A 3-D X-Ray Microtomographic System With a CMOS Image Sensor

Seung Wook Lee, Ho Kyung Kim, Gyuseong Cho, Member, IEEE, Young Hoon Shin, and Ye Yeon Won

Abstract—High-resolution and three-dimensional X-ray imaging is becoming more and more popular. An X-ray microtomographic system with a CMOS image sensor has been developed. We have developed a novel area X-ray detector with a cost-effective CMOS image sensor. The sensing area of the detector is $55 \times 55$ mm$^2$ and the light from the phosphor screen is collected to the CMOS image sensor by a carefully designed optical system. Six lenses are assembled to reduce the radiation damage effect and increase the resolution and sensitivity. A microfocus X-ray tube that can reach up to 5 $\mu$m of focal spot size and microprecision motor system that can move in $x$–$y$–$z$ directions for both alignment and magnification and rotate the object have been adopted. A conventional three-dimensional cone-beam Feldkamp reconstruction algorithm was used and a human cancellous bone has been imaged with this system. Currently, the resolution of this system is about 40 $\mu$m but the application in microtomography seems very promising using this CMOS X-ray detector.

Index Terms—CMOS, cone-beam CT, micro-CT, microtomography, X-ray detector.

I. INTRODUCTION

X-ray microtomography can be considered as miniaturized medical computed tomography. It makes it possible to see the internal structure of small objects in a nondestructive way. The applications of X-ray microtomography are various from biomedical to industrial area.

The essential components for a microtomography system are a microfocus X-ray source, a precise object manipulator, and a high resolution X-ray detector. Synchrotron radiation is also a good source candidate because they generate highly intense and monochromatic X-rays [1]. But synchrotron facilities are not easy to access for most people. On the other hand, X-ray tube technology has been steadily improved and microfocus X-ray tubes that have accurate magnifying capability are now commercially available. Several microtomographic systems with this microfocus X-ray tube have been developed during the past few years [2]–[5]. X-ray detectors based on charge-coupled devices (CCDs) [2], [3], photodiode arrays [4], and image intensifiers [5] have been the detectors of choice for this microtomography application.

In this paper, we present a cone-beam-type X-ray microtomographic system with a CMOS image sensor. The performance of the CMOS image sensor is much improved and is now comparable to that of CCD [6], [7]. It has the advantages of low power consumption, on-chip integration capability, selective readout, and low cost. We have made a lens-coupled-type X-ray detector based on this CMOS technology and applied it into our X-ray microtomographic system. The description of our system and the result will be shown.

II. SYSTEM DESCRIPTION

A. System Overview

The measuring system is depicted in Fig. 1. A commercially available microfocus X-ray tube was used as an X-ray source and has the following specifications: high voltage 9–160 kV, target current 0–1 mA, focal spot adjustable $<5–1000$ $\mu$m. The X-ray source has the W target with a thin beryllium window [8].

The object can be translated in $x$–$y$–$z$ directions and rotated with high positional accuracy. Not only the rotative scanning but also other motions such as helical scanning are also possible with this manipulator. Small objects are mounted on the holder, which can be easily replaced depending on the object shape.

The scanner is mounted on an optical table for isolation of vibration and is installed in a well-shielded room. The control of the X-ray tube, object manipulation, data acquisition, and image processing are done in the control room. All the systems are controlled by a PC.
B. CMOS X-Ray Detector

We have developed the area X-ray detector module based on a CMOS image sensor. It is schematically shown in Fig. 2. A fine lanex screen with 4 lp/mm at 30% modulation transfer function (MTF) has been used as the phosphor screen and the sensing area is 55 x 55 mm². The optical system is specially designed and optimized that six lenses are assembled to reduce the radiation effect on the sensor and electronics and increase the resolution and light collection efficiency. The CMOS image sensor has 640 x 480 pixels, and each pixel size is 9 μm² [9]. A 10-bit analog-to-digital converter is integrated in the sensor and the data are transferred to a PC via a readout electronics and peripheral component interconnect interface, which is custom-designed. The resolution of this detector module is 2 lp/mm. The MTF of this detector is shown in Fig. 3.

We tested the X-ray magnification effect and 12 lp/mm could be seen with a standard test pattern (Nuclear Associates US model 07–550).

Another important feature of this detector is that we can expand the sensing area by modular-based mosaic architecture. We have made a digital radiographic detector by creating an 8 x 8 array of this detector module. The detailed characteristics of this detector and our mosaic DR system are described in [10].

C. Reconstruction and Image Processing

Volume data could be obtained by reconstruction of a stack of parallel slices from independent two-dimensional (2-D) measurements. However, this approach makes a poor utilization of the available photon flux. We have adopted a cone-beam acquisition method. It maintains a high signal-to-noise ratio, while it also scans the whole volume as fast as the scanning of one slice in the 2-D case.

The Feldkamp algorithm [11] has been implemented with a commercially available software [12]. Scanner motion, detector, and data acquisition are controlled through graphical user interface on a Windows-based PC.
Fig. 6. A slice image of the reconstructed 3-D volume.

(a)

(b)

Fig. 7. Rendered images of the trabecular network reconstructed. The size of this image is $100 \times 100 \times 100$ voxels. (a) Projection view and (b) shaded-surface view.

III. EXPERIMENTAL RESULT

One of the most important application areas of microtomography is osteoporosis research. The microtomographic system is an important tool to let researchers see the 3-D trabecular structure, which is the key to explain the strength of bone [13].

The image in Fig. 4 is a human bone sample taken from the iliac wing of a real hip bone. A projection image of this sample is shown in Fig. 5. For this scan, the X-ray tube was biased at 100 kV and the tube current was set to 0.4 mA. One hundred eighty projections were acquired at every $1^\circ$ to cover half of a rotation.

The exposure time for each projection was set to approximately 1 s. Fig. 6 is the reconstructed slice image of the bone. The cortical shells and the trabecular network between the shells can be seen. No postprocessing is applied in this image.

Fig. 7 shows the reconstructed 3-D images. We smoothed the 3-D voxel data and thresholded it to get the binary image, which discriminates bone and air. The binary image acquired has been rendered in two ways. Fig. 7(a) is the projection view and Fig. 7(b) is the shaded-surface view.

IV. DISCUSSION AND CONCLUSION

Application of the developed X-ray CMOS detector to microtomography was quite successful considering it was a color CMOS image sensor. The present X-ray detector was developed by using a color CMOS image sensor and VGA formatting of the signal from green pixels only. So the other signals from red and blue pixels were discarded. We are going to substitute this color CMOS image sensor with a monochrome image sensor. Then, we can enhance the resolution at least twice better than this. We expect that the CMOS image sensor will continue to progress and we can make a cost-effective microtomographic system.

REFERENCES

[12] Interactive Data Language 5.1, Research Systems, Boulder, CO.