PC-BASED ULTRASOUND IMAGING SYSTEM IN A PROBE

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Abstract – Current state-of-the-art medical ultrasound scanners can depict structure and function, e.g. images of tissue and blood flow, with exceptional quality. However, the systems are large and relatively expensive. The clinical value and widespread acceptance of ultrasound as a diagnostic imaging modality opened an opportunity for Teratech Corporation to expand its technology by creating the Terason™ 2000 Handheld Ultrasound System—an ultrasound system that provides excellent image quality while being much smaller in size and lower in cost than conventional systems. Unlike conventional machines with proprietary system architecture, the Terason 2000 deploys an open architecture that supports direct access to image data files and facilitates seamless integration into the emerging realm of digital radiology, including internet-based teleradiology, medical informatics systems, and digital image archiving and retrieval. To achieve these goals, Teratech leveraged its unique silicon system-on-a-chip capability, and dramatically reduced the typical rack-mounted conventional system to a Terason SmartProbe™ weighing approximately 10 ounces (0.28 kg). Employing Teratech's proprietary Charge Domain Processing (CDP), the beamformer supports a continuous computation throughput of 10.2 billion operations/s and a delay update rate of 10 billion bits/s while consuming less than 1W, providing more than 10-fold savings in power and weight compared to the conventional implementation. The system is linked to a host PC through an IEEE 1394 (a.k.a. FireWire) serial cable. The PC, running Windows NT or 2000 with plug-and-play standard compatibility, allows the system to utilize all of the control, display, videorecording, and networking capabilities currently available for PCs.

I. INTRODUCTION

Medical ultrasound is a safe, clinically efficacious and widely used diagnostic imaging modality. However, current ultrasound systems are expensive, large, and heavy, so that in the hospital environment, it is often more practical to bring the bed-ridden patient, bed and all, to the ultrasound machine rather than vice versa. Only in the case of critically ill patients who cannot leave the intensive care unit is the ultrasound system maneuvered, with difficulty, to the patient. Commercially available, high-quality handheld systems would permit routine bedside scanning, bringing the ultrasound machine to every patient. This could improve patient throughput while reducing time and cost expenditures. Such portable ultrasound systems could also improve patient access to safe, noninvasive diagnostic imaging in venues such as private offices and community clinics.

For emergency medicine applications, where pre-admission treatment is carried out and space is at a premium, rapid access to diagnostic imaging via portable ultrasound could be an invaluable aid to clinical decision-making. Similarly, in the battlefield environment, where the highest mortality rate (95%) occurs within the first hour after the injury [1], rapid diagnostic imaging, available in the field, would facilitate optimal medical decision-making and treatment, either within a few hundred yards of the line by a FAST (Forward Area Surgical Team) unit, or if the soldier has some level of stability, by a MASH (Mobile Army Surgical Hospital) unit.

A handheld system with excellent image quality and color flow capability would also meet the needs of many current users who already own ultrasound systems and are familiar with the technology. OB/GYN, radiology, and cardiology users, for example, all would be well served by such a system. For radiology applications, the portable ultrasound unit must offer performance comparable to or better than currently used systems; reductions in image quality are not acceptable. Similar caveats apply to cardiovascular ultrasound (echocardiography) applications. Additionally, color-flow imaging is particularly important for cardiology, as is the availability of a phased array probe. For OB/GYN and urologic applications additional probes, including transvaginal and transrectal, are essential. Specialties in which physicians currently do not directly use ultrasound may also benefit from the availability of a high-performance handheld system. General practitioners and emergency medicine physicians are good examples of this latter category.

This paper describes the development of a handheld ultrasound system that can address all the applications described above. We describe the core technology behind the system and compare its performance with existing state-of-the-art technologies. We then describe the complete integrated ultrasound system and results from clinical evaluations.

II. TECHNOLOGY ASSESSMENT

This section describes Teratech's unique system-on-a-chip technology, which enables us to drastically reduce the power, weight, and cost of an ultrasound scanner. Charge domain processing (CDP) beamforming will then be used as an example to illustrate the power, weight, and cost advantages offered by our patented proprietary approach.

