GPU-Based Real-Time Imaging Software Suite for Medical Ultrasound

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***Abstract*—We developed a GPU-based real-time imaging software suite for medical ultrasound imaging to provide a fast real-time imaging platform for various probe geometries and imaging schemes. The imaging software receives raw RF data from a data acquisition system, and processes them on GPU to reconstruct real-time images. The most general-purpose imaging program in the suite displays three cross-sectional images for arbitrary probe geometry and various imaging schemes including conventional beamforming, synthetic beamforming, and plane-wave compounding. The other imaging programs in the software suite, derived from the general-purpose imaging program, are optimized for their own purposes, such as displaying a rotating B-mode plane and its maximum intensity projection (MIP), photoacoustic imaging, and real-time volume-rendering. Real-time imaging was successfully demonstrated using each of the imaging programs in the software suite.**

Keywords- Real-time imaging; Volumetric imaging; GPU; CMUT;

I. INTRODUCTION

Capacitive micromachined ultrasonic transducers (CMUTs) have advantages over piezoelectric transducers in manufacturing arrays with arbitrary geometries or many number of elements, as well as in easy integration with front-end electronics [1]. To provide a flexible real-time imaging platform for various probe geometries and many different imaging schemes, we have previously developed real-time volumetric ultrasound imaging software on a multi-core CPU platform, and presented imaging results using annular, rectangular, and linear CMUT arrays [2], [3]. However, the frame rate obtained using this software was not sufficient for some applications requiring high frame rates, such as cardiac imaging. In addition, it was not suitable for more compute-intensive jobs, for example, real-time volume-rendering and ultrafast Doppler imaging [4].

To overcome these limitations, we developed a new GPU-based software suite. Exploiting massive data-level parallelism in beamforming and image processing operations, the new software reconstructs real-time images at a faster rate and performs additional computations to better visualize the volume.

We explain the overall system design and the GPU-based software implementation in Section II, and describe the real-time imaging programs in the software suite in Section III. In Section IV, we present some of the imaging results obtained using these programs and our various CMUT arrays.

II. SYSTEM AND SOFTWARE IMPLEMENTATION

As shown in Fig. 1, the overall imaging system consists of a Verasonics data acquisition system with 128 transmit channels and 64 receive channels (Verasonics, Inc., Redmond, WA), a Mac Pro PC (Apple Inc., Cupertino, CA) with a Tesla C2070

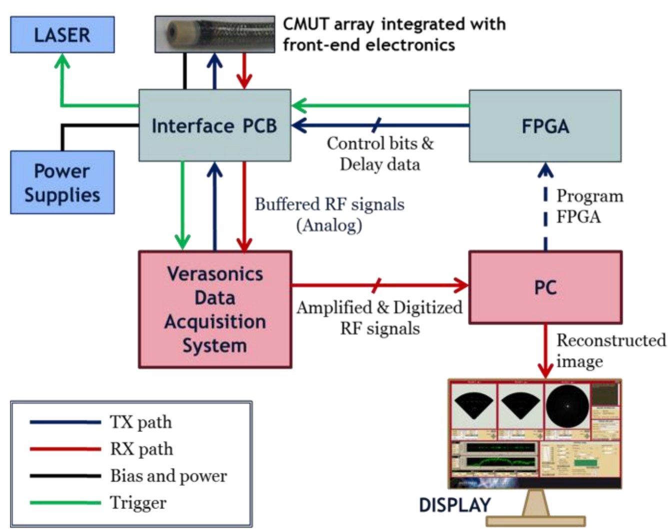

Figure 1. Top-level architecture of the imaging system.

