



Mobility Research & Development

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United States Army
2016



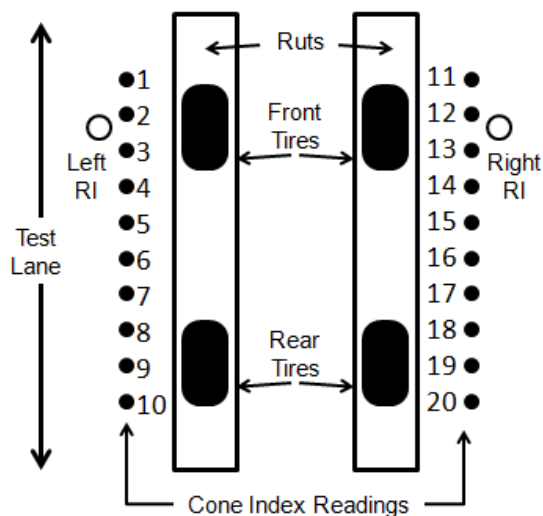


Off-Road Mobility Challenges





Empirical Approach: NATO Reference Mobility Model



NATO Reference Mobility Model (NRMM)

- Dr. M. G. Bekker of TARDEC is the “Father of Terrain-Vehicle Systems”
- NRMM was developed in 1960-70 by TARDEC and ERDC
- Accepted as a NATO standard in 1977-78
- Methodology relied on empirical relationships and **not** physics-based
- Does **not** extrapolate to contemporary vehicle designs and technologies
- Does **not** benefit from advances in simulation and computational capabilities

Qualitative

NRMM

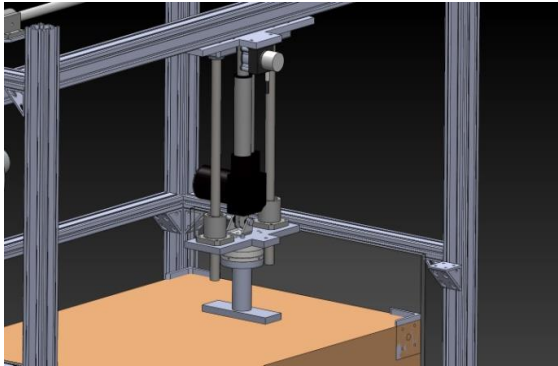
1970



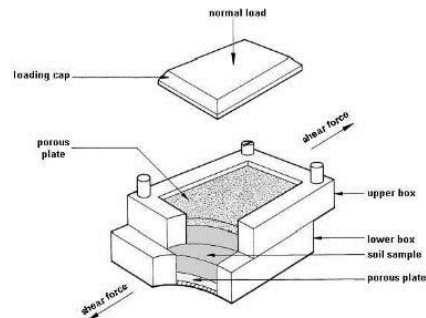
Building Blocks: Scaled Experiments



Pressure – Sinkage Test



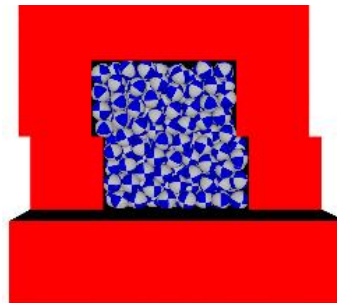
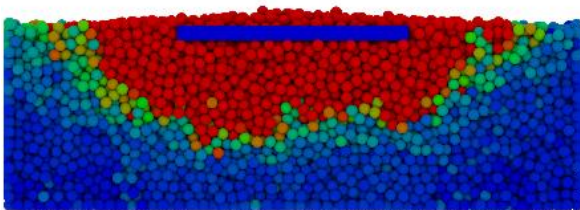
Direct Shear Test



