Massive parallel Ultrasound and Photoacoustic PC-based system

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ABSTRACT

PhotoSound Technologies specializes in the development of electronics solutions for massive parallel data acquisition applicable to the fields of photoacoustics (PA), X-ray acoustics, including 3D dosimetry, and ultrasound. PhotoSound's Legion ADC256 R1.1, released in 2018, is a 256-channel 12-bit ADC with a sampling rate of 40 MHz. The ADC256's average data bandwidth is limited by its USB3 PC interface, which has a data rate up to 3 Gbps per board. Multiple ADC256 boards can operate fully in parallel. On software level configurations, multiple ADC256 boards are represented as a single ADC board with increased number of channels. The incoming ultrasound (US) upgrades and modifications of ADC256 will enable combination and alternation of US and PA modes using the same probe. PhotoSound MoleculUS is a medical-grade Telemed US system combined with a PA-optimized ADC. MoleculUS utilizes clinical US probes to produce US images which can be interleaved with PA imaging by enabling optical fiber illumination. The other ADC256 modification, advanced PAUS oriented for research, will have PCIe PC interface for raw PA and US data and arbitrary software control over beamformer profiles, limited by high-voltage power only. The data in ultrasound and photoacoustics modes is user accessible in raw format and can be delivered to CUDA GPU using MATLAB® parallel computing (CUDA) toolbox or other tools. Multiple PAUS boards can work in parallel in both PA and US modes.

Keywords: Photoacoustic imaging, ultrasound imaging, x-ray acoustic imaging, preclinical imaging, quantitative imaging, parallel data acquisition, multi-channel, photosound.

1. INTRODUCTION: BASE HARDWARE, LEGION ADC/DAQ256

PhotoSound Legion ADC256 board can acquire data from 256 parallel channels. A larger number of channels requires parallel operation of multiple ADC boards. ADC256 is equipped with both USB3 and PCIe Gen2 PC interfaces. USB3 interface is supported by drivers and software. Its data bandwidth is sufficient for all photoacoustic applications with laser repetition rate (trigger rate) up to 200 Hz and 4096-points per trigger in all channels. ADC256 PCIe interface is not officially supported, but used for research and development of future products with dual US and PA modalities.

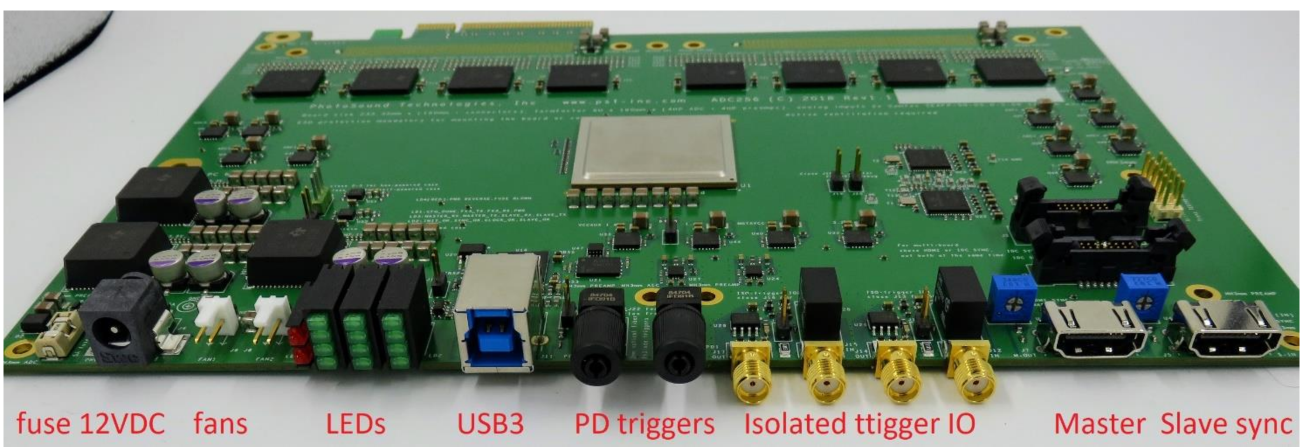

Figure 1: Bare ADC256 board with labeled digital IO connectors.

