A Volumetric Contact Model for Space Robot and Planetary Rover Application

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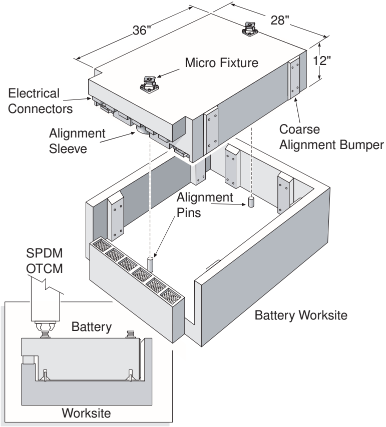
Outline

Motivation

Figure: Dextre at the tip of Canadarm2 (Gonthier, 2007).

Contact Models



ISS battery box (Gonthier, 2007).

Point contact models

- Small contact patches only
- Simple, convex geometries
- No rolling resistance, spinning friction torque

FEM

- Too complex for real-time

Volumetric contact model

Ball-table simulation: real-time (Gonthier, 2007)

Volumetric contact model

Advantages

- Larger, more complex, and conforming contact patches possible
- Includes both translational (normal and friction forces) and rotational (rolling resistance and spinning friction torque) dynamics.

- Validation of the model still required for hard contact (metals)

Goals

1. Experimentally validate the normal force components of the volumetric contact dynamics model for hard-on-hard (metal) contact
2. Demonstrate parameter identification for this model

Volumetric model

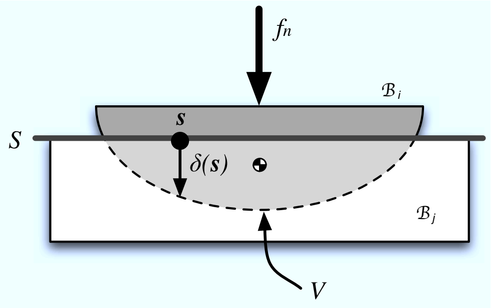
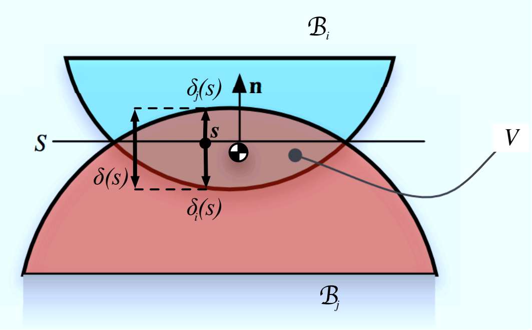


Figure: A volumetric contact model based on a Winkler foundation.

$$p(\mathbf{s}) = \frac{df_n}{dS} = k_v \delta(\mathbf{s})(1 + a v_n)$$

Volumetric properties



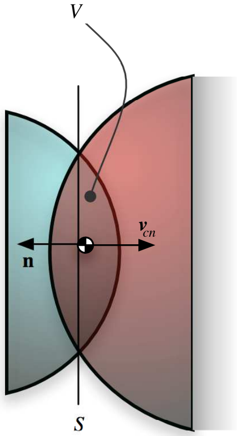
Volumetric properties

V - volume of interference
$\mathbf{n}$ - contact normal
$\mathbf{J}_s$ - surface-inertia tensor
$\mathbf{J}_v$ - volume-inertia tensor

Normal forces

Normal force

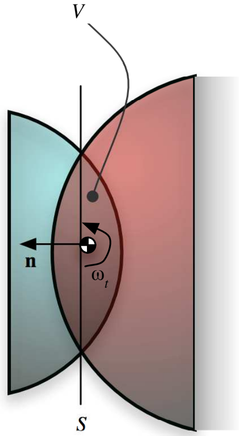
$$\mathbf{f}_{\mathrm{n}} = k_v V(1 + a v_{cn})\mathbf{n}$$



Rolling resistance

Rolling resistance torque

$$\boldsymbol{\tau}_{\mathrm{r}} = k_{\mathrm{v}}\, a\, \mathbf{J}_{\mathrm{s}} \cdot \boldsymbol{\omega}_{\mathrm{t}}$$



