A CCD Based X-Ray Imaging System for Industrial Applications

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Abstract

The presented x-ray imaging system is based on a typical industrial grade charge-coupled device (CCD) which is coupled to a phosphor screen and operated at room-temperature. Image acquisition and data analysis is performed using a commercial 8-bit frame grabber and a personal computer. The setup, noise reduction, and the response of fluorescent converters were evaluated with an x-ray tube. Measurements indicate that the system can achieve a spatial resolution of 16 line pairs per mm and a contrast of sensing a piece of 0.1 mm thick plastic sheet. Demonstrations have shown that the system can detect the fluid level in opaque plastic bottles, flaws in mechanical parts, wiring diagram in electrical parts, and to the extreme, 30 μm gold wires in plastic capped integrated circuit chips.

I. INTRODUCTION

The present work is motivated by the popularity of charge-coupled device (CCD) based video cameras.[1] For crystallography, the large area low-temperature operated CCD sensors are superior to conventional x-ray detectors in linearity and resolution.[2-4] For industrial x-ray imaging applications where the dynamic range of x-ray intensities is not as demanding, the CCD camera operated at room temperature appears to be attractive. In comparison with microchannel plates, position sensitive photomultiplier tubes, vidicon, and the labor-intensive x-ray film approach, the CCD camera is low cost, low voltage operation, and low power consumption. Additionally, the video output signal form of a commercial CCD camera is standardized and can be easily interfaced with a personal computer using popular image frame grabbers; thus, one can have a real-time digital image data acquisition and processing system with a modest budget.

The purpose of the study is to set up a room temperature operated CCD x-ray imaging system and to evaluate its feasibility for industrial product examinations. Sections II of the paper describes the main features of the hardware and image processing algorithms. To have an adequate picture size, we have to use optical lenses and a phosphor screen to convert x-ray into visible light. The characteristics of the front-end converter would affect the image quality significantly. We thus tested several commercial products; section III presents the effect of converters on light output and spatial resolution. For demonstration, we have examined plastic and metal objects and wiring diagram inside electrical components; section IV presents the digital images and their implications.

II. SYSTEM DESCRIPTION

The CCD black/white camera is a typical industrial grade product [5]; the sensor has a dimension of 6.4 mm x 4.8 mm containing 600 x 500 picture cells and a nominal on-surface light sensitivity of 0.005 lux. The camera has an NTSC-standard composite video output and is interfaced with a personal computer through a commercial 8-bit 512 x 484 frame grabber for image collection and processing. The transmitted x-ray image is detected indirectly by converting into visible light through a phosphor screen and optical lenses. Several phosphor screen products were tested and reported in section III.

The phosphor screen, lenses, and the CCD camera are mounted together through pipes with an adjustable length for adequate focusing and viewing size. The converter-camera assembly is installed inside an aluminum box with a plastic lining to reduce background x-ray/light interference. The x-ray source used for performance evaluation is a tungsten-target x-ray tube. The machine has a maximum output power of 400 kV x 30 mA and is equipped with a 42 cm long collimator with an aperture set at 0.6 mm. During testing, the examined object is brought close to the x-ray converter with a distance of 20 cm to the collimator outlet. The picture sizes on the object is adjustable from 1 cm x 1 cm to 20 cm x 15 cm. Arrangement of the hardware is sketched in Fig. 1.

The CCD is a silicon-base material and is subject to thermal noise background. During set up, we also noticed spot noise attributed from the scattered x-rays. For the real-time digital imaging system, it is easier and more flexible to use software means to process the image. Measurements indicated that the fluctuation of thermal noise background level followed the Poisson statistics; we thus chose the simple frame averaging approach for thermal noise reduction. Averaging five picture frames reduced the background fluctuation by approximately half and was found adequate in considering performance and processing time. The scattered spot noise gives scattered bright spots; the most efficient way is to use a median filter. We applied a nine-point median filter; if the brightness of the center pixel of a 3 x 3 square array exceeds the average level by an unreasonable large amount - e.g., 5 times higher, the datum of the spot is replaced by the average level of the rest eight pixels. Using the stated image processing algorithms, one can have a processed image in 100 ms running with a 33 MHz 32-bit microprocessor.