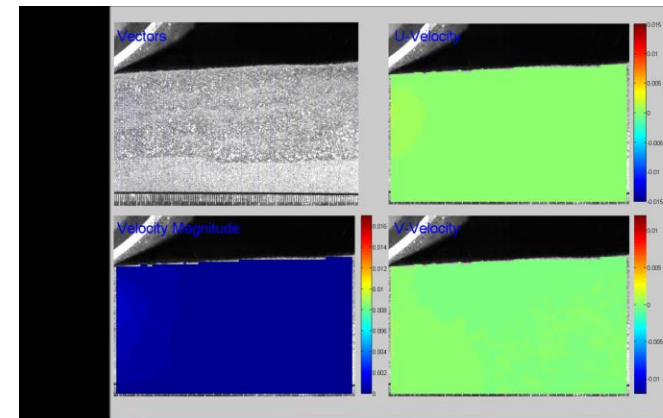
Single Wheel Test



Simulations



Particle Image Velocimetry

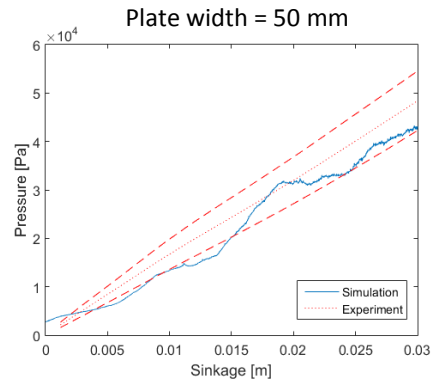




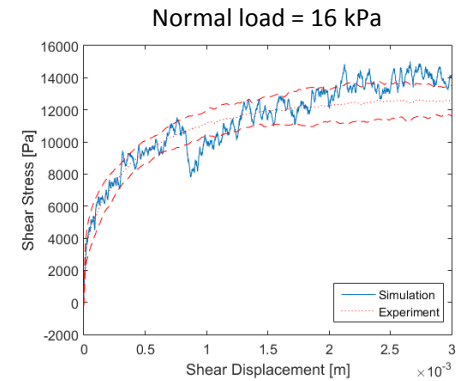
Validation of Theory: Scale Test Results



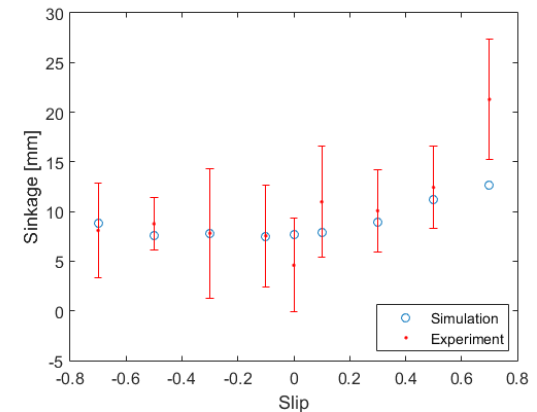
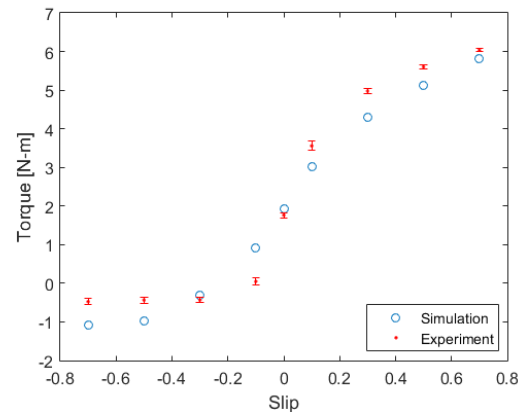
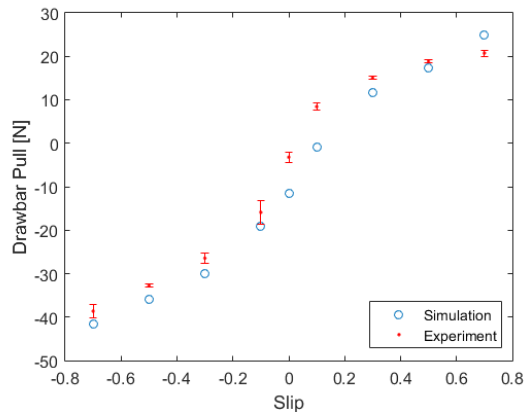
Pressure – Sinkage Test



