Development of Solid Earth Simulation Platform

Group Representative
Hiroshi Okuda Department of Quantum Engineering and Systems Science, University of Tokyo, Associate Professor

Author
Hiroshi Okuda Department of Quantum Engineering and Systems Science, University of Tokyo, Associate Professor

With respect to GeoFEM, which has been developed as a simulation platform for the solid Earth problems, the following issues are investigated: analysis system coupling by the plug-in strategy, fast linear equation solvers, large-scale parallel visualization, and other general purpose utilities. When using up to 176 nodes of the ES, the computational speed of the static linear analysis by the optimized ICCG solver, has reached 3.8 TFLOPS (33.7% of peak performance of 176 nodes). Parallel visualizer can provide many visualization methods for analysis modules covering scalar, vector and tensor datasets, and have been optimized in parallel performance. The analysis modules plugged in for various solid earth fields have also been vectorized and parallelized suitably for the ES and coupled on memory with the parallel visualizer.

Keywords: Parallel Finite Element Method, Solid Earth Analysis Platform, GeoFEM, Parallel Iterative Solver, Parallel Visualization

1. Overview of Software

GeoFEM consists of the components 'platform', 'analysis modules' and 'utilities'. Platform includes device-independent I/O interface, iterative equation solvers and visualizers. Analysis modules are linked to platform on memory by device-independent interface such that the copies of data should be avoided as much as possible for large scaled-data and high-speed calculations. To deal with various problems of solid earth, analysis modules plugged-in are elastic, plastic, viscoelastic and contact structural analysis, wave propagation analysis, thermal analysis and incompressible thermal fluid analysis modules. Utilities are for domain partitioning and pre/post viewers.

GeoFEM is written in Fortran90 (in C for visualization module). Inter-node parallelization is done by the domain decomposition based SPMD with MPI. For Intra-node parallelization, OpenMP (Pthread for visualization module) is used. Intra-node parallelization and vectorization are done by considering the reordering of the matrices such that the long vector length of the independent operations can be obtained.

2. Optimization of Iterative Solvers and Performance Evaluation

Each subdomain is assigned to one SMP node. In order to achieve efficient parallel/vector computation with unstructured grids, the following 3 issues are critical: 1) Local operation and no global dependency, 2) Continuous memory access, 3) Sufficiently long loops. In order to satisfy these requirements, sophisticated reordering technique has been integrated with parallel iterative solvers with localized preconditioning. The reordering procedures are summarized as follows: (1) RCM (Reverse Cuthil McKee) reordering on the original local matrix for independent sets. (2) CM (Cyclic Multicolor) reordering to obtain loops whose length is sufficiently long and uniform. (3) DJDS (Descending-order Jagged Diagonal Storage) reordering for efficient vector processing, producing 1D arrays of coefficients with continuous memory access. (4) Cyclic reordering for load-balancing among PEs on an SMP node. (5) Parallel DJDS/CM-RCM reordering is complete.

The typical loop structure of the matrix-vector operations for PDJDS /CM-RCM reordered matrices with vector and OpenMP directives is described as follows:

```
do col= 1, COLORtot
  do j= 1, NUmax(col)
!$OMP PARALLEL DO PRIVATE (iS, iE, i) : OpenMP Directive
    do pe= 1, SMP_PE_tot
      iS= NstartU(col,j,pe)
      iE= NendU(col,j,pe)
!CDIR NODEP : Directive for Vectorization
      do i= iS, iE
        (operations)
      enddo
    enddo
  enddo
enddo
```

As shown in Fig.1, simple 3D linear elastic problems up to 2.2×10^9 DOF using 176 SMP nodes (1,408 PEs) have been solved by the localized 3×3 block ICCG(0) with the additive Schwarz domain decomposition and PDJDS/CM-RCM reordering. In this series of computations, DOF per SMP node is fixed. When using 176 SMP nodes, 3.8 TFLOPS (33.7% to peak) has been attained. The work ratios are more than 95%.

3. Development of Integrated Platform for Solid Earth Analysis by Plug-in Strategy

The concurrent visualization with analysis modules on the ES has been developed. Thus, there is no need to save the results generated by analysis modules on the hard disk or transfer huge data by network, which can avoid the limitations of storage capacity for large-scale data. Meanwhile, full use of the ES's huge memory can be made to complete visualization. Moreover, at each time step, multiple visualization methods can be performed to generate visualization results by different visualization methods and different parameters. Two kinds of output styles are provided. One is to output the simplified geometric visual elements to clients. On each client, the users can set viewing, illumination, shading parameter values, and so on, and display the graphic primitives by the GPPView viewing software. On the ES, the users only specify in the batch files the visualization methods such as cross-sectioning, streamlines, and related parameters. The second style is to output an image or a sequence of animation images directly to clients in case that even the simplified geometric primitives are still too large to transfer.

