Real-time modeling of tool and wheel interactions with soil for mining applications

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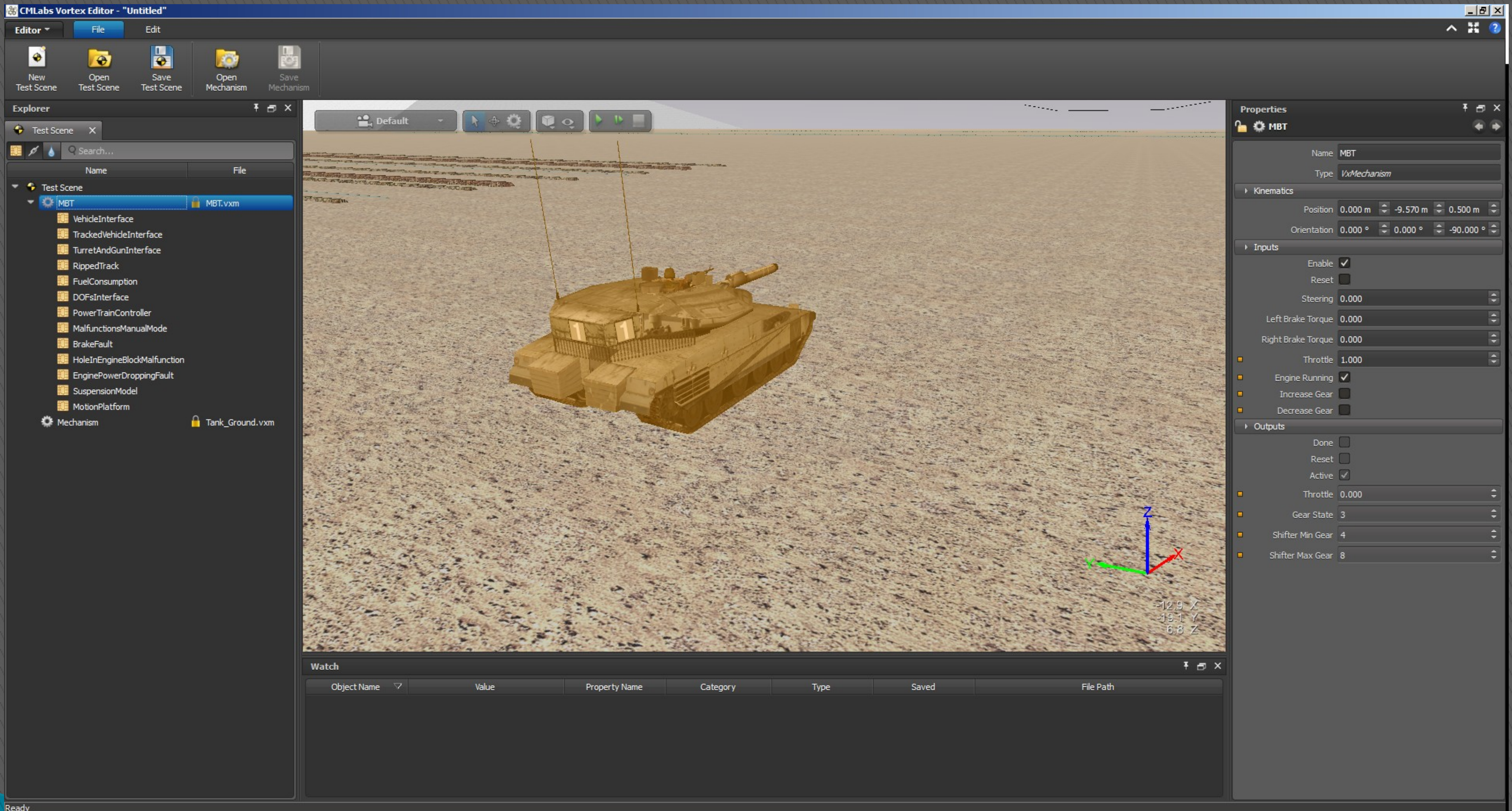
CMLabs Simulations Inc.

Vortex Multibody Simulation Library

- Real-time, high fidelity, rigid body dynamics
- Extensive set of Multibody Constraints (2 to 6+ bodies)
- Collision Detection and Response
- LCP and Iterative solvers on Lagrangian formulation
- Advanced Modules:
  Cables, Vehicles, Soft Terrain Tire Model (Wong), Fluid
- C++ Toolkit and Visual Editor

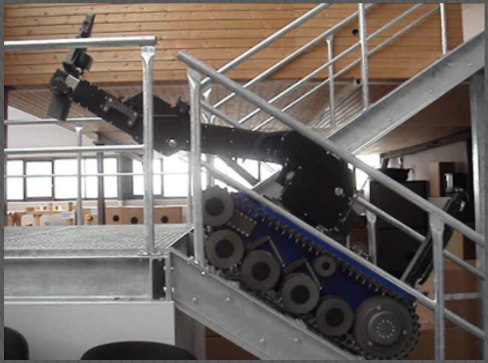
CM LABS

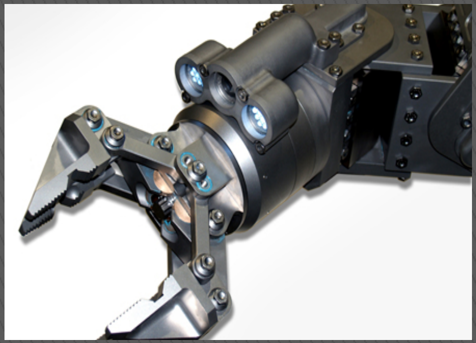
Vortex Editor



Vortex Multibody Simulation Library Applications

More Applications





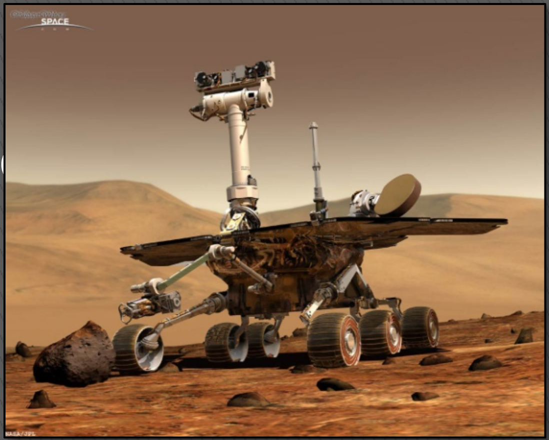
- CSA ESM Mobility Platform

Soft Soil Tire Model

Soil/Wheel Interaction

Soft Soil Wheel Interaction
Motivation

- Vehicle performance defined by whe
ground interface:
  - wheel radius, grouser shape
  - vehicle weight
  - soil properties



- Applications in Military and Rover mobility

- Heavily influences vehicle design and operation (training value)

Soft Soil Wheel Interaction
Motivation

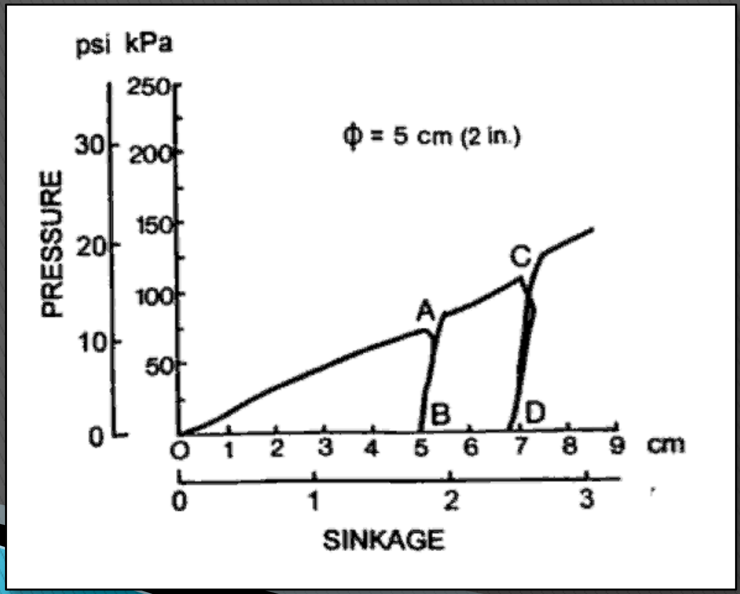
- Example: Spirit Rover 2006 and 2009

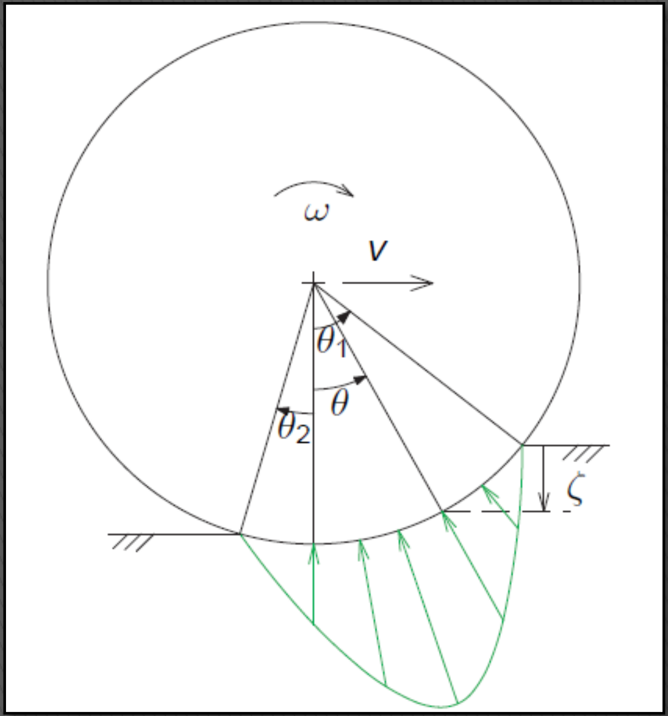
Pictures: nasa.gov

Soft Soil Wheel Interaction

Method

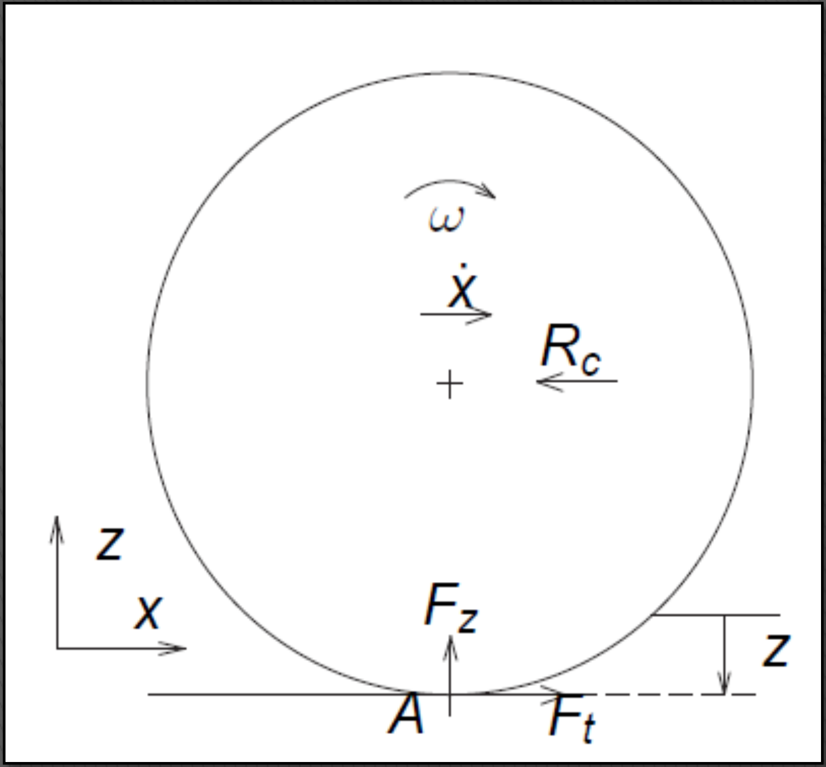
- Semi-empirical models based on Bevameter tests, measuring relation between pressure and sinkage
- Models suppose a stress distribution vs. sinkage
- Ex: Bekker and Wong model





