SOIL MECHANICS OF LUNAR REGOLITH SIMULANTS FOR PROBE LANDING AND ROVER LOCOMOTION

Kazuya Yoshida[*1], Keiji Nagatani[*1],
Genya Ishigami[*1], Shigehito Shimizu[*1]
Kozo Sekimoto[*2], Akira Miyahara[*3],
Takaaki Yokoyama[*4]

[*1] Tohoku University
[*2] Sekimoto SE Engineering
[*3] JAXA
[*4] Graduate University for Advanced Studies

Background:
Increasing interest in lunar missions

- **Exploration of the areas where Apollo or Luna did not go**
- **In-situ resource utilization**
- **Outpost for human habitation on Moon**
- **Technology demonstration and crew training for future Mars expeditions**

- **Robotic precursor missions**
  - **Autonomous landing**
  - **Surface locomotion**
  - **Core sampling and excavation**
  - **Construction**
- **International cooperation**

Agenda

- ☑ **Autonomous precision landing**
  - **Impact dynamics on regolith surface**
  - **Scaling law to infer the real motion from lab experiments**
- ☐ **Surface locomotion**
  - **Wheel traction model on loose soil**
  - **Soil and wheel parameters**
- ☐ **Drilling and sampling**
  - **Design challenge for a mole-like robot**

Probe Landing

**To evaluate the mechanical design, control performance and landing safety of the probe,
we need a simulation model that describes proper dynamics of the landing behavior.**

(Movie)
http://www.astro.mech.tohoku.ac.jp/
~yoshida/VideoLibrary/KD_flat_vx.mpeg

Drop Impact Test

Drop and impact tests are carried out in a vacuum chamber with *Lunar Regolith Simulant.*

(Movie)
http://www.astro.mech.tohoku.ac.jp/~yoshida/
VideoLibrary/soil_impact_landing_vacuum.mpg

Test with Scale Models

***The Scaling Law* is used to infer the real motion on Moon from the lab experiments with scale models.**

The scaling law in Moon landing (1)

Dominant physics of Moon landing

1. Inertia forces of the lunar probe:	$F_{is} = \rho_s l^2 v^2$
2. Inertia forces of the lunar soil:	$F_{ir} = \rho_r l^2 v^2$
3. Gravity forces applied to the lunar probe:	$F_{gs} = \rho_s g l^3$
4. Gravity forces applied to the lunar soil:	$F_{gr} = \rho_r g l^3$
5. Cohesion forces of the lunar soil:	$F_c = c l^2$
6. Friction forces:	F_f

ρ_s : the density of the lunar prove

ρ_r : the density of the lunar soil

l : the representative length

v : the velocity

c : the cohesion forces of the lunar soil

g : the gravitation acceleration

The scaling law in Moon landing

Derivation of the π-numbers from the basic equations

$$\begin{aligned}
\pi_1 &= F_{is}/F_{ir} &&= \rho_s/\rho_r &&= \rho'_s/\rho'_r \\
\pi_2 &= F_{gs}/F_{gr} &&= \rho_s/\rho_r &&= \rho'_s/\rho'_r \\
\pi_3 &= F_{is}/F_{gs} &&= v^2/gl &&= v'^2/g'l' \\
\pi_4 &= F_{is}/F_c &&= \rho_s v^2/c &&= \rho'_s v'^2/c' \\
\pi_5 &= F_f/F_{gr} &&= \mu &&= \mu'
\end{aligned}$$

$$\frac{l'}{l} = \frac{g\rho_s c'}{g'\rho'_s c} \longrightarrow \frac{l'}{l} = \frac{1}{6}$$

If the scale model is 1/6 in size, the Earth-based experiments will properly simulate the motion of landing behavior on Moon.

Question:

Do we need to do our experiments
always with a 1/6 scale model?

The answer may be NOT

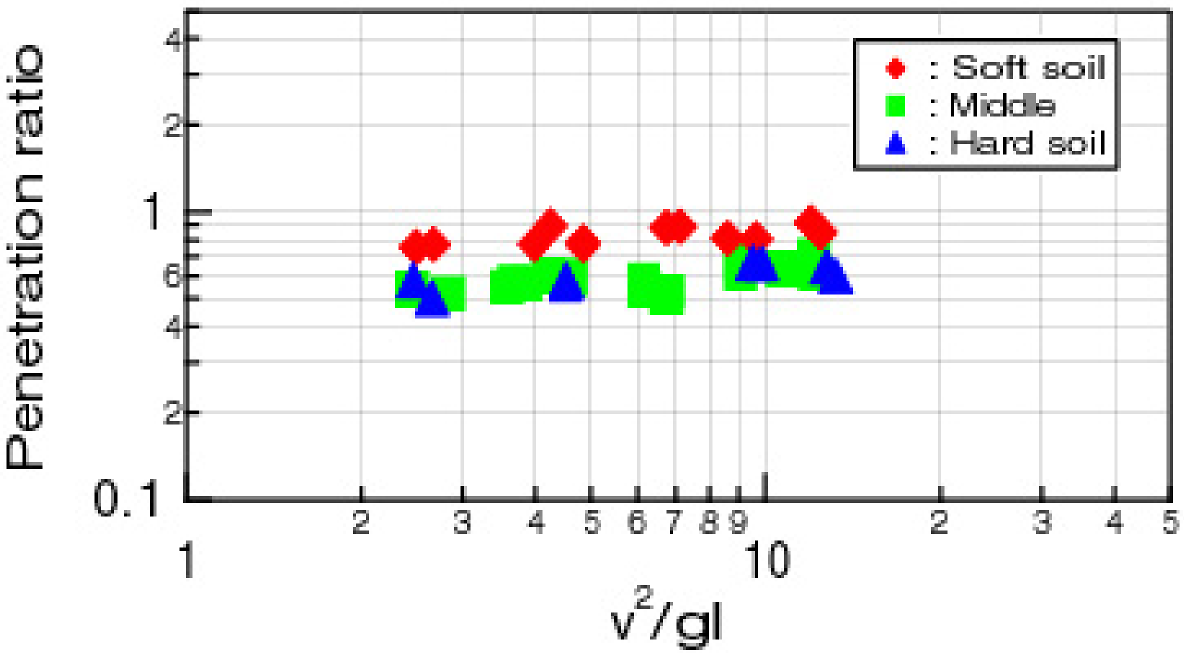
⇨ **Relaxation of the constraints**

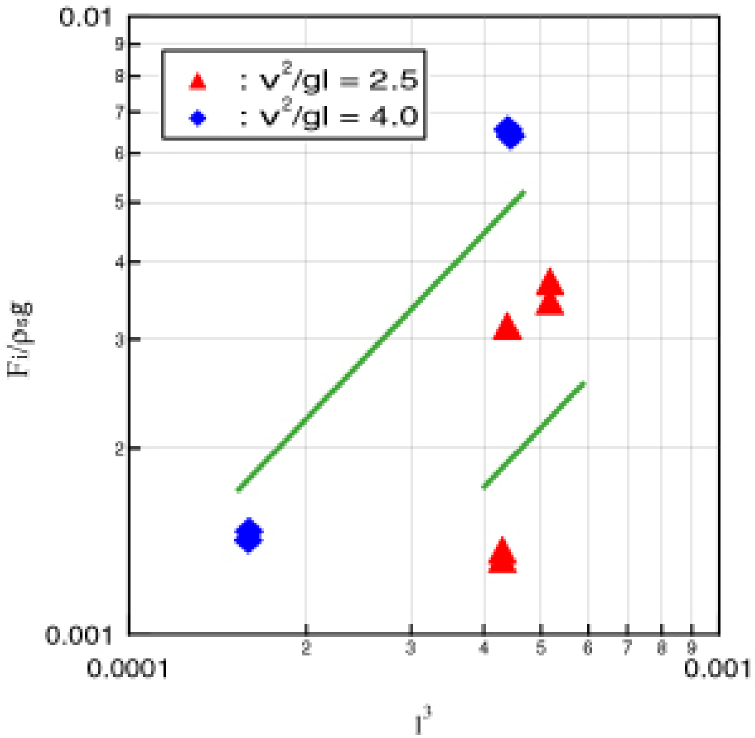
Case A : Elimination of the cohesion forces from the law

- Inertia forces
- Friction forces
- Gravity forces
- ~~Cohesion forces~~

$$\frac{\rho'_r}{\rho_r} = \frac{\rho'_s}{\rho_s} \quad \frac{g'l'}{gl} = \left(\frac{v'}{v}\right)^2$$

$$\frac{v^2}{gl} = \frac{v'^2}{g'l'}$$





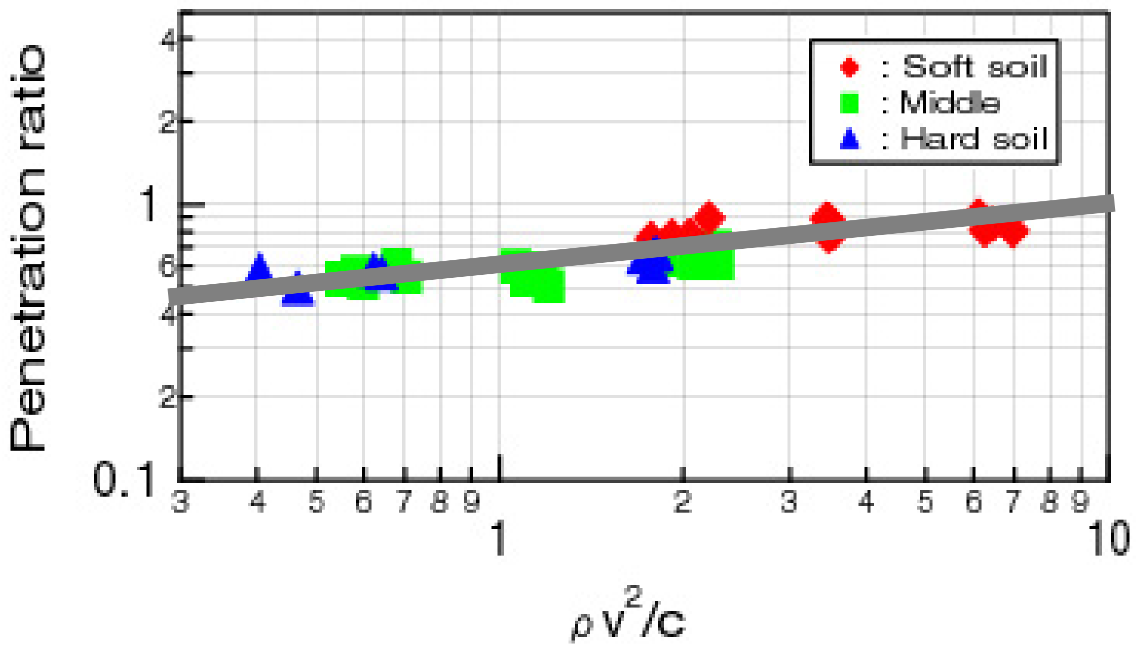
Case B : Elimination of the gravity forces from the law

