GPU-Enabled Computing in Robotics and Advanced Manufacturing Applications

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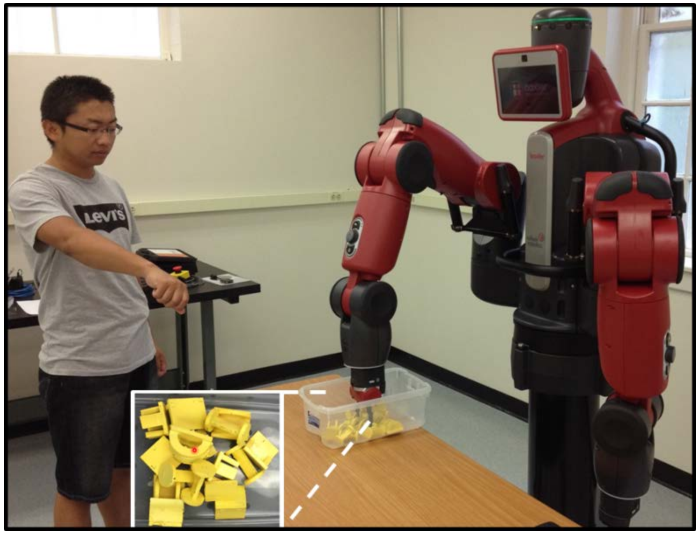
Motivation

- Robotics and manufacturing applications utilize extensive geometric and physical simulations
- Simulations are needed to enable automated planning and optimization
- High simulation fidelity is very important
- High simulation speed is needed to solve problems in a reasonable amount of time



