High Performance Computing for Fast Hybrid Simulations

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UCDAVIS

Outline

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Real Time Simulations

- Structural and Geotechnical component testing is rate dependent
- Algorithmic measures are only partially fixing the problem
- Goal: use **real time** computational simulations for hybrid testing
- In other words, use real time computational simulations to control the test

Fast Computer Simulations: Various Models and Algorithms

- Implicit vs Explicit (on local and global level, both offer advantages and disadvantages)
- Hierarchy of material models (use only required level of sophistication for the purpose)
- Reduced Order Modeling (ROM) now available for nonlinear models

Standard Application Programing Interface: OpenSees

- Core framework (class libraries UCB, modifications by UCD),
- Material models (UCD, UCB, UCSD, UW, Stanford ...)
- Finite Elements (UCD, UCB, Stanford ...)
- Procedures (loading, dynamics, solution control) (UCD, UCB, Stanford ...)
- Parallel Simulations (Plastic Domain Decomposition, UCD)

- *Official* Manuals available (**UCB**, personally do not like it)
- Our own effort **UCD**, covering only our efforts, but will expand to cover other areas of interest.
  - Theory
  - Command (interactive)
  - Examples (verification and validation)

Fast Computer Simulations: Programming (CompSci)

- Mix and match efficient programming languages (C++, C, Fortran, Tcl, Python...)
- Efficient compilers (GNU, Portland Group, Intel (KAI), Metroworks)
- HPC programming techniques (loop unrolling, template metaprograming...)

Fast Computer Simulations: Hardware

- Fast sequential machines (balance multiple levels of cache and RAM, disk, CPUs clock speed, data bus speed...)
- Parallel machines (SMPs and DMPs, networking...)
- It it time for another Finite Element Machine (NASA endeavor from some 20 years ago)

Symmetric Multiprocessor Parallel (SMP) Machines

- aka Shared Memory Parallel machines (dual core machines count too)
- Shared memory communications, bandwidth 555.831 MB/s, latency: 7.897micro seconds
- Cache coherence problem
- Not scalable above 16 or so CPUs
- High price
- Fine grained parallelism (matrix–vector multiply...)
- Automatic tools for parallelization (somewhat effective)

Distributed Memory Parallel (DMP) Machines

- aka Beowulf clusters (or clusters of SUNs as available at CU in '95)
- Networked communications: bandwidth 74.935 MB/s, latency: 62.487 micro seconds
- Message passing paradigm for parallel programming
- Scalable to a large number of machines (CPUs, thousands)
- Very good price/performance ratio (low)
- Communication controls performance
- problems arise with power consumption, cooling and placement area

Clusters of Clusters

- aka DMPs of SMPs
- SMPs can be used as DMPs, with a very fast network
- Cluster a number of SMPs (dual core machines count too)
- Even better price/performance ratio (low)
- Multiple levels of communication performance
- Very efficient and flexible setup!
- Example: GeoWulf ($8 \times 2 + 1 \times 4 + 1 \times 8 + 4 \times 1$ and adding as funding permits)
- Example: Hemisphere (64×2)

Interdependence of Software and Hardware

- Specifics of the problem dictate the hardware design
- Example #1: large scale (20,000+ DoF) problems (SFSI for example, solids for soils, beams and plates/shells for structure) can be efficiently simulated on DMPs, while SMPs might be too restrictive (size)
- Example #2: Smaller scale problems (1,000+ DoF) can be efficiently simulated on SMPs and/or DMPs (mostly in real time)
- Example #3: Small scale problems (below 1,000 DoF) are best suited for SMPs can be efficiently simulated on SMPs and even DMPs (in real time)
- PDD is designed to take advantage of all the above architectures automatically

Outline

PDD Method: Design Goals

- Graph partitioning → balance multiple phases simultaneously, while also minimizing the inter-processor communications costs
- It is a multi-objective optimization problem (minimize both the inter-processor communications, the data redistribution costs and create balanced partitions)
- Take into the account (deterministic or probabilistic):
  - heterogeneous element loads that change in each iteration
  - heterogeneous processor performance (multiple generations nodes)
  - inter-processor communications (LAN or WAN)
  - data redistribution costs