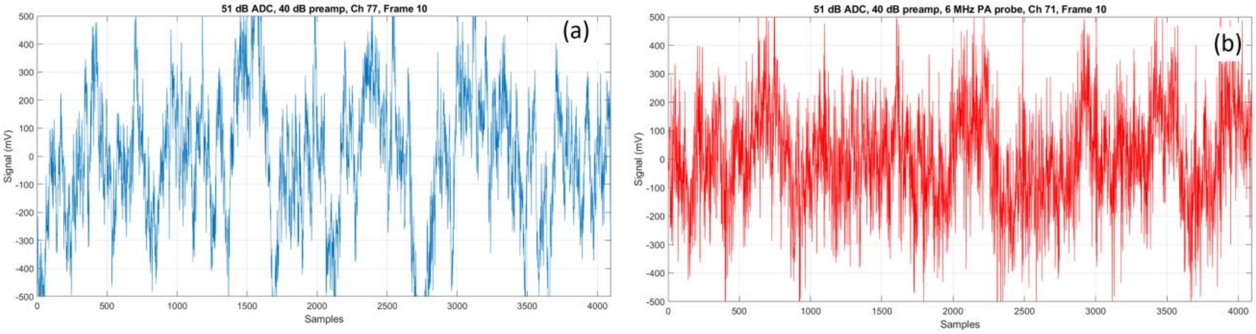

Figure 2: Noise traces from individual channels with RMS close to or equal to the average value. (a) 51 dB ADC + 40 dB preamplifier; (b) same amplification + PA probe with element capacitance 105pF, notice low frequency noise reduction.

Legion ADC256 can be equipped with 128-channel preamplifiers to form Legion DAQ256 or DAQ128 system. The gain of preamplifier is 40 dB to 50 Ω load over 25 kHz – 35 MHz -6 dB bandwidth. ADC has extra programmable gain in range from 6 to 51 dB, which makes total gain range 46 – 91 dB. The dynamic range of the used 12-bit ADC is 2 Vpp. Preamplifiers support multiple probe connectors with different pinouts, e.g. Cannon QLC156/260, Cannon DLM156/260, SCSI-68 connectors. The equivalent input noise level for DAQ is about 8 µV without the probe and 5 µV with the probe. The noise spectral density level is about 2.3 and 1.4 nV/√Hz over 12.5 MHz BW without the probe and with the probe accordingly. This numbers are close to the noise spectral density of a 50 Ω resistor, which is equal to 0.91 nV/√Hz[1].

2. MOLECULUS128 US AND PA SYSTEM WITH PARALLEL DESIGN

Figure 3: MoleculUS128 ultrasound and photoacoustic system (left) and matching probes (two linear and endocavity, right, different scale).

Dual-modality ultrasound and photoacoustic system architecture can be based on **parallel** ultrasound and photoacoustic channels sharing the same probe elements. This approach was used in new PhotoSound MoleculUS system, which consists of (1) the existing PhotoSound Legion ADC256 designed for photoacoustics, (2) PhotoSound PAUS128 adapter, which has 128-channel photoacoustic preamplifier behind transmit-receive (TR) switches, and (3) a custom OEM version of a medical-grade ArtUs ultrasound system from Telemed (note: MoleculUS is a research system not certified for medical or veterinary applications). The analog signal path of MoleculUS system is split into PA and US paths on the PAUS128 adapter right out of the probe connector. In PA mode, the US multiplexer switches on PAUS128 adapter are all closed and PA part does not see US system behind them. In US mode, TR switches on PAUS128 adapter are closed and US part does not see PA system behind TR switches and high-voltage transmit signal is isolated from the PA unit.

Unlike some competing commercial systems, MoleculUS PA mode uses dedicated PA preamplifier with high input impedance and fixed 40 dB gain. The PA preamplifier has the same design as the preamplifier used in Legion DAQ128 system, but its input impedance is limited by bleed resistors of high-voltage switches at about 40 kΩ. MoleculUS PA performance and PA signal path are equivalent to PhotoSound Legion DAQ128, but the applications are limited by the probe selection for ultrasound modality. MoleculUS ultrasound performance, probe interface, and US signal path are equivalent to that of Telemed ArtUs system. MoleculUS is compatible with Telemed SmartUs medical probes, including linear, convex, and endocavity arrays, and 3d party US probes with 128-channels with tZIF-260 type transducer connector, QLC type. Future upgrades of MoleculUS will be compatible with up to 192-ch probes. Fiber-optical illumination for PA might be delivered independently or integrated into the probe. Software SDK and user interface are written in MATLAB® (compiled and source code versions); the back-end is a compiled C++ 64-bit DLL library.

