Biomedical Signal Processing and Control 26 (2016) 58–63

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

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

Compressive Sampling Photoacoustic Microscope System based on Low Rank Matrix Completion

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form
30 November 2015
Accepted 22 December 2015
Available online 19 January 2016

ABSTRACT

Photoacoustic Microscopy (PAM) has developed into a powerful tool for deep tissue imaging with a better spatial resolution. But the data acquisition time in PAM is so long that it is a great challenge for real time imaging. In this paper, a new PAM data acquisition and image recovery method, called Compressive Sampling PAM System based on Low Rank Matrix Completion (CSLRM-PAM) is proposed to obtain a high-resolution PAM image with relatively low sampling rates.

In order to successfully set up a CSLRM-PAM system, the two key problems which we need to keep focus on are design of the compressive sampling scheme and the corresponding image recovery algorithm. In this paper, two compressive sampling schemes based on expander graphs are proposed to replace the conventional point-by-point scanning scheme to implement fast data acquisition. Then, the low rank matrix completion is utilized to obtain high-resolution PAM image directly from the compressive sampling data.

The effectiveness of the proposed scheme is validated using both numerical analysis and PAM experiments. In contrast with the conventional system, the proposed CSLRM-PAM system is able to dramatically decrease the total sampling points for a relatively high-resolution PAM image and to implement accelerated data acquisition.

1. Introduction

As a unique optical absorption microscopy technology, PAM can provide high-sensitivity and high-resolution image of deep tissue samples in vivo [1–3], especially for breast tumor detection. It employs laser light pulse which is non-ionizing radiation to irradiate the tissues [4]. Due to the contrast in optical absorption coefficient between the tissues and background medium, the consequent thermal expansion caused by heating effect induces an acoustic wave at the position of the tissue [4]. The final PAM image is reconstructed by the received photoacoustic signals. Taking the breast environment into account, the background tissue is fat and lobules, which has much lower blood ratio than tumors [4]. Based on this fact, the tumor has much higher absorption coefficients [5] such that it could be clearly shown in PAM images.

The effectiveness of a PAM system depends on many critical techniques, the most important one being the sampling scheme. For conventional scanning PAM system, the scanning scheme is always implemented point-by-point in the field of view [6,7], as shown in Fig. 1(a). Over the past five years, various resolution enhancement techniques have been developed for the PAM system. For example, Liang et al. [8] proposed a spatially Fourier-encoded photoacoustic microscopy using a digital micromirror device to improve the SNR. However, the measurements required by their system are twice as many as the conventional PAM system. Unfortunately, the more the number of measurement points employed, the longer will be the acquisition and processing time [9]. Therefore, it will be a great challenge for the system memory. In addition, the more the number of measurements the more is the radiation to tissues. Thus, a fast data acquisition PAM system is preferred.

In recent years, significant efforts have been made to improve the PAM resolution without increasing the cost of the system, and the most excellent results on this aspect are some advanced data acquisition schemes and novel signal processing methods [7]. As demonstrated in many researches, most medical images have spatial sparsity themselves or in a certain domain by an appropriate sparse transformation [10–12]. Fortunately, it has also been proven that the photoacoustic image has spatial sparsity property

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http://dx.doi.org/10.1016/j.bspc.2015.12.008
1746-8094/

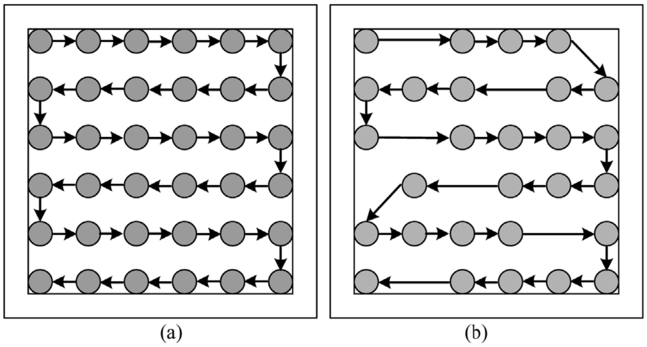

Fig. 1. Illustration of the PAM scanning scheme. (a) Conventional sampling scheme and (b) compressive sampling scheme.

[12–14]. For instance, the early stage breast tumors are so small and sparsely distributed that they only cover a very small region in the imaging area [4]. Therefore, the sparsity of the PAM has been thoughtfully explored and the finally image is reconstructed from far less measurements[9–11,15–17]. This analysis somewhat suggests that the conventional scanning system is over-sampling and it can be replaced by a compressive sampling scheme. An example of compressive sampling mask is shown in Fig. 1(b).

