Research on Biomedical Engineering
rbejournal.org
Volume 31, Number 3, p. 277-281, 2015

Technical Communication

DOI: http://dx.doi.org/10.1590/2446-4740.0700

A flexible multichannel FPGA and PC-Based ultrasound system for medical imaging research: initial phantom experiments

Amauri Amorin Assef*, Joaquim Miguel Maia, Eduardo Tavares Costa

Abstract **Introduction:** In this paper, we present the initial results of a fully programmable 128-channel FPGA and PC-based system that has been developed for medical ultrasound (US) imaging research in our University laboratory (Federal University of Technology - Paraná, Brazil). **Methods:** In order to demonstrate the feasibility of the US research system, two applications involving unfocused plane wave transmission and conventional B-mode beamforming were evaluated using a commercial tissue-mimicking phantom and a 3.2 MHz 128-element convex array transducer. **Results:** Testing results show that the hardware platform is able to synthesize arbitrary pulses up to 100 Vpp with second order harmonic distortion below 80 dB. For the first application, a 41-tap digital FIR bandpass filter was applied to the acquired RF echoes, sampled at 40 MHz with 12-bit resolution, to improve the noise suppression. In the second application, after offline apodization weighting, filtering, delay-and-sum processing, envelope detection, log compression and scan conversion, the reconstructed B-mode image is displayed over a 50 dB range. **Conclusion:** The presented results indicate that the open US imaging system can be used to support different ultrasonic transmission and reception strategies, which typically cannot be implemented in conventional data flow architectures that are mainly based on hardware.

Keywords: Ultrasound research, Open-Platform, Beamforming, FPGA.

Introduction

Although the ultrasound (US) imaging modality is considered a well-established and one of the most important tools in diagnostic medicine, novel approaches based on modern signal and image processing methods are constantly being proposed by research laboratories with the goal of improving the image quality and diagnostic accuracy. Unfortunately, most of the commercial US scanners, traditionally used for experimental tests and evaluation of new US modes, are very expensive and do not always fit the requirements for data access and extensive control over imaging and systems parameters (Saniie et al., 2012; Wilson et al., 2006).

Due to the interest of scientific research in such areas for, e.g., transmission or reception of US, aperture control, focusing, apodization, beamforming, and other general digital signal and imaging processing, some research groups and laboratories have proposed innovative approaches to the challenges in US image formation (Boni et al., 2012; Qiu et al., 2010). Other imaging researchers have met their demand for data access by purchasing a multi-purpose US system with available research interfaces or by working with a manufacturer to make custom hardware modifications for acquisition and transfer of the ultrasonic RF data.

In this paper, we present the initial results of a fully programmable 128-channel FPGA (Field-Programmable Gate Array) and PC-based US imaging research system, which has been completely developed in our University laboratory in the city Curitiba/PR, Brazil. The main features of the ultrasonic pulse-echo imaging system include its capability for simultaneous arbitrary waveform generation, digital access to the raw radio frequency (RF) data and flexible software back-end processing.

Methods

The multichannel US system architecture can be separated into two segments: the FPGA-based hardware platform and the PC-based control and processing unit. The hardware platform (Figure 1) was previously described by Assef et al. (2012) and consists of eight 16-channel dedicated transmitter/receiver (Tx/Rx) boards, controlled by two low-cost EP3C16Q240C8N FPGAs (Cyclone III, Altera Inc., USA) each. A backplane board used for connections to US array probes completes the rack.