Soft Soil Wheel Interaction
Method

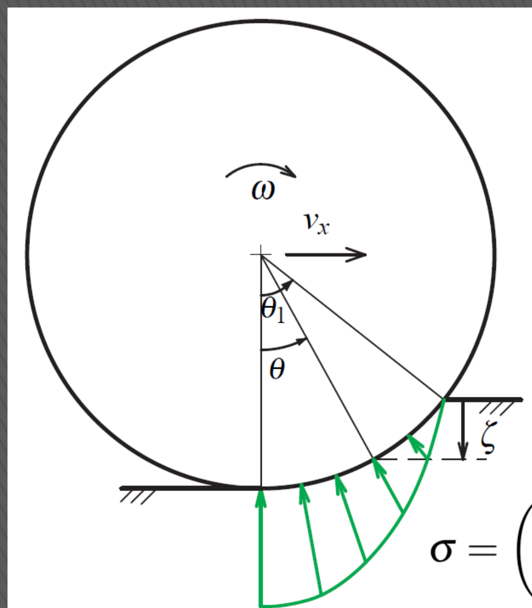
- Normal force (Fz), traction forces (Ft) and rolling resistance (Rc) computed from the selected model are injected in Vortex contact model



CM LABS

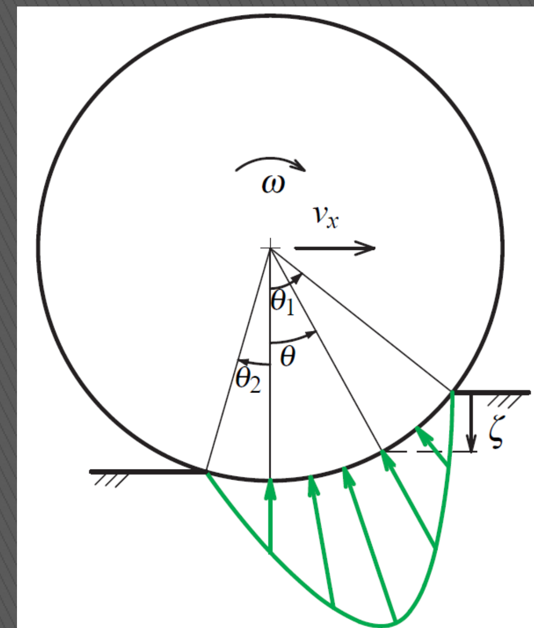
Semi-empirical Models

- Normal stress under the wheel:



$$\sigma = \left(\frac{k_c}{b} + k_\phi\right) \zeta^n$$

Bekker model



Wong and Reece model

- Shear stress under the wheel:

$$\tau(\theta) = (c + \sigma(\theta)\tan\phi)\left[1 - \exp\left(-\frac{|j_x(\theta)|}{K_x}\right)\right] \operatorname{sign}(j_x)$$

$$j_x(\theta) = R[(\theta_1 - \theta) - (1 - i_s)(\sin\theta_1 - \sin\theta)]$$

Semi-empirical Models (cont.)

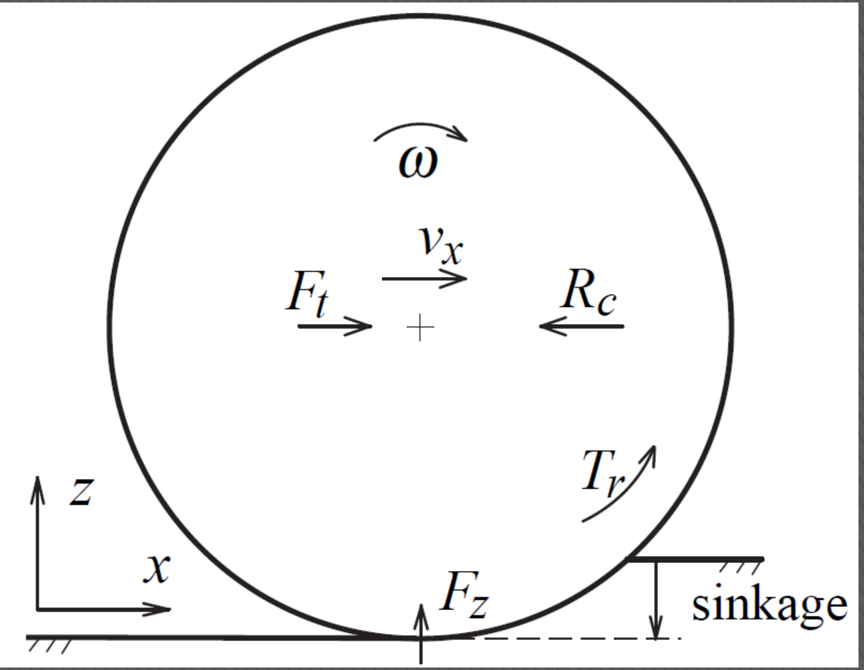
$$F_z = Rb \int_{\theta_2}^{\theta_1} [\tau(\theta)\sin\theta + \sigma(\theta)\cos\theta]\, d\theta$$

$$R_c = Rb \int_{\theta_2}^{\theta_1} \sigma(\theta)\sin\theta\, d\theta$$

$$F_t = Rb \int_{\theta_2}^{\theta_1} \tau(\theta)\cos\theta\, d\theta$$

$$T_r = R^2 b \int_{\theta_2}^{\theta_1} \tau(\theta)\, d\theta$$

r: wheel radius
b: wheel width

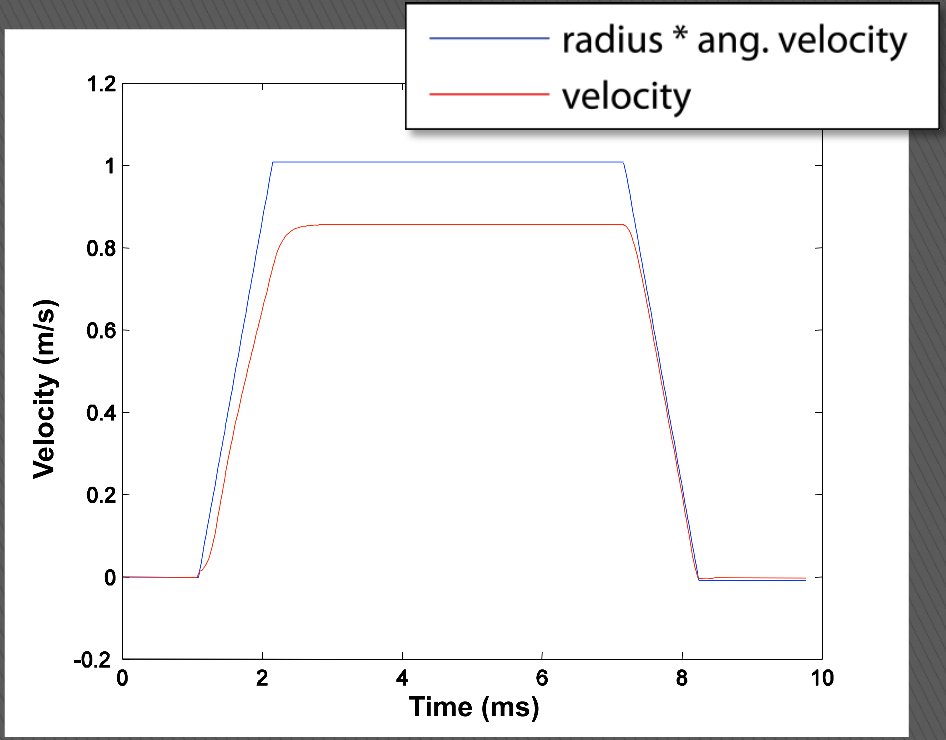


- Implementation of these relations in *Vortex* and necessary modifications are discussed by Azimi et al. (2010).

Soft Soil Wheel Interaction
Results

- Validation Procedure:
  compare dynamic Vortex simulation results with Steady State model (in Matlab)

- Simple Scenario:
  Vehicle driving straight



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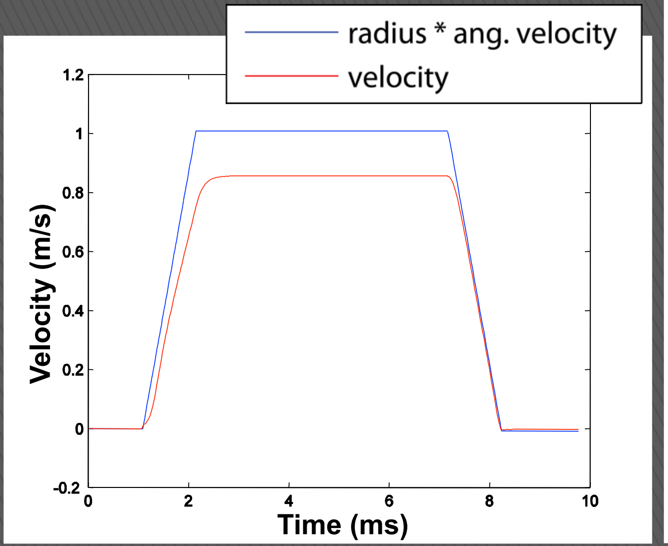
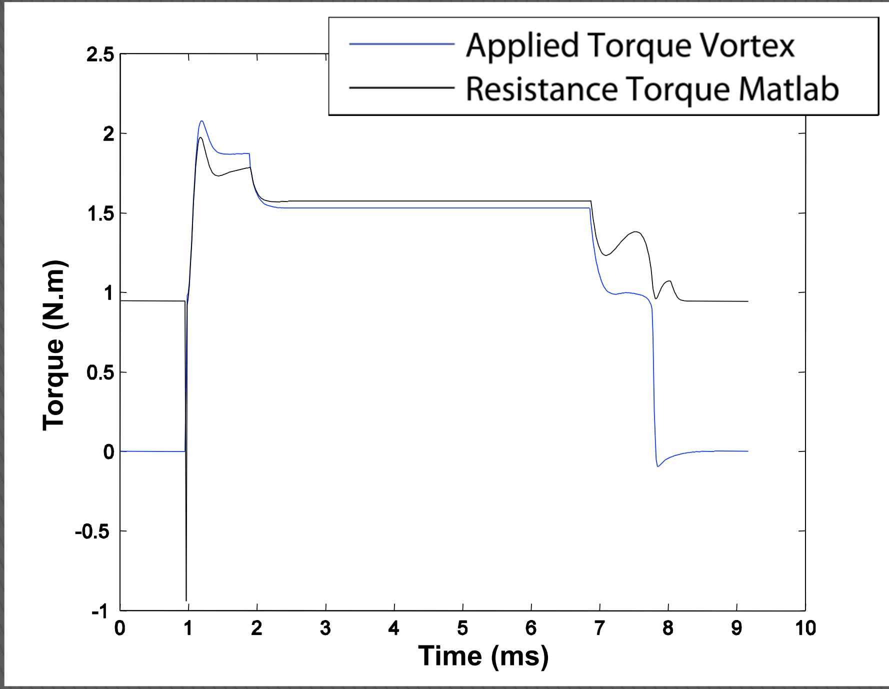
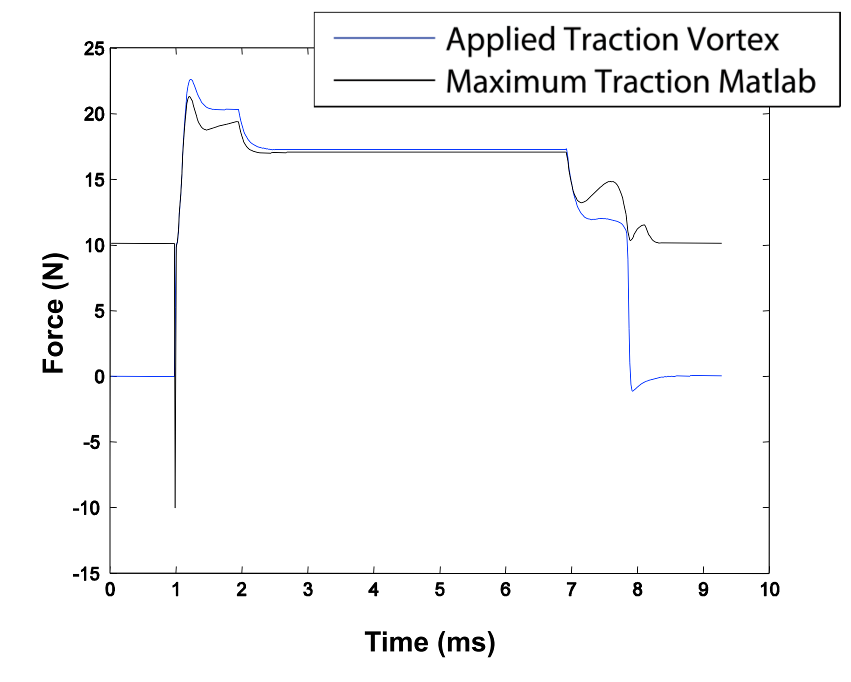
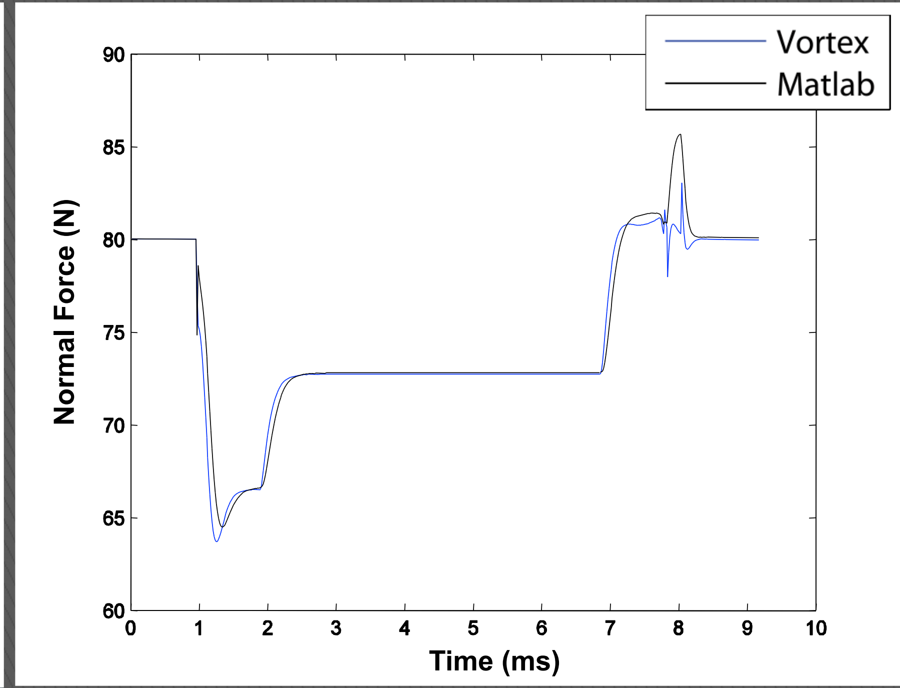
Soft Soil Wheel Interaction

