CASCADED MODEL ANALYSIS OF PIXELATED SCINTILLATOR IMAGING DETECTORS

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June, 7, 2007

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Conventional DR detectors

• Direct-detection scheme
  ▫ High-resolution imaging capability (high MTF)
  ▫ But, noise-aliasing due to the high MTF
  ▫ Lower X-ray sensitivity (with the conventional photoconductor materials, e.g., a-Se)

• Indirect-detection scheme
  ▫ Higher X-ray sensitivity (e.g., CsI:Tl)
  ▫ Relatively poorer MTF

• Best way: use of a scintillator with band-limited MTF property
  ▫ Maintaining higher X-ray sensitivity of a scintillator
  ▫ Avoiding noise-aliasing due to the band-limited MTF

• Pixelated scintillator?
How we can realize a pixelated scintillator design?

- Growing onto pixel-patterned substrates (thermal evaporation)
- Filling scintillation materials into pixel-structured mold
Objective

- Investigating a feasibility of the pixelated scintillator, theoretically
  - Using the *cascaded linear-systems transfer theory*
  - Predicting detective quantum efficiency (DQE), which is an essential metric representing an image quality of an imaging system

\[
DQE(u,v) = \frac{\text{Fluence} \times \text{System Gain}^2 \times \text{MTF}^2_{sys}(u,v)}{\text{NPS}(u,v)} = \frac{\bar{q}_0 G^2 T^2_{sys}(u,v)}{\text{NPS}(u,v)} = \frac{T^2_{sys}(u,v)}{\bar{q}_0 \text{NNPS}(u,v)}
\]

- Developing a DQE formalism of the pixelated scintillator detector
  - Numerical simulation with respect to various design parameters; pixel pitch, fill factor, additive noise ...
  - Comparing with the conventional scintillator-based detectors with various MTF properties
Cascade model of the conventional scintillator imager

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Symbol</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Incident X-ray</td>
<td>$q_0$</td>
<td>Uniform distribution</td>
</tr>
<tr>
<td>1</td>
<td>Quantum detection</td>
<td>$g_1 = A_Q$</td>
<td>Binomial selection</td>
</tr>
<tr>
<td>2</td>
<td>Quantum amplification</td>
<td>$g_2 = A_M$</td>
<td>Binomial selection</td>
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<tr>
<td>3</td>
<td>Quantum scattering</td>
<td>$T_3$</td>
<td>Stochastic blurring</td>
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<tr>
<td>4</td>
<td>Quantum conversion</td>
<td>$g_4 = A_D$</td>
<td>Binomial selection</td>
</tr>
<tr>
<td>5</td>
<td>Aperture integration</td>
<td>$T_5$</td>
<td>Deterministic blurring</td>
</tr>
<tr>
<td>6</td>
<td>Sampling</td>
<td>III</td>
<td>Deterministic process</td>
</tr>
<tr>
<td>7</td>
<td>Additive noise</td>
<td>$\sigma_{add}$</td>
<td>Deterministic process</td>
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• DQE of the conventional scintillator imager

\[
\text{DQE}(\rho) = \sum_{k=0}^{\infty} \bar{q}_0 a_{\text{scn}}^4 A_Q A_M A_D \left[ 1 + A_D \left( \frac{A_M}{I_{\text{scn}}} - 1 \right) T_{\text{scn}}^2(\rho \pm \frac{k}{d_{\text{pix}}}) \right] T_{\text{pix}}^2(\rho \pm \frac{k}{d_{\text{pix}}}) + d^2 \sigma^2_{\text{add}}
\]

Fluence \quad \text{System gain} \quad \text{System MTF}

Noise power spectrum \quad \text{Additive electronic noise}
Cascaded modeling of the pixelated scintillator imager

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</tr>
<tr>
<td>5</td>
<td>random redistribution</td>
<td>$T_5$</td>
<td>statistical relocation</td>
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<tr>
<td>6</td>
<td>Quantum conversion</td>
<td>$g_6 = A_D$</td>
<td>binomial selection</td>
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<td>7</td>
<td>Aperture integration</td>
<td>$T_7$</td>
<td>deterministic blurring</td>
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<td>8</td>
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<td>III</td>
<td>deterministic process</td>
</tr>
<tr>
<td>9</td>
<td>Additive noise</td>
<td>$\sigma_{\text{add}}$</td>
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• Stage 0: Incident X-ray
  ▫ Signal $\overline{q}_0 = \overline{q}_0$
  ▫ NPS $W_0(p) = \overline{q}_0$

• Stage 1: Screen aperture integration
  ▫ Signal $\overline{q}_1 = \overline{q}_0 a_{scn}^2$
  ▫ NPS $W_1(p) = W_0(p) a_{scn}^4 \text{sinc}^2(\pi a_{scn} p) = \overline{q}_0 a_{scn}^4 \text{sinc}^2(\pi a_{scn} p)$

• Stage 2: X-ray Sampling
  ▫ Signal $\overline{q}_2 = \overline{q}_1 \times \frac{1}{d_{scn}^2} = \overline{q}_0 a_{scn}^2 \frac{1}{d_{scn}^2} = \gamma_{scn} \overline{q}_0$
  ▫ NPS $W_2(p) = \frac{a_{scn}^4}{d_{scn}^4} \sum_{k=0}^{\infty} q_0 \text{sinc}^2\left(\pi a_{scn} (p \pm \frac{k}{d_{scn}})\right) = \frac{a_{scn}^4}{d_{scn}^4} \overline{q}_0 \left(\frac{d_{scn}}{a_{scn}}\right)^2 = \gamma_{scn} \overline{q}_0$
• Stage 3: Quantum detection
  ▪ Signal \( \bar{q}_3 = \bar{q}_2 \times A_Q = \gamma_{scn} \bar{q}_0 A_Q \)
  ▪ NPS \( W_3(\rho) = A_Q^2 \left[ W_2(\rho) - \bar{q}_2 \right] + \bar{q}_2 A_Q = \gamma_{scn} \bar{q}_0 A_Q \)

• Stage 4: Quantum amplification
  ▪ Signal \( \bar{q}_4 = \bar{q}_3 \times A_M = \gamma_{scn} \bar{q}_0 A_Q A_M \)
  ▪ NPS \( W_4(\rho) = A_M^2 W_3(\rho) + \bar{q}_3 \sigma_M^2 = \gamma_{scn} \bar{q}_0 A_Q A_M^2 + \gamma_{scn} \bar{q}_0 A_Q A_M \left( \frac{1}{I_M} - 1 \right) = \frac{\gamma_{scn} \bar{q}_0 A_Q A_M^2}{I_M} \)

• Stage 5: Random redistribution
  ▪ Signal \( \bar{q}_5 = \bar{q}_4 = \gamma_{scn} \bar{q}_0 A_Q A_M \)
  ▪ NPS \( W_5(\rho) = \left[ W_4(\rho) - \bar{q}_4 \right] \text{sinc}^2 (\pi a_{scn} \rho) + \bar{q}_4 = \gamma_{scn} \bar{q}_0 A_Q A_M \left[ 1 + \left( \frac{A_M}{I_M} - 1 \right) \text{sinc}^2 (\pi a_{scn} \rho) \right] \)
• Stage 6: Quantum conversion
  
  ▫ Signal \[ q_6 = q_5 \times A_D = \gamma_{\text{scn}} q_0 A_Q A_M A_D \]
  
  ▫ NPS \[ W_6(p) = A_D^2 W_5(p) + q_5 \sigma_D^2 = \gamma_{\text{scn}} q_0 A_Q A_M A_D \left[ 1 + A_D \left( \frac{A_M}{I_M} - 1 \right) \text{sinc}^2 (\pi a_{\text{scn}} p) \right] \]

• Stage 7: Aperture integration
  
  ▫ Signal \[ q_7 = q_6 \times a_{\text{pix}}^2 = \gamma_{\text{scn}} a_{\text{pix}}^2 q_0 A_Q A_M A_D \]
  
  ▫ NPS \[ W_7(p) = \gamma_{\text{scn}} a_{\text{pix}}^4 q_0 A_Q A_M A_D \left[ 1 + A_D \left( \frac{A_M}{I_M} - 1 \right) \text{sinc}^2 (\pi a_{\text{scn}} p) \right] \text{sinc}^2 (\pi a_{\text{pix}} p) \]
• Stage 8: Sampling
  ▫ Signal  \( \bar{q}_8 = \bar{q}_7 = \gamma_{\text{scn}} A_{\text{pix}}^2 \bar{q}_0 A_Q A_M A_D \)
  ▫ NPS  
    \[ W_8(p) = \gamma_{\text{scn}} A_{\text{pix}}^4 \bar{q}_0 A_Q A_M A_D \left[ 1 + A_D \left( \frac{A_M}{I_M} - 1 \right) \sum_{k=0}^{\infty} \text{sinc}^2 \left( \pi a_{\text{scn}}(p \pm \frac{k}{d_{\text{pix}}}) \right) \text{sinc}^2 \left( \pi a_{\text{pix}}(p \pm \frac{k}{d_{\text{pix}}}) \right) \right] \]

