Mobile Wireless Ultrasound with GPU Beamforming

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Denmark
The Alexandra Institute

• Private not-for-profit company within IT
  – Technology transfer from University research through GTS institutes (Danish model)

• Application oriented research
• Consultancy for companies
FutureSonic

- “A new platform and business model for on-demand diagnostic ultrasound imaging”
- 2013-2018
- Budget: 23 mio US$
Joint work

- Center for Fast Ultrasound Imaging, Technical University of Denmark
  - Martin Christian Hemmsen
  - Borislav G. Tomov
  - Jørgen Arendt Jensen

- BK Medical
  - Carsten Kjær

- Computer Graphics Lab, Alexandra Institute
  - Thomas Kim Kjeldsen
  - Lee Lassen
  - Jesper Mosegaard

Medical Ultrasound

http://www.bkmed.com/products_en.htm
Mobile transducer
Leveraging disruptive technology
Ultrasound

• From acoustic (pressure) waves to images

<table>
<thead>
<tr>
<th>Medium</th>
<th>Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>1450</td>
</tr>
<tr>
<td>Water</td>
<td>1480</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>1540</td>
</tr>
<tr>
<td>Kidney</td>
<td>1560</td>
</tr>
<tr>
<td>Blood</td>
<td>1570</td>
</tr>
<tr>
<td>Muscle</td>
<td>1580</td>
</tr>
<tr>
<td>Bone</td>
<td>4080</td>
</tr>
</tbody>
</table>

http://www.sensorwiki.org/doku.php/sensors/ultrasound
Beamforming to reconstruct images
Shooting for a number of scanlines
Dynamic Receive beamforming

Multiple transducer elements

Dynamic focus point

Scanline
Beamforming

- Traditional beamforming requires a high data bandwidth.
- A typical system could have 128 channels and use a 12-bit 40 MHz sampling system.
- This generates $128 \times 40 \times 10^6 \text{ Hz} \times 2\text{B} = 9.54 \text{ GB/s}$
SASB – dual beamforming

• Simple first stage
  – Single focal point for both transmit and receive

• Advanced second stage
  – combining information from multiple first stage focused scan lines

• Reduction in data-transfer requirement
  – Reduced by a factor of receive elements (192)

Algorithmic engineering

Minutes per frame → interactive
1. stage: Fixed focus transmit and receive

Receiver $r$ receives at time $a+2b+c$

Fixed focus point

First stage line
2. stage: reconstruct focus

1. Find index scanline entries
2. Add contribution
The math behind it

\[ I(r, \phi) = \sum_{k=0}^{N_l-1} W(r, |\phi - \phi_k|) s_k(t(r, \phi - \phi_k)) \]

\[ t(r, \phi) = \frac{2}{c} \left( d_{\text{focus}} \pm \sqrt{r^2 + r_{\text{focus}}^2 - 2rr_{\text{focus}} \cos \phi} \right) \]
for all image samples \( p \) with polar coordinates \((i,j)\)

for all first stage scanlines \( k \)

\[
a = \text{calculateWeight}(i,k) \\
d = \text{calculateDelay}(i,k) \\
s = \text{getScanline}(d,k)
\]

\[
l(i,j) += a * s
\]
Three implementations

OpenCL
OpenGL®
C++
AVX Multithreaded
Benchmark, simple implementation

Simple

ms per frame

<table>
<thead>
<tr>
<th>Method</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matlab</td>
<td>600,000</td>
</tr>
<tr>
<td>C (1 thread)</td>
<td>2950</td>
</tr>
<tr>
<td>C (8 threads)</td>
<td>699</td>
</tr>
<tr>
<td>OpenCL</td>
<td>3.05</td>
</tr>
</tbody>
</table>

Intel Core i7 2600
Nvidia GTX 680 GPU
Algorithmic optimization

- Sampling the beamforming directly in the scan line sample locations

\[ I(r, \phi) = \sum_{k=0}^{N_l-1} W(r, |\phi - \phi_k|) s_k(t(r, \phi - \phi_k)) \]

\[ I(r_i, \phi_j) = W_{i0}s_j(t_{i0}) + \sum_{k'=1}^{N(r_i)} W_{ik'} [s_{j+k'}(t_{ik'}) + s_{j-k'}(t_{ik'})] \]
Weights and delays precalculated