Direct Shear Test

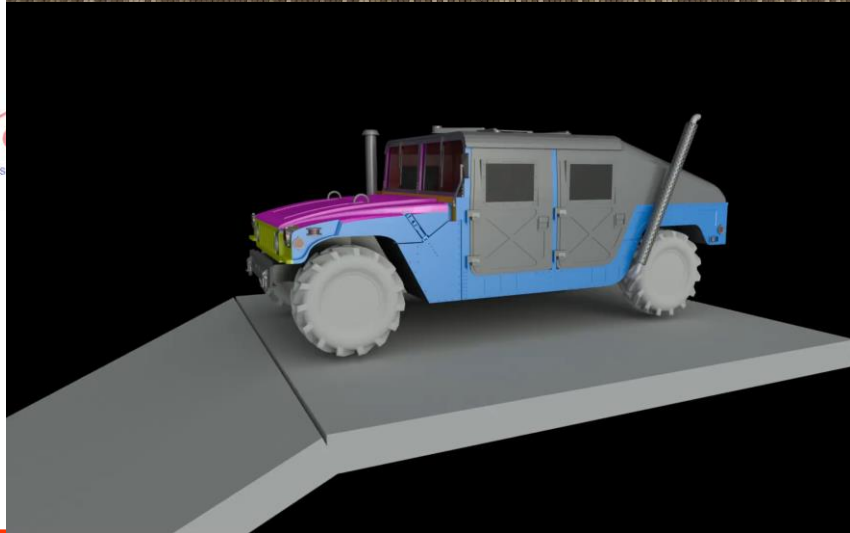
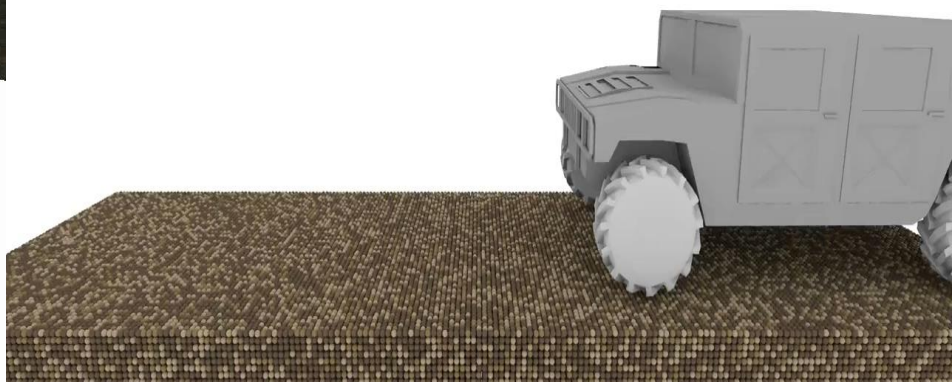
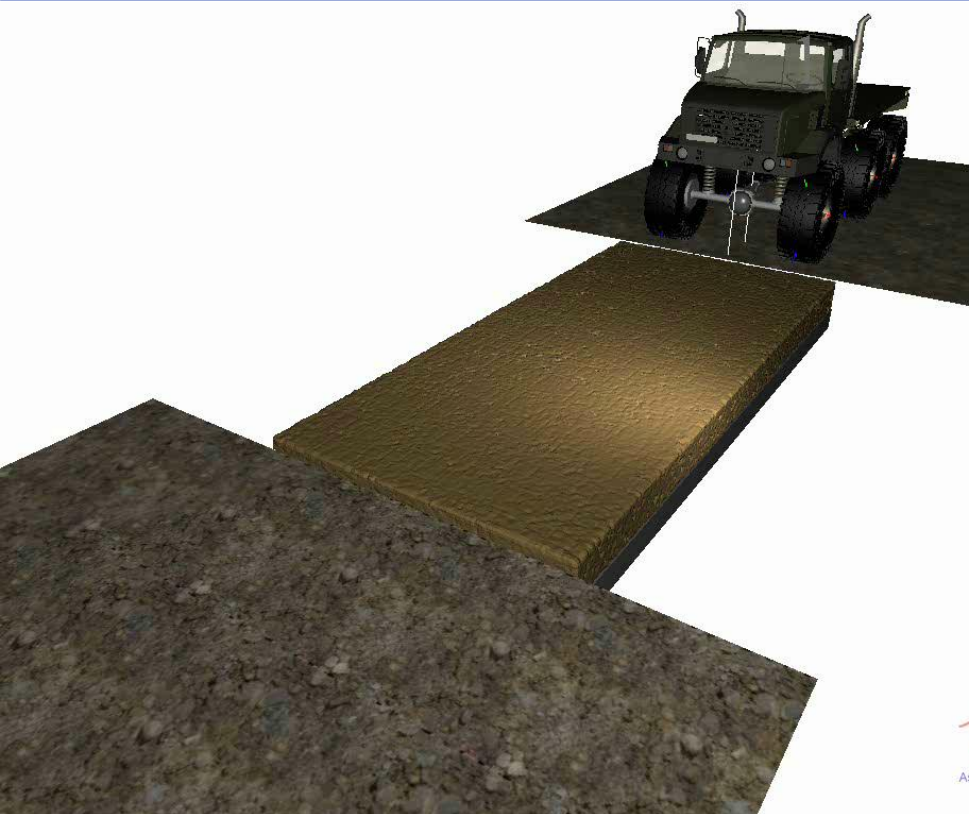