Friction

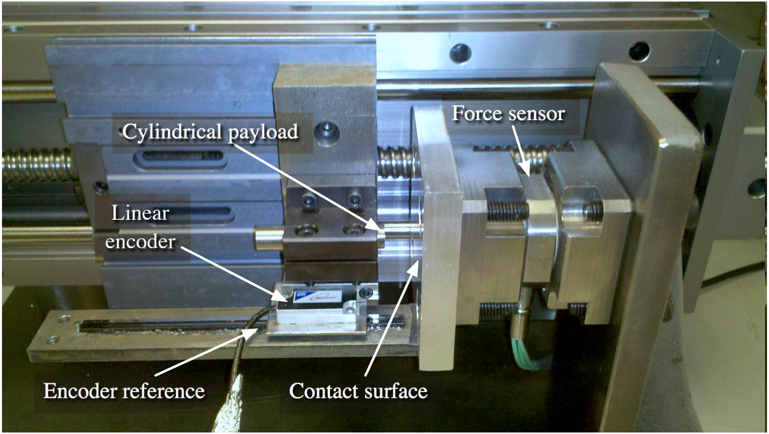
The model can include tangential friction forces and spinning friction torque.

Friction forces (Gonthier et al., 2007)

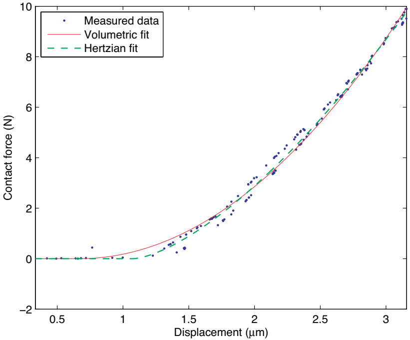
$$\mathbf{f}_\mathrm{t} = -\mu_c f_\mathrm{n} \frac{\mathbf{v}_\mathrm{ct}}{v_\mathrm{avg}}$$

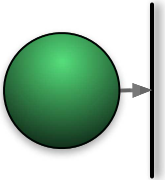
$$\boldsymbol{\tau}_\mathrm{s} = -\frac{\mu_c f_\mathrm{n}}{V v_\mathrm{avg}} \mathbf{J}_\mathrm{s} \cdot \boldsymbol{\omega}_\mathrm{n}$$

Apparatus in normal configuration



Quasi-static results with sphere on aluminum

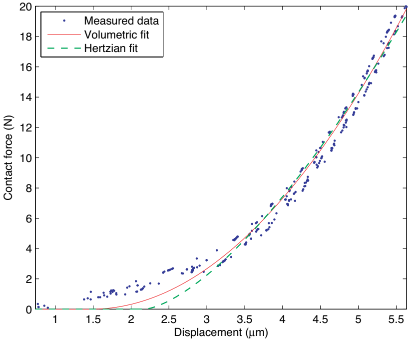




Volumetric stiffness

$$k_v = 7.59 \times 10^{13} N/m^3$$

Quasi-static results with sphere on magnesium



Magnesium surface tarnished quickly after polishing

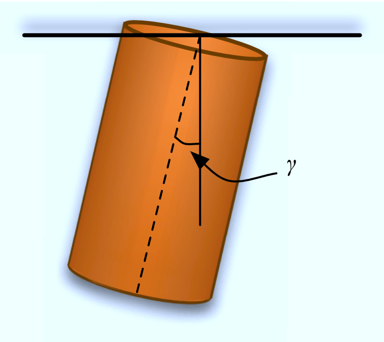
Anisotropic material

Volumetric stiffness

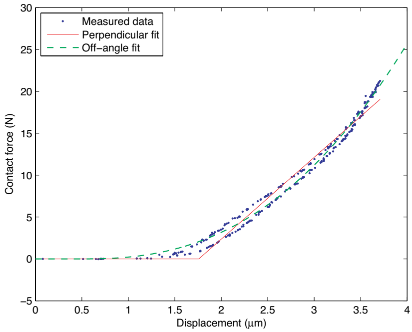
$k_v = 3.82 \times 10^{13} N/m^3$

Problems with cylinders

- Non-linear force-displacement relationship
- Either misalignment or surface asperities
- Used a cylindrical wedge to estimate possible misalignment for the volumetric model