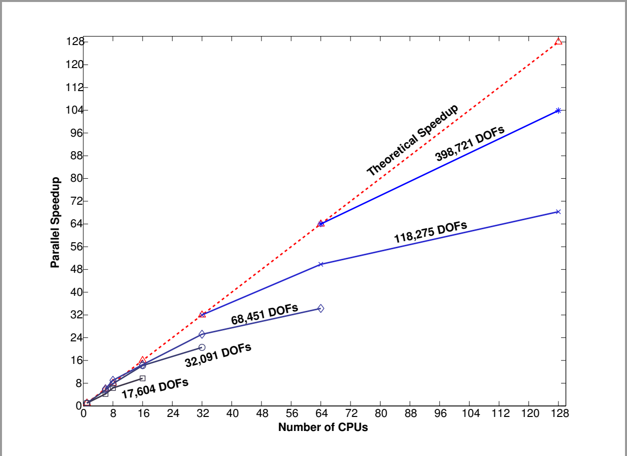
PDD Method: Implementation

- Perform global optimization for both (a) internal state determination and system of equations solution phases
- Adaptive partitioning done using ParMETIS
- Parallel direct and iterative system of equations solvers within PETSC interface. Iterative: CG, GMRES; preconditioners BLOCKSOLVE95, HYPRE and SPAI; Direct: SPOOLES, MUMPS, SuperLU_DIST
- OpenSees: standard interface and framework
- Works on SMPs, local DMPs, grids of computers

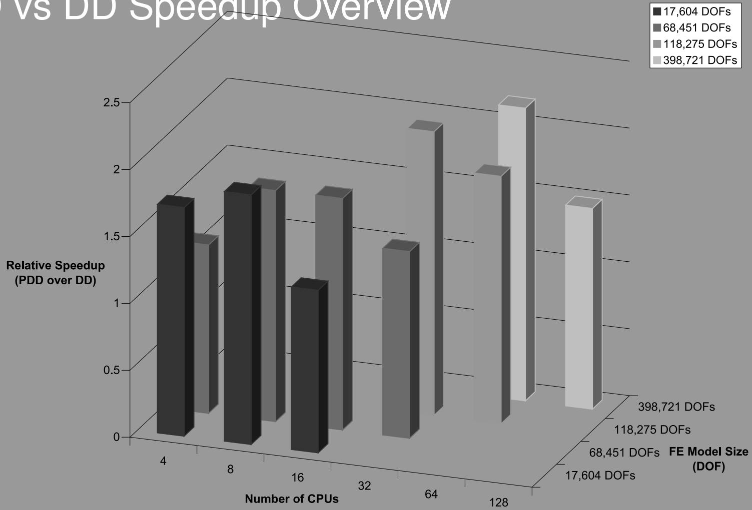
Features

- Initial domain partitioning
- Adaptive domain repartitioning depending on CPU imbalance, LAN and/or WAN performance
- Repartitioning works with loads, constraints..., all necessary movable objects
- Available for elements (solid, structural) with standard OpenSees API (sendSelf, RecvSelf, timer or CL weight estimate)
- Scalable to a large number of CPUs
- Performance tuning (GeoWulf (UCD), TeachingMachine (UCD), Hemisphere (CU Boulder), IA64 (SDSC))

Absolute Speedup Overview



PDD vs DD Speedup Overview



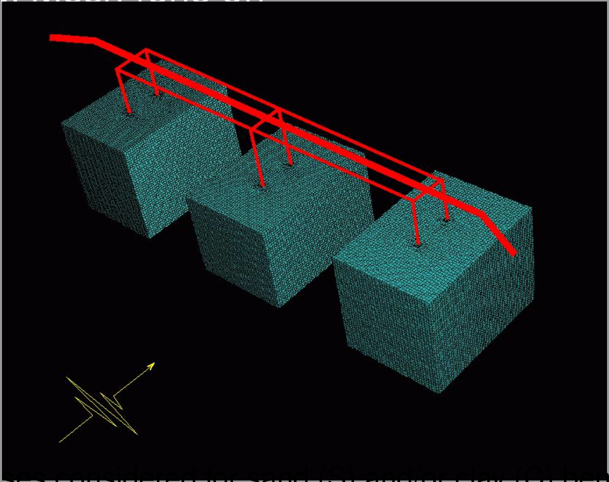
Outline

Detailed 3D FEM model

- Construction process
- Two types of soil: stiff soil (UT, UCD), soft soil (Bay Mud)
- Deconvolution of given surface ground motions
- Use of the DRM (Bielak et al.) for seismic input
- Piles → beam-column elements in soil holes
- Structural model developed at UCB (Fenves et al.)
- Element size issues (filtering of frequencies)