2.1 SYSTEM-ON-A-CHIP CAPABILITY

The dramatic cost-performance improvement offered by the Terason 2000 can only be achieved by true system chips, defined here as devices that implement system level function in a single chip or chip set and where several different types of functions are integrated monolithically. Integrated within the system chip are the front-end analog RF circuit, parallel mixed-signal and digital signal processors, digital control/logic/memory units and a back-end data processor. The fully integrated chip not only provides significant improvement in system throughput rate and I/O bandwidth, despite orders-of-magnitude reduction in size and power consumption, but also dramatically lowers system costs and improves system reliability. While the payoff of the system chip approach is high, and there are compelling motivations for developing system chips, the implementation is not straightforward and requires integration of multi-disciplinary expertise. The successful development of the Terason system chip was based on an efficient mixed-signal system architecture, low-noise RF circuits, low-power proprietary CDP technology, mixed-signal VHDL verification tools, a silicon-verified standard cell library and use of low-cost standard CMOS processes.

Efficient Mixed-Signal System Architecture

In the Terason 2000 we sought to design a cost-effective low power-consumption system that would be flexible enough to support all modes of operation, including B-mode, M-mode, power Doppler, color flow imaging, spectral Doppler, and harmonic imaging. These performance goals could only be reached by an efficient mapping of the requirements onto a system architecture which minimizes the data/control routing complexity, streamlines memory I/O paths, optimizes digital/analog partitioning, and fully supports programmability via software control.

Low-Noise RF Circuits

It is crucial for a system chip to have a low-noise analog RF front-end circuit. However, the successful integration of an analog circuit on a digital substrate is at least as challenging as inventing new circuits. A thorough understanding of device physics and silicon fabrication techniques allowed us to successfully integrate large dynamic range, low-noise analog RF circuits on a digital substrate.

Low-Power Proprietary Charge-Domain Processing (CDP) Technology

For a high-end ultrasound scanner, more than 20 billion mathematical operations per second are required to perform the dynamic beamforming function alone. The number of computations provided for a given amount of electrical power by a processing element, i.e., millions of operations per second per Watt, is a critical design parameter for low power implementation. CDP technology combines high-speed, low-power, sampled-data, charge-domain components with conventional CMOS digital control and memory circuitry to create a new type of electronics—chips that provide tremendous computational throughput while exhibiting low power consumption, with low production costs and ease of system integration. Our proprietary low-power, high-throughput CDP processor is capable of performing more than 10 billion operations per second per Watt. This allows the total power dissipation of the Terason 2000 to be kept below 10W.

Mixed-Signal VHDL Verification Tool

There are several million transistors on a system chip. Software verification tools are essential in order to bring the system chip to realization with reduced development cycle time and cost. While Very high-speed integrated circuit Hardware Description Language (VHDL) modeling tools for digital circuits are readily available, there are very few robust mixed-signal VHDL tools. Our proprietary mixed-signal VHDL tool is essential to our success in bringing hybrid CDP/CMOS electronics into operational status with minimum cycle time and cost.

Silicon-Verified Standard Cell Library

For system level integration, it is highly desirable to have a modular approach, i.e., one that allows adding arbitrary combinations of silicon-verified standard cells to an unchanged CMOS platform; thereby, assuring high levels of reuse and success. Cells are added only when they provide enabling capability and are engineered to provide the necessary performance at minimum cost. In the course of our previous image and signal processing work, we developed an extensive CMOS/CDP cell library that includes multipliers, adders, accumulators, filters, memory cells, comparators, output amplifiers, A/D and D/A converters and logic and clock drivers [2-4]. With this large menu of silicon-verified cells, Terason has the flexibility to produce designs that provide the optimal balance between system performance and cost.

Low-Cost Standard CMOS Process

By integrating both analog and digital circuits on a standard CMOS process, the Terason chip set can be fabricated at low cost. Because the standard CMOS process is a mature technology, the chip set is also robust to manufacturing and to environmental variability.

