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Rapid Display of Radiographic Images

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ABSTRACT

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The system includes an Image Server with storage for over 600 4 megapixel images and a high-speed link. A subsampled megapixel image is fetched from disk and transmitted to the display in about one second followed by the full resolution 4 megapixel image in about 2.5 seconds. Other system components include a megapixel display with a 6 megapixel display memory space and frame-rate update of image roam, zoom and contrast. Plans for clinical use are presented.

1. INTRODUCTION AND BACKGROUND

Rapid display of high-resolution images is a primary concern in the design of electronic radiology systems. Radiologists and referring physicians alike prefer images to be displayed with response times of about a second or less. Even if careful studies were to show a negligible effect on viewer performance as a result of response times of many seconds, the lack of satisfaction likely with slower systems makes their acceptance problematical in a hospital environment. This observation is consistent with experience with other interactive computer systems.

In other environments the situation may be different. The radiologist that is asked to read an image when at home is likely to prefer a telecommunications delay of several minutes to a trip to the hospital. The physician that is asked while seeing patients in the office to decide on therapy for a hospitalized patient is likely to prefer a delay of ten seconds or more to postponing the decision until the next hospital visit. However, primary diagnosis of chest images and patient care in an ICU are examples of circumstances in which such delays are burdensome and likely to produce dissatisfaction.

Issues associated with the rapid display of radiographic images have been discussed throughout the last decade.[1,2] Relevant technical issues are spatial and contrast resolution of the display system; effectiveness of lossy or lossless compression; disk, bus and network transfer rates; and congestion in image traffic. These issues are interdependent and technology sensitive and some comments on them, based in part on our experience, are presented in the next few paragraphs.

Spatial Resolution. Film scanners with spatial resolution of 4k x 5k pixels have been developed [3] and seem to be adequate to reproduce almost all relevant detail.[4] Practical soft-copy displays are limited to 2k x 2.5k pixels (MegaScan), but demonstrate acceptable performance on a wide range of diagnostic tasks.[5,6] Economical displays are now available at 1k x 1k pixels,[7] but equivalent low cost for higher resolution displays will probably await developments attendant to the volume production of HDTV and high-speed, 4-megabit video RAMs. Tradeoffs need to be explored between expensive high-resolution displays and more economic, smaller format ones that use zoom to achieve comparable resolution. For example, the advantages of viewing complete images at full resolution have been recognized,[8] but questions remain regarding the acceptability of viewing smaller format images with the aid of zoom.

Contrast Resolution. The number of density values available from today's scanners range from 1k (10 bits) to 4k (12 bits). Some of the least significant bits in the scanned images may not provide diagnostically useful information, but companding algorithms for taking advantage of this fact have not yet been thoroughly tested.[9] In the meantime it seems wise to provide the capability to record 12 bits of intensity information. This is an awkward number because the workstation community has established a de facto standard of 8 bits of intensity information, a standard that is apparently insufficient for the needs of the radiologist. Questions remain concerning the usefulness of companding algorithms,[9] high-speed decoding algorithms[10] and protocols that routinely preselect window and level settings for the viewer.

Compression. Eliminating redundant information in an image has the potential to both reduce storage costs and improve the response time for image display. Single DSP-based JPEG [11] decompression algorithms operating at rates between 300 and 800 kp/s [12,13] are too slow to improve response time, but the recently introduced JPEG chip [14] can decompress at 13.5 megapixels/sec(Mp/s) and so 8-bit 2k x 2k images can be reconstructed in under a half second. This lossy method leads to compression factors of at least 10:1 without appreciable distortion.[12] Questions remain, however, related to the adequacy of 8-bit images and to the potential that zooming and contrast manipulation have for revealing differences between the original image and its compressed and reconstructed version. Lossless algorithms have demonstrated compression factors of between 2:1 and 4:1,[15] apparently leading to an insufficient gain in response time to justify, so far, the required special decompression hardware.

Transfer Rates. Disk transfer rates are commonly about one megabyte/second (Mbyte/s) for generally available products and platforms. Several recently introduced buses have a peak transfer rate of between 80 and 100 Mbyte/s (DEC TURBOchannel, NeXTbus and Sun S-bus), but popular disks, disk controllers, bus chips and operating system software cannot yet take advantage of this speed. Certainly transfer rates capable of delivering a 2k x 2k image in under a second are on the horizon for inexpensive, popular platforms, but at the moment a parallel disk array (PDA) or some other expensive, high-performance approach is required to achieve the desired access time. Network transfer rates are, for the most part, limited to 10 megabits/sec (Mb/s) as provided by the Ethernet standard, but the increasing popularity of the FDDI and ATM standards promise an order of magnitude increase in bandwidth at reasonable cost within a few years.

Congestion. Heavy traffic at several points in an electronic radiology system can lead to additional delays. Congestion can occur at the disk, on the bus, within the network and as a result of multiple layers of system software. Reliance on a single image storage device aggravates the problem. A hierarchical image storage system with distributed image caches can ameliorate this problem provided that requests for images have adequate locality.[1]

2. SYSTEM ARCHITECTURE

The hardware architecture of the Mallinckrodt Institute of Radiology (MIR) Radiology Image & Information Manager (RIM) is shown in overview in Figure 1. A variety of image sources are available in MIR-RIM, but for the purposes of this discussion we concentrate on high resolution sources, computed radiography (CR) and film scanning (FS). Ethernet is used for communication between the image sources and the distributed Radiology Database Management System (DBMS) because image delivery is not time critical in this case. The Inquiry & Display Station is representative of a variety of such stations implemented at MIR on different platforms, but all with Auxiliary Displays specialized for the presentation of radiological images. User interactions with the DBMS travel via Ethernet, but the pixel stream that delivers the image travels via a separate high-speed fiber path (or a high-speed copper path in some cases where distances are short).