- Inertia forces
- Friction forces
- ~~Gravity forces~~
- Cohesion forces

$$\frac{\rho_r'}{\rho_r} = \frac{\rho_s'}{\rho_s} \qquad \frac{c'\rho_s}{c\rho_s'} = \left(\frac{v'}{v}\right)^2$$

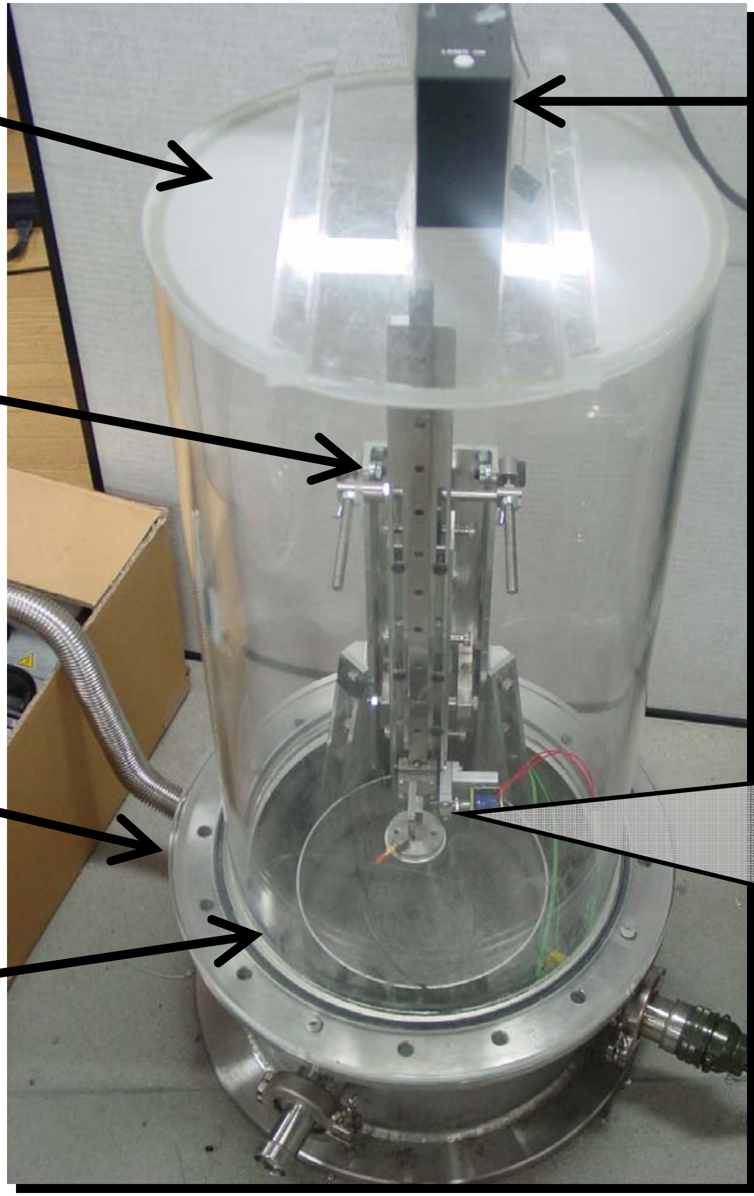
$$\frac{\rho v^2}{c} = \frac{\rho' v'^2}{c'}$$

Relationship between the models

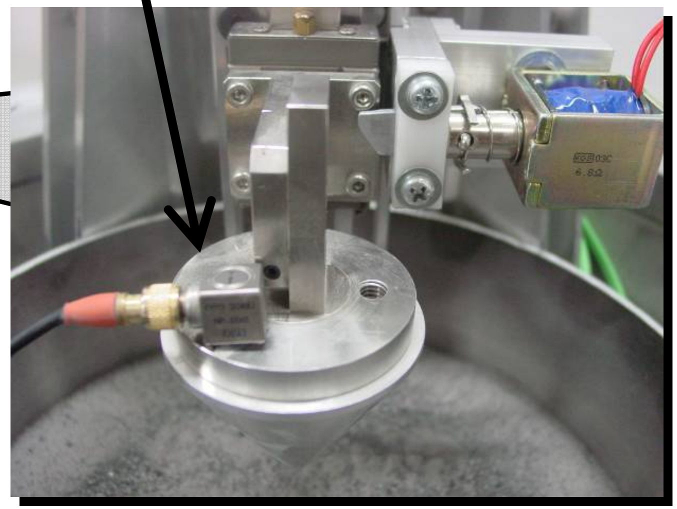


K. Yoshida, S. Shimizu, K. Sekimoto, A. Miyahara, T. Yokoyama,
"Scale Modeling for Landing Behavior of a Lunar Probe and Experimental Verification"
16th Workshop on Astrodynamics and Flight Mechanics, JAXA/ISAS, August 2006.

Experimental setup



For the measurement of the vertical position of test pieces.



Conditions of drop tests

Specifications of test pieces

Shape: Circular cone

Tip angle: 60, 90, 120 [deg]

Mass: 991, 482, 367 [g]

Landing velocity: 1.4 - 2.7 [m/s]

Atmosphere: 100 [Pa] (1/100 atm)

Soil density: 1,900-2,300 [kg/m^3]

Remarks 1 (Impact Landing on Regolith)

- Impact dynamics for the landing on lunar regolith was studied theoretically and experimentally.
- Both the theory and experiments suggest that the gravity forces have less effects than other forces to soil impact dynamics.
- Even if we eliminate the gravity from our consideration, the results hold a proper approximation.
- With such approximation (relaxation), we can choose any scaling ratios and use the following formula to infer the real motion dynamics from experiments:

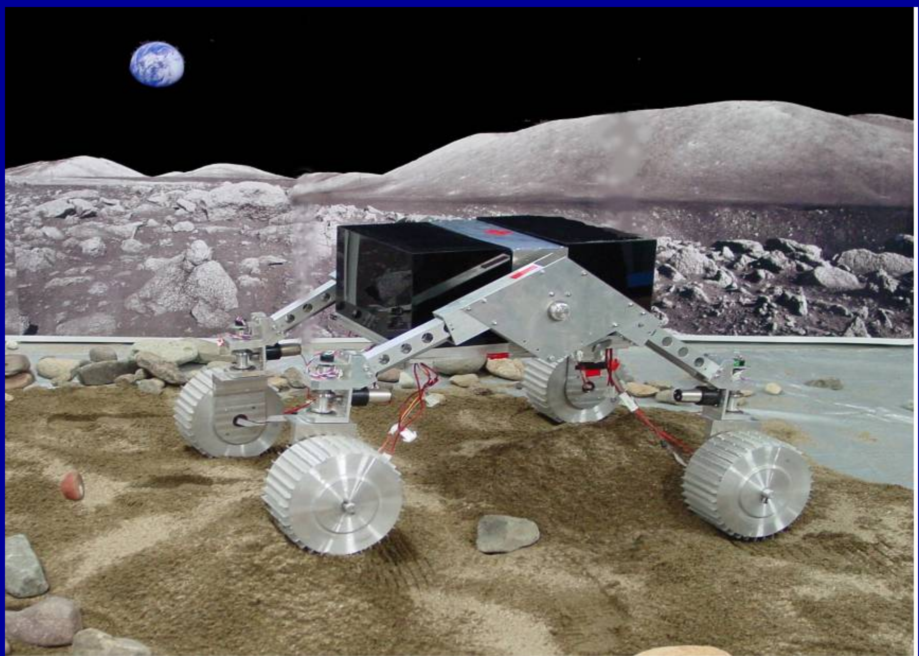
$$\frac{v'}{v} = \sqrt{\frac{c'\rho_s}{c\rho'_s}}$$

Symbols with a prime are the values obtained ground-based experiments.
Symbols without a prime are the inferred real value on the Moon.