The transmit beamforming control (channel enable, aperture, 8-bit amplitude apodization weighting, pulse selection, phase angle adjustment and time delay

*e-mail: amauriassef@utfpr.edu.br

Received: 25 December 2014 / Accepted: 02 September 2015

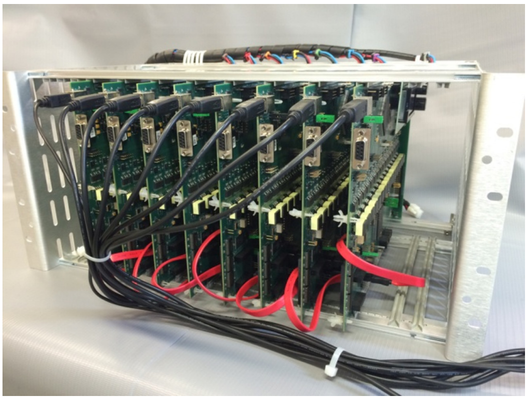

Figure 1. Hardware platform overview. Two EP3C16Q240C8N FPGAs are used on each 16-channel ultrasonic board to control the transmitters and analog front-ends embedded.

for focusing on transmission) was implemented on the first FPGA Tx. In this design, high-end devices MD2131 (Supertex Inc., USA) beamformer source drivers were chosen. These arbitrary waveform generators (AWGs) are capable of synthesizing high-voltage and wideband excitation signals with transmit resolution of 4ns and center frequency of up to 25 MHz. The second FPGA Rx was used to acquire the digitized RF echoes sampled at 40 MHz with 12-bit resolution from two analog front-ends AFE5805 (Texas Instruments Inc., USA), through serial low voltage differential signaling (LVDS) interfaces. Moreover, it controls the ramp pattern applied to the digital-to-analog converters (DACs) for time gain compensation (TGC), wherein each AFE chip are programmed with a maximum gain of 50 dB.

During the reception process, each acquired ultrasonic RF-A-scan trace with 2048 samples was buffered into separate FIFO (first-in first-out) allocated on the FPGA Rx. Once the buffers are filled, the individual channel acquisition data are transferred to the host computer through a USB 2.0 channel, in which a graphical user interface (GUI) has been developed based on Matlab (The MathWorks, USA) programming environment. This software application presents a user-friendly interface to facilitate its interaction with the hardware system. The user can select and upload the hardware front-end operating parameters, control the frame trigger sign to the embedded modules and visualize the graphical output results from the back-end offline signal processing.

Initially, the functionality of the MD2131 transmitter was tested by generating an arbitrary pulse with the Gaussian profile and 35% relative bandwidth, using the method presented by Assef et al. (2013). In order to demonstrate the feasibility of the US research system, two applications are illustrated below. An unfocused plane wave transmission demonstrates the versatility for 128-channel arbitrary waveform generation in addition to direct access to the 128-channel raw RF data. Conventional B-mode beamforming emphasize the flexibility of the hardware-based Tx and the software-based Rx beamformers to perform image reconstruction while preserving the ability for data access to any stage of the image processing chain.

The performance of the imaging system was evaluated with a single plane wave excitation method (i.e., an unfocused transmit beam) with all the 128 channels transmitting and receiving. Data acquisition was performed without time delay between the channels. For the traditional B-mode imaging, a group of 8 piezoelectric elements (active aperture) were fired with the appropriate time delays to generate a narrow and focused US beam. The focusing delays were calculated from the work of Jensen (1999) according to the geometry of the transducer and applied in both transmission and reception for a focal depth of 25 mm. These values were converted to FPGA Tx clock cycles, which runs at 250 MHz (waveform clock rate), and previously uploaded to the hardware system for the transmission procedure. A Hanning apodization was applied to the received RF signals, which were digitally filtered through a bandpass filter and then aligned properly and summed up coherently to achieve a better spatial resolution and SNR. After the delay-and-sum processing, the aperture was shifted and the process was then repeated to form adjacent scan lines until the end of array elements. Finally, envelope detection based on Hilbert transform (followed by absolute value), log compression and scan conversion were applied to form the B-mode image using built-in Matlab functions.

A 3.2 MHz (70% bandwidth) 128-element convex array probe AT3C52B (Broadsound Corporation, Taiwan) was employed during pulse-echo imaging experiments carried out on a commercial multipurpose tissue-cyst mimicking US phantom (Model 84-317, Victoreen Inc., USA). The phantom contain precision-spaced groups of nylon monofilament targets embedded in a medium with a speed of sound of 1540 ± 6 m/s and an attenuation coefficient of 0.5 dB/cm/MHz. The RF data sets were acquired with the transducer positioned at the top of the phantom and aligned with a group of embedded wires spaced 1 cm apart in a vertical plane (position C - see the user manual for details).