Quasi-static results with cylinder on aluminum



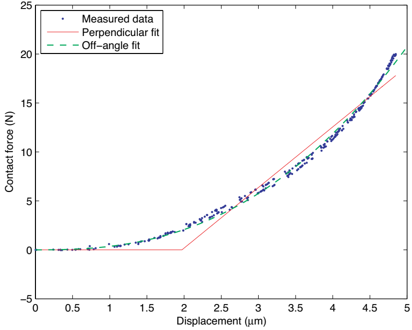
Theoretical volumetric stiffness

$$k_v = 8.82 \times 10^{12} N/m^3$$

Estimated misalignment

$$\gamma = 0.32^\circ$$

Quasi-static results with cylinder on magnesium



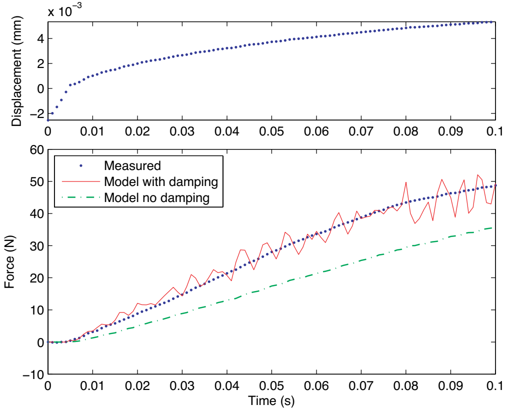
Theoretical volumetric stiffness

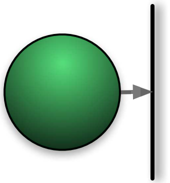
$k_v = 5.17 \times 10^{12} N/m^3$

Estimated misalignment

$\gamma = 0.46°$

Dynamic experiment with magnesium at 0.58 mm/s

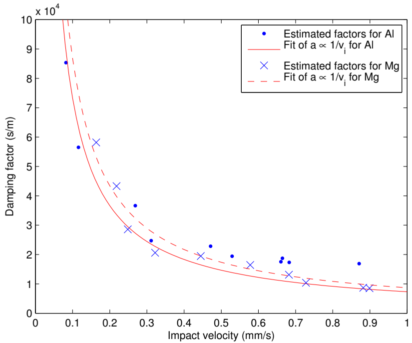




Damping factor

$a = 1.6 \times 10^4 \; s/m$

Measured damping factors



Model in free collision

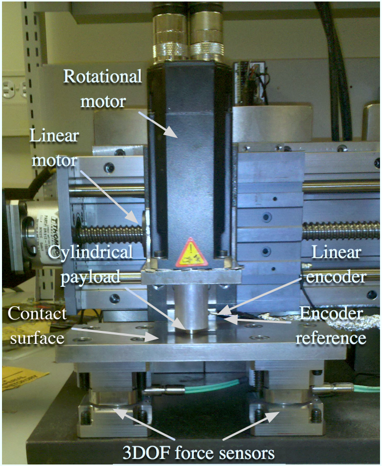
$$a \approx \frac{1-e_{eff}^2}{e_{eff} v_n^i}$$

$$e_{eff} = 1 - \alpha v_n^i$$

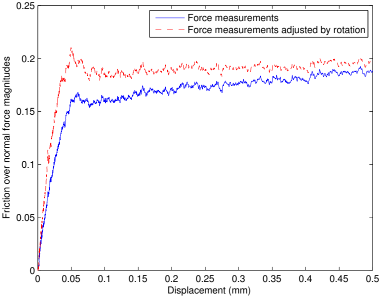
Measurements (driven)

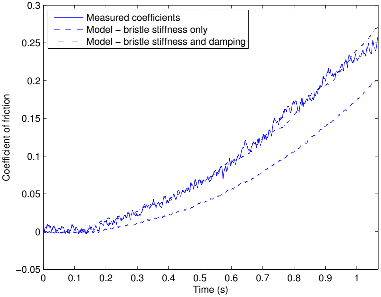
$$a_{Al} \approx \frac{18.7}{v_n^i} \qquad a_{Mg} \approx \frac{8.68}{v_n^i}$$

