33rd Workshop on JAXA Astrodynamics Symposium and Flight Mechanics
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# 着陸脚地面間の摩擦力低減による垂直離着陸ロケットの耐転倒性の向上に関する研究

## Improvement of Tipping Resistance of Vertical Takeoff and Landing Rocket by Reducing Friction Force between Landing gear legs and Ground

Sakata Taiki
Maru Yusuke， Kawano Taro,
Mori Osamu， Sawai Shujiro ‡
Nohmi Masahiro †

†：University of Shizuoka
‡：Japan Aerospace Exploration Agency

# Contents

# Introduction



- Low-cost, high-volume, high-frequency space transportation
- Commercial Space Transportation by Private Companies

⇒Increased movement toward reusing rockets

Falcon9 Tip Over [1]



Rocket＝tall,　high center of gravity

↓

<u>High likelihood of tipping over on landing</u>

**Landing of Lunar Lander with 4 Legs [2]**

Coefficient of friction between landing leg and ground

- ➢ High ⇒ liable to topple over
- ➢ Low ⇒ difficult to topple over

↓

Reduced friction between the landing legs and the ground in reusable rockets ⇒ **Improved fall down resistance**

[1] https://www.youtube.com/watch?v=bvim4rsNHkQ&t=50sの50秒～53秒抜粋
[2] 能見公博， 宮原啓，“四脚月着陸機の接触力学解析と転倒性評価”，日本機械学会論文集（C編），78巻790号（2012-6）

# Research Purpose



**Verification of the fall down resistance of Reusable Rocket when the Friction Force between the Landing Legs and the Ground is Reduced**

Contents of implementation

1. landing simulations in ADAMS

   ⇒ change the coefficient of friction to static

   → Observation of landing behavior

2. Verification of the usefulness of the wheel

   ・Methods to change the coefficient of friction ：**wheel**

   2-D drop experiment of a test model

   ⇒Observation of landing behavior

# Rocket geometry in simulations

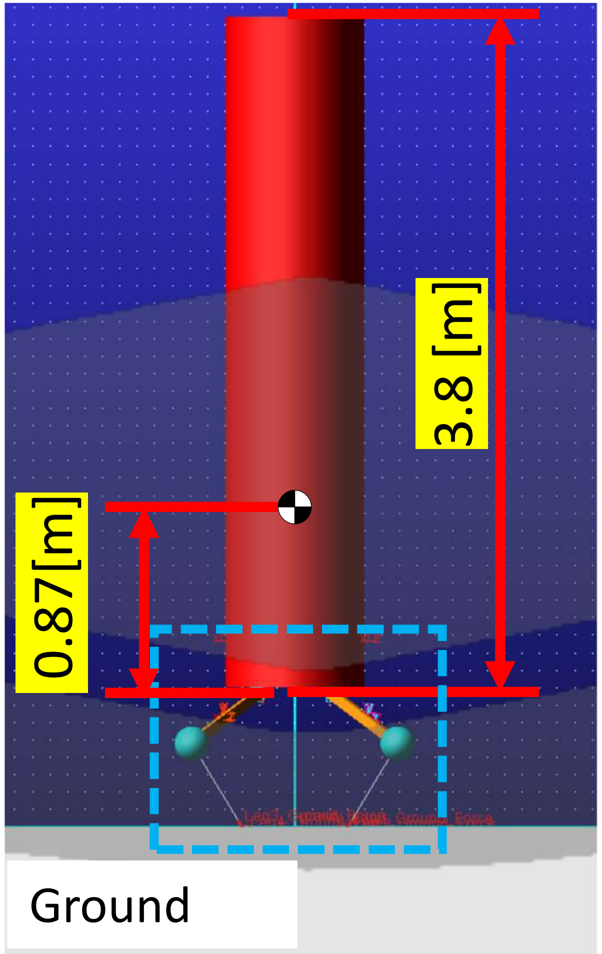


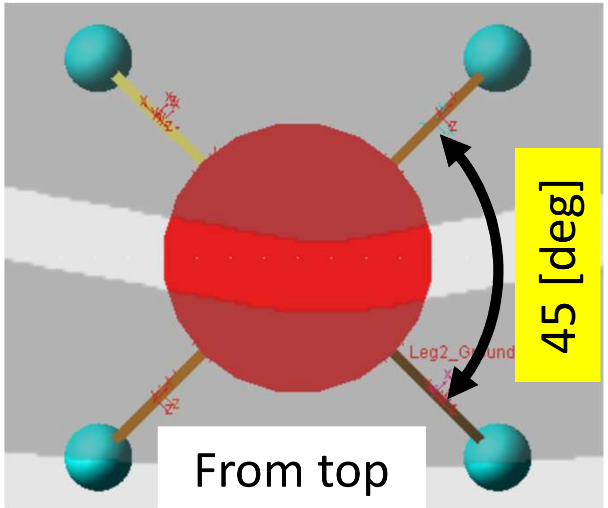
➢ Landing simulation → change the coefficient of friction to static
⇒Verification of whether reducing frictional force is effective in improving fall down resistance

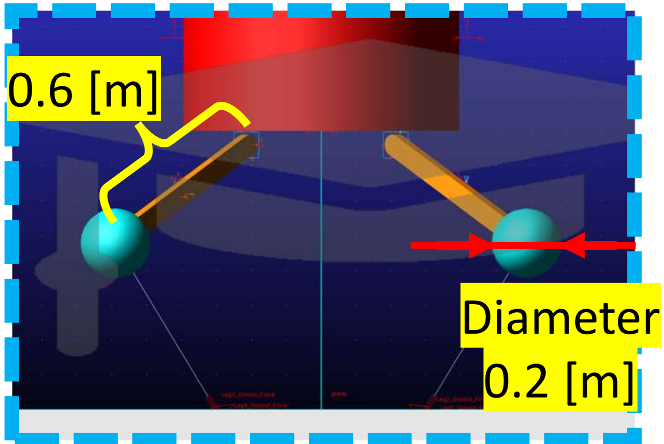
✓ Landing analysis using ADAMS

ADAMS：a MSC Software product in multibody dynamics

Rocket geometry




Refer to the dimensions of the FTB of the air breathing engine planned by JAXA.

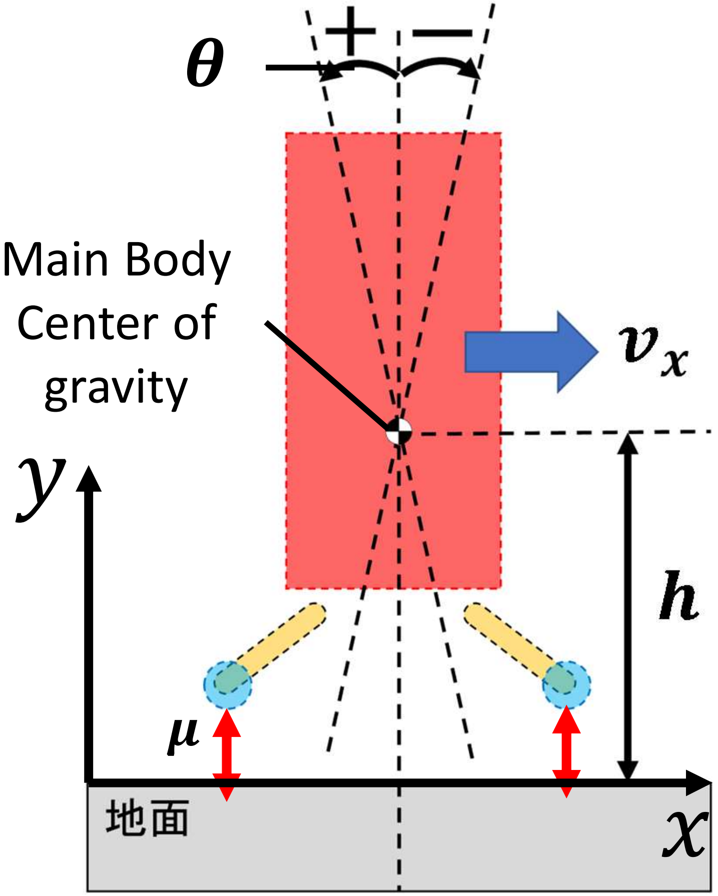
| parameter | value |
|---|---|
| mass | 1000 kg |
| Ixx | 1018 kg・$m^2$ |
| Iyy | 90.67 kg・$m^2$ |
| Izz | 1018 kg・$m^2$ |

