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# MULTI-PROCESSOR SYSTEM FOR REAL-TIME DECONVOLUTION AND FLOW ESTIMATION IN MEDICAL ULTRASOUND

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## Abstract

More and more advanced algorithms are being introduced for performing signal and image processing on medical ultrasound signals. The algorithms often use the RF ultrasound signal and perform adaptive signal processing. Two examples are the cross-correlation estimator for blood velocity estimation and adaptive blind deconvolution. The first algorithm uses the RF signal from a number of pulse emissions and correlates segments within different pulse-echo lines to obtain a velocity estimate. Real-time processing makes it necessary to perform around 600 million multiplications and additions per second for this algorithm. This has until now only been possible by using the sign of the signals, and such an implementation does not give optimal performance. The second algorithm also uses the RF data, and first performs an estimation of the one-dimensional pulse in the tissue as a function of depth. Then a Kalman filter is used with a second time-reversed recursive estimation step. Here it is necessary to perform about 70 arithmetic operations per RF sample or about 1 billion operations per second for real-time deconvolution. Furthermore, these have to be floating point operations due to the adaptive nature of the algorithms. Many of the algorithms can only be properly evaluated in a clinical setting with real-time processing, which generally cannot be done with conventional equipment.

This paper therefore presents a multi-processor system capable of performing 1.2 billion floating point operations per second on RF ultrasound signals. It consists of 16 ADSP 21060 processors each capable of 80 Mflops. Four processors are placed on one board with 24 MBytes external storage and an internal storage of 0.5 MBytes per processor. All processors can access all storage on its physical board, and are further connected through parallel interface channels. Each channel can transmit 40 MBytes a second without slowing the processor down, and each processor has 6 of these channels. Four of these are accessible through front panel connectors, so that an almost arbitrary network of the 16 processors can

be made. The system has been interfaced to our previously-developed real-time sampling system that can acquire RF data at a rate of 20 MHz and simultaneously transmit the data at 20 MHz to the processing system via several parallel channels. These two systems can, thus, perform real-time processing of ultrasound data.

The advantage of the system is its generous input/output bandwidth, that makes it easy to balance the computational load between the processors and prevents data starvation. Due to the use of floating point calculations it is possible to simulate all types of signal processing in modern ultrasound scanners, and this system is, thus, a complete software scanner.

The system has been connected to a B & K Medical type 3535 ultrasound scanner. Data is received by the PC through an Analog Devices EZ-LAB card with a ADSP21062 processor.

## 1 Introduction

Medical ultrasound is following the general trend in electrical engineering that more and more of the processing is done on digital signals. The reason is that more accurate and advanced algorithms can be employed, that can significantly increase the diagnostic value of the presented result. Digital processing can also significantly enhance the available signal-to-noise ratio, and it makes the scanners easier to produce and essentially self calibrating. The downside of digital processing is that often a large number of calculations need to be done in real time, due to the use of sampling frequencies in the MHz range. Therefore, specialized electronics must be made to make the processing feasible within the frame of a scanner, and this makes it difficult to evaluate experimental algorithms in a clinical setting. A system capable of performing a sufficient number of calculations per second has therefore been developed, so real-time processing can be attained for nearly all commercial and experimental algorithms devel-

oped. The paper first describes some common calculation-intensive algorithms for deconvolution and flow estimation, and from that the general demands on the system are deduced. A system that can fulfill these demands is then described, and its various features are given.

## 2 Demands on system for ultrasound signal processing

Modern ultrasound scanners perform blood velocity estimation in real time and display a cross sectional image of the velocity [1]. The estimation is done by acquiring RF signals from the same direction in the image, and then finding the movement of the blood scatterers from pulse to pulse. The estimation of the movement can be found as either a phase shift through the autocorrelation method by Kasai et al. [2], or through the cross-correlation approach as developed by Bonnefous and Pesqué [3]. The last method demands on the order of 500 million multiplications per second, due to the correlation of RF signals. This has led to the suggestion of using the sign of the signals, and a compact implementation doing this was suggested by Jensen [4]. The RF correlation also necessitates RF sampling of the involved signals, and data must be transported at a rate of 40 to 60 MBytes per second.

Another area where demanding algorithms have been used is that of deconvolution. Here the RF signal from the transducer is measured and processed to sharpen the image. An algorithm that has been successfully applied on in-vivo images was suggested by Jensen [5], [6]. Here the basic ultrasound pulse is estimated for a number of RF lines as a function of depth using a prediction error approach and an ARMA model [7]. The signal-to-noise ratio is then estimated throughout the image from the pulse parameters and the measured time-gain compensation curve. These parameters are the used in a Kalman filter and a subsequent backwards time-recursive estimation of the reflection signal. The combined algorithm has the capability of taking into account variations from patient to patient and the change in pulse shape and signal-to-noise ratio down through the tissue. Roughly 70 calculations are performed per RF sample, and at a sampling frequency of 20 MHz, 1.4 billion calculations must be performed for real-time processing. The calculations for the parameter estimations are added to this demand, but they are significantly smaller, since the pulse estimation only have to be performed once every second.