2.2 TECHNOLOGY COMPARISON

Beamforming Processor

At a 40-MHz clock rate, our CDP beamformer provides a continuous computation throughput of 10.2 billion operations/s and a delay update rate of 28 billion bits/s while consuming less than 1W.

Table I. Technology comparison between the Texas Instruments TMS 320C6201B DSP, the Intel Pentium Pro microprocessor, and Teratech's Charge Domain Processor.

	Texas Instruments	**Intel**	**Teratech**
Technology	0.18-μm CMOS 5Metal	0.18-μm CMOS 5Metal	0.35-μm CMOS 3Metal
Architecture	TMS320C6 201B	Pentium Pro	Dedicated Processor
Max. rated throughput, BOPs (Billion Operations/s)	1.86	0.8	10
Power Dissipation per chip (W)	2	24	1
No. of chips for 10 BOPs	6	12	1
Total Power requirement for 10 BOPs (W)	12	288	1

A technology comparison (Table I) between a state-of-art dedicated DSP (TI TMS320C6201B), a state-of-art general purpose processor (Intel Pentium Pro) and Teratech's low-power beamforming processor demonstrates the tremendous savings in both power and weight offered by the Teratech solution.

III. THE TERASON™ 2000 HANDHELD ULTRASOUND SYSTEM

The Terason 2000 was developed based on strategies and approaches commonly employed by the computer industry, i.e., leveraging semiconductor integrated circuit (IC) integration and plug-and-play standard compatibility. First, we selected an architecture that combines a PC-based controller with a custom chip-set for high-speed, low-power implementation. As a result, unlike conventional ultrasound implementations, which consist of a large chassis filled with multiple 9" by 16" boards, our custom CDP-based ASIC chip-set allows a major part of the system to be mounted on small (2" by 5") cards that are housed directly within the scan probe. The probe is linked to a host PC through an IEEE 1394 (a.k.a FireWire) serial cable. Consequently, the system is extremely simple, comprising only a PC-compatible host (running Windows NT or 2000) and an ultrasound probe (see Figure 1). The probe with its embedded signal processing cards can be manufactured by virtually any current computer-peripherals vendor. In sharp contrast to conventional stand-alone proprietary-architecture ultrasound systems, our plug-and-play standard compatibility allows the Terason 2000 to utilize all of the control, display, videorecording and networking capabilities currently available for PCs. This approach increases the reliability of the product and reduces manufacturing and maintenance costs. Consequently, the Terason 2000 system provides excellent image quality and features equivalent to those of current full-platform high performance ultrasound systems, yet it can be sold at a price comparable to that of current low-end systems.

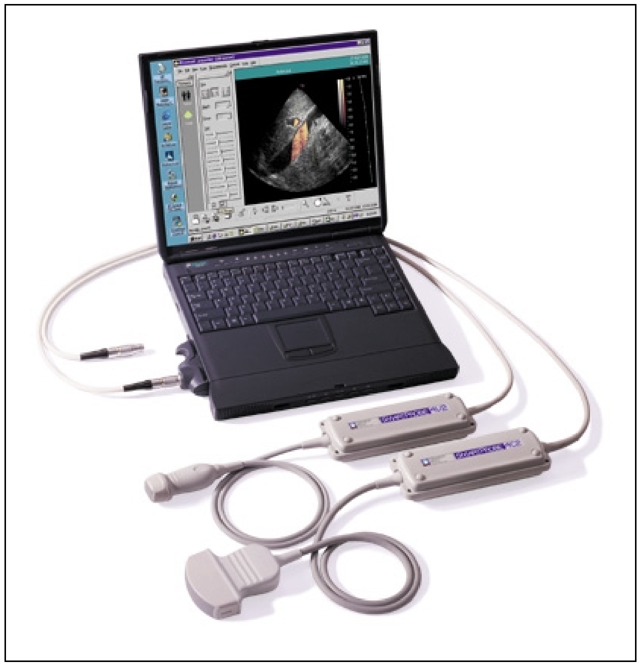

Figure 1. Terason™ 2000 Handheld Ultrasound System – Host Laptop Computer and Probe.

