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Design of real-time neutron radiography at china advanced research reactor

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Abstract

A real-time detector system for neutron radiography based on CMOS camera has been designed for the thermal neutron imaging facility under construction at China Advanced Research Reactor (CARR). This system is equipped with a new scientific CMOS camera with 5.5 million pixels and speed up to 100 fps at full frame. The readout noise is below 2.4 e/pixel. It is capable of providing images with much higher resolution and sensitivity at high frame rate. With optimized optical design and custom-built lens, the capture of quantitative information may be greatly enhanced. The maximum photon received by detector is calculated to be $2.1 \times 10^3$/pixel, while the camera resolution is 0.2mm at 30 fps according to the expected flux ($5 \times 10^7$ n/cm$^2$/s) at the sample position.

Keywords: real time; neutron radiography; SCMOS

1. Introduction

Real-time (RT) radiography is widely used in various fields, such as water flow management of fuel cell[1-3], working engines[4], two-phase flow[5-8], etc. However, major difficulties must be overcome related to the low number of neutrons detected in one measurement time frame and the number of pixels that

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can be read. It requires a high-flux neutron source, fast decay time neutron scintillation materials, and the fast readout camera to meet this challenge. There are two methods for Real-time (RT) radiography, one is stroboscopic imaging for fast but periodic processes, and the other is dynamic imaging for real-time measurement (around 30 fps) but continuous processes [9]. The typical camera for stroboscopic imaging is the MCP-intensified CCD camera. This device has been already used at two facilities, one is Neutrograph at the Institut Laue-Langevin (ILL), the other is ANTARES at FRM-II.[10] Recently, popular detectors for continues processes applications were based on electron multiplying charge-coupled device (EMCCD) technology [11]. Using this CCD, dynamic neutron imaging in integrated mode was conducted at the National Institute of Standards and Technology. However, restricted by read-out speed, EMCCD detector could not achieve both high resolution and fast capture speed. A recently developed prototype detector based on scientific CMOS sensor provides possibility to attain real-time neutron imaging. The detector system based on this novel device is expected to achieve 4 million pixels per frame at 30 fps measurement without capture distortion.

2. Design of detection system based on CMOS camera

A thermal neutron imaging facility is under construction at the China Advance Research Reactor (CARR) [12]. A high neutron flux of at least $5 \times 10^7$ n/cm$^2$/s is available at the sample position, as shown in Table 1. It gives great advantages on real-time imaging applications.

| Aperture size Diameter (cm) | Umbra Size(cm) | L/D | Flux (n/cm$^2$/s) |
|-----------------------------|----------------|-----|------------------|
| 4                           | 10             | 293 | $2 \times 10^8$  |
| 2                           | 20             | 585 | $5 \times 10^7$  |

Table 1. The routine beam flux at the sample position.

In principle, an arrangement for investigation through neutron radiography consists of a neutron source, a collimator, an investigated object and a neutron detector. The video camera is one of the key component in real-time neutron radiography system. The scintillator was used in the conversion of neutrons to the visible light, which will be subsequently detected by the camera and digitally stored in a PC.

The detector with scintillator and video camera offer some advantages: high sensitivity, high dynamical range, good linearity and reproducibility, high temporal resolution (offers real time imaging). There are many traditional video camera for low light capture on high sensitive real time measurement based on charge-coupled device technology (CCD), such as Interline CCD and EMCCD [13]. The advantage of this technology is low noise performance but it has a relatively slow signal readout speed. Due to this shortage it is extremely difficult to achieve million pixels resolution at 30 fps, which means that the spatial resolution is insufficient for large area measurement on our facility. Conversely, although another sensor based on traditional CMOS technology has much higher capture speed, its poor noise background has restricted its application for high-resolution real-time neutron radiography.