Single Wheel Test





Full-Scale Demonstration: Physics-Based Mobility M&S



Computational Burden

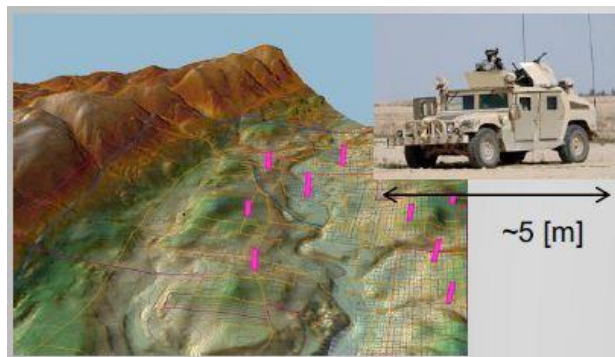
- **Hardware:** Cray XC40 32 cores
- **Software:** IVRESS; **Contact method:** DEM-P
- **Run time:** **14,000x slower than real time**
- **Model particle dia / Physical :** 30 mm / 0.002 mm
= **15,000x bigger than real size**



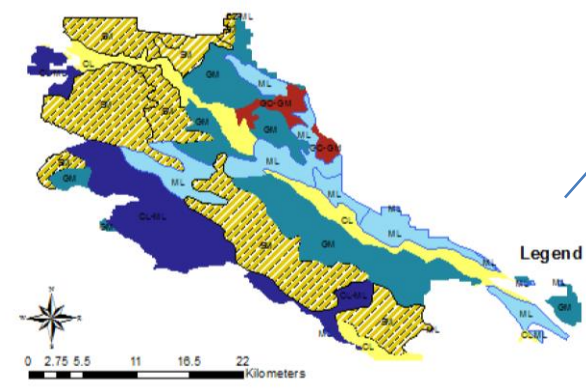
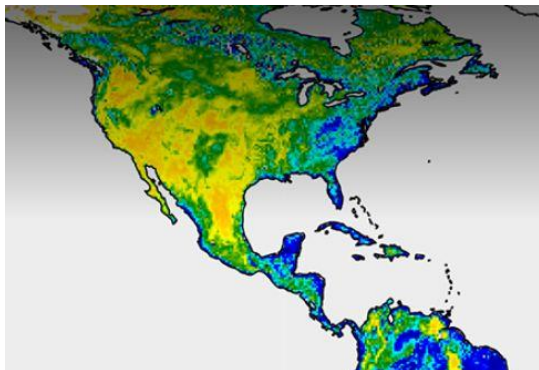
Goal: NextGen NATO Reference Mobility Model



Terrain Elevation Map



Soil Moisture Map

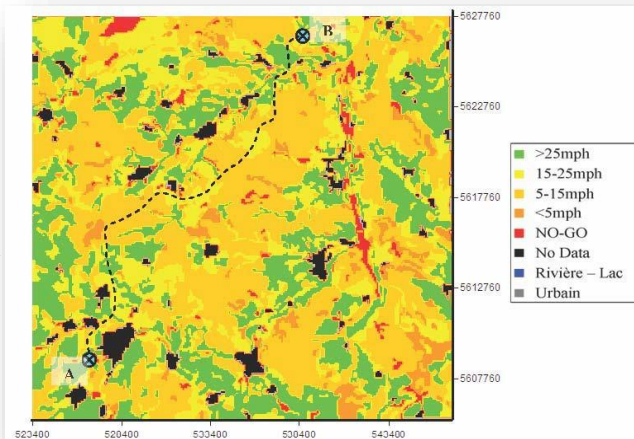


Soil Type

Physics-Based M&S



Mobility Go/NoGo Map



Qualitative

NRMM

NG-NRMM

1970

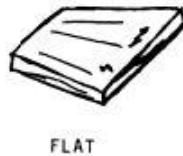
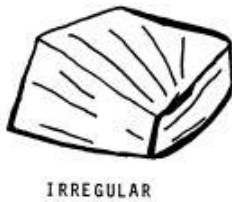
2020