The Terason 2000 supports multiple types of probes (e.g. phased array, linear and curved array, and endo-cavity) with frequencies ranging from 2-10 MHz. The probe, which includes all the electronics, weighs approximately 10 ounces (0.28 Kg). The dimensions are: height = 6.5” (16.5 cm), width = 2.4” (6.1 cm), and depth = 1.45” (3.7 cm).

Figure 2 is a block diagram of the Terason 2000. The laptop microprocessor coordinates post signal processing and image display functions. The ultrasound program is stored on the internal hard-disk drive of the PC and runs as an ordinary application. Operation of the ultrasound system (controls and settings) is performed via a Graphical User Interface (GUI) with a familiar Windows-application look and feel. Patient information and image data (e.g. still frames and cine loops) can be stored directly on the PC hard drive or transmitted, e.g. via the hospital or clinic network, to a central archival and informatics system.

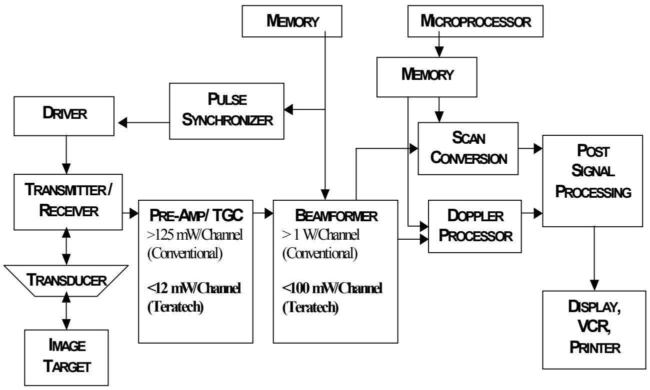

Figure 2. Block diagram of Terason™ 2000 Handheld Ultrasound System.

IV. RESULTS

The performance of the Terason 2000 has been evaluated using a variety of probes. Examples of results obtained for B-Mode, power Doppler and directional power Doppler are shown in the following figures (Figs. 3-8).

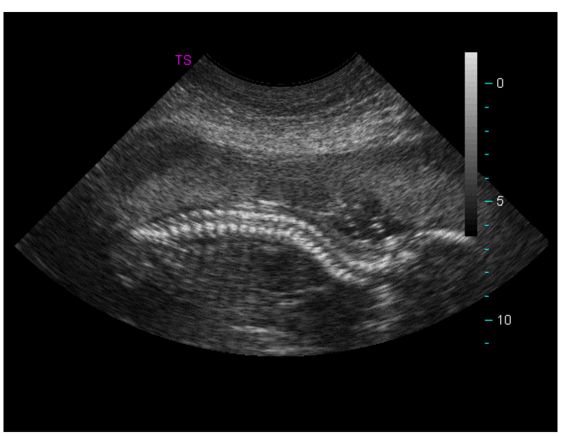

Figure 3. 20-week fetal spine.

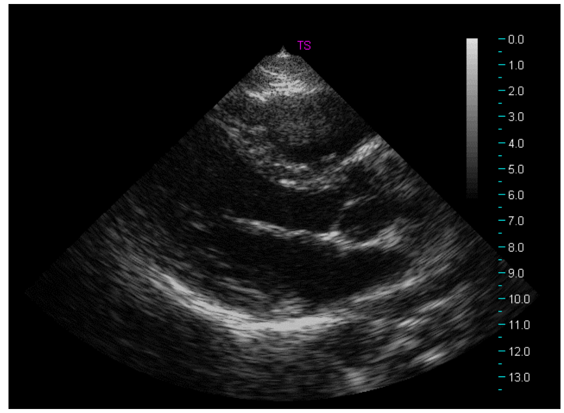

Figure 4. Parasternal long-axis view of the heart.