Autonomous Unmanned Surface Vehicles

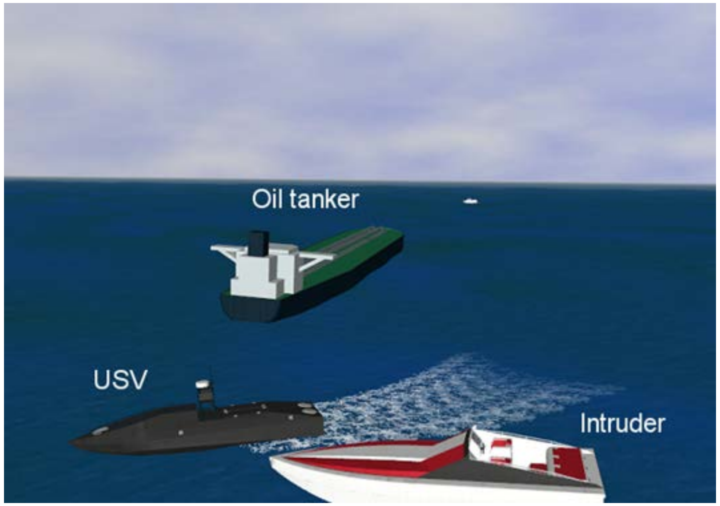
Sponsor: Office of Naval Research

Collaborators: Max Schwartz, Brual Shah, Petr Švec, and Atul Thakur

Introduction

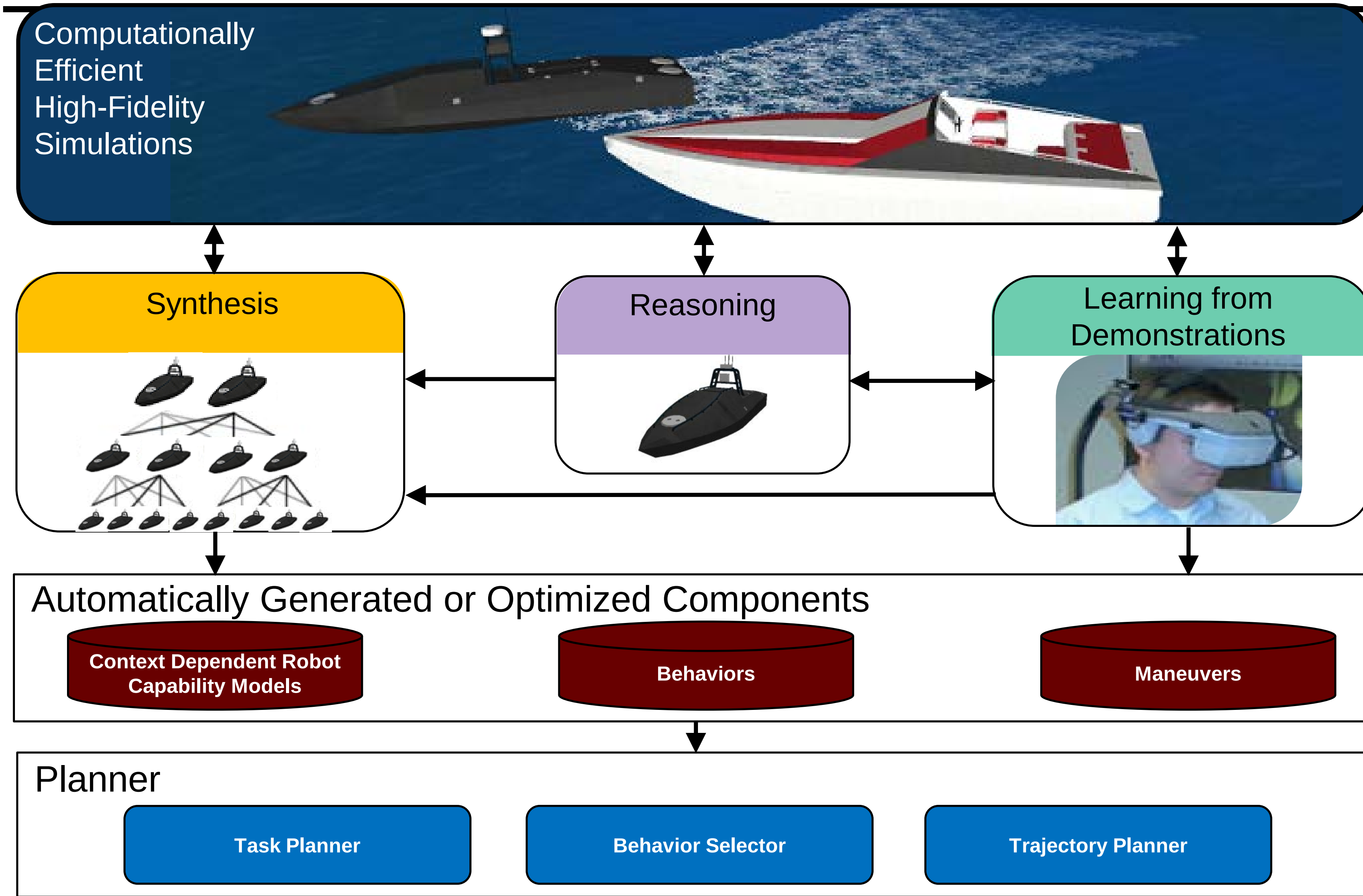
- Autonomous operations in complex environments require combination of deliberative and reactive components
- Manual design and tuning of behaviors for large variety of missions requires significant effort and is not scalable!
  - Boats may have different physical capabilities
  - Environment imposes motion as well as sensing uncertainties

Unmanned Surface Vehicle (USV)



Simulation Environment

Overview of Approach



USV Simulation

Compute velocity potential

$$\phi = \sum_{j=1}^{Q} \frac{gA_j}{\omega_j} \exp(k_j z) \sin(k_j x \cos\theta_{w,j} + ky \sin\theta_{w,j} - \omega_j t + \psi_j)$$

Intersect USSV geometry with wave elevation

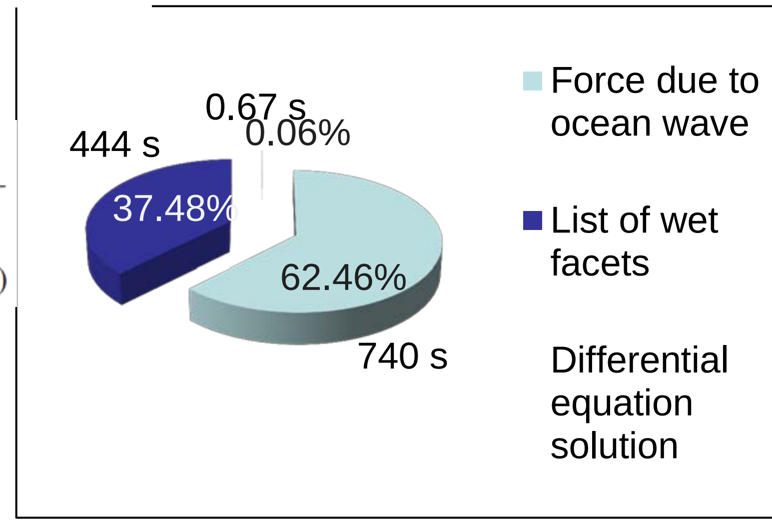
$$\eta(x,y,t) = \sum_{j=1}^{Q} A_j \cos(k_j x \cos\theta_{w,j} + k_j y \sin\theta_{w,j} - \omega_j t + \psi_j) + 0.5A_j^2 k_j \cos(2k_j x \cos\theta_{w,j} + 2k_j y \sin\theta_{w,j} - 2\omega_j t + 2\psi_j)$$

Compute wave force

$$F_W = \begin{bmatrix} \rho \oint_{S_B} \left[\frac{\partial\phi}{\partial t} + 0.5\nabla\phi.\nabla\phi\right] d\vec{S} \\ \rho \oint_{S_B} \left[\frac{\partial\phi}{\partial t} + 0.5\nabla\phi.\nabla\phi\right] \left(\vec{r} \times d\vec{S}\right) \end{bmatrix}$$