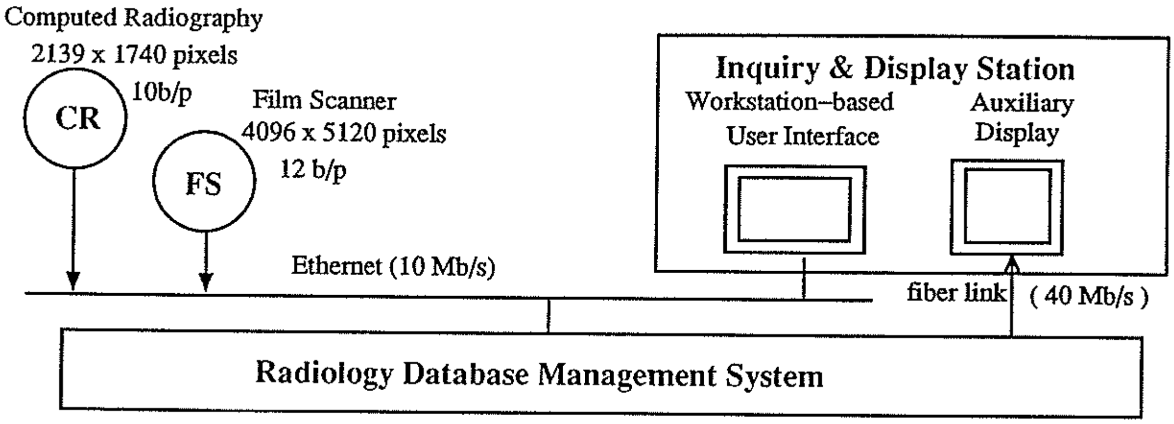

Figure 1. Images acquired from computed radiography (CR) and film scanners (FS) are stored and linked with alphanumeric patient and examination data. Queries from a user at a workstation determine which patient is to be studied and query responses provide associated demographic, examination and report information. A key derived from a unique examination number is used to access related images. In one version of the Inquiry & Display Station, a fiber-optic link carries images to an Auxiliary Display, specialized to radiology viewing needs. In another version (not shown) images are delivered to the Auxiliary Display via Ethernet. The entire system, with multiple scanners and displays, is called the Mallinckrodt Institute of Radiology (MIR) Radiology Image & Information Manager (RIM).

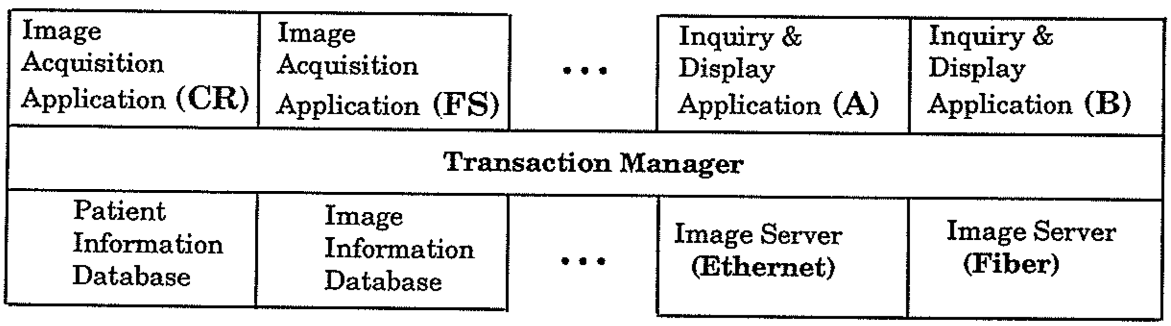

Figure 2. The software architecture of MIR-RIM is centered on a Transaction Manager that executes on all participating platforms. Multiple software modules acquire, store, serve and display images and related information. Both CR and FS images are presently supported. Images can be served over Ethernet (10 Mb/s) or over a fiber link (40Mb/s). Throughput for entire images is slower than that indicated by the maximum transmission rates and depends upon pixel size, image size, network traffic and system load.

An overview of the software architecture of MIR-RIM is shown in Figure 2. Any number of Image Acquisition Applications specialized to each scanner can be connected to a distributed Transaction Manager executing on all participating platforms in MIR-RIM. MR and CT image modalities can be supported in addition to CR and FS. The Patient Information Database is a custom application [16] that operates on several separate and distinct platforms all accessible to the Transaction Manager via DECnet. The Image Information Database contains keys and descriptors for images. It utilizes commercial packages (SQL, DECnet and RDB) and the database resides on its own platform. Inquiry & Display applications (which we call RIVA for Radiology Image Viewing Application) can execute on many platforms concurrently. RIVA is written in C and currently runs with a DECwindows interface under VMS. It is essentially the same whether images are served over Ethernet or a fiber link. The Image Servers are simple systems which store and retrieve pixel data, transfer pixels over high-speed links to Auxiliary Displays and manage free space. The Ethernet and the fiber link versions operate on different hardware and with different architectural approaches.