MoleculUS PA and US systems operate sequentially in time. MoleculUS design supports US preview mode and continuous on-fly multiplexing between PA and US modes as shown in Fig. 5.

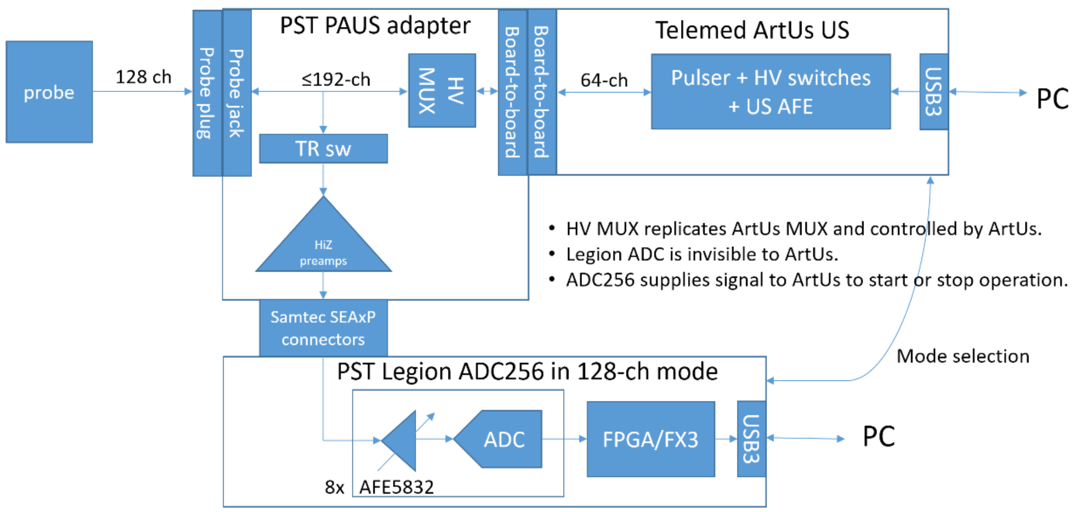

Figure 4: MoleculUS US and PA system block-diagram.

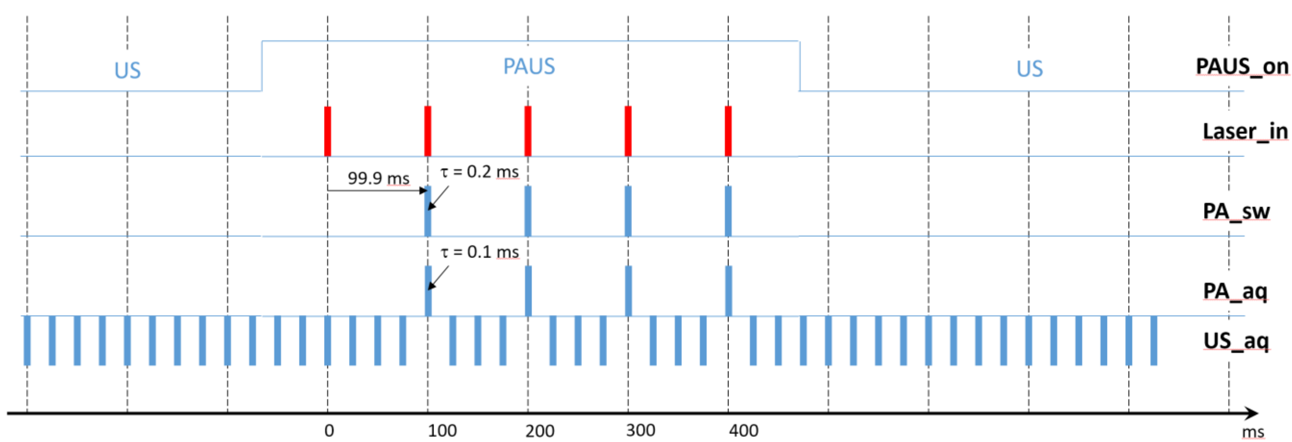

Figure 5: MoleculUS US-PA communication protocol with a 10 Hz laser. Frame rates up to 200 Hz are supported for PA applications.

