Hardware and Software Design for a 1000 FPS Real-Time Soft-Field Tomography System

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Content

1. What is Soft-Field Tomography?
2. What it Needs to be That Fast?
3. Hardware Design and Data Acquisition
4. GPU Based Image Reconstruction
5. System in Action
6. Conclusion
What is Soft-field Tomography?

Basics

- Method for generating cross-sectional images
- Use of non ionizing radiation, unlike hard-field tomography

- Example: Electrical Impedance Tomography (EIT)
  - Attach surface with electrodes
  - Inject electrical currents
  - Measure corresponding voltages
What is Soft-field Tomography?
EIT-System

Electrodes
Reconstruction
Voltage Measurement
Current Sources
What is Soft-field Tomography?

Use Cases

http://www.draeger.com/
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6. Conclusion
What it needs to be that fast?
Situation

Reconstruction

1 ms

Transferring

Preprocessing

Measurement
What it needs to be that fast?
Consequences

- Parallel hardware design
- Hardware based preprocessing
- Pipelining
- Reconstruction on GPUs
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Hardware Design and Data Acquisition
Parallelizing Measurement Procedure

TDMA

FDMA
Hardware Design and Data Acquisition
Parallel Hardware Architecture

- 36 gold-plated electrodes
- 9 parallel floating current sources
  - Direct digital synthesis
  - Controlled floating current sources
- 18 parallel measurement channels
  - 18 analog-to-digital converters
  - 3 field programmable gate arrays for fast Fourier transform
- Digital system control unit
  - Ethernet and USB interface
  - Central clock generation and distribution
Hardware Design and Data Acquisition

Preprocessing

- FPGA based FFT calculation
- In parallel with data acquisition
- Synchronized with signal generation
  → no leakage-effect of FFT

- 1024 Samples in 0.5 ms for 2 multiplexing steps
Hardware Design and Data Acquisition

Package generation

- Main-FPGA collects all data
- Only relevant frequency points are transmitted
- Total data transfer rate: 9.89 MBit/s
Hardware Design and Data Acquisition
Complete System
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GPU Based Image Reconstruction

Algorithm

- Underlying PDE, derived from Maxwell's Equations

\[ \nabla \cdot (\sigma (\vec{r}) \nabla \Phi (\vec{r})) = 0 \]

- Only solvable with ideal boundary conditions
- Better suited is solving an optimization problem

\[ \sigma (V_m) = \arg \min_{\sigma} \| V_m - V_c(\sigma) \|^2 \]

- Algorithm split up into inverse and forward problem
GPU Based Image Reconstruction
Solving Forward Problem

- PDE solved with Finite Element Method

- Domain split up into elements
  - Piecewise constant conductivity
  - Electrical potential interpolated from nodes

- Equation transformed into linear system

\[
\left( S(\sigma) + \left( \frac{n\pi}{z_m} \right)^2 R(\sigma) \right) \vec{V}_n = B\vec{I}_n
\]

\[
S_{i,j}(\sigma) = \sum_{k=1}^{K} \sigma_k \int_{\Omega_k} \nabla u_i \cdot \nabla u_j dV
\]

\[
R_{i,j}(\sigma) = \sum_{k=1}^{K} \sigma_k \int_{\Omega_k} u_i u_j dV
\]
GPU Based Image Reconstruction
Matrix assembly on GPU using Metaprogramming

- FEM model matrices need to be updated often
- Matrices need to be as accurate as possible
- Solution: Analytic integration using Metaprogramming

Matrix assembly algorithm on GPU
GPU Based Image Reconstruction
Matrix assembly on GPU using Metaprogramming

\[ R_{i,j}(\sigma) = \sum_{k=1}^{K} \sigma_k \int_{\Omega_k} u_i u_j dV \]

@kernel
def integrateWithBasis(self, points, ci, cj):
    # create coordinates
    x, y = symbols('x, y')

    # basis function
    ui = self.basis_function([x, y], ci)
    uj = self.basis_function([x, y], cj)

    # equation
    equation = ui * uj

    # integrate on triangle
    return integrateOnTriangle(equation, x, y, points)
GPU Based Image Reconstruction
Matrix assembly on GPU using Metaprogramming

```c
mpFlow::dtype::real mpFlow::FEM::basis::Linear::integrateWithBasis(
    const std::shared_ptr<dLinear> &other
)
{
    return (0);
}
```
GPU Based Image Reconstruction
Solving Inverse Problem

- Newton’s method used for solving inverse problem

\[ \tilde{\sigma}_{n+1} = \tilde{\sigma}_n + \Delta \tilde{\sigma} \]
\[ J(\tilde{\sigma}_n) \Delta \tilde{\sigma} = [V_m - V_c(\tilde{\sigma}_n)] \]

- Very ill-posed
  \( \rightarrow \) Regularization necessary

\[ \Delta \tilde{\sigma} = (J^T J + \lambda^2 L^T L)^{-1} J^T \Delta \tilde{V} \]

- Usually, only one step is performed
  \( \rightarrow \) Differential EIT
GPU Based Image Reconstruction
Pipelining for 1000 FPS

- Data set too small for maximum performance
- Solution: Pipelining
  — reconstruction of multiple images simultaneously
- Tradeoff between Latency and FPS

- Values measured on one Tesla K20
GPU Based Image Reconstruction
Visualization in Real-Time

- Streaming reconstructed data to imaging server (i.e. iPad)
- Only subset of images viewable in real-time
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System in Action
Video Presentation
Conclusion

- Soft-field tomography using non-ionizing radiation
- Pipelining and parallel hardware design necessary
- GPU for solving the linear systems
- Metaprogramming for analytical integration
- Pipelining to better utilize GPU resources
Thank You for your being here ;)}