TABLE I
SPECIFICATIONS OF THE GRAPHICS CARD (TESLA C2070, NVIDIA)

Multiprocessor (MP) count	14
Number of GPU cores	448
Processor clock speed	1.15 GHz
Total memory size	6 GB
Constant memory size	64 KB
Shared memory per MP	48 KB
Number of registers per MP	32,768 (32-bit registers)
Memory clock speed	1.5 GHz

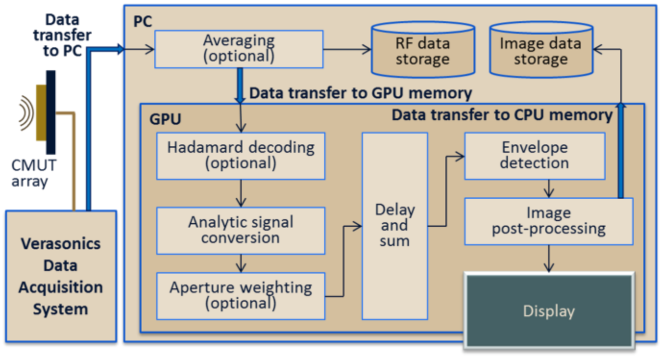

Figure 2. Real-time image reconstruction procedure.

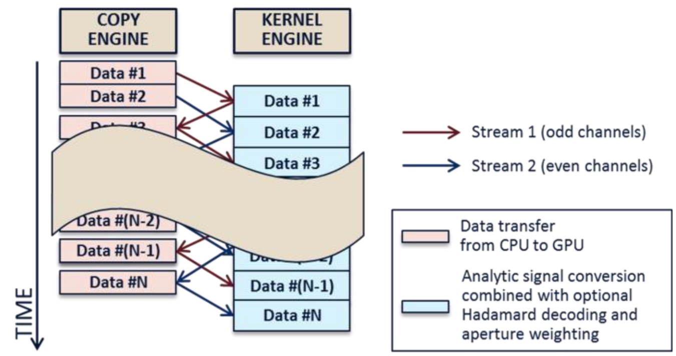

Figure 3. Task parallelism in data transfer and data processing.

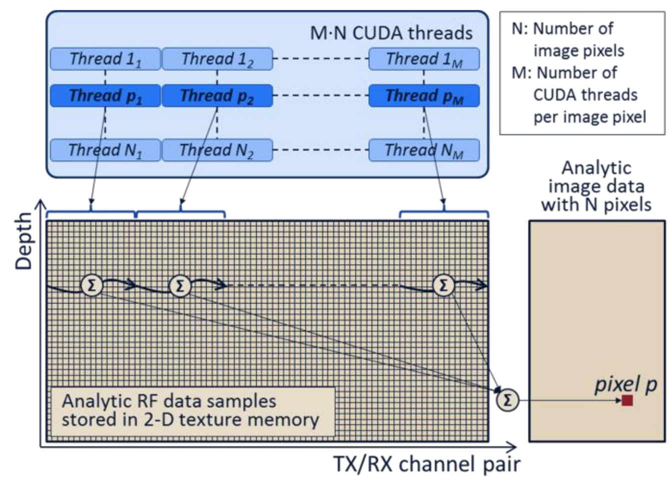

Figure 4. Data-level parallelism in delay-and-sum operations.

graphics card (Nvidia, Santa Clara, CA), a Virtex-6 FPGA board (ML605, Xilinx Inc., San Jose, CA), a Surelite OPO Plus laser (Continuum, Santa Clara, CA), and a custom-designed interface PCB. Table I lists relevant specifications of the graphics card we used in this implementation.

As this system aims to be a flexible imaging platform for various types of probes and imaging schemes, it provides multiple options for excitation. To excite the transducers for transmit, we can either program the FPGA to control the on-chip pursers integrated with the CMUT probe, or simply use the Verasonics pulsers. In photoacoustic imaging mode, the FPGA is programmed to control the laser and synchronize it with the data acquisition system.

The software takes raw RF data collected by the Verasonics data acquisition system, and processes them on GPU to reconstruct real-time images. Fig. 2 shows the real-time image reconstruction procedure of this software. Task parallelism between the copy engine and the kernel engine of GPU was implemented using two CUDA streams. While the copy engine transfers a block of raw data to the GPU memory, the kernel engine processes the previous data block for analytic signal conversion combined with optional Hadamard decoding and aperture weighting, as depicted in Fig. 3. Delay-and-sum operations are single instruction multiple data (SIMD) executions, and are thus suitable for GPU parallel processing. Fig. 4 describes the data-level parallelism implemented for delay-and-sum operations. To reconstruct an image with N pixels, $M{\cdot}N$ CUDA threads are created and M threads are assigned to each pixel, where M is empirically optimized for each imaging application. The threads assigned to adjacent pixels are grouped together in the same thread block to maximize the memory access efficiency by utilizing the spatial locality of the raw data samples stored in the 2-D texture memory.