Compute position and velocity

$$M_H\dot{v} + C_H(v)v + D_H(v)v + g(p) = F_E + F_P$$
$$\dot{p} = J_p(v)$$



- Test done on boat model with 916 facets for 1500 simulation time step of size 0.07 s
- Simulation performed on computer with Intel Core Quad 2.83GHz CPU and 8GB RAM

Computation of simulation time step (of size 0.07 s) requires ~0.8 s

USV Simulation Model Speedup

- Developed high-fidelity simulation model and corresponding physics based meta-model
  - Six DOF dynamics model
  - Geometric model simplification techniques to speed up computations
  - Combined with GPU computing

http://youtu.be/NCXSFZ4xxkg

Summary of Simulation
Speed-up During Transition Probability Computation

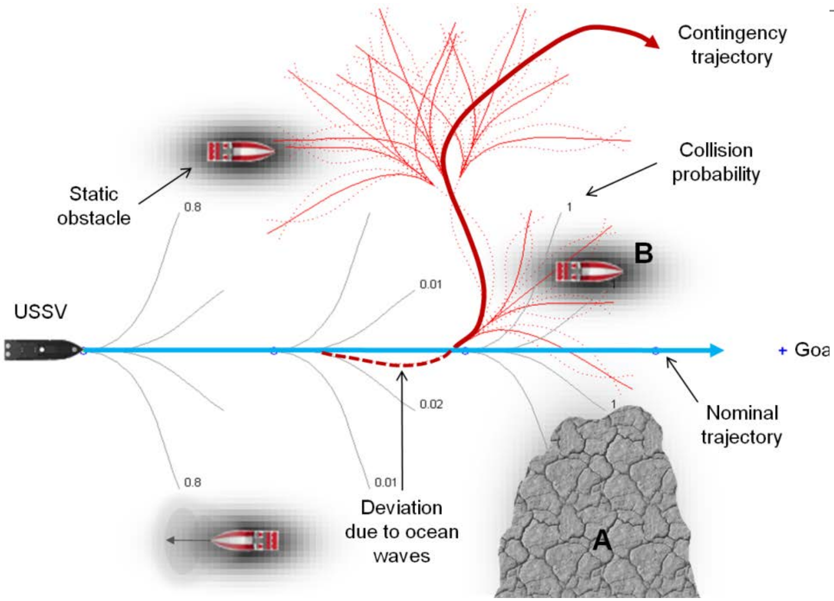
	CPU baseline	GPU baseline	CPU with clustering and temporal coherence	GPU with temporal coherence
Computation time (min)	395.0	28.2	80.2	9.1
Speedup Factor over CPU baseline	1.0	14.1	4.9	43.4
Error %	0.0	0.0	1	1

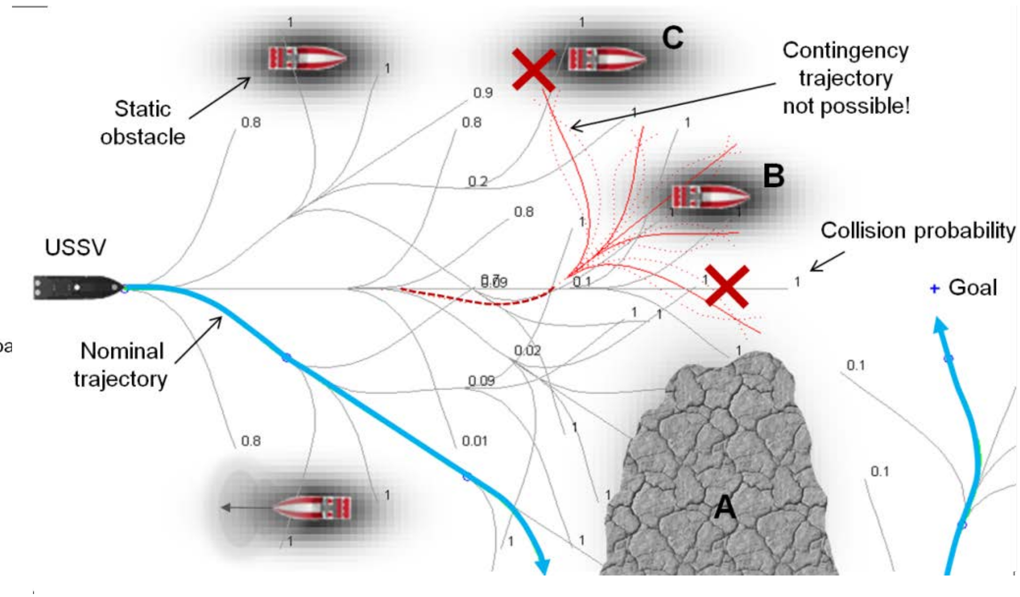
Computations done for 4800 nodes, 7 actions, and 256 samples with time span of each action 10 s

Computation speed-up by a factor of 43 with error of 1%

- A. Thakur, and S.K. Gupta, Real-time dynamics simulation of unmanned sea surface vehicle for virtual environments. *Journal of Computing and Information Science in Engineering*, 11(3), 2011.
- A. Thakur, P. Švec, and S.K. Gupta. GPU Based Generation of State Transition Models Using Simulations for Unmanned Sea Surface Vehicle Trajectory Planning. *Robotics and Autonomous Systems*, 60(12), 1457–1471, 2012.