## 3 Multi-processor system

The general demands for the system are that it must be capable of performing in excess of 1 billion floating point calculations per second, and at the same time handle a data stream of

60 MBytes or more per second. Currently no single processor exists that can do this. It is thus necessary to use a number of processors that can cooperate in processing the data. Such multi-processor systems can either be in a SIMD (Single Instruction Multiple Data) structure or in a MIMD (Multiple Instruction Multiple Data) structure. In the SIMD structure a single operation is performed on all data at the same time, and these systems are very efficient for matrix operations. They are, however, complicated to program, and more advanced adaptive algorithms can be very difficult to implement. A MIMD structure is therefore chosen, where different algorithms can be performed independently on different processors. The processors should be able to share data, and to transfer data quickly both from a sampling system and to a computer for display.

Many different floating point processors exist with a variety of features. Analog Devices has during the last two years introduced the ADSP21060 family of floating point processors. They have 0.5 MBytes of internal memory and have 6 link channels that each can send 40 MBytes a second using only 6 parallel wires. The data transfer can be performed concurrently with the processing by the DMA controller in the chip. It is, thus, possible to send up to 240 MBytes of data while doing processing. The chip also contains a fast floating point unit, that can make 40 million 32-bit additions and multiplications a second along with alignment of data, so that the processor is rated at 80 Mflops. The processor does also have a multiprocessor interface, so that up to 6 processors can be connected together and share an external memory. The individual processors can also access the internal memory of the other processors. It is thereby possible to have a large external memory for image data, and at the same time have smaller amounts of data internally in the chip for fast processing.

The ADSP21060 processor was selected for the system due to its fast computation capabilities and its good communication and multi-processor capabilities. A board was designed using four closely connected chips with an external DRAM memory as shown in Fig. 1. The DRAM can either consist of 16-MByte or 64-MByte standard SIMM modules, giving access to either 24 or 96 MBytes of memory over a 48-bit bus. Bus arbitration between the processors is automatically performed, and it is possible for each processor to access the internal 0.5 MBytes of each of the other processors. It is also possible to perform a broadcast write, where all processors are written to simultaneously. Two of the fast link channels are used for connecting the processors in a ring configuration and the other four links are routed to T-plugs on the front panel as shown in Fig. 2. This gives 16 link channels on the front, and very complicated networks can be set up using these links. A DMA transfer can be done to a link, so no time is wasted on data transfer while processing takes place. A simple serial interface has also been made. This is used for

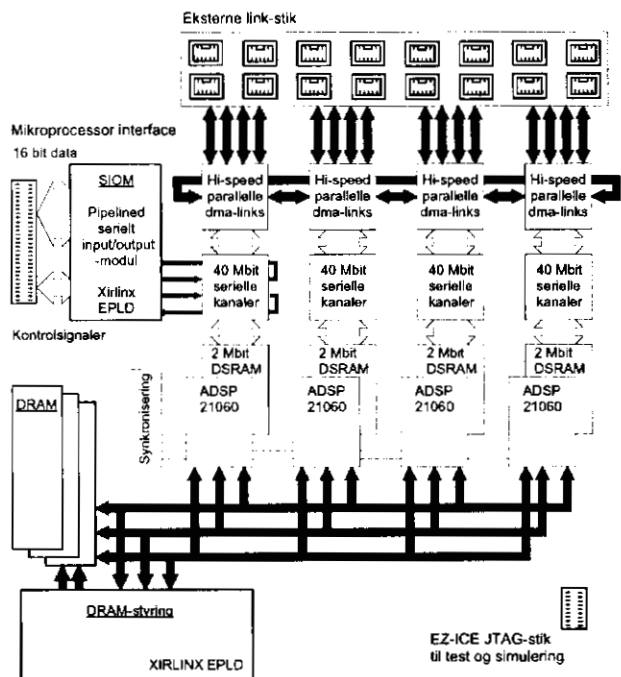


Figure 1: Overview of the board containing 4 processors, 16 link channels and from 24 to 96 MBytes of DRAM.

