Optical processing architecture and its potential application for digital and analog radiography

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In this report we introduce the fundamental architectures and the potential applications of optical processing techniques in medical imaging. Three basic optical processing architectures were investigated for digital and analog radiography. The processors consist of a module that converts either the analog or the digital radiograph into a coherent light distribution; a coherent optical processing architecture that performs various mathematical operations; a programmable digital–optical interface and other accessories. Optical frequency filters were implemented for mammographic and other clinical feature enhancement. In medical image processing, digital computers offer the advantages of programmability and flexibility. In contrast, optical processors perform parallel image processing with high speed. Optical processors also offer analog nature, compact size, and cost effectiveness. With technical advances of digital–optical interface devices, the medical image processor, in the foreseeable future, may be a hybrid device, namely, a programmable optical architecture. © *1999 American Association of Physicists in Medicine.* [S0094-2405(99)01804-0]

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I. INTRODUCTION

A. Clinical need for optical processing

Digital image processing and computer-aided diagnosis (CAD) have been widely investigated for improving the sensitivity and specificity of radiography for clinical diagnosis.[1,2] However, some radiographs, such as digital mammographic images, contain large amounts of information. A state-of-the art film digitizer creates 4 K×5 K×12 bit (40 megabytes) digital images. The full field digital mammography systems being developed by both industrial and academic groups acquire digital mammograms in 3 K×4 K×12 bits (24 megabytes) or 4 K×6 K×12 bits (48 megabytes) format.[3–5] Commonly, digital computer manipulate image data in series, thus it is time consuming to apply rigorous computer image processing or computer-aided diagnosis (CAD) programs to these datasets, even in today's fast computers. Without dramatically increasing the speed, and reducing the cost, the current digital processing techniques can only be applied to selected cases at academic institutions. In order to allow both academic institutions and community hospitals to take the advantages of the image processing, and to apply CAD widely to screening mammograms, parallel image processing techniques, such as optical processing techniques, have to be investigated.

B. Advantages of optical processing

Optical processor offers distinct advantages over current digital electronic techniques, and it will impact radiological diagnosis significantly in the following aspects:

1. Speed

The power of optical processing lies in the ability to manipulate image data rapidly via parallel processing.[6] Using an optical technique, every pixel of a two-dimensional image can be both relayed and processed at the same time. The speed of the optical technique is at least a few hundreds times faster than that of electronic digital computers. This feature allows the application of rigorous image processing and computer-aided diagnosis to all screening procedures in radiology such as screening mammograms.

2. Compact size and low cost

The optical processors is, generally, assembled with inexpensive, commercially available optical components, such as lenses and mirrors. The optical processor can be assembled into a compact device, like a camcorder. Once assembled, little or no maintenance is needed. These low cost devices may significantly improve radiographic image quality and can be economically incorporated into existing and future (analog and digital) radiographic systems. These features would allow the application of rigorous image processing and computer-aided diagnosis, for instance, to all screening mammograms at both academic and community hospitals.

3. Analog processing

The analog nature of optical processors avoids some of the disadvantages of electronic processors. Electronic digitization of an analog image into a discrete pixel array degrades resolution and contrast. Further, digital detectors (and films) have a limited dynamic range, introducing noise into the image. Some optical technique processes the original image prior to digitization, rejecting spiky noise, greatly reducing the noise generated by scattered radiation, smoothing background noise, and enhancing the contrast of the region of interest. This creates a ''cleaner'' image and more fully utilizes the dynamic range and contrast resolution of digital detectors. These improvements in image acquisition and processing are expected to improve the accuracy of radiological diagnosis.

C. Modern optical processing techniques

Since VanderLugt first demonstrated the concept of optical matched filtering in 1964,[7] optical processing has been investigated for image analyses such as pattern recognition, edge and contrast enhancement, feature extraction, object replication, noise suppression, and optical subtraction and division.[8,9] Several practical filtering techniques have been developed: (1) the VanderLugt filter and processor;[10] (2) the joint transform correlator;[11] and (3) the wavelet analyzer.[12,13] The development of programmable spatial light modulators, and other optoelectronic devices has merged the flexibility of digital electronics with the speed and analog nature of optics.[14]

The theory and key components of optical processing have been applied successfully in many military and industry applications. These modern optical techniques, however, have not been utilized widely for medical imaging. The medical images, such as mammographic images, are different from industrial targets in their complexity, information composition, and in noise sources. For instance, some of the industrial optical correlators are designed to process binary-phase targets (images with only two gray scales).[14,15] In contrast, it is essential in medical imaging, such as in breast imaging, to maintain a large dynamic range (12 bits or larger). Therefore, the optical processing architectures for medical images have to be customarily developed to meet specific clinical requirements.