Computing Trajectories for Various Sea States





- P. Švec, M. Schwartz, A. Thakur, and S. K. Gupta. Trajectory Planning with Look-Ahead for Unmanned Sea Surface Vehicles to Handle Environmental Disturbances. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '11), San Francisco, CA, USA, pp. 1154-1159, 2011.
- A. Thakur, P. Švec, and S.K. Gupta. GPU Based Generation of State Transition Models Using Simulations for Unmanned Sea Surface Vehicle Trajectory Planning. *Robotics and Autonomous Systems*, 60(12), 1457–1471, 2012.

Simulation of Optical Micromanipulation

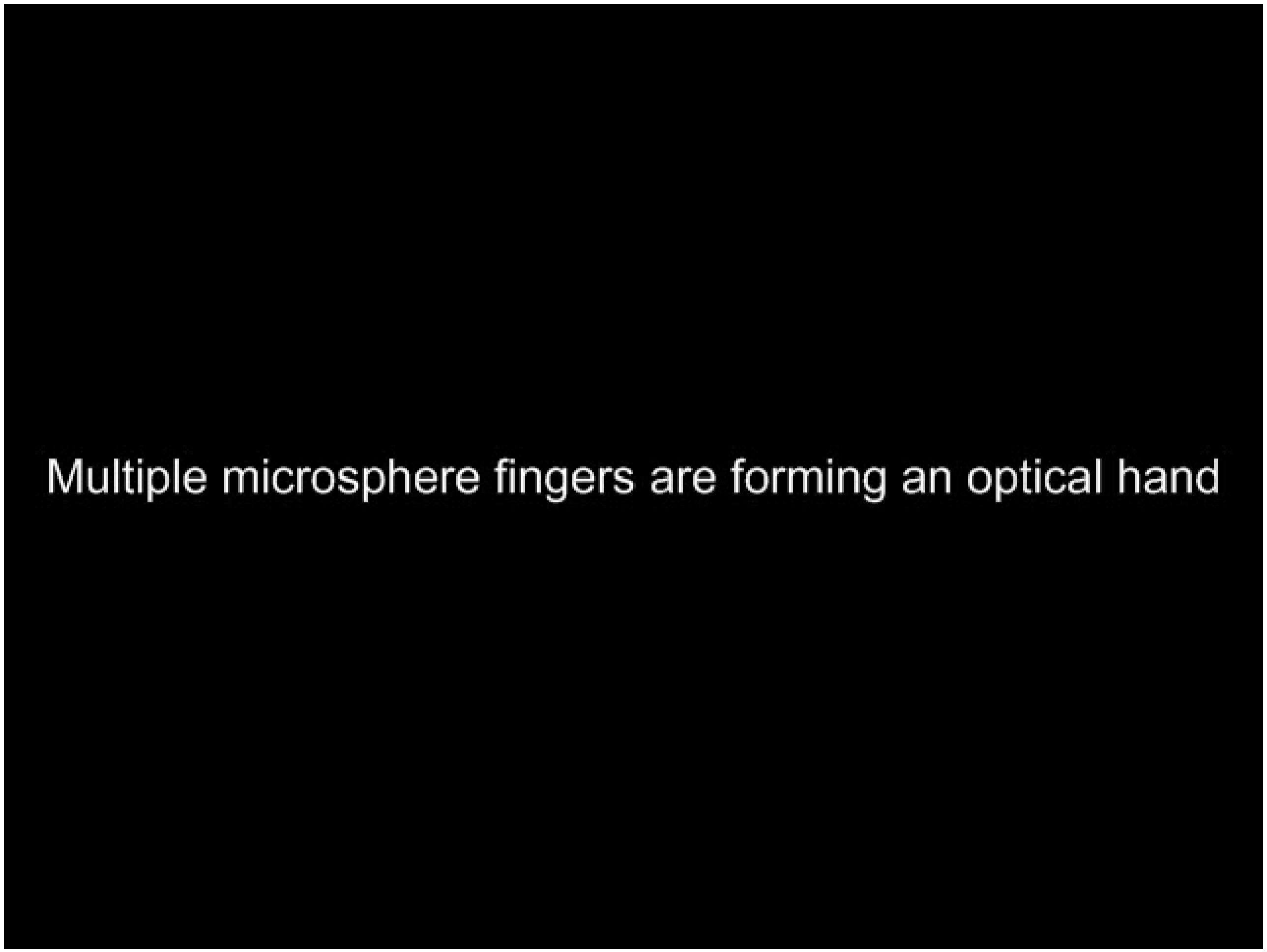
Sponsor: National Science Foundation

Collaborators: Sujal Bista, Sagar Chowdhury, and Amitabh Varshney

Optical Trapping

Non-contact micro and nano-manipulation technique

Optical Hand



Simulation Challenges

- Simulation is computationally intensive
  - Brownian motion in fluid
  - Interacting particles
  - Laser particle interactions
  - Very small time steps

