Ultrasound in Med. & Biol., Vol. 41, No. 3, pp. 871–883, 2015

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2014.11.005

● *Original Contribution*

GPU-BASED MINIMUM VARIANCE BEAMFORMER FOR SYNTHETIC APERTURE IMAGING OF THE EYE

Billy Y. S. Yiu and Alfred C. H. Yu
Medical Engineering Program, University of Hong Kong, Pokfulam, Hong Kong

(*Received* 29 *June* 2014; *revised* 27 *September* 2014; *in final form* 8 *November* 2014)

Abstract—Minimum variance (MV) beamforming has emerged as an adaptive apodization approach to bolster the quality of images generated from synthetic aperture ultrasound imaging methods that are based on unfocused transmission principles. In this article, we describe a new high-speed, pixel-based MV beamforming framework for synthetic aperture imaging to form entire frames of adaptively apodized images at real-time throughputs and document its performance in swine eye imaging case examples. Our framework is based on parallel computing principles, and its real-time operational feasibility was realized on a six-GPU (graphics processing unit) platform with 3,072 computing cores. This framework was used to form images with synthetic aperture imaging data acquired from swine eyes (based on virtual point-source emissions). Results indicate that MV-apodized image formation with video-range processing throughput (>20 fps) can be realized for practical aperture sizes (128 channels) and frames with $\lambda/2$ pixel spacing. Also, in a corneal wound detection experiment, MV-apodized images generated using our framework revealed apparent contrast enhancement of the wound site (10.8 dB with respect to synthetic aperture images formed with fixed apodization). These findings indicate that GPU-based MV beamforming can, in real time, potentially enhance image quality when performing synthetic aperture imaging that uses unfocused firings. (E-mail: alfred.yu@hku.hk) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Synthetic aperture imaging, Minimum variance (Capon) beamforming, Eye imaging, Image quality, Parallel computing, Graphics processing unit.**

INTRODUCTION

In recent years, synthetic aperture data acquisition methods have affirmed themselves as new paradigms for medical ultrasound imaging. Facilitated by point-source emissions (Jensen et al. 2006) or plane-wave firings from an array transducer (Lu et al. 2006; Montaldo et al. 2009), these methods can effectively acquire raw image data over the entire field of view in a single pulse-echo sensing event. Thus, they are well regarded as an alternative to the classic beamline-based imaging paradigm that involves lateral sweeping of a focused beam over the field of view (Whittingham 2007). However, one known deficiency in using synthetic aperture data acquisition methods is that pulse-echo sensing is conducted with unfocused transmissions, whose achievable image quality from each individual firing is generally inferior to that for image frames formed via beamline-based imaging, which includes a well-defined transmit focus. While coherent image compounding may be performed to mitigate this shortcoming (Jensen et al. 2006; Montaldo et al. 2009), it is after all not a statistically adaptive solution because the image frames in the compounding group are merely combined with equal weighting. Alternatively, one emerging approach that has been proposed is to adaptively define the channel summation weights (commonly dubbed as *apodization weights*) in delay-and-sum beamforming according to the correlation statistics of the time-delayed channel-domain data samples (Holfort et al. 2009; Wang and Li 2009). Often referred to as adaptive beamforming (Synnevag et al. 2007; Wang and Li 2010), this approach to apodization weight definition can be achieved using different formulations (Guenther and Walker 2007; Ranganathan and Walker 2003; Viola et al. 2008; Wang et al. 2005). Among them, the minimum variance (MV) beamforming approach (also known as Capon beamforming), which optimizes based on a minimum output energy criterion, has particularly exhibited strong potential (Asl and Mohloojifar 2009; Mehdizadeh et al. 2012a; Synnevag et al. 2009; Vignon and Burcher 2008).