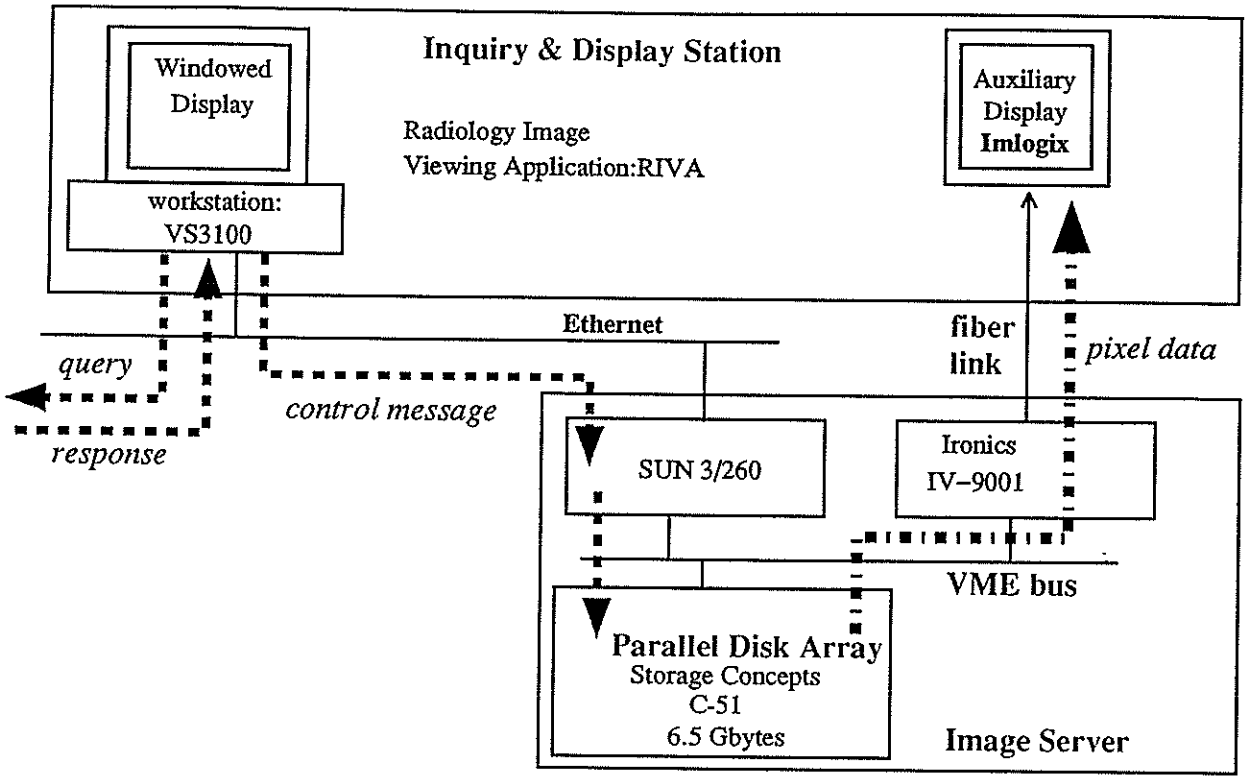

Figure 3. Specialized image transfer components are required to achieve high-speed display. User queries, originating from the Inquiry & Display Application (RIVA) executing on the workstation, are resolved by the Patient Information or the Image Information Database. The file descriptors of desired images are transferred via a control message to the Image Server where a Parallel Disk Array (PDA) transfers the image pixel data to a high-speed processor (Ironics). The processor formats the data for transmission over a fiber optic link to an Auxiliary Display (Imlogix).

3. IMAGE SERVER

In this paper we focus on the high-speed version of the Image Server and the Inquiry & Display Station. Figure 3 shows a more detailed view of the version of the Image Server and the Inquiry & Display Station that are specialized to store up to 600 4 Mp CR images and to achieve their rapid display. Control messages containing keys obtained from the Image Information Database direct the controller for the Storage Concepts Parallel Disk Array (PDA) to deliver an image to memory on the Ironics high-speed, RISC processor (AMD 29000) board. Blocks of 500 kbyte 12-bit pixels are transmitted across the VME bus to the Ironics IV-9001 16-bits at a time (the four most significant bits are zero). The Ironics formats these blocks for transmission over the fiber link in the form of a sequence of 10-bit transmissions (each pixel requires two bytes and each byte is accompanied by two parity bits; see Figure 4). A TAXI transmitter chip converts its 10-bit parallel input into a 5/6 coded data stream to allow for clock recovery at the receiver and to allow for the insertion of control codes in the data stream.[17]

The link operates at 60 Mb/s, but information flows at the rate of 40 Mb/s or 2.5 Mp/s. Throughput is limited by the size of the buffer on the Ironics board and by software that does not support all possible opportunities for pipelining. When the Ironics board has no pixel data to send, the TAXI sends sync characters. An inexpensive distributor (Imlogix TAXI Distribution Box) is available that allows a single Image Server port to transmit images to up to eight Imaging & Display Stations in a multidrop topology.

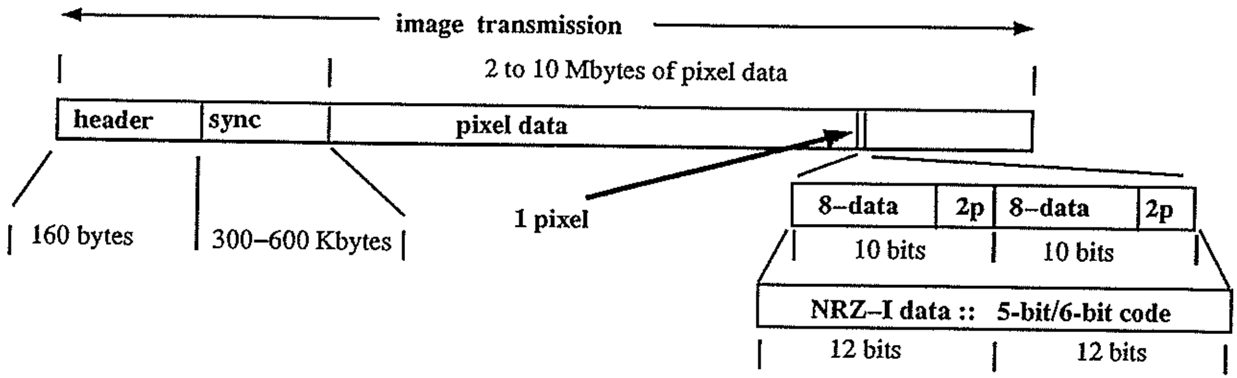

Figure 4. An image is formatted as a single data block (two bytes per 12-bit pixel) preceded by header and sync blocks for transmission on the fiber-optic link. Each byte is augmented with two parity bits. A 5/6 transmission code is used that is similar to the code used in the data link layer of FDDI. The line rate is 60 Mb/s and the pixel rate is 2.5 Mp/s.

