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Real-time automated image segmentation technique for cerebral aneurysm on reconfigurable system-on-chip

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ABSTRACT

Cerebral aneurysm is a weakness in a blood vessel that may enlarge and bleed into the surrounding area, which is a life-threatening condition. Therefore, early and accurate diagnosis of aneurysm is highly required to help doctors to decide the right treatment. This work aims to implement a real-time automated segmentation technique for cerebral aneurysm on the Zynq system-on-chip (SoC), and virtualize the results on a 3D plane, utilizing virtual reality (VR) facilities, such as Oculus Rift, to create an interactive environment for training purposes. The segmentation algorithm is designed based on hard thresholding and Haar wavelet transformation. The system is tested on six subjects, for each consists 512 × 512 DICOM slices, of 16 bits 3D rotational angiography. The quantitative and subjective evaluation show that the segmented masks and 3D generated volumes have admitted results. In addition, the hardware implement results show that the proposed implementation is capable to process an image using Zynq SoC in an average time of 5.2 ms.

1. Introduction

An aneurysm is a swelling on the side of a blood vessel wall and it can burst and lead to bleeding. It looks like a thin balloon or weak spot on an inner tube. The aneurysm in the brain is called cerebral aneurysm [1]. Statistics show that between 1.5% and 5% of the population have or will develop cerebral aneurysm [2]. Annually, almost from 0.5% to 3% of patients with a brain aneurysm may suffer from bleeding [1].

When an aneurysm ruptures, blood leaks into the subarachnoid space called subarachnoid hemorrhage (SAH). SAH represents one of the most prevalent and devastating diseases among adults worldwide. Endovascular approaches to treatment of intracranial aneurysms (ICAs) are more effective than other methods in terms of reducing operative risk, hospital stay, pains and indirectly cost [3]. These approaches, which are centered around the use of intra-aneurysmal coils, may sometimes fail because of incomplete occlusion of the defect, which could be due to the miscalculation of the aneurysm anatomy. Therefore, appropriate segmentation of cerebral aneurysm is always desired for an effective treatment planning (i.e. deciding the right size and type of the first coil) [4].

Since the result after applying the automated aneurysm segmentation algorithm is a 3D volume that contains features from the aneurysm, this helps doctors in diagnosing and deciding the right treatment, because knowing some parameter about the aneurysm is crucial for such purposes. Manual segmentation is typically utilized to get these parameters, nevertheless, it is not precise because it heavily depends on inter-observer variability. Hence, employing an automatic segmentation technique will be more accurate and reliable.

While image segmentation is a general field and has many applications, angiography also includes a wide range of anatomical applications (e.g. cerebral, retinal, hepatic, peripheral, pulmonary, cardiac, etc.) and modalities (e.g. X-ray, computed tomography angiography (CTA), magnetic resonance angiography (MRA), ultrasound, 2D or 3D, etc.) [5–7]. Therefore, there are many methods in literature for vascular segmentation. The segmentation algorithms of cerebrovascular MRA medical images can be categorized into

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the following four methods. The deformation model, the statistical model, the Hessian matrix and the region growing [8,9]. Well known deformation models are parametric and geometric in which usually exploits several internal and external forces to find connected curves in the images [10,11]. Statistical algorithms aim to fit a statistical model to the distribution of the intensities of the images and compute the parameters of model. Usually, they assume that brain MRA images consists of three different regions with different intensity margins and therefore try to determine these regions on the intensity histogram. The first region has the lowest intensities and consists of cerebrospinal fluid, cerebral bones, air and other organizations. The second region with medium intensity has cerebral gray and white matter. The third region with higher intensity includes cerebral vessels and subcutaneous fat [9,11]. Cerebral vessels are worm and tube like and therefore have typical characteristics of tubes. Some of these characteristics are the eigenvalues and eigenvectors of the Hessian matrix. These method mostly used for vessel enhancement as a preprocessing step for segmentation [12,13]. Alternatively, optimally oriented flux (OOF) was introduced by Law and Chung to overcome the shortcomings of Hessian-based filters. OOF and its anisotropic variations have gained attention for the segmentation of different anatomical structures including vessels [14,15]. The region growing methods are a conventional algorithms for angiography and other applications of segmentation. Typically, there is a good connectivity and a complete topological structure for resulting vessel voxels [16,17].