Agenda

- ☐ Autonomous precision landing
  - Impact dynamics on regolith surface
  - Scaling law to infer the real motion from lab experiments
- ☑ Surface locomotion
  - Wheel traction model on loose soil
  - Soil and wheel parameters
- ☐ Drilling and sampling
  - Design challenge for a mole-like robot

Rover Test Beds
developed at Tohoku University



Research Focus on Lunar Rovers

- Mechanical Design
  - Choice of locomotion mode: wheels, tracks, or legs
  - Chassis design
- ✓ Traction Control
  - Makes difference in performance
  - *Slip* on loose soil
- ✓ Navigation
  - Path planning with tip-over & slip criteria
  - Path following with slip compensation

Experiment of Slip-Based Traction Control

- ***Without*** **Slip control**

(Movie)
http://www.astro.mech.tohoku.ac.jp/
~yoshida/VideoLibrary/slope1.mpg

- ***With*** **Slip control**

(Movie)
http://www.astro.mech.tohoku.ac.jp/
~yoshida/VideoLibrary/slope2.mpg

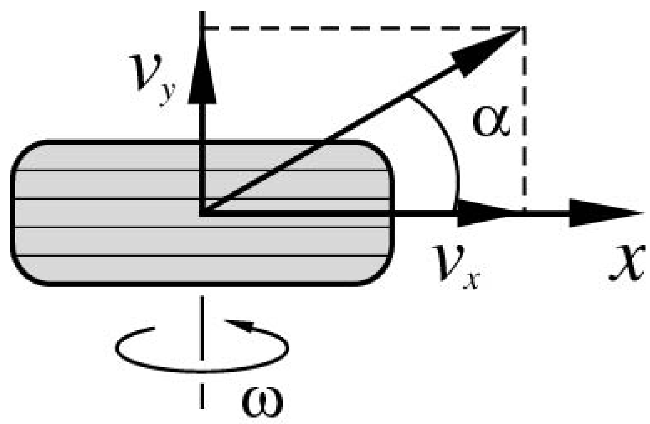
Slip is a key state variable

Slip Ratio

$$s = \begin{cases} \dfrac{r\omega - v_x}{r\omega} & (r\omega > v_x) \\[2ex] \dfrac{r\omega - v_x}{v_x} & (r\omega < v_x) \end{cases}$$

S > 0 while accelerating

S < 0 while braking



Even though the rover travels slowly, the phenomena around the wheels are dynamic.

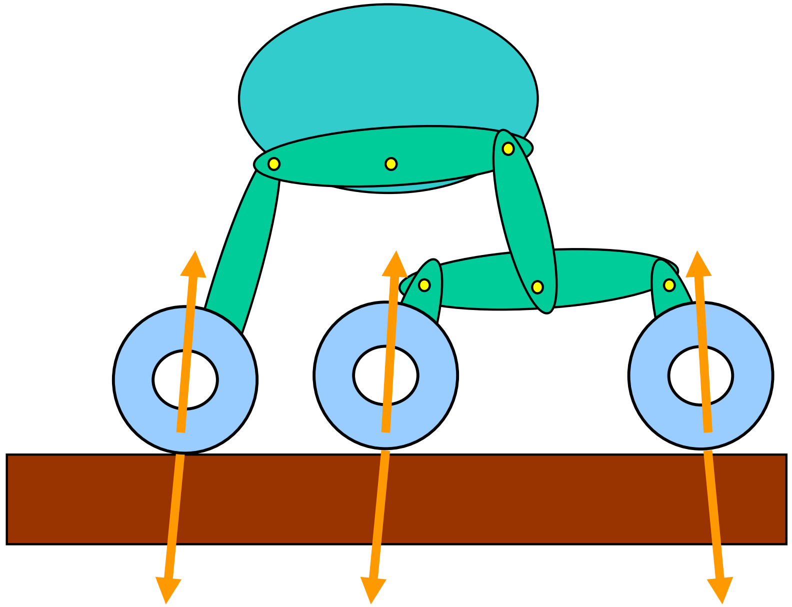
Side slips and side forces should be also studied.

(Movie)
http://www.astro.mech.tohoku.ac.jp/
~yoshida/VideoLibrary/slope_traverse03.mpg

(Movie)
http://www.astro.mech.tohoku.ac.jp/
~yoshida/VideoLibrary/slope_traverse02.mpg

Traction Model for a Rigid Tire on Soft Soil

(Bekker 1956, Wong 1978)



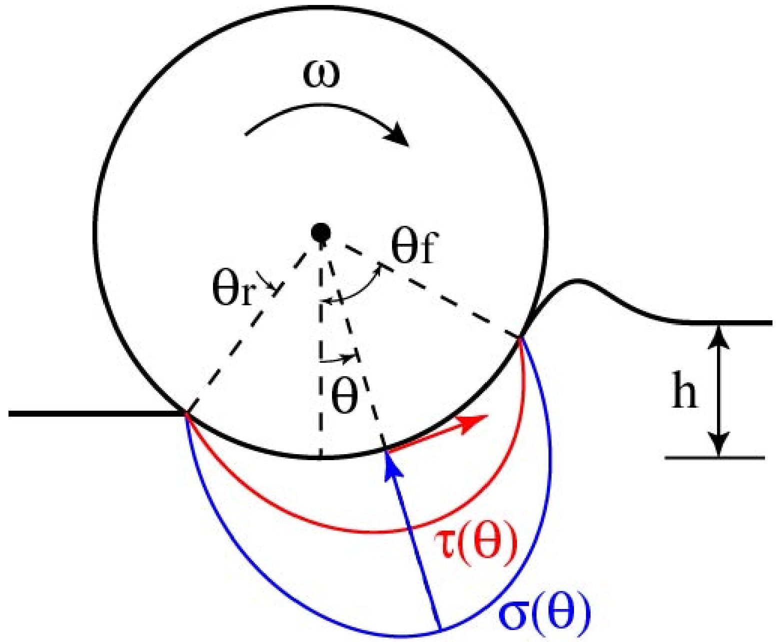
$$W = rb\int_{\theta_r}^{\theta_f} \{\sigma(\theta)\cos\theta + \tau(\theta)\sin\theta\} d\theta$$

$$DP = rb\int_{\theta_r}^{\theta_f} \{\tau(\theta)\cos\theta - \sigma(\theta)\sin\theta\} d\theta$$

$$T = r^2 b\int_{\theta_r}^{\theta_f} \tau(\theta) d\theta$$

$$\tau(\theta) = (c + \sigma\tan\varphi)\left(1 - e^{a(s)}\right)$$

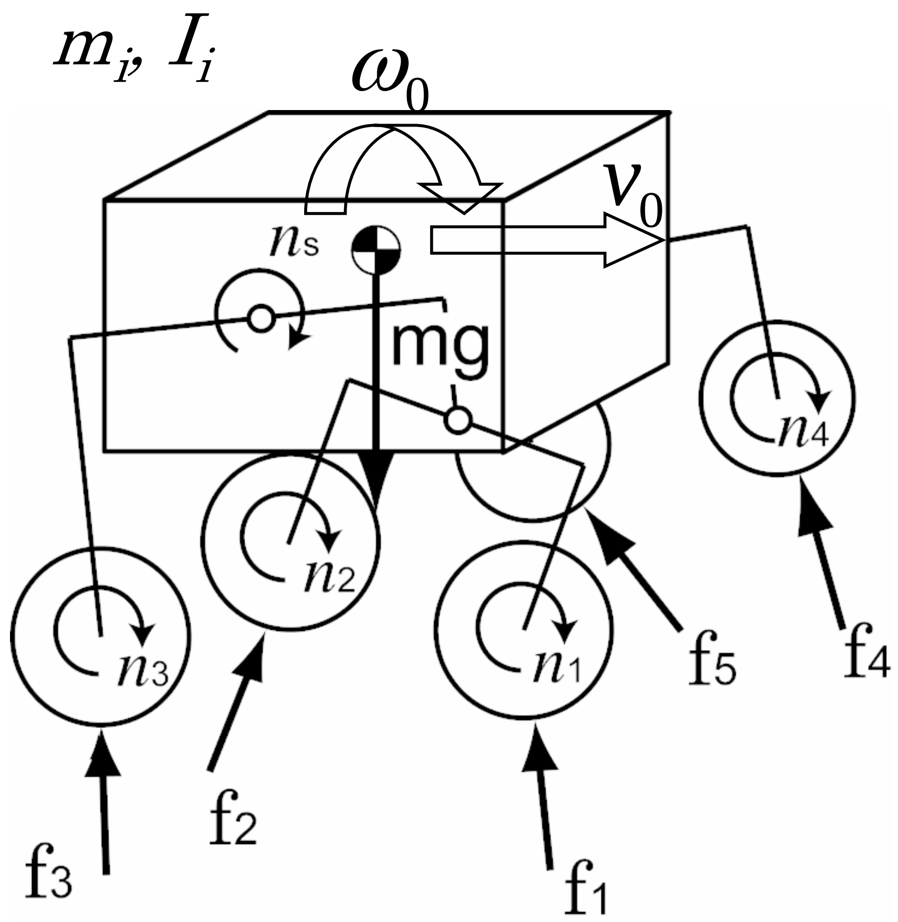
$$a(s) = -\frac{r}{k}\left[\theta_f - \theta - (1-s)(\sin\theta_f - \sin\theta)\right]$$