Results







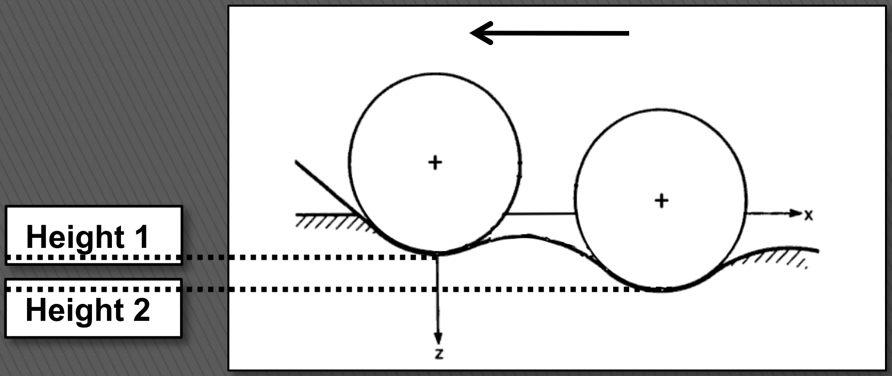


Deformable Terrain Simulation

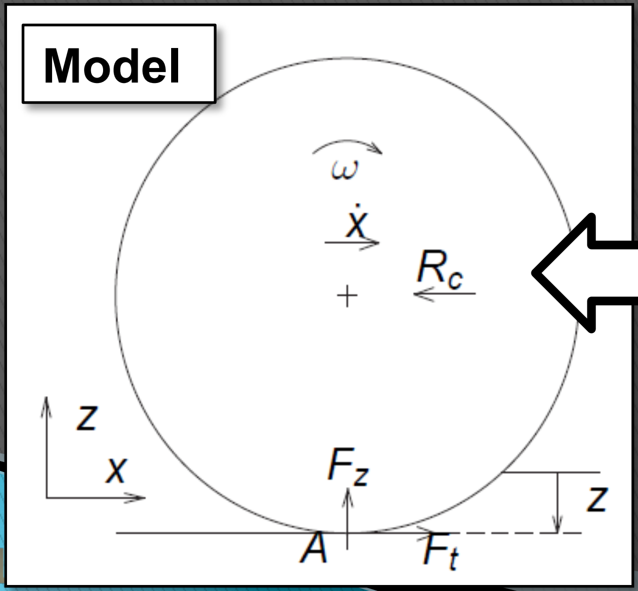
- Compaction

Soft Soil Wheel Interaction
Recent Improvements

- Consider ground deformation/compaction
- Enable multi-pass effect:

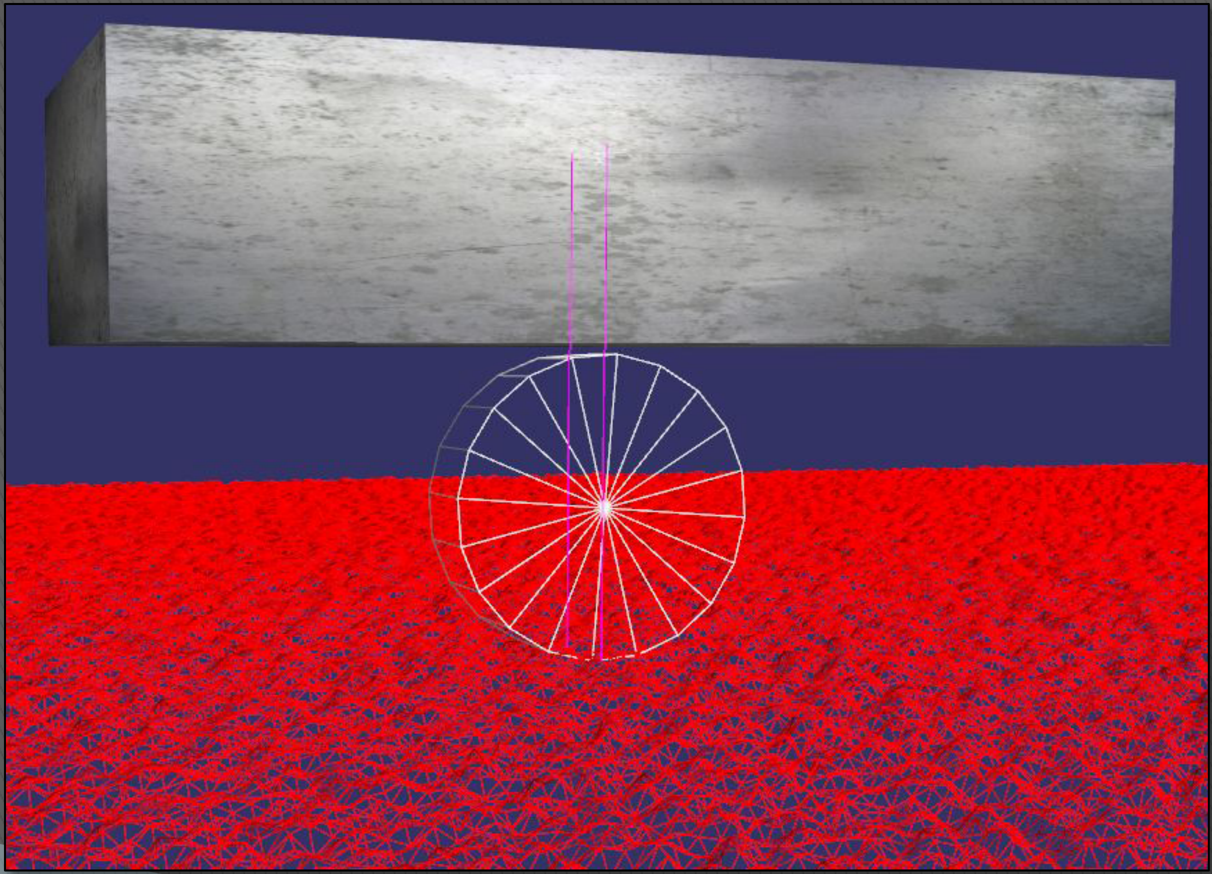


Problem: rough surfaces hard to model!



Soft Soil Wheel Interaction
Modeling Compaction

- Use heightfield terrain representation



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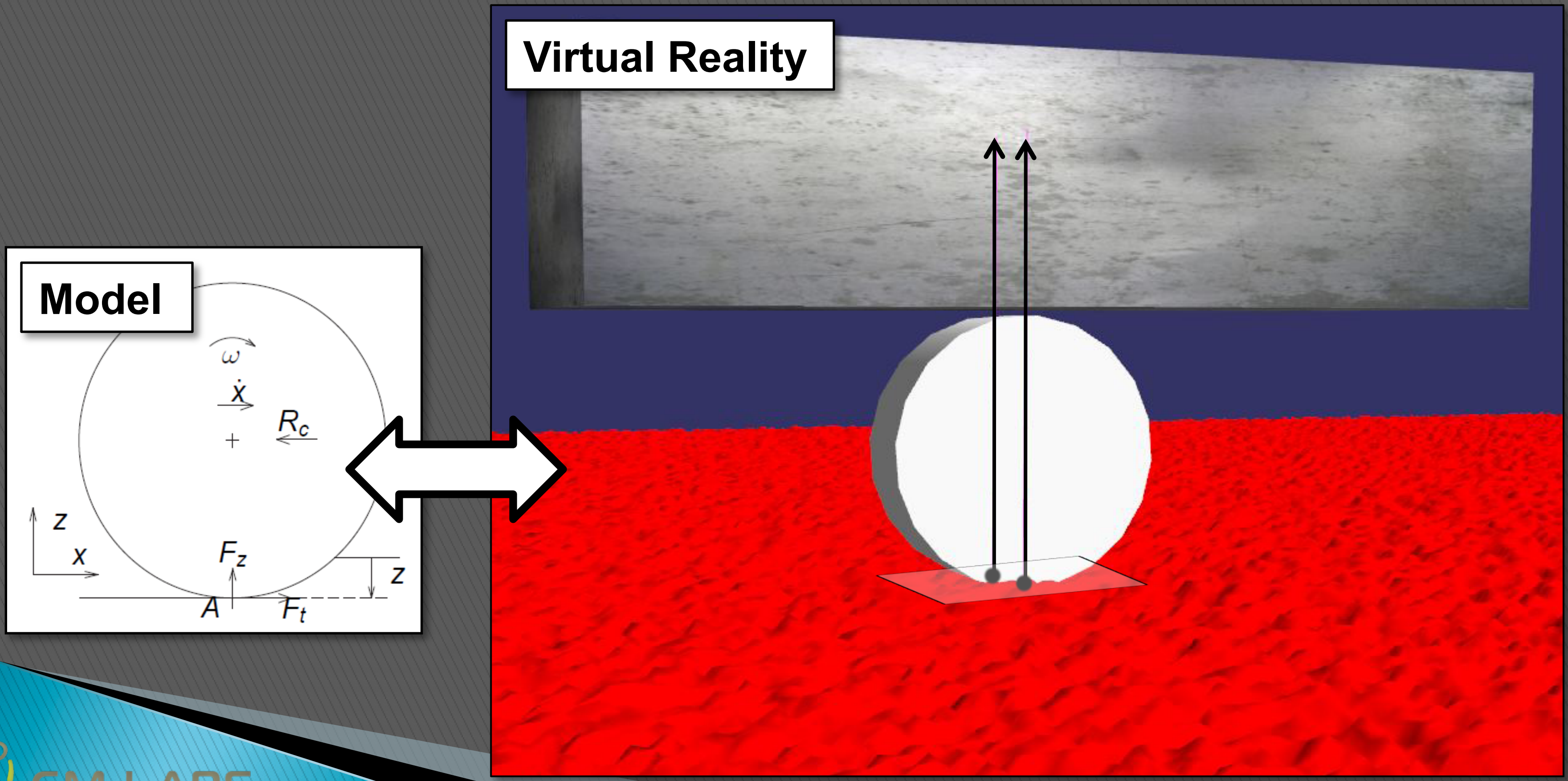
Soft Soil Wheel Interaction

Modeling Compaction

- Use heightfield terrain representation
- Perform least-squares approximation of contact area