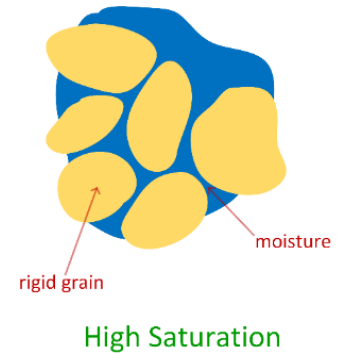
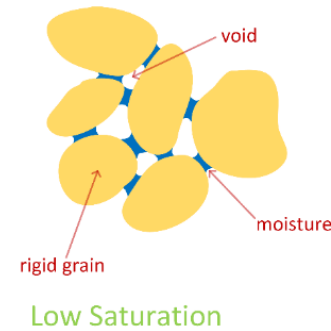
Challenging Nature of Terramechanics



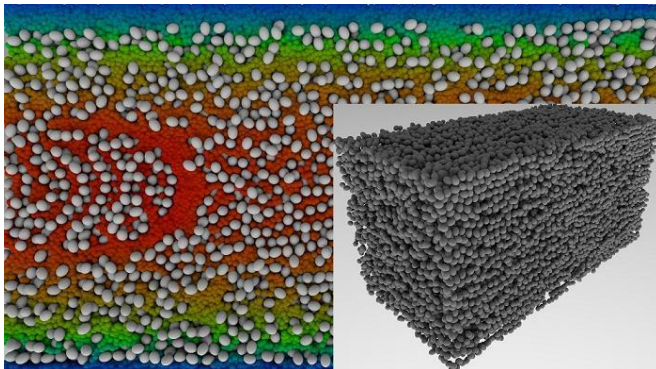
Heterogeneity



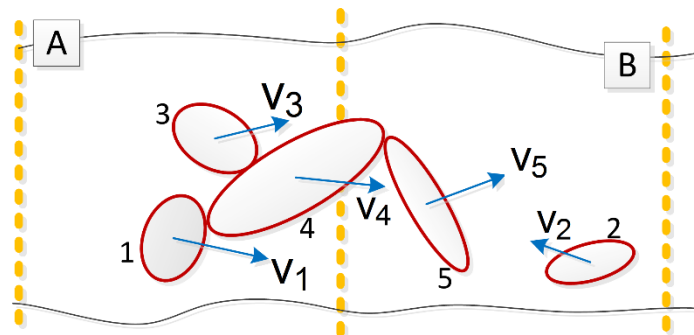
Multi-Physics



Scalability



Dynamics



Multi-Scale

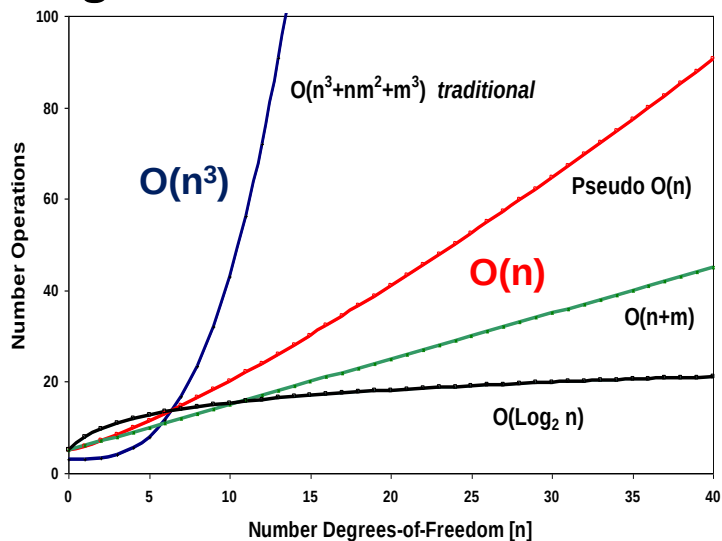




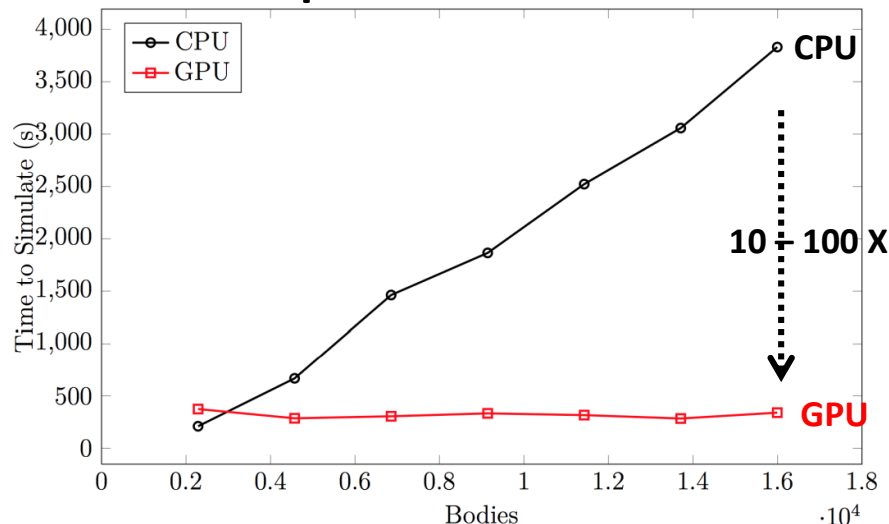
Performance Challenges: Algorithms and Hardware