II. THEORY: OPTICAL PROCESSING USING FOURIER LENSES

Optical processing architecture uses a set of lenses, mirrors, polarizers, and other components to perform mathematical operations required by medical image processing and CAD. For instance, the complicated two-dimensional Fourier Transform can be performed simply by a positive lens.[8] The positive lens is a transparent optical component consisting of one or more pieces of optical glass (or other appropriate optical material) with surfaces so curved that they serve to converge the transmitted rays from an object. However, a simple spherical-curved positive lens may introduce transformation errors while the input field is wide due to the aberrations of the lens. In practice, the lenses used for optical Fourier transform are specially designed and manufactured with either nonspherical curvature or with multiple pieces of glass to correct an aberration.[16] Using these lenses, usually called a Fourier lens, the exact Fourier transform can be conducted for both wide and narrow input fields.

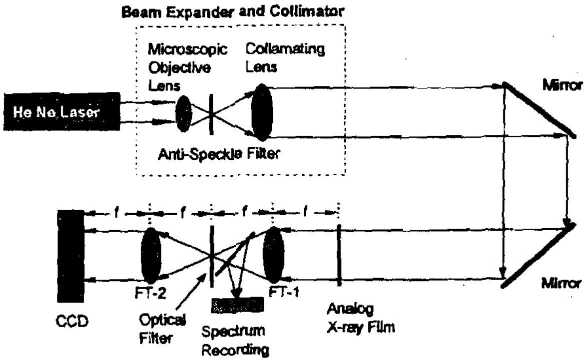


FIG. 1. An optical processing architecture for an analog radiograph.

III. METHOD: OPTICAL PROCESSOR ARCHITECTURES FOR MEDICAL IMAGES

A. Optical processing for analog radiograph

A prototype optical processor was assembled on an optical table for analog radiograph (Fig. 1). The architecture is called the ''4f'' system since the distance from the input radiograph to the output image is equal to four times the focal length of the Fourier lenses. There are two Fourier lenses in this system. A HeNe laser, a laser beam collimator/expander, and a polarizing beamsplitter, provide a high quality laser beam for generating the coherent optical image of the radiograph. A state-of-the-art CCD camera is mounted on the optical table to acquire the optically processed final radiograph.

The following describes how the system works.

(1) During experiments. The analog radiograph (film) is placed at the input image plane (refer to Fig. 1). The homogeneous laser beam illuminates the film and generates a coherent optical radiograph immediately behind the film.

(2) The first Fourier Lens (FT-1) transforms the coherent optical radiograph into a frequency spectrum. The exact spectrum is located at the focal plane (frequency domain) of the Fourier lenses, where the optical spectrum is multiplied with an optical filter. In experiments, optical filters such as simple bandpass filters, and more complicated wavelet filters, were used.

(3) The filtered optical spectrum is inversely Fourier transformed by the second Fourier Lens (FT-2) and the processed optical radiograph is then recorded by a CCD camera for display and image storage.

B. Optical processing for digital radiograph

Digital radiography is currently an active area of investigation. Using such digital techniques, x-ray images are acquired by electronic detectors in a digital format. Figure 2 shows an optical processing architecture for digitally acquired radiographic images. The technique combines the advantages of digital computer (programmability) and optical processing (high-speed/parallel image manipulation). The

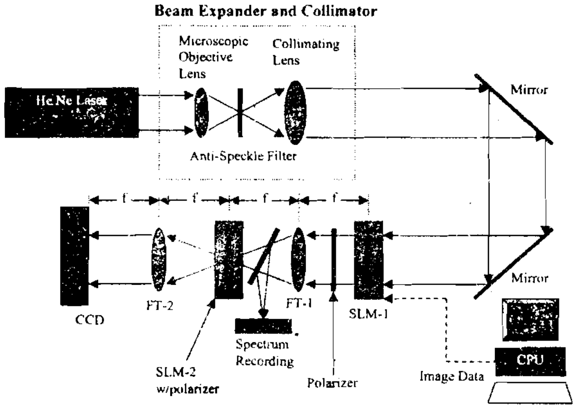


FIG. 2. An optical processing architecture for a digitally acquired radiograph.