※Center of gravity is a little low

# Landing simulation conditions

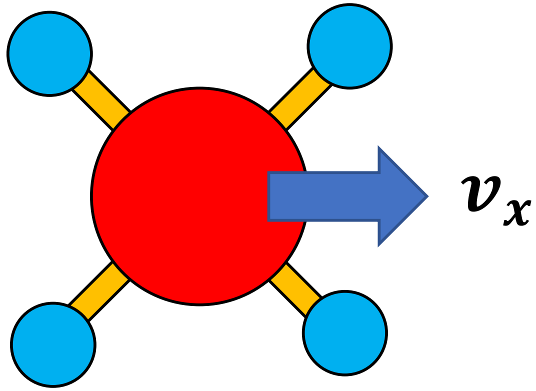


Initial conditions of the rocket



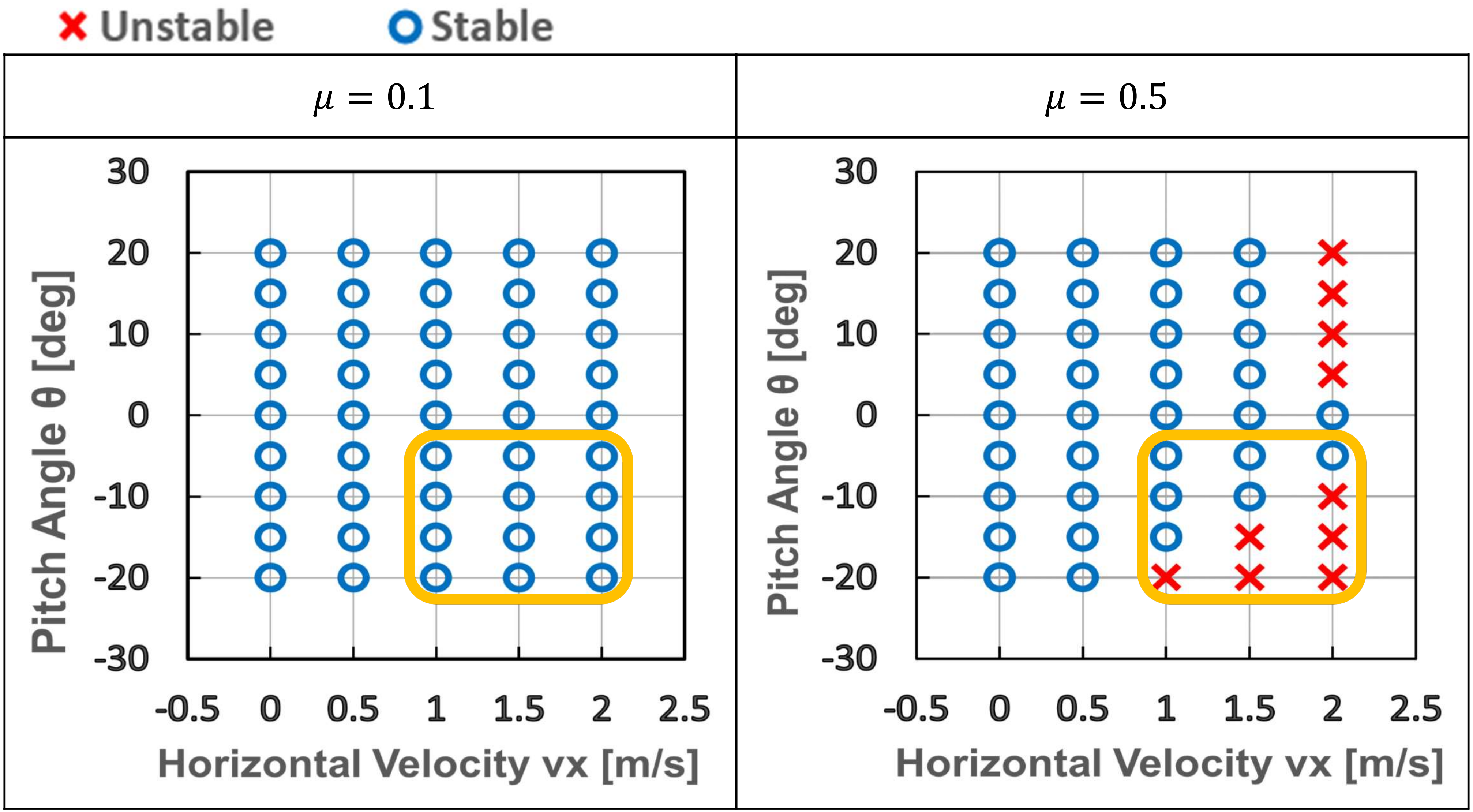

## Landing simulation conditions

| | |
|---|---|
| Pitch Angle $\theta$ [deg] | 0 / ±5 / ±10 / ±15 / ±20 |
| Horizontal Velocity $v_x$ [m/s] | 0 / 0.5 / 1 / 1.5 / 2.0 |
| coefficient of friction $\mu$ | 0.8 / 0.5 / 0.3 / 0.1 / 0.01 |
| height $h$ [m] | 2.1 |




Simulated with landing legs oriented 2-2 when viewed from the side

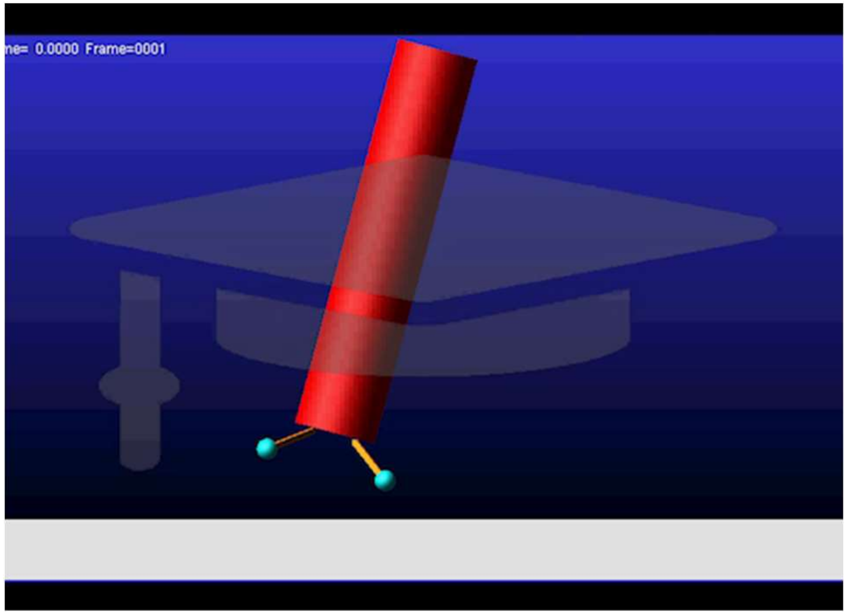
# Landing simulation results



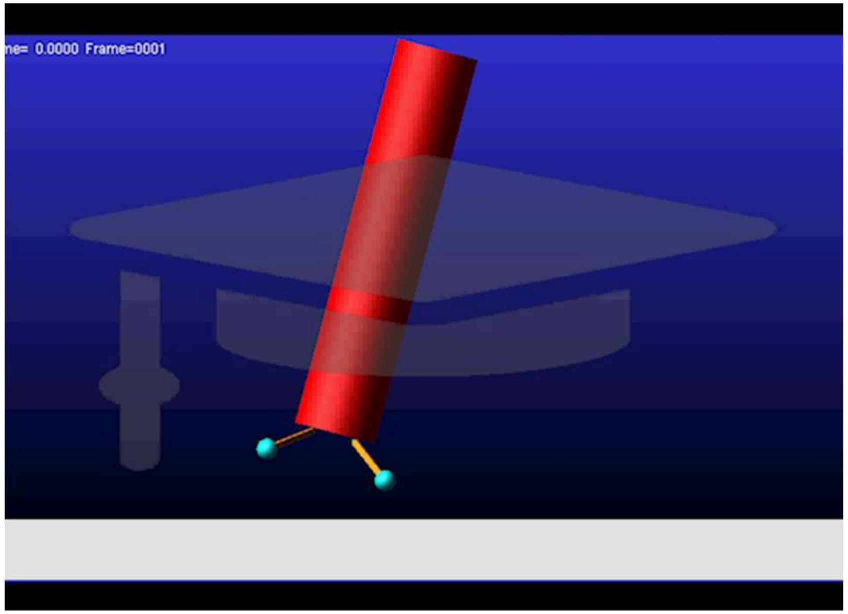

- ✓ At Pitch angle $\theta$ is negatively large, High horizontal speed
  ⇒Smaller coefficient of friction is more stable.
- ✓ Reduction of frictional force⇒Effective in improving fall down resistance

