*ICRA '07 Space Robotics Workshop*
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# Terramechanics Based Analysis and Motion Control of Rovers on Simulated Lunar Soil

**Kazuya Yoshida and Keiji Nagatani**

**Dept. Aerospace Engineering**
**Graduate School of Engineering**
**Tohoku University, Sendai, Japan**

Apollo mission © NASA

# Increasing Interest in Lunar Missions

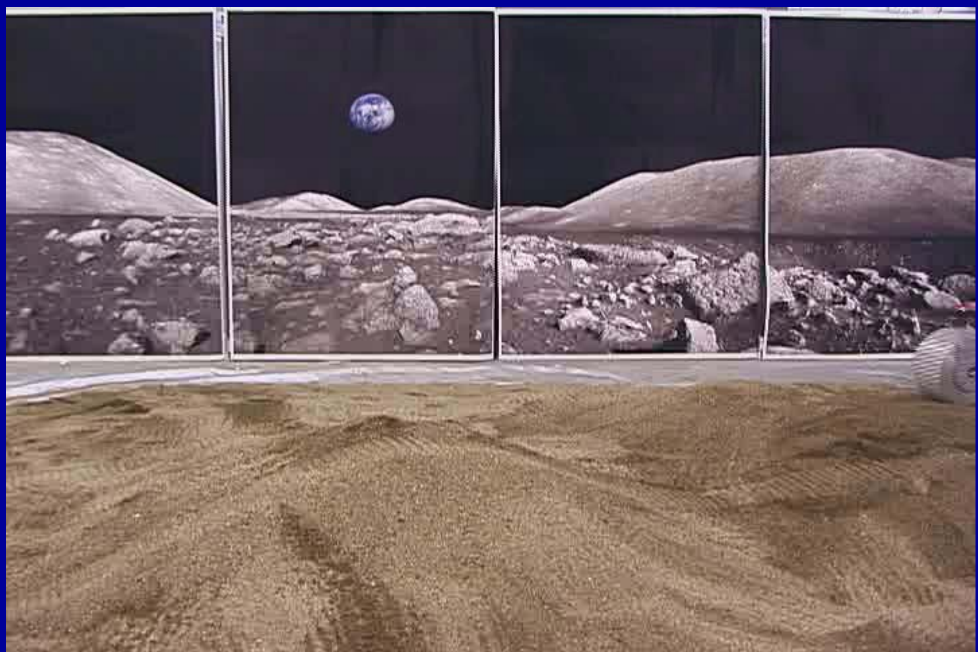
- **Exploration of the areas where Apollo or Luna did not go**
- **In-situ resource utilization**
- **Outpost for human habitation on Moon**
- **Technology demonstration and crew training for future Mars expeditions**

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

# Design and Control Issues for Lunar / Mars Rovers

- Mobility on Natural Terrain
- Traversability（Rocky obstacles, Slope climbing/traversing)）
- Navigation（Teleoperation v.s. Autonomy）
- Positioning, Localization, Map Generation…
- In-Situ Analysis
- Sample Acquisition and Handling, Preprocessing
- Power, Communication
- Versatility to Hostile Environment（Thermal, Dust.. eg. –170～+130℃ on Moon）

# Rover Test Beds *since 1997*



# Research Focus on Lunar / Planetary 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 stability & slip criteria
  - Path following with slip compensation

# Experiment of Slip-Based Traction Control

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

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

***Side slip phenomena is very interesting, which should studied well.***

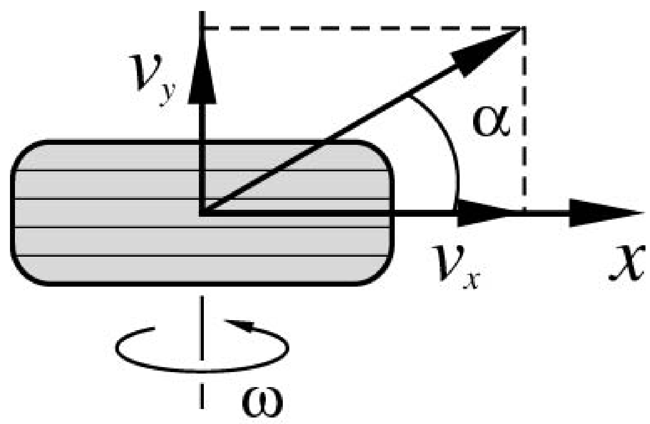
# *Slip* is a key state variable

## Slip Ratio

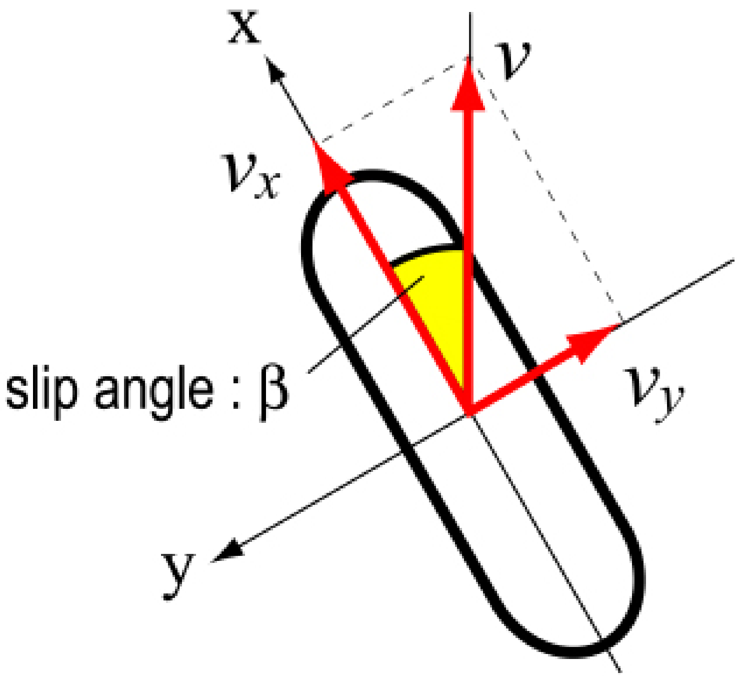
$$s = \begin{cases} \dfrac{r\omega - v_x}{r\omega} & (r\omega > v_x) \\ \\ \dfrac{r\omega - v_x}{v_x} & (r\omega < v_x) \end{cases}$$

S > 0 while accelerating

S < 0 while braking



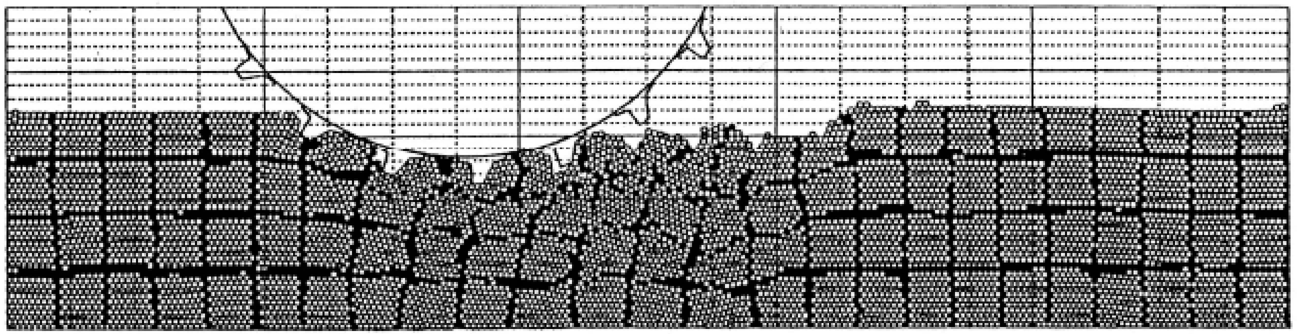
# Slip Angle

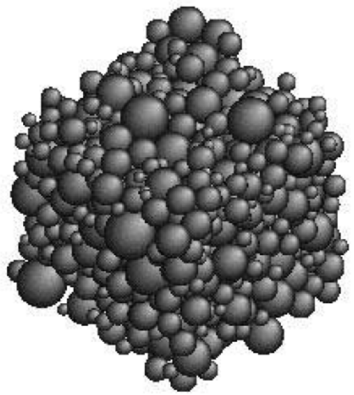



$$\beta = \tan^{-1}\frac{v_y}{v_x}$$

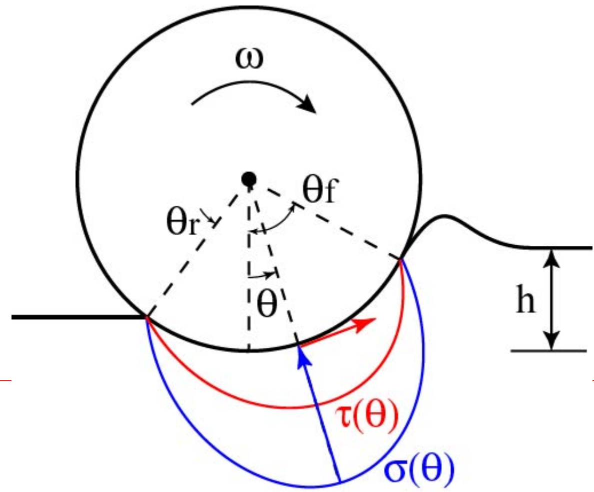
# Two Modeling Approaches for the Study of Soil Behavior under a Wheel