Delays

Apodization
\[ l = 0 \]

\[ \text{for all} \ \text{image samples} \ p \ \text{with polar coordinates} \ (i,j) \]
\[ \text{for all} \ \text{first stage scanlines} \ k \ - \ up \ to \ N(r_i) \]
\[ a = \text{getWeight}(i,k) \]
\[ \text{if} \ a=0 \ \text{then} \ \text{break} \]
\[ d = \text{getDelay}(i,k) \]
\[ s = \text{getScanline}(d,j+k) \]
\[ l(i,j) += a \cdot s \]
\[ \text{if} \ (k>0) \ \text{then} \]
\[ s = \text{getScanline}(d,j-k) \]
\[ l(i,j) += a \cdot s \]
Benchmark, Optimization

- Matlab: 600,000 ms per frame
- C (1 thread): 2950 ms per frame (20.9 improvement with optimization)
- C (8 threads): 699 ms per frame (5.4 improvement with optimization)
- OpenCL: 3.05 ms per frame (0.49 improvement with optimization)

Intel Core i7 2600
Nvidia GTX 680 GPU
### Resulting image quality

<table>
<thead>
<tr>
<th></th>
<th>Matlab</th>
<th>SIMD/Multicore</th>
<th>OpenGL</th>
<th>OpenCL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RMSE</strong></td>
<td>0.0044</td>
<td>0.0042</td>
<td>0.0040</td>
<td></td>
</tr>
<tr>
<td><strong>PSNR</strong></td>
<td>47.23dB</td>
<td>47.79dB</td>
<td>48.01dB</td>
<td></td>
</tr>
</tbody>
</table>
Going mobile (OpenGL ES 3.0)
# Mobile hardware

<table>
<thead>
<tr>
<th></th>
<th>LG G2</th>
<th>Samsung Galaxy Tab</th>
<th>Samsung Nexus 10</th>
<th>Nvidia Jetson TK1</th>
<th>HTC Nexus 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>SoC</td>
<td>Snapdragon 800</td>
<td>Exynos 5</td>
<td>Exynos 5220</td>
<td>Tegra K1</td>
<td>Tegra K1</td>
</tr>
<tr>
<td>GPU</td>
<td>Adreno 300</td>
<td>Mali T628</td>
<td>Mali T604</td>
<td>Kepler</td>
<td>Kepler</td>
</tr>
<tr>
<td>Screen</td>
<td>1920x1080</td>
<td>2560x1600</td>
<td>2560x1600</td>
<td>1920x1080</td>
<td>2048x1536</td>
</tr>
<tr>
<td>OS</td>
<td>Android</td>
<td>Android</td>
<td>Android</td>
<td>Linux4Tegra</td>
<td>Android</td>
</tr>
</tbody>
</table>
Mobile WIFI capabilities

- Need 25.3 MB/s $\rightarrow$ IEEE 802.11ac

WIFI throughput

<table>
<thead>
<tr>
<th>Device</th>
<th>WIFI throughput (MB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG G2</td>
<td>28.8</td>
</tr>
<tr>
<td>Galaxy Tab Pro</td>
<td>18.5</td>
</tr>
<tr>
<td>Nexus 10</td>
<td>11.2</td>
</tr>
<tr>
<td>Jetson TK1 + Intel 7260HMW</td>
<td>43.4</td>
</tr>
<tr>
<td>Nexus 9</td>
<td>35</td>
</tr>
</tbody>
</table>
### Mobile performance

#### Timings

<table>
<thead>
<tr>
<th>Device</th>
<th>Ms</th>
<th>Scanconversion</th>
<th>Beamformation</th>
<th>IQ demodulation</th>
<th>Datatransfer</th>
<th>Total Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG G2 (Adreno 330)</td>
<td>15</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Galaxy Tab Pro (Mali T628)</td>
<td>40</td>
<td>10</td>
<td>15</td>
<td>5</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Nexus 10 (Mali T604)</td>
<td>60</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Jetson TK1 (Tegra K1)</td>
<td>15</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Nexus 9 (Tegra K1)</td>
<td>15</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>25</td>
</tr>
</tbody>
</table>
Going mobile, Nexus 9

NVIDIA® Tegra® K1
IMPOSSIBLY ADVANCED
Digital or wireless?
Thank you for your attention

Mail: jesper.mosegaard@alexandra.dk
Twitter: @mosegaard
LinkedIn: linkedin.com/in/mosegaard

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