Optimization by three-level hybrid parallelization has been performed on Parallel Surface Rendering and Parallel Volume Rendering modules on the ES, including the message passing for inter-node communication, p-thread or microtasking for intra-node parallelization, and the vectorization for each PE. Furthermore, the dynamic load balancing is considered for achieving good speedup performance.

Visualization images have been obtained by applying the above techniques to some unstructured earthquake simulation datasets, stress analysis of Pin Grid Array (PGA) and flow analysis of outer core. A volume rendered image for 5,886,640 elements and 6,263,201 nodes (image resolution 460*300 pixels) took about 0.977 seconds using 8 SMP nodes, and the speedup of 20.6 was attained by virtue of the three-level of parallelization compared with the result using flat MPI without vectorization. Figure 2 shows the parallel volume rendering image for a large earthquake simulation dataset of the Southwest Japan in 1944, with 2,027,520 elements. With 8 SMP nodes, it took about 1.09 seconds to generate a single image (image resolution: 400*190 pixels), and about 5.00 seconds to generate 16 animation images with a rotation of the viewpoint along the x axis.

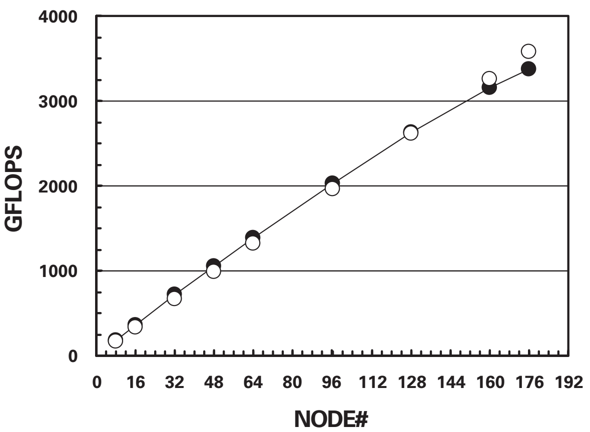

Fig. 1 Problem size and parallel performance (GFLOPS rate) for the 3D linear elastic problem, using up to 176 SMP nodes (Black circle: Flat MPI, White circle: Hybrid)

4. Feasibility Study of the Integrated Platform

Such modules as ground water flow and mass dissipation analysis, tsunami analysis and thermal stress analysis have been plugged in to the platform. Here, we note that not only the iterative solver but also the matrix construction and assembling process are optimized for the ES parallel architecture. Their computational performances are as follows:

- Ground water flow and mass dissipation analysis : 1PE, 2.8 GFLOPS (35% to peak)
- Tsunami analysis : 8 SMP nodes, 222 GFLOPS (43% to peak)
- Thermal stress analysis : 64 SMP nodes, 2.8 GFLOPS/PE (35% to peak)

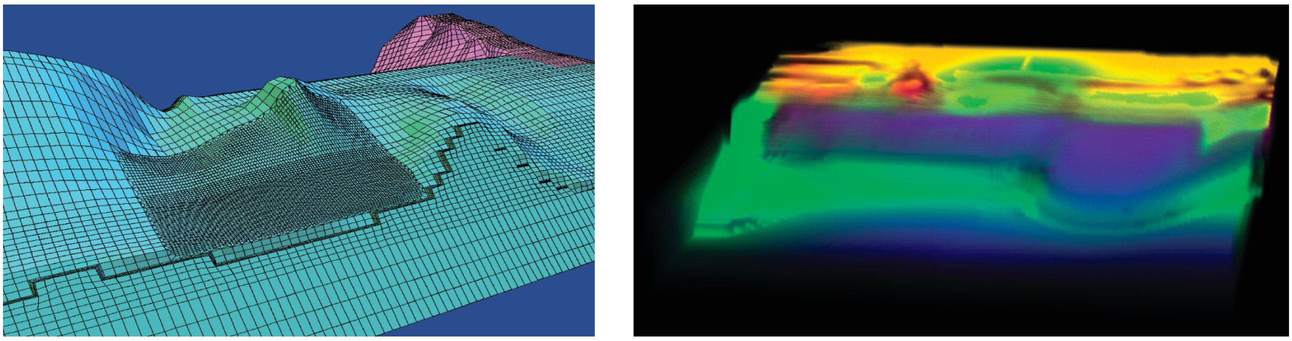

Fig. 2 Parallel volume rendering of a large earthquake simulation dataset of the southwest Japan in 1944, with 2,027,520 elements. Left: complicated mesh of the dataset; Right: a volume rendering image in which the magnitude of the displacement data attribute is mapped to color

The parallel efficiency of the thermal stress analysis module has been evaluated for simple 3D linear elastic problem. A problem of 8.0×10^8 DOF is solved by using 256 and 512 SMP nodes. From their elapsed time and the Amdahl's law, it can be estimated that, when using 512 SMP nodes, 84% of parallel efficiency and 99.9955% of parallelization ratio are attained as shown in Fig. 3. Figure 4 shows the thermal stress distribution of Pin Grid Array (PGA) with 5,886,640 elements and 6,263,201 grid nodes. The figure is generated by the parallel visualization module, which is concurrently connected to the thermal stress analysis module via memory.