- Discrete Element Method (DEM)





- Continuum Modeling
  - Bekker 1956
  - Wong 1978



# Traction Model for a Rigid Tire on Soft Soil

(Bekker 1956, Wong 1978)

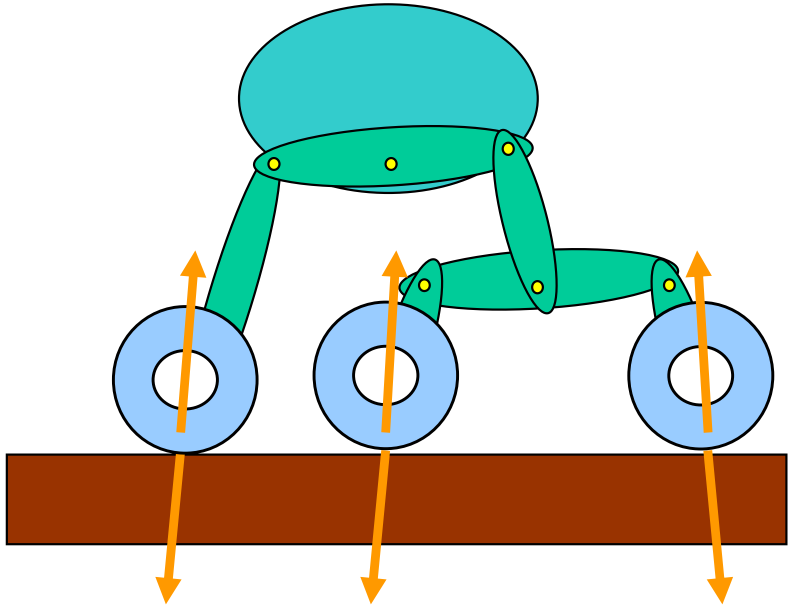
$$W = rb\int_{\theta_r}^{\theta_f} \{\sigma(\theta)\cos\theta + \tau(\theta)\sin\theta\}d\theta$$

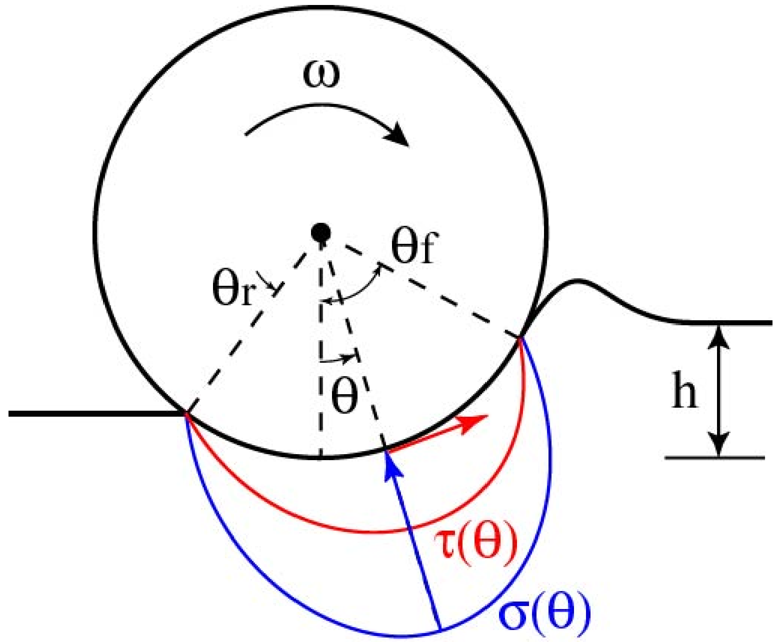
$$DP = rb\int_{\theta_r}^{\theta_f} \{\tau(\theta)\cos\theta - \sigma(\theta)\sin\theta\}d\theta$$

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

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

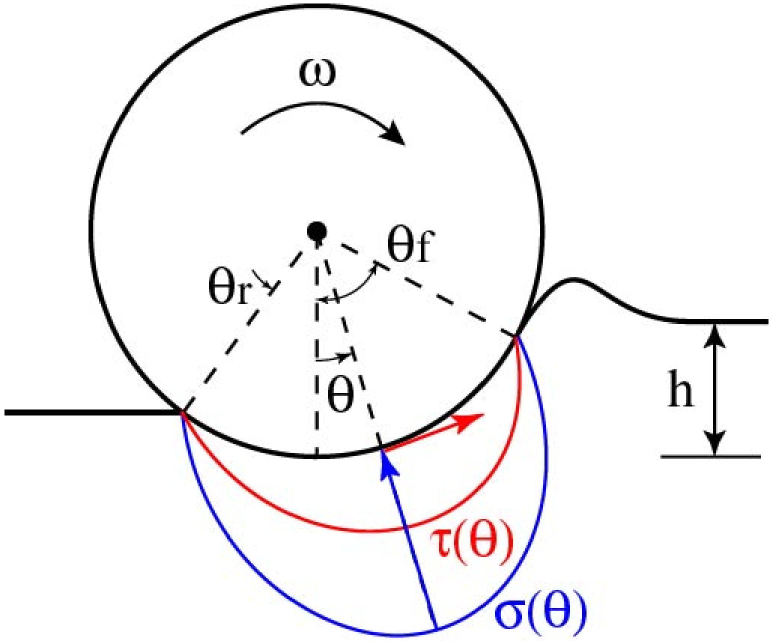
$$a(s) = -\frac{r}{k}\left[\theta_f - \theta - (1-s)(\sin\theta_f - \sin\theta)\right]$$





# Traction Model for a Rigid Tire on Soft Soil

(Bekker 1956, Wong 1978)

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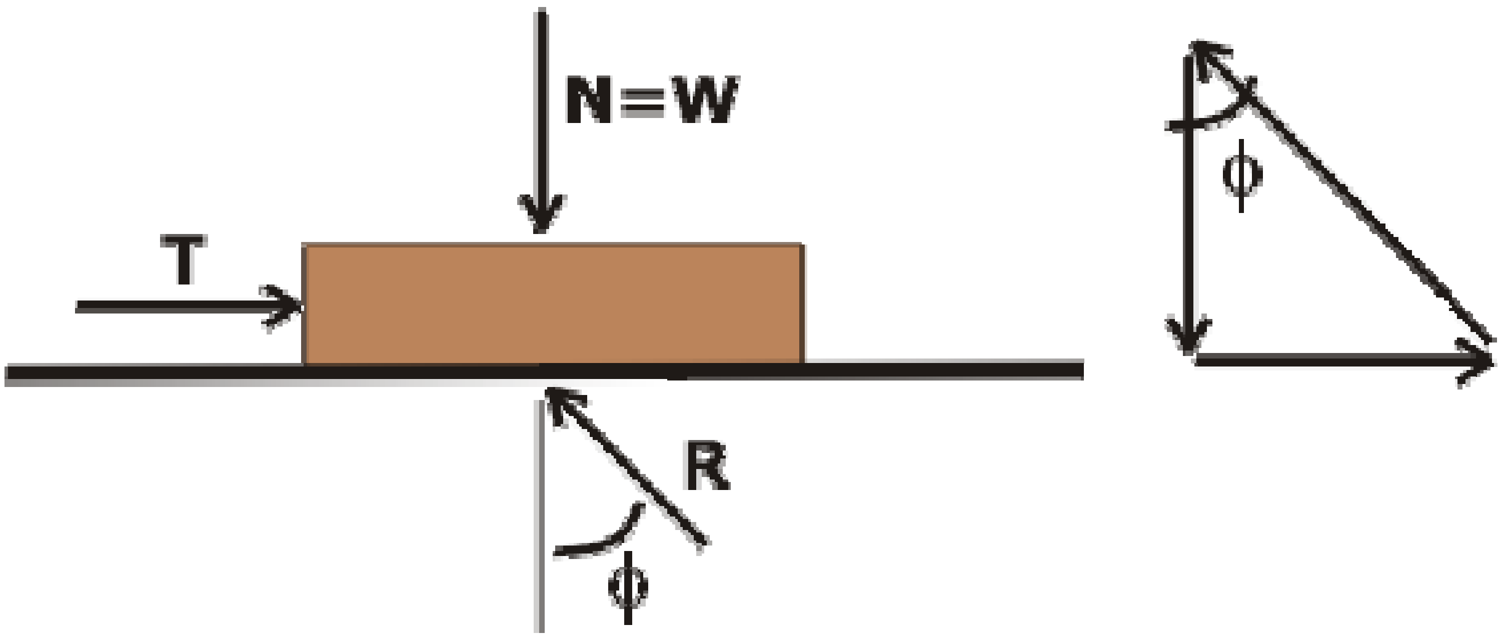
**Key parameters:**