Apparatus in friction configuration



Static friction





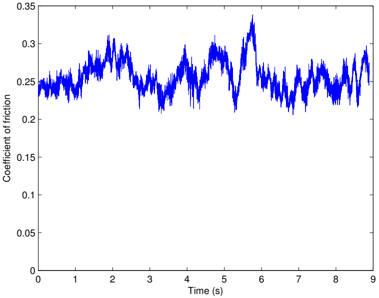
Coefficient of static friction

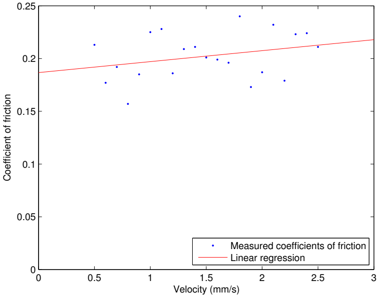
$\mu_s \approx 0.2$

Bristle stiffness and damping

$\sigma_0 = 4500 m^{-1} \quad \sigma_1 = 300 s/m$

Kinetic friction

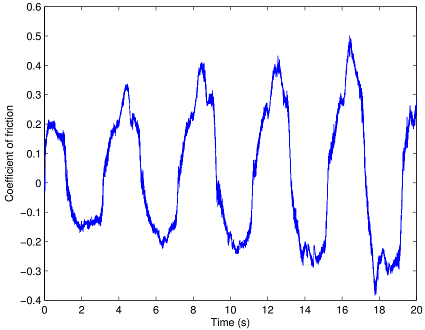




Coefficient of kinetic friction

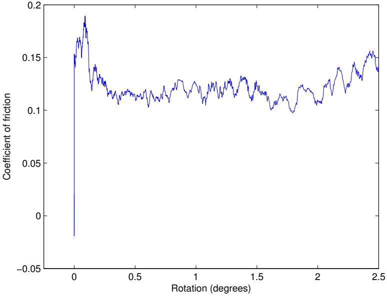
$\mu_d \approx 0.2$

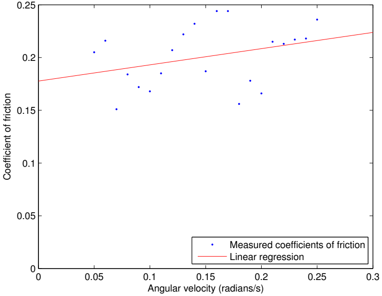
Dwell-time dependency experiment



- Could not detect dwell-time dependency
- Adhesion effect observed where friction force increased with time

Rotation experiments





Coefficient of static friction

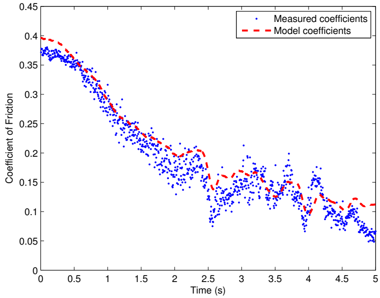
$\mu_s \approx 0.2$

Coefficient of kinetic friction

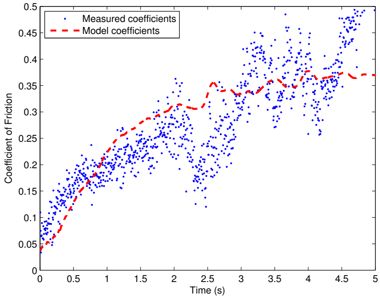
$\mu_d \approx 0.2$

Conensou effect experiment

Tangential force measurements



Spinning torque measurements



Conclusions

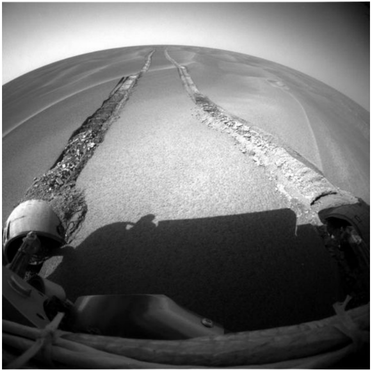
- Normal contact
  - Experiments compare well against Hertzian models
  - Applicability to unusual geometries demonstrated
  - Inverse relationship between impact velocity and damping
- Friction contact
  - Similar results for translation and rotation
  - Adhesion effect observed
  - Contensou effect demonstrated