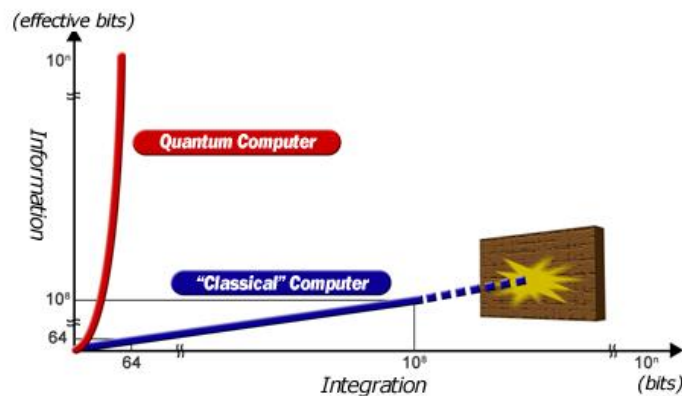
Algorithm Cost vs. Problem Size



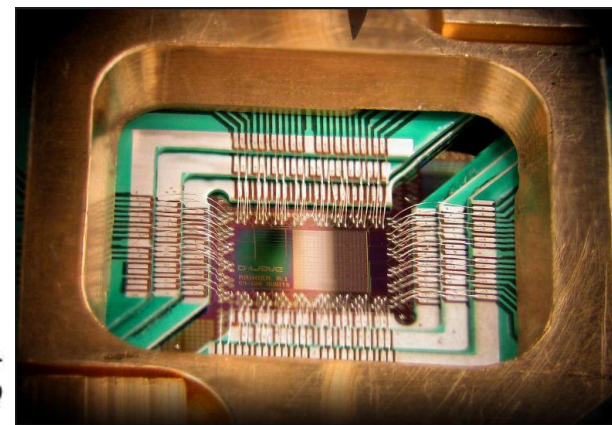
Compute Cost: CPU vs. GPU



Massive Parallelization



Quantum Computing





Physics of Terramechanics and Quantum Computing



$$\dot{\mathbf{q}} = \mathbf{L}(\mathbf{q})\mathbf{v}$$

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}} = \mathbf{f}(t, \mathbf{q}, \mathbf{v}) - \mathbf{g}_{\mathbf{q}}^T(\mathbf{q}, t)\lambda + \sum_{i \in \mathcal{A}(\mathbf{q}, \delta)} \underbrace{(\hat{\gamma}_{i,n} \mathbf{D}_{i,n} + \hat{\gamma}_{i,u} \mathbf{D}_{i,u} + \hat{\gamma}_{i,w} \mathbf{D}_{i,w})}_{\text{Frictional Contact Force}}$$

$$\mathbf{0} = \mathbf{g}(\mathbf{q}, t)$$

Frictional Contact Force

$$i \in \mathcal{A}(\mathbf{q}(t), \delta) : \begin{cases} 0 \leq \Phi_i(\mathbf{q}) \perp \hat{\gamma}_{i,n} \geq 0 \\ (\hat{\gamma}_{i,u}, \hat{\gamma}_{i,w}) = \underset{\sqrt{(\bar{\gamma}_u^i)^2 + (\bar{\gamma}_w^i)^2} \leq \mu_i \hat{\gamma}_{i,n}}{\text{argmin}} \mathbf{v}^T \cdot (\bar{\gamma}_u^i \mathbf{D}_{i,u} + \bar{\gamma}_w^i \mathbf{D}_{i,w}) \end{cases}$$

Complementarity Condition

Friction Dissipation Energy

Mobility Problem reduces to:
Quadratic Constrained Continuous Optimization Problem

Note that Quantum Computer can solve:
Quadratic Unconstrained Binary Optimization Problem