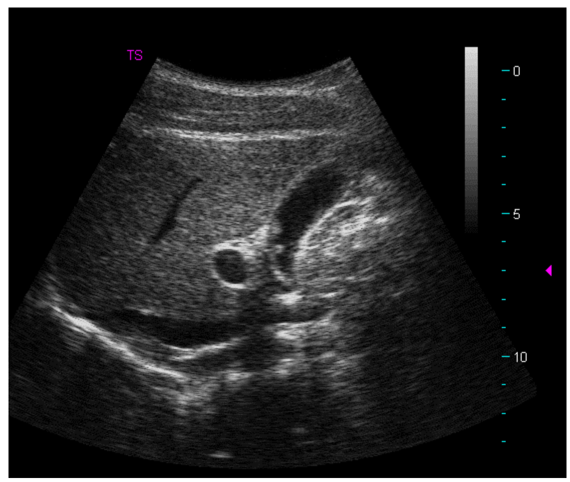

Figure 5. Gallbladder polyps.

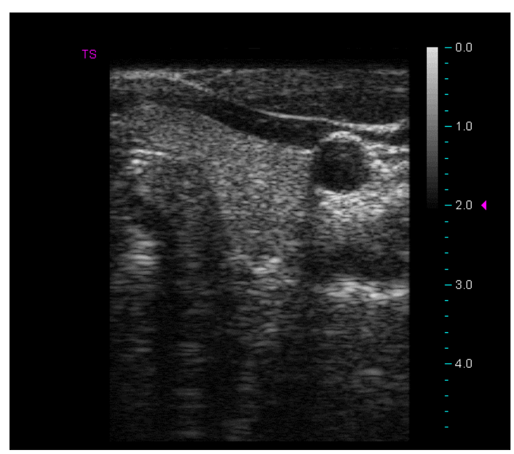

Figure 6. Thyroid.

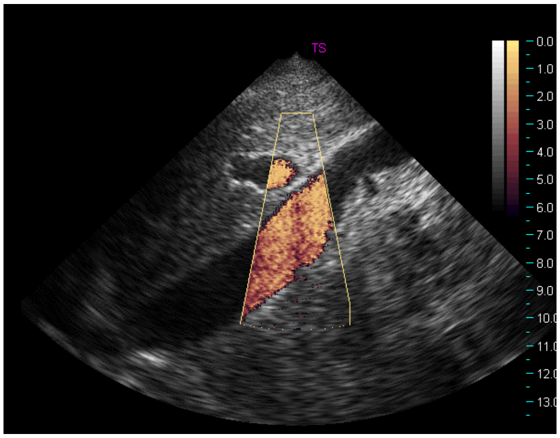

Figure 7. Power Doppler flow image of portal vein and inferior vena cava.

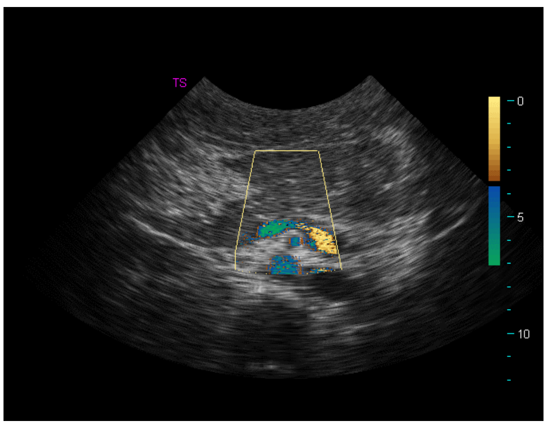

Figure 8. Directional power Doppler flow image of splenic vein and superior mesenteric artery.

VI. CONCLUSION

The use of diagnostic ultrasound has expanded dramatically over the past two decades. However, to further expand its application and points of care while minimizing health care expenditures, a low cost, portable ultrasound scanner with high image quality and color flow imaging capability is essential. The computer and semiconductor industry have also achieved remarkable advances during the past decades. Teratech has leveraged these advances and combined with them its proprietary Charge Domain Technology to develop a PC-based handheld ultrasound scanner that is low in cost and easy to fabricate, and has high channel count, a wide range of computer options, broad applications coverage, and excellent image quality.

ACKNOWLEDGEMENTS

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