Obtaining low energy γ dose with CMOS sensors (Postprint)

Authors: WANG Fang, WANG Ming-Yuan, LIU Yu-Fang, MA Chun-Wang, CHANG Le

Date: 2023-06-18T00:00:00+00:00

Abstract

A method is established for measuring low-energy γ-ray dose using CMOS sensors without any X-/γ-ray converters. Gamma-ray sources of 241Am and 152Eu are used to test the system. Based on gray value, an analysis method is proposed to obtain the γ-ray dose. Cumulative dose is determined by correlating the gray value to the dose readings of standard dosimeters. The relationship between gray value and the cumulative dose of γ-rays is trained using a back-propagation neural network with the BFGS algorithm. After comparison, it shows that BFGS algorithm training is suitable for different γ-ray sources under higher error conditions. These indicate the feasibility of measuring low-energy γ-ray dose using common CMOS image sensors.

Full Text

Preamble

Obtaining Low Energy γ Dose with CMOS Sensors

WANG Fang (王芳),[1] WANG Ming-Yuan (王明远),[1],[2] LIU Yu-Fang (刘玉芳),[1],[†]
MA Chun-Wang (马春旺),[1] and CHANG Le (常乐)[1]
[1]College of Physics and Electrical Engineering, Henan Normal University, Xinxiang 453007, China
[2]Department of Information Science and Engineering, Wanfang College of Science and Technology HPU, Zhengzhou 451400, China
(Received April 10, 2014; accepted in revised form May 15, 2014; published online December 9, 2014)

A method is established for measuring low-energy γ-ray dose using CMOS sensors without any X-/γ-ray converters. Gamma-ray sources of ^{241}Am and ^{152}Eu are used to test the system. Based on gray value analysis, a method is proposed to obtain the γ-ray dose. Cumulative dose is determined by correlating the gray value to the dose readings of standard dosimeters. The relationship between gray value and the cumulative dose of γ-rays is trained using a back propagation neural network with the BFGS algorithm. After comparison, it shows that BFGS algorithm training is suitable for different γ-ray sources under higher error conditions. These results indicate the feasibility of measuring low-energy γ-ray dose using common CMOS image sensors.

Keywords: CMOS image sensor, Low energy γ-ray detection, Image processing, BP neural network, BFGS algorithm
DOI: 10.13538/j.1001-8042/nst.25.060401

Introduction

CMOS (complementary metal oxide semiconductor) image sensors offer advantages in low power consumption, low cost, and good radiation resistance [**?**, **?**, **?**]. In recent years, CMOS image sensors have been widely used in detecting X- and γ-rays. Using scintillating materials as converters for X-ray to visible light photons, CMOS image sensors are employed in X-ray imaging detectors for medical imaging applications [**?**]. However, the use of converters narrows the dynamic range [**?**]. CMOS sensors are also used in γ-ray detection and classification [**?**].

In this paper, we explore the possibility of measuring low-energy γ-ray dose using CMOS sensors without any converters. Results of dosimetry measurements using ^{241}Am and ^{152}Eu γ-ray sources are presented and discussed. The article is organized as follows: fundamentals of low-energy γ-ray detection using CMOS are described in Sec. II. In Sec. III, the gray value analysis method is introduced to fit the correlation between the energy of γ-rays and the cumulative gray value, and a network model based on back propagation (BP) neural network and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is adopted to reduce detection error and improve convergence speed. A summary is presented in Section IV.

II. Methods

[Figure 1: see original paper] shows a schematic diagram of the system. The key component used in this experiment is the UPA1021 CMOS digital image sensor produced by Philips. The CMOS image sensor is composed of an image array of 307,200 (640 × 480) pixels, plus an on-pixel amplifier, timing and control circuits, dual 8-bit A/D and video port, and signal processing unit [**?**]. The pixel size of the sensor is 2.2 µm × 2.2 µm, and the optical size is 1/10 inches. The sensors are kept in a black environment to reduce interference from visible light during measurements. Additionally, the CMOS image sensor is covered by aluminum foil to prevent α particles from reaching the sensor [**?**, **?**].

The CMOS pixel unit is composed of a photodiode, an electrical signal conversion unit, signal transmission transistors, and a signal amplifier [**?**]. X- or γ-ray photons produce a photoelectric effect inside the photodiode. The photocurrent is proportional to the luminance component of the CMOS. The digital signal processor (DSP) produces the driving signal for the CMOS and controls its working conditions. It also transforms the received signals into 2D images, calculates the cumulative dose of γ-rays, and sends the image and cumulative doses to the display screen. The SDRAM improves the image processing speed.