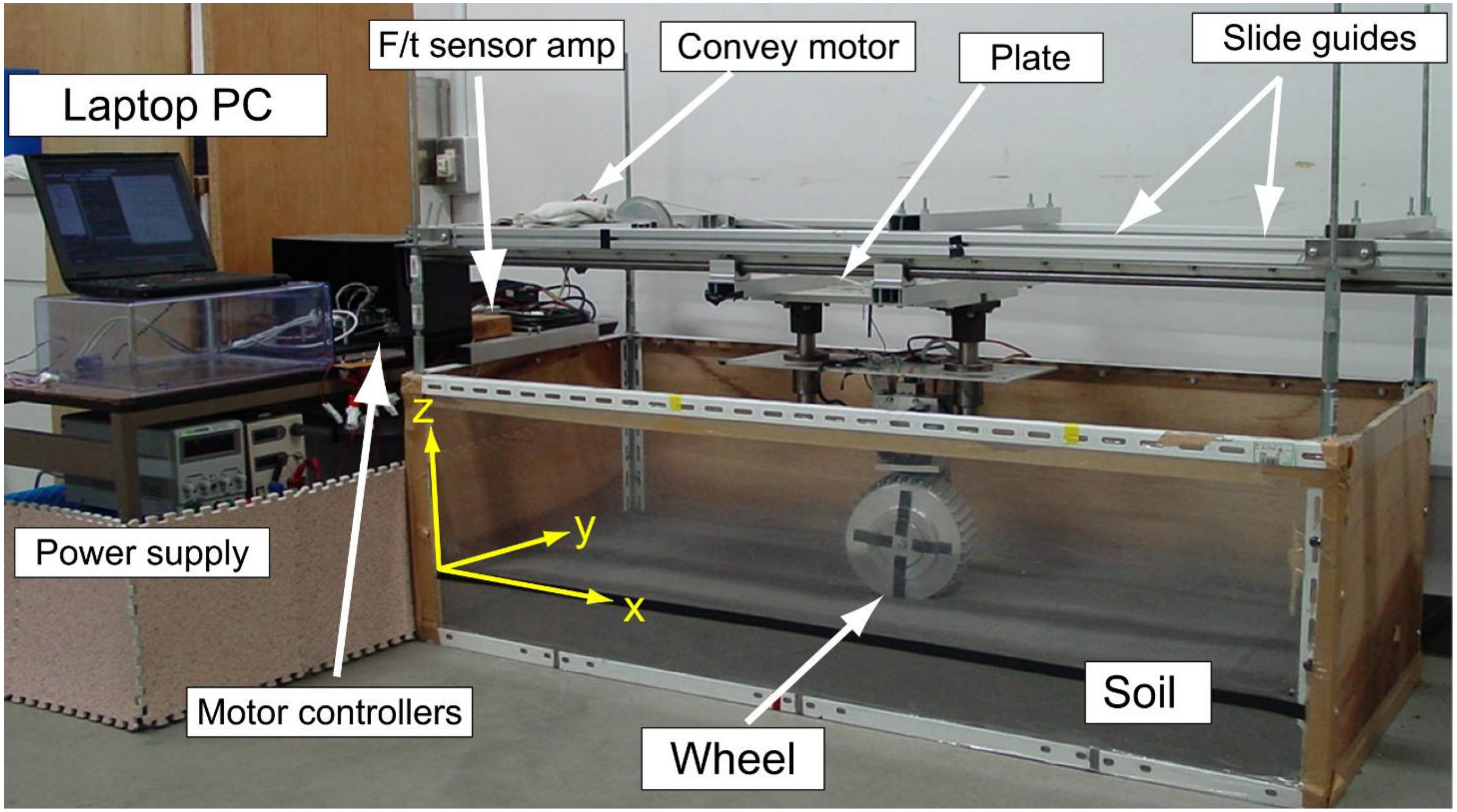
Vehicle Dynamics = **Multibody Dynamics with a Moving Base + Multi-Contact Points + Gravity**

Equation of Motion

$$H \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \\ \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} + C = \begin{bmatrix} F_0 \\ N_0 \\ n_w \\ n_s \end{bmatrix} + J^T \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_6 \end{bmatrix}$$

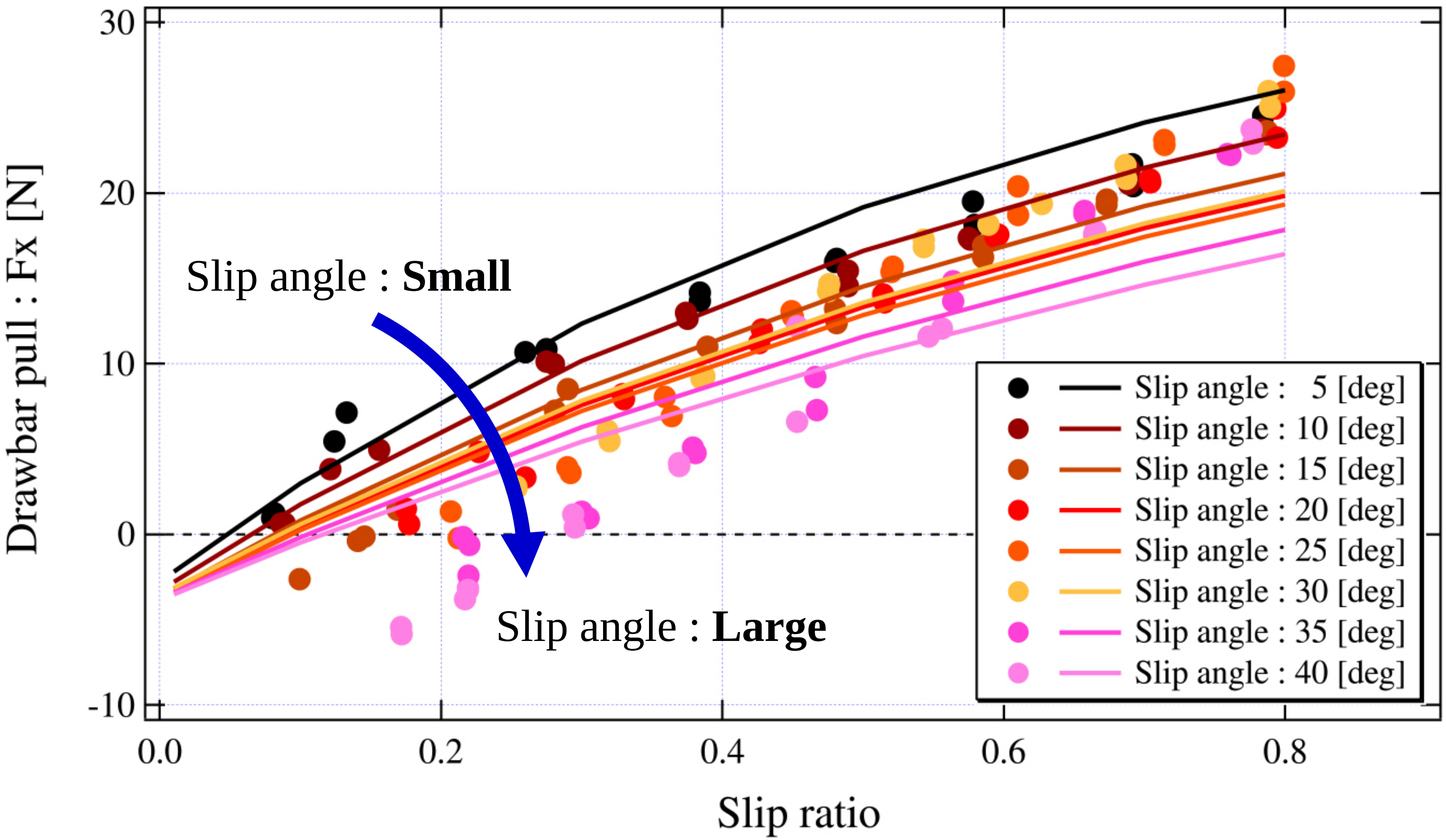


Single Wheel Test Bed



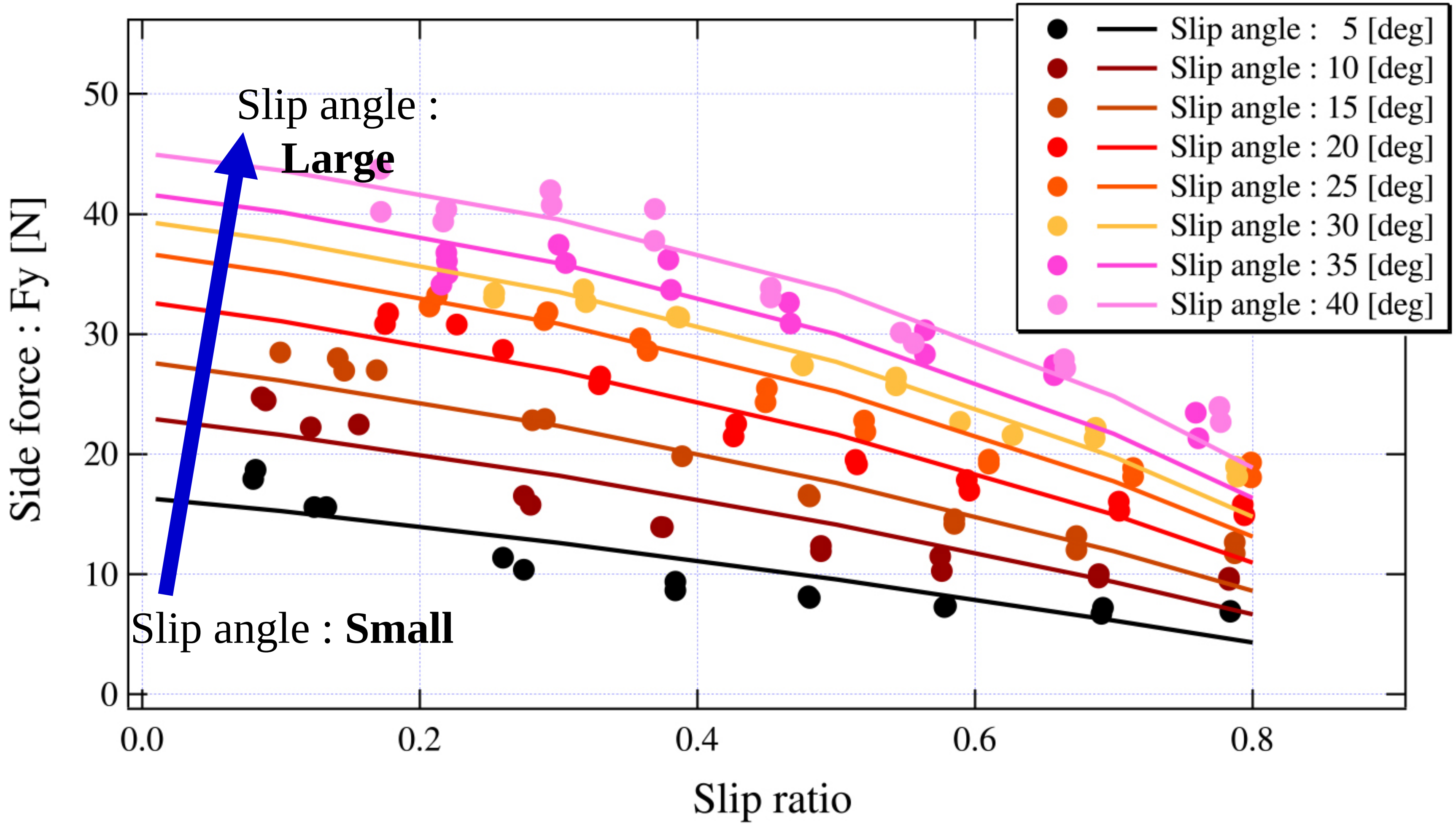
Wheel	Diameter：184[mm], Width:107[mm]
Slip Ratio	0 – 0.8
Slip Angle	0 – 45 degrees
Soil	*Lunar Regolith Simulant (FJS-1 equivalent)*