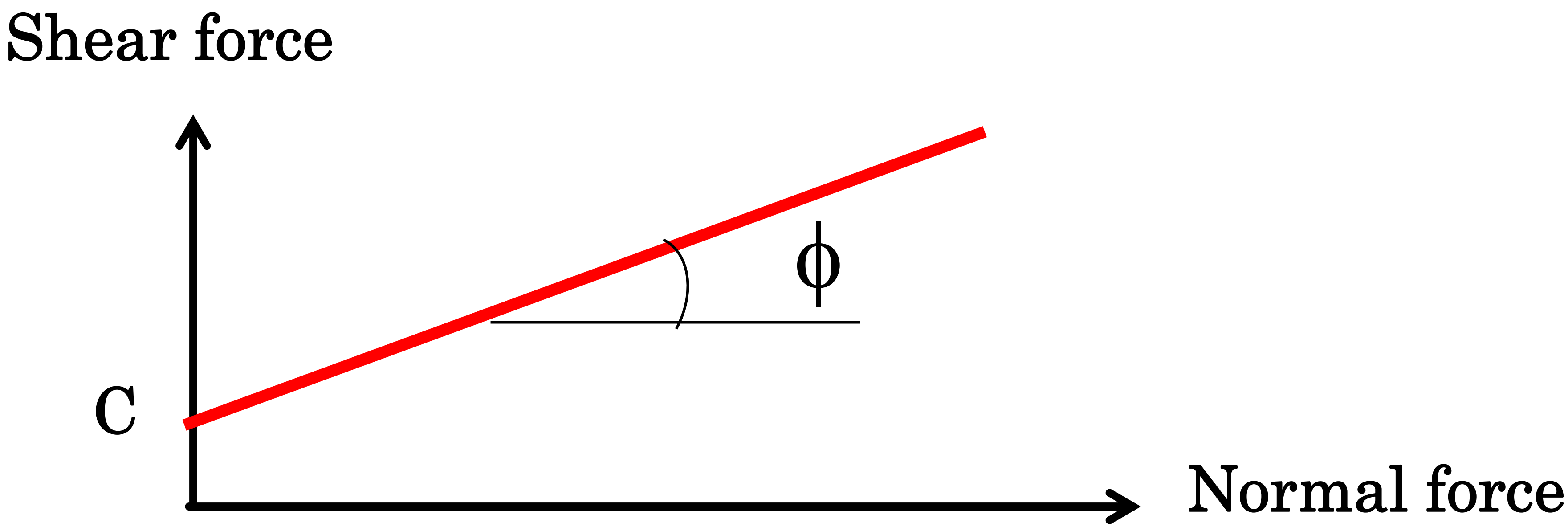
$c$ : soil cohesion

$\varphi$ : friction angle

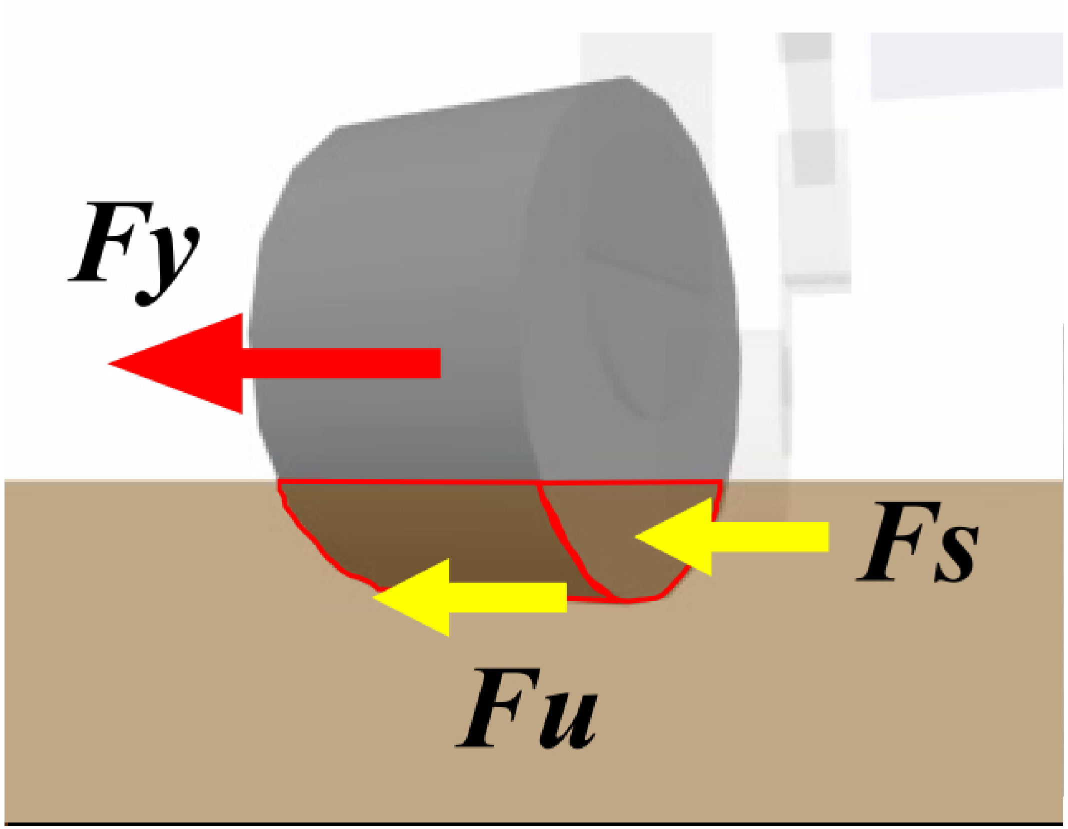
$k$ : shear deformation modulus

# Angle of Internal Friction



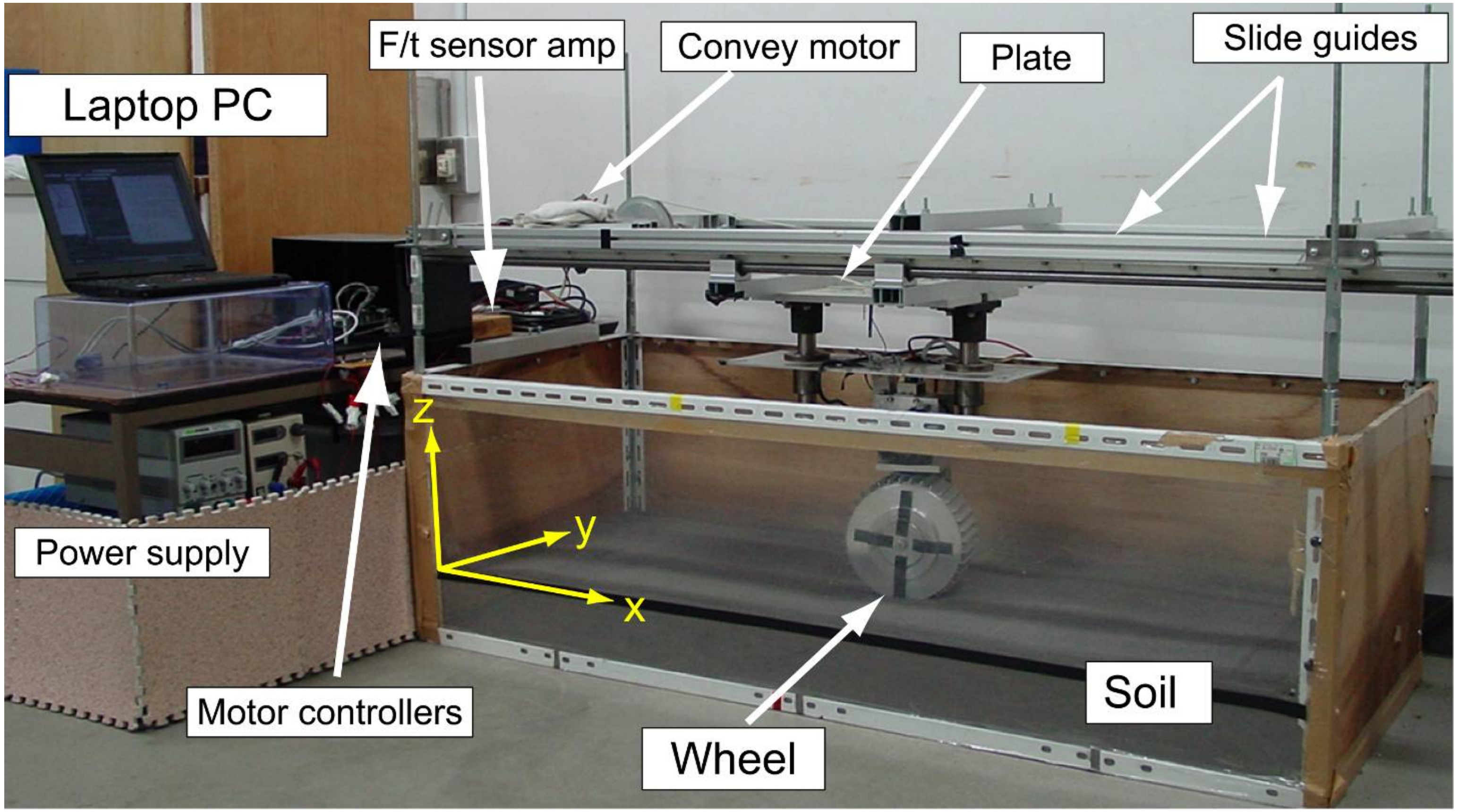
# Modeling of Side Forces : $F_y$



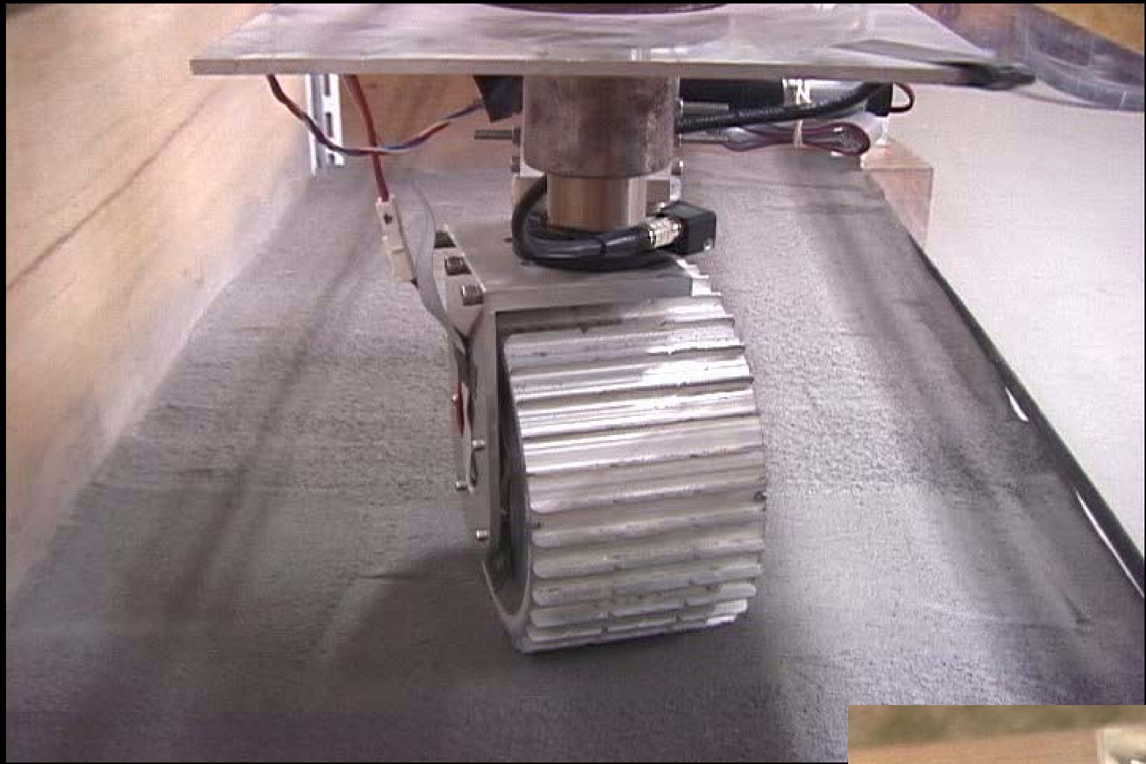