# Landing simulation results






$v_x$ : 1.5[m/s] $\theta$ : -15[deg] $\mu = 0.1$




$v_x$ : 1.5[m/s] $\theta$ : -15[deg] $\mu = 0.5$

Landing behavior varies depending on the coefficient of friction

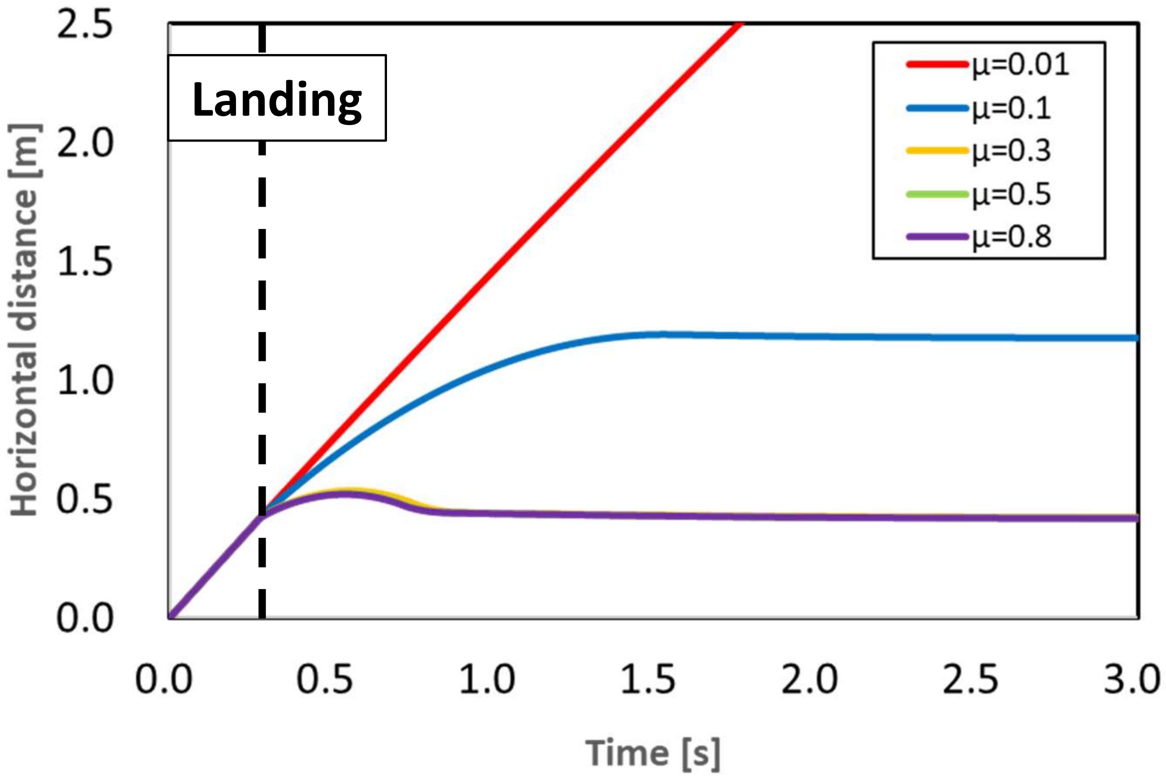
**Coefficient of friction**

✓ Low → The rocket slips, and the rocket's rotational motion is used as the horizontal motion.
⇒ Stable

✓ High →The rocket didn't slip, and rocket tipped over with landing legs as fulcrum
⇒ Unstable

## Coefficient of friction and Horizontal movement distance

condition：Pitch Angle $\theta = 0$[deg], Horizontal Velocity $v_x = 1.5$[m/s]




| $\mu$ | fall down resistance | Horizontal distance |
|---|---|---|
| **High** | △ | **Short** |
| **Low** | ○ | **Long** |

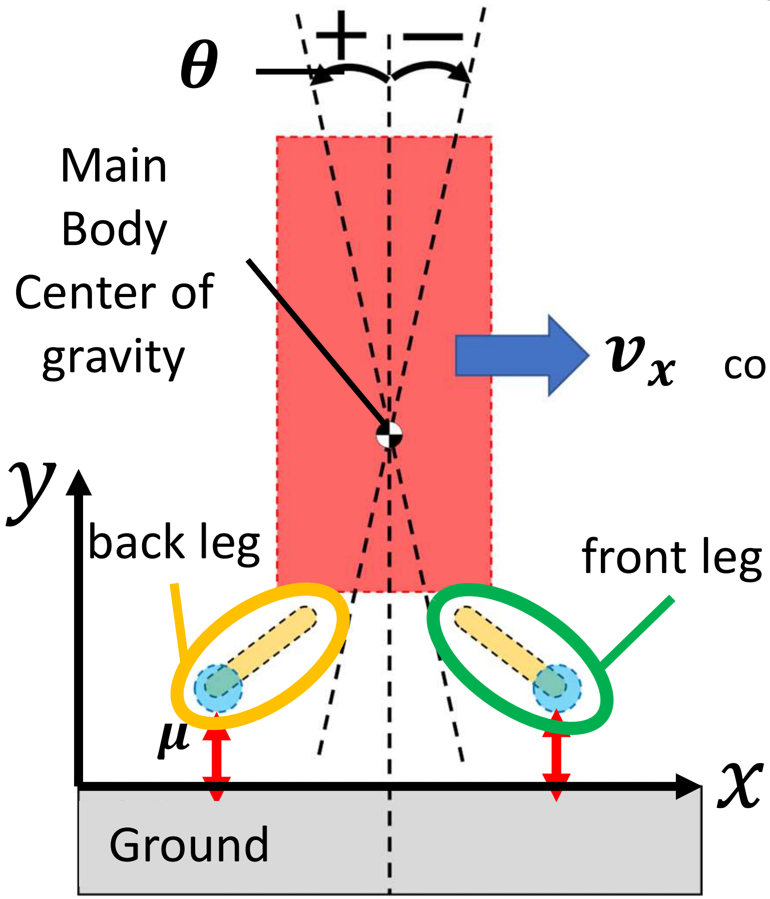
# Counter-measure for horizontal movement

- Different friction coefficients for each landing leg

Considering the direction of movement of the rocket

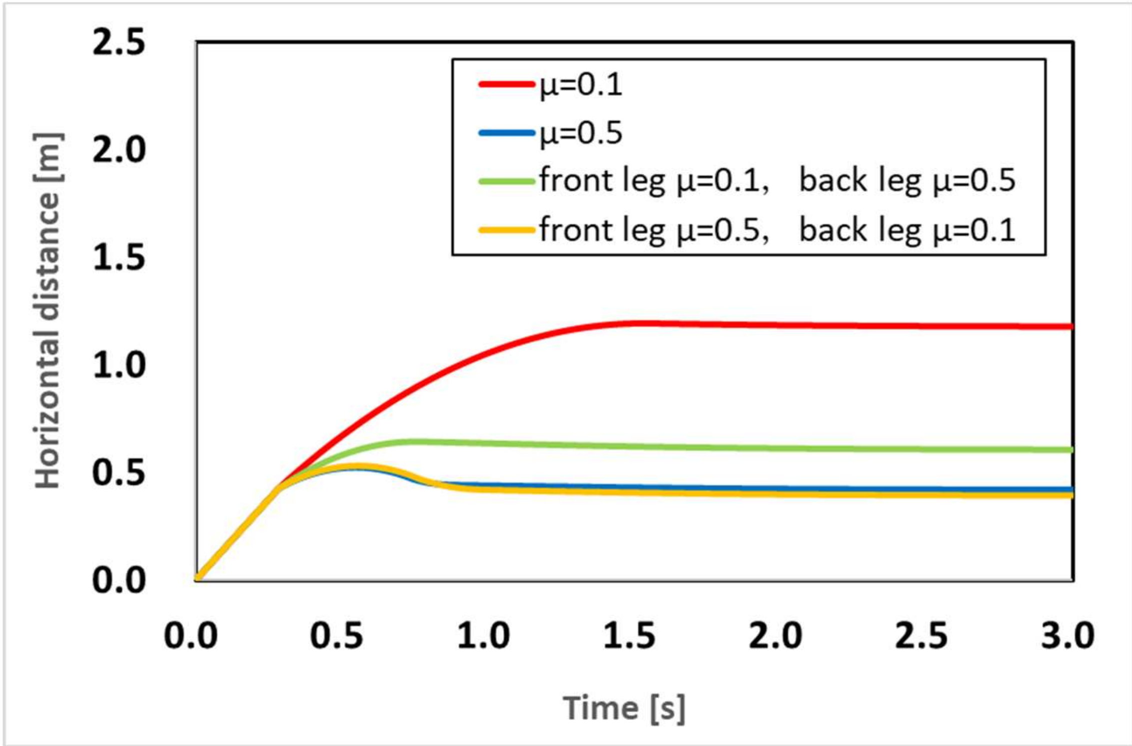
→Landing legs in $v_x$ direction ： front leg

Landing legs in opposite $v_x$ direction ： back leg




| | | |
|---|---|---|
| ① | front leg $\mu$ ：0.5 | back leg $\mu$ ：0.1 |
| ② | front leg $\mu$ ：0.1 | back leg $\mu$ ：0.5 |

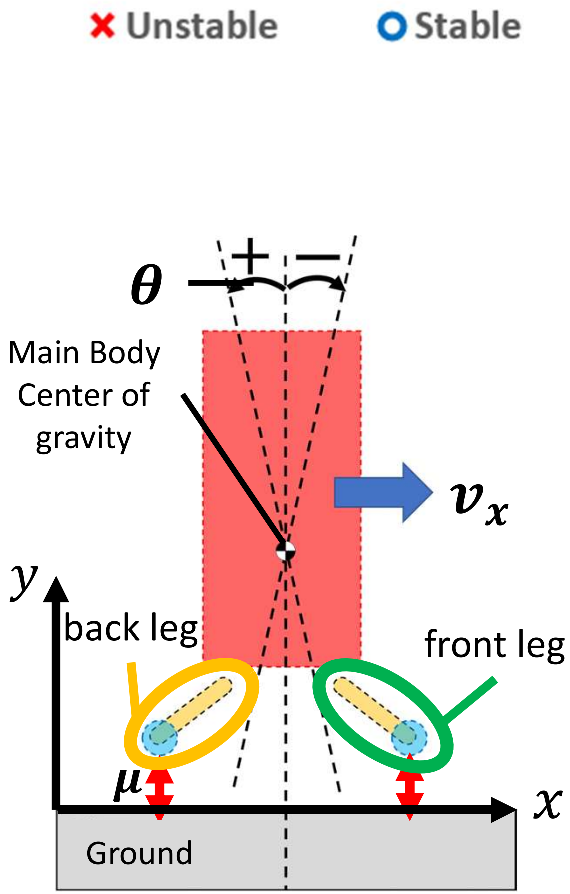
condition ：Pitch Angle $\theta = 0$[deg], Horizontal Velocity $v_x = 1.5$[m/s]