Approach

- GPU based
- 3D grid data structure
- Steps
  1. Ray Object Intersection
  2. Force Calculation
     I. Using ray tracing
     II. Using Non-Negative Matrix Factorization
  3. Force Integration

Summary

- The GPU-based application computes the forces when laser beams interact with multiple microparticles
- On 32 interacting particles, GPU-based application is able to get approximately a 66-fold speed up compared to the single core CPU implementation of traditional approach

Automated Mold Design

Sponsor: National Science Foundation

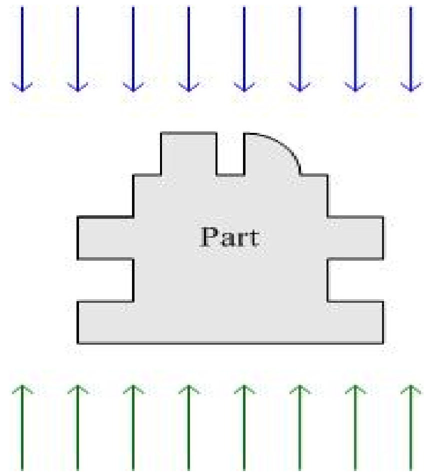
Collaborators: Ashis Banerjee and Alok Priyadarshi

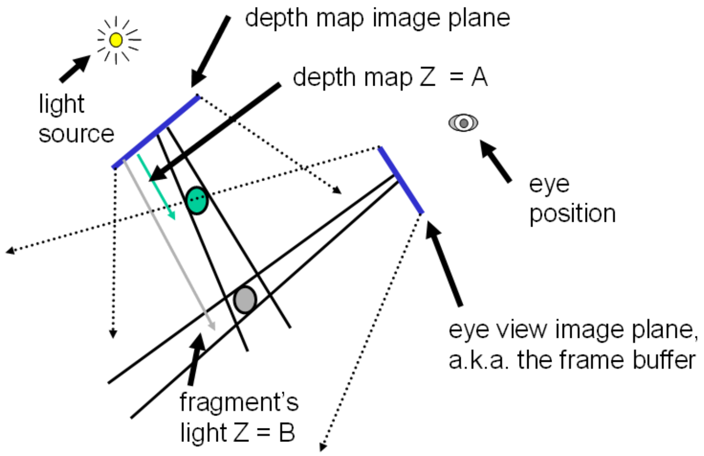
Mold Design

- A surface is moldable from a direction if it is accessible in that direction
- Given a parting direction ***d***, each mold-piece region has the following property
  - Core (C_o) is accessible from +***d***, but not –***d***
  - Cavity (C_a) is accessible from –***d***, but not +***d***
  - Both (B_o) is accessible from both. +***d*** and –***d***
  - Undercut (U_c) is not accessible from either +***d*** or –***d***
- Perform accessibility analysis of the part along the parting direction

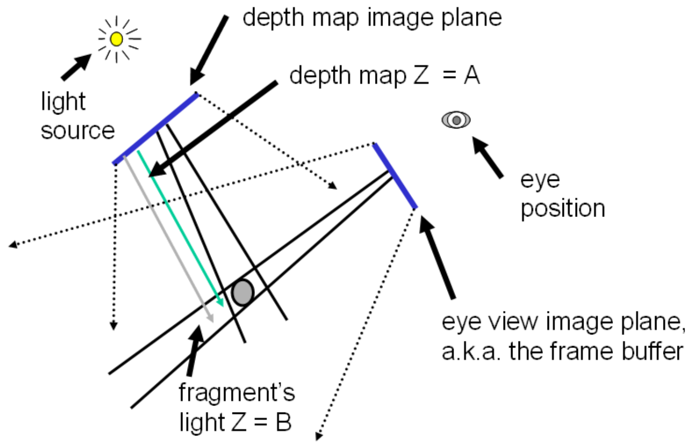
GPU-Based Algorithm

- Place two directional lights above and below the part
  - Regions lit by the upper light form *core region*
  - Regions lit by the lower light form *cavity region*
  - Regions lit by both lights form *both region*
  - Regions in shadow form *undercut region*
- Use shadow mapping two-pass algorithm
  - Render depth buffer from the light's point-of-view
  - Render scene from the eye's point-of-view