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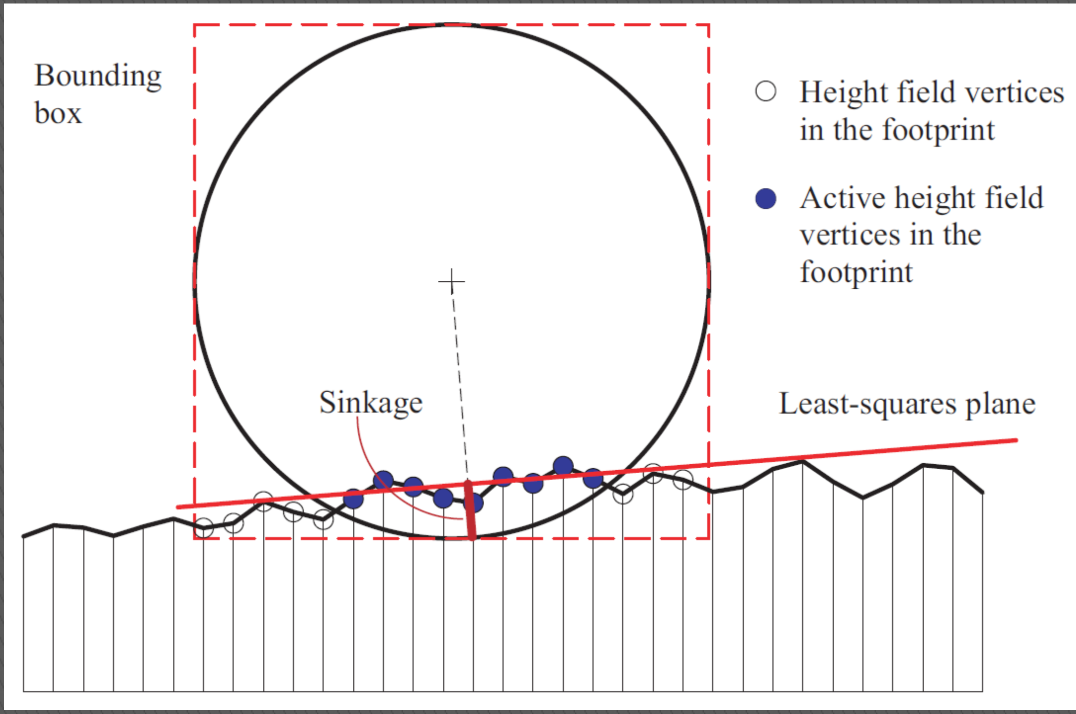
Irregular Terrain

- Terrain is represented by a height field
- Soil data are stored in the vertices of the height field
- Contact area is approximated by a plane
  - Sinkage estimation
  - Stable simulation
- Active vertices are used in determining soil hardening and compaction



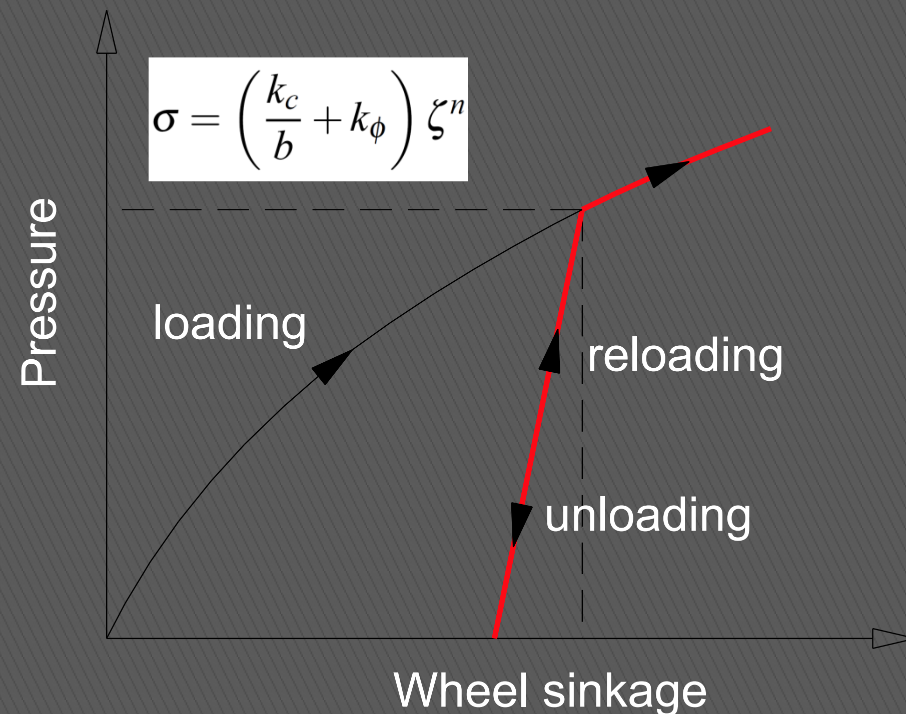
Soil Hardening and Compaction

- Active vertices are used in determining soil hardening and compaction

- Multi-pass model of Wong is adapted here

    - Normal stress (σ), as shown:

$$\sigma = \left(\frac{k_c}{b} + k_\phi\right)\zeta^n$$



    - Shear stress(τ): same relation as uncompacted soil:

$$\tau(\theta) = (c + \sigma(\theta)\tan\phi)\left[1 - \exp\left(-\frac{|j_x(\theta)|}{K_x}\right)\right]\mathrm{sign}(j_x)$$

$$j_x(\theta) = R[(\theta_1 - \theta) - (1 - i_s)(\sin\theta_1 - \sin\theta)]$$

Void ratio computation

- Inverse density
- Inspired from fluid dynamics Particle-In-Cell method
  - hash the particles into a grid
  - assign to each grid cell the sum of the contained particle volume. Compute void ratio by comparing the particle volume (solid volume) with the max cubic volume (total volume) in the grid cell (void ratio = solid volume / void volume). Note: void volume = total volume – solid volume.
  - for each particle:
    - place a square (cubic) kernel at particle center (kernel side length same as grid cell side length)
    - compute average of the void ratio of all overlapping grid cells weighted by the overlap volume.
- This gives the void ratio assigned to the particle.

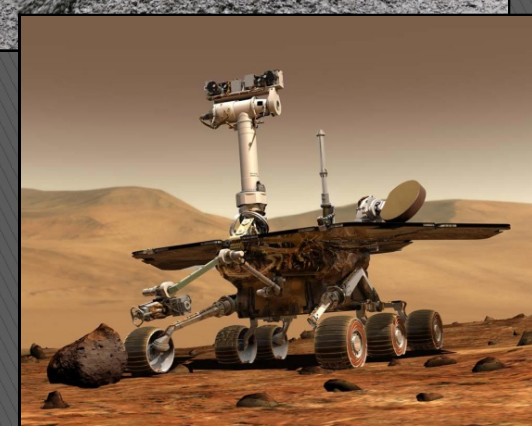
CM LABS

Deformable Terrain Simulation

- Soil/Tool interaction

Deformable Terrain Simulation
Motivation

- Soil is a highly complex medium
  - Many different soil types
  - Different soil physical properties
- Simulate
  - Lateral motion
  - Separation,
  - accumulation, etc..
  - e.g. performance of military/ construction vehicles/rovers
- Evaluate performance of military/ construction vehicles/rovers
- Knowledge of phenomena is essential
  - *How strong does soil compact when*



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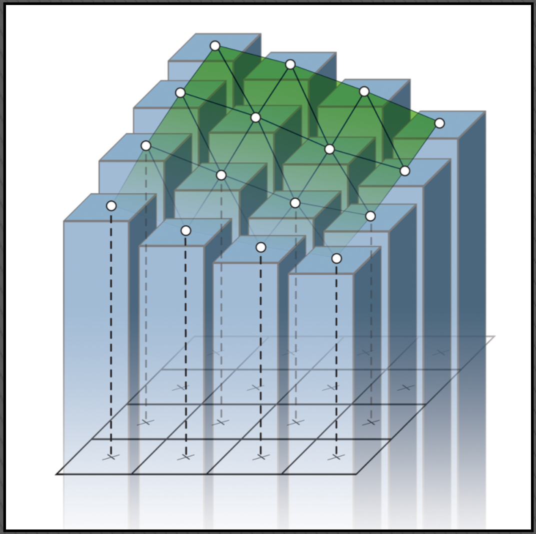
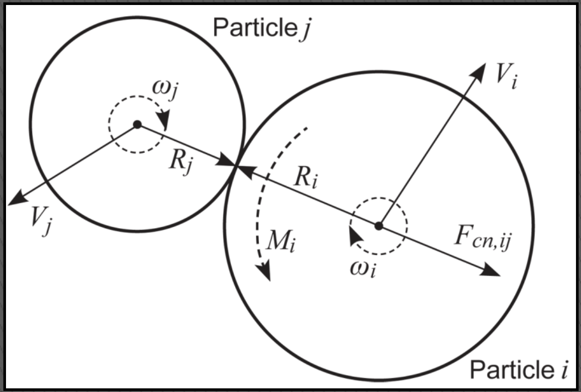
Deformable Terrain Simulation
Physical Model



- High requirements on simulators:
  1. Real-time performance
  2. High realism
  - ➢ **Need balance between interactivity and physical correctness!**

- Idea: **Hybrid Approach**
  1. Soil grid representation: "*Heightfield*" structure
     - ➢ *Good representation of **static soil***
  2. Soil particle representation: *DEM*
     - ➢ *Good representation of **dynamic soil***

generate / merge



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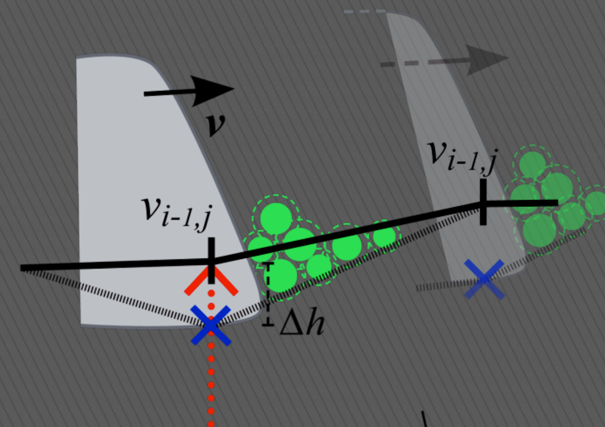
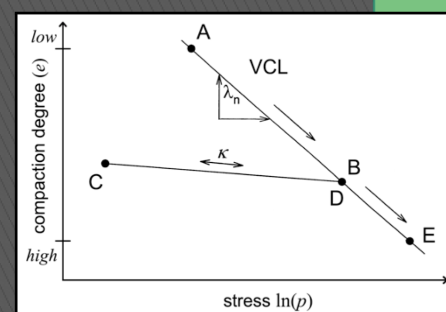
Deformable Terrain Simulation
Physical Model

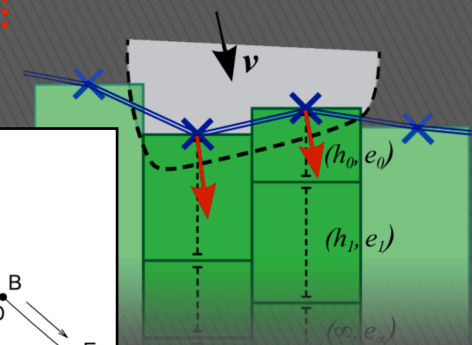
- Soil Particle Generation

  On soil grid / object collision...
  - ➢ Identify object's "footprint" (ray casts)
  - ➢ Replace grid / object overlaps with particles (lower grid vertex by Δh)



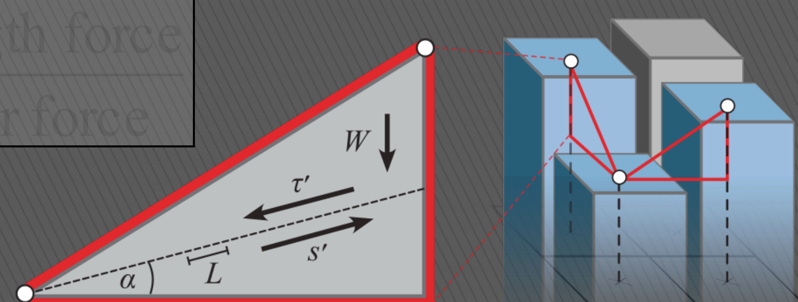
- Soil Compaction
  - ➢ Compaction of 1D soil profile
  - ➢ Based on Critical State Soil Mechanics *(stress-strain relationship)*