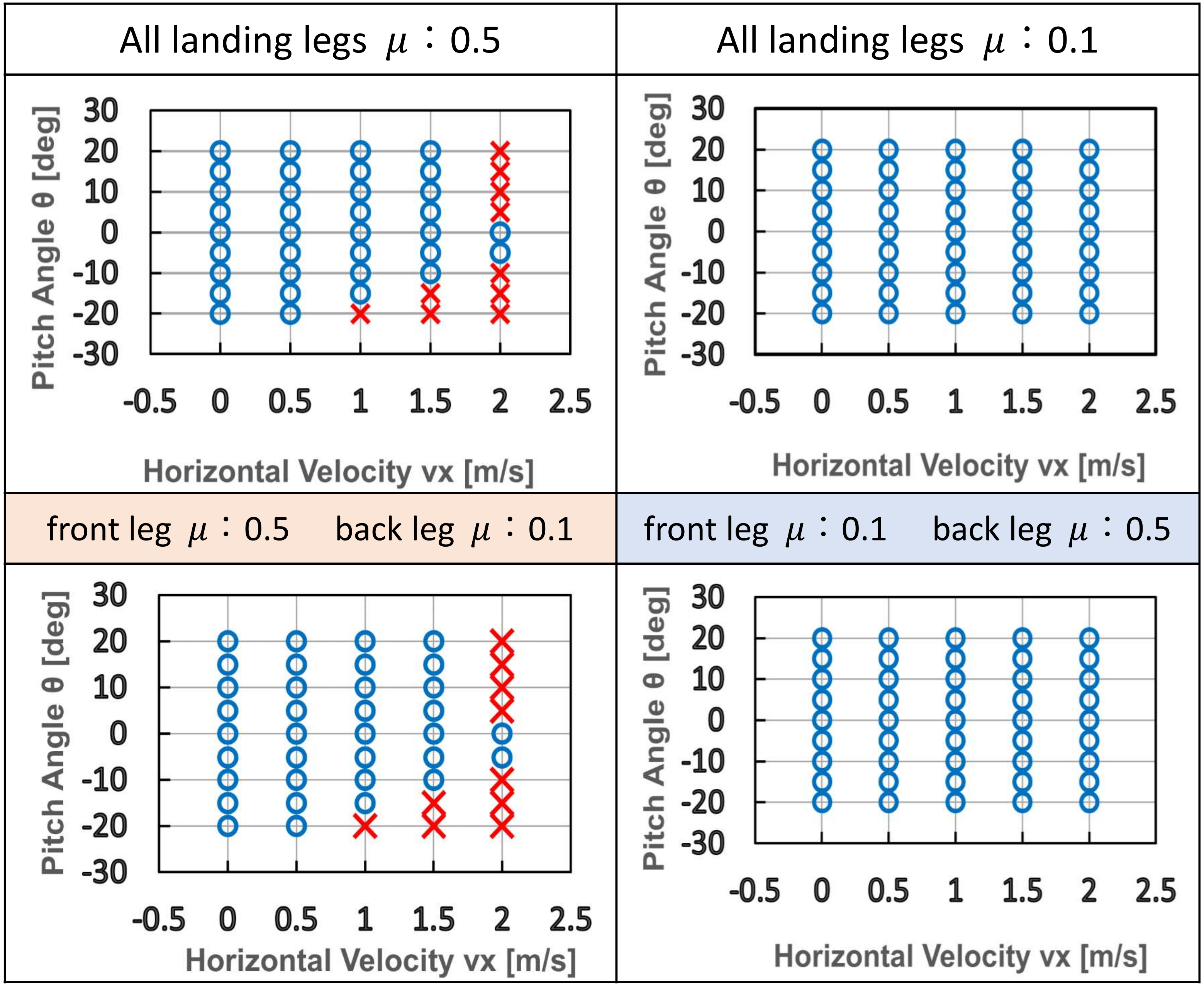



⇒Horizontal distance has been reduced.

# fall down resistance when μ differs from front to back

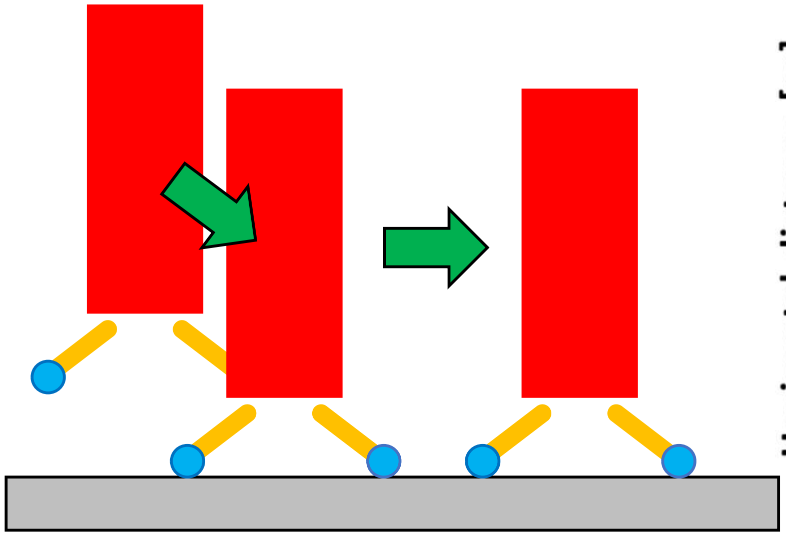




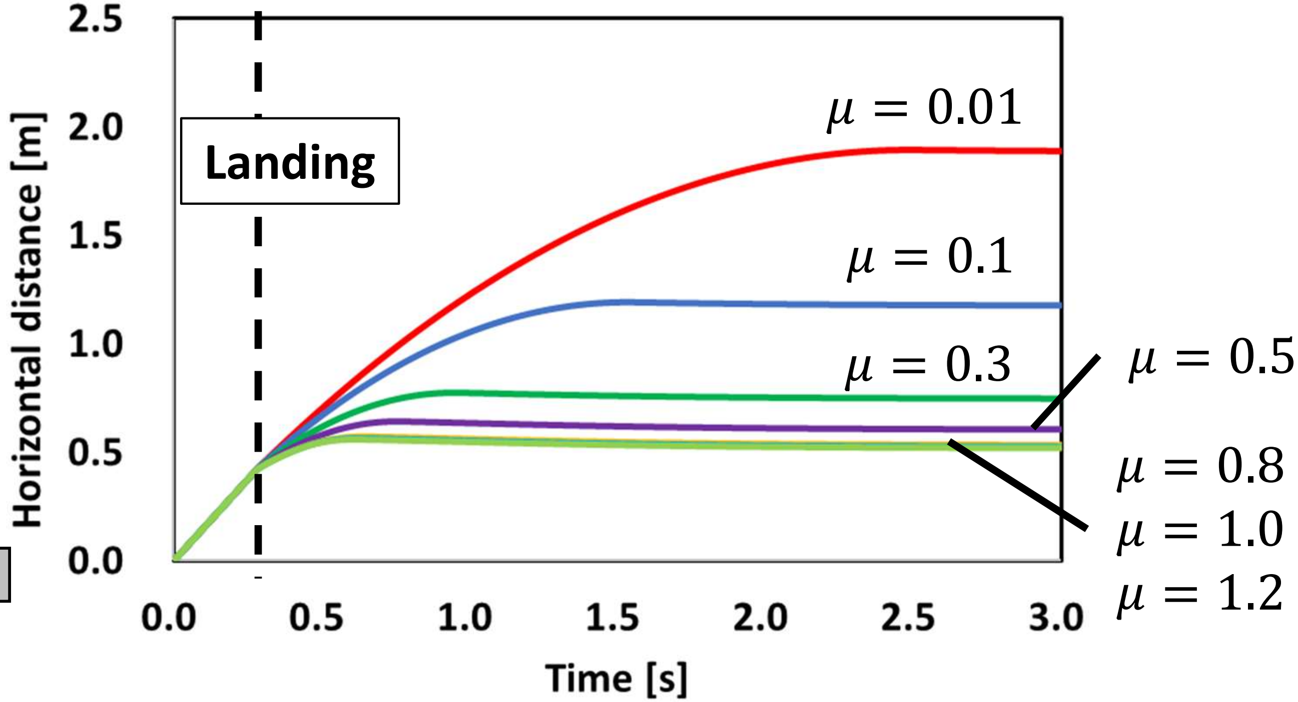




fall down resistance of a rocket depends on the coefficient of friction of the front legs