Fortunately, a new generation scientific CMOS sensor developed by Andor technology, PCO Imaging and Fairchild imaging, provides the possibility to attain both quick readout speed and excellent noise performance on low light measurement. Figure 1[14] depicts the signal-to-noise-ratio (SNR) comparison of EMCCD, Scientific CMOS and interline CCD at different light level, which indicates that the scientific CMOS has a better noise performance than EMCCD when the photons received by senor per pixel on one capture is more than 100. Under the regular conditions of our real-time neutron radiography, the photons received by senor per pixel on one capture are much more than 100. It makes SCMOS more suitable for our
neutron detector system.

![Theoretical signal to Noise plot comparisons for scientific-grade CMOS vs. interline CCD vs. back-illuminated EMCCD sensors.](image)

For purposes of an objective comparison, it is assumed that the 6.5μm pixels of the sCMOS and interline CCD sensors are 2×2 binned in order to equal a 13 μm pixel of a back-illuminated EMCCD [14].

The sCMOS has 2560×2160 pixels with 6.5μm×6.5μm pixel sizes, which can provide more details on measurement. Table 2 shows maximum capture speed of cameras based on sCMOS and EMCCD when choosing different regions of interest on sensor area.[15] The speed of sCMOS camera can achieve 50 fps at full frame for global shutter mode which has better scanning tolerance. At real time measurement (30 fps) the camera noise that is mainly due to readout noise is less than 2.5 e− on a global shutter mode, and quantum efficiency is around 40% at 450 nm. It is very convenient to select scan speed by chosen interest of area at the sensor. For instance, full frame and 280×280 pixels of sensor area may be chosen at 30 fps and 500 fps respectively. Benefited from new electronic technology development, sCMOS is expected to attain higher resolution or faster capture speed compared with the traditional EMCCD, but only at the half expense.

| Sensor area   | Frame rate of sCMOS | Sensor area   | Frame rate of EMCCD |
|---------------|---------------------|---------------|---------------------|
|               | Rolling shutter mod |               | Global shutter mod  |                     |
| 2560×2160     | 100 fps             | 50 fps        | 256×256             | 60.9 fps            |
| 1280×1024     | 212 fps             | 105 fps       | 256×256             | 8.9 fps             |
| 640×480       | 450 fps             | 222 fps       | 512×512             | 31.9 fps            |
| 320×240       | 893 fps             | 435 fps       | 1024×1024           | 8.9 fps             |

As a result, this new sCMOS camera (see Figure 2.) was chosen for our real-time neutron radiography detector system, with sketch depicted in Figure 3. For real-time measurement, LiF-ZnS (Ag) is a suitable choice of scintillator due to its short time response (85 ns). The neutron beam has 20cm × 20cm size and an intensity of 5×10⁷n/cm²/s in the plane of the detector at the thermal neutron radiography facility at CARR as
the aperture diameter is 2cm. The $^6$LiF-ZnS(Ag) scintillator was chosen to have 20cm×20cm dimensions and with the light emission peak at 450 nm. The aluminized mirror has 200mm×280mm dimensions and was obtained by an aluminum plate with thickness of 5 mm. The aluminum layer (100 nm) is covered by a SiO$_2$ (3-4 nm) protective layer. The large lens provides more light entrance to the camera in achieving high efficiency for light transfer systems. The lens has the F number equal to 0.9 for visualization of entire scintillator at this detector system. In order to measure different temporal resolution, custom lens of f=50 mm and 17 mm have been chosen.

Fig 2. The new sCMOS camera provided by PCO Tech.

Fig 3. The diagrammatic sketch of real-time neutron radiography detector systems.

3. Discussion

The investigated object modifies the incident neutron beam according to neutron cross-sections of its constituents. In order to assess of the quality of the capture picture, a calculus of the number of photoelectrons/pixel ($N_{pe}$) that appears in the sensor of the sCMOS camera under various situations is made. Previous work indicates that $N_{pe}$ could be expressed as follows [17]:

$$N_{pe} = I \times D^2 \times \eta \times n_{pe} \times \Delta t$$  \hspace{1cm} \text{(1)}$$

$I$= the neutron beam intensity at sample position

$D$= the area size of the scintillator corresponding to a pixel

$\eta$ = the efficiency of neutron detection=30% For a commercial scintillator (EJ426HD2) in our system

$\Delta t$ = explosion time for one picture

$n_{pe}$ is the CMOS signal in photoelectrons per detected neutron [1] which is given by:
\begin{equation}
  n_{pe} = \eta_{og} \eta_{le} \eta_{cmos} n_e / [4F(m + 1)]^2
  = 0.93 \times 0.98 \times 0.4 \times 4.53 \times 10^5 / [4F(m + 1)]^2
  = 1.65 \times 10^7 / [4F(m + 1)]^2 
\end{equation}

Where:
- \( n_e \): captured neutron determines an emission of photons = 4.53 \times 10^5 [17]
- \( \eta_{og} \): optical efficiency of mirror (reflection)= 0.93 in our system
- \( \eta_{le} \): optical efficiency of lens (transmission)= 0.98 in our system
- \( \eta_{cmos} \): quantum efficiency of CMOS= 0.4 at 450nm light spectrum in our system
- \( F \): F number of the lens =0.9 in our system
- \( m \): magnification ratio (\( l_{obj} / l_{cmos} = m \))
- The factor \([4F(m + 1)]^2\) is the fraction of solid angle inside the light is collected by lens.

\textbf{a. routine measurement mode}

For regular real-time measurement, the expected neutron beam intensity is 5 \times 10^7 n/cm²/s at the sample position. The area of the scintillator corresponding to 2k×2k pixels is \( D^2 = (20\text{cm} / 2000)^2 = 1 \times 10^{-4} \text{cm}^2 \) when the entire scintillator is visualized. With full frame measurement at 30fps, each scan exposure time is around \( \Delta t = 30 \text{ms} \).

As a result of Eq. (2), (1):

\[ n_{pe} = 47.4 \text{ photoelectrons/captured neutron.} \]

\[ N_{pe} = I \times D^2 \times \eta_e \times n_{pe} \times \Delta t = 5 \times 10^7 \times 1 \times 10^{-4} \times 0.3 \times 47.4 \times 0.03 = 2133 \text{ photoelectrons/pixel} \]

\textbf{b. fast measurement mode}

For fast measurement, the expected direct neutron beam intensity will be achieved 4 \times 10^8 n/cm²/s at the sample position. If there is a projected area of 100mm×100mm of the scintillator on the CMOS sensor, the activation pixels will be 280×280. Thus we will have \( D^2 = (10\text{cm} / 280)^2 = 1.28 \times 10^{-3} \text{ cm}^2 \). With the fastest measurement at 500 fps capture speed, each scan exposure time is around \( \Delta t = 2 \text{ ms} \). A similar calculus for entire surface leads to \( n_{pe} = 4.07 \text{ photoelectrons/captured neutron.} \)

\[ N_{pe} = I \times D^2 \times \eta_e \times n_{pe} \times \Delta t = 4 \times 10^8 \times 1.28 \times 10^{-3} \times 0.3 \times 4.07 \times 0.002 = 1250 \text{ photoelectrons/pixel} \]

In summary, for both routine and fast modes, excellent performance of thousands of photoelectrons/pixel can be obtained. It means that sCMOS camera should have a better noise performance than EMCCD for our system at this light level (see Figure 1.).

4. \textbf{Conclusion}

The new sCMOS camera is a suitable tool for a variety of real-time investigations at the thermal neutron radiography of CARR, and is capable of producing static and dynamic images with good quality. This detector system assures a geometrical resolution of 0.2 mm for the visualization of the entire scintillator at 30 fps scanning. For 500 fps scanning the camera assures a detector system geometrical resolution of 0.7 mm given the field of view (FOV) =10cm. The next step is to achieve up to 1000 fps measurement with even higher resolutions, which may only be possible with a CMOS camera combined with an image intensifier.
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