Recommendations

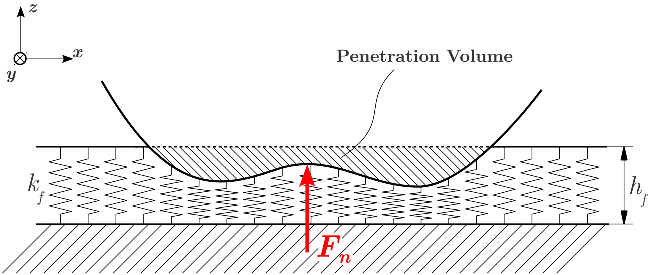
- Incremental improvements to apparatus:
  - Alignment
  - Force and speed ranges
  - Increased surface area/reduced contact pressure in friction contact
- Investigate other aspects of contact:
  - Rolling resistance torque
  - Understanding of adhesion effect

Motivation for Hyperelastic Foundation Model

- Highly nonlinear soil properties
- Large deformation of the soft soil



Volume vs. Hypervolume



Elastic Foundation:

$$\mathbf{F}_{n,L} = k_v \underbrace{\int f_S(\mathbf{S})\, dS}_{\text{Volume } V} \;\mathbf{n}$$

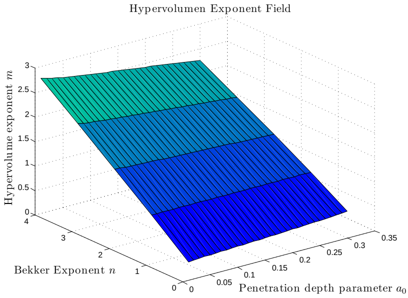
Hyperelastic Foundation:

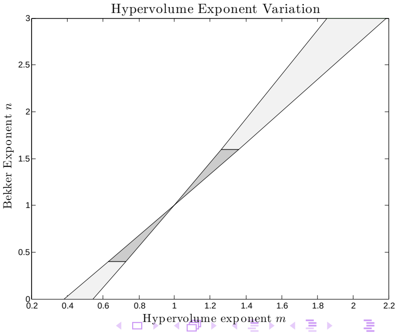
$$\mathbf{F}_{n,NL} = k_v \underbrace{\int f_S^n(\mathbf{S})\, dS}_{\text{Hypervolume } V_h} \;\mathbf{n}$$

Cylinder on Flat Ground

Exact Solution: Find m for a variation of n

$$\int f_S^n(\mathbf{S})\, dS - V^m = 0$$



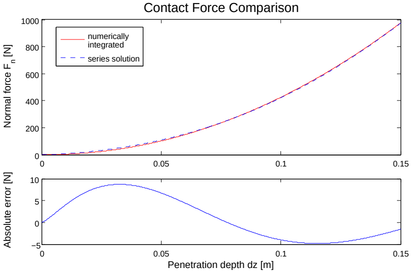


Cylinder on Flat Ground

Series Solution: Find α_i for a certain n and $dz = 0..R$

For $n > 1$:

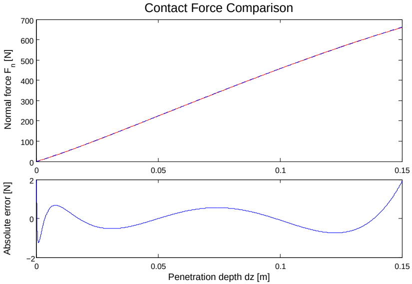
$$\int f_S^n(\mathbf{S})\, dS - \sum_{i=1}^{4} \alpha_i\ V^i\ = 0$$



Error: 1.38%

For $n < 1$:

$$\int f_S^n(\mathbf{S})\, dS - \sum_{i=1}^{8} \alpha_i\ V^{1/i}\ = 0$$



0.129%

Cylinder on Flat Ground

Mean Value Solution: Find $c_v(V)$ for a variation of n

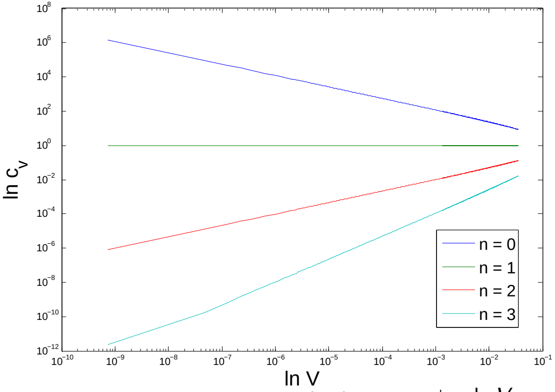
$$F_{n,NL} = k_v b \int_{-a}^{a} g(x)^n \, dx$$
$$= k_v b \int_{-a}^{a} g(x)^{(n-1)} g(x) \, dx$$