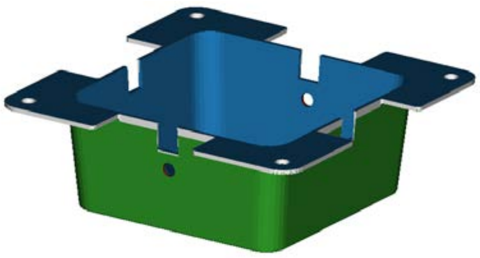


The A < B shadowed fragment case



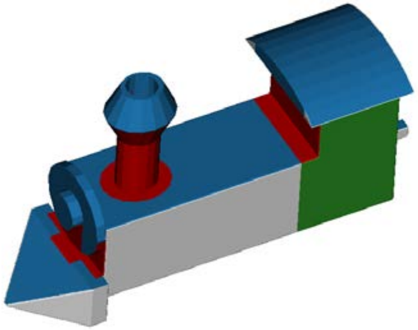
The A ≅ B unshadowed fragment case

Results

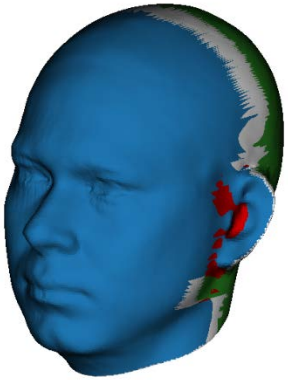


2219 facets, 16 ms

3122 facets, 17 ms



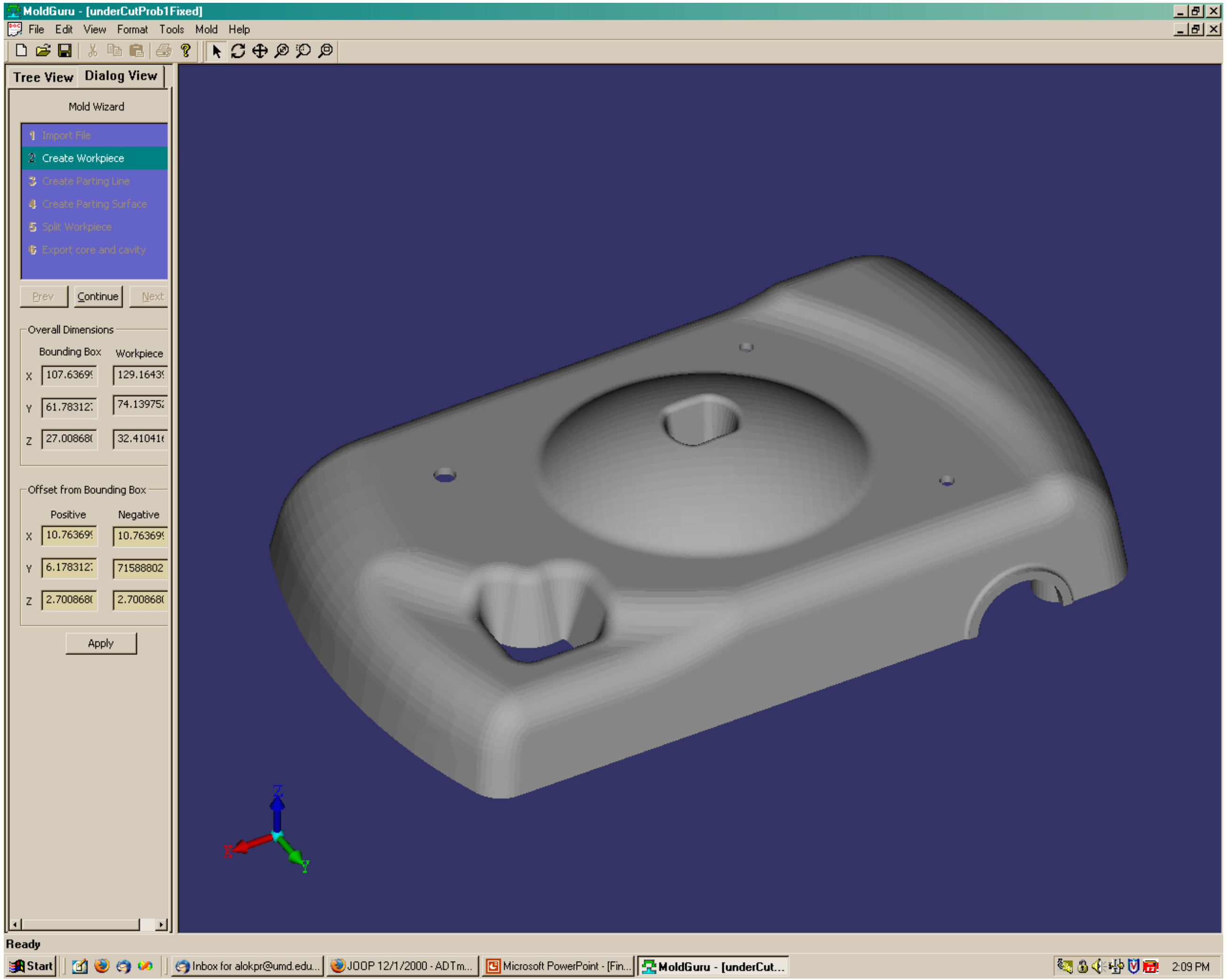
5716 facets, 17 ms



50,000 facets, 20 ms

- Implemented as shader programs
  - Vertex program operates (transforms) on each vertex
  - Fragment program operates (colors) on each fragment
  - Can be executed on any OpenGL 2.0 compliant GPU
- Color Scheme
  - Core – Blue
  - Cavity – Green
  - Both – Gray