4. AUXILIARY DISPLAY

Two styles of Auxiliary Displays (MegaScan and Imlogix) are in use in MIR-RIM, one with 2k x 2.5k pixels and the other with 1k x 1k pixels. It is the latter, lower resolution and more economical display that is described here (Imlogix 1000 Display Station). The block diagram in Figure 5 shows the pixel path at the top with heavy lines. Pixels transmitted over the fiber link are converted from serial to parallel by the TAXI Receiver subsystem and stored in the 6 Mp Image Memory under DMA control. The Image memory is made up of 72 one-megabit video RAM chips which provide effective dual port access through their high-speed, 4-bit wide, shift-register outputs. Three such chips make up a 256k pixel memory segment. Thus, 12 chips are required for each megapixel of memory (see Figure 6). The resampler shown in Figure 5 carries out bilinear interpolation on four neighboring pixels in the stored image at a rate sufficient to refresh a 1k x 1k resampled image at 60 Hz or greater. Details of the interpolation method are shown in Figure 7 where two resampled pixels (□) in a single scan line are interpolated from six neighboring samples (o) in the stored image. Three intermediate vertical linear interpolations are indicated (x), but in this example only one new vertical interpolation need be carried out to generate each new resampled pixel. Just one horizontal linear interpolation is required for each resampled pixel and thus a total of only two linear interpolations are needed so long as the spacing of the resampled pixels is less than the spacing of the stored pixels. This condition holds for magnification factors (zoom) of greater than unity and results in a pixel data rate at the input to the resampler of only twice its output pixel rate. Successive resampled scan lines will repeat the entire process even if the same pixels from the Image Memory are used as input to the resampler.

The design of the Imlogix Display described above makes possible a form of progressive transmission that reduces the response time for a 2k x 2k image. First a down-sampled 1k x 1k image is transmitted to one half of the 2 Mp bank of the Image Memory (the left-hand lower section in Figure 6). The resultant displayed image has less resolution than provided by the original image, but yields the highest resolution consistent with complete image display. While the user is examining and manipulating this image the 4 Mp bank of Image Memory is filled with the full-resolution, 2k x 2k image. If the user then zooms the image (e.g., the magnification window shown shaded in Figure 6), the pixels delivered to the resampler are fetched from the corresponding shaded window in the 4 Mp bank whenever the magnification factor is 2 or greater; full resolution data is thus available to the viewer.

Under most circumstances, the transition from the lower bank to the upper is usually imperceptible. However, portions of the image that contain significant high spatial frequency components allow the careful viewer to notice the increase in resolution that accompanies this transition. Plate 1 (on the last page of this paper) shows a chest image [A] that demonstrates this effect. Here a spring (on an external clip) is visible at the upper boundary of the lung. This portion of the image is magnified from the down-sampled 1k x 1k image in [B] and from the 2k x 2k image in [C]). Note in [C] the improved resolution of the spring.

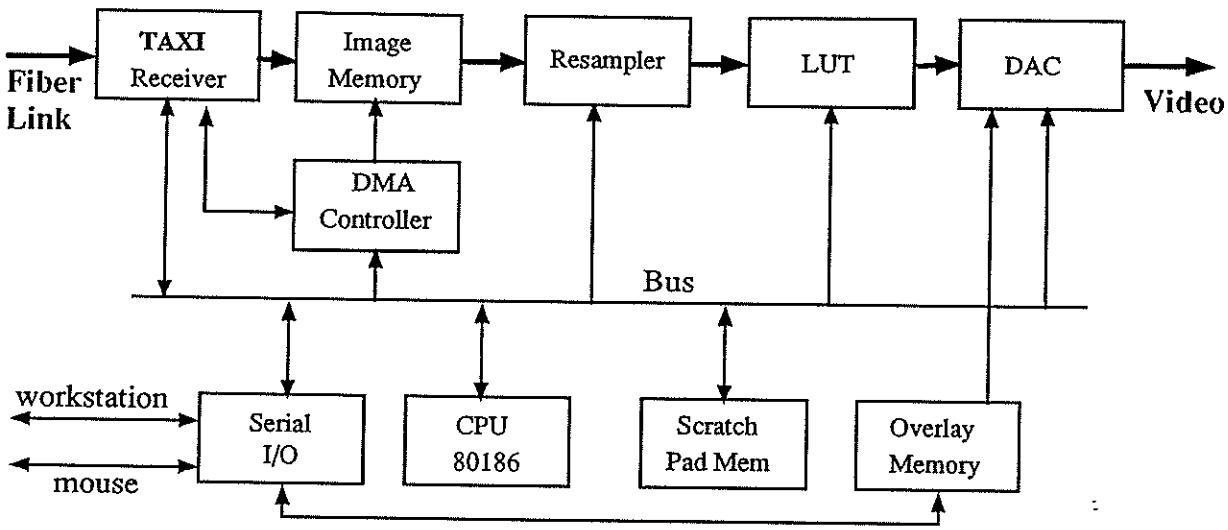

Figure 5. The block diagram of the Auxiliary Display (Imlogix 1000) showing the pixel path at the top (heavy lines) and control below. The TAXI Receiver converts the transmitted data from serial to parallel passing 1k by 1k 12-bit pixels to the Image Memory under DMA control. The Resampler generates a 1k by 1k 12-bit pixel image with an arbitrary magnification factor and arbitrary origin within the Image Memory. The Look-Up-Table (LUT) remaps the intensities in the 12-bit resampled image to 8 bits for display. Finally, the 60 Hz video that drives the monochrome display is generated by the 8-bit Digital-to-Analog Converter (DAC).