Results

Figure 2 shows a 100 Vpp 3-cycle 3.2 MHz arbitrary pulse with the Gaussian envelope produced by one Tx channel and recorded by an oscilloscope MSO6034A (Agilent Technologies, USA). The calculated spectrum of the output pulse has a 6 dB absolute bandwidth of 1.19 MHz, which is equivalent to a relative bandwidth of 37.19% and suitable for B-mode imaging. As expected, the magnitude of the second order harmonic distortion is less than 80 dB.

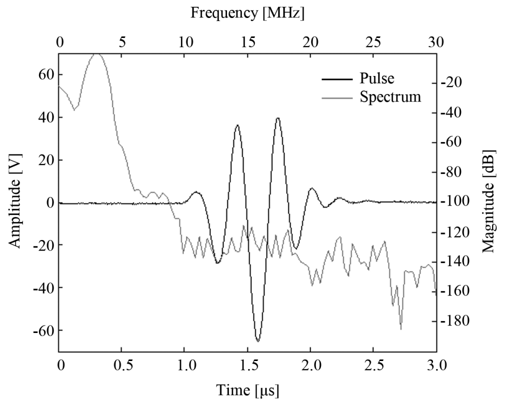

Figure 2. High-voltage 3.2 MHz central frequency arbitrary pulse with the Gaussian envelope and its spectrum with a 6 dB absolute bandwidth of 1.19 MHz (relative bandwidth of 37.19%).

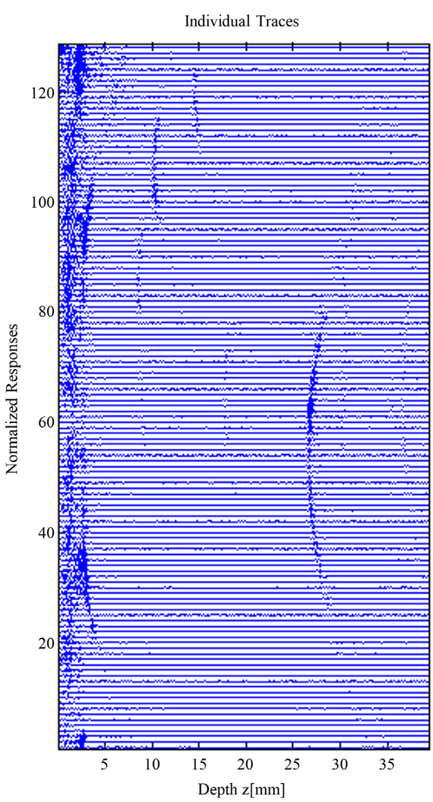

Figure 3. Normalized radio-frequency echo signals acquired from individual elements of the 128-element convex array probe.

Figure 3 shows the individual received response from the 128-element convex array transducer where all elements were fired simultaneously (in phase) to produce a flat-focus transmitted pulse. The image depth is 39.42 mm (assuming a sound speed of 1540 m/s). A 41-tap digital FIR bandpass filter in the bandwidth of the probe was applied, achieving more than 40 dB of noise suppression.

As a preliminary example of software-based back-end processing, Figure 4 shows the B-mode image of the phantom. The image is constituted by 121 adjacent scan lines (total number of elements minus the number of the active aperture plus 1) in the same region of interest (ROI) of the plane wave evaluation and displayed over a 50 dB dynamic range. A Matlab-based scan conversion algorithm, recently presented by Assef et al. (2014), has also been applied to convert the processed data captured from polar coordinates (r,θ) to cartesian coordinates (x,y) suitable for displaying on the computer monitor.

Discussion

The initial phantom experiments conducted in this study demonstrate the flexibility of FPGA and PC-based system architecture. The system design uses the same concept of high-end commercial research systems, such as Verasonics Vantage Research US System (Verasonics Inc., USA) and Ultrasonix Sonix RP (BK Ultrasound, Canada), in which hardware and software-based technologies are combined to provide a flexible platform for US imaging research.