  - Undercut – Red

Load Part



MoldGuru - [underCutProb1Fixed]
File Edit View Format Tools Mold Help
Tree View
Dialog View
Mold Wizard
1 Import File
2 Create Workpiece
3 Create Parting Line
4 Create Parting Surface
5 Split Workpiece
6 Export core and cavity
Prev
Continue
Next
Overall Dimensions
Bounding Box
Workpiece
X 107.63699 129.16439
Y 61.78312 74.13975
Z 27.00868 32.41041
Offset from Bounding Box
Positive
Negative
X 10.76369 10.76369
Y 6.178312 71588802
Z 2.700868 2.700868
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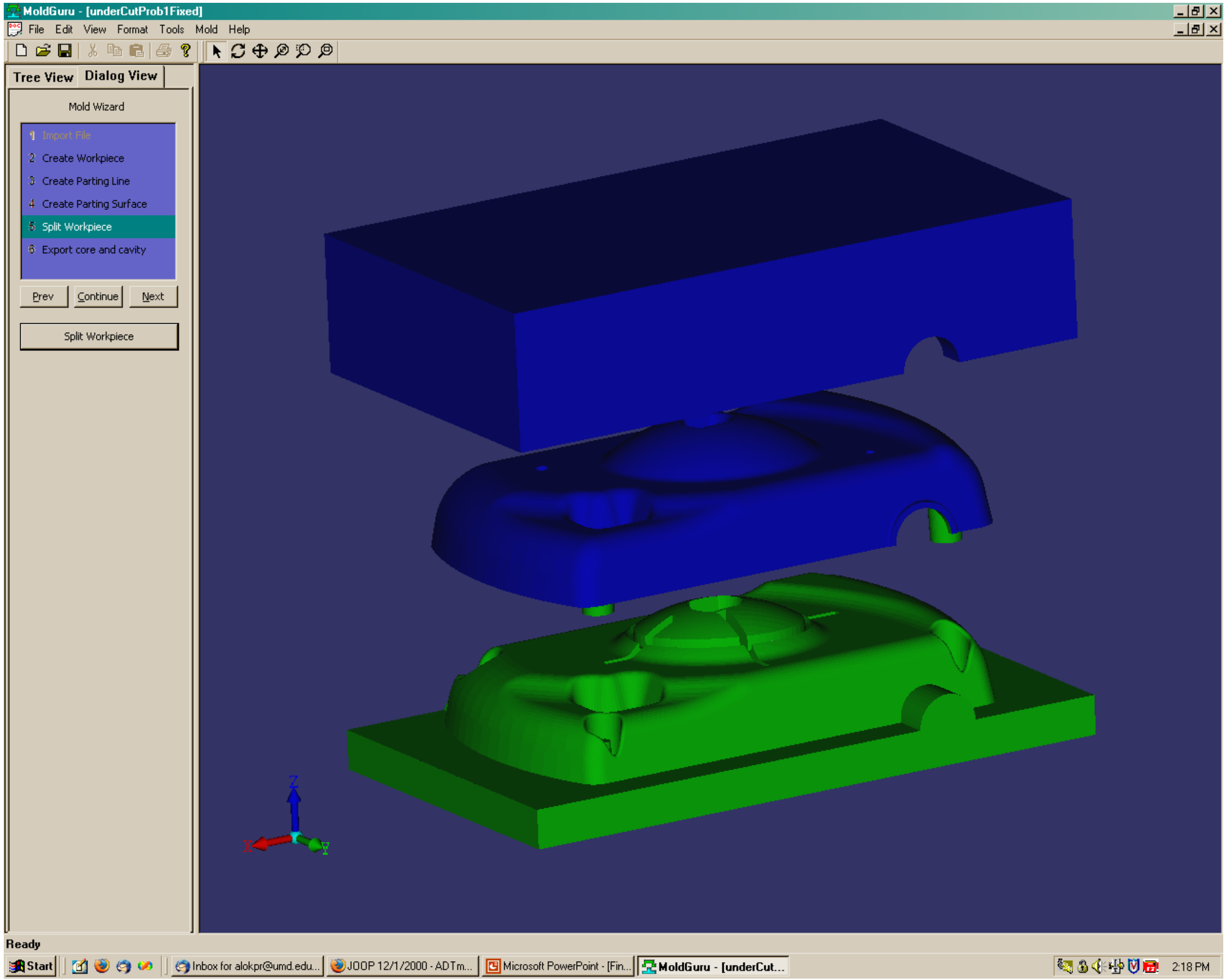
Create Mold