- Soil Erosion
  - ➢ Factor of slope safety
  - ➢ Slips if $F \leq 1$

$$F = \frac{s'}{\tau'} = \frac{\text{strength force}}{\text{shear force}}$$



Deformable Terrain Simulation
Visualization

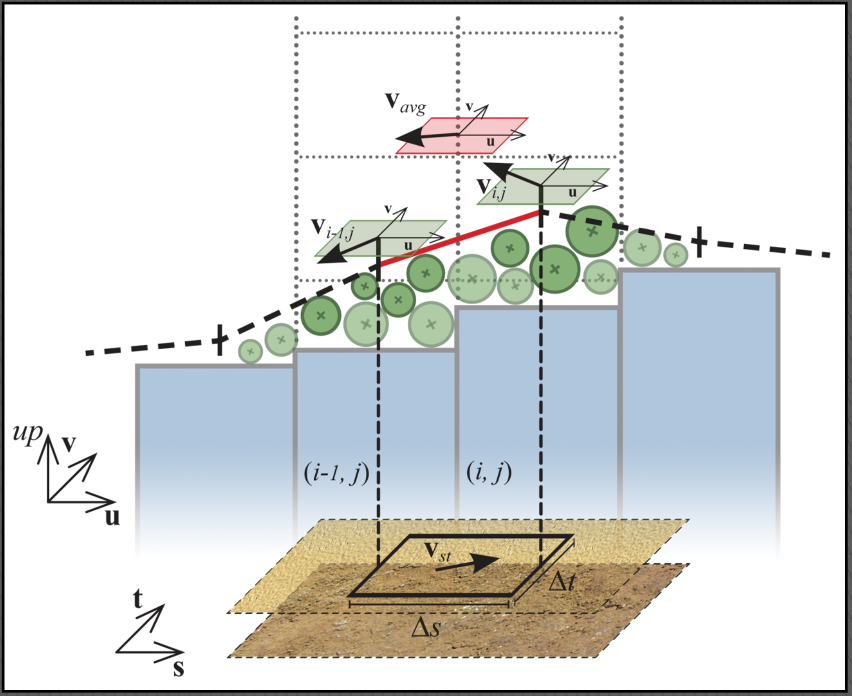
- Soil particles (primary): Meshes
  - fast rendering (instancing)
  - various shapes
- Soil particles (secondary): Sprites
  - velocity-based
  - random emission (gaussian distribution)
  - external forces (gravity, wind, collisions)
- Soil dust: Sprites
  - volume-based
  - soft particle rendering
  - external forces (gravity, wind, collisions)

CM LABS

Deformable Terrain Simulation
Visualization

- Soil surface visualization
  - height field
  - fast rendering (vertex positions/ normals in shader)
  - tri-planar texture mapping

- Soil particle merging
  - volume/density-based
  - velocity-based
  - distance-based
- Soil texture animation
  - overlay texture
  - shift tex-coords (fast)



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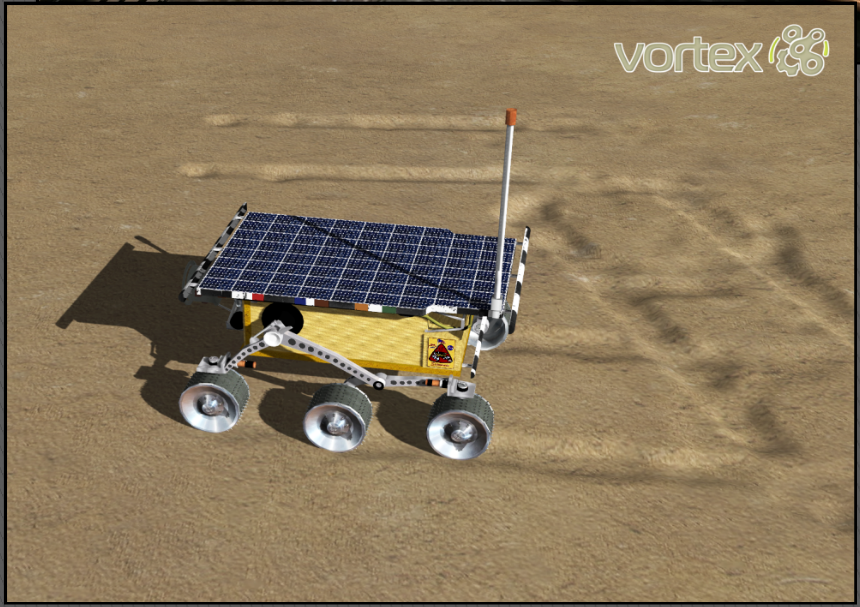
Deformable Terrain Simulation
Results



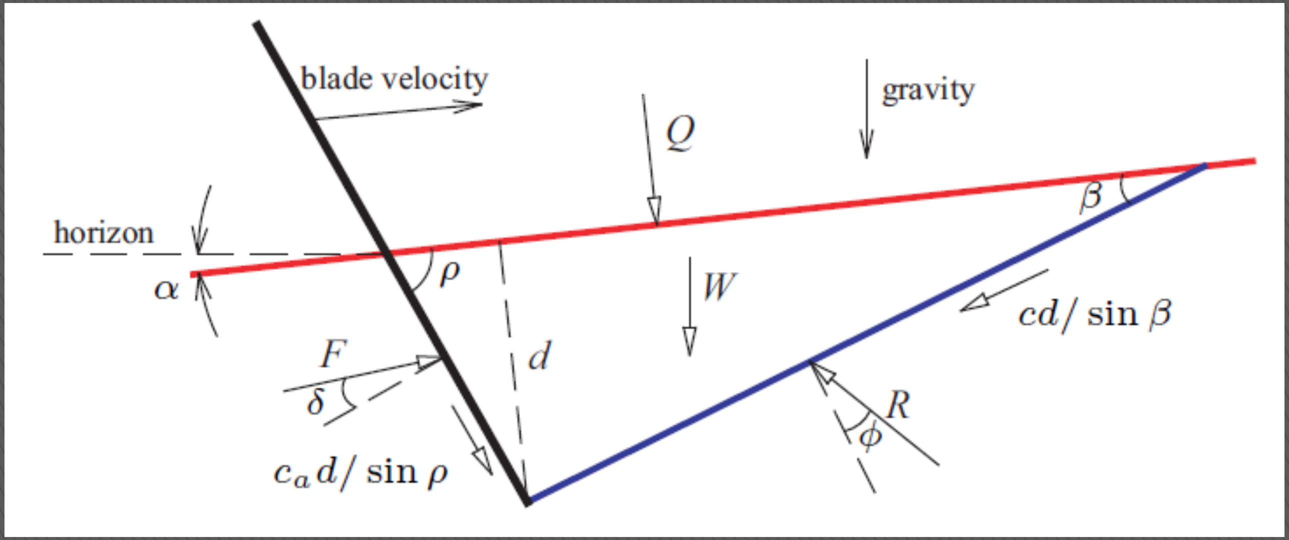
Technical demo

Deformable Terrain with accurate forces

- Soil/Tool interaction

Tool ground interaction forces

- Forces acting on the soil wedge
- **Fundamental Earth Moving Equation** (Reece 64)
- Method of trial wedges (McKyes 85)



- *F* depends on
  - Tool penetration depth (*d*), tool soil friction angle (δ),
  - Soil failure angle (β), soil internal friction angle (Φ)
  - Soil cohesion (*c*), etc…

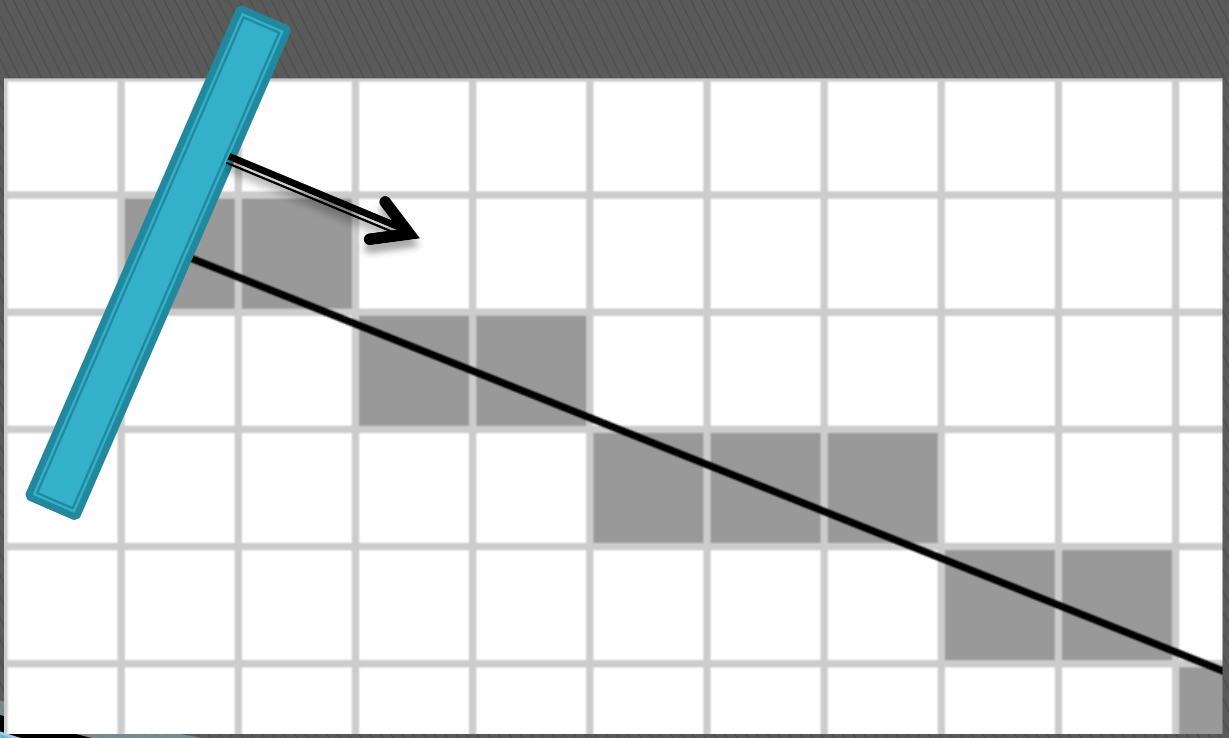
Surface Plane Generation

- Vertical planes across terrain in direction of motion
- Sample heights for each plane
- Use least squares approximation to extract input for FEE.
- Add force constraint to integrate forces into simulation

- Future generalization needed: FEE for more general cases.

