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A real-time EIT imaging system based on the split augmented Lagrangian shrinkage algorithm

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ABSTRACT

With advantages of portability, low-cost and noninvasive detection, electrical impedance tomography (EIT) has great potential application value as a bedside monitor. Because image reconstruction in EIT involves addressing serious ill-posed inverse problems, realizing EIT online dynamic display still remains a challenging work. In this paper, an EIT imaging system with the function of online dynamic display was designed. Split augmented Lagrangian shrinkage algorithm (SALSA), which transforms an unconstrained optimization EIT inverse problem into an equivalent constrained optimization problem, was adopted in the proposed system. On the basis of EIT imaging simulation, a high-precise Compact PCI-based EIT system was implemented with FPGA. And experiments of EIT cylinder imaging and in-vivo monitoring were conducted to verify the feasibility of the system. The results indicated that the online dynamic display frame rate of the system, which was centered with a computer (Intel i7 2.2 GHz, 4 GB RAM), was up to 32 fps.

1. Introduction

Electrical impedance tomography (EIT) is a noninvasive medical imaging technique in which an image of the conductivity or permittivity of a part of the body is inferred from surface electrode measurements. Following decades of development and basic research into EIT, an overall development trend is emerging—from single frequency to multi-frequency, two-dimensional to three-dimensional, and low-speed to online dynamic display. Progressively, more researchers have begun to pay attention to clinical trials such as for breast cancer detection [1–3], lungs anomaly detection [4–6], and neurocranium detection [7–9]. These studies have made some progress and have provided theoretical guidance for the clinical application of EIT. Currently, the EIT research on intelligent image interpretation has only just begun, the diagnosis relies on visual observation of the doctors. Generally, the maximum frame rate that a human vision can distinguish is 24 fps. Therefore, an online EIT dynamic monitoring system with over 25 fps will have broad application prospects, which includes monitoring of cerebral hemorrhage, abdominal bleeding, blood circulatory system, pulmonary ventilation, etc.

Although the data acquisition rate of existing EIT systems was up to 110 fps [10] when the number of electrodes is 32, realizing the function of online dynamic display still remains a very challenging work because the image reconstruction speed of a low-cost universal commercial computer is slow. Among conventional EIT imaging algorithms, the back-projection algorithm was formally regarded as the most likely one to achieve online dynamic imaging. However, limited by the problem of artifacts, the back-projection algorithm was only preliminarily implemented rather than designed for real applications in most studies. On the other side, the Newton algorithm-based EIT image reconstruction is time-consuming because it has to perform matrix inversion. Moreover, the computing time of the Newton algorithm increases sharply with the number of electrodes or the number of finite elements. By reducing the number of electrodes, using a faster computer, or designing an improved image reconstruction algorithm all can improve the imaging speed. However, reducing the number of electrodes is not an acceptable choice because it leads to lower accuracy. In 2012, a hierarchical reconstruction algorithm for electrical capacitance tomography was proposed in [11], which is 2–8 times faster than the traditional Newton algorithm. The algorithm improves the quality of the reconstructed images and keeps the computation time significantly lower than the traditional Newton algorithm by gradually restricting and refining the finite element mesh size of the region of interest. This algorithm

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provides a new idea to improve the speed of image reconstruction without affecting the image quality. And then, a constrained hierarchical reconstruction method was proposed in [12], the spatial resolution and the speed of reconstruction are enhanced. However, these two methods are not able to meet the requirement of real-time imaging. In addition, two new electrical capacitance tomography (ECT) algorithms for real-time reconstruction of a sequence of images of moving objects passing through a given two-dimensional section of electrical electrodes were presented [13]. In this literature, a processing time of up to 175 frames/s was achieved on a single processor calculated using a FEM mesh with 2542 linear triangular elements and eight electrodes. However, the finite element model of the 8 electrode is not accurate enough for the thoracic model of adult males. And the method proposed in [13] is difficult to achieve real-time imaging when the number of electrodes is 16 or more.

Adopting a high-speed system or workstation can reduce the image reconstruction time without loss of image quality. Dodd and Mueller [14] implemented a fast D-bar algorithm by adopting parallel mechanism and optimizing computing processes. And a frame rate up to 129 fps was achieved on a computer which ran 64-bit Linux and was equipped with four 2.3 GHz 16-core processors and 512 GB of RAM with 562 elements. However, this solution was too expensive to capitalize on low-cost advantages of EIT. In 2015, Meribout et al. [15] proposed a new parallel VLSI architecture for real-time electrical capacitance tomography, the simulations indicate that the proposed architecture achieves a speed-up of up to three orders of magnitude over the software version when the reconstruction algorithm runs on 2.53 GHz-based Pentium processor or DSP Ti's Delphino TMS320F32837 processor. In addition, Meribout et al. [16] proposed a pipelined parallel hardware architecture for 2-D real-time electrical capacitance tomography imaging using interframe correlation, the method achieved around 560 frames of 4096 moving boundary pixels in 1 s using IEEE754 floating-point data representation and a clock frequency of 400 MHz. This satisfies the real-time constraint of many industrial applications. However, for the purpose of EIT for disease diagnosis, we hope to obtain better computational accuracy by floating-point computation. Therefore, a real-time imaging algorithm still needs to be developed.