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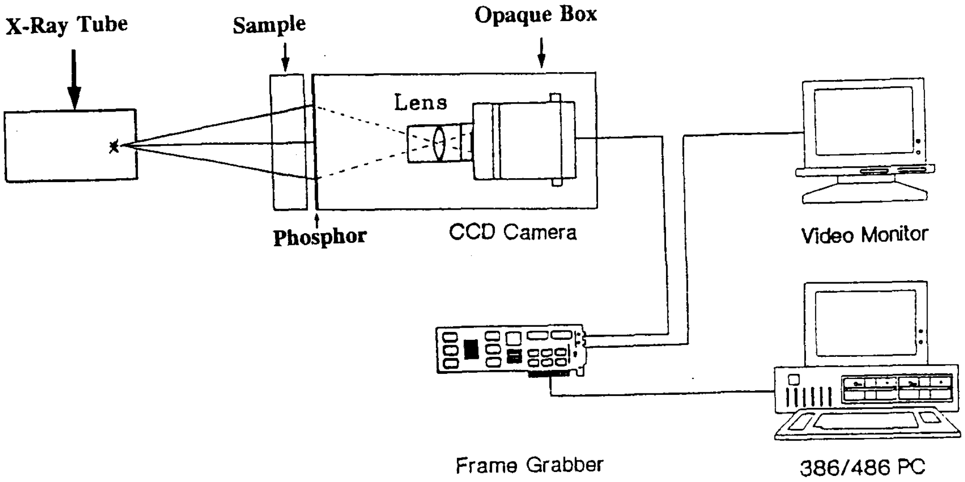

Fig. 1 Sketch of the system hardware arrangement

III. Experiments

The CCD sensor detects x-ray indirectly through a phosphor screen. The performance of the conversion would affect the overall system response significantly. As listed in table I, we have acquired several commercial products, among them two CsI crystals [6] and KYOKKO [7], CAWO [8], Kodak [9], and OKAMOTO [10] products; only the KYOKKO (named type A) has a known composition of ZnCdS/Ag. Experiments were performed with a nominal x-ray tube current of 10 mA and a tube voltage of 150 kV. The camera lens had an f number of 5.6 and the picturing area on the object was 3 cm square. Figure 2 shows the light output versus the x-ray tube current of the converters. As indicated, the response curve of all samples is nearly linear in the tested range. The type A has the largest slope while the Kodak Min-R fast front screen, named type K, has the smallest one; the difference is about one order of magnitude.

The other tested parameter is spatial resolution which is measured by directly examining a calibrated lead line pattern which has a maximum 20 line paris per mm (LP/mm). Results in terms of LP/mm are listed in Table I; the CsI samples have a poor resolution attributed to a non-uniform surface condition and are omitted in the list. As shown, the best resolution can be achieved is up to the test pattern limit 20 LP/mm. Combining the results of spatial resolution with the light output measurement, we notice that the screen giving a lower light output has a better spatial resolution. The reason is thought to be that the screen having a higher light output is thicker and has a larger grain size; this may leads to a poor resolution. Compromising the light output with the resolution, we chose the group of type C, D, and E screens for the current design.

For demonstration, we examined plastic and metal samples using the type C converter, CAWO ORTHO intensify screen. First, we perform mass attenuation coefficient measurements by examining a calibration set of plastic, Al, and Cu plates.

Table I
Tested phosphor screens and measured spatial resolution

Type	Product	Resolution(LP/mm)
A	KYOKKO F-4 fluorescent screen	2
B	CAWO-62 fluorescent screen	5
C	CAWO ORTHO intensify screen	9
D	Kodak Lanex regular screen	9
E	OKAMOTO LUS intensify screen	14
F	Bicron 3mm thick CsI(Tl)	–
G	Kodak Min-R intensify screen	16
H	Kodak Lanex fine screen	16
I	Bicron 5mm thick CsI(Tl)	–
J	Kodak Min-R medium screen	16
K	Kodak Min-R fast front screen	20
L	Kodak Min-R fast back screen	16
M	Kodak Lanex fast front screen	12
N	Kodak lanex fast back screen	7