prototype consists four subsystems: (1) an input digital–optical interface device for converting digital images into a coherent light image (coherent optical radiograph); (2) an optical image processor (designated as the "4f system" with two optical Fourier lenses); (3) an optical frequency filter; the filtering can be performed either by a pure optical filter or by a digitally addressed, programmable spatial light modulator; (4) an output digital–optical interface device for converting the processed coherent optical image into digital format.

The following describes how the system operates (refer to Fig. 2).

(1) The digitally acquired radiographic image is first transmitted to an electronically addressed spatial light modulator (SLM-1 in Fig. 2) through a PCI bus. Controlled by a pair of pixellated electrodes, the polarization nature of each "pixel" of the SLM is proportional to the "gray scale" of the corresponding pixel of the digital image.

(2) Simultaneously, an expanded, collimated and homogeneous laser beam (630 nm) illuminates the SLM-1. Each "pixel" of the SLM modulates the laser beam passing through it and, in association with the polarizer placed behind the SLM-1, the homogeneous laser beam is converted into a heterogeneous light distribution (coherent optical radiograph).

(3) The first Fourier Lens (FT-1) transforms the coherent optical radiograph into a frequency spectrum. The spectrum is then transmitting through a second electronically addressed Spatial Light Modulator (SLM-2), which is placed at the focal plane (frequency domain) of the Fourier lenses.

(4) Simultaneously, a digital image of an optical filter that was previously created using a digital computer is transmitted to the SLM-2, and it alters the polarization nature of the SLM-2. The light distribution right behind the SLM-2 is actually the multiplication of the optical filter and the spectrum.

(5) The resulting spectrum is inversely Fourier transformed by the second Fourier Lens (FT-2) and a CCD camera then records the reconstructed radiograph.

C. An integrated architecture for image acquisition and optical processing

Here we introduce a laboratory prototype for performing both x-ray image acquisition and optical processing with an integrated system.

As shown in Fig. 3, the prototype consists of three subsystems: (1) an x-ray image acquisition module that collects an x-ray mammogram and converts it into an incoherent light

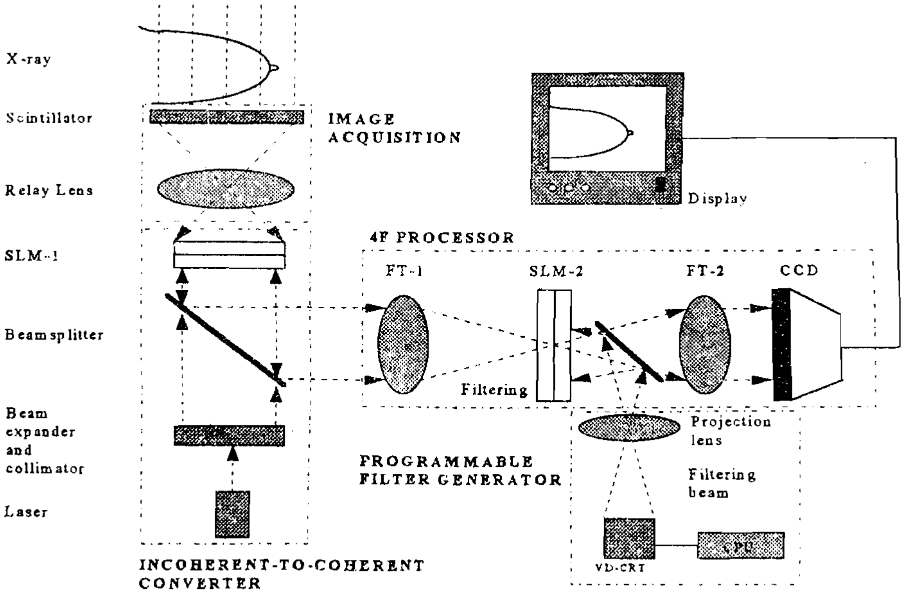


FIG. 3. An integrated optical architecture for x-ray image acqusition and optical processing.

image using a scintillator; (2) a spatial light modulator (SLM) and associated laser that converts the incoherent light image to a coherent light image (coherent optical mammogram); and (3) a coherent 4f optical processor. Using this optical system, the x-ray image acquisition and parallel optical image processing are performed as follows.

