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Systematic Study for Touch-and-Go Sampling Probe

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Abstract

Touch-and-Go Sampling (TAG) Probe

Avoid the risk of breakdown by touchdown

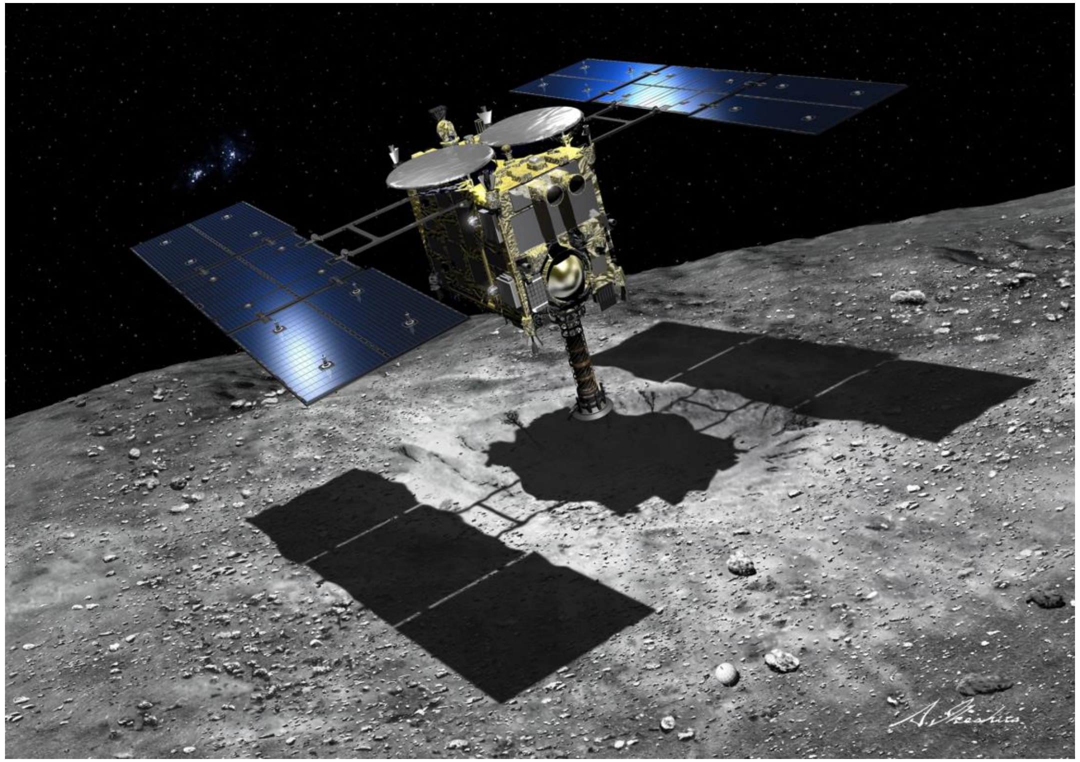
Systematic Study

Analysis of TAG probe's **peculiar behaviors**

- The speed of response
- The multi-body dynamics

Table of Contents

Hayabusa2 Mission



Hayabusa2

Touchdown (Hayabusa2)