A. Gray Value Analysis

Gray value analysis is applied to analyze the results in this work. Gray value represents the brightness of an image or the degree of color shades. Generally, the gray value of a pixel is acquired before complex image processing. Gray value analysis is widely used in satellite images, aerial photographs, geophysical observations, etc. [?]. If the color values of a certain pixel in an original image are (Red, Green, Blue), the gray value is calculated by [?]:

$$h = 0.299\text{Red} + 0.587\text{Green} + 0.114\text{Blue}$$

One γ photon usually hits several adjacent pixels at the instant of imaging. Additionally, crosstalk in CMOS image sensors always occurs in adjacent pixels because of their proximity [?]. Therefore, the cumulative gray value of CMOS pixels irradiated by photons can be used to detect γ-rays. The gray value of one pixel is denoted as $h(x, y)$, where (x, y) represents the coordinates of pixels around the brightest one in the light spot. The cumulative gray value can be calculated by:

$$H = \sum h(x, y)$$

B. Dose Measurement

The γ photon response on the CMOS image sensor can be denoted by cumulating the gray values of all pixels. A standard dosimeter is used to record the radiation dose. The gray values obtained by the CMOS sensor and the standard doses are used to deduce the correlation. The dose on the dosimeter is recorded every three minutes, while the video of γ-rays on the CMOS sensor is recorded continuously. Each frame of images is analyzed because the cumulative doses are represented by the cumulative gray value of each γ photon.

The largest gray value of each frame is compared with the background. If the largest gray value exceeds the background, the frame is abandoned. Otherwise, the pixels with the largest gray value are selected and the gray values of pixels around the largest one are accumulated. These procedures are repeated with other images, and the cumulative dose of ^{241}Am is denoted by the accumulated gray value of all the images, which is called H'.

III. BFGS Algorithm

BP (back propagation) neural network is a multilayer feed-forward network based on the error BP algorithm and is used to approximate any continuous function with arbitrary precision. Theoretically, a neural network with combinations of different training functions, nodes, and layer numbers can fit any input-output nonlinear functions [?]. Many improved learning algorithms have been proposed based on the classical BP algorithm. In numerical optimization, BFGS is an iterative method to solve unconstrained nonlinear optimization problems [?, ?]. As an improvement of Newton' s method, it performs well even for non-smooth optimizations. In the MATLAB optimization toolbox, the BFGS algorithm is implemented by `trainbfg` [?].

IV. Experiments

A. Gray Level Response of ^{241}Am

The CMOS image sensors were irradiated by a ^{241}Am source (1.26×10^5 Bq, 4.0534×10^4 γ/s) at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. In its α decay, the ^{241}Am nuclide emits 59.5 keV and 26 keV γ-rays. The CMOS chip was covered by aluminum foil to prevent α particles.

First, the system was set in a radiation-free environment to test the background before the experiment. The results show the background gray value is 22. Next, the ^{241}Am source was placed 30 cm from the CMOS image sensor, and the γ-rays were recorded at a rate of 30 fps. A typical image is shown in [Figure 2: see original paper], where pixel units not exposed by γ-rays remain black. The gray values of the lighted units were calculated using MATLAB and plotted in the figure. The light spot is composed of units with different gray values, some of which are lower than the background due to crosstalk in adjacent pixels.

B. Matrix Size Optimization

It was found that the cumulative gray values (H') change with the sizes of the pixel matrix. To determine a proper matrix size, 13 × 13, 11 × 11, and 9 × 9 matrices were compared. A two-tier BP neural network (5 nodes in the input layer, 1 node in the output layer with expected error 10^{-5}) was created. The accumulated gray values (H') were used as inputs, and the dose values recorded on the standard dosimeter were used as outputs. Thirty-two sets of sampling data were used to train the network using the BFGS algorithm.

The correlation between the accumulated gray values (H') and the cumulative dose for the ^{241}Am source is plotted in Figure 3: see original paper. The cumulative dose and accumulated gray value show good correlation for all three matrices. The H' value is larger with a larger matrix under the same cumulative dose.

The best method with the proper matrix is selected by global consistency comparison. Data not used for training are often used as testing data to estimate global consistency, which is characterized by the dose error. Six sets of testing data were taken as inputs of the trained network, and the corresponding cumulative dose was the actual output. The actual dose (a) was acquired by the network, and the expected dose (e) was measured by the standard dosimeter. Relative error of the dose (Δ) is calculated by:

$$\Delta = \frac{(a-e)}{e} \times 100\%$$

The dose errors using the three matrices are shown in Figure 3: see original paper. The dose error of the 9 × 9 matrix is the highest of all matrices, and the error of the 13 × 13 matrix is the lowest. Therefore, the 13 × 13 matrix pixels show better global convergence and are chosen for the following analysis within the precision allowed.

C. Comparison Between Different Sources

^{152}Eu (9.97 kBq) is an important radionuclide for energy and efficiency calibration of γ spectrometers [**?**]. ^{152}Eu has a complex decay scheme, with 27.9% by β^- emission and 72.1% by electron capture. It emits over 140 γ-rays ranging from 122 keV to 1408 keV. For comparison, ^{152}Eu γ-rays were measured, with aluminum foil used to block β particles.