Horizontal movement after landing



Friction coefficient of the back leg and horizontal distance moved




condition：Pitch Angle $\theta = 0$[deg], Horizontal Velocity $v_x = 1.5$[m/s]

Coefficient of friction of back leg 【High】⇒ Reduced horizontal distance

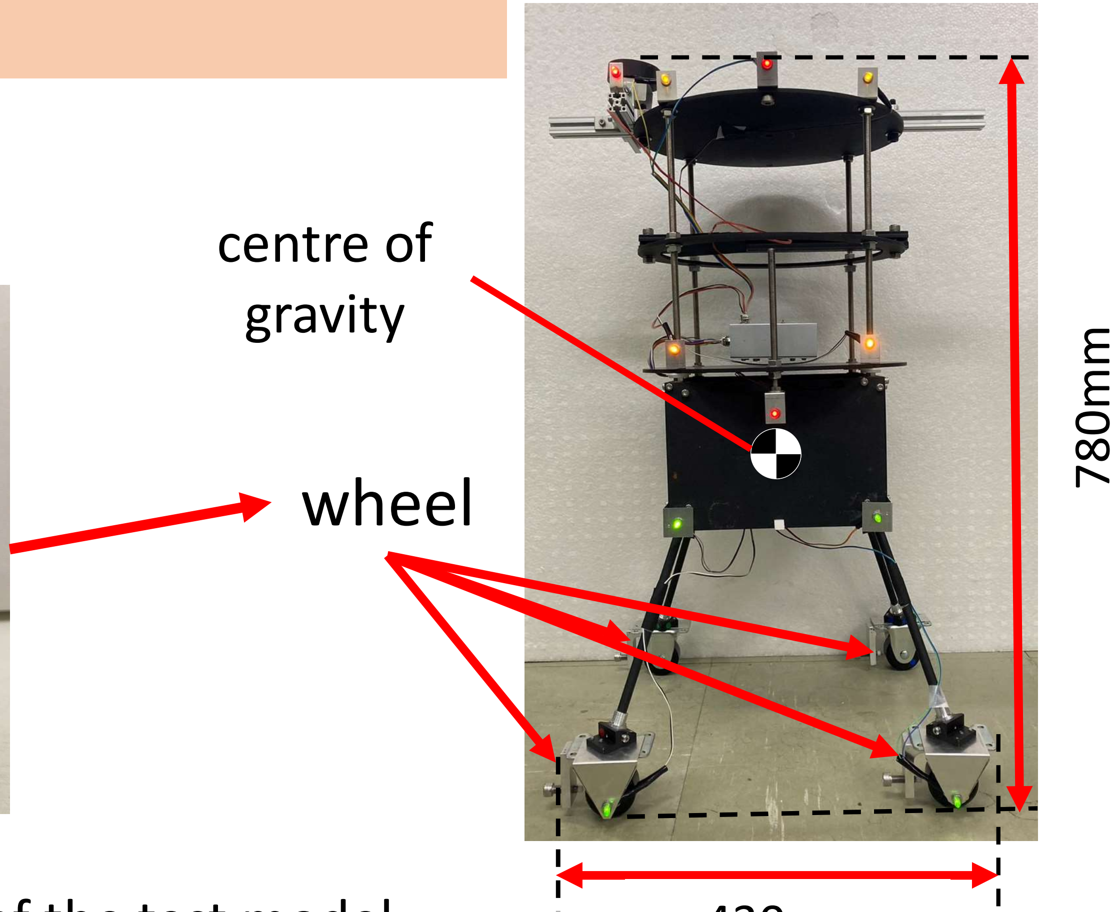
front leg $\mu$：【Low】 back leg $\mu$：【High】

⇒ Improved fall down resistance ＋ Reduced horizontal movement

## Methods to reduce frictional forces in actual rockets ⇒ wheel

Wheel attached to Test model

Test model




mass:6.5 kg

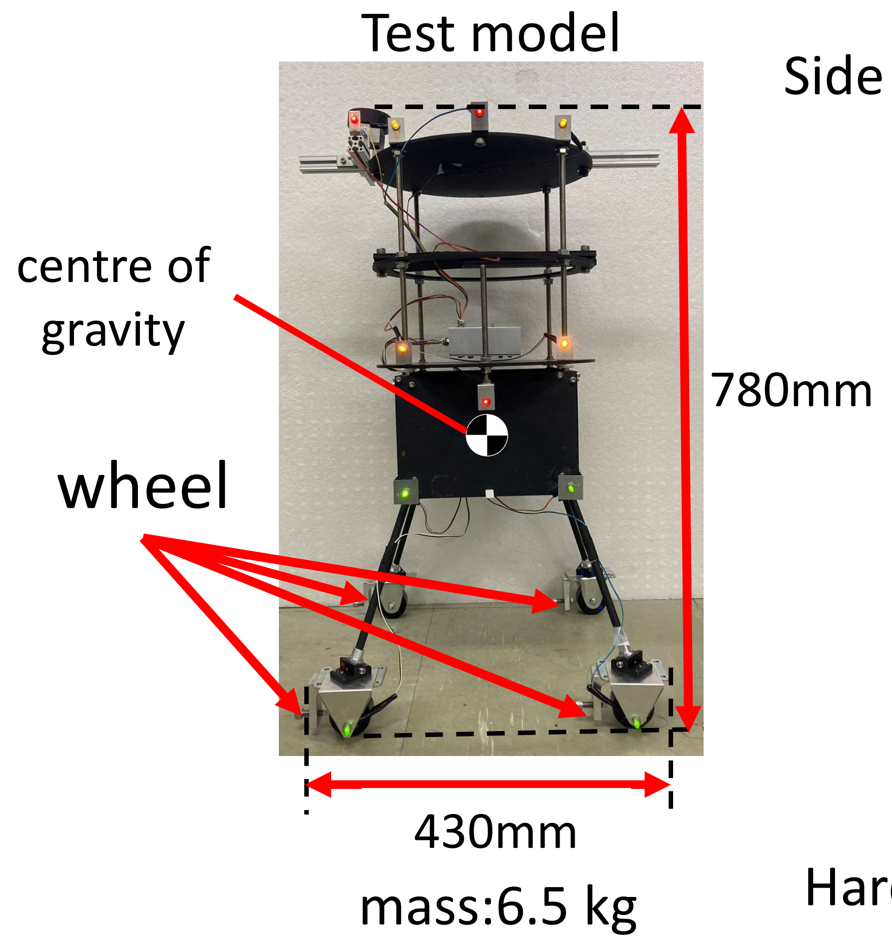
✓ Verification of the landing behavior of the test model when wheels are attached

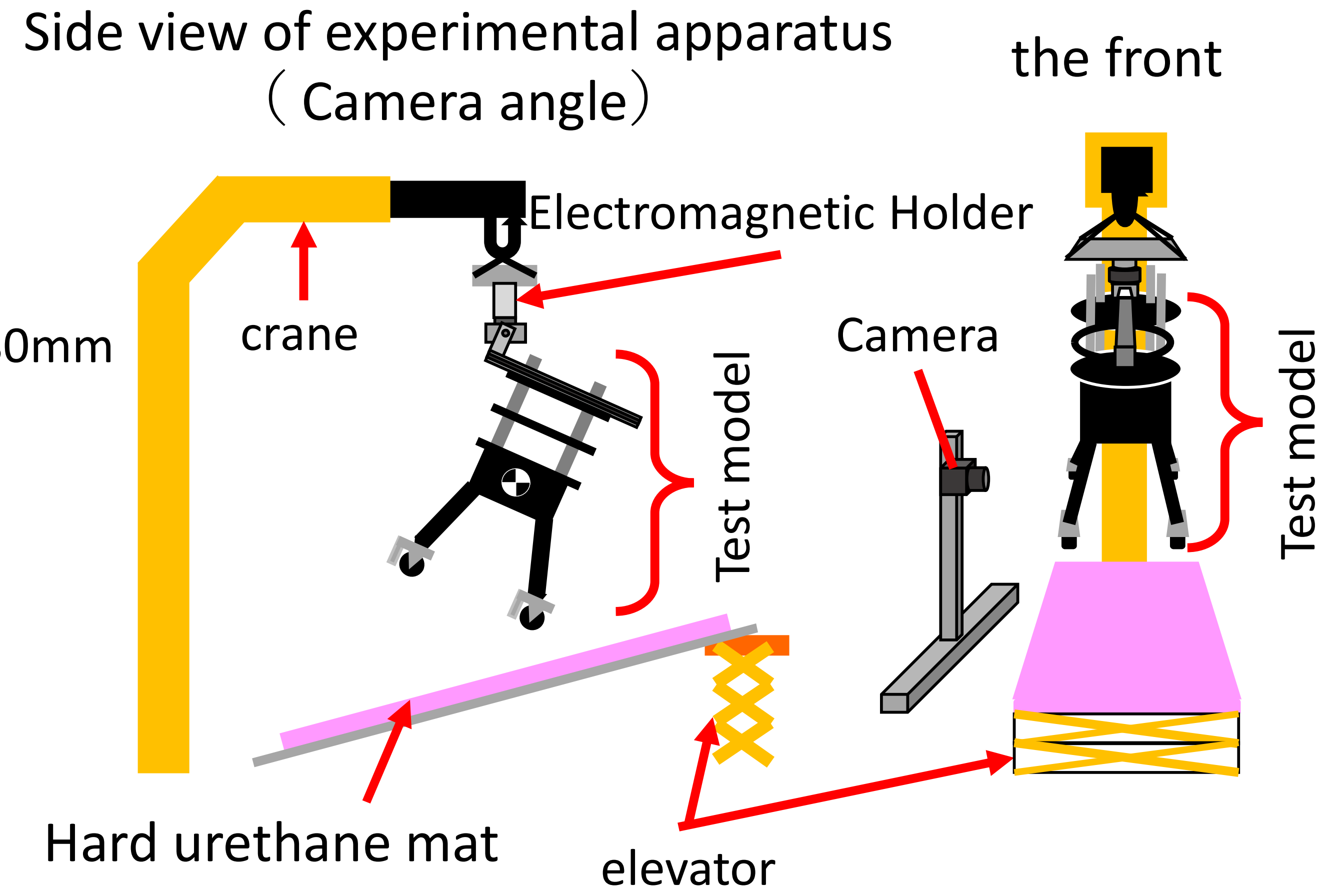
⇔ But, **difficult to give horizontal velocity**