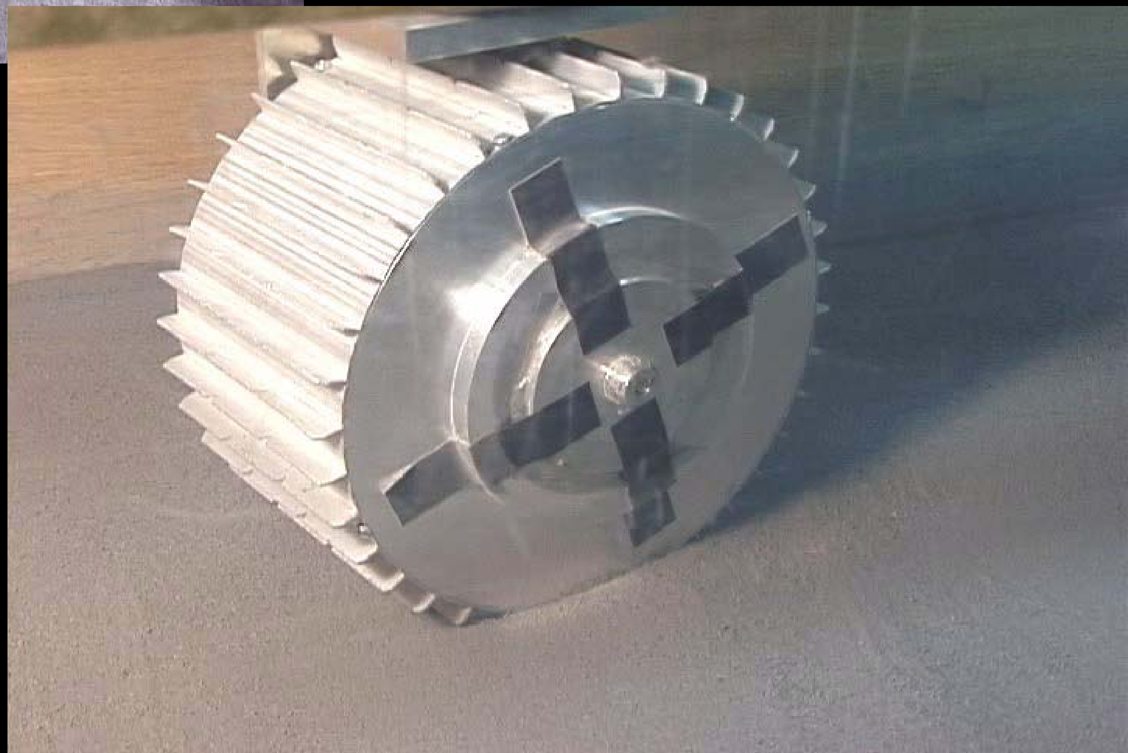

(Yoshida & Ishigami, IROS2004)

$$F_y = F_u + F_s \quad \begin{cases} F_u = rb\int_{\theta_r}^{\theta_f} \tau_y(\theta)\,d\theta \\ F_s = \int_{\theta_r}^{\theta_f} R_b(r - h\cos\theta)d\theta \end{cases}$$