There are few other methods have been designed for the vascular aneurysm segmentation problem. Wilson et al. proposed a fully automatic, statistically based algorithm for segmenting the three-dimensional vessel information from time of flight (TOF) MRA data [18]. They introduced a mixture distribution for the data, motivated by a physical model of blood flow, that is used in a two stage segmentation algorithm. In the first stage they use a variant of the traditional EM algorithm to classify vessel voxels, on the assumption that all voxels are independent. Based on this initial segmentation, they then estimate the two thresholds to perform hysteresis thresholding. An algorithm based on a geometric deformable model with energy functional along with a non-parametric statistical framework which exploits high-order multiscale features is presented in [19]. The method is based on a geometric deformable model that uses also information from the image gradient and statistics of the different tissue regions. Cross-validation and feature selection techniques are used to determine the non-parametric statistical model and fit the model to the specific application and achieve the best tissue classification. In [20] an evaluation study is reported to evaluate the suitability of their automatic segmentation method based on geodesic active regions (GAR) for segmenting cerebral vasculature with aneurysms. Three aspects of the GAR method have been improved: execution time, robustness to variability in imaging protocols and robustness to variability in image spatial resolutions. They evaluate their method on 3D X-ray rotational angiography (3DRA) and time of flight magnetic resonance angiography (TOF-MRA) images. Similarly, the work presented in [21] introduce a new cerebral aneurysm segmentation approach, which is based on geodesic active contours (GAC). In this method, the wall of the aneurysm in 3D has been considered as the zero level set, and the convergence of the embedding function is used to define the surface of the extracted aneurysm. The results show that the prior de-noising shows slight improvement in the segmentation results, but the algorithm needs to initiate a seed point manually where the segmentation starts.

In [22], a new method has been proposed for CTA, where the segmentation is based on region growing and level set approaches. In the first stage, CTA scans are smoothed with the use of a median filter, and then, the region growing-based approach is used to segment the area of interest. Finally, the selection criteria of the connectivity of the points is applied to recognize the artery range. The proposed method demonstrates good results, however, it still needs the user to initiate a seed point to guide where the segmentation should be started. Authors in [23] proposes a threshold-based level segmentation (TLS) method for segmenting the cerebral aneurysm. The approach uses the Geodesic active contours and Chan-vese segmentation model. The proposed method combines the region and boundary information to decide the global threshold and gradient magnitude to be used in the segmentation. The threshold keeps updating through the segmentation process until the boundary of the aneurysm is reached. The TLS allowed promising results and more accurate results than other methods mentioned previously, and it does not require an initial seed point or intensity threshold. The segmentation of brain vascular from low contrast MRA is presented in [4], where the segmentation algorithm is based on principle component analysis (PCA). The PCA is used to filter the unwanted elements from the image and keep the details of the variation of the width of the vessels. However, since there is no prior noise filter used in the algorithm, the achieved results are not significant and de-noising has been suggested to improve the segmentation results further.

Field programmable gate array (FPGA) has been widely used to accelerate the image processing algorithms in biomedical imaging area. Although there are some implementations of image segmentation targeted on FPGAs, there is no FPGA implementation for automated cerebral aneurysm segmentation [24–27]. In this paper, we design and implement an automated aneurysm segmentation algorithm on Zynq SoC. The segmented results are visualized on a 3D plane using virtual reality (VR) facilities to create an interactive environment for training purposes. The aneurysm segmentation approach is first implemented and simulated in MATLAB as a proof of concept, and then the appropriate C/C++ codes of the algorithm are written and implemented on hardware using Vivado HLS. The system is tested on six subjects, each subject consists of 512×512 16 Bit DICOM slices of Computed tomography angiography while the total number of images is 451. The main contributions of this paper can be summarized as follows:

- A novel SoC solution for real-time automated segmentation technique is introduced. In addition, a hardware friendly aneurysm segmentation algorithm has been proposed for hardware implementation. Finally, the segmented results are visualized on a 3D plane using virtual reality (VR) facilities to create an interactive environment for effective treatment planning and training purpose.
- The proposed approach introduces a way to integrate the aneurysm segmentation and processing unit into heterogeneous reconfigurable hardware. This allows the implementation of a high-performance state-of-the-art data processing system which is also highly adaptive. The communication, visualization, segmentation and flow simulation can be realized on one piece of hardware without making the compromise of resource sharing and time-consuming sequential execution of tasks.

The rest of the paper is organized as follows. Section 2 introduces the aneurysm segmentation algorithm. The corresponding software and hardware implementations are presented in Section 3. The experiment results are discussed in Section 4. Finally, Section 5 concludes the paper and highlights some perspectives of future work.

2. Proposed method

The proposed aneurysm segmentation algorithm is based on wavelet transform [28] and hard thresholding [29] algorithms. The