For the compressive sampling, many missing values will occur in the sampling data. Matrix completion algorithms have been shown recently to be effective in estimating missing values in a matrix from a small sample of known entries [19]. It has been widely used in many applications, such as recommendation systems, positioning, computer vision and molecular biology [20]. To address this ill-conditioned problem, matrix completion methods often assume that the recovered matrix has low-rank structure and then uses this as a constraint to minimize the difference between the given incomplete matrix and the estimated matrix [21]. Candès et al. have proved that, most low-rank matrices can be perfectly recovered from a small number of given entries [21,22]. More recently, the low-rank structures of PAM have been studied [18]. For this prior information, the PAM image has the low rank nature. As a matter of fact, this kind of image can be approximated using their low-rank components. Thus, the image recovery method used in this paper is low rank matrix completion. It is a recently developed sparse signal representation and analysis framework which handles image recovery from the low rank components [4].

Therefore, a CSLRM-PAM system is proposed in this paper to achieve fast data acquisition with much smaller sampling points and shorter measurement time. In the system, a compressive scanning scheme is proposed and the final high-resolution PAM image could be recovered directly from the compressive sampling data by low rank matrix completion.

Many researchers have proved that a random uniform expander graph could be a good compressive sampling mask for PAM system, for it can be perfectly recovered by low rank matrix completion [23,24]. However, the significant part of the PAM image is ignored. Thus, a non-uniform sampling scheme is more appropriate. According to the edge expander graphs theory, different sampling rates could be used for the region of interest and other background areas. Intuitively, the more measurements will be performed on the significant region of the image for exact recovery. This operation can further reduce the sampling number and obtain a high-resolution image. It is worth noting that the goal of the CSLRM-PAM system is to achieve fast photoacoustic data acquisition with decreasing spatial sampling number without degrading the image quality. Furthermore, from the perspective of clinical application, the reduction of sampling numbers will significantly reduce the radiation to a patient [4].

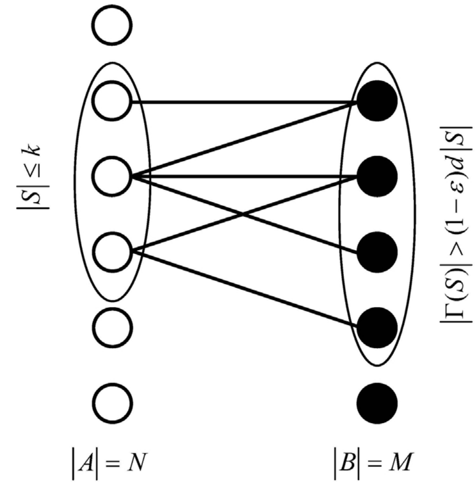

Fig. 2. The illustration of an expander.

In this paper, a low rank matrix completion based compressive sampling PAM system is investigated for biomedical applications. As we have analyzed above, the two key issues in a successful CSLRM-PAM system are the designs of sampling mask and image recovery algorithm. In this paper, the sampling mask is reasonably designed based on expander graphs while the corresponding image recovery problem is correctly solved by low rank matrix completion. The remainder of the paper is organized as follows. In Section 2, the basic idea of the proposed method is presented, including the image recovery method based on low rank matrix completion and the compressive sampling PAM scanning scheme. In Sections 3 and 4, the proposed method has been validated and discussed both by numerical analysis and results from real PAM image. Conclusions are drawn in the final section.

2. Methods

2.1. Uniform and non-uniform sampling system based on expander graphs

One of the most important issues within CSLRM-PAM framework is the design of sampling schemes. The most widely used scheme is implemented with the assumption that the measurement data are obtained by uniform random sampling in the imaging region, which leads to a fresh sampling scheme for every new matrix. Recently, a universal sampling scheme is provided for matrix completion by leveraging expander graphs [25]. It shows that if the set of sampled indices are designed by an expander, then all low rank matrices that satisfy certain incoherence properties can be exactly recovered by the nuclear norm minimization based method [25,26]. Expander graphs have also been combined to compressed sensing method to construct a new algorithm.

The regular left degree c is defined by the number of edge emanating from each variable node. Based on the bipartite graph, a d-regular expander graph is defined below.

Definition 1. (d-regular Expander Graph): As shown in Fig. 2, a bipartite graph (G, A, B), $|A| = N$, $|B| = M$, where A is the set of variable nodes and B is the set of parity nodes, with regular left degree d such that for any $S \subset A$, if $|S| \le k$, then the set of the neighbors $\Gamma(S)$ of S has size $\Gamma(S) > (1-\varepsilon)d\,|S|$.

Based on the d-regular expander and the result of universal sampling scheme, a uniform PAM sampling scheme is obtained in this paper. The uniform sampling system could acquire a high resolution PAM image with fewer measurement points. However,