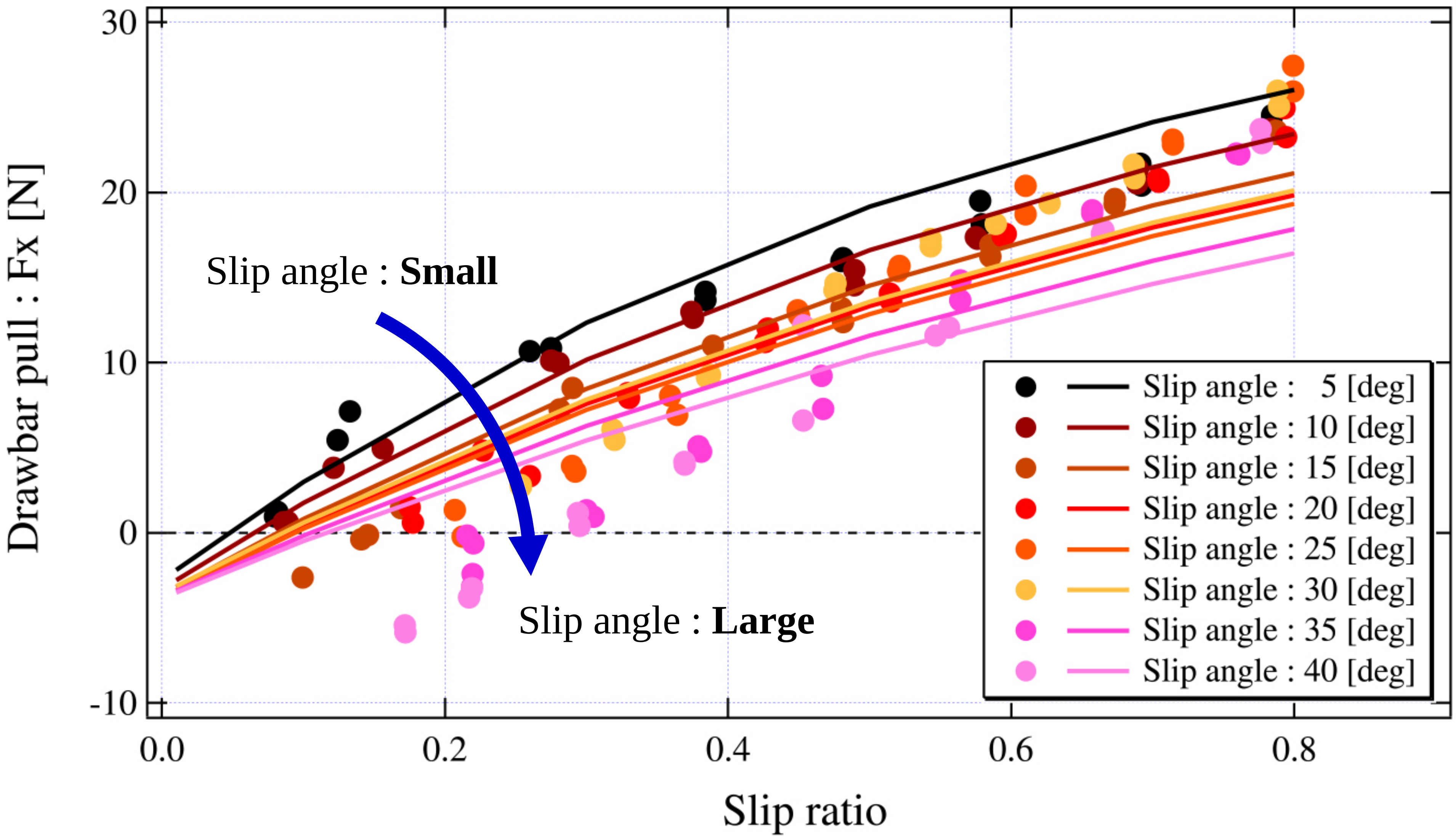
# Single Wheel Test Bed




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

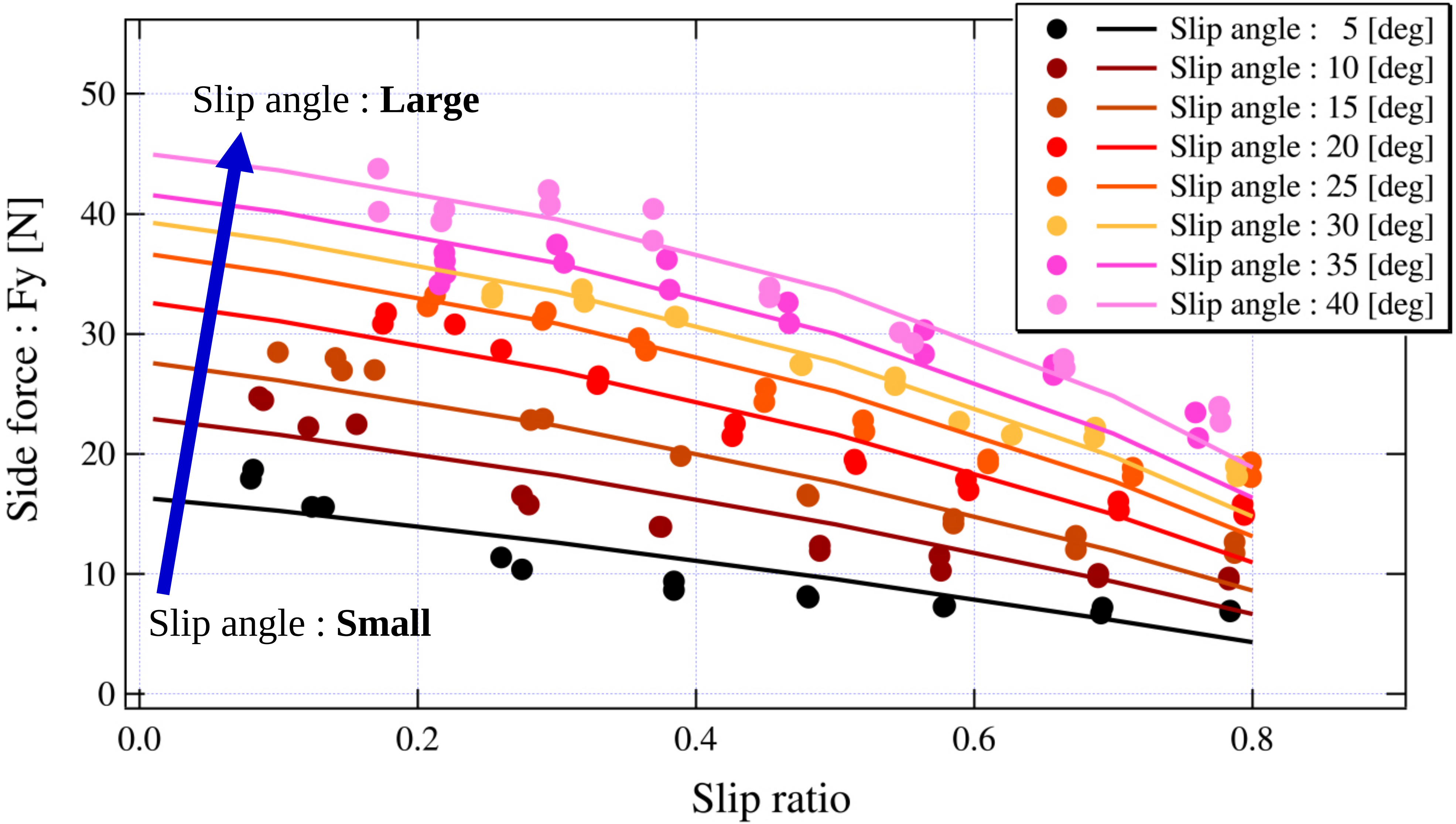



# Experimental Results (longitudinal force)




**(Ishigami, Nagatani, Yoshida, J. of Field Robotics, 2007)**

# **Experimental Results** (side force)

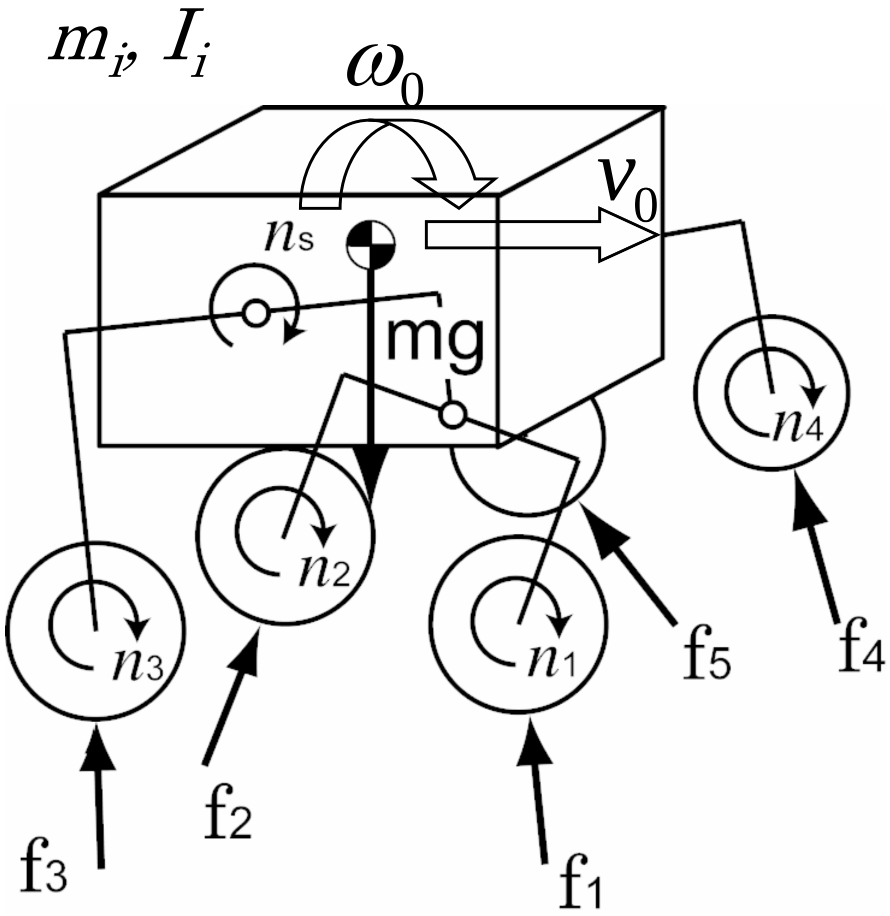



**(Ishigami, Nagatani, Yoshida, J. of Field Robotics, 2007)**

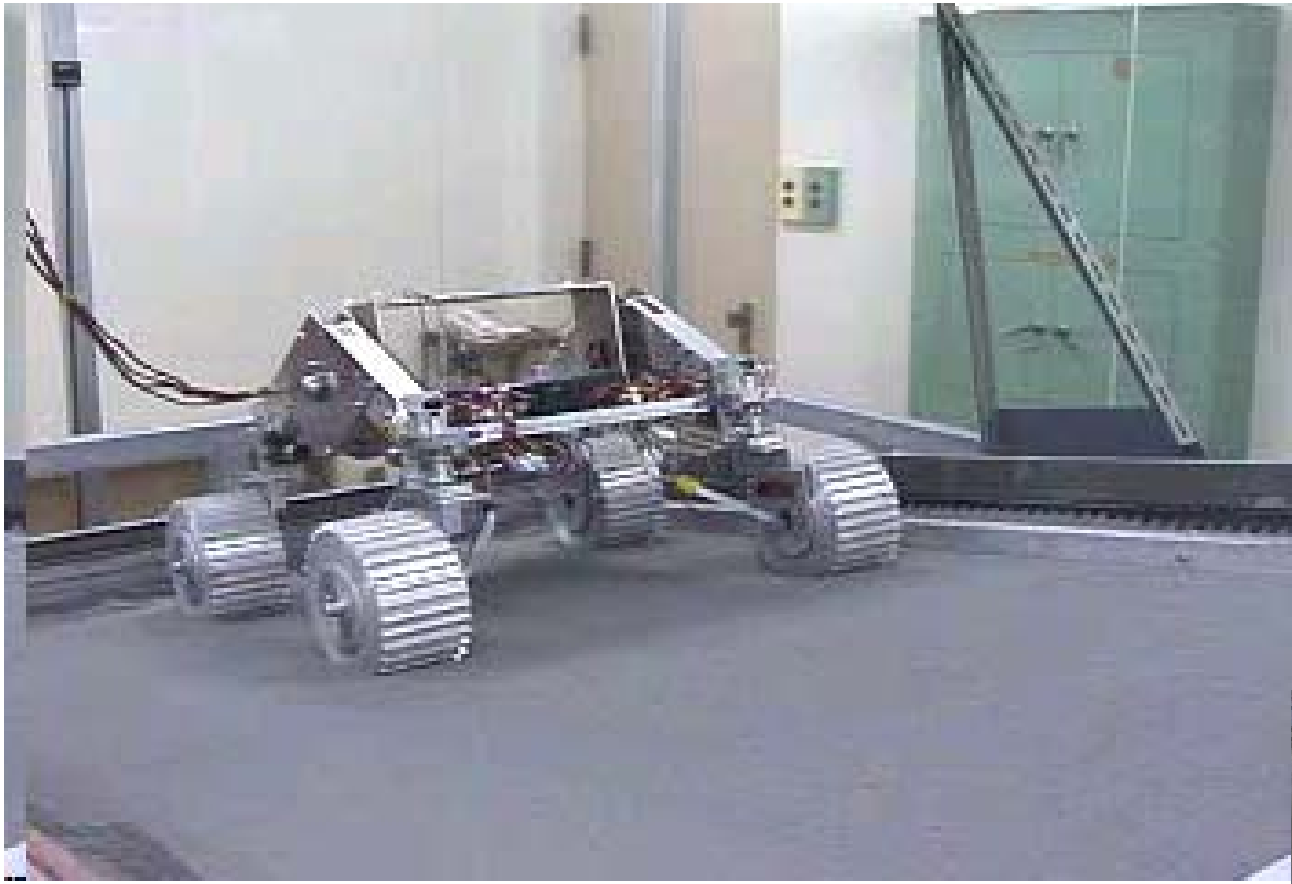
**Vehicle Dynamics** = **Multibody Dynamics with a Moving Base + Multi Contact, Gravity**

