A Volumetric Contact Model for Space Robot and Planetary Rover Application

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Outline





- **Experimental Validation** 3
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Motivation



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

Image: A mathematical states and a mathem

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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

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Contact Models

Falling ISS battery box: real-time (Gonthier, 2007)

Point contact models

- Small contact patches only
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FEM

• Too complex for real-time

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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.

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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)

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- 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

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Volumetric model Normal forces Friction forces

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- Volumetric model
- Normal forces
- Friction forces

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Volumetric model

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Volumetric model



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

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

Image: A math a math

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Volumetric model Normal forces Friction forces

Volumetric properties



Volumetric properties

- V volume of interference \mathbf{J}_{s} surface-inertia t
- n contact normal

 J_s - surface-inertia tensor J_v - volume-inertia tensor

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Volumetric mode Normal forces Friction forces

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Normal forces

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Normal force

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



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Rolling resistance

Rolling resistance torque

 $oldsymbol{ au}_{\mathrm{r}} = oldsymbol{k}_{\mathrm{s}} \cdot oldsymbol{\omega}_{\mathrm{t}}$



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Friction

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

Friction forces (Gonthier et al., 2007) $\mathbf{f}_{t} = -\mu_{c} f_{n} \frac{\mathbf{v}_{ct}}{V_{avg}}$ $\boldsymbol{\tau}_{s} = -\frac{\mu_{c} f_{n}}{V V_{avg}} \mathbf{J}_{s} \cdot \boldsymbol{\omega}_{n}$

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- Normal force experiments
- Friction force experiments

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Normal force experiments Friction force experiments Key findings

Normal force experiments Friction force experiments Key findings

Apparatus in normal configuration



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Normal force experiments Friction force experiments Key findings

Quasi-static results with sphere on aluminum



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Normal force experiments Friction force experiments Key findings

Quasi-static results with sphere on magnesium



Magnesium surface tarnished quickly after polishing Orthotropic material

Volumetric stiffness $k_{\rm v} = 3.82 \times 10^{13} N/m^3$

Normal force experiments Friction force experiments Key findings

Cylinder-on-plane contact

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



Normal force experiments Friction force experiments Key findings

Quasi-static results with cylinder on aluminum



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Normal force experiments Friction force experiments Key findings

Quasi-static results with cylinder on magnesium



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Friction force experiments

Normal force experiments Friction force experiments Key findings

Apparatus in friction configuration



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Normal force experiments Friction force experiments Key findings

Static friction for translation





Coefficient of static friction
$$\mu_s \approx 0.2$$
Bristle stiffness and damping
 $\sigma_0 = 4500 m^{-1}$ $\sigma_1 = 300 s/m$ Y. GonthierA Volumetric Contact Model for Space Application

Normal force experiments Friction force experiments Key findings

Kinetic friction for translation





Coefficient of kinetic friction $\mu_d \approx 0.2$

Friction force experiments

Rotation experiments





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Normal force experiments Friction force experiments Key findings

Conensou effect experiment

Tangential force measurements



Spinning torque measurements



Normal force experiments Friction force experiments Key findings

Key findings

- Normal contact
 - Experiments compare well against Hertzian models
 - Applicability to unusual geometries demonstrated
 - Inverse relationship between impact velocity and damping

Normal force experiments Friction force experiments Key findings

Key findings

- 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

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Motivation for Hyperelastic Foundation

Tire Model for Planetary Rover Simulation

Off-Road Tire Models

- Rigid/Flexible wheel
- Soft soil

Contact Modelling

- Soft-soft contact
- Large deformation
- Highly nonlinear soil properties



Hyperelastic foundation model is required

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:

$$\mathbf{F}_{n,NL} = k_{v} \underbrace{\int f_{S}^{n}(\mathbf{S}) \, dS}_{\text{Hypervolume } V_{h}} \mathbf{n}$$

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Cylinder on Flat Ground

Exact Solution: Find m for a variation of n

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



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Cylinder on Flat Ground

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



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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'

$$F_{n,NL} = k_{v}bc_{v}(V)\int_{-a}^{a}g(x) dx$$

= $k_{v}bc_{v}(V)V$ with $c_{v}(V) = \frac{\int_{-a}^{a}g(x)^{n} dx}{\int_{-a}^{a}g(x) dx}$

Cylinder on Flat Ground

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



Tire/Soil Contact Model



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

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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



Planetary Rover Simulation

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

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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



- Y. Gonthier. *Contact Dynamics Modelling for Robotic Task Simulation*. PhD thesis, University of Waterloo, 2007.
- Y. Gonthier, J. McPhee, and C. Lange. On the implementation of Coulomb friction in a volumetric-based model for contact dynamics. In *Proceedings of ASME IDETC*, Las Vegas, Nevada, September 2007.