Large and Massively-Parallel Image Reconstruction Accelerated with the Multilevel Fast Multipole Algorithm

Mert Hidayetoglu, Carl Pearson, Izzat El Hajj, Weng Cho Chew, Levent Guerel, and Wen-Mei Hwu
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Inverse-Scattering Problems

Original Object Imaged
Transmitter
Reconstructed Object

Reconstruction Window

Full-wave methods do not impose any approximation by solving the wave equation with its full glory.

Transmitter
Reconstructed Object

Reconstruction Window

Original Object with High Contrast
Single-scattering Reconstruction
Multiple-scattering Reconstruction

Original Object Imaged with Limited View
Single-scattering Reconstruction
Multiple-scattering Reconstruction

Nonlinear Optimization

There is not a single way to do this, however, we found nonlinear conjugate-gradient method is efficient for this algorithm.

- Gradient-Descent: $\nabla \Phi = -F^H \Phi$
- Conjugate-Gradient: $C \cdot \Phi = \nabla \Phi$
- Newton-Type Methods: $[\mu^2 I + F^H F] \delta \Phi = \nabla \Phi$

\[ F = G_R [I + O_b \{ I - G_b O_b \}^{-1} G_b ] \]

Distortion-Born Approximation

\[ \delta \Phi \approx \delta \Phi^{(1)} = G_b \delta \Phi_b + G_b \Phi_{b,0} \delta \Phi \]

Variational Equation: $\delta \Phi = G_{b,0} \delta \Phi_b + G_b \Phi_{b,0} \delta \Phi$

Discretization with a subspace projection method.

- $O_{b,0}$: Dense, $N \times N$
- $O_{b,1}$: Dense, $N \times T$
- $G_{b,0}$: Dense, $R \times N$
- $F$: Functional Derivative Operator

MLFMA Provides fast solutions of forward-scattering problems with O(N) computational complexity.

Multilevel Fast Multipole Algorithm (MLFMA) Schematic

Level 3: Region A
- Translation
- Multipole Expansions

Level 4: Nearfield
- Nearfield
- Multipole Conv.
- Scattering

Level 5: Basis Pixels
- Basis Pixels
- Nearfield
- Multipole Conv.
- Scattering

Level 5: Testing Pixels
- Testing Pixels
- Far-Field
- Interact.
- Far-Field
- Interact.

Strong Scaling

Parallelizing Illuminations: $2.5 \times 10^4$ GPU Nodes: 40.2 sec.

Parallelizing MLFMA (Simultaneously with illuminations): $4,096$ GPU Nodes: 2.4 min.

Conclusion

- Exploiting multiple-scattering is effective, but has a huge computational burden.
- MLFMA provides algorithmic speedup.
- A hierarchical parallelization strategy improves the scalability on large supercomputers.
- GPUs and multi-core CPUs provide massively-parallel reconstructions.

See More Results & Animations

Future Plans

- Further algorithmic improvements like compressive-sensing.
- 2.5-D and 3-D extensions (not trivial because of computational requirements).
- Real measurement data will be used for imaging. Not trivial because of noise, calibration, etc.