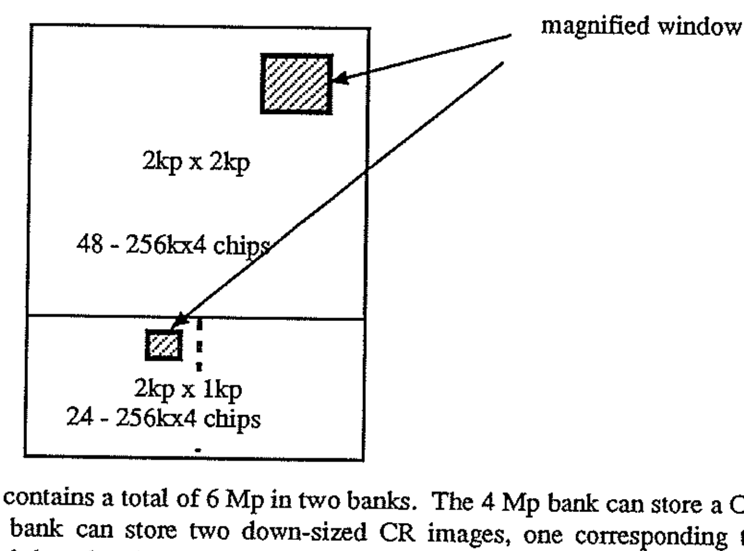

Figure 6. The 12-bit Image Memory contains a total of 6 Mp in two banks. The 4 Mp bank can store a CR image at virtually full resolution. The 2 Mp bank can store two down-sized CR images, one corresponding to the full-resolution image in the upper bank and the other (at the right) serving the function of a buffer for the next incoming image. A magnified window on the image may be displayed from either bank as indicated by the two shaded squares.

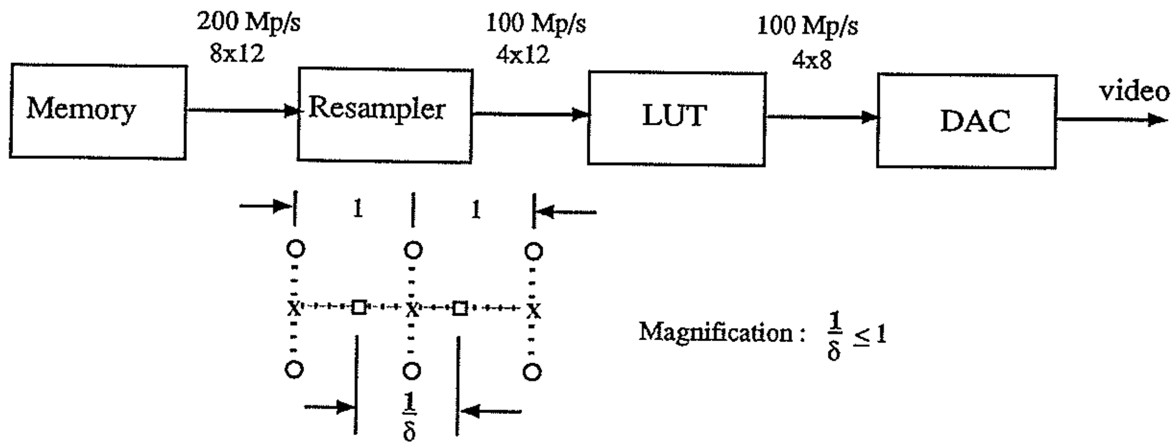

Figure 7. Magnification in the Imlogix display is restricted to factors greater than unity. Under this restriction resampled pixels (□) are spaced by $1/\delta$ which is less than the spacing of the pixels in the stored image. The data rates shown above are based upon the assumption of a 70 Hz refresh rate (The 70Hz refresh rate is to be introduced in a future product to replace the present 60 Hz display).

5. RESULTS

The Inquiry & Display Station based on a DEC VS 3100 Workstation and an Imlogix 1000 Display is shown in Figure 8. This combination was tested with the Image Server described in Section 3 to determine system response times. A user request to view an image triggers five sequential events:

1) The workstation queries the Image Information Database.
2) The workstation sends a control message to the Image Server.
3) The Image Server transfers pixel data over a high-speed link to an Auxiliary Display.
4) The Image Server sends a control message to the workstation.
5) The workstation sends a control message to the Auxiliary Display containing configuration information, such as preselected center and window values.

The time needed to transmit a control message is short in comparison to the times for the database query and pixel transfer and will be included with the database query time for this discussion.

The query to the Image Information Database returns information about the location of the pixel data for the requested image. This information includes the name of the server storing the pixel data, an access string used to determine the location of the pixels on the server, the storage format and the size of the image file. The pixel data for a particular image may exist as different instances on more than one server, and the workstation determines which instance should be sent to the destination display. Once the proper instance is located, the workstation and Image Server exchange control messages to implement the image transmission. In our prototype system, the time needed to perform the database query and send the control messages is 0.6 to 1.0 second depending on system load.