III. REAL-TIME IMAGING SOFTWARE SUITE

The software suite consists of multiple imaging programs customized for different purposes, a real-time RF data analyzer, and a Verasonics transmit controller. The individual programs in the suite are listed and briefly described in Table II.

General Imager is the most-general purpose imaging program that works with arbitrary probe geometry and various imaging schemes, including conventional phased array imaging, synthetic phased array imaging with and without

TABLE II
PROGRAMS IN THE REAL-TIME IMAGING SOFTWARE SUITE

Program	Description
General Imager	The most general-purpose imaging program displaying three arbitrary cross-sectional images
Rotating Plane Imager	A fast real-time imaging program showing one B-mode image rotating about the axis
MIP Imager	Software displaying a rotating B-mode image and its maximum intensity projection (MIP)
PA Imager	Photoacoustic and ultrasound dual-mode imaging software
Volume Imager	Real-time volume reconstruction program displaying a volume-rendered image and three cross-sectional images.
Flow Imager	Ultrafast flow imaging software (*under development*)
RF Analyzer	A 4-channel real-time RF data analyzer
TX Controller	Verasonics transmit controller for use in drug delivery and high-intensity focused ultrasound (HIFU) applications

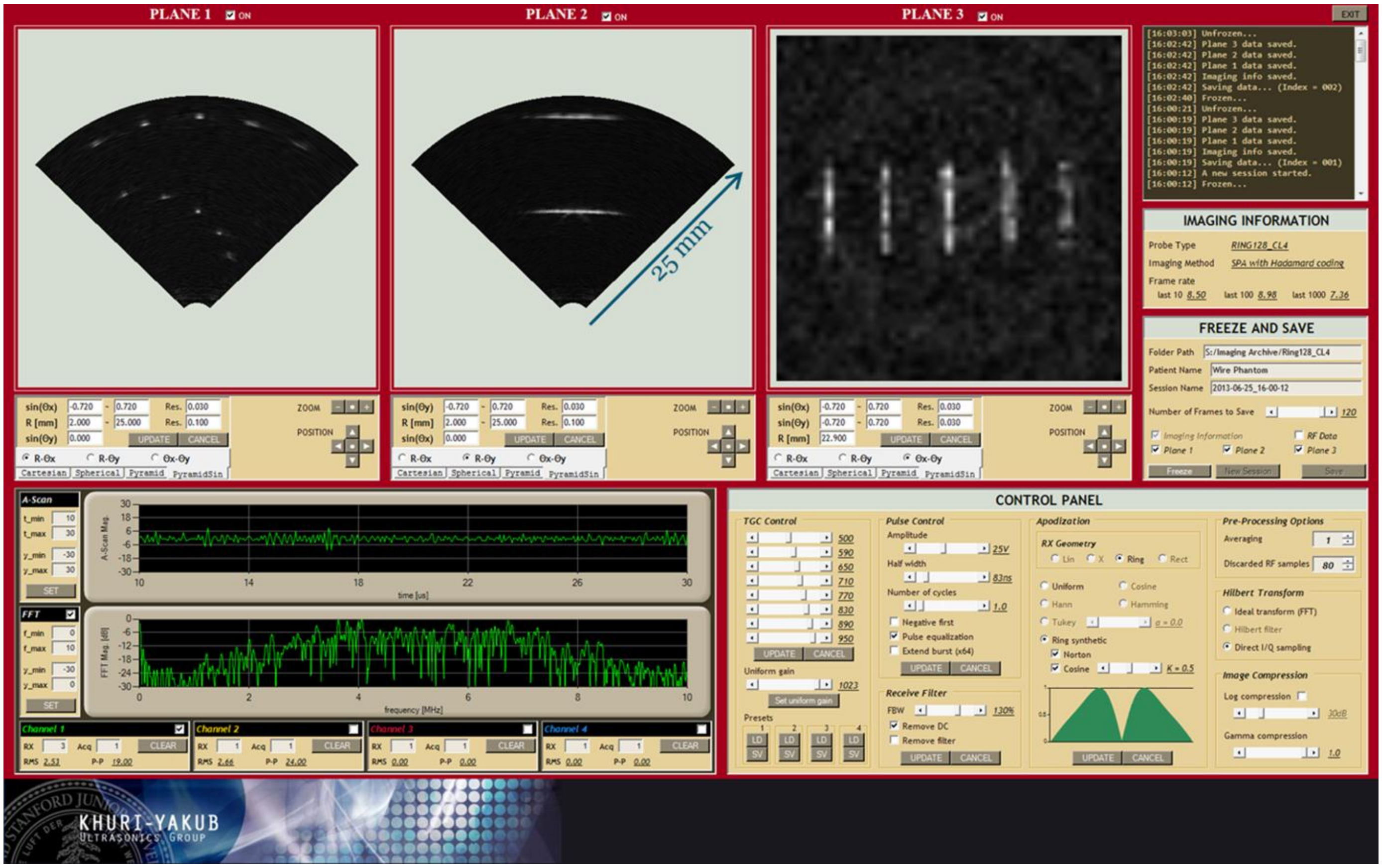

Figure 5. The user interface of a real-time imaging program for displaying three cross-sectional images. The shown images are real-time images of ten fishing wires obtained using a 128-element ring CMUT array.