3. ADVANCED USPA SYSTEM WITH SEQUENTIAL (LINEAR) DESIGN

The other approach to dual-modality photoacoustic and ultrasound system is a sequential (linear) design, which is a novel approach to dual modality systems invented by PhotoSound: The same analog and digital signal path is used for both PA and US modalities. All design modules are arranged linearly along the signal path starting from the probe connector, as shown in Fig. 6. The modules which are not used in the signal path are bypassed. Pulse-beamformer is disabled and bypassed in receive PA and US modes. PA preamplifiers are disabled and bypassed in US modes. Linear (sequential) design allows to (1) maintain the best performance for each modality of the dual-modality system. Performance of the US modality is equivalent to the performance of a US system without PA modality. Performance of PA modality is equivalent to the performance of a PA system without US modality, but the input impedance is limited by high-voltage bleed resistor value, like in the described above parallel architecture case. The main advantage of the sequential architecture is maximal sharing of components between US and PA modes and reduction in the number of high-voltage switches. The shared components include AFE (ADC), FPGA, reconstructions and PC interface, including software interface, which constitute substantial cost and size to the system. Saving of the components allows to reduce component counts and increase the number of parallel channels per board. The design integrates a dual modality USPA system with a fully parallel 256 analog channels and PCIe PC interface to a single PCB, with dimensions roughly equal to those of the ADC256 board shown in Fig.1. Competing ultrasound systems' photoacoustic receive modes (Verasonics Vantage™ and similar systems) reuse ADC, FGPA, and PC interface for both modalities, but cannot be considered as dual modality systems with sequential (linear) design, because such systems are lacking dedicated photoacoustics preamplifier with high input impedance and extra gain in PA mode. PA mode for such system is equivalent to ultrasound receive mode. The 3rd party external photoacoustic preamplifier upgrades for ultrasound systems does not allow to use of such system in US mode, which transforms a single modality US system into a single modality PA system.

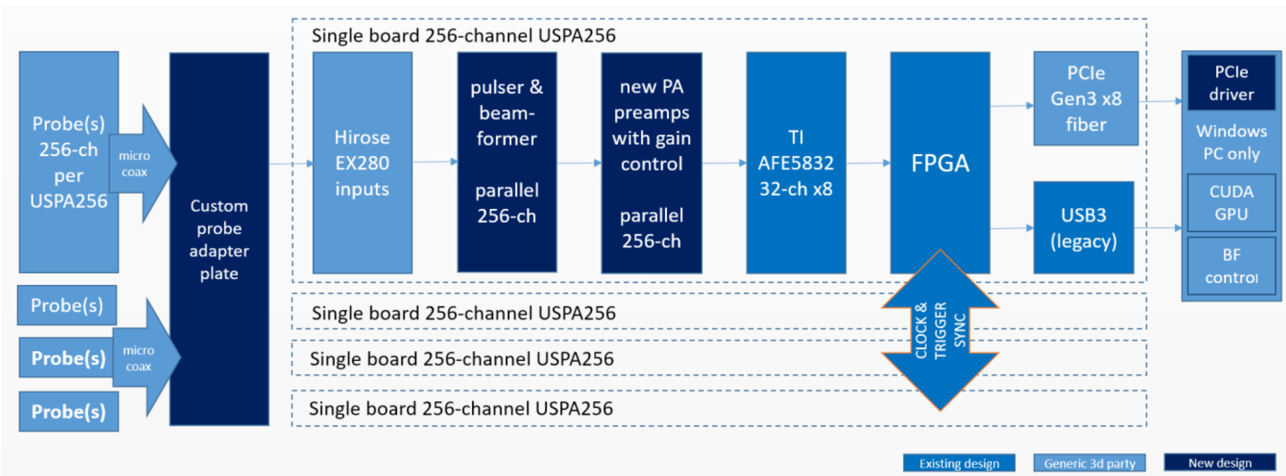

Figure 6: Advanced USPA ultrasound and photoacoustic system consists of a single or multiple USPA256 256-channel boards (only the first board out of 4 boards is shown in details), optional custom probe adapter plate, PC with optical fiber PCIe interface (supplied by PhotoSound). Digital control path from PC to FPGA and from FPGA to pulser-beamformer, PA preamplifiers, and AFE (ADC) modules is not shown. Legacy USB3 interface might be used in the single USPA256 board configurations with US image reconstruction on FPGA chip of USPA256 board.