The Image Server receives the control message which contains an access string describing the location of the pixel data, the size of the data file and the destination Auxiliary Display. In the case of the PDA server, general purpose software supplied by the vendor is used to maintain a catalog on the UNIX system disk. The access string is the name of a file on the system disk which is read to get the physical location of the data on the PDA. For the VMS-based Image Server (using 10 Mb/s Ethernet and standard disk technologies) the access string contains the name of the file used to store the pixel data.

The VMS-based Image Server is a multi-threaded process that will service several requests concurrently. Due to the nature of the PDA/TAXI combination, the PDA server is written to service requests from multiple workstations sequentially. Times reported below for the high-speed Image Server do not include contention delays as our experiments were run with a single workstation.

When the high-speed Image Server receives a request to transfer an image to an Auxiliary Display, it opens the UNIX file containing the catalog information and then performs the pixel data transfer. We measure the overhead associated with opening and reading the UNIX file to be on order of 0.2 to 0.3 second and refer to this as server setup time. Transfer of data from the PDA to the Imlogix Display Station consists of PDA reads overlapped with transfers to the TAXI unit. Transfer times depend on the size of the ring buffer on the Ironics board (1.5 or 7.5 MB), the size of the buffers used during each DMA transfer and the size of the image.

Table 1 below lists average transfer times and rates for:

- Transferring pixels from the PDA to the ring buffer
- Transferring pixels from the ring buffer to the display
- Transferring pixels from the PDA through the ring buffer to the display using overlapped I/O

The transfer time from PDA to the ring buffer for 1Mp images was too short for us to measure accurately.

Table 1. Pixel transfer times and rates involving the high-speed Image Server and Imlogix Display Station

	1.5 MB Ring		7.5 MB Ring	
	Time (sec)	Rate (Mbyte/s)	Time (sec)	Rate (Mbyte/s)
1 Mp ring buffer to display	0.64	3.3	0.54	3.9
1 Mp PDA to display	0.77	2.7	0.72	2.9
4 Mp PDA to ring buffer	1.79	4.7	1.35	6.2
4 Mp ring buffer to display	1.92	4.4	1.80	4.7
4 Mp PDA to display	2.95	2.8	2.49	3.4
5 Mp PDA to display	3.72	2.8	3.21	3.3

For small images, the ring buffer size has a negligible effect on overall throughput rate as measured from the PDA to the Auxiliary Display. This time is on the order of 0.75 second. When displaying larger images we are able to see the effects of the overlapped pixel transfers and of the larger ring buffer size. Effective transfer rate from the PDA to the ring buffer increases from 4.7 MB/s to 6.2 MB/s with the larger ring buffer. Likewise, the TAXI transfer rate is improved by using the larger ring buffer.

If we could not overlap the PDA read with the TAXI transfer, the time to display the 4 Mp image would be 3.71 seconds for the 1.5 MB ring buffer (1.79 + 1.92) and 3.15 seconds for the 7.5 MB ring buffer (1.35 + 1.80). Using overlapped DMA, we were able to reduce these times to 2.95 and 2.49 seconds with corresponding aggregate throughput rates of 2.8 and 3.4 Mbyte/s.

When operated strictly in the 1 Mp mode, the system response time will be the sum of the database query time, the server setup time and the server transfer time. With a 1.5 Mbyte ring buffer, this response time is 1.7 to 2.1 seconds. When operated in the 1k/2k mode, the system transfers the 1 Mp image first, followed by the 4 Mp image. System response time is the sum of the database query time and the server transfer time for both the 1 Mp and 4 Mp images. With a 7.5 Mbyte ring buffer, this response time is 4.1 to 4.5 seconds. Note the user sees a full 1 Mp image in approximately 2 seconds and the system then fills in the full resolution 4 Mp image, usually without the viewer being aware of it, soon thereafter.

6. DISCUSSION

The issues associated with the rapid display of radiological images raised in Section 1 (resolution, compression, transfer rates and congestion) do not lend themselves to definitive analysis at this time. Many of these issues can be resolved most expeditiously through the installation and evaluation of a clinically useful electronic radiology system. The difficult part of this approach is the level of medical and engineering judgment required to specify a system that has an adequately fast response time, presents images with excellent quality, is complete enough to be clinically useful, provides ample user amenities and yet is inexpensive enough to contemplate substantial penetration of a clinical service. The architecture described in the preceding paragraphs is our best present approach to such a clinically useful system. We believe it has high enough quality to gain acceptance and is flexible enough to allow investigation of some of the open questions.

In making the architectural design choices we have given considerable thought to the issues associated with rapid display discussed in Section 1. The *spatial resolution* chosen is that provided by a mixture of 2k x 2.5k and 1k x 1k displays. The higher resolution devices are used for primary diagnosis, and the lower resolution ones are used wherever prior diagnostic information is available. The economies achieved by this choice seemed important to us.

In the case of *contrast resolution* we have chosen a 12 b/p Image Memory followed by a LUT for interactive contrast control (usually window and level). Displays with only 8 b/p may be satisfactory in some circumstances, but we do not have enough information to take a step that would eliminate our options in this matter. In any case, cost seems not to be a prime distinction between 8 b/p and 12 b/p fast-response displays specialized to electronic radiology.

The use of *compression* has been deferred. Too many questions remain regarding allowable image distortion for us to use lossy methods in primary diagnosis. Perhaps, if it is found that a preselected and fixed contrast setting is preferred by radiologists, a lossy compression method could be incorporated, even in primary diagnosis where its effect on improving response time would be significant. More research is required. Lossless compression may soon be a viable alternative providing appropriate chips become available. However, chances for sufficiently inexpensive bandwidth and memory are good and lossless methods may be bypassed because of the modest compression achievable.