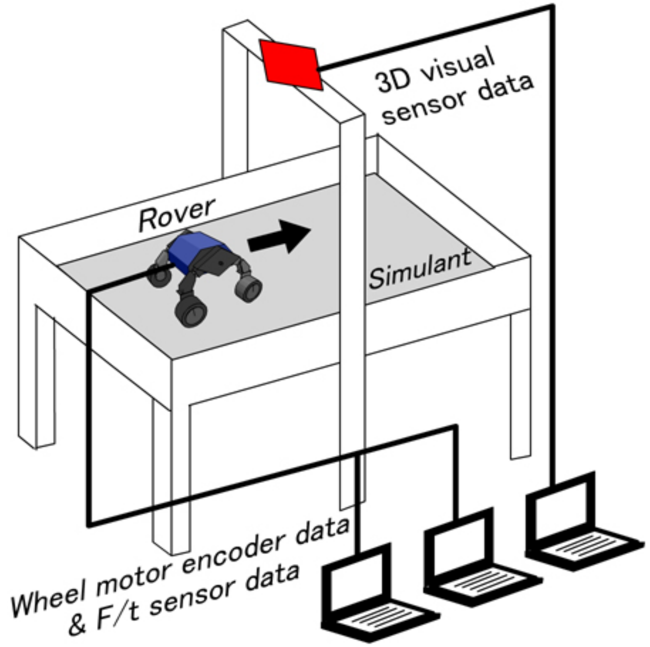
## *Equation of Motion*

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



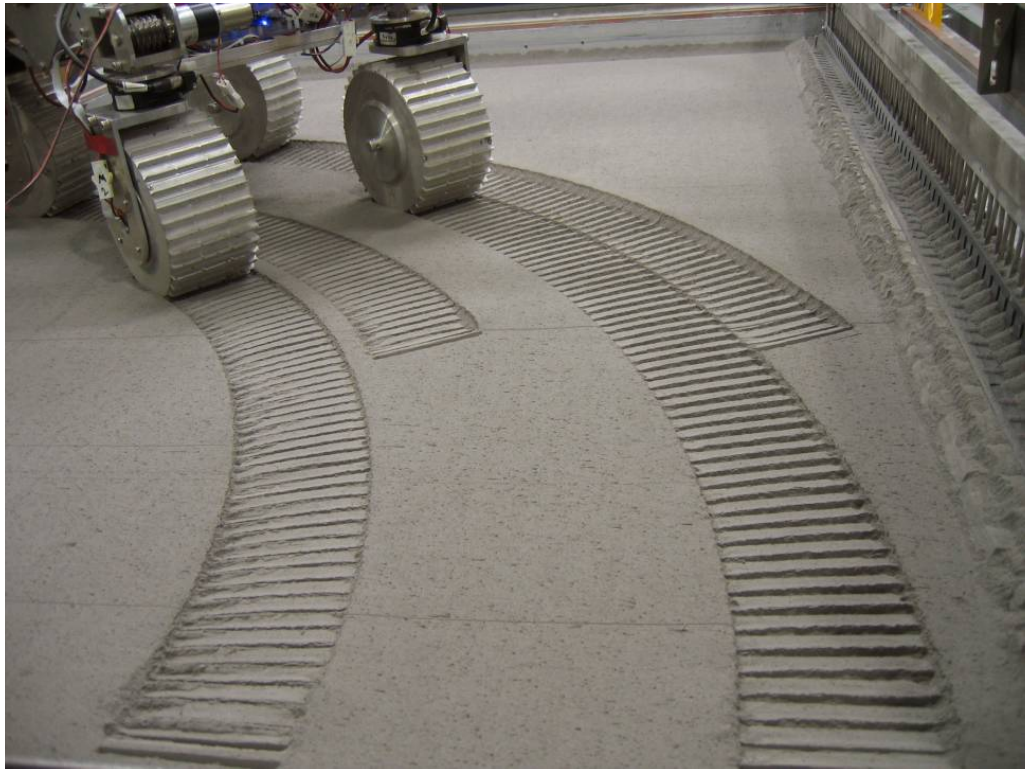
# Slope Climbing Experiment at JAXA, Aerospace Research Center