As an example, comparing to the Verasonics US system, the main differential of our platform

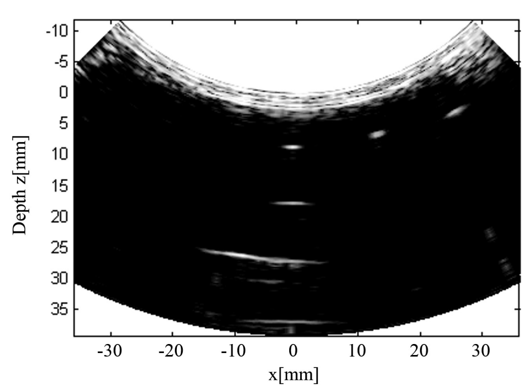

Figure 4. Reconstructed B-mode ultrasound sector image of the tissue mimicking phantom (50 dB dynamic range).

are: (1) capability to independently control all Tx parameters to generate arbitrary waveforms with the Gaussian profile, while the commercial system generates arbitrary pulses of Tri-state transitions (Verasonics, 2015); (2) direct digital access to the 128-channel raw RF signals (without any processing, such as filtering, apodization, and others); (3) use of Matlab-based open source code for evaluation of new beamforming algorithms, while Verasonics uses proprietary Matlab-based software technologies and patented algorithms to perform image reconstruction (Verasonics, 2015).

On the other hand, the Verasonics US system has the ability to perform real-time imaging using 8 PCI Express 3.0 lanes to transfer data to the host computer with a sustained transfer rate of up to 6.6 GB/s. This is the main drawback of our approach, since the front-end hardware was built to transfer the acquired raw RF signals to the PC by the USB port, which is limited to a rate of 35 MB/s. Unfortunately, this feature makes it impossible to process and generate image in real-time, due to the massive amount of data, USB latency and throughput combined with the time required for Matlab computation.

The presented results using a conventional delay-and-sum beamforming are in good agreement with those found in literature. For instance, Qiu et al. (2010) and Hu et al. (2011) developed real-time digital beamformers using high-end FPGAs. In both studies, computer was used only for displaying the resulting B-mode image and the quality of the design system was evaluated by tungsten wire phantoms.

Comparing to the reconfigurable arbitrary waveform generators presented by Ricci et al. (2007) and Qiu et al. (2012), we can list the following advantages of the Tx beamformer design of this study: (1) the capacity for carrying out synthetic aperture algorithms with independent control of the excitation amplitude up to 256 levels (maximum of 200 Vpp/3 A peak output); (2) an angular resolution of 7.5° for focusing phase adjustment with the total range of 48 steps; (3) a fully parallel excitation control of up to 128 transducer elements without the use of multiplexer circuits.

In conclusion, we have successfully developed and evaluated an open multichannel system suitable for US research and teaching applications. The presented results indicate that the open US imaging system can be used to support different ultrasonic transmission and reception strategies, which typically cannot be implemented in conventional data flow architectures that are mainly based on hardware. In addition, we believe that our system has the potential to be useful in a large range of medical US imaging and NDT (Nondestructive Testing) applications, including test of novel transmission and reception methods and sequences, excitation amplitude and aperture control, apodization windowing, beamforming techniques and others.

Acknowledgements

The authors would like to thank CNPq, CAPES, Fundação Araucária, FINEP and the Brazilian Ministry of Health for their financial support.

References

Assef AA, Maia JM, Schneider FK, Costa ET, Button VL. Design of a 128-channel FPGA-based ultrasound imaging beamformer for research activities. In: Proceedings of the 2012 IEEE International Ultrasonics Symposium (IUS); 2012 Oct 7-10; Dresden, Germany. Dresden: IEEE; 2012. p. 635-8.

Assef AA, Maia JM, Schneider FK, Button VL, Costa ET. A reconfigurable arbitrary waveform generator using PWM modulation for ultrasound research. Biomedical Engineering Online. 2013; 12(1):24. http://dx.doi.org/10.1186/1475-925X-12-24. PMid:23514530.