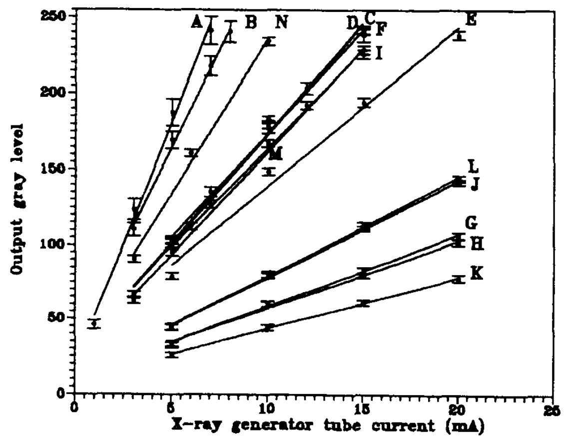

Fig.2 Light output of phosphor screens

Figure 3 shows the results obtained using a nominal x-ray tube voltage of 200 kV and a tube current of 10 mA. The smooth line is a least square fit with the slope representing the mass attenuation coefficients of 0.15, 0.23, and 0.65 cm^2/g for plastic (density 1.15 g/cm^3), Al, and Cu respectively. The maximum penetration depth is the abscissa of the last datum, which corresponds approximately to 15, 5, and 1 cm for plastic, Al, and Cu respectively and are limited by the thermal noise background. The error bar associated with the data points in Fig. 3 represents the one standard deviation (1 σ) of the gray level distribution and the amount of 2 σ is considered as the detection sensitivity which are approximately five gray levels for all three materials. A test also indicates that the system is capable of sensing a piece of 3M scotch tape about 0.1 mm thick.

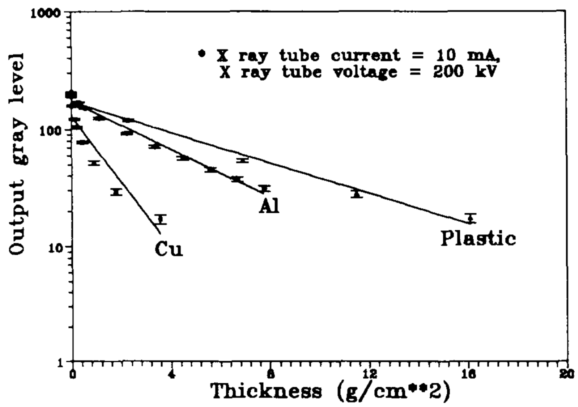

Fig.3 Mass attenuation measurement

IV. IMAGE DEMONSTRATION

Adjusting the x-ray tube voltage according to the tested materials, we have examined plastic bottles, metal objects, electrical parts, and integrated circuit (IC) boards and chips. Digitized images shown are printed by a 256 gray level printer Acer Laser 3G model. Figure 4 is to detect the fluid level in a white-out plastic bottle; one can also clearly identify the two hiding balls. Figure 5 is to examine the defects inside a copper medal. From the signal trace of a scanned line, one can identify the three bubbles according to the variation of the signal amplitude. The example illustrates the advantage of a digital imaging system; one can setup the system for on-line process monitoring using a image processing software for fault detection. Figures 6 and 7 demonstrate the system is capable to show the wiring of transistor, capacitor, potentiometer, and multi-layer circuit boards. Figure 8 shows the pictures of a plastic capped IC chip. The 30 μm gold wires can be detected in a closeup view using an f number of 1.3 lens. Figure 9a shows the image of a plastic integrated circuit (IC) card. There are also thin connecting wires but is difficult to detect. We enhanced the image by the histogram modification technique[11] to reveal the wires as shown in Fig. 9b. The example further suggests the capability of the system.