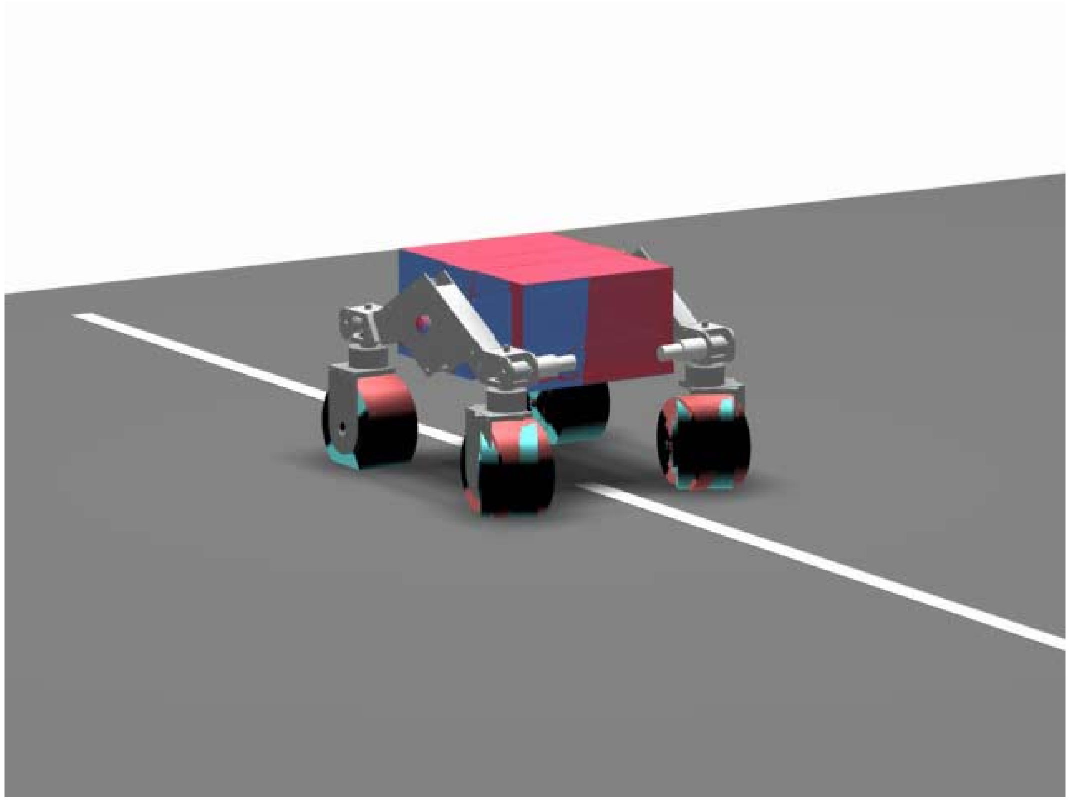



*Lunar Regolith Simulant*
arbitrary inclination 0-30 deg or over

# Slope Traversing Experiment at JAXA, Aerospace Research Center



*Experimental trace*



*Red is simulation, blue is experiment*

*Lunar Regolith Simulant*

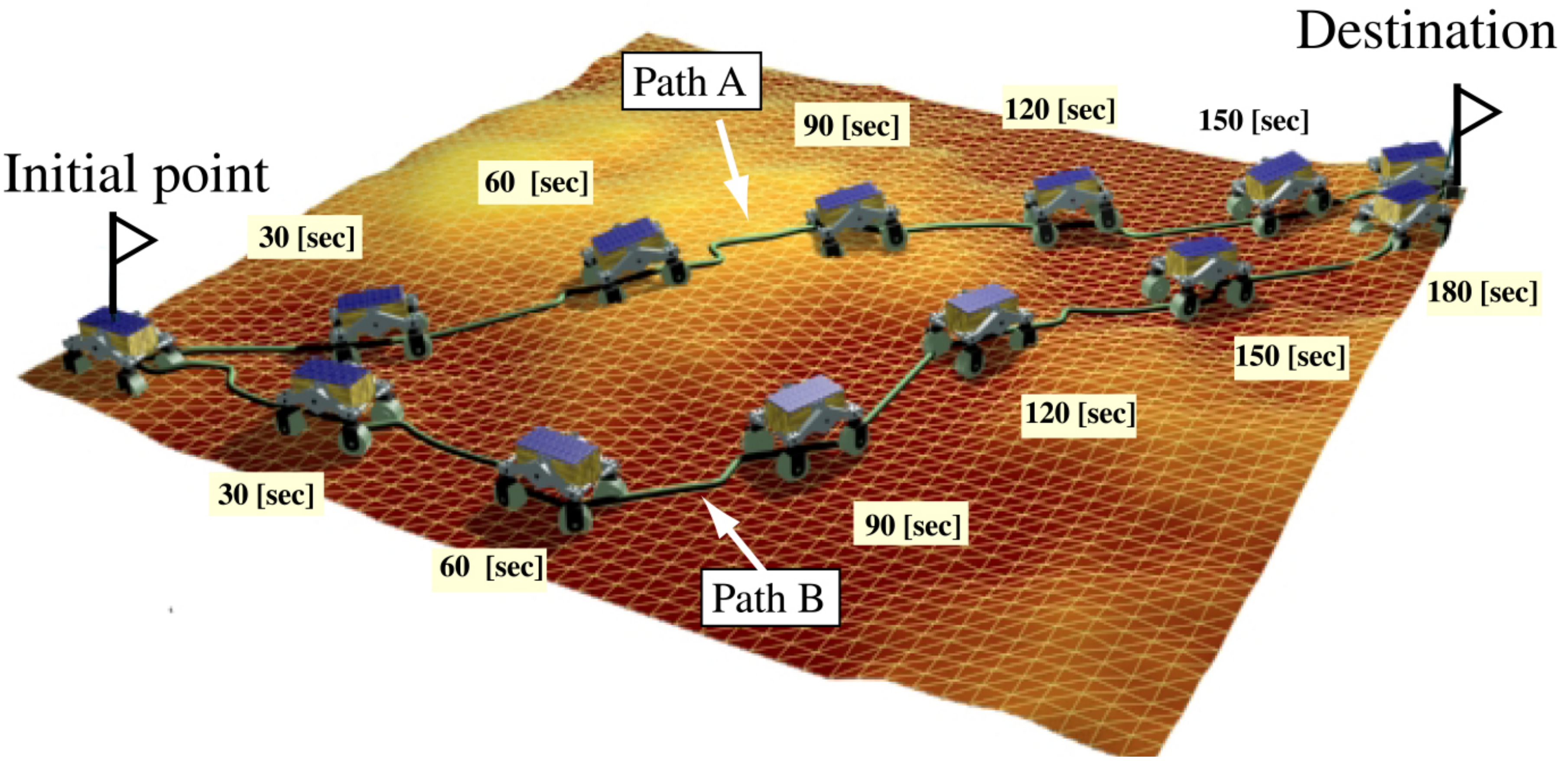
arbitrary inclination 0-30 deg or over

# Research Focus on Lunar/Planetary Rovers

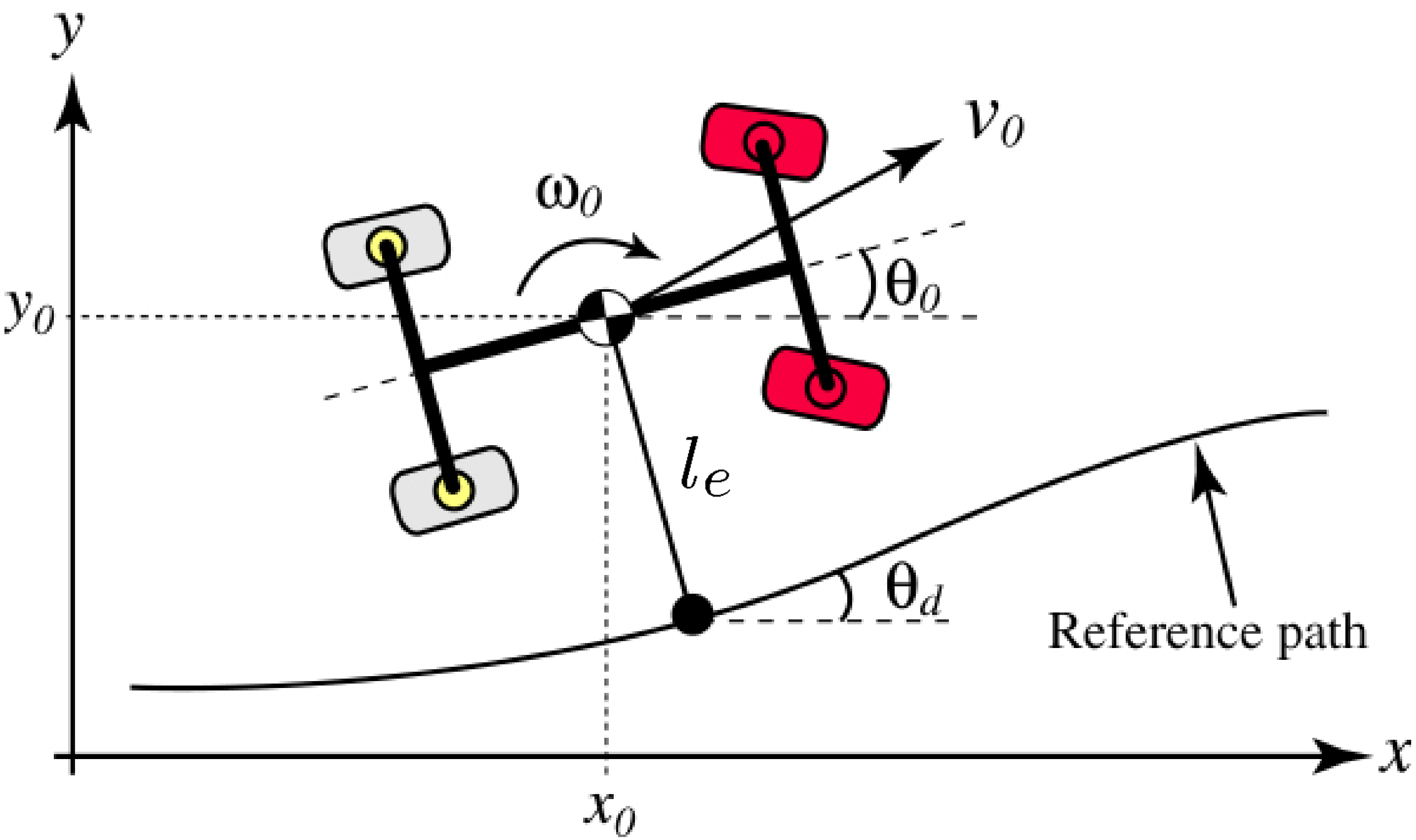
- Mechanical Design
  - Choice of locomotion mode: wheels, tracks, or legs
  - Chassis design
- Traction Control
  - Makes difference in performance
  - *Slip* on loose soil
- Navigation
  - Path planning with stability & slip criteria
  - Path following with slip compensation

# Path Planning Issue

***Evaluate candidate paths by dynamic simulation which takes both longitudinal and lateral slip effects into account .***