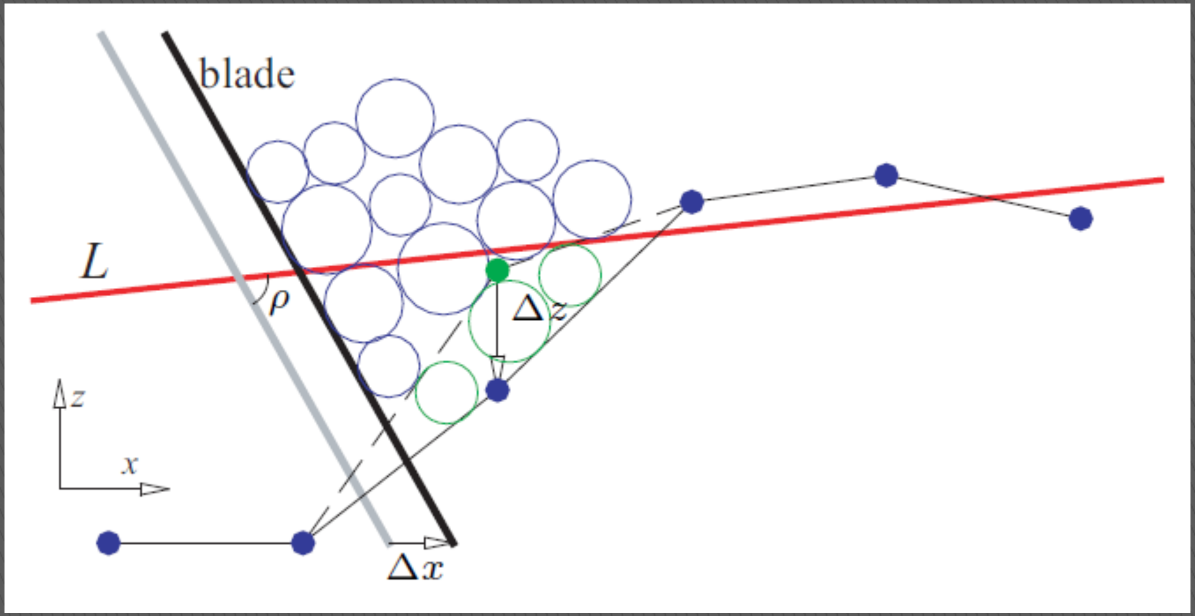
Bresenham's line drawing alg

- Traversing grid (2D or 3D)
- Collecting point samples

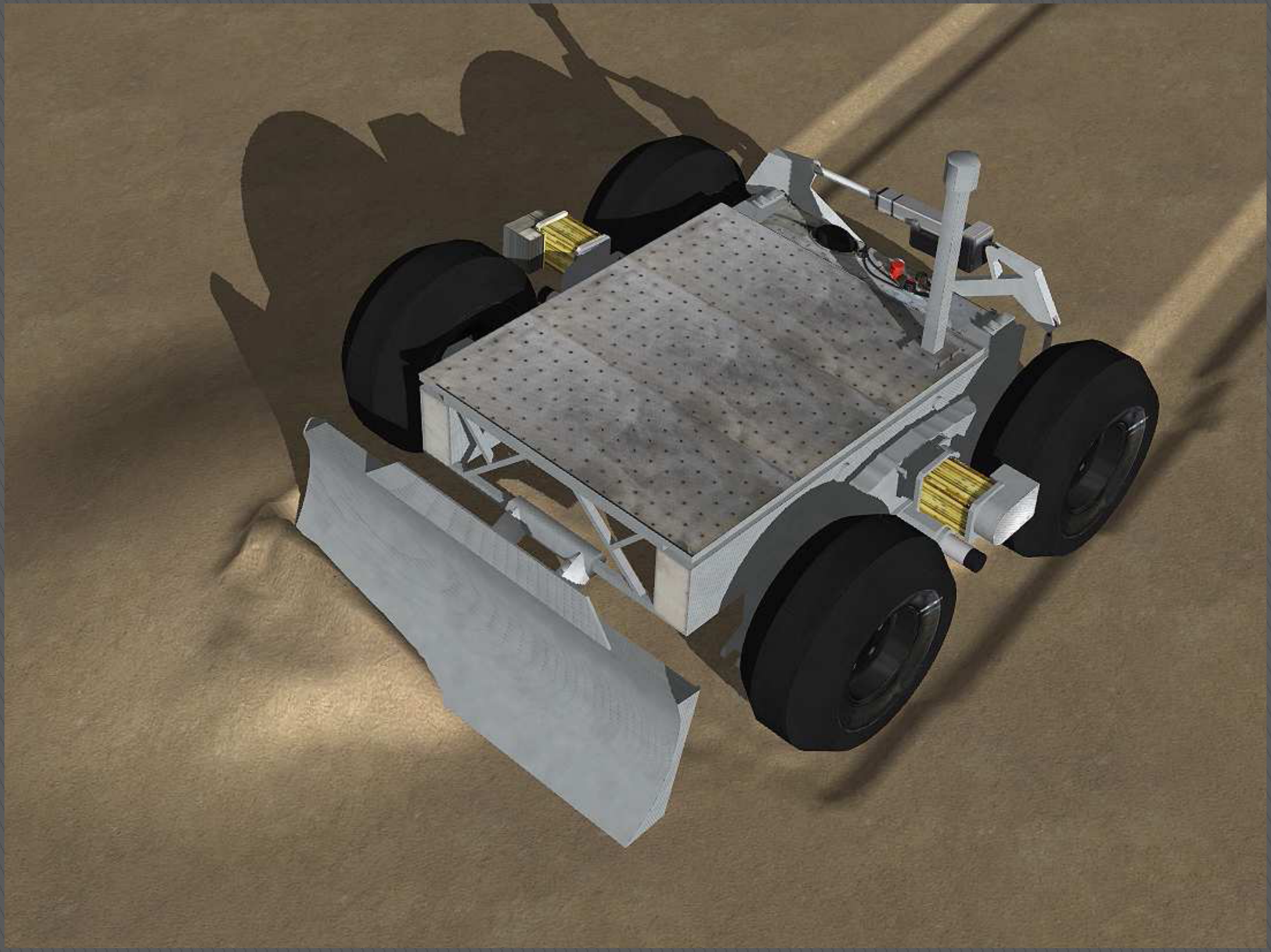


Particle generation

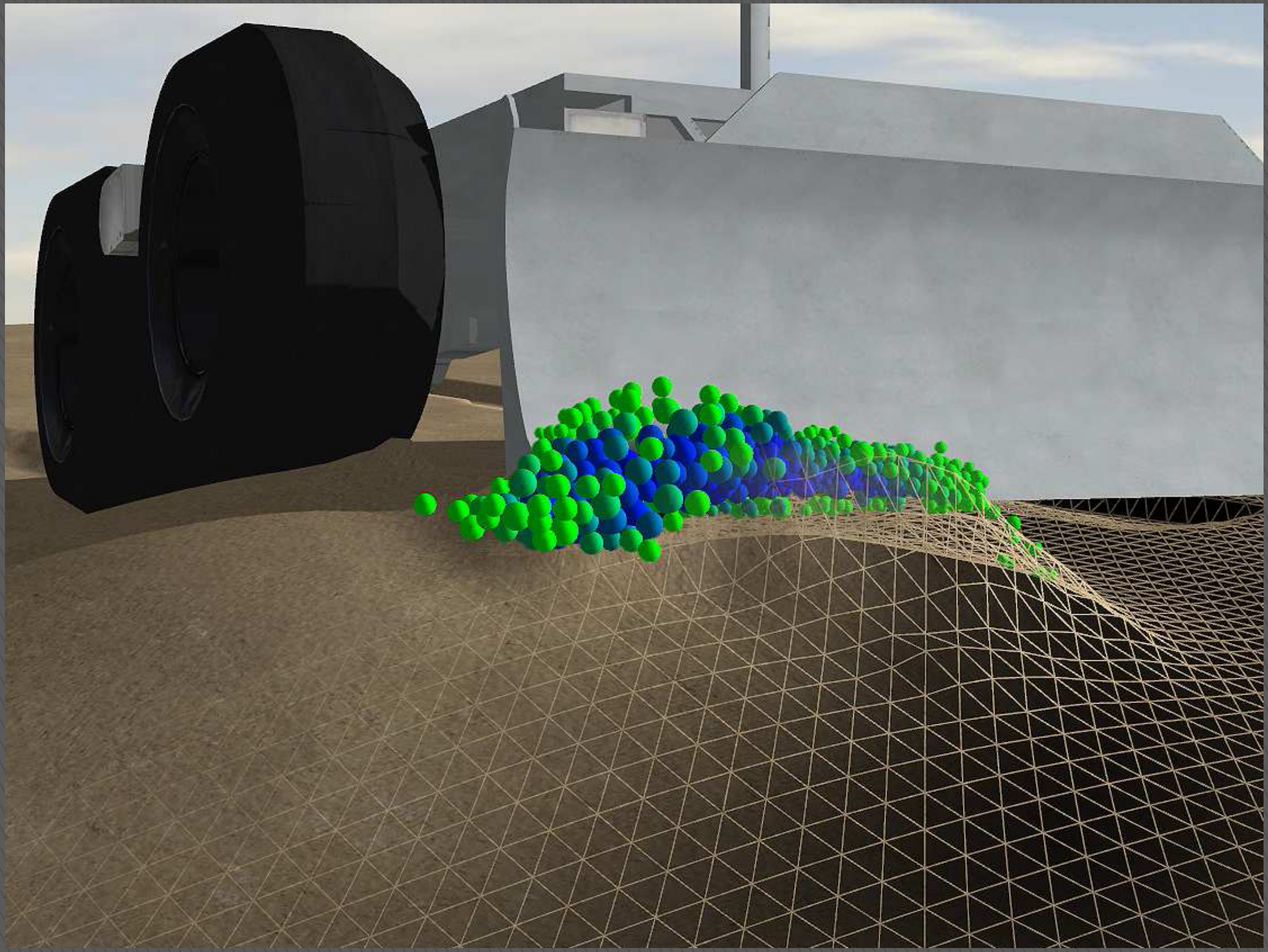
- Surface vertices
- Least squares approximation to surface
- Blade motion (Dx) cause surface deformation (lower the surface)
- Particle generation (green)
- Preexisting particles (blue)



Rover/shovel soil interaction



Hybrid particle-heightfield



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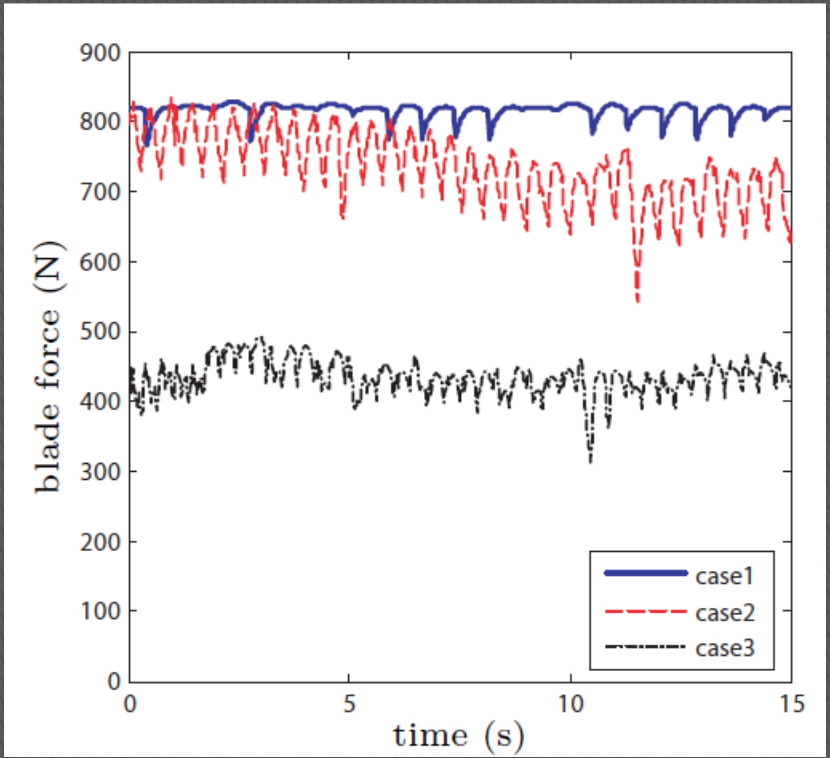
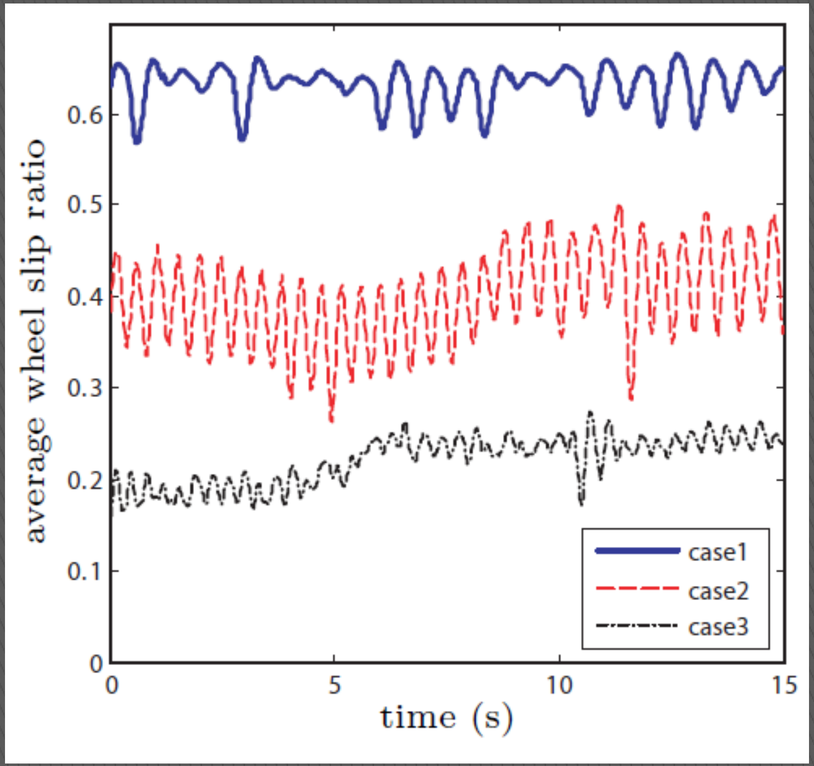
Results:
blade force wheel slip ratio