Address correspondence to: Alfred C. H. Yu, Medical Engineering Program, University of Hong Kong, Hong Kong. E-mail: alfred.yu@hku.hk

Although MV beamforming has theoretical merit in generating high-quality images when performing ultrasound imaging with unfocused firings (Holfort et al. 2009; Wang and Li 2009), the medical ultrasound community has yet to see this technique adopted in practice. Such a lack of progress toward practical realization can be partly attributed to the technique's high computational complexity: in particular, the MV beamforming algorithm inherently involves a matrix inverse operation that requires a cubic-order number of floating point operations to execute (Nilsen and Holm 2010). While a few algebraic simplifications may be leveraged to reduce the computational complexity (Asl and Mohloojifar 2012; Synnevag et al. 2010), the overall computing load is aggravated by another factor: that is, the need to perform MV beamforming independently for every pixel position in the image frame. As a potential solution to this technical bottleneck, graphics processing units (GPUs) have drawn significant interest in recent years (So et al. 2011). These many-core parallel computing devices, as compared to field programmable gate arrays, generally have lower device cost (typically below US $1,000 today) and require less intensive development effort (because of their software-level programmability) (Fowers et al. 2013). As such, they appear to be well suited as a new class of high-throughput processors for ultrasound scanners to realize MV beamforming in real time. In fact, the feasibility of performing GPU-based MV beamforming for individual beamlines has already been confirmed in a few pilot studies by us (Chen et al. 2011) and others (Fathi et al. 2012; Kim et al. 2013), and its application in cardiac imaging has lately been reported (Asen et al. 2014). Motivated by these initial findings, we reckon that it is well plausible to formulate a GPU-based approach to execute MV beamforming operations over all pixels in an entire image frame, as would be required in synthetic aperture imaging.

In this article, we present the first experimental demonstration that real-time, pixel-based MV beamforming can be achieved using GPUs, with the intention of fostering its translation from theory toward practice in synthetic aperture ultrasound imaging. Our contributions can be considered to be two-fold. First, we report an algorithmic framework that is founded on parallel computing principles, and it is practically realized on a multi-GPU platform. Second, we offer new practical insights into the performance of GPU-based synthetic aperture MV beamforming in the context of eye imaging: an application domain that has not been considered hitherto in adaptive beamforming investigations. Note that our current effort is readily distinguished from previous work on GPU-based beamformers for synthetic aperture imaging (Hansen et al. 2011; Lewandowski et al. 2012; Yiu et al. 2011). In those prior studies, fixed apodization weights were used during GPU-based beamforming, whereas the current body of work is the first to incorporate adaptive apodization into the computational process.

IMAGING METHODS

Theoretical background

When using synthetic aperture data acquisition methods, raw imaging data is essentially obtained by performing pulse-echo sensing at different point-source positions (Jensen et al. 2006) or plane-wave steering angles (Lu et al. 2006; Montaldo et al. 2009). As illustrated in Figure 1 for a virtual point-source configuration, an M-channel pre-beamformed data array can be acquired in each transmission event, and multiple data arrays can be formed from a group of L independent sensing events. After conversion of the L data arrays in the same group to their analytic form via Hilbert transform as described earlier (Yiu et al. 2011), they are used as input to form one adaptively apodized synthetic aperture image by performing MV beamforming on a pixel-by-pixel basis. In this work, our aim is to determine the analytic value (*i.e.*, with magnitude and phase) of each image pixel using a GPU-based MV beamforming approach.

MV beamforming generally works by deriving a set of apodization weights (**w** in vector notation) based on the correlation matrix (**R**) of the post-delay channel-domain analytic data samples for a given image pixel position (**x**). It has been previously shown that the closed-form solution to **w** for a unity (*i.e.*, distortionless) signal gain is of the form (Synnevag et al. 2007, 2009)

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{a}}{\mathbf{a}^T\mathbf{R}^{-1}\mathbf{a}} \quad \text{for } \mathbf{R} = E\{\mathbf{x}\mathbf{x}^H\}, \mathbf{a} = [1 \quad 1 \quad \ldots \quad 1]^T, \tag{1}$$

where $E\{.\}$, T, H and **a** respectively refer to expected value, matrix transpose, Hermitian (complex conjugate) transpose and a vector of ones. This solution is based on the optimization rationale that, since the signal gain is constrained to be constant, minimizing the beamformer's output pixel value would result in optimal suppression of unwanted interference (*i.e.*, clutter).

Parallelized estimation of correlation matrix

Our real-time MV beamforming framework begins by first estimating, for each pixel position, the channel-domain correlation matrix **R** in (1). For this operation, a two-stage estimation approach is used to achieve robust computation performance (and, in turn, produce consistent MV beamforming results). First, at a given image pixel position, a temporal-mean post-delay channel-domain data ensemble $\bar{\mathbf{x}}$ is formed via multi-ensemble averaging of a