Hadamard coding, flash imaging, plane wave compounding, and linear array imaging. Fig. 5 shows the user interface of this program, captured in a real-time imaging experiment using a 128-element ring CMUT array with a 4.84-mm radius and a 6.5-MHz center frequency.

The other imaging programs are derived from this general-purpose imaging program, and optimized for their own special purposes. The high computing power of GPU enables not only fast real-time image reconstruction, but also other compute-intensive operations for effective volume visualization, real-time volume rendering, and ultrafast Doppler imaging. For example, *MIP Imager* reconstructs one B-mode image rotating about the axis by a small angle step from frame to frame, and displays its maximum intensity projection (MIP) in real-time [5]. Another imaging program in the suite, *Volume Imager*, reconstructs the entire volume in real-time, and displays one volume-rendered image along with three cross-sectional images on the screen. *PA Imager* is a photoacoustic imaging program with dual-mode imaging capability for both photoacoustic and ultrasound imaging [6]. Imaging results with some of these programs are presented in the next section.

IV. Imaging Results

Figs. 5-7 show the real-time images from *General Imager*, *MIP Imager*, and *PA Imager*, respectively. These images were

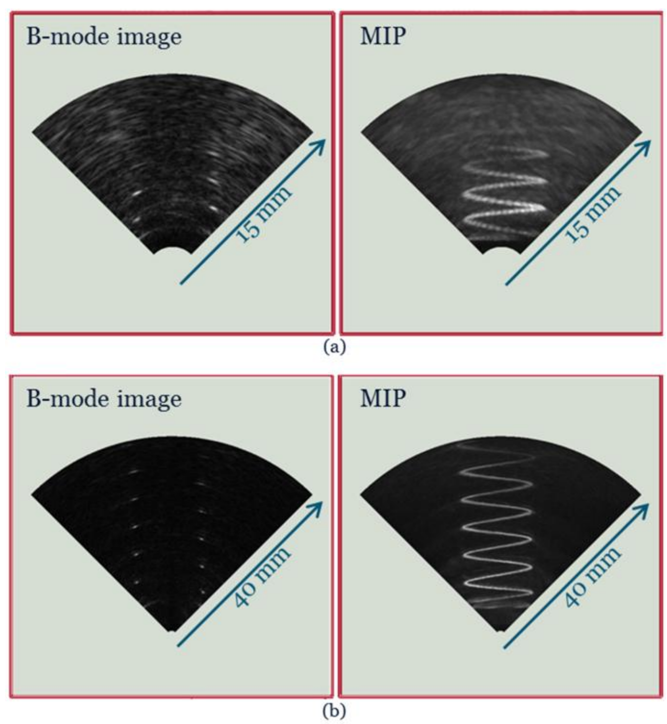

Figure 6. Real-time images of metal spring targets from *MIP Imager* obtained using (a) a 64-element ring CMUT array and (b) a 128-element ring CMUT array.