# Model for Path Following Control




$l_e$ : **Distance error**

$\theta_e$ : **Orientation error** $(= \theta_0 - \theta_d)$

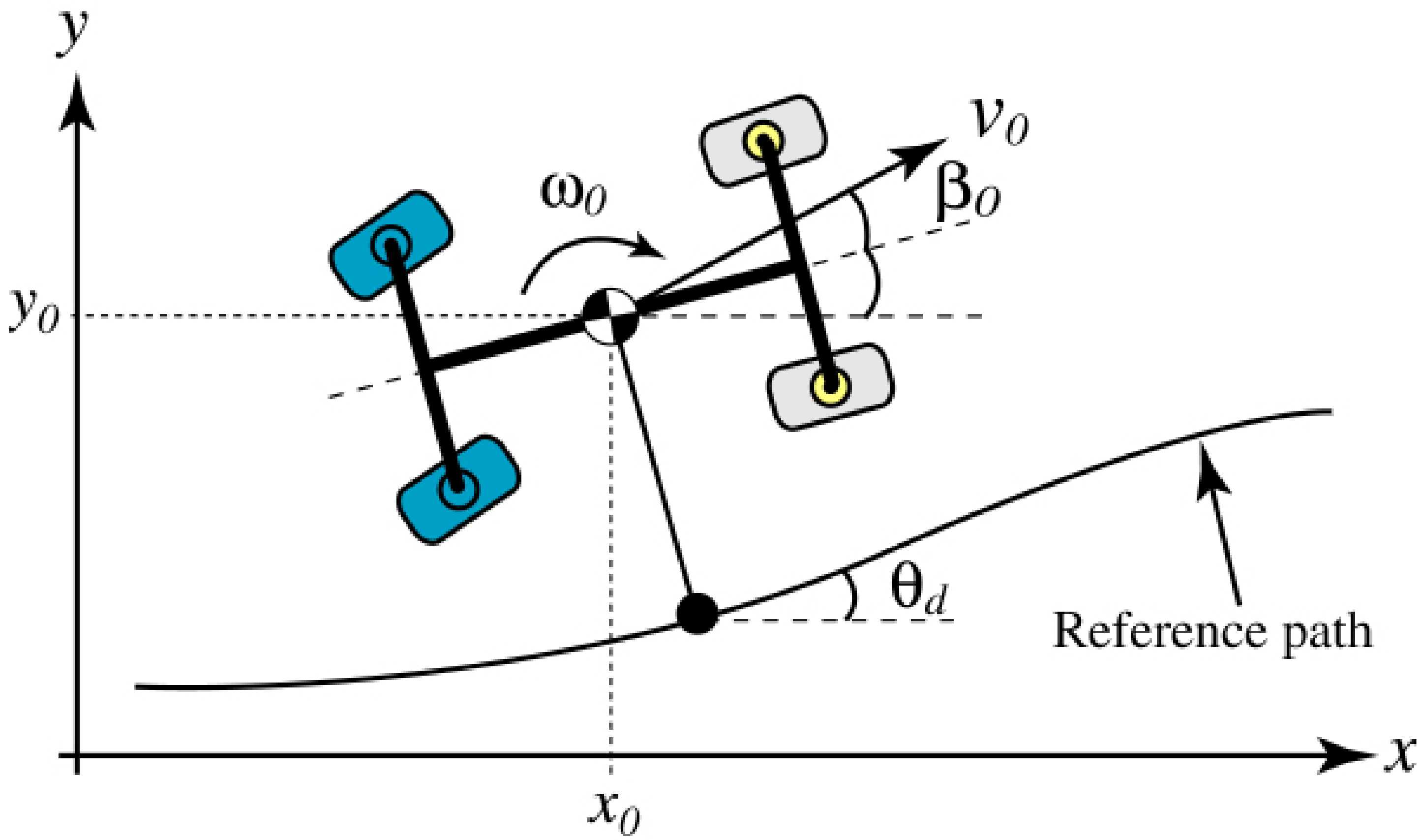
$\theta_0$ : Vehicle orientation angle

$\theta_d$ : Desired orientation angle

Control objectives

$$l_e \rightarrow 0$$
$$\theta_e \rightarrow 0$$

# Sideslip Compensation




Sideslip is measured by slip angle, $\beta_0$ .

Control objective

$$\beta_0 \rightarrow 0$$

# Slope Traversal (10 deg)

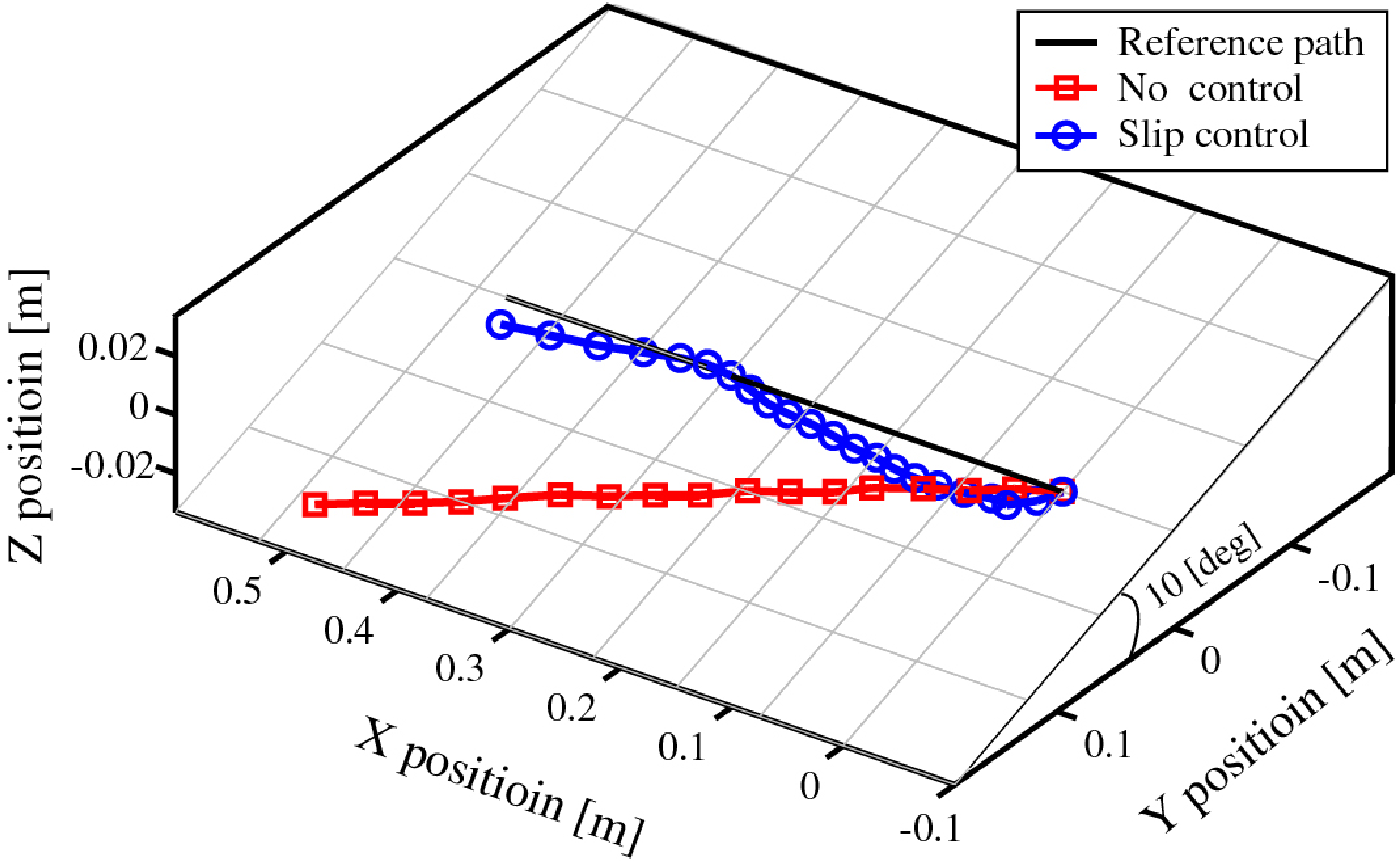
With path-following control and slip compensation

Video presentation is 4-time faster than the real motion

# Conditions of Experiments

| | |
|---|---|
| Slope angle [deg] | 5.0 / 7.5 / 10.0 |
| Sensor accuracy of SLC [mm] | 3.44@1.5 [m] |
| Wheel angular velocity [rad/sec] | 0.30 |
| Wheel radius (including paddles) [mm] | 113.0 |
| Approx. total weight of the rover [kg] | 15.0 |
| Control loop cycle time [s] | 0.16-0.17 |

# Experimental result (10 deg slope)



# Summary

- In this presentation, the state-of-art study on terramechanics based analysis and motion control of rovers are overviewed.
- Models for wheel traction mechanics on loose soil is focused, where *slip* is a key state variable to describe the traction performance.
- Experimental data of the traction measurement on *simulated lunar soil* is presented for various slip ratios and slip angles.
- An example is illustrated for the path following control of a rover with compensating the side slips.

# References


- Bekker, M. G. (1960), *Off-The-Road Locomotion,* The University of Michigan Press.
- Wong, J. Y. (1978), *Theory of Ground Vehicles,* John Wiley & Sons.
- Iagnemma, K. and Dubowsky, S. (2004), *Mobile Robots in Rough Terrain : Estimation, Motion Planning, and Control with Application to Planetary Rovers* (Springer Tracts in Advanced Robotics 12), Springer.
- G. Ishigami, A. Miwa, K. Nagatani and K. Yoshida (2007) "Terramechanics-based Model for Steering Maneuver of Planetary Exploration Rovers on Loose Soil" Journal of Field Robotics, vol.24, no.3, pp.233-250.

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

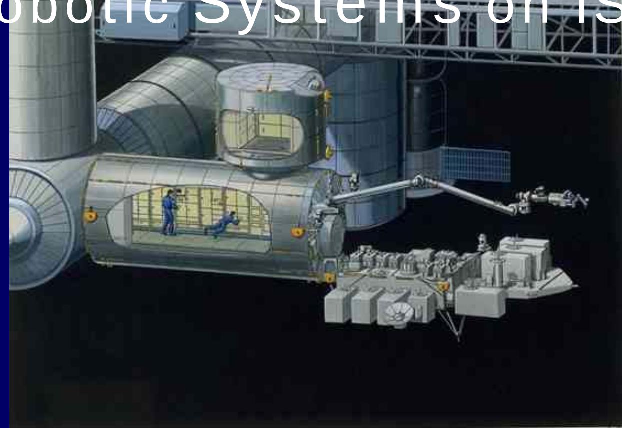
*Directed by Prof. Kazuya Yoshida*

***yoshida@astro.mech.tohoku.ac.jp***

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

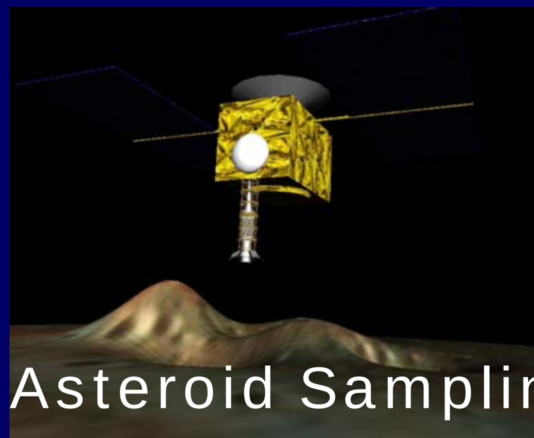
Free-Flying Space Robot

Robotic Systems on ISS



The SPACE ROBOTICS Lab.

Planetary Exploration Rovers



Asteroid Sampling