The limitations imposed by the *transfer rates* of popular platforms have been avoided in our architecture by the use of Auxiliary Displays with high-speed pixel paths that deliver images from a high-speed Image Server. Finally, *congestion* has been avoided by use of a hierarchical, distributed storage structure featuring an image cache in the Image Server.

The architecture described in Figures 1 and 2 will soon be applied to clinical diagnosis and medical decisions in connection with the MIR chest service. As shown in Figure 9, Inquiry & Display Stations will be installed in two locations, the chest service reading room and in an intensive care unit. A total of five Auxiliary Displays (2 MegaScan and 3 Imlogix) will be controlled by one workstation in the reading room. Two Auxiliary Displays (Imlogix) will be controlled by one workstation in the intensive care unit.

An electronic radiology system, MIR-RIM, has been designed with 1) a two-second image response time; 2) an Image Memory capable of storing 12-bit images with 2k x 2k resolution; 3) tight integration with an existing radiology information system; 4) timely acquisition of CR and FS images and 5) ample user amenities provided by a convenient windowed interface. Even though the system is in prototype form, it is inexpensive enough to contemplate substantial penetration of at least one clinical service. An early installation in the MIR chest service is planned. We anticipate that the clinical use of MIR-RIM will help to us investigate several of the open issues regarding the fast display of radiological images.

7. ACKNOWLEDGMENTS

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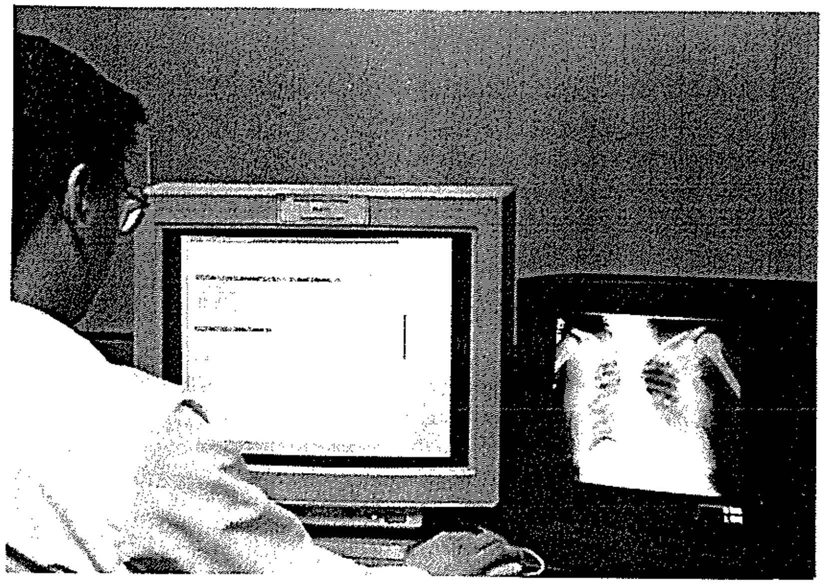


Figure 8. A VS 3100 workstation and Imlogix Display provide an example of an Inquiry & Display Station.