The same method was used to obtain the cumulative dose of ^{152}Eu. The 13 × 13 matrix pixels were used for statistics. Testing dose errors of the networks trained by data from the ^{152}Eu and ^{241}Am sources are plotted in [Figure 4: see original paper].

It can be seen from [Figure 4: see original paper] that the correlation between H' and the cumulative dose trained for the ^{241}Am source by the BP network is also suitable for the ^{152}Eu source, and ^{241}Am has a lower testing dose error. The BFGS algorithm is employed to compensate for energy loss and reduce measurement error in this experiment. Additionally, the number of sampling points and the corresponding H' increase with the dose, which can offset some errors from energy loss. Therefore, the error decreases as the accumulated gray value increases.

From [Figure 4: see original paper], the testing dose error of ^{241}Am differs from ^{152}Eu due to the different responses in CMOS pixels. In this work, the cumulative dose is measured with the known source type.

D. Radiation Damage Analysis

The performance of CMOS (especially dark current) is always characterized by the gray value of dark images [**?**]. Radiation damage is analyzed by comparing the gray value of images acquired before and after irradiation. Images were collected every three minutes. The largest gray value of each image was extracted from pre-test and post-test measurements, and both results were 22. After two days of irradiation by ^{241}Am and ^{152}Eu, only one dead pixel was found on the CMOS image sensor. The gray value of the dead pixel is less than 40. Experimental results showed that dead pixels did not influence the dose error. Therefore, exposure to small doses of radiation over short periods does not damage the CMOS or its functionality.

V. Summary

In summary, a method is proposed to obtain the cumulative dose of ^{241}Am and ^{152}Eu using common CMOS sensors without any converters, while the type of γ source is distinguished. Gray value analysis of the recorded images is adopted as image preprocessing. The BP neural network and BFGS algorithm are used to train the network and fit the correlation between cumulative gray value and cumulative dose. Experimental results show that the γ dose is calibrated using this method. The error for ^{152}Eu is lower than for ^{241}Am in the experiments. The simulation results show that cumulative dose detection for low-energy γ-rays (^{241}Am and ^{152}Eu) is completed successfully. The irradiation experiments show that radiation damage is minimal and can be ignored. Based on the experimental results, it is proposed that general CMOS image sensors can be used to measure the cumulative dose of low-energy γ rays when the source type is known.

Acknowledgements

The authors are grateful to Prof. Ma Yu-Gang at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, for arranging the ^{241}Am and ^{152}Eu experiments. We also thank Prof. Wang Hong-Wei and his colleagues for their kind help in the experiments.

References

[?] Konstantinidis A C, Szafraniec M B, Speller R D, et al. Nucl Instrum Meth A, 2012, 689: 12–21.
[?] Lu B, Cui W W, Wang Y S, et al. Chin Phys C, 2012, 36: 846–850.
[?] Gamal E A and Eltoukhy H. IEEE Circuit Devic, 2005, 21: 6–20.
[?] Cha B K, Kim C R, Jeon S, et al. Nucl Instrum Meth A, 2013, 731: 315–319.
[?] Dai R. Info Electro Eng, 2007, 5: 462–465. (in Chinese)
[?] Cogliati J J, Derr K W, Wharton J. arXiv: 1401.0766.
[?] Meng X T, Huang Q, Ma Y X, et al. Chin Phys C, 2008, 32: 794–797.
[?] Paris R, Thurner T, Berndorfer T, et al. e & i Elektrotechnik und Informationstechnik, 2012, 129: 34–41.
[?] Wang F, Wang M Y, Ma C W, et al. J Henan Norm Univers (Nat Sci Ed), 2013, 41: 39–41. (in Chinese)

[?] Konstantinidis A C, Szafraniec M B, Speller R D, et al. Nucl Instrum Meth A, 2012, 689: 12-21.
[?] Kang W X, Li H S, Deng F Q. Sci China, 2010, 53: 2062-2073.
[?] Russ J C. The Image Processing Handbook. Florida (USA): CRC Press Inc., 2010.
[?] Sue L and Huang Q Y. Trans Microsys Technol, 2008, 27: 65-68. (in Chinese)
[?] Chen H, Nian X, Jin F. Comput Appl, 2006, 26: 1106-1108.
[?] Bonnans J F, Gilbert J C, Lemaréchal C, et al. Numerical Optimization: Theoretical and Practical Aspects. Berlin (GER): Springer, 2006, 490.
[?] Lu K Z, Wang R C, Zhang J S. Appl Res Comput, 2007, 24: 17-19. (in Chinese)
[?] Sivanandam S N and Deepa S N. Introduction to Neural Networks Using Matlab 6.0. New Delhi (IN): Tata McGraw-Hill Education, 2006.
[?] Yang L Y, Wang J Q, Yao S H, et al. Atom Energ Sci Technol, 2008, 42: 296-299. (in Chinese)
[?] Han Z S, Zhao Y F. Introduction to Radiation Hardened Integrated Circuit. Beijing (CHN): Tsinghua University Press, 2011, 45-46. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.