DESIGN AND REALIZATION OF HIGH SPEED SINGLE EXPOSURE DUAL ENERGY IMAGE PROCESSING

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Abstract

At the department of Medical Physics at the University of Wisconsin-Madison research on dual energy chest imaging including the algorithm and patient studies is done using a Pixar image processor computer. Processing patient images can easily take one and a half hours. Besides that, the Pixar image computer is far too expensive to put in hospitals for clinical use. In this project we studied which low cost system is able to replace the Pixar and provide high speed dual energy image processing. The dual energy algorithm was analyzed and the user and system requirements were obtained. A single workstation (e.g. Sun Sparc Station 2) does not provide enough processing power. Therefore accelerator boards for the workstation were reviewed. The use of RISC processors, transputers and digital signal processors was considered. The only single processor available that was able to run the dual energy algorithm within the required time of 45 seconds, is the Intel i860 RISC processor. A prototype system was developed, using an i860 based accelerator board, i.e. the CSPI SuperCard-1, in a Sun 3/150 host computer. Bare computer time for the dual energy algorithm was reduced from 25 minutes using the Pixar image computer to less than three minutes using the SuperCard-1 processor board. The results of the current realization on the SuperCard were extrapolated to a system with a Sun Sparc Station 2 host computer and a CSPI SuperCard-2 accelerator board with 16 MByte of memory. Running the current dual energy algorithm will give a processing time of 48 seconds. The system described here is presently being used for a clinical observer study at the University of Wisconsin.

Introduction

The department of Medical Physics at the University of Wisconsin (UW) has developed a method to make material selective images using single exposure dual energy radiography [1]. The method uses two different images which are acquired from one X-ray exposure (e.g. the high and low energy images). The two images are digitized using a PCR (Philips Computed Radiography, a system used clinically for conventional single energy radiography) and are routed to a Pixar image computer which performs the image processing and calculates two images on which different material can be seen. In one image all bone is cancelled and only tissue remains. In the other image tissue is cancelled and only bone remains. In Figure 1 the four pertinent images are shown.

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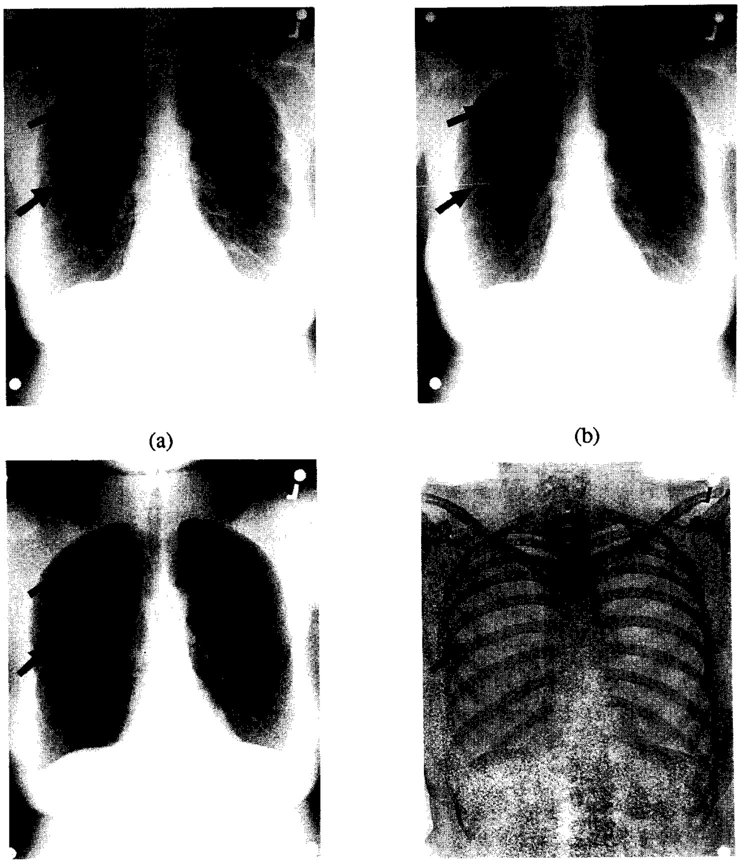

(a) (b)

(c) (d)

Figure 1. Images pertinent to the dual energy algorithm. Respectively (a) the low energy image, (b) the high energy image, (c) the tissue image and (d) the bone image are shown.