Experimental Results (longitudinal force)



G. Ishigami, A. Miwa, K. Ngatani, K. Yoshida
“Terramechanics-based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil”
Journal of Field Robotics vol.24, 2007 (to appear)

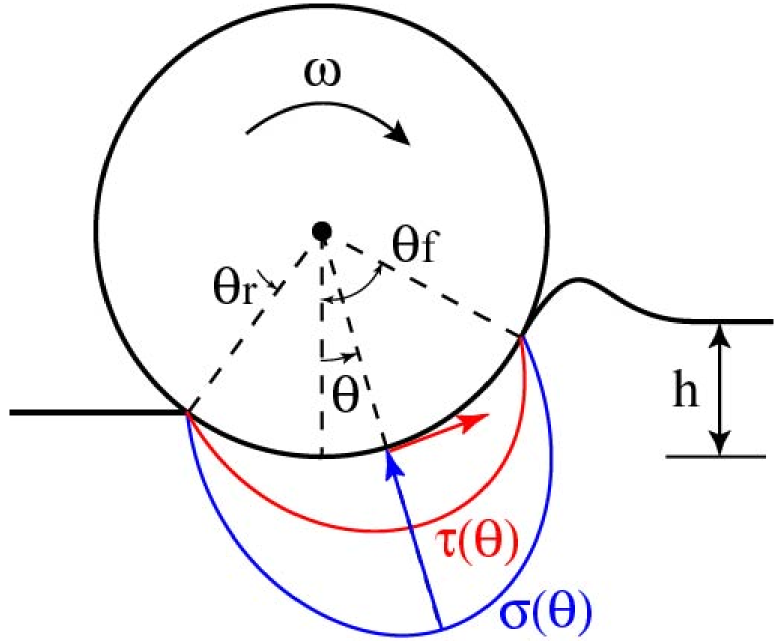
Experimental Results (side force)



G. Ishigami, A. Miwa, K. Ngatani, K. Yoshida
"Terramechanics-based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil"
Journal of Field Robotics vol.24, 2007 (to appear)

Traction Model for a Rigid Tire on Soft Soil

(Bekker 1956, Wong 1978)



$$W = rb\int_{\theta_r}^{\theta_f} \{\sigma(\theta)\cos\theta + \tau(\theta)\sin\theta\} d\theta$$

$$DP = rb\int_{\theta_r}^{\theta_f} \{\tau(\theta)\cos\theta - \sigma(\theta)\sin\theta\} d\theta$$

$$T = r^2 b\int_{\theta_r}^{\theta_f} \tau(\theta) d\theta$$

$$\tau(\theta) = (c + \sigma\tan\varphi)\left(1 - e^{a(s)}\right)$$

$$a(s) = -\frac{r}{k}\left[\theta_f - \theta - (1-s)(\sin\theta_f - \sin\theta)\right]$$

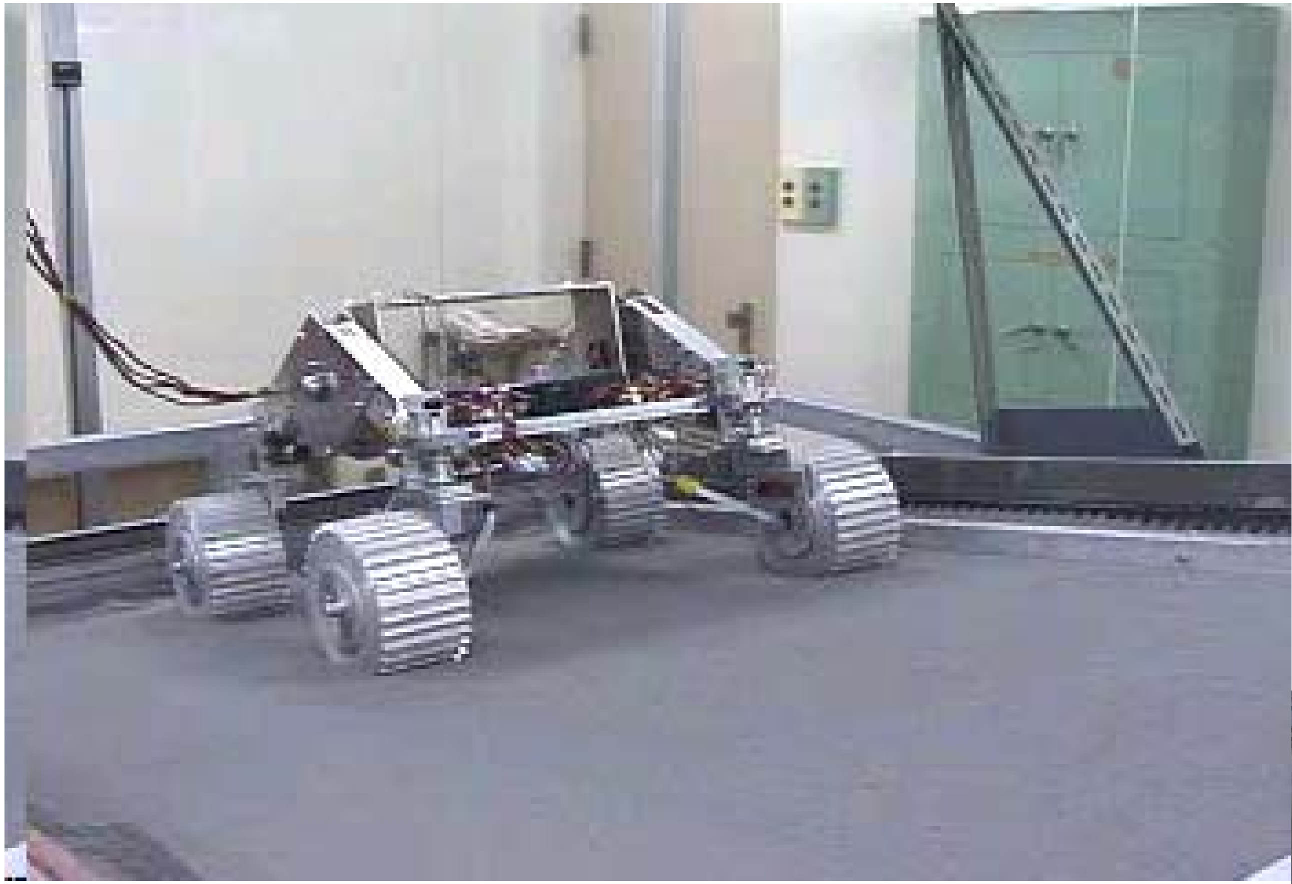
Key parameters:

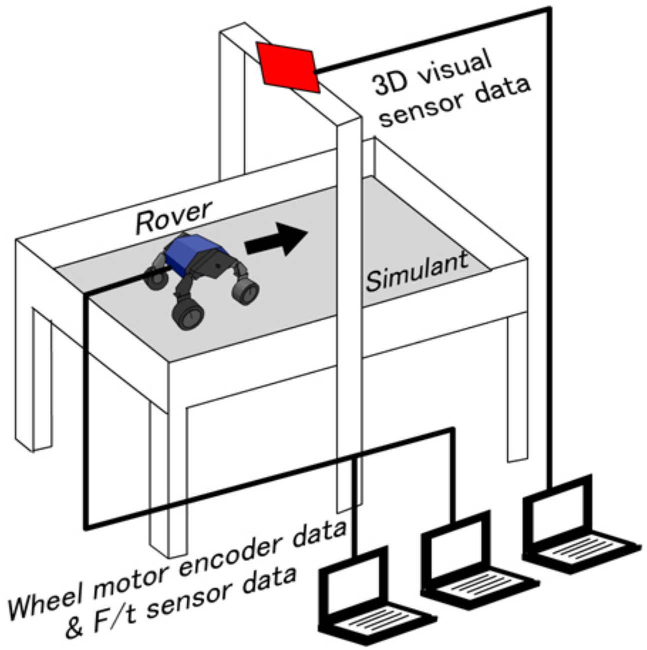
c : soil cohesion

φ : friction angle

k : shear deformation modulus

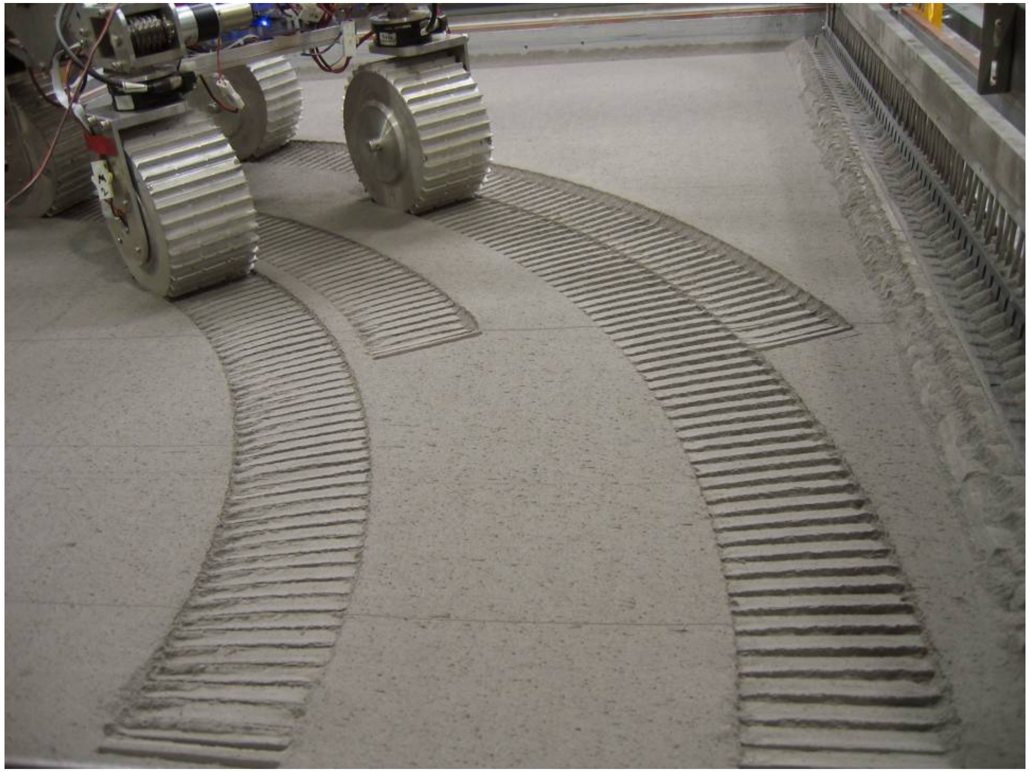
Slope Climbing Experiment
at JAXA Aerospace Research Center



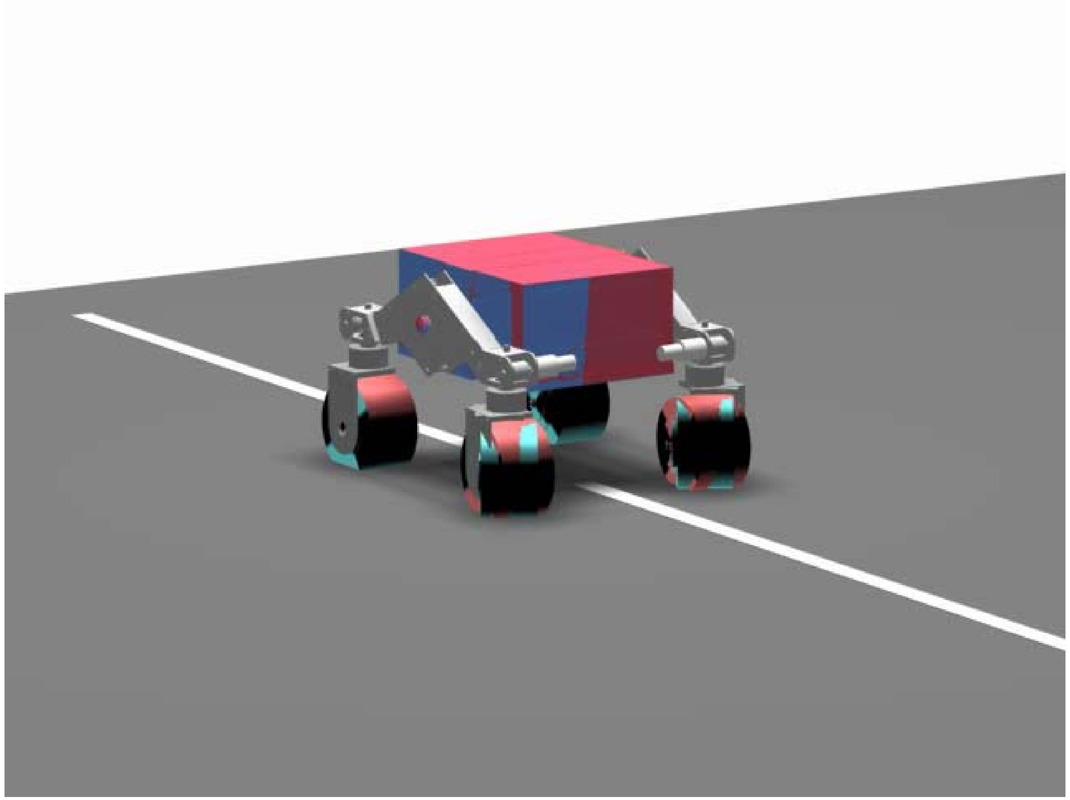


Lunar Regolith Simulant
arbitrary inclination 0-30 deg or over

Slope Traversing Experiment
at JAXA Aerospace Research Center



Experimental trace



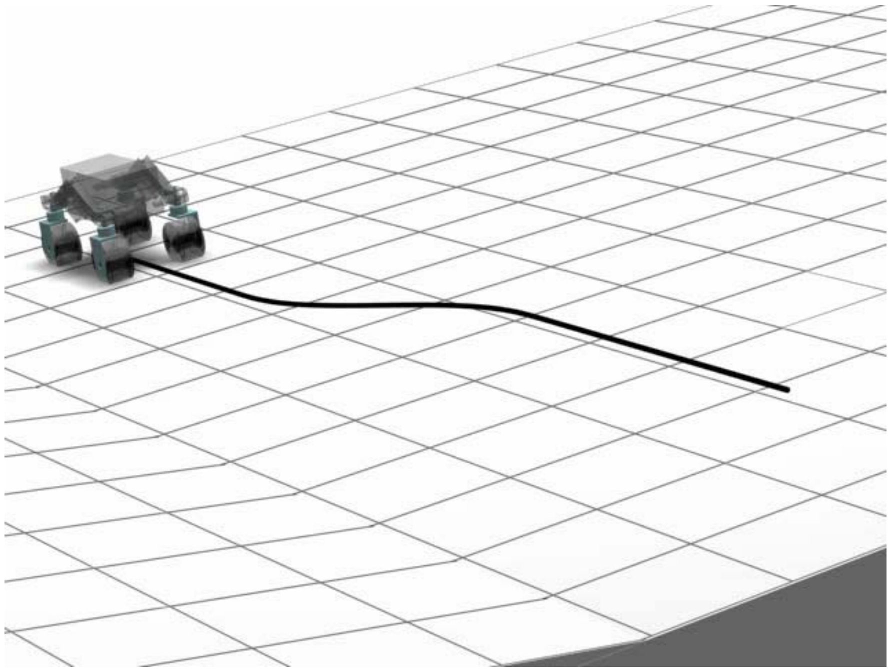
Red is simulation, blue is experiment

Lunar Regolith Simulant

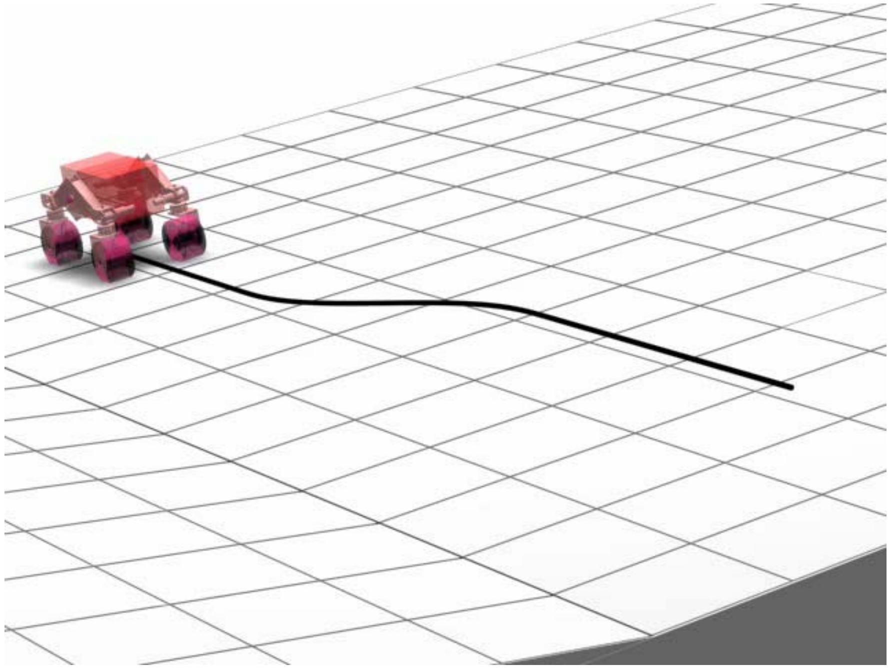
arbitrary inclination 0-30 deg or over

Path Planning and Control

Execute path-tracking navigation with taking the longitudinal and lateral slip effects into account.