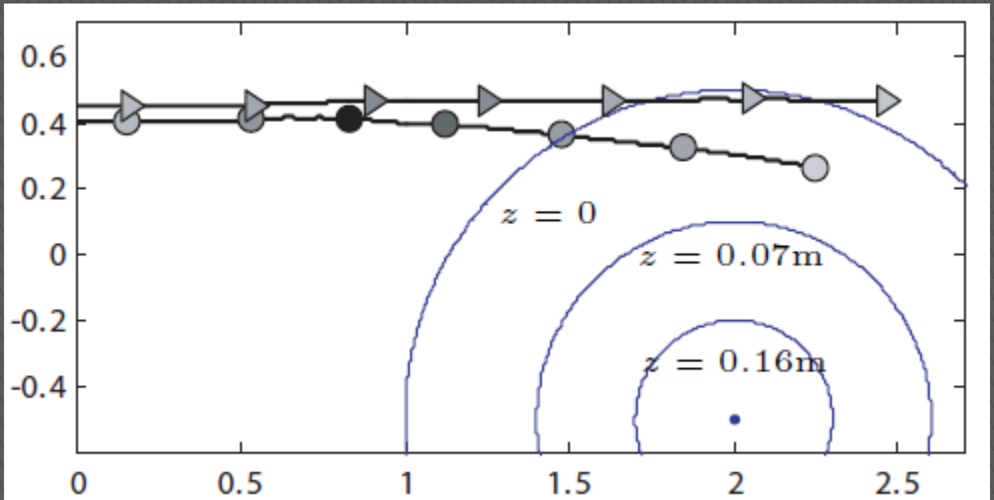


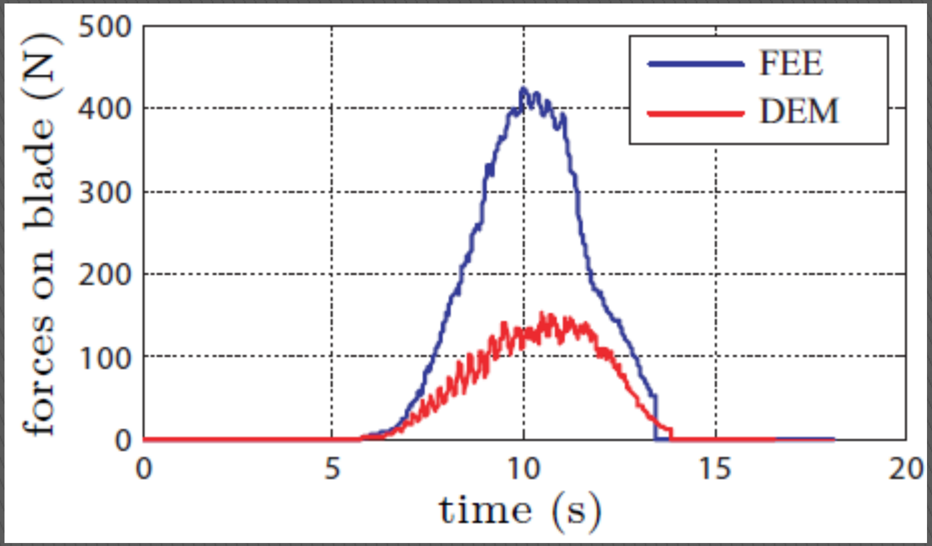
- Blade depth 0.13m, 0.14m, 0.11m
- Average tool-soil angle 89°, 77°, 71°.

CM LABS

Bulldozing

- Two runs over bump (h=.2m)
- One with blade up, one down
- Increase wheel slip
- Trajectory deviation
- CLAWAR 2012





CM LABS

3D Terrain Simulation

- Soil/Tool interaction

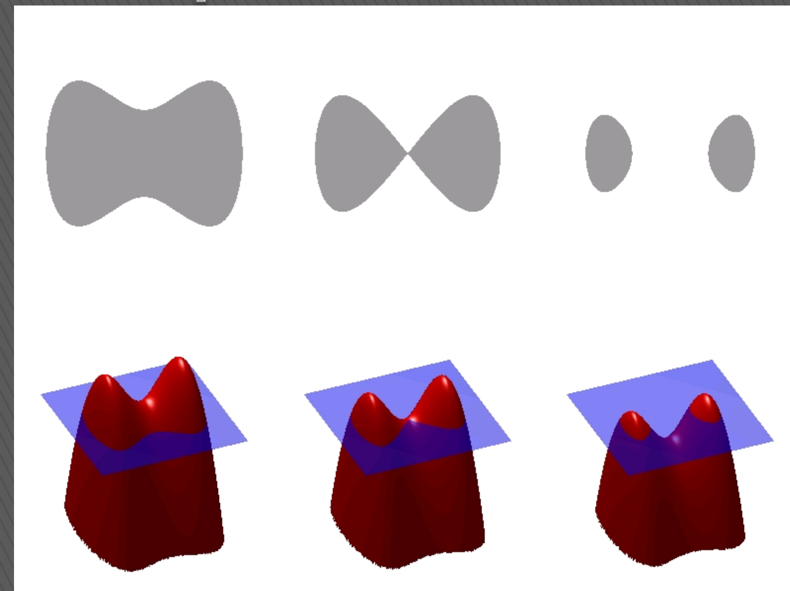
Full 3D terrain representation

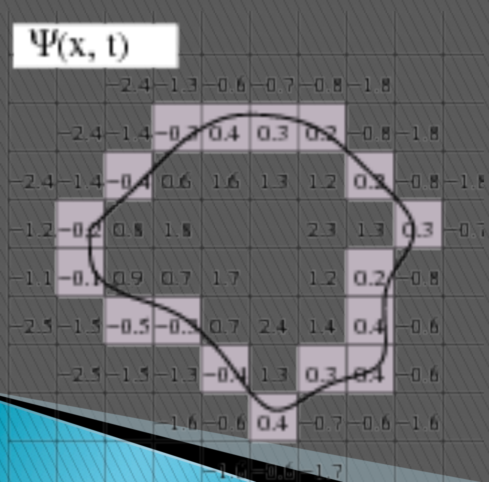
- Case of overhangs or steep walls

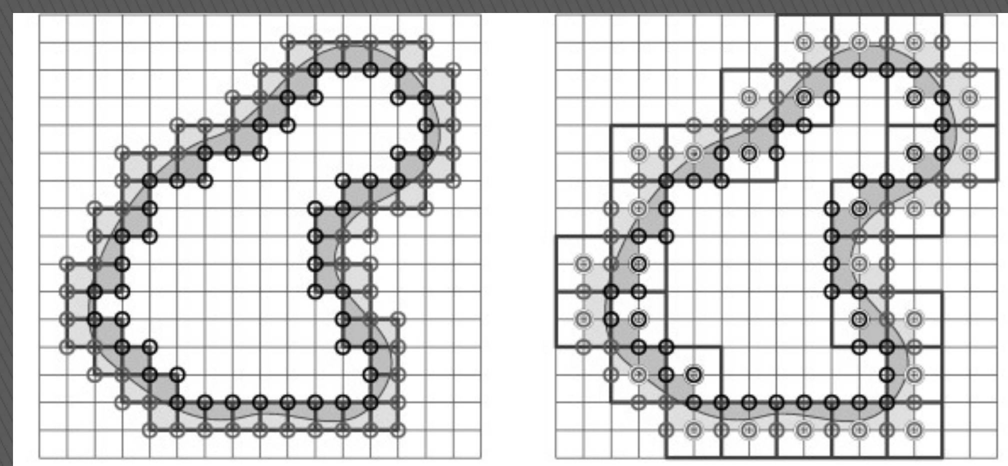
CM LABS

Level set surface representation

- Level set of signed distance function
- Defined on a 3D grid



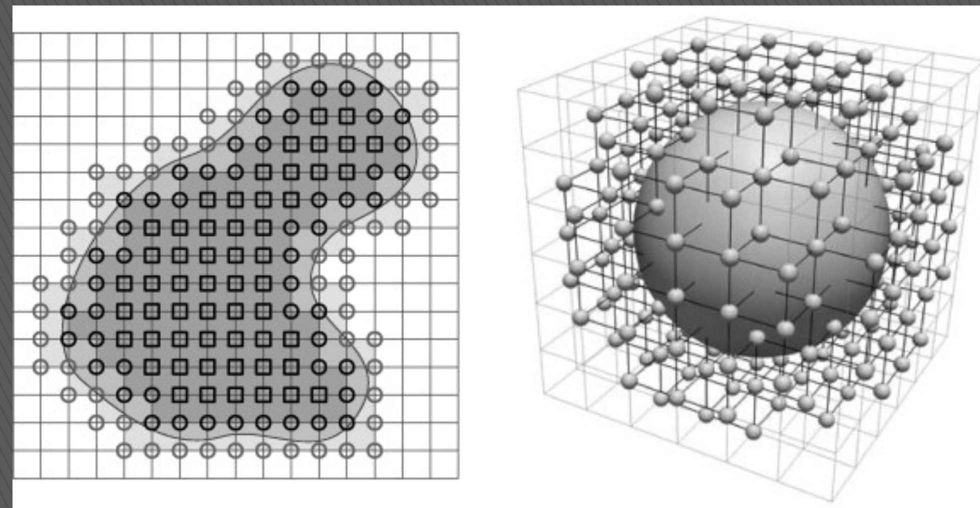




CM LABS

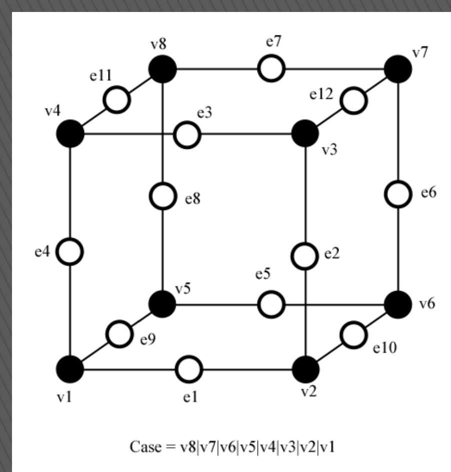
Level sets in 3D

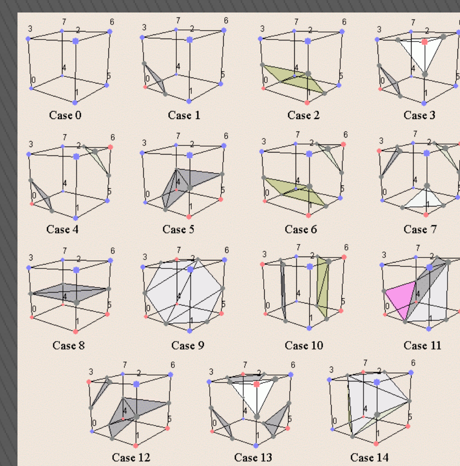
- 3D Grid
- Signed distance function



(a) Embedding in 2 dimensions (b) Embedding in 3 dimensions

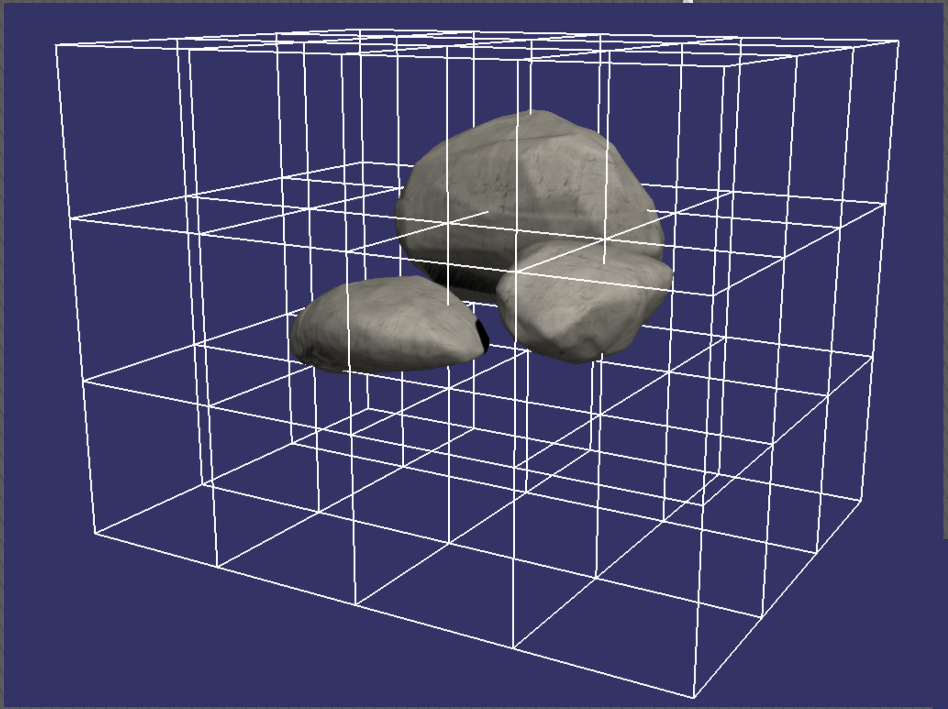
- Surface reconstruction
- **Marching Cubes** algorithm