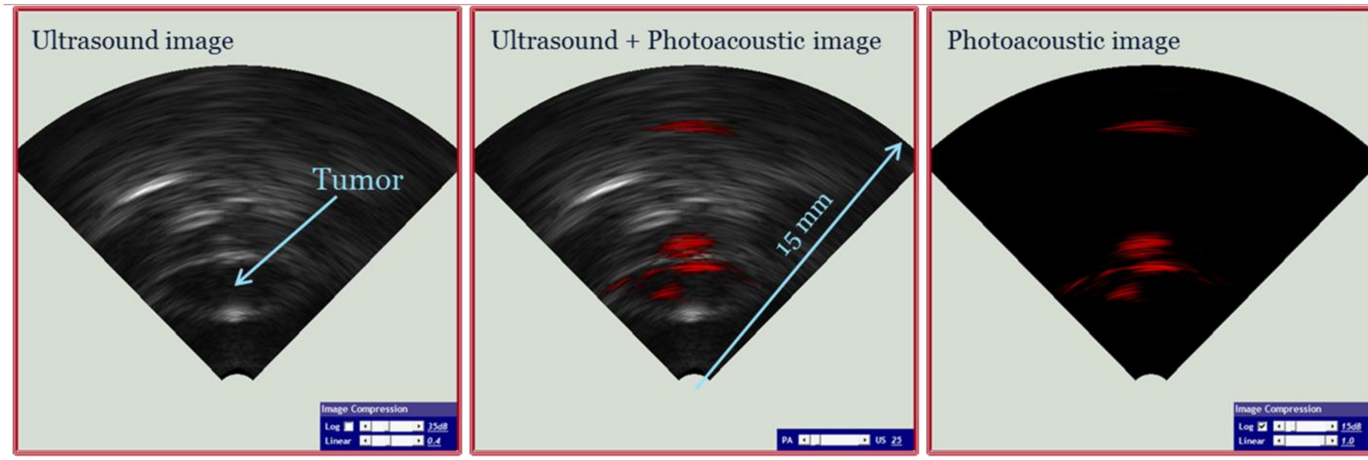

Figure 7. Real-time images of a mouse subcutaneous kidney tumor from *PA Imager* obtained using a 24-element 1-D CMUT array. The vasculature in the tumor is visible in the photoacoustic image.

TABLE III
EXPERIMENTAL CONDITIONS AND IMAGING RATES OF FIGS. 5-7

	Fig. 5	Fig. 6(a)	Fig. 6(b)	Fig. 7
Imaging program	*General Imager*	*MIP Imager*	*MIP Imager*	*PA Imager*
Probe	128-element ring CMUT array (4.84-mm radius)	64-element ring CMUT array (1.16-mm radius)	128-element ring CMUT array (4.84-mm radius)	24-element 1-D CMUT array (63-µm pitch)
Probe center frequency	6.5 MHz	10 MHz	6.5 MHz	8.5 MHz
Imaging scheme	SPA-HW[1]	SPA-HW[1]	SPA-HW[1]	CPA[2] + Photoacoustic
Imaging target	Ten fluorocarbon fishing wires (150-µm thickness)	A metal spring (6-mm diameter)	A metal spring (13-mm diameter)	A mouse subcutaneous tumor
Imaging depth	25 mm	15 mm	40 mm	15 mm
Imaging rate in frames per second	14	104	11	100 for ultrasound image 10 for photoacoustic image[3]

[1]SPA-HW: Synthetic phased array imaging with Hadamard coding and aperture weighting (Norton weighting and cosine weighting)
[2]CPA: Classic phased array imaging
[3]Imaging rate for photoacoustic image is limited by the 10-Hz laser repetition rate.

obtained using different targets and different probes. Experimental conditions and acquired imaging rates from these experiments are summarized in Table III.

V. CONCLUSION

We developed a GPU-based ultrasound imaging software suite that is capable of real-time volumetric imaging with arbitrary probe geometries and various imaging schemes including non-conventional techniques such as synthetic beamforming and Hadamard coding. Exploiting massive data-level parallelism in beamforming operations, this software successfully generated volumetric images in real-time for various imaging schemes. The real-time imaging was demonstrated using our custom CMUT probes with annular, linear, and rectangular shapes.

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