GPU-Accelerated Design Optimization on the Cloud

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Design Optimization

A structure subject to loading

Reduce weight subject to constraints

(GE/GrabCAD)

Design Optimization
Domains

(OptiStruct) (Generico)
Big Players, Big $

- ANSYS
- Abaqus
- Altair/OptiStruct
- Nastran
- SolidWorks
- ...

$10 billion investment annually
technavio.com
Design Optimization on the Cloud

Client
- No software/hardware investment
- Pay as you go
- Anywhere, anytime
- …

Service Provider
- Easier maintenance
- Larger market
- …
3D-Printing

Democratization of fabrication
Democratization of design
Catch?
Design Optimization

Design Space → Finite Element Analysis (FEA) → Optimal?

Change Design

10^5 ~ 10^7 dof
Solve Kd = f
K: Sparse SPD

100’s of iterations!
A naïve port to cloud will not work!
Cloud Based Design Optimization
Cloud Based Design Optimization

Fast Limited Memory FEA
**FEA Bottleneck: \( Kd = f \)**

- **Design Space**
- **Finite Element Analysis (FEA)**
- **Optimal?**
- **Change Topology**

100’s of iterations!

\( 10^5 \sim 10^7 \) dof
Solve \( Kd = f \)
\( K: \) Sparse SPD
15

\( Kd = f \) \((GTC)\)

- Fine-grained Parallel Preconditioners
- CULA
- MAGMA
- Accelerating Iterative Linear Solvers
- Efficient AMG on Hybrid GPU Clusters
- Preconditioning for Large-Scale Linear Solvers
- …
Design Optimization

\[ K_d = f \]

- Exploit mesh congruency
- Exploit physics behavior
- \( K \) constantly changing
- ...
Exploit Mesh Congruency (GTC 2014)

Mesh-aware SpMV Acceleration: Congruence
Observation: Large-meshes contain many similar elements!

Elements are ‘rigid-body/scaling’ congruent

⇒ Identical element stiffness $K_e$

62350 elements
2780 distinct
95.5% congruent

Only store $K_e$ of distinct elements
Implication: SpMV

*Kd*: Sparse Matrix-Vector Multiplication (SpMV)

Critical operation in ALL iterative solvers

**Classic:**

\[ Kd = \sum_{i=1}^{N} (K_e) d \]

**Assembly-free:**

\[ Kd = \sum_{i=1}^{N} (K_e d_e) \]

Only store \(K_e\) of distinct elements + Assembly Free
Experiment

10^6 Elements
1 Distinct element

One Kd (SpMV)

- Same number of FLOPS!
- Reduced memory
Physics Aware Deflation

Model \rightarrow \text{Discretize} \rightarrow \text{Assemble/Solve} \rightarrow \text{Post-process}

Kd = f
Physics Aware Deflation

\[ Kd = f \]

**Deflated CG**

1. Construct the deflation space \( W \)
2. Choose \( d_0 \) where \( W^T r_0 = 0 \) & \( r_0 = f - Kd_0 \)
3. Solve \( W^T K W \mu_0 = W^T K r_0 \); \( p_0 = r_0 - W \mu_0 \)
4. For \( j = 1, 2, ..., m \), do:
   
   5. \[ \alpha_{j-1} = \frac{r_{j-1}^T r_{j-1}}{p_{j-1}^T Kp_{j-1}} \]
   6. \[ d_j = d_{j-1} + \alpha_{j-1} p_{j-1} \]
   7. \[ r_j = r_{j-1} - \alpha_{j-1} Kp_{j-1} \]
   8. \[ \beta_{j-1} = \frac{r_j^T r_j}{r_{j-1}^T r_{j-1}} \]
   9. \[ \text{Solve } W^T K W \mu_j = W^T K r_j \text{ for } \mu \]
   10. \[ p_j = \beta_{j-1} p_{j-1} + r_j - W \mu_j \]
11. End-do

Agglomeration/Grouping

Treat each group as rigid body

\[ \tilde{K}_0 = W^T K W \]

\[ \langle \tilde{K}_0 \rangle << \langle K \rangle \]
Example

3.15 million DOF
Cloud Based Design Optimization

Fast Limited Memory FEA
1. Mesh Congruency
2. AF Deflation

Pareto Optimization
**Design Optimization**

K Matrix: Constantly changing

- Update $K$?
- Update deflation?

$\tilde{K}_0 = W^T KW$

$\tilde{K} = \tilde{K}_0 - W^T (\Delta K_e) W$

$\langle \tilde{K} \rangle \ll \langle K \rangle$

Assembly-free: $Kd \equiv \sum_{i=1}^{N} (K_e d_e)$

Skip deleted finite elements

SpMV accelerates further
Example: Design Optimization

- OptiStruct (commercial)
- Xeon E5 2697, 92 GB
- 20 hours!
- Pareto
- I7 4770, 8 GB
- 42 mins
Framework

Fast Limited Memory FEA

Pareto Optimization

GPU Acceleration
Mesh Aware SpMV on GPU

Assign node a thread

Gather Elements Connected to Node

Initialize $\hat{u} = 0$

For all elements connected to node

Gather Nodal Data for element from global vector

Gather $K_e$ data for the node using Element ID

Update $\hat{u} += u_e^T \cdot K_e$

Synchronize Threads

Write result[node] = $\hat{u}$
Deflation on GPU

Prolongation

\[ W \mu \]

- Assign node a thread
- Gather Group d-o-f for node
- Gather nodal coordinates
- Compute nodal projection to Solution space
- Synchronize Threads
- Write result[node]

Restriction

\[ W^T d \]

- Assign group a block
- Assign node index in the group a thread
- Gather Nodal Data from global vectors for each thread
- Compute nodal projection to workspace
- Synchronize Threads
- Reduce nodal projections corresponding group d – o – f

Use Thread0 to write result[group]
Example: Design Optimization

- OptiStruct (commercial)
  - Xeon E5 2697,92 GB
  - 20 hours!

- Pareto
  - I7 4770,8 GB
  - 42 mins

- Pareto
  - GTX 480,1.5 GB
  - 6 mins
Cloud Based Design Optimization

Fast Limited Memory FEA

Pareto Optimization

GPU Acceleration

WebGL
WebGL & Three.js

WebGL
- JavaScript API for 3D graphics in browsers
- [www.khronos.org](http://www.khronos.org)
- Almost all browsers

ThreeJs
- Higher-level library
- [www.threejs.org](http://www.threejs.org)
- Almost all browsers
Finally ...

Three JS (Browser)
- User interaction
- Geometry display
- Error checking
- Light computing

Geometry, loading design goals

Optimal design, performance results

PareTO (Server)
- Structural analysis
- Optimization
- Load balancing
- Heavy computing
A Pilot Service

www.cloudtopopt.com

- Entry level server
  - E3-1270 V3
  - 8 GB
- Limited to 150,000 degrees of freedom
- 300+ users

www.3ders.org
3D printer and 3D printing news

Optimize your STL designs for 3D printing using this new browser-based software

Dec 9, 2014 | By Alec
Available compute time: 2190.24 (secs)

Time estimates for this model
StaticFEA: 2.70 (secs)
ModalFEA: 6.50 (secs)
Topopt: 21.6 (secs)
Available compute time: 2214.402 (secs)

Time estimates for this model
StaticFEA: 5.20 (secs)
ModalFEA: 12.5 (secs)
Topopt: 66.6 (secs)
Plans

www.cloudtopopt.com

- Port to HPC provider
- NSF funding
- Launch startup
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