MoldGuru - [underCutProb1Fixed]
File Edit View Format Tools Mold Help
Tree View
Dialog View
Mold Wizard
1 Import File
2 Create Workpiece
3 Create Parting Line
4 Create Parting Surface
5 Split Workpiece
6 Export core and cavity
Prev
Continue
Next
Split Workpiece
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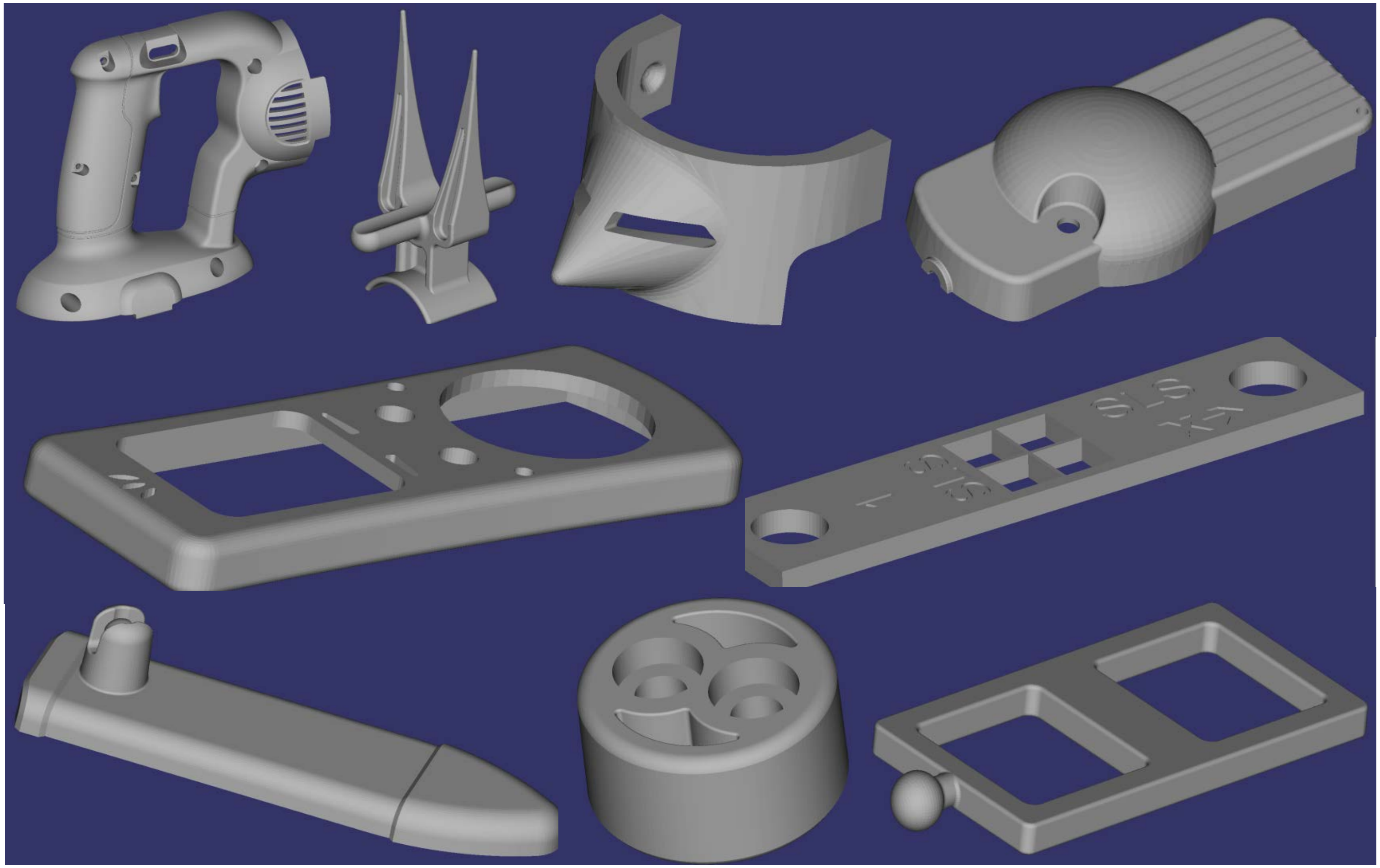
Some Example Parts



Conclusions

- High speed high fidelity simulations are very useful in automated planning and optimization applications on advanced manufacturing and robotics
- There are numerous opportunities
- Wider adoption of GPU technology in these applications will require publicly available libraries
- There is significant interested in cloud computing in robotics

Questions?