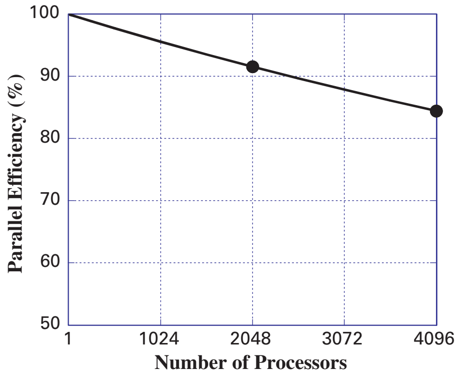

Fig. 3 Parallel efficiency for the 3D linear elastic problem, using up to 512 SMP nodes (4,096 PEs)

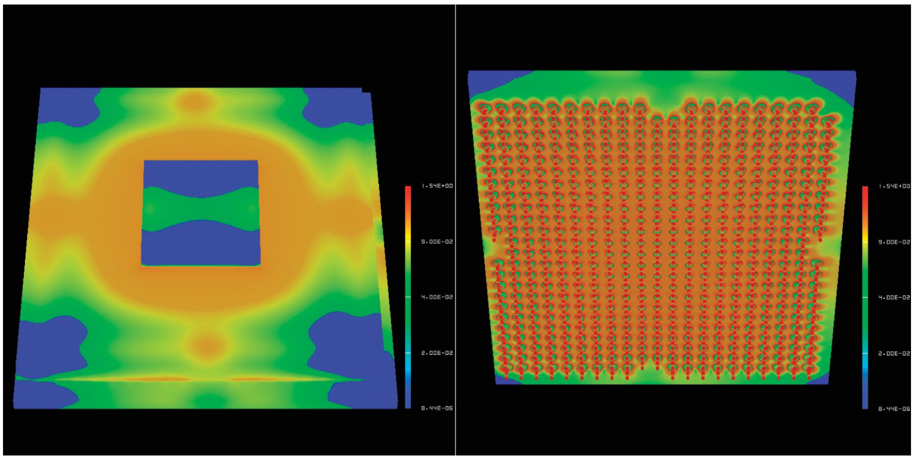

Fig. 4 Thermal stress analysis of PGA with 5,886,640 elements and 6,263,201 nodes

固体地球シミュレーションプラットフォームの開発

利用責任者
奥田　洋司　　東京大学大学院　工学系研究科　システム量子工学専攻　助教授
著者
奥田　洋司　　東京大学大学院　工学系研究科　システム量子工学専攻　助教授

固体地球変動予測のための大規模シミュレーションプラットフォームGeoFEMについて、以下の成果を得た。
① 並列反復法ソルバのSMPクラスタ向け最適化、性能評価
(1) 線形弾性解析ベンチマークにおいて、176ノードまでの使用で同ノード数に対するピーク性能の33.7%(3.8 TFLOPS, 22億自由度)を達成した。
(2) MPI/OpenMPハイブリッドとFlatMPIの性能比較を行い、計算粒度が十分大きい場合(1,200万自由度/ノード)にはほぼ同性能が得られること、などの知見を得た。
② 並列メッシュ生成、反復法ソルバ、固体地球解析サブシステム、可視化、連成解析カプーからなる統合化プラットフォーム開発
(1) Volume Rendering, Surface Mappingの可視化機能について、MPI/ Pthreadハイブリッド、ベクトル化を行った。
(2) 解析部と可視化部のシステム結合を実現した(ダイナモ解析、東北日本断層解析、熱応力解析で実施)。
(3) 並列解析支援ツール群(パーティショナー、PMR (Parallel Mesh Relocator))の移植を行った。
③ 地下水流動・物質拡散、津波、熱応力、の解析サブシステム開発およびシミュレーションの実施を通じた統合化プラットフォームフィージビリティの検討
(1) 地下水流動・物質拡散解析機能、津波解析機能、熱応力解析機能をプラグインし、小規模問題において、弾性解析ベンチマークとほぼ同様の演算性能を確認した。
(2) 熱応力解析機能をプラグインしたシステムにおいて弾性解析ベンチマークを行い、512ノード使用時(このときの解析自由度は8億自由度)に並列化効率84%、並列化率0.999955、を達成した。

キーワード:並列有限要素法、固体地球解析プラットフォーム、GeoFEM、並列反復法ソルバー、並列可視化