In regular X-ray images (like the low energy image in Figure 1) the complexity of anatomic structures often limits the perception of lesions [2]. An advantage of looking to the bone or tissue image is the reduced complexity of the anatomic structure. Both material selective images may play an important role in early diagnosis of lung cancer. A clinical study is in progress at the UW which examines the detection of pulmonary nodules using the single exposure dual energy technique. In Figure 1 arrows denote visible nodules. In this example there are two nodules present in the right lung. Although they can be seen in the low energy image, it is not possible to distinguish between benign nodules which contain calcium and nodules which might be malignant containing no calcium. Using the bone image, one can tell the difference between nodules that are calcified or not, because only the nodules that contain calcium will show up. In our example the lower nodule is calcified. The tissue image can be used to discover the nodules more easily, especially if a nodule is present under a bone.

Currently the image processing part of the dual energy algorithm is done on a Pixar image computer, which is connected to a Sun 3/160 host computer. Processing one patient takes at least 25 minutes of computing time, ignoring user interaction time. If we include the time for user interaction, processing one patient on the Pixar image computer can easily take one and a half hours. The long processing time makes the Pixar unsuitable for routine clinical work.

Background

Dual energy subtraction requires two X-ray chest images which must be made with two different mean X-ray energies. A technique to acquire these two X-ray images is to make two separate exposures with different X-ray energies by changing the kVp. This is referred to as dual exposure dual energy. A disadvantage of making two X-ray images at different times is that the patient can move in between, which can lead to unrecoverable misregistration artifacts. Another disadvantage of exposing twice is that the radiation dose for the patient is greater than that of conventional radiography. Another way to obtain two X-ray images acquired with different mean energies is to expose only once and use a filter to obtain a spectral energy separation. In that case the system configuration to record the two images will be as shown in Figure 2.

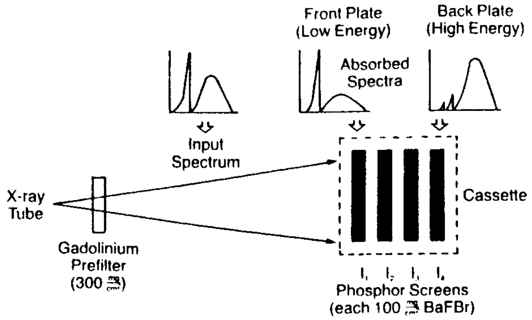

Figure 2. Schematic of recording X-ray images with different mean energy spectra.

The main elements in this system are the K-edge prefilter which makes a double peaked input spectrum and the first and last phosphor detection plates. The detection plates are flexible plates, 1 mm in thickness, coated with fine photostimulable phosphor crystals (BaFBr). The first plate mainly absorbs the low energy peak of the input spectrum and due to filtering by the two intermediate phosphor plates the absorption of the last phosphor plate mainly is the high energy peak of the input spectrum.

After exposure, the phosphor plates are taken to the PCR which scans the plates in a raster fashion with a 633 nm He-Ne laser one by one. Stimulated luminescent light is detected by a photomultiplier tube. The analog output signal of the tube is logarithmically amplified and digitized by a ten bit analog to digital converter. The resulting image is stored on optical disk. After laser scanning, the plate is erased using high intensity visible light, so it can be reused. Using an Ethernet connection both images are routed to the hard disk of the Sun workstation for dual energy image processing. Processed dual energy images are sent back to the PCR for printing hardcopies.