The main applications for advanced USPA are high-end research in PA, US, X-ray acoustics, and hyperthermia. Multiple USPA256 boards function in parallel in both US and PA modes, forming an advanced USPA system. Each USPA256 board has pulser-beamformer with programmable high-voltage power supply, programmable photoacoustic preamplifier, ADC/AFE chips and PCIe Gen3 x8 PC link. Advanced USPA does not have multiplexing; all channels support fully parallel operation in transmit (TX) and receive (RX) US modes and RX PA mode. Unlike competitor systems, advanced USPA PA mode uses dedicated PA preamplifiers with high input impedance. For high power applications, like hyperthermia, external high-voltage programmable power supplies might be used with a special configuration of the USPA system. Advanced USPA system delivers all raw US and PA data to PC and uses GPU CUDA or PCIe FPGA card for real-time image reconstruction. Frame rate estimate for advanced USPA256:

- PA mode frames 512-ch x 12-bit x 2048-points = 12.6 Mb each.
- US mode at 15 fps requires up to 12.6 Mbit x 512 x 15 fps = 96.7 Gbps, which is just within the practical limits of PCIe Gen3 x16

USPA system is designed to operate with various types of probes, including common medical probes, linear phase arrays (like 512-element 2D ring array), planar phase arrays (like 32 x 32 elements array) in both US and PA modes. Selection of custom detachable probe adapters allows using different probe connectors. Note: advanced USPA is a research system not certified for medical or veterinary applications. Software SDK and user interface will be written in MATLAB® (compiled and source code versions); the back-end is a compiled C++ 64-bit DLL library.

4. SOFTWARE FOR ADC256, MOLECULUS128 AND ADVANCED PAUS

PhotoSound ADC256 software for PA data acquisition consists of firmware, PC driver, back-end, and front-end levels. Firmware level is loaded to FPGA on ADC board and used to capture the data and configure ADC modes, including trigger control, data capture control, and AFE (ADC chip) control. All other software levels run on a PC under Microsoft Windows 10 64-bit OS. Software might be also implemented under Linux 64-bit, which has MathWorks MATLAB®, Nvidia CUDA, and USB3 / PCIe drivers support. Currently NVidia supports many GPUdirect PCIe data transfer modes for its professional graphics cards under Linux only.