Another important feature of EIT is that it produces images with strong sparsity due to low resolution compared with other medical imaging techniques. This provides the possibility of EIT sparse image reconstruction, which several EIT researchers have attempted. Tehrani et al. [17] applied the sparse reconstruction algorithm (an interior point method for solving L1-regularized least squares problems (L1-LS)), total variation using a Lagrangian multiplier method (TVAL3), two-step Iterative Shrinkage/Thresholding (TwIST), and the Least Absolute Shrinkage and Selection Operator (LASSO) to EIT image reconstruction and concluded that all four algorithms have better spatial resolution than traditional algorithms, and also concluded that TwIST is the fastest algorithm. Dung et al. [18] proposed a Block-Based Compressed Sensing Approach. Compared to simply using compressive sensing, simulation results show that when block-based sampling and threshold sparse are added to a TwIST approach, improvement in speed occurs. Javaherian and Soleimani [19] and Javaherian et al. [20] also performed related work including compressed sampling for boundary measurements, sampling of finite elements, and sparse reconstruction. Their work provides a good template for introducing sparse reconstruction to EIT and addressing the large matrix inverse problems. These studies on sparse reconstruction applied to EIT show that EIT image sparse reconstruction can improve the imaging speed while maintaining without significant image quality degradation.

However, the methods cited above are not satisfactory for online dynamic display; further, most of the research focused on computer simulation. The image reconstruction speed needs to be further improved and more verification imaging experiments based on hardware measurement systems need to be conducted. Specifically, the traditional Newton algorithm has good imaging quality. However, the Newton algorithm-based EIT image reconstruction is time-consuming because it has to perform matrix inversion. The hierarchical reconstruction algorithm improves the quality of the reconstructed images while keeping the computation time decreased significantly. However, the method is not able to meet the requirement of real-time imaging. EIT reconstruction algorithm based on the sparse recovery is another novel method. TwIST and sparse reconstruction by separable approximation algorithm (SpaRSA) [21] are two advanced algorithms for solving ill-conditioned inverse problem. The reconstruction speed of the TwIST is about 4 frames per second when the finite element number is 1600 [17]. And an enhanced SpaRSA method that projected SpaRSA is able to achieve a speed of about 9 frames on an Intel Core2 Duo CPU of 2.93 GHz when the finite element number is 907 [22]. Therefore, these two sparse reconstruction algorithms are also difficult to achieve real-time imaging. In essence, the sparse reconstruction methods mentioned above only use gradient information from iterative processes. If the Hessian matrix of data fidelity term was utilized, a faster rate of decline in iteration can be achieved in comparison to previous algorithms. The split augmented Lagrangian shrinkage algorithm (SALSA) has achieved this faster rate [19]. SALSA is a new fast image recovery method that uses variable splitting and constrained optimization. Its fast-convergent rate has been proved by [19], which is a requirement for dealing with serious ill-posed problems of EIT image reconstruction. SALSA transforms an unconstrained optimization problem into an equivalent constrained optimization problem obtained by the augmented Lagrange method, which is a solution to the EIT problem of needing fast imaging. In this study, an online dynamic display EIT system was implemented based on SALSA. Consequently, the results of a series of EIT comparative imaging experiments in which the proposed system was compared with the current fast sparse reconstruction algorithms SpaRSA [21], TwIST [24], and the traditional Gauss-Newton algorithm algorithm (Newton) prove that the proposed method can significantly improve imaging speed and has stronger anti-noise capabilities than other algorithms.

The remainder of this paper is organized as follows. Section 2 introduces the EIT image reconstruction algorithm, the basic theory of SALSA application to EIT, and reconstruction results. Section 3 discusses EIT imaging simulation with SALSA as the reconstruction algorithm based on EIDORS [21]. Further, it is shown that the SALSA algorithm improves the reconstructing speed compared with current state of the art methods and with a certain anti-noise ability. In addition, 32fps (or 0.0308 s/frame) are realized with 1024 elements on a portable compact PCI platform (cPCIS-2501) running 32-bit Microsoft Windows on a 2.2 GHz i7 core Intel CPU with 4 GB of RAM. Section 4 describes the implementation of the hardware system, of which acquisition frame rates can up to 120HZ when current's frequency is 50KHZ. The hardware system included a cylindrical thorax model and a high-speed AD acquisition card. A high-precision signal acquisition method based on the digital phase sensitive detection technology (DPSD) algorithm was implemented in FPGA and applied to the acquisition system to remove noise. Section 5 describes a series of cylinder model imaging experiments and in vivo monitoring by using designed hardware system. Section 6 summaries and concludes this paper. The significance and contribution of the proposed method are illustrated.