Assef AA, Maia JM, Schneider FK, Gewehr PM, da Costa R, de Moraes AF. Método computacional de conversão de varredura para apresentação de imagens setoriais por ultrassom. In: Proceedings of the XXIV Congresso Brasileiro de Engenharia Biomédica (CBEB 2014); 2014 Oct 13-17; Uberlândia, Brazil. Uberlândia: SBEB; 2014. p. 324-7.

Boni E, Bassi L, Dallai A, Guidi F, Ramalli A, Ricci S, Housden J, Tortoli P. A reconfigurable and programmable FPGA-based system for nonstandard ultrasound methods. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2012; 59(7):1378-85. http://dx.doi.org/10.1109/TUFFC.2012.2338. PMid:22828833.

Hu C, Zhang L, Cannata JM, Yen J, Shung KK. Development of a 64 channel ultrasonic high frequency linear array imaging system. Ultrasonics. 2011; 51(8):953-9. http://dx.doi.org/10.1016/j.ultras.2011.05.010. PMid:21684568.

Jensen JA. Linear description of ultrasound imaging systems [internet]. 1999. [cited 1999 Jul 5]. Available from: http://field-ii.dk/documents/ref_jaj_1999.pdf.

Qiu W, Yu Y, Sun L. A programmable, cost-effective, real-time high frequency ultrasound imaging board based on high-speed FPGA. In: Proceedings of the 2010 IEEE Ultrasonics Symposium (IUS); 2010 Oct 11-14; San Diego, USA. San Diego: IEEE; 2010. p. 1976-9.

Qiu W, Yu Y, Tsang FK, Sun L. A multifunctional, reconfigurable pulse generator for high-frequency ultrasound imaging. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2012; 59(7):1558-67. http://dx.doi.org/10.1109/TUFFC.2012.2355. PMid:22828850.

Ricci S, Bassi L, Boni E, Dallai A, Tortoli P. Multichannel FPGA-based arbitrary waveform generator for medical ultrasound. Electronics Letters. 2007; 43(24):1335-6. http://dx.doi.org/10.1049/el:20072859.

Saniie J, Oruklu E, Yoon S. Introduction to the special issue on novel embedded systems for ultrasonic imaging and signal processing. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2012; 59(7):1329-31. http://dx.doi.org/10.1109/TUFFC.2012.2333. PMid:22828831.

Verasonics. Vantage brochure and specifications [internet]. 2015. [cited 2015 May 1]. Available from: http://www.verasonics.com/uploads/files/Vantage%20Family%20Brochure%20and% 20Specifications%281%29.pdf.

Wilson T, Zagzebski J, Varghese T, Chen Q, Rao M. The ultrasonix 500RP: A commercial ultrasound research interface. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 2006; 53(10):1772-82. http://dx.doi.org/10.1109/TUFFC.2006.110. PMid:17036786.

Authors

Amauri Amorin Assef[1,2*], Joaquim Miguel Maia[2,3], Eduardo Tavares Costa[4]

[1]Graduate Program in Energy Systems – PPGSE, Electrical Engineering Department – DAELT, Universidade Tecnológica Federal do Paraná – UTFPR, Av. Sete de Setembro, 3165, CEP 80230-901, Curitiba, PR, Brazil.

[2]Graduate Program in Electrical and Computer Engineering – CPGEI, Electrical Engineering Department – DAELT, Universidade Tecnológica Federal do Paraná – UTFPR, Av. Sete de Setembro, 3165, CEP 80230-901, Curitiba, PR, Brazil.

[3]Graduate Program in Biomedical Engineering – PPGEB, Electronic Engineering Department – DAELN, Universidade Tecnológica Federal do Paraná – UTFPR, Curitiba, PR, Brazil.

[4]Biomedical Engineering Department, School of Electrical and Computing Engineering – DEB/FEEC, Biomedical Engineering Centre – CEB, Universidade Estadual de Campinas – UNICAMP, Campinas, SP, Brazil.