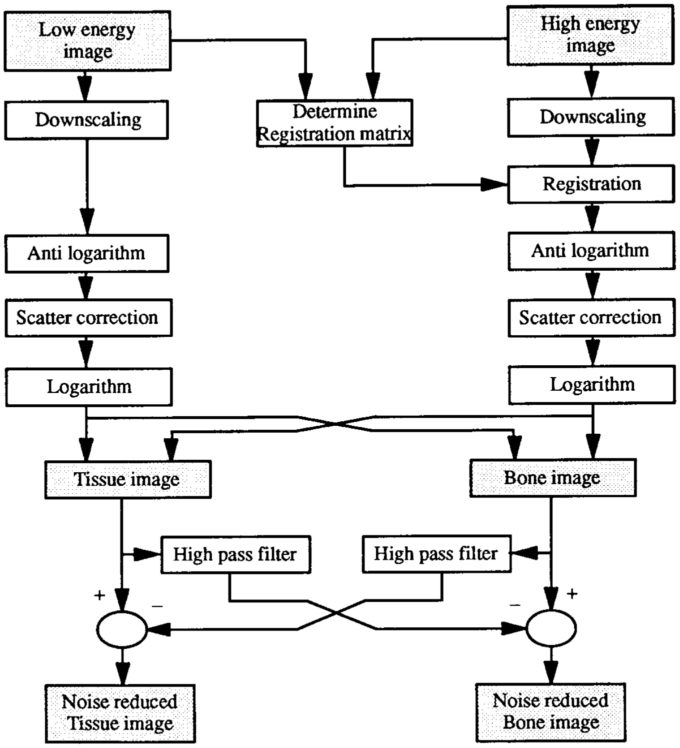

Figure 3. Overview dual energy algorithm.

In Figure 3 a flow chart of the processing algorithm is depicted. The first step in the dual energy algorithm is downscaling of the images from the PCR by a factor two. Downscaling the high and low energy images by a factor two decreases the memory needed by a factor four and increases processing speed significantly. The downsampling is performed by taking every other row and column in the image. To avoid aliasing, a prefilter operation is performed on the image before sampling.

The high energy and low energy phosphor plates are read separately by the PCR. Due to imperfect placements of the phosphor plates in the cassette and during the reading process, (x,y) positions in the high energy image do not match with (x,y) positions in the low energy image. This misregistration is typically a few pixels large. Dual energy subtraction requires registered images, because derivative images from the high and low energy images will be subtracted. Our experiments have shown that misregistration of one fifth of a pixel or more is not acceptable. Due to the character of the plate treatment, only 2D-translation, rotation and magnification will occur. In order to register the high and low energy images, the amount of translation, rotation and magnification must be determined. To facilitate this, four small lead markers are attached to the corners of the dual energy cassette. Once the position of each marker is determined, a registration matrix for the affine transformation of the coordinate system can be calculated. The registration procedure can be divided into two parts. The first part is the determination of the registration matrix (containing six constants) and the second part is the calculation of the new coordinate system for the high energy image from this matrix. After resampling the high energy image the high energy image is registered with respect to the low energy image.

The present X-ray system suffers from contrast degradation due to scattered radiation in the patient. A correction will be applied before the material selective images are composed. This must be done using pixel values linearly related to the intensity. Unfortunately the PCR provides logarithmic values. This is due to data acquisition and display routines which ensure that single energy images acquired within the 4 decades of exposure range are optimally displayed. So, before scatter correction can be done, a conversion has to be made for both high and low energy images. The algorithm for scatter correction is adopted from Naimuddin [3]. We have to note however, that this algorithm for scatter correction is only an approximation of the real scatter. At the moment research is going on in order to improve the algorithm for scatter correction.