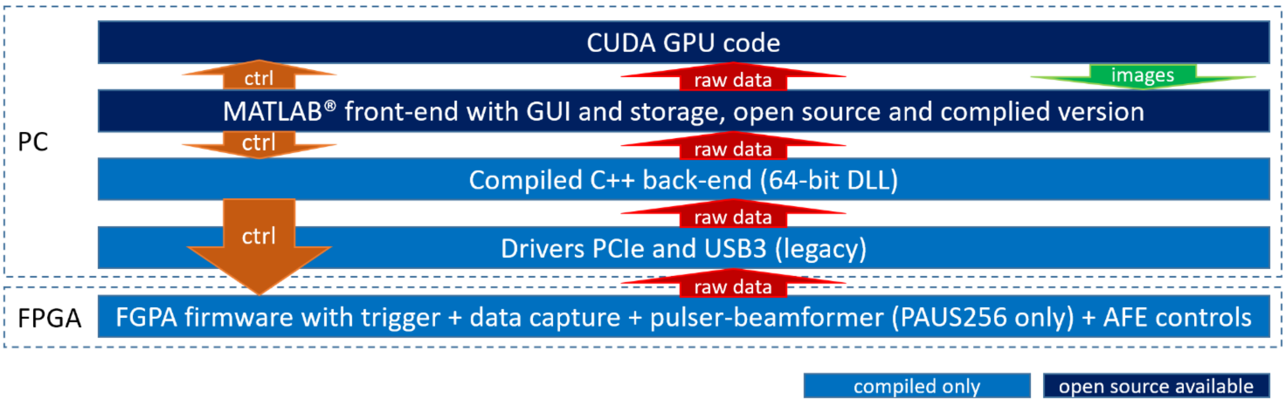

Figure 7: ADC256 and PAUS256 software levels: The target system for software, PC or FPGA on ADC256 or PAUS256 board, is shown as dashed frame with captions on the left. PC level software supports operation of multiple ADC/PAUS boards connected to one PC, but only one ADC/PAUS board is shown. CUDA GPU reconstruction layer is optional for ADC256 software and might be provided as an open source example for PAUS256 software. The control flow is shown in brown, the raw data flow in red, and the processed image flow in green. Complied software modules are shown with the light blue background. Software modules available with the open source code are shown in the dark blue.

The front-end level of PhotoSound software is written in MATLAB® and available as a complied application and an open source code. The front-end contains GUI and provides access to the raw data as well as user-configurable parameters of lower software levels. User accessible firmware parameters includes ADC256 data acquisition configuration, trigger configuration, and analog signal path configuration within Texas Instruments AFE5832 ADC chips. Open source front-end also allows use of their own or 3rd party reconstruction and visualization tools, including CUDA GPU reconstruction using MATLAB® Parallel Computing Toolbox on Nvidia graphic cards. Note: PhotoSound does not provide MATLAB® application and runtimes required to run front-end source code or compiled code. MATLAB® development environment and optional Parallel Computing Toolbox are available for purchase from MathWorks. Free MATLAB® runtime is available for download at MathWorks web-site.

Back-end software is C++ compiled as 64-bit DLL accessible through front-end. Back-end software interface is documented, which allows use almost any 64-bit development environment for development of the custom front-end, including LabVIEW 64-bit, C++, and others. MATLAB® front-end and limited LabVIEW 64-bit source examples are provided by PhotoSound to the end-users.

MoleculUS128 system combines PhotoSound ADC256 front-end software with Telemed ArtUs US system SDK (back-end). Unlike ADC256, Telemed ArtUs perform US reconstruction on FPGA level, and visualization on SDK level accessible through MATLAB® based GUI. Because MoleculUS is based on a medical-grade ArtUs US system, the raw US data and US beamformer and reconstruction algorithms are not user accessible.

Advance PAUS research US and PA system software will be based on GPU reconstruction of PA and US images. All raw data in both modes will be user accessible through MATLAB® front-end or back-end interface, which allows use of any custom or 3rd party reconstruction and visualization algorithms in both modes. Beamformer profiles and pulser parameters are also user accessible, and can be loaded to the PAUS board memory through high level front-end or back-end interfaces. Multiple beamformer profiles can be preloaded to the PAUS board and selected on fly or sequenced automatically during multiple TX/RX cycles required to collect data for a single US frame (image).

5. CONCLUSION

Multiple PhotoSound Legion series products designed for different applications were based on ADC256 R1.1 hardware and software. These products include standalone ADC256, ADC256 integrated with custom PA preamplifiers, and MoleculUS128 dual modality US and PA system with dedicated high-impedance PA preamplifier for all probe channels. ADC256 system has USB3 PC interface, which is used in the current applications. ADC256 R1.1 has also PCIe interface not accessible to end-users, because of its physical formfactor. PCIe on ADC256 R1.1 is used for future driver and software development only. ADC256 upgrade with pulser-beamformer, compact PA preamplifier with digital control, and a new PCIe physical interface over optical cable will be advanced USPA256 single-board system with US and PA abilities. Multiple advanced USPA256 boards will form advanced USPA system with more than 256 parallel channels. Advanced USPA256 single board system and advanced USPA many board systems will be the most compact US systems with all parallel channels, dedicated high-impedance PA preamplifier for all channels, and US and PA reconstruction on PC level with full hardware control access and open raw data and top-level PC software.

ACKNOWLEDGMENTS

The work was partially supported by the grant 1R37CA240806-01A1 from the National Cancer Institute (NIH). Dual modality UltraSound and PhotoAcoustics MoleculUS system was designed in collaboration with Telemed Medical Systems (Vilnius, Lithuania).

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