➢ Consider alternatives to horizontal velocity

⇒**Ground slope**

# 2-D drop experiment： experimental configuration




- The airframe model is attached to a electromagnetic holder attached to the crane.
- Release the permanent electromagnetic holder and drop the fuselage model.
- Video of landing on a hard urethane mat..

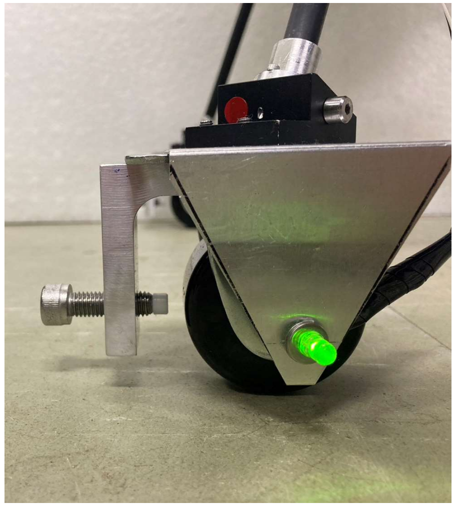
# Experimental Conditions



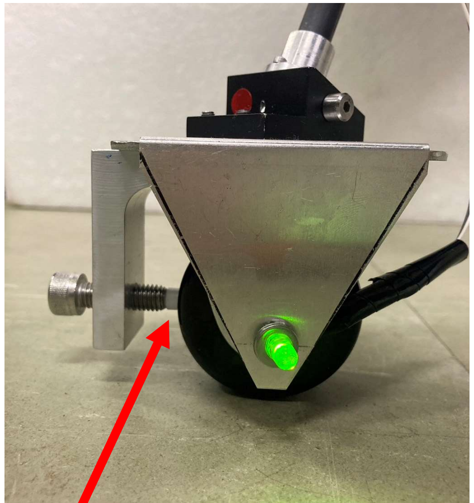
Experimental Conditions

| | |
|---|---|
| Initial height $h$ [m] | 0.35 / 0.45 |
| Pitch Angle $\theta$ [deg] | -0.6 ± 0.6 / -9.3 ± 1.05 / -18.4 ± 1.29 /- 26.3 ± 0.56 |
| Ground slope $\gamma$ [deg] | 0 / 2 / 4 / 6 |
| wheel rotation | Free / Semi-fixed |

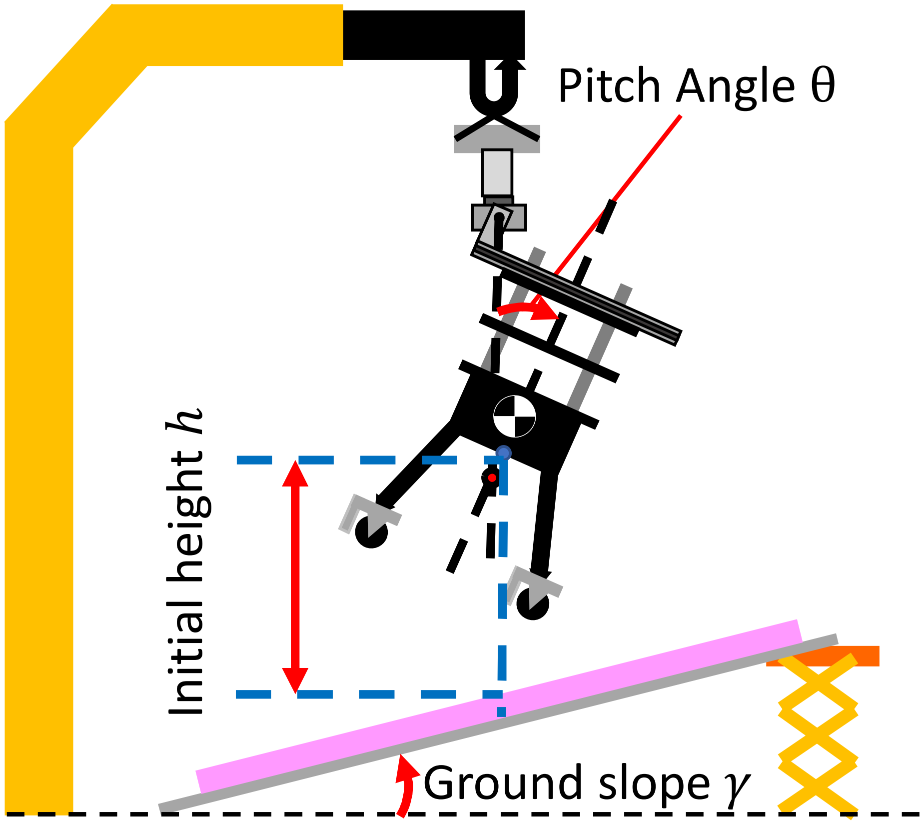
**Free**



**Semi-fixed**



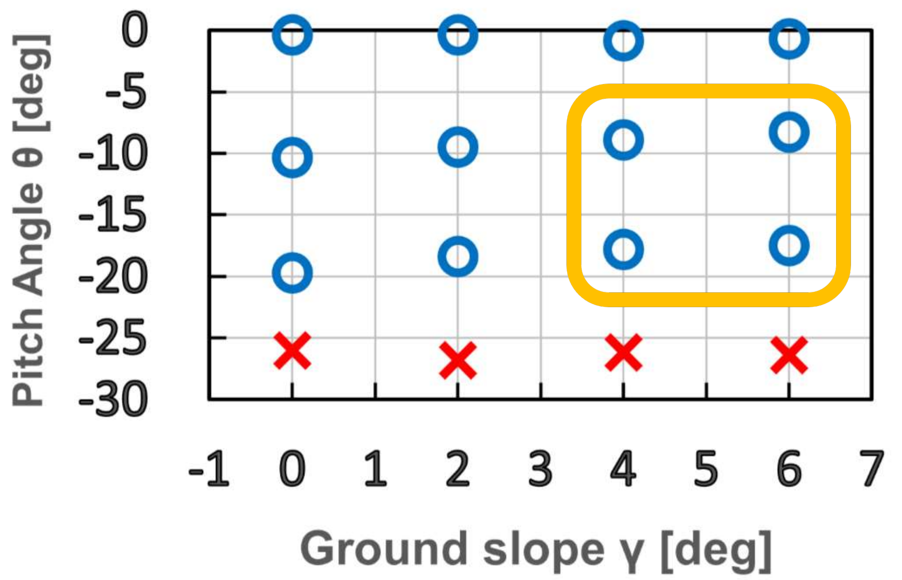
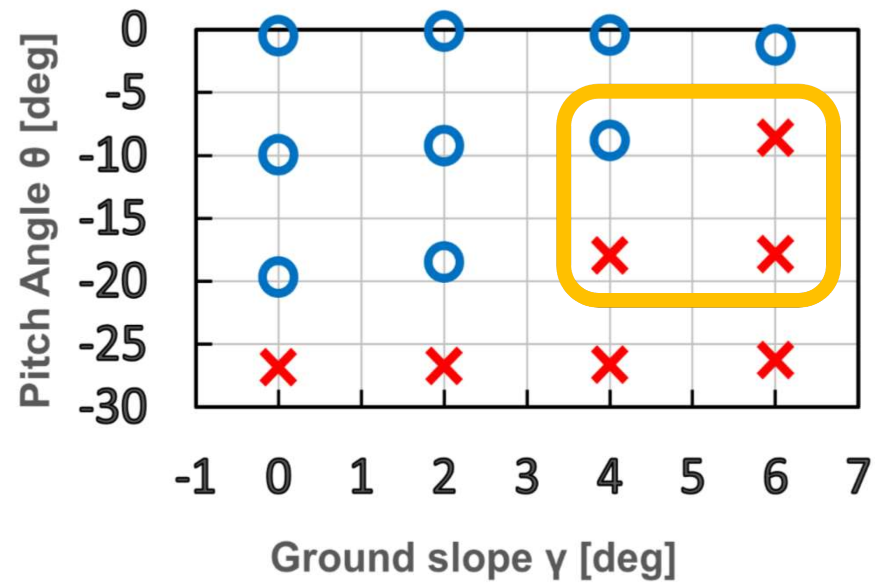
Push the bolt with POM on the wheel.
⇒Makes it harder to spin the wheel