The material selective images are formed by subtracting from the logarithmically transformed low energy image a weighted version of the logarithmically transformed high energy image. Therefore a logarithmic operation has to be performed on both images before the composing of the material selective images can be done.To achieve satisfactory images, the weighting factor can not be chosen uniform, but has to vary throughout the image. Prior work has shown that reasonable results are obtained if the grey values in the low energy image (in log space) are taken to determine the weighting factor [1]. For composing the tissue image we need to make a weighting factor which depends only on the grey values of the pixels in the low energy image. To compose the bone image the same procedure is used, except that the weighting factor must be chosen very carefully to achieve a satisfactory bone image. Currently acquiring the weighting factors is a time consuming part, because it takes a lot of time to regenerate a new image and the weighting factors can only be determined interactively. Research to make this part of the algorithm less user interactive is in progress.

The last step in the dual energy algorithm is noise reduction. The algorithm is based on the work of W. Kalender [4]. The bone and tissue images are both combinations of logarithmically transformed low and high energy images. Therefore the noise in both images is highly correlated. The Kalender algorithm reduces noise in a material selective image by subtracting from the image a high pass filtered version of the complementary material selective image using a weighting factor. Unfortunately the high pass filtered image contains also some of the complementary material, which appear as artifacts. A trade off between noise reduction and artifacts has to be made.

Technical Approach

Before a design can be made user requirements must be known. Issues like how expensive the system is allowed to be and what the average processing time is, have to be settled. Once we know the user requirements and the algorithm we can determine the system requirements. This deals with matters like amount of memory necessary, number of bits to use, performance of the system, disk speed and memory access time. All this results in the following system requirements :

- The platform for dual energy will be a Sun Sparc Station 2 workstation.
- If a flexible system can satisfy the user requirements, this is preferred above a hard wired system.
- The overall processing time for dual energy subtraction must be about 45 seconds.
- The system must be cost effective. The market is expected to be a few dozen.
- When storing images, for each pixel at least 10 bits are needed.
- The computational power of the processor must be at least 37 MOPS. Only 2% of these operations have to be floating point operations. To achieve a processing speed of 37

MOPS it seems reasonable to assume that a maximum processing capacity is needed of about 90 MOPS.
* An effective disk speed of 2 MBytes/s is needed.
* Memory access must be faster than 36 MBytes/s.
* In the total system there must be at least 6 MBytes of memory available.

Considering these requirements, the first idea to implement the dual energy algorithm would be to write the algorithm in software and run it on the Sun Sparc Station 2 computer. In order to see what processing speed this would offer, we can look at the computational performance of the workstation. An image processing benchmark, convolving a 512^2 image with a 3^2 kernel, has a quoted processing time of 0.485 seconds. One computational intensive step in the dual energy algorithm is the convolution of a 16 bit 880*1070 image with a 75^2 kernel in the scatter correction step. Linear extrapolation of the benchmark results in 18 minutes processing time for this convolution. Although one can argue about the validity of the linear extrapolation, it is clear that using only the Sun Sparc Station 2 workstation, the required processing time can never be reached. We still want to use the Sun Sparc Station 2 computer for image handling and displaying the images. The idea is to let the host do disk transfer, image display and other related I/O and use an accelerator board to perform the necessary computations in the required time. The Sun Sparc Station 2 computer has a S-bus which can be used for expansion.

Considering the relatively small market for dual energy image processing and the long design cycle of making a customized acceleration board, buying an acceleration board with the necessary requirements would be preferable. If a board with the required functionality does not exist, we would have to design our own board. Because the microprocessor on the acceleration board will mainly determine the speed of processing we will start by looking at the available processors. Three categories are distinguished, Digital Signal Processors (DSPs), Transputers and Reduced Instruction Set Computer (RISC) processors. In Table 1 the most important processors are depicted.

Table 1. Comparison between DSP, Transputer and RISC chips.