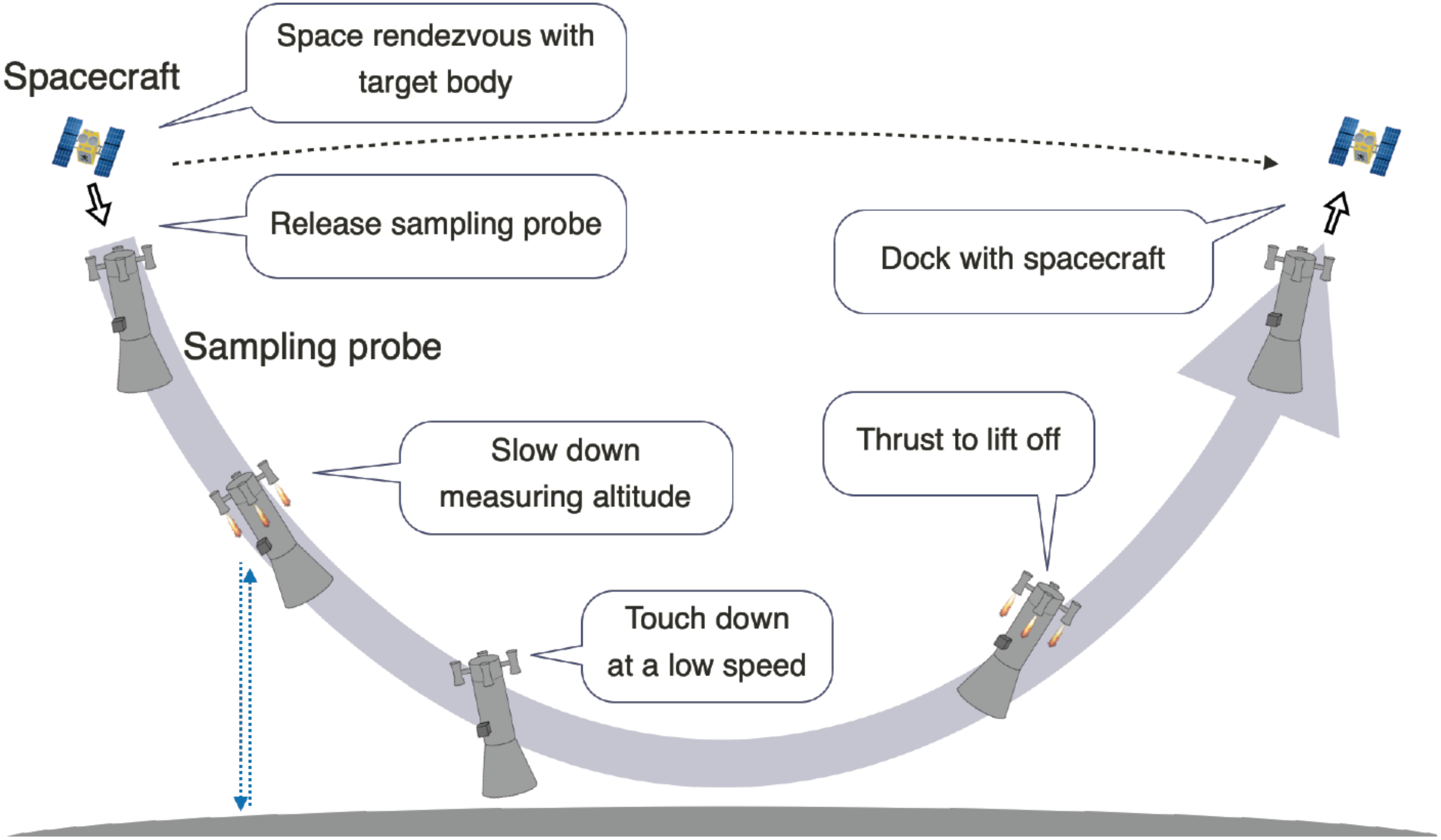
Spacecraft landed itself

↓

Risk

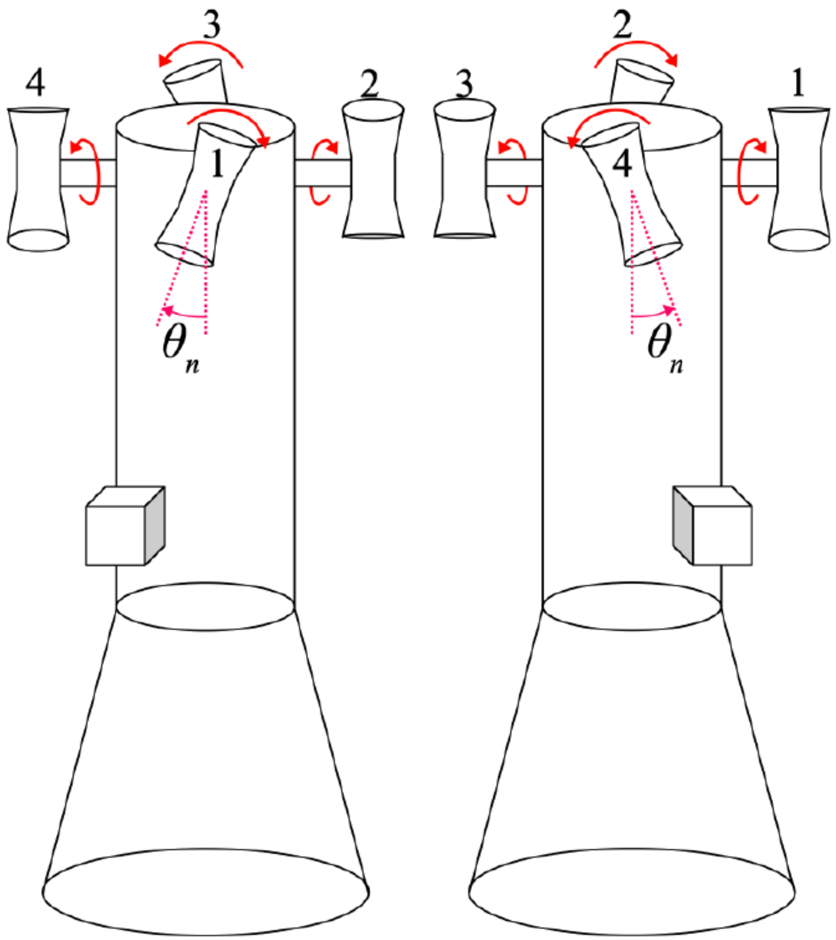
1. Breakdown
2. Lost of sample

New Mission Concept



K, Namiki., et al, "A concept study for sample return mission with touch-and-go sampling probe", *Astrodynamics Symposium*, 2021

Touch-and-Go(TAG) Sampling Probe



TAG Probe

= Sampler Horn × 1

\+ Solid rocket motor × 4

Control system

◆ Axis of thrusters

◆ Nominal inclination

⇒ Acceleration / Deceleration