(1) During x-ray exposure, the x-ray beam passes through a phantom, is attenuated, interacts with the scintillator, and generates an incoherent light scene (incoherent optical mammogram). A large aperture relay lens then relays the incoherent optical mammogram onto the photosensitive surface (write side) of an optically addressed Spatial Light Modulator (SLM-1).

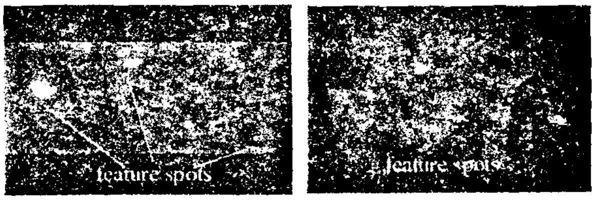
(2) Simultaneously, an expanded and collimated laser beam (630 nm) illuminates the SLM-1 and multiplies with the incoherent optical mammogram. The incoherent optical mammogram, in association with the SLM, modulates the homogeneous laser beam and converts it into a coherent optical mammogram.

(3) The first Fourier Lens (FT-1) transforms the coherent optical mammogram into a frequency spectrum. The spectrum is written onto the "write" side of a second Spatial Light Modulator (SLM-2), which is placed at the focal plane (frequency domain) of the Fourier lenses. Onto the other side of the SLM-2, an optical filter is projected. The optical pattern of the wavelet and other filters is created by a programmable optical filter generator.

(4) The multiplication of the optical filter and the Fourier spectrum of the coherent optical mammogram is obtained at SLM-2. The resulting optical spectrum is inversely Fourier transformed by the second Fourier Lens (FT-2) and the resultant mammogram is then recorded by a CCD camera for display and image storage.

IV. EXPERIMENTS WITH CLINICAL MAMMOGRAMS

The prototype optical processors were assembled on an optical table and initial experiments were conducted with clinical mammograms and other clinical images. For mammographic image processing, a circularly shaped wavelet filter for extracting breast microcalcifications was implemented.[17–19] The gray-scale pattern of the filter was lithographically composed on an optical substrate, and then placed at the spatial frequency domain (i.e., at the back focal plane of the first Fourier lens; refer to Fig. 1) of the 4f processor. During experiments, x-ray mammograms were input to the optical processor, and its Fourier spectrum multiplies with the circular wavelet filter. Figure 4(a) shows a region of interest (ROI) of a mammogram prior to optical processing. Figure 4(b) shows the optically processed image. The feature of interest, a cluster of microcalcifications, was enhanced and extracted from the background noise. Our preliminary results demonstrate the feasibility of using optical processors for feature extraction in radiographic image analysis. Many other image processing and image analysis algorithms can be implemented using the prototype optical processor as well.



X-ray Mammogram without optical processing
(a)

X-ray mammogram with optical processing
(b)

FIG. 4. (a) A portion of a mammogram prior to optical processing. (b) The optically processed mammogram.

V. DISCUSSION AND CONCLUSION

In image processing, the electronic digital computer offers advantages of programmability and flexibility; the optical processor offers high speed, analog nature, compact size, and cost effectiveness. The investigators of this project envision that some of the future image processing and CAD algorithms will first be developed and tested using electronic digital computers and then implemented optically for clinical utilization. With technical advances of digital–optical interface devices, the future image processor could be a hybrid device, namely, a programmable optical architecture.

Many of the image processing techniques have been approved effective in computer-aided diagnosis. The optical architectures for implementing each of these techniques would be different. However, they would contain the core modules being investigated in this preliminary investigation: coherent processor, incoherent-to-coherent converter, programmable optical filter. These are the "CPUs" of the optical processor. In the forthcoming research, the optical properties of each of these major components and their impact to the diagnostic quality of various clinical procedures will be experimentally investigated. The results of this and other ongoing investigations will provide initial building blocks for introducing modern optical processing technology to benefit medical diagnosis and many other clinical applications.

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