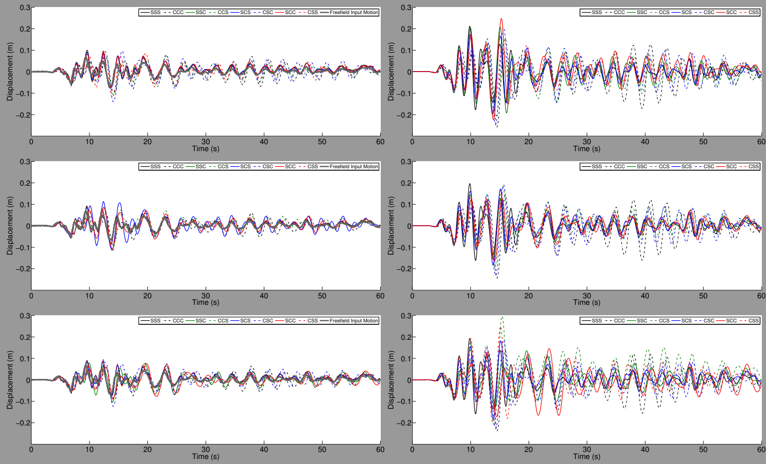
model size	el. size	f_{cutoff}	min. $G/Gmax$	γ
12K	1.0 m	10 Hz	1.0	<0.5 %
15K	0.9 m	>3 Hz	0.08	1.0 %
150K	0.3 m	10 Hz	0.08	1.0 %
500K	0.15 m	10 Hz	0.04	3.0 %

SFSI FEM Mesh (one of)

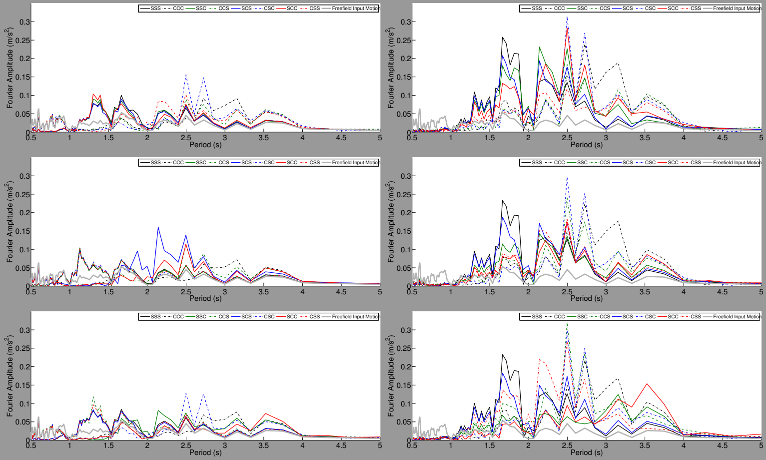


Eight cases considered for sand (S) and/or clay (C) beneath each bent.

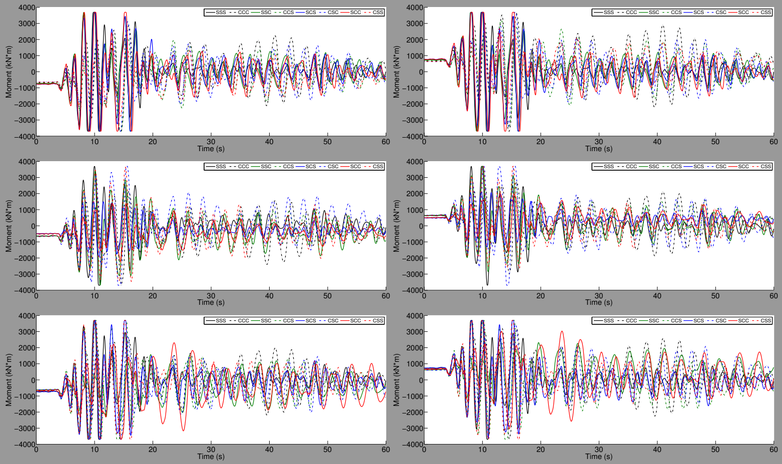
Soil and Structure Displacement Response



