used for the new medical task at hand.

There are three innovative points which have eventually made this proposed work successful. First, the proposed method has shifted, or in another word, simplified the typical retinal vessel segmentation problem from full-size image segmentation to regional vessel element recognition. This is to say, vessel pixels are to be recognized from region to region and merged together in the end. Second, because of this problem shifting, the training data, therefore, can be augmented from a hundred to a hundred thousand, which guarantees the effectiveness of deep network training. Third, the proper method of fine tuning the pre-trained semantic segmentation model has made the regional segmentation task much easier. This pre-trained semantic segmentation model is the fully convolutional version of AlexNet, which well performs the pixel-to-pixel and end-to-end segmentation.

In the following sections, this paper will further present and discuss the implementation of the proposed method. The organization of the paper is as follows. Section 2 will introduce the retinal image databases and the related works. Section 3 will demonstrate the proposed implementation of data augmentation, the training of the fully convolutional network, and post-processing. Section 4 will present the experimental setup and results, and performance evaluation. Section 5 will conclude and discuss the value of this work.

2. Datasets and related works

2.1. Retinal blood vessel databases

The study of the retinal blood vessel segmentation starts from importing public retinal blood vessel databases, where offer researchers with retinal color images and the corresponding information. Some of the databases provide vessel ground truth images, which shows exactly where each vessel pixel is located. With those databases, researchers are able to design their algorithms and compare their performances in the same criterion.

Currently there exist 9 publicly available retinal blood vessel databases, among which CHASE_DB1 (Retinal image analysis), DRIVE (Staal et al., 2005), HRF (Kohler et al., 2013), STARE (The stare project, 2013) databases contain both retinal color images and retinal blood vessel ground truth images. As the study of vessel segmentation requires the vessel ground truth as a golden standard, the other 5 databases such as DiaRetDB1 V2.1 (Tomi et al., 2009), Messidor (Decencière et al., 2014), REVIEW (Al-Diri et al., 2008), ROC (Niemeijer et al., 2010), and VICAVR databases are not used in this work.

Most of the retinal blood vessel segmentation methodologies are evaluated on DRIVE and STARE databases because they are all decent in quality and have been created for at least 15 years. CHASE_DB1 and HRF databases are relatively new but also built with good image quality. These four databases will be used to train and test the proposed supervised method.

2.2. Related works

The proposed systems from this work are enlightened by numerous previous works and based on both classic image processing algorithms and cutting edge machine learning techniques. In the past decades since 1989, hundreds of papers about retinal blood vessel segmentation have been published, and plenty of methods have been proposed. According to Fraz's survey (Fraz et al., 2012a) in the year of 2012, the existing