Kinematics-based control



Dynamics-based control

Genya Ishigami, Keiji Nagatani, and Kazuya Yoshida,
"Path Following Control with Slip Compensation on Loose Soil for Exploration Rover",
Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5552-5557, 2006

Remarks 2 (Locomotion on Loose Soil)

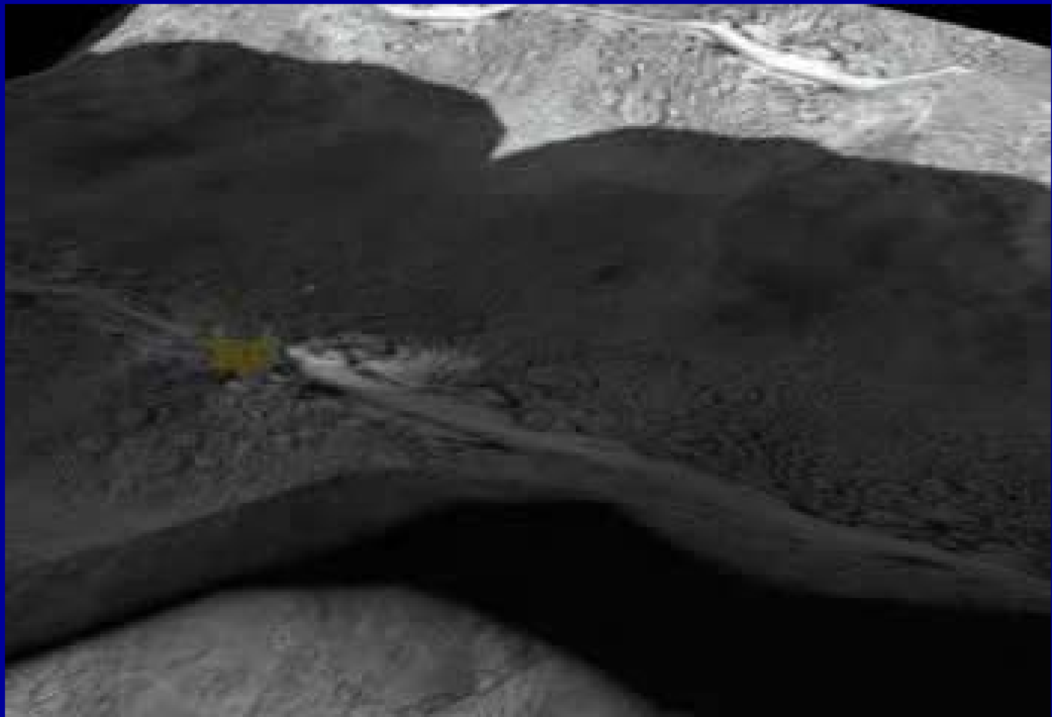
- Traction mechanics of a rigid wheel on loose soil has been clarified using an analytical model and validated by laboratory experiments.
- Key parameters of the traction mechanics are *soil cohesion*, *friction angle* and *shear deformation modulus*.
  But the shear deformation modulus is a *magic number*, which represents the wheel-soil interaction for each wheel-soil combination.
- If we can measure the slippage (both in longitudinal and lateral directions) on board, smart path following control of a rover with slippage compensation will be achieved.

Open question: how to measure the *slippage* by only onboard sensors?

Agenda

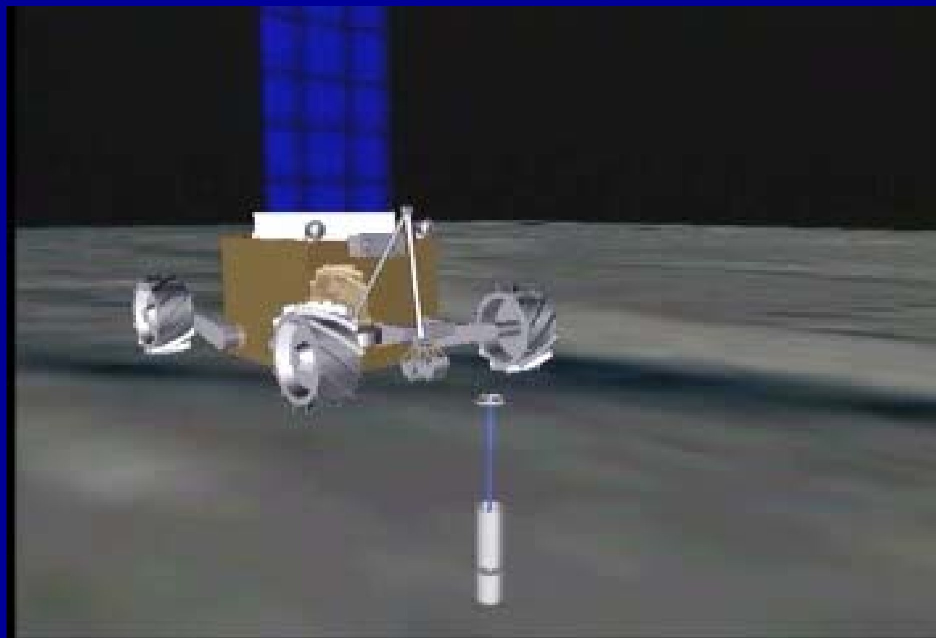
- ☐ Autonomous precision landing
  - Impact dynamics on regolith surface
  - Scaling law to infer the real motion from lab experiments
- ☐ Surface locomotion
  - Wheel traction model on loose soil
  - Soil and wheel parameters
- ☑ Drilling and sampling
  - Design challenge for a mole-like robot

Design Challenge for Excavation and Transportation



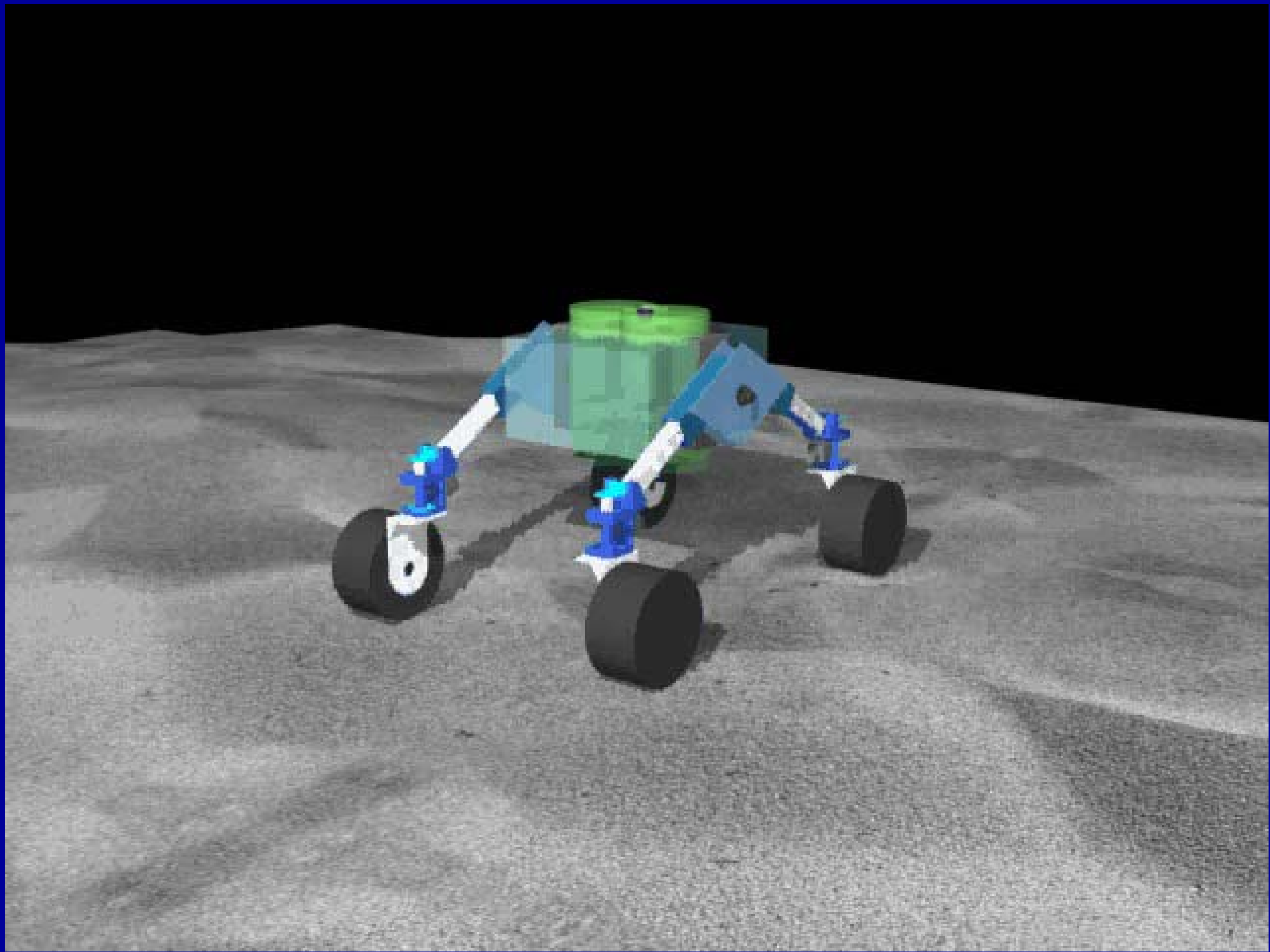
(Movie)
http://www.astro.mech.tohoku.ac.jp/lunar-mission/mog-rov1.mpg