Soil and Structure Acceleration Spectra



Top of Columns Moment Response (Redistribution)



Fast Hybrid Testing Model

- Real time (**fast**) simulation is imperative for Fast Hybrid Testing (FHT)!
- Hierarchy of models with different levels of sophistication
  - 2D frame
  - 3D frames
  - 2D excitations
  - 3D excitations
  - material modeling
  - SFSI!

Fast Hybrid Testing Computational Setup

- Parallel computer Hemisphere
- Computer nodes used as DMP of SMPs (cluster of cluster)
- Extremely fast, dedicated interconnect (fiber optics) from Hemisphere to FHT lab (latency below 0.1*ms*)
- Allows for possible expansion of computational resources (at the FHT lab), while maintaining LAN with Hemisphere.
- This will create a cluster of clusters, a very efficient (price/performance) design.
- Current Hemisphere users can (transparently) use additional computational resources as well

Fast Hybrid Testing (outside) Networking

- Connection from UCD (GeoWulf) is not fast enough
- Physics (speed of light) issue,
- GeoWulf (UCD) - 1428.76km - FHT;
- Surface fiber optics, one way trip $\sim 7.0ms$ or ideally in vacuum $\sim 4.8ms$,
- In reality it is $10\times$ that much (and it is probabilistic)
- Similarly SDSC (NEESit) is 1329.79km away from FHT

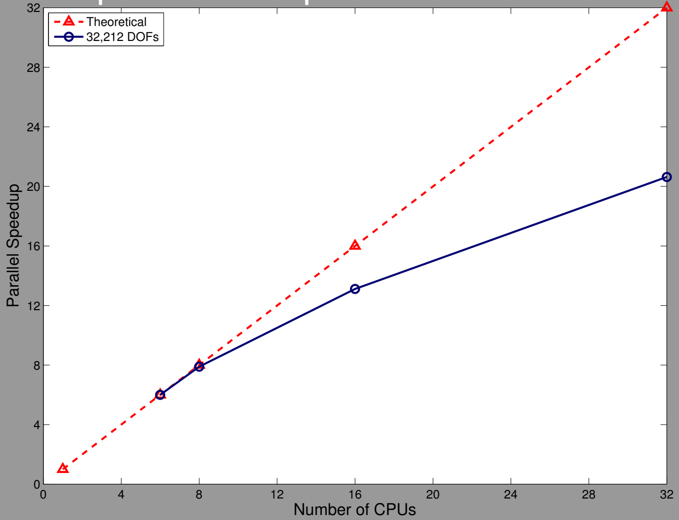
SAC Frame Model, PDD and FHT

- Basic model is a 2D frame on fixed foundations
- Elements and material models: Elastic beams and plastic hinge elements
- Sophisticated model (realistic) is a 3D frame with SFSI effects, 3D seismic wave propagation
- Choice of # of computational nodes on Hemisphere parallel machine depends on a the size and sophistication of the model

Computational Trials

- Very small model (2D, or 3D but no SFSI) uses efficiently up to 8 CPUs
- More sophisticated model (3D, SFSI) uses efficiently 32 or more CPUs
- Very sophisticated model (3D struct., SFSI, 3D seismic waves) uses efficiently all 128 CPUs (and would use more if available)
- For a very sophisticated model the challenge is performance (real time, fast)

Parallel Computer Hemisphere Performance



Summary

- High performance, parallel simulations are needed
  - Fast Hybrid Testing (control)
  - High fidelity model based simulations
  - Soil–Foundation–Structure control during seismic events
  - ...
- PDD parallel finite element code is GPL (available)
- `http://sokocalo.engr.ucdavis.edu/~jeremic/PDD/`