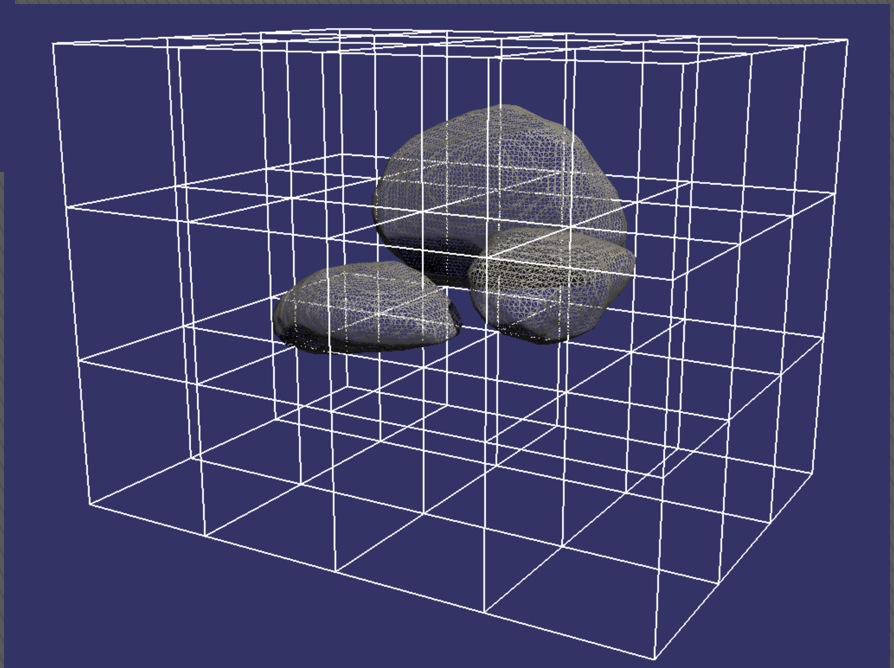




CM LABS

Level set representation



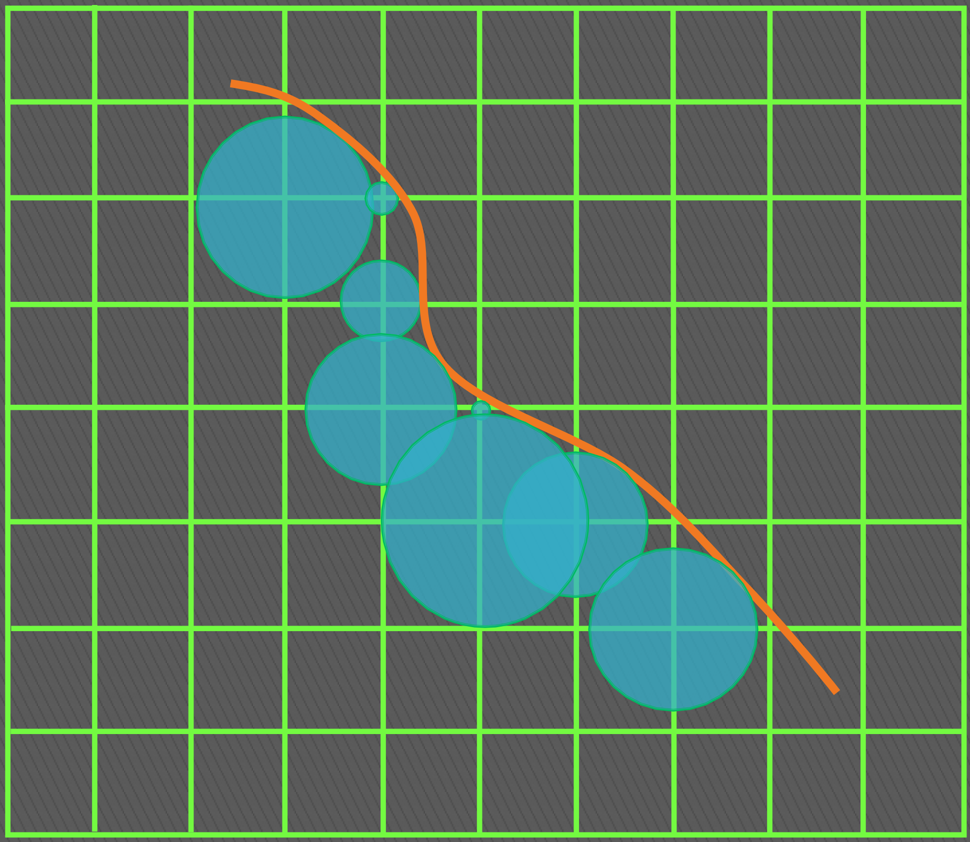


Geometric surface modification

Approximation of distance fn

- Requirements
- Fast queries
- Fast update

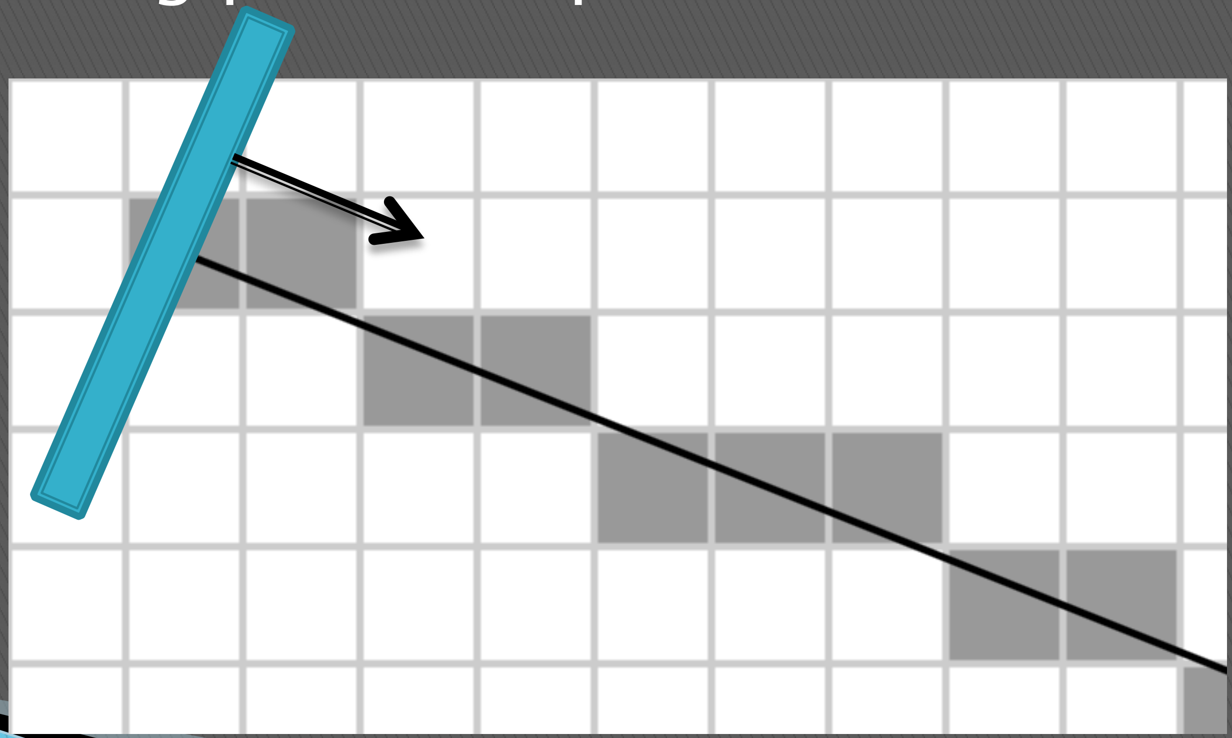
- Use spheres of radius 1 to represent distance function
- Surface updated during excavation



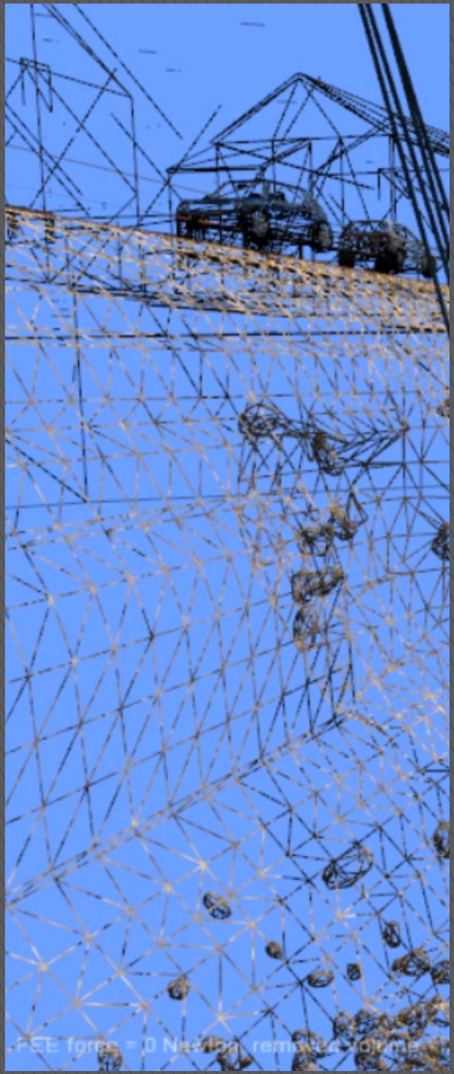
CM LABS

FEE computation generalized to 3D

- Bresenham's line drawing alg in 3D
- Traversing grid in 3D
- Collecting point samples



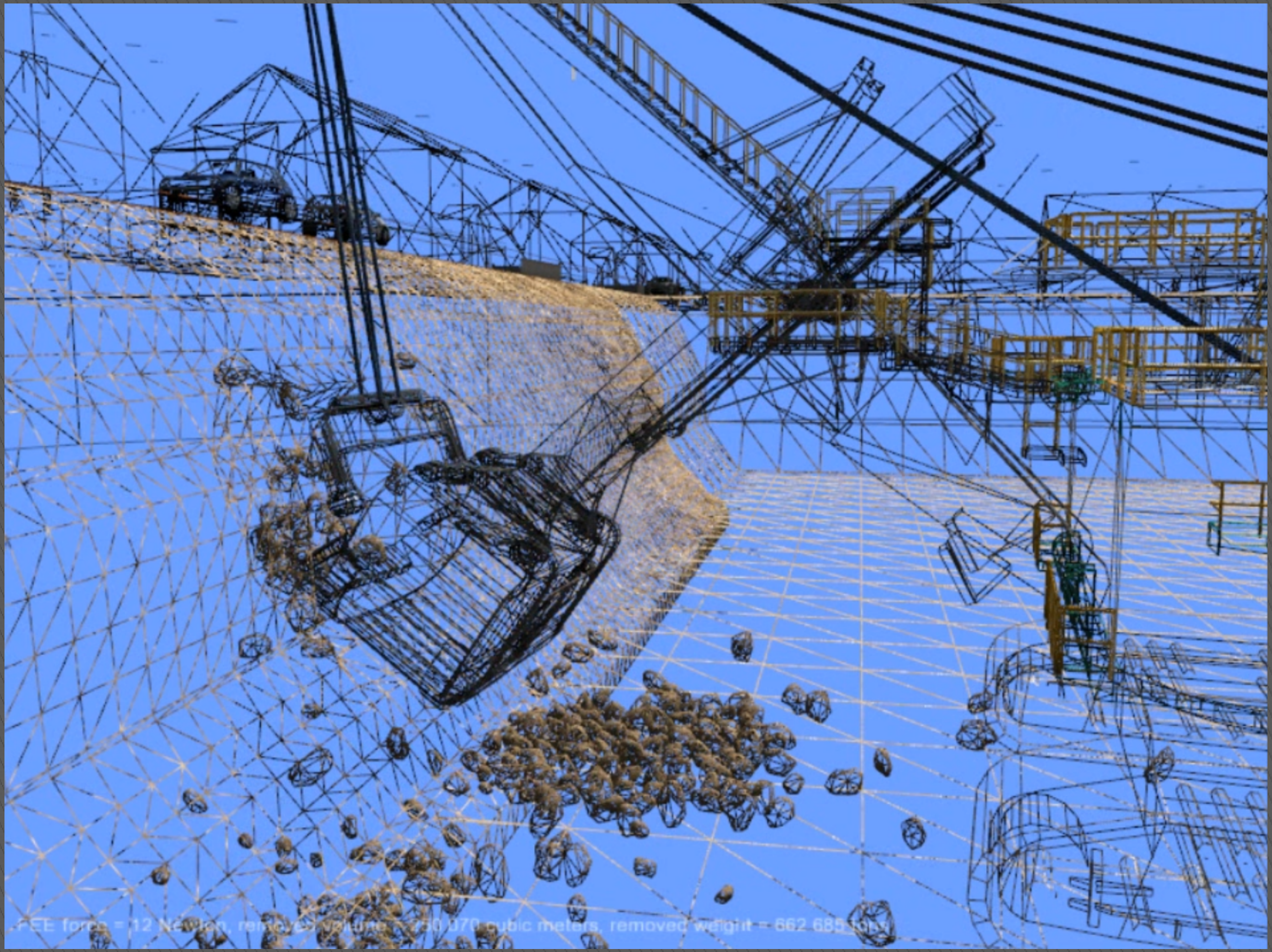
Soil level set for mining site



CM LABS

Electric Shovel Simulation

Electric Shovel Simulation



Conclusion

- Real-time soil model for
  - ➢ wheel interaction
  - ➢ Excavation
  - ➢ Really any interaction (ex. Clamshell, drill)
- Application to bone drilling and milling
- Open issues
  - ➢ Regolith modeling
  - ➢ Validation of wheel/tool interaction forces
- Collaborations with McGill University, CSA