(Movie)
http://www.astro.mech.tohoku.ac.jp/lunar-mission/mog-rov4.mpg



These simulation movies were created in 1999

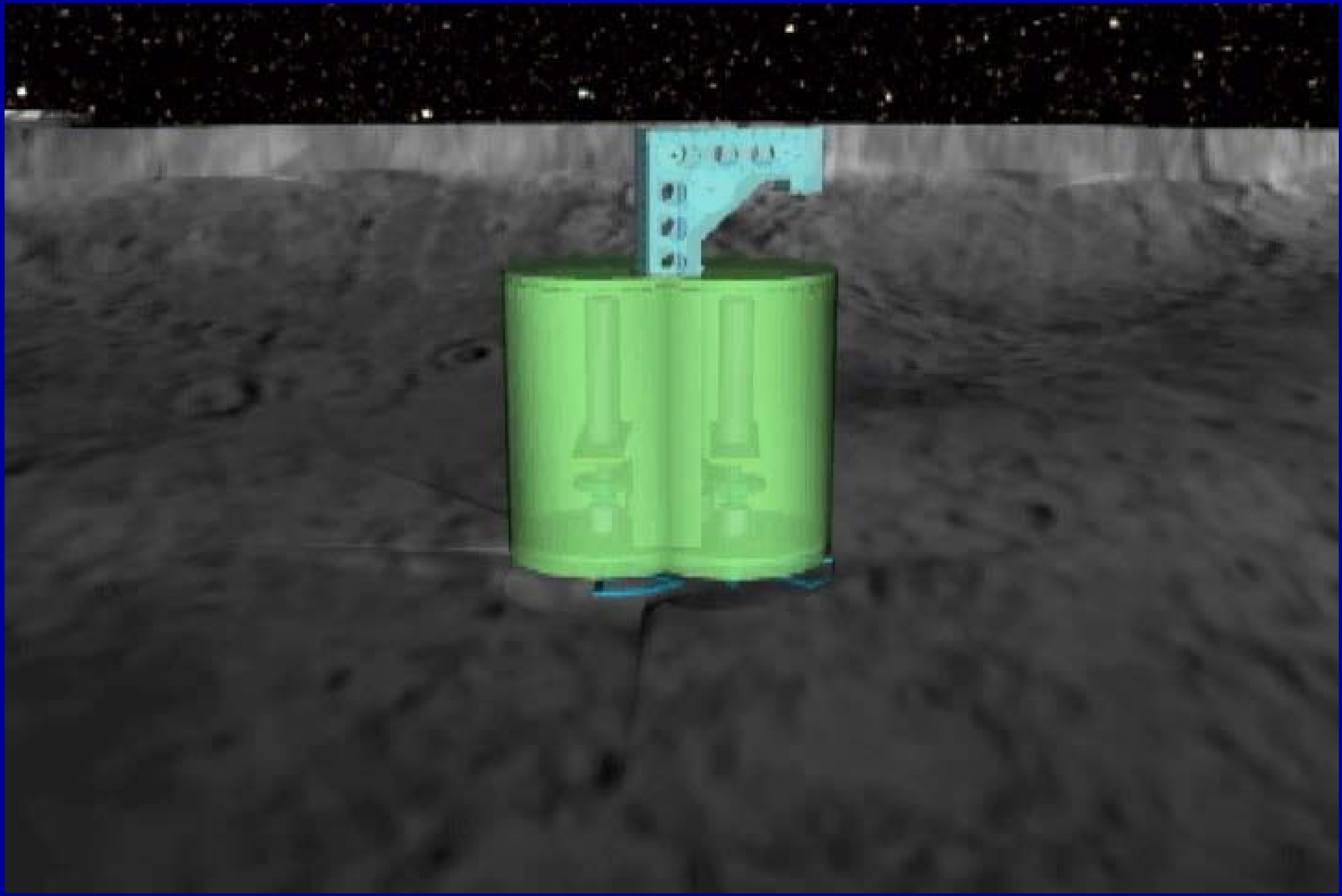
Design Challenge for Excavation and Transportation



(Movie)
http://www.astro.mech.tohoku.ac.jp/~yoshida/VideoLibrary/mog-rov1.mpg

MOGURA2001

Design Challenge for Excavation and Transportation



(Movie)
http://www.astro.mech.tohoku.ac.jp/~yoshida/VideoLibrary/mog-rov2.mpg

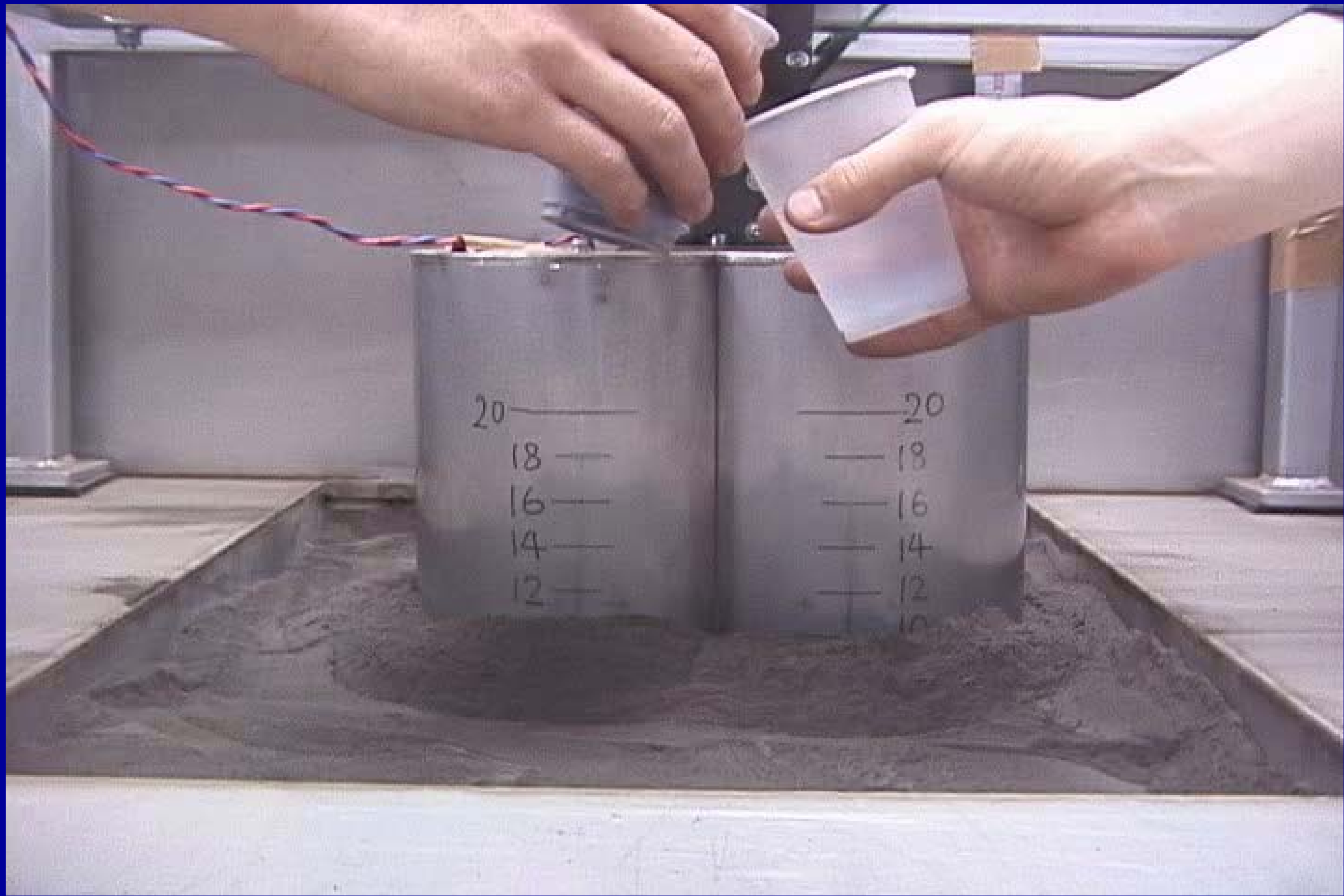
MOGURA2001

Design Challenge for Excavation and Transportation

(Movie)
http://www.astro.mech.tohoku.ac.jp/~yoshida/VideoLibrary/mog-rov-exp1.mpg

MOGURA2001

Design Challenge for Excavation and Transportation



(Movie)
http://www.astro.mech.tohoku.ac.jp/~yoshida/VideoLibrary/mog-rov-exp2.mpg

MOGURA2001

Remarks 3 (Robotic Excavator)

- A test bed for a mole-like self-excavation (tunnel builder) robot was developed and tested using *Lunar Regolith Simulant*.
- Double-roter system was introduced to cancel the reaction each other. This idea was successful.
- A conveyer mechanism to transport the soil ejecta from the cutting front (bottom) to above the surface was necessary to make the robot move forward.
- By virtue of the double-roter system and the soil conveyer mechanism, the robot successfully sank into the soil by its own weight, without any rig to support or push the robot.
- The excavation was successful as deep as the length of the robot body, but difficult to dig more than that, due to the increased soil resistance.
  More study is necessary to analyze the mechanics to limit the excavation depth.

The Space Robotics Lab.
Dept. of Aerospace Engineering
Tohoku University, JAPAN

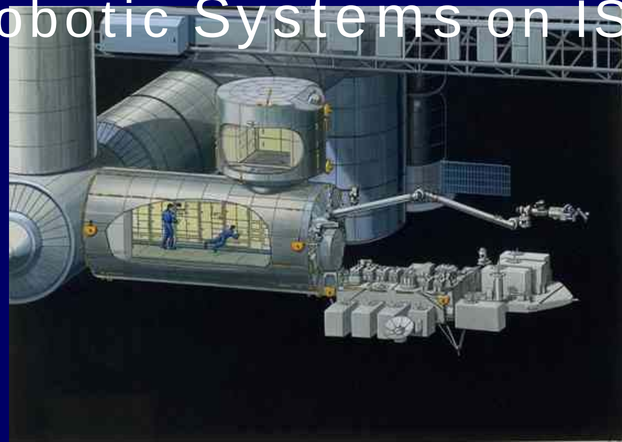
Directed by Prof. Kazuya Yoshida

yoshida@astro.mech.tohoku.ac.jp

http://www.astro.mech.tohoku.ac.jp/home-e.html

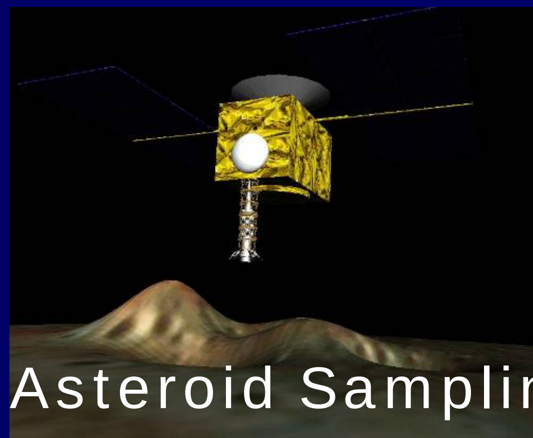
Free-Flying Space Robot

Robotic Systems on ISS



Planetary Exploration Rovers

The SPACE ROBOTICS Lab.



Asteroid Sampling