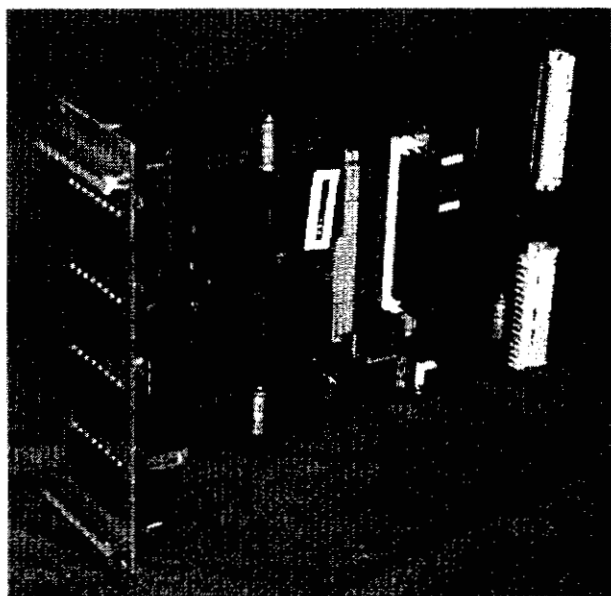


Figure 2: Multi-processor board containing four ADSP21060 processors and 24 MBytes of external DRAM. 16 external link channels are accessible at the front.

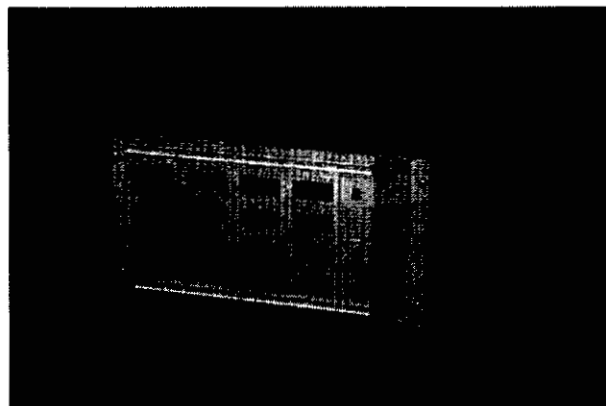


Figure 3: Multi-processor system with four boards and 16 processors. The system can perform 1.2 billion floating point operations per second.

downloading programs to the system and to receive ASCII text from C programs running on the different processors.

Four boards have been manufactured and enclosed as one system, shown in Fig. 3. This system can perform up to 1.2 billion floating point operations per second, and can at the same time transfer hundreds of MBytes per second. The system holds 104 MBytes of memory currently, but can easily be expanded to contain 392 MBytes. Our dedicated sampling system [8] has been modified to interface to the multi-processor system. A card holding one ADSP21062 processor and 6 external links has been made. The card is housed in the sampling system, and demands for data transfers are received on two links and data is transferred out of the system on the other four links. Currently the system can transfer 3 Msamples or 6 MBytes of data per second.

A typical set-up of the various systems is shown in Fig. 4. The B & K Ultrasound Systems 3535 scanner is connected to the sampling system, and controls the sampling frequency, in order to have a fully coherent system. The high frequency signal from the scanner is sampled in real time and stored in the 2 Msamples memory of the sampling system. Data is then transferred on demand to the multi-processor system for processing. The processed data is then transferred to the PC. An EZ-LAB PC-card holding one ADSP21062 CPU with two external links is installed in the PC and used for the data transfer. Finally the images are presented on the PC screen. Currently the system can process and transfer up to 5 images a second using this setup.

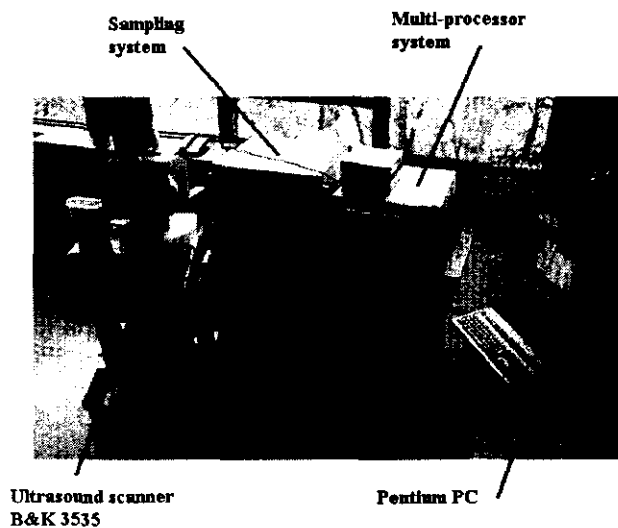


Figure 4: Set-up of system for doing real-time processing.

## 4 Future work

The system is currently equipped to do real time processing. Software has been developed for acquiring images and sending them through the system for display on the PC. It is possible to compile and download C programs, and see messages on the attached PC. Furthermore, programs for doing pulse estimation and deconvolution of in-vivo ultrasound images have been developed, and now need to be ported to run on a number of processors, so that real-time deconvolution can be performed. Both the cross-correlation and autocorrelation estimators for color flow imaging will also be implemented, and the system will be used for a direct comparison of the two techniques. In addition, algorithms for lesion contrast enhancement have been developed which use adaptive frequency filtering and grayscale mapping [9]. Clinical implementation of these algorithms requires real-time definition of regions of interest, RF filtering, and parallel calculations of statistics of the envelope-detected signals. This is only possible through the use of specialized hardware or a flexible, programmable system such as the one presented here.

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