Apply 'Mean Value Theorem'

$$F_{n,NL} = k_v b c_v(V) \int_{-a}^{a} g(x) \, dx$$
$$= k_v b c_v(V) V \quad \text{with} \quad c_v(V) = \frac{\int_{-a}^{a} g(x)^n \, dx}{\int_{-a}^{a} g(x) \, dx}$$

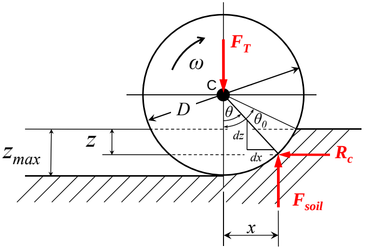
Cylinder on Flat Ground

Results of $c_v(V)$ for wheel with $R = 0.15$



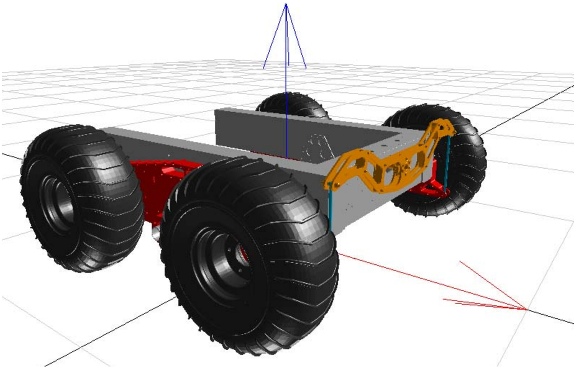
$$\text{Possible Solution :} \quad c_v(V) = e^{a_0 + a_1 \ln V}$$

Tire/Soil Contact Model



- Vertical Force:
  - Hyperelasic foundation model
  - Bekker soil parameters
- Longitudinal Force:
  - Traction force (Janosi-Hanamoto, grousers)
  - Resistance force (soil compaction)

Planetary Rover Model



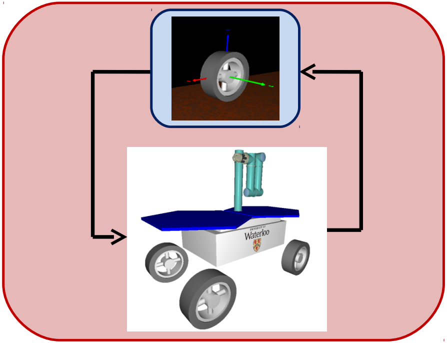
- Developed MapleSim 4.5 Model
- Exported symbolic equations to S-function block
- Developed Simulink model and with LLG contact models

Planetary Rover Simulation Platform

Combine tire model with rover dynamics

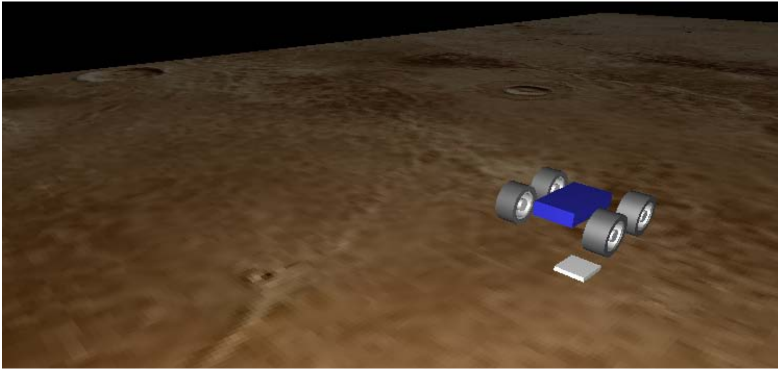
MuT (Multibody Toolbox)

Contact Model
Libraries
in
Numeric Simulation
Environment



Planetary Rover Simulation

Simulation and animation of rover with Parallel Geometry Inc. (LLG) software



Future work

1. Experimental validation of hyperelastic contact models

2. Use more sophisticated tire and terrain geometries

3. Develop models to run on a high performance computer