	CPU	Performance
RISC	M88000 i860 Sun SPARC Am29000 R3000	17 MIPS , 6 MFLOPS 40 MIPS, 80 MFLOPS 24 MIPS, 2.6 MFLOPS 25 MIPS 20 MIPS, 3.6 MFLOPS
Transputer	T222 T425 T801	20 MIPS 30 MIPS 30 MIPS, 4.3 MFLOPS
DSP	DSP16A DSP32C DSP96002 TMS320C30 TMS320C50	40 MIPS 28 MFLOPS 40 MFLOPS 33 MFLOPS 60 MIPS

The first class of microprocessors considered is the RISC processor. The RISC is a general purpose computer, but distinguishes itself from the CISC (Complex Instruction Set Computer) by the number of instructions in the instruction set. Therefore the control unit for RISC chips can be much smaller then the one for CISC chips and more place is available for registers. A lot of registers saves memory transfer. Because the control unit is simpler and smaller it will have less logic circuitry, compared to the CISC control unit, and fewer stages of logic gates in the path of signals. This means that the logic gates will propagate with less delay, and most of the instructions can be done in one clock cycle. The nowadays most important RISC processors are the Motorola M88000, the Intel i860, the Sun Sparc, the Advanced Micro Devices Am29000 and the MIPS Computer Systems Inc. R3000. It turns out that the i860 is the only processor which meets the system requirements. Using another processor will require parallelism. We will discuss parallelism later.

The second class of microprocessors considered is the transputer. A transputer contains a processor, memory, and a number of standard point-to-point communication links, all integrated into one chip, together with an interface for external memory. A system is constructed from one or more transputers operating concurrently and communicating through standard links. Therefore the transputer is typically a device for parallel processing. The only transputer available for performing floating point operations is the T801. We will require at least three or four of these transputers to meet the required performance. In the near future INMOS will market a new high performance transputer, the T9000. Preliminary information claims that the transputer has a performance of 200 MIPS and 25 MFLOPS, enough to perform the dual energy algorithm within the user requirements.

The last type of microprocessors considered is the DSP. The DSP is designed for special applications with extensive arithmetic operations. The instruction set of the DSP is small and all instructions can be performed in one clock cycle. Some main characteristics of the DSP are fast multiply and accumulate operations and high speed memory access. This makes the DSP potentially a suitable device for dual energy image processing. We considerated the AT&T DSP16A and DSP32C, the Motorola DSP96002 and the Texas Instruments TMS320C30 and TMS320C50. In all cases we need at least three to four DSPs to meet the requirements.

In most cases we need parallelism to meet the user requirements. Three types of parallelism can be distinguished [5], *algorithmic* parallelism where we divide the algorithm in different processes, *geometric* parallelism where we divide the image on different processors and *farming*, where a master processor divides processes on slave processors. Looking at the algorithm overview in Figure 3 we see that algorithm parallelism is a suitable technique, because the algorithm consist of two relatively independent parallel stages. Although this is possible for two processors, three or more processors will give a considerable overhead. When using the other two types of parallelism also a considerable amount of overhead will be necessary and programming the processors will be more complicated. Furthermore boards with more than two processors and with enough fast memory are hardly available. We looked at information from 15 vendors of accelerator boards and found that the only type of boards that satisfy the requirements are the boards using an i860 processor. If we want to use a different processor it would be necessary to develop a custom made board.

From three vendors (CSPI, Mercury and Sky) that manufacture array processor boards based on one i860 RISC processor, specifications were acquired of their products. Whether or not the user requirements of 45 seconds total processing time will be met depends largely on the processing speed that can be practically obtained. Therefore it is important that highly efficient program code is used, preferably written in assembly and optimized for the resources in the i860. All three vendors provide a similar library functions for one dimensional vector processing. Because the libraries supplied by the three vendors do not differ much and timing information of the routines is very similar the dual energy algorithm will run in about the same time on each of the boards and there is technically no preference for one of the boards. However there is a substantial difference in price between the boards. Therefore a prototype system was built using the cheapest board, the CSPI SuperCard.