# Experiment : Results



× Unstable ○ Stable

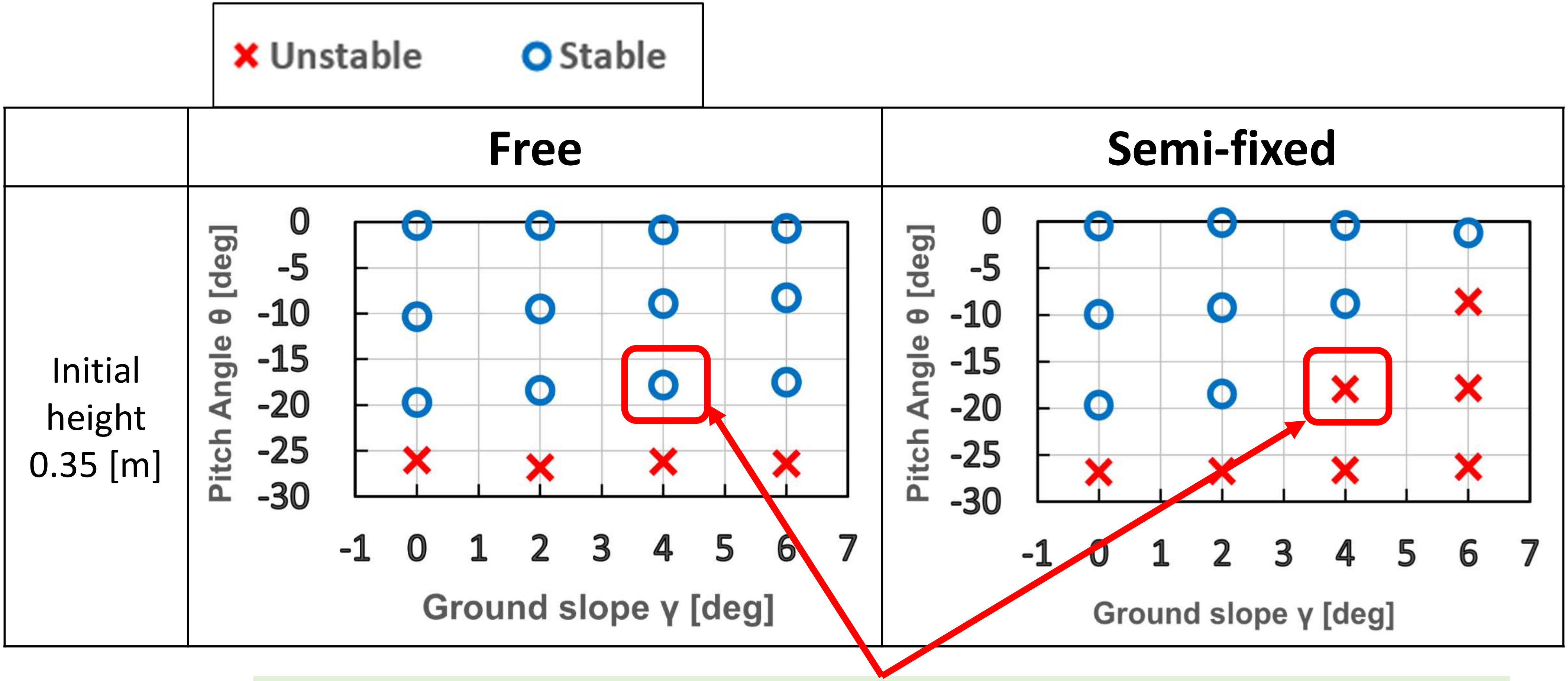
| | Free | Semi-fixed |
|---|---|---|
| Initial height 0.35 [m] |  |  |





- At Pitch angle $\theta$ is negatively large, Ground slope is large.
  ⇒ Rotation of the wheel 【Free】 is more stable.

# Experiment : Results 



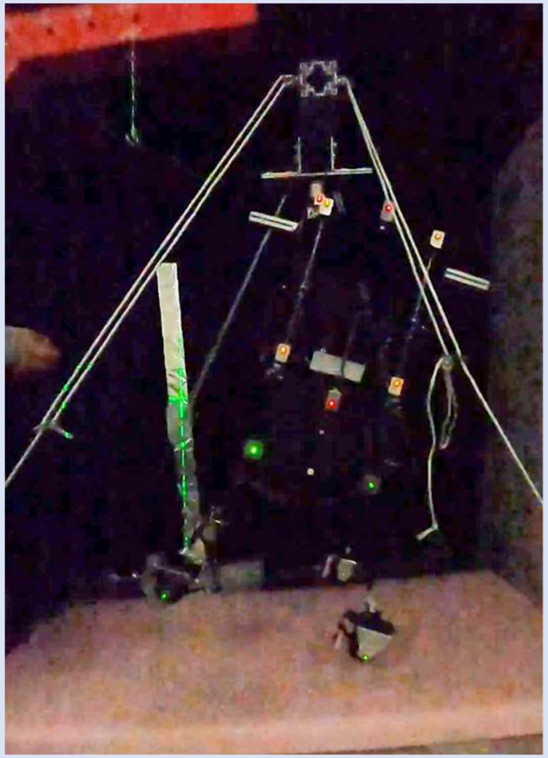

Here is a video of an experiment under these conditions.

- At Pitch angle $\theta$ is negatively large, Ground slope is large.
  ⇒ Rotation of the wheel 【Free】 is more stable.

# Experiment：Results


Change in wheel rotation⇒fall down resistance changes

$\gamma$ = 4[deg], $h$ =0.35[m], $\theta$ =-18[deg]



wheel rotation【Free】

wheel rotation【Semi-fixed】

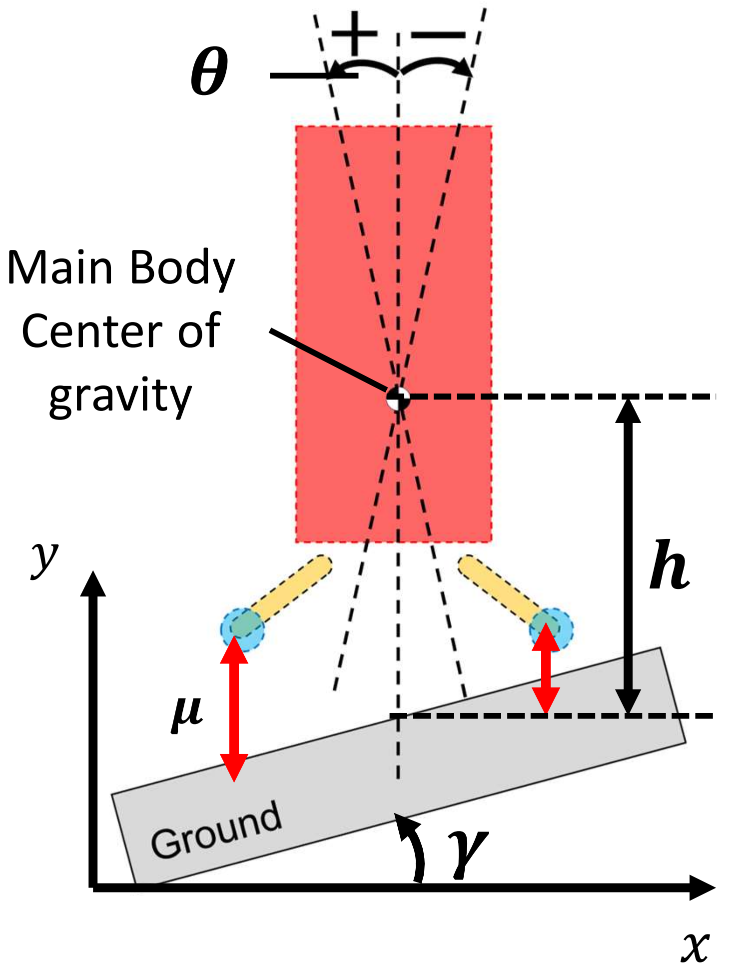
Movement changes when the leg on the underside of the slope is grounded

- ✓ 【Free】→Aircraft model slides down the slope and does not fall down ⇒Stable
- ✓ 【Semi-fixed】→Rotation of the aircraft model with the fulcrum at the ground contact point of the leg on the lower side of the slope ⇒ Unstable

Rocket geometry in lainding simulation

- Use the same model as with horizontal speed
- Ground slope as a parameter instead of horizontal velocity
- Wheels are not simulated,　change the coefficient of friction to static

