Design of a dual CCD configuration to improve the signal-to-noise ratio

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The noise of a digital charge coupled device (CCD) detector increases with the readout speed, causing problems in a number of important applications, such as x-ray fluoroscopy and micro-CT. In this paper, we present an approach for the design of a dual-CCD configuration to improve the average signal-to-noise ratio, and hence provide an inexpensive solution within the constraint of the current technology. © 2000 American Association of Physicists in Medicine.

Key words: medical imaging, data acquisition, digital CCD detector arrays, signal-to-noise ratio (SNR)

I. INTRODUCTION

Digital charge coupled device (CCD)-based image acquisition is widely used in medical imaging systems.1–3 A large dynamic range and a high signal-to-noise ratio (SNR) are highly desirable with the medical imaging systems to provide adequate contrast resolution for diagnosis and intervention. The dynamic range of a CCD array is determined by the full-well capacity and the detector noise.3–5 For example, a state-of-the-art CCD camera may have a full-well capacity of 450 000 electrons in slow scan mode and a noise level of 10–20 electrons, which leads to a 14 bit digitization.4

The noise of a CCD detector increases with the readout speed. Therefore, the dynamic range of a fast readout CCD is significantly narrower, compromising the associated SNR. For example, the state-of-the-art CCD only permits a 10 to 12 bit digitization at 30 frames of 1k by 1k pixels/s. Such a dynamic range is not sufficient in a number of important imaging applications, such as optical imaging, x-ray fluoroscopy, and micro-CT.5–10 In this paper, we present an approach for the design of a dual-CCD configuration to address this problem.

II. DUAL-CCD CONFIGURATION

As shown in Fig. 1, with a dual-CCD configuration an incoming optical beam is divided into two components by an optical splitter. A larger percentage \( r_1 \) of the beam is routed to the first CCD detector array CCD-1, while a small percentage \( r_2 = 1 - r_1 \) of the beam is routed to the second array CCD-2. Both of the CCD arrays detect photons and convert them into electronic charges. These charges are accumulated within CCD cells and digitized into discrete levels through AD conversion.

Mathematically, the CCD output \( y \) is linearly proportional to the optical exposure \( x \) according to

\[
y = kx + c\xi,
\]

where \( k = S/F \), \( S \) denotes the dynamic range, \( F \) the full-well capability, \( \xi \) the detector noise with a standard deviation \( \sigma \), and \( c \) the conversion factor.

For the dual-CCD configuration, we have the formulas in the same form but with different coefficients:

\[
y_1 = k_1 x_1 + c_1\xi_1, \quad y_2 = k_2 x_2 + c_2\xi_2,
\]

where

\[
k_1 = \frac{S_1}{F_1}, \quad k_2 = \frac{S_2}{F_2},
\]

\[
x_1 = r_1 x = \frac{F_1}{F_1 + F_2} x, \quad x_2 = r_2 x = \frac{F_2}{F_1 + F_2} x,
\]

and CCD-1 and CCD-2 have the noise deviations \( \sigma_1 \) and \( \sigma_2 \), \( x \) the intensity of the primary beam, and the dynamic ranges \( S_1 \) and \( S_2 \) are determined by the full-well capabilities \( F_1 \) and \( F_2 \) as well as noise deviations \( \sigma_1 \) and \( \sigma_2 \) of CCD-1 and CCD-2 as follows:

\[
S_1 = \frac{F_1}{\sigma_1}, \quad S_2 = \frac{F_2}{\sigma_2},
\]

As a result, we have

\[
y_1 = K_1 x + c_1\xi_1, \quad y_2 = K_2 x + c_2\xi_2,
\]

where

\[
K_1 = \frac{F_1}{(F_1 + F_2)\sigma_1}, \quad K_2 = \frac{F_2}{(F_1 + F_2)\sigma_2}.
\]

III. SNR ANALYSIS

Because both the CCD arrays record the same input signal, their readings should be combined to better measure the original signal. Specifically, we have two calibrated individual measures,

\[
s_1 = \frac{y_1}{K_1} = x + \frac{c_1\xi_1}{K_1}, \quad s_2 = \frac{y_2}{K_2} = x + \frac{c_2\xi_2}{K_2},
\]
Consequently, the noise deviation \( t \) estimate more reliable than either \( s \) be expressed as

\[
\hat{t} = \frac{c_1 \sigma_1}{K_1}, \quad \tau_2 = \frac{c_2 \sigma_2}{K_2}. \tag{9}
\]

Statistically, \( s_1 \) and \( s_2 \) should be linearly merged for an estimate more reliable than either \( s_1 \) or \( s_2 \), that is,

\[
s = w s_1 + (1 - w) s_2, \tag{10}
\]

where \( w \) is a coefficient for the linear combination. In the case, the noise deviation associated with \( s \) can be expressed as

\[
\tau(w) = \sqrt{w^2 \tau_1^2 + (1 - w)^2 \tau_2^2}. \tag{11}
\]

It can be proved that the optimal coefficient \( \hat{w} \) that leads to the minimum noise deviation \( \hat{\tau} \) is expressed as

\[
\hat{w} = \frac{\tau_2^2}{\tau_1^2 + \tau_2^2}. \tag{12}
\]

Consequently, the noise deviation \( \hat{\tau} \) of the combined signal is

\[
\hat{\tau} = \sqrt{\hat{w}^2 \tau_1^2 + (1 - \hat{w})^2 \tau_2^2} = \frac{\tau_1 \tau_2}{\sqrt{\tau_1^2 + \tau_2^2}} \tag{13}
\]

\[
= \frac{c_1 c_2 \sigma_1 \sigma_2}{\sqrt{K_2^2 c_1^2 \sigma_1^2 + K_1^2 c_2^2 \sigma_2^2}} = \frac{c_1 c_2 \sigma_1 \sigma_2 (F_1 + F_2)}{\sqrt{F_2^2 c_1^2 \sigma_1^2 + F_1^2 c_2^2 \sigma_2^2}}.
\]

Note that \( \hat{\tau} \) is less than either \( \tau_1 \) or \( \tau_2 \).

Finally, the average SNR \( \bar{R} \) of the dual-CCD system can be expressed as

\[
\bar{R}(F_1, F_2, \sigma_1, \sigma_2) = \frac{1}{F_1 + F_2} \int_0^{F_1 + F_2} \frac{dx}{\tau} = \frac{F_1 + F_2}{2 \tau} = \frac{1}{2} \sqrt{\frac{F_1^2}{\sigma_1^2} + \frac{F_2^2}{\sigma_2^2}}. \tag{14}
\]

As an illustrative example, we set \( c_1 = c_2 = 1 \), and have the distribution of \( \bar{R} \) plotted in Fig. 2 for \( F_1 + F_2 = 1000 \) K electrons and \( \sigma_1 + \sigma_2 = 100 \) electrons. Suppose two identical sensors are used, we have

\[
\bar{R}(F, \sigma, \sigma) = \frac{\sqrt{F}}{2 c \sigma^2}. \tag{15}
\]

IV. CONCLUSION

In conclusion, we have presented an approach for the design of a dual-CCD data acquisition system that can significantly improve the overall SNR and accordingly extend the dynamic range of an imaging system. The average SNR discussed in this paper is an important criterion for characterization of the detector capability. The analysis applies to other types of digital detectors. This method provides an inexpensive solution within the constraint of the current technology. Further research possibilities include combinations of multiple CCD arrays as well as evaluation in various applications.

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REFERENCES