Results

In the previous section we have seen that the CSPI SuperCard seems a well suited board for performing the dual energy algorithm in a Sun host environment. In order to see what processing speed can actually be obtained, the dual energy algorithm was implemented on a CSPI SuperCard-1 with 8 MByte on board memory using a Sun 3/150 as host computer.

In Figure 4 the present configuration is given. A CSPI SuperCard-1 with 8 MByte memory on board resides on the VME bus of the Sun 3/150 host computer, together with a SCSI disk controller and a Sun CG3 color graphics card. The SCSI controller drives a 1/4" cartridge and a 140 MByte hard disk. Attached to the color graphic card is a Sun 8 bit greyscale monitor with a resolution of 1152*900 pixels, used for displaying the images.

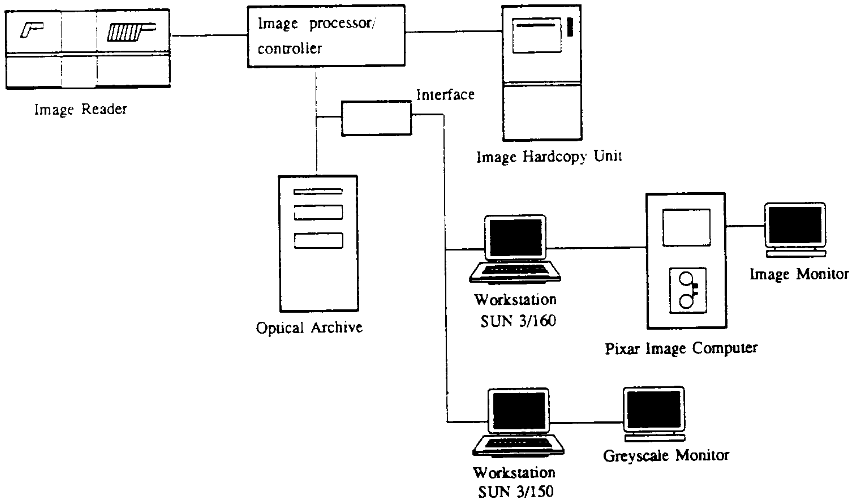

Figure 4. Present configuration.

The central processing unit for the dual energy algorithm is the SuperCard-1. The SuperCard-1 is a single board computer with a 33 MHz i860. It has a maximum performance of 66 MFLOPS and 33 MIPS. Internal memory access speed is 132 MBytes/s. The 8 MByte memory is split in two portions in different address areas. As executive space, 0.5 MBytes are used, which includes system data, user program code, stack space, heap space, system flags etc. The remaining 7.5 MBytes of memory can be used as data memory.

In Table 2 the results of the implementation of the dual energy algorithm on the SuperCard are shown. Only bare processing times are given, with weighting coefficients already fixed by the user. The implementation of the SuperCard is compared to the implementation of the algorithm on the Pixar image computer. A third column shows the theoretical processing speed. This theoretical estimation of the processing time on the SuperCard is based upon information CSPI provides about the speed of all functions of the standard library.

Table 2. Dual energy processing times on the Pixar, using the present SuperCard-1 configuration and a theoretical estimation of the processing time.

	Pixar [s]	SuperCard [s]	SuperCard (theoretic) [s]
Disk Access	262	101	–
Computation Time	958	73	71
Total Process Time	1220	174	–

From Table 2 we see that the bare processing time is reduced from 1220 seconds (20 minutes and 20 seconds) on the Pixar image computer to 174 seconds (2 minutes and 54 seconds) using the SuperCard. If we compare the estimated computation time on the SuperCard with the results of the realization we note that the estimated time is only two seconds off.

