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Real time fast ultrasound imaging technology and possible applications

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Abstract

In this work, a novel hardware architecture for fast ultrasound imaging based on FPGA devices is proposed. A key difference over other approaches is the unlimited scalability in terms of active channels without performance losses. Acquisition and processing tasks share the same hardware, eliminating communication bottlenecks with smaller size and power losses. These features make this system suitable to implement the most demanding imaging applications, like 3D Phased Array, Total Focusing Method, Vector Doppler, Image Compounding, High Speed Part Scanning and advanced elastographic techniques. A single medium sized FPGA allows beamforming up to 200 scan lines simultaneously, which is enough to perform most of the above mentioned applications in strict real time.

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Keywords: Fast ultrasound imaging; High frame rate; Beamformer Architecture; Image Compounding; TFM; 3D Phased Array

1. Introduction

Ultrafast ultrasonic imaging is nowadays receiving increased attention due to the large number of new applications that could be addressed. Ultrafast imaging assumes operation at rates above one thousand frames per second. Since the sound propagation velocity sets a physical limit to the frame rate, new imaging algorithms and hardware architectures with real-time parallel processing capabilities are required.

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The widely used phased array technique builds the image in a line-per-line basis, generating a single beam, single focus in emission, with dynamic focusing in reception for improved image quality. A single image line is obtained in the two-way transit time of the ultrasound pulse up to the desired depth. For example, if depth is 60 mm in biological tissue (propagation speed $c \approx 1500$ m·s^{-1}), acquiring a single image line takes 80 µs; for an N=128-element array with linear scan, the time to acquire the image is over 10 ms, limiting the maximum frame rate to less than 100 images/s. However, several emissions (F) with focus at different depths, followed by reception beamforming, are commonly used, which further reduce the imaging frame rate.

Ultrafast ultrasonic imaging opens opportunities to new applications. In the medical field, high frame rates are required for 3D/4D imaging (Wygant et al., 2006). It will also improve the evaluation of the myocardial function by allowing real-time accurate imaging of the heart movements (Hasegawa and Kanai, 2011). New diagnosis tools linked to the viscoelastic properties of tissue, like Transient Elastography and Supersonic Shear Imaging, require also very high frame rate imaging, typically around 5 Kframes/s (Tanter, 2002; Bercoff, 2004). A single reflection tomogram for breast cancer diagnosis by incoherent circular image compounding can be achieved in few milliseconds; this allows taking hundreds of tomograms to image the full breast volume in a short time, which could be an alternative to mammography for breast cancer screening (Camacho et al., 2012). Automated Ductal Echography (Teboul, 2010), could be also achieved in few seconds, thus improving medical practices.

For Non Destructive Testing (NDT) ultrafast ultrasonic imaging will allow scanning parts at high speed with high spatial resolution. For example, to obtain one image per mm scanning at 1 m/s, a frame rate of 1000 images/s is required. Scanning speed with this tight resolution is currently limited to less than 0.07 m/s (Smith et al., 2003).

Achieving high frame rates requires new image formation algorithms linked to new processing architectures. The explososcan technique composed several image lines in parallel by adding small individual delays to every scan line (Shattuck et al., 1984). Simultaneous beamforming of four to sixteen lines have been reported using 2D arrays (von Ramm et al., 1991; Rasmussen, 2012) and the frame rate is increased by a factor of x4 to x16.

Another technique reported to increase the frame rate is Synthetic Aperture Imaging (SAI), also called Total Focusing Method (TFM). In this case, a single array element or a small de-focused aperture is used in emission to illuminate the whole region of interest, obtaining a low-resolution partial image with a larger aperture. After averaging K images taken from a set of different emitter positions, a high quality image is formed (Nikolov et al., 2005). Assuming that the hardware resources are fast enough, the frame rate increases with regard to a multi-focal phased array by about N/K. SAI or TFM image formation is usually carried out by software following the acquisition phase. Some recent implementations based on GPUs achieve this task in real time (Yiu et al., 2011), but without considering the time involved in transferring the acquired data, which is currently the bottleneck of the procedure.

However the improvements in frame rate given by these techniques are insufficient for the requirements of ultra-fast imaging applications. Other recent ideas allowed reaching rates of thousands of images/s. One is based on plane wave emission (simultaneous triggering of all array elements) followed by RF echo data recording for post-processing (Bercoff et al., 2004). Frame rates of 6000 images/s along a time limited by the available memory resources have been reported, although with a limited image quality due to the lack of emission focusing.

Plane wave emission has also been used for coherent image compounding (Montaldo et al., 2009). In this case, the image is formed by superposition of RF images acquired with plane waves propagating with different angles. In this aspect, this is a technique analogous to SAI, producing well focused images in emission and reception at all depths with frame rates above 1000 images/s.

These new concepts require the development of hardware with very fast performance to achieve these ultrafast imaging rates, which is the main objective of this work, where we propose a new architecture that exploits the possibilities offered by state-of-the-art FPGAs.

2. Parallel beamforming for ultrafast imaging

Conventional phased array beamforming introduces time-varying delays to the signals received by array elements that compensate the two-way time-of-flight differences from every focus to every array element. This operation produces the aperture data, which are coherently added together (in RF) to provide the focused A-scan along the steering direction. The focusing delay T_i for element i must be modified for every output sample k to get strict