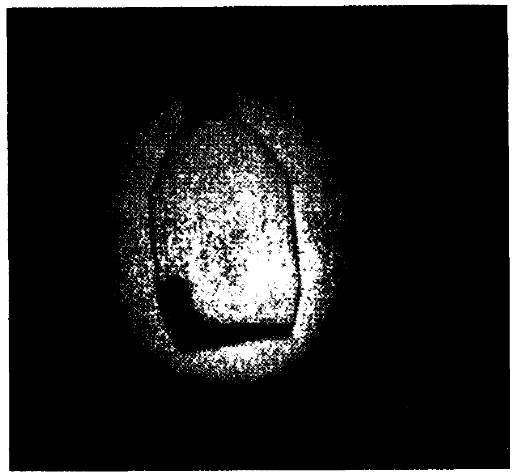

Fig.4 Image of a white-out plastic bottle to show the contained fluid level and the two balls.

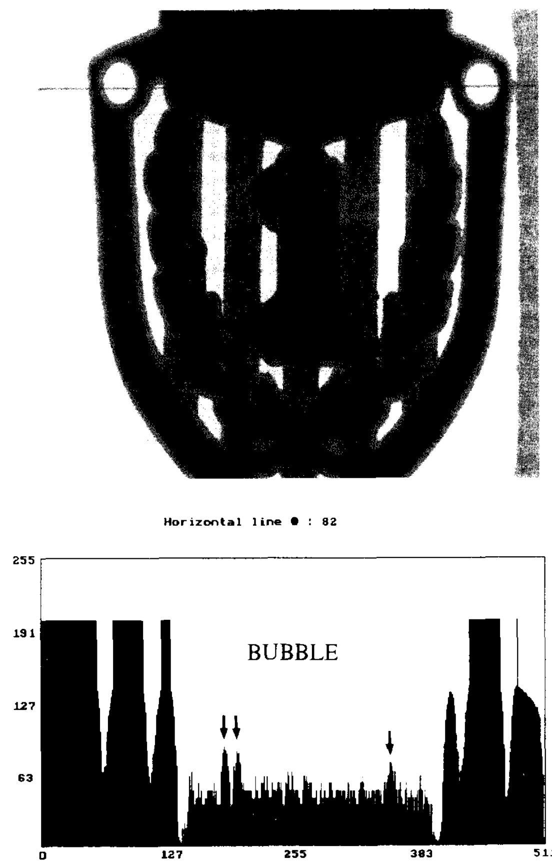

Fig.5 Image of a copper made medal to show the hiding bubbles; the gray level trace along a scanned line is to indicate the locations of the defects.

