Ultrasound goes GPU: real-time simulation using CUDA

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Clinical Problem

- Despite increasing use of CT, MRI, etc. medical US remains widely in use because of low cost, non-invasiveness, real-time visual feedback, etc.
- Many procedures like US-guided needle insertion require a high degree of hand-eye coordination and extensive training.
- For ethical and patient safety reasons training on simulations is preferred.
Related Work

- Jensen 1996: exhaustive simulation of US imaging on the scatterer level
- Aiger and Cohen-Or 1998: real-time simulation by slicing 2D US images from 3D volume
- Hostettler et al. 2005: ray-tracing US waves, combined with CT textures
- Zhu et al. 2006: using synthetic 3D textures based on 2D US samples
- Wein et al. 2007: physically derived estimation of US reflection

Common problem: computational effort, e.g. resolution is limited in favor of real-time simulation.

Idea: take advantage of modern graphics processors (GPU) and their capabilities for parallel processing

Goal: realistic simulation in real-time
Ultrasound Artifacts

- US reflection at tissue boundaries
- US attenuation in tissue, shadowing
- Speckle noise
- Radial blur
Implementation: Overview

Probe Position \((x, y, z, \varphi)\)

3D CT Volume

2D CT Slice

Acoustic Impedance

3D Noise

2D Noise

Absorption

Reflection

Gradient

Simulated US image

Image synthesis

Blending
US Physics: Acoustic Impedance

- Estimation of acoustic impedance from CT values (Wein et al. 2007)
- Using quadratic instead of linear interpolation

\[ Z = \rho \times c \]

\begin{align*}
\rho & \quad \text{Density of the tissue} \\
\rho & \quad \text{Density of the tissue} \\
C & \quad \text{Speed of sound} \\
\end{align*}

<table>
<thead>
<tr>
<th></th>
<th>( \rho ) [kg/m(^3)]</th>
<th>( C ) [m/s]</th>
<th>( Z ) [Rayl]</th>
<th>( \text{CT} ) [HU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.2</td>
<td>330</td>
<td>( \sim 400 )</td>
<td>-1000</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>1480</td>
<td>1.48 M</td>
<td>0</td>
</tr>
<tr>
<td>Bone</td>
<td>1800</td>
<td>4330</td>
<td>( \sim 7 ) M</td>
<td>1000</td>
</tr>
</tbody>
</table>
US Physics: Snell’s Law

• Specular reflection:

\[
\frac{I_r}{I_i} = \left( \frac{Z_2 \cdot \cos \theta_i - Z_1 \cdot \cos \theta_i}{Z_2 \cdot \cos \theta_i + Z_1 \cdot \cos \theta_i} \right)^2
\]

• Simplification:

\[
\theta_i \approx 0 \quad \frac{I_r}{I_i} = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2
\]

• Combination of specular and diffuse reflection:

\[
\frac{I_r}{I_i} = \cos(\alpha)^n
\]

• Using n=2:

\[
\frac{I_r}{I_i}(x) = \left( \frac{d^T \cdot \nabla Z(x)}{2 \cdot Z(x)} \right)^2
\]
US Physics: Absorption

- Approx. 95-100% of attenuation due to absorption
- Exponential law, similar to X-ray attenuation:

\[ \frac{I}{I_0} = 10^{\alpha \cdot f/10} \]

- \( f \) US frequency
- \( \alpha \) attenuation coefficient
Transmitted Intensity

\[ I_t(x) = I_0 \cdot \prod_{0 \leq k \leq x} \left[ \frac{I_i}{I_i(k)} \cdot \left(1 - \frac{I_a(k,d)}{I_i} \right) \right] \]

Transmission  Absorption
Reflected Intensity

\[ I_r(x) = I_0 \left( \prod_{0 \leq k \leq x} \left[ \frac{I_t(k)}{I_i} \right] \left[ 1 - \frac{I_a(k,d)}{I_i} \right] \right)^2 \cdot R(x) \]
Implementation: Real-time Simulation

Demo 1: Image quality

Demo 2: Interaction
Implementation: Simulation Options

Simulation properties:
- Probe Type:
  - Transcranial Probe
  - Obstetric Probe
- Frequency: 3.5 MHz
- Intensity: 2.6 mW/cm²
- Radius: 9 mm
- Stick to Surface
- Enable Fan Shape
- Center Distance: 123 px
- Enable Stencil
- Sweep Angle: 60 deg
- Distance min: 25 px
- Distance max: 343 px
- Enable Noise
- Speckle Size: 3.7 px
- Enable Blurring
- Axial Blur: 1.14 AL
- Lateral Blur: 1.02 AL

Display Options:
- Display Mode:
  - Reflection Ratio
  - Absorption Ratio
  - Transmitted Intensity
  - Reflected Intensity
  - Probe Geometry
  - Acoustic Impedance
  - Gradient Magnitude
  - Original CT data
- Noise Only
- Inset Display:
  - Display 2-D Inset
  - Inset size: 1024 px
- Log-compression
- Dyn. Range: 61 dB
- Use Pre-defined Brightness

Time Gain Compensation:
- TGC 7: 0 dB
- TGC 6: 0 dB
- TGC 5: 0 dB
- TGC 4: 0 dB
- TGC 3: 0 dB
- TGC 2: 0 dB
- TGC 1: 0 dB
- TGC 0: 0 dB
• ~3.3 ms for main computation
• Transfer between OpenGL and CUDA might become unnecessary with CUDA 2
• Much time needed for post-processing (blurring, compression)
Results: Image Quality

- Comparison: simulated image (left), real image (right)
- Positive feedback from clinicians, collaboration for comparing and validating our results (Robarts Research, Canada)
Conclusion

• New physically plausible approach where computation is possible within the virtual US scan plane, i.e. using only one 2D slice from the original 3D CT volume
• No manual annotation or adjustment of the input data necessary
• Real-time simulation with „maximum“ resolution (i.e. same as CT data)
• Artifacts simulated: shadowing / attenuation, speckle noise, radial and lateral blurring
• All virtual acquisition parameters can be interactively changed: US frequency, US intensity, time-gain compensation, field geometry
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Thank you for your attention!

• Questions?