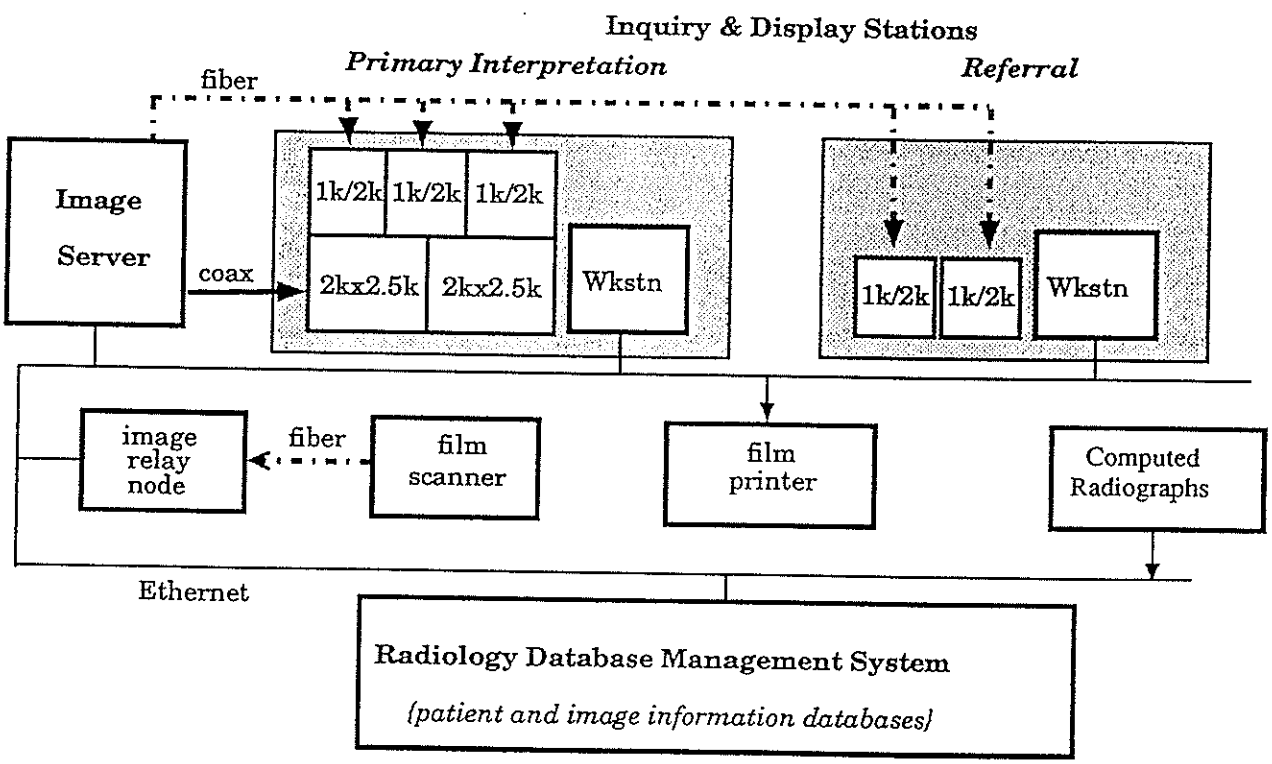
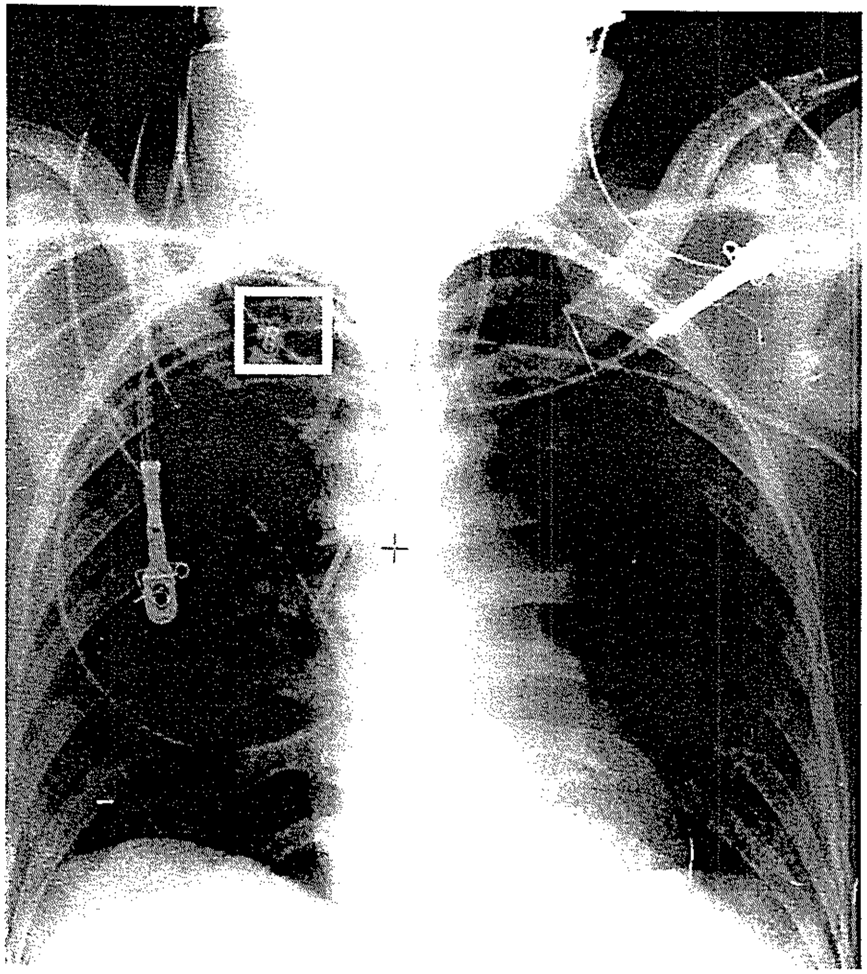
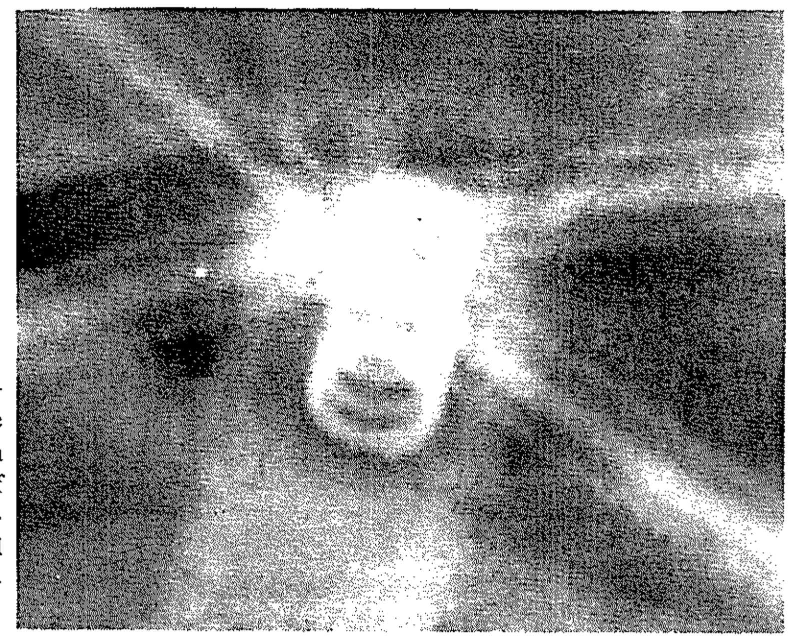


Figure 9. A demonstration project is planned utilizing the approach described above. Additional components are the MegaScan 2k by 2.5k displays and a Kodak Laser Printer. Use for primary diagnosis on the chest service is planned.



A

B



C

Plate 1. An example portable chest radiograph [A] (produced by computed radiography) illustrates image resolution issues when viewing with "magnification." Here a 2k x 2k image down-sampled to 1k x 1k is displayed on an Imlogix display, with a highlighted region of interest (contains an external spring clip). In [B] the region of interest is resampled and magnified from the 1k x 1k data set by the bilinear interpolator (internal to the Imlogix display). In [C] the region of interest is magnified to the same scale from the full resolution 2k x 2k data set. Access to the full resolution data assists in visualization of fine structure.