Discussion

Using the described system configuration, the goal of a processing time of about 45 seconds is not reached yet. If we distinguish in the overall time the time that the SuperCard is calculating and the time that the host performs disk access reading or writing images from/to the SuperCard memory we see that 101 seconds of the 174 seconds processing time (= 58%) is due to disk access. The reason for this long disk access time is that our present Sun host can practically transfer data only at a maximum rate of 0.33 MBytes/s from and to disk. This relatively slow disk access is partially due to the limited memory in the Sun computer. With the use of a Sun Sparc Station 2 with a standard disk as host computer, disk access speed can be up to 2 MBytes/s. These improvements will make a total disk access time of 12 seconds instead of 101 seconds.

To improve speed a SuperCard-2 with 8 MBytes of memory can be used. The main difference between the two boards is the clock frequency. The SuperCard-1 uses a 33 MHz system clock, while the SuperCard-2 uses a 40 MHz clock. So from upgrading from a SuperCard-1 to a SuperCard-2 the total process time can be decreased to 72 seconds.

The i860 is a processor capable of performing 66 MFlops. That means it is fast at calculating floating point datatypes. That is why the standard libraries use floating point format. If we store the data in short integer format, conversions have to be done. In total about 90 times during the algorithm an image must be converted from short integer to floating point data or the other way around. On a SuperCard-1 all these conversions take about 30 seconds. If a SuperCard-2 is used with 16 MBytes of memory we can store the data in floating point format and the total process time will become about 49 seconds. Another possible configuration is to use two SuperCards with each 8 MBytes on board. Using algorithmic parallelism the process time can be reduced to 28 seconds. In Table 3 a list is made of total processing times and costs of the various configurations.

Another point of discussion is whether or not downscale the images. In the study for pulmonary nodules no details seem to be lost processing the downsampled images. Downsampling is strongly encouraged by the long processing times on the Pixar. Now, using the SuperCard, the processing time of the present dual energy algorithm comes within user requirements, so we can look into the possibilities of processing the images with the original size. Because the original images are four times the size of the images that are currently processed, calculating with the original images will take about four times as long. The algorithm will be the same except for the downsampling which

Table 3. List of total processing times and costs of the various configurations.

Accelerator board(s)		Process Time [s]	Costs [$]
SuperCard-1	8 Mbyte	85	8500
SuperCard-2	8 Mbyte	72	9500
SuperCard-2	16 Mbyte	49	12500
2 SuperCard-2	8 Mbyte	28	19000

can be skipped. Therefore we estimate that processing the original images on one i860 processor can be done in about three minutes and running the algorithm on two i860 processors can be done in about two minutes. The amounts of memory necessary in each configuration will respectively be 32 MBytes and 64 MBytes. Making a board with 64 MBytes of memory with the current memory technologies does not seem reasonable, a board with 32 MBytes of memory seems possible. Presently no SuperCard with 32 MBytes of memory exists, but will be available in the near future. Implementation of the algorithm on a Sun Sparc Station with the original size of the input images is in progress.

The department of Medical Physics is conducting a clinical study using the described prototype. The increased speed in relation to the Pixar configuration has been quite helpful. Preliminary results are encouraging.

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References

[1] D.L Ergun, C.A. Mistretta et al., "Single Exposure Dual Energy Computed Radiography: Improved Detection and Processing," *Radiology* 174:243-249, 1990.

[2] H.L. Kundel, G. Revesz, "Lesion conspicuity, structured noise and film reader error," *AJR* 126:1233-1238, 1976.

[3] S. Naimuddin, "Optimization of Selective Exposure Radiography of the Chest," Ph.D. Thesis, Department of Medical Physics, University of Wisconsin-Madison, 1986.

[4] W. Kalender, E. Klotz, L. Kostaridou, "An Algorithm for Noise Suppression in Dual Energy CT Material Density Images," *IEEE Transactions in Medical Imaging* 7:218-224, 1988.

[5] C. Whitby-Stevens, "Transputers - Past, Present and Future," *IEEE Micro*, 12:16-19, 76-82, 1990.