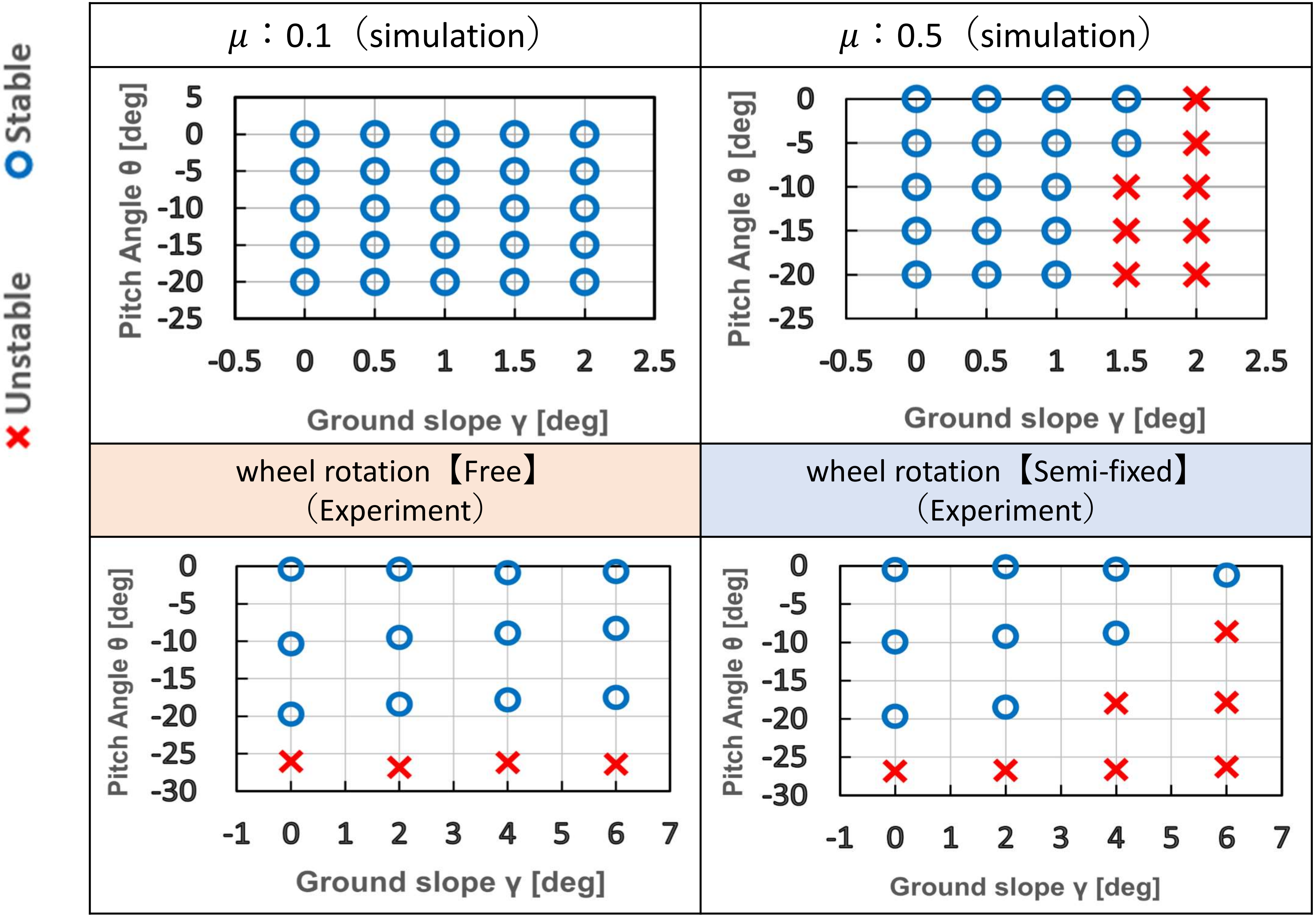
Initial conditions of the rocket




Landing simulation conditions

| | |
|---|---|
| Pitch Angle $\theta$ [deg] | 0 / ±5 / ±10 / ±15 / ±20 |
| Ground Slope $\gamma$ [m/s] | 0 / 2 / 4 / 6 / 8 |
| coefficient of friction $\mu$ | 0.8 / 0.5 / 0.3 / 0.1 / 0.01 |
| height $h$ [m] | 2.1 |

# Simulation of landing on a slope : Results




⇒The same effect as friction force reduction can be achieved by the wheel

# Summary



- Reduction of frictional force⇒Effective in improving fall down resistance
- front leg $\mu$： 【**Low**】 back leg $\mu$： 【**High**】

  ⇒ Improved fall down resistance ＋ Reduced horizontal movement
- 2-D drop experiment and simulation of landing on a slope

  ⇒The same effect as friction force reduction can be achieved by the wheel

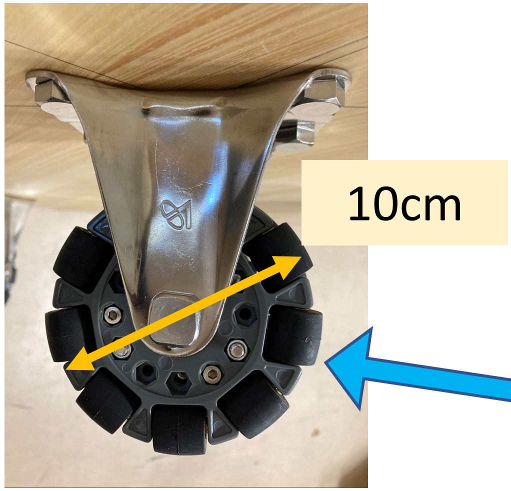
# Problems・Future Prospects



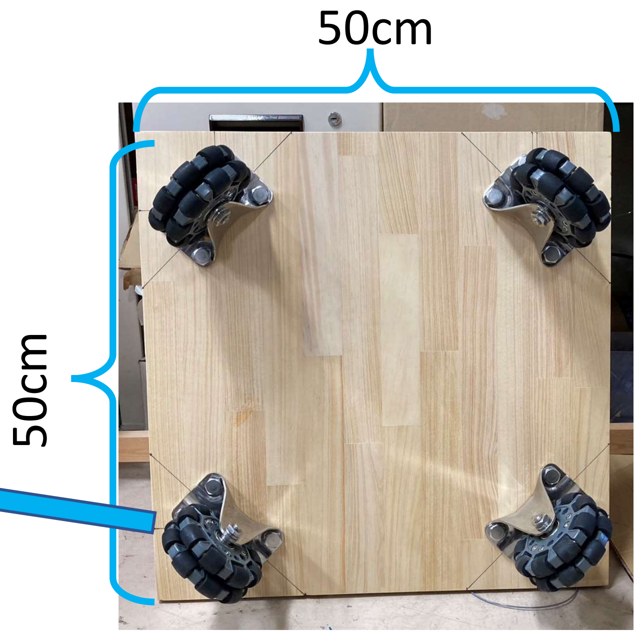
I. Adaptation to 3D movement

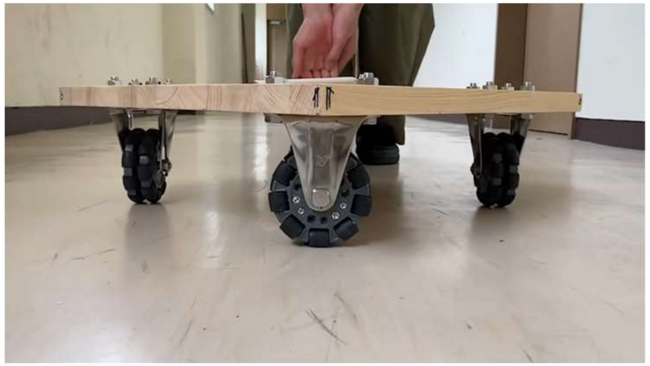
Wheels attached to landing legs ⇒ Need to adapt to 3D movement

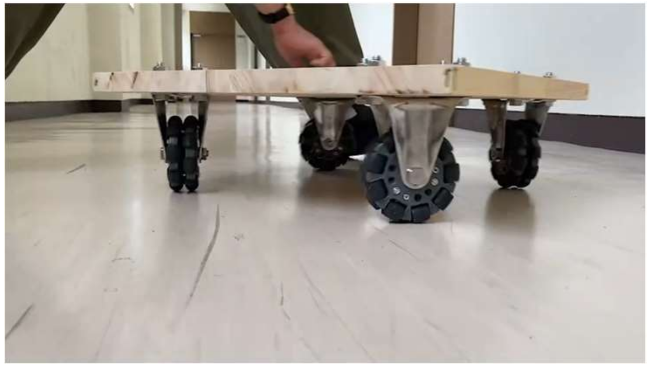
♦Example：Omni-Wheel




Omni-Wheel





Mechanism like an omniwheel ⇒ Adaptable to 3-D movement

# Problems・Future Prospects



II. change the coefficient of friction to dynamic
- Counter-measure for horizontal movement
  - ✓ Equipped with a mechanism like a brake
  - ✓ Limits the direction of wheel rotation