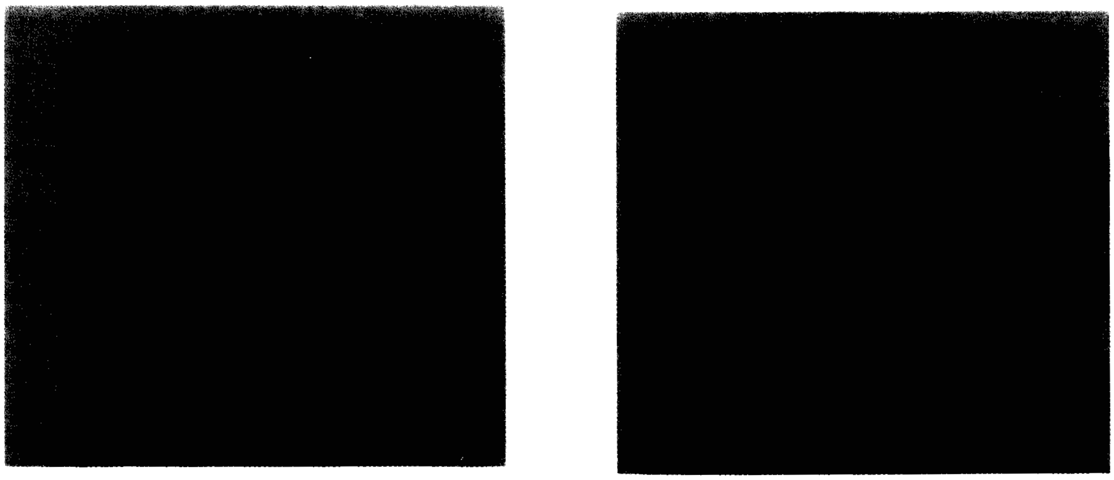

Fig.6 Images of a transistor, a capacitor and a potentiometer

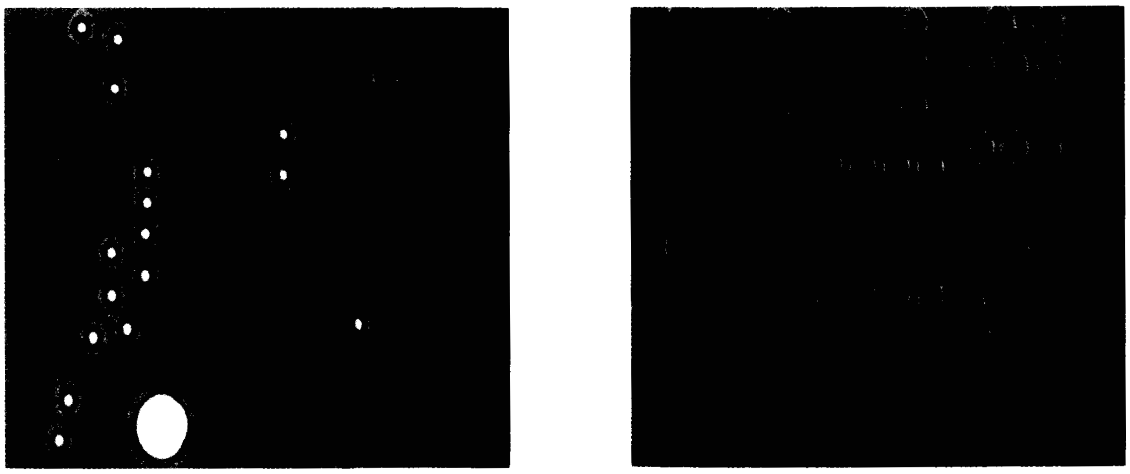

Fig.7 Images of multi-layer circuit board to show wiring diagram

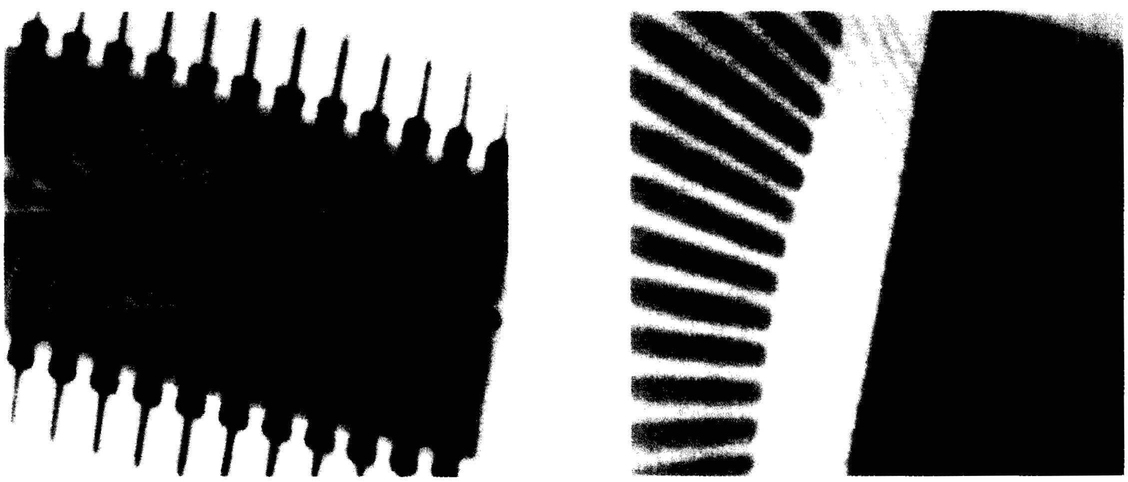

Fig.8 Images of an IC chip; the close-up view is to show the 30 μm fine gold wires

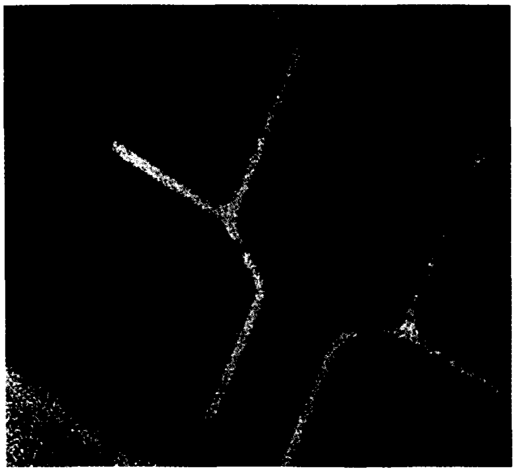

Fig.9a Image of a plastic IC card

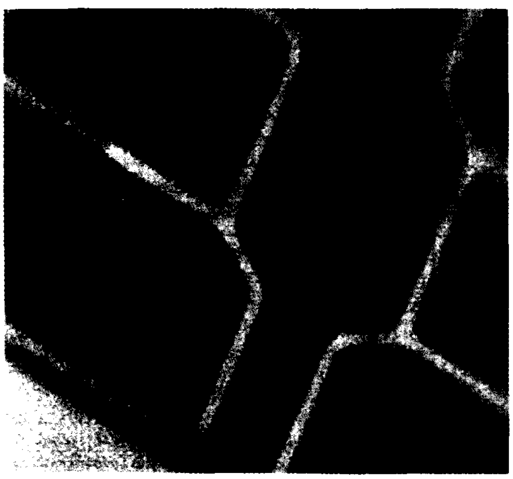

Fig.9b Using image enhancement technique to reveal the fine connecting wires

V. CONCLUSION

We present a room-temperature operated x-ray imaging system which takes an industrial-grade CCD camera in working with a phosphor screen and optical lenses. The standard video output format allows the camera system to interface easily with a microcomputer using a commercial frame grabbers, thus provides the system a real-time digital imaging capability. Imaging demonstrations of examined plastic and metal parts as well as electrical components indicate that the system is capable for industrial product examinations. Although we have not applied the system for medical purpose, evaluation of the detection efficiency, spatial resolution, and contrast indicates the present system is a promising alternative to the conventional x-ray films and expensive x-ray imaging devices. The digital image processing capability and the image quality also suggest that the present system has a potential to serve as an on-line quality control device to perform x-ray examinations of products in an industrial manufacturing process.

VI. REFERENCES

[1] S.M. Gruner, "CCD and Vidicon X-Ray Detectors: Theory and Practice (Invited)," *Rev. Sci. Instrum.*, vol.60, pp.1545-1551, 1989.

[2] M.G. Strauss, I. Naday, I.S. Sherman, M.R. Kraimer, E.M. Westbrook, and N.J. Zaluzec, "CCD Sensors in Synchrotron X-Ray Detectors," *Nucl. Instr. Meth.*, vol.A266, pp.563-577, 1988.

[3] R. Clarke, "Use of CCD Detectors for Spectroscopy and Scattering Experiments," *Nucl. Instr. Meth.*, vol.A291, pp.117-122, 1990.

[4] E.F. Eikenberry, M.W. Tate, A. L. Belmonte, J.L. Lowrance, D. Bilderback, and S.M. Gruner, "A Direct-Coupled Detector for Synchrotron X-Radiation Using a Large Format CCD," *IEEE Trans. Nucl. Sci.*, vol. 38(2), pp.110-118, 1991.

[5] Model CCD-9-12E, BISCHKE GmbH, Germany.

[6] Bicron Corp., Newburry, OH 44065-9677, USA.

[7] KASEI OPTONIX, Ltd., Minato-Ku 105, Japan.

[8] CAWO Photochemische Fabrik GmbH, 8898 Schrobenhausen, Germany.

[9] Eastman Kodak Company, Rochester, N.Y. 14650,USA.

[10] Okamoto Manufacturing Co., Ltd., Japan.

[11] R.C. Gonzalez and P. Wintz, *Digital Image Processing*, Addison-Wesley, 1977, pp.115-136.