Simulation of Computed Radiography X-ray Imaging Chain Dedicated to Complex Shape Objects

Min YAO
Philippe DUVAUCHELLE
Valérie KAFTANDJIAN
Angéla PETERZOL-PARMENTIER
Andreas SCHUMM

INSA de LYON
INSA de LYON
INSA de LYON
AREVA
EDF
**CONTEXT**

- **Film replacement**: digital technique
- **Computed Radiography (CR)**
  - Medical imaging: good performance
  - Industrial inspection:
    - poor performance at high energies (problem for the inspection of nuclear industry equipment)
- **Modeling and simulation**
  - Complex object
  - Short simulation time
  - CR optimization
OUTLINE

1. Computed Radiography principle
2. CR modeling
3. Simulation results
4. Conclusions
1. Computed radiography principle

1. X-Ray Exposure
   - X-Ray Exposure
   - Imaging Plate
   - Photostimulable phosphor (BaFBr:Eu$^{2+}$) irradiation
   - Latent image

2. Readout
   - Rotating Polygon Mirror
   - Stimulating Laser
   - Photomultiplier Tube
   - Imaging Plate Moved Translationally
   - Digitized Signal

3. Erasure
   - Intense Light
2. CR modeling: Methodology

Analytic model combined with off-line Monte Carlo approach
2. CR modeling: X-ray interactions

- Spectral image of a complex shape object
- Method: deterministic or probabilistic (Monte Carlo)

* P. Duvauchelle et al., NIMB (2000).
2. CR modeling: Methodology

Complex object

Deterministic MC ...

Spectral image of object

Obj(E,x,y)

X-ray latent image generation

Detector response model

PSF_{det}(E,x,y,z)

Factor

(E_{dep} to storage center)

Deposited energy image

3D latent Image

Limg(x,y,z)

Readout

Factor

(Signal collection, amplification and digitization)

Optical readout model

(Laser stimulation & PSL emission)

PSL image

2D CR Image

Dimg(x,y)
2. CR modeling: X-ray latent image generation

- Detector response model obtained with **off-line Monte Carlo simulation** (scattering, fluorescence, electron…)
- Database (all IP/screens combinations required by standards)
2. CR modeling: X-ray latent image generation

Latent image \( \text{Limg}(x, y, z) \) = \( H_1(\text{Obj}, PSF_{\text{det}}) \)

\[
\begin{align*}
\text{Limg}(x, y, z) &= H_1(\text{Obj}, PSF_{\text{det}}) \\
&= g_{sc} \int_E \left[ E \cdot \text{Obj}(E, x, y) * PSF_{\text{det}}(E, x, y, z) \right] dE \\
&= g_{sc} \int_E \left[ E \cdot \int_{u,v} \text{Obj}(E, u, v) \cdot PSF(E, x-u, y-v, z) dudv \right] dE
\end{align*}
\]
2. CR modeling: Methodology

- Complex object
  - Spectral image of object: \( \text{Obj}(E,x,y) \)
  - Detector response model: \( \text{PSF}_{\text{det}}(E,x,y,z) \)
  - Deposited energy image
- Factor (\( E_{\text{dep}} \) to storage center)
- 3D latent image: \( \text{Limg}(x,y,z) \)
- Optical readout model (Laser stimulation & PSL emission)
- Factor (Signal collection, amplification and digitization)
- Readout
  - 2D CR Image: \( \text{Dimg}(x,y) \)
2. CR modeling: Readout

- Laser propagation in IP: off-line optical Monte Carlo
- Scanning parameters: laser power, scanning speed, pixel size
2. CR modeling: Readout

Latent image $L_{\text{img}}(x,y,z)$

Scanning parameters

Optical response model $f(x,y,z)$

$D_{\text{img}}(x,y) = H_2(L_{\text{img}}, f, \text{scanning parameters})$

$$= \int_z P(z)dz \int_{x,y} L_{\text{img}}^{(\text{mod})}(x,y,z)\{1 - \exp[-\sigma \cdot f(x-x_m, y-y_m, z) \cdot P_{\text{laser, scan}}]\}dxdy$$

Modified latent image by laser scanning
3. Results: Simulation parameters

- Source energy: 100 keV
- Detector: 700 × 700 pixels
- 100 energy channels
- Pixel size: 10 µm
- 3 detector configurations:
  - IP alone
  - IP+0.2mmPb
  - IP+0.2mmPb+0.8mmSn
3. Results: Latent image

- Ideal detector (Obj)
- IP alone
- IP+0.2Pb
- IP+0.2Pb0.8Sn
3. Results: Latent image

- Influence of the screens for image quality optimization
3. Results: Readout

- **Obj**
  - Readout factor $10^{10}$

- **Limg**
  - Readout factor $10^{16}$
3. Results

The normalized profile is shown in the graph. The y-axis represents the normalized profile values ranging from 0.79 to 0.87, while the x-axis represents the y(mm) values ranging from -10 to 10. The graph compares different cases labeled as Obj, Limg (IP alone), Dimg (factor=1E10), and Dimg (factor=1E16).
4. Conclusions

- **CR imaging chain modeling**
  - From X-ray energy deposition in IP to optical readout
  - Adapted to complex shape objects
  - Detector model database

- **A simulation tool**
  - Comprehensive study on the operating parameters (detector configuration, laser power etc)
  - Optimization of a given application
  - Reasonable simulation time:
    - A few minutes to a few tens of minutes (without optimization)
    - Goal: a few seconds

- **Comparison with experimental results in progress**
THANK YOU FOR YOUR ATTENTION!
Source: Ir192
Step-wedge: 40 mm and 30 mm with IQI
Step thickness: 30 mm
Step thickness 40 mm

Experiment
Simulation
Experiment
Simulation
Digital image: readout efficiency

\[ \text{Efficiency} = \frac{\text{Digitalimage}}{\text{Latentimage}} \]
ADVANTAGES AND LIMITATIONS

• Advantages
  + Flexibility of detector
  + Direct digital image
    • Image processing and enhancement
    • Long distance image sharing
  + Reusability
    → low long-term cost
  + High dynamic range up to $10^5$

• Limitations
  – Poor efficiency at high energies
  – Poor spatial resolution
due to light scattering in laser readout process