• Stage 9: Additive noise
  ▫ Signal  \( \bar{q}_9 = \bar{q}_8 = \gamma_{\text{scn}} A_{\text{pix}}^2 \bar{q}_0 A_Q A_M A_D \)
  ▫ NPS  
    \[ W_9(p) = W_8(p) + d^2 \sigma_{\text{add}}^2 \]
• DQE of the pixelated scintillator imager

\[
DQE(\rho) = \frac{q_0 (\gamma_{\text{scn}} a_{\text{pix}}^2 A_Q A_M A_D)^2 T_{\text{scn}}^2(\rho) T_{\text{pix}}^2(\rho)}{1 + A_D \left( \frac{A_M}{I_{\text{scn}}} - 1 \right) \sum_{k=0}^{\infty} \text{sinc}^2 \left( \pi a_{\text{scn}}(\rho \pm \frac{k}{d_{\text{pix}}}) \right) \text{sinc}^2 \left( \pi a_{\text{pix}}(\rho \pm \frac{k}{d_{\text{pix}}}) \right) + d^2 \sigma_{\text{add}}^2}
\]
Model validation

• Experimental condition
  • 60 kVp, 17 mR

<table>
<thead>
<tr>
<th>Microfocus X-ray source</th>
<th>L8121-01, Hamamatsu Tungsten anode 200 µm beryllium window 1mmAl add-filtration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS photodiode array</td>
<td>C7943, Hamamatsu 2400 x 2400 array format 50 µm pixel pitch 79% fill factor</td>
</tr>
<tr>
<td>Scintillator</td>
<td>Columnar structured CsI:TI 200 µm thickness ~80% packing density</td>
</tr>
</tbody>
</table>

• Degraded DQE at lower frequencies: due to the pixelated design (X-ray quanta sampling)
• Improved DQE at higher frequencies
Numerical simulation

- Default parameters
  - Providing an ideal performance of an imager

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidence of X-ray</td>
<td>$q_0 = 1 \times 10^6$</td>
</tr>
<tr>
<td>Quantum absorption efficiency of scintillator</td>
<td>$A_Q = 1$</td>
</tr>
<tr>
<td>Average conversion efficiency of scintillator</td>
<td>$A_M = 1000$</td>
</tr>
<tr>
<td>Quantum efficiency of photodiode</td>
<td>$A_D = 1$</td>
</tr>
<tr>
<td>Additive electronic noise</td>
<td>$\sigma_{add} = 10^3$</td>
</tr>
<tr>
<td>Scintillator and pixel pitch</td>
<td>$d = 50\mu m$</td>
</tr>
<tr>
<td>Scintillator and pixel Fill factor</td>
<td>$\gamma = 80%$</td>
</tr>
<tr>
<td>Scintillator and pixel aperture</td>
<td>$a = \sqrt{\gamma d^2}$</td>
</tr>
</tbody>
</table>
Effect of a pixel pitch

Due to X-ray sampling

DQE

Spatial Frequency (mm$^{-1}$)

- $d = 200 \, \mu m$
- $d = 100 \, \mu m$
- $d = 50 \, \mu m$
- $d = 30 \, \mu m$
Effect of a pixel fill factor

- DQE at the lower frequency is gradually further decreased as the fill factor decreases due to the relatively enhanced additive noise term.
Comparison with the various conventional imagers

\[ MTF(\rho) = \frac{1}{1 + k\rho^2} \]

- \( k \) = the experimental fitting parameter
  - 0.06 (Lanex\textsuperscript{TM} Fine)
  - 0.43 (Lanex\textsuperscript{TM} Regular)
  - 0.69 (CsI 554\textmu m)
  - 1.25 (Lanex\textsuperscript{TM} Fast)
Effect of the additive noise

- 80% fill factor, 50 μm pitch, 0.43 (Lanex™ Regular),

- Pixelated design is relatively immune to the additional electronic noise
Conclusion

• Pixelated scintillator imagers
  ▫ Degradation of DQE at lower spatial frequencies due to the X-ray quanta sampling process
  ▫ However, maintaining DQE properties even in the higher frequency band due to the band-limited MTF properties
  ▫ Relatively strong to the additive electronic noise
  ▫ Appropriate to the high-sensitivity and -resolution imaging systems, and imagers with small pixel pitch
    e.g., Mammography, Intra-oral imaging etc.

• Based on this study, we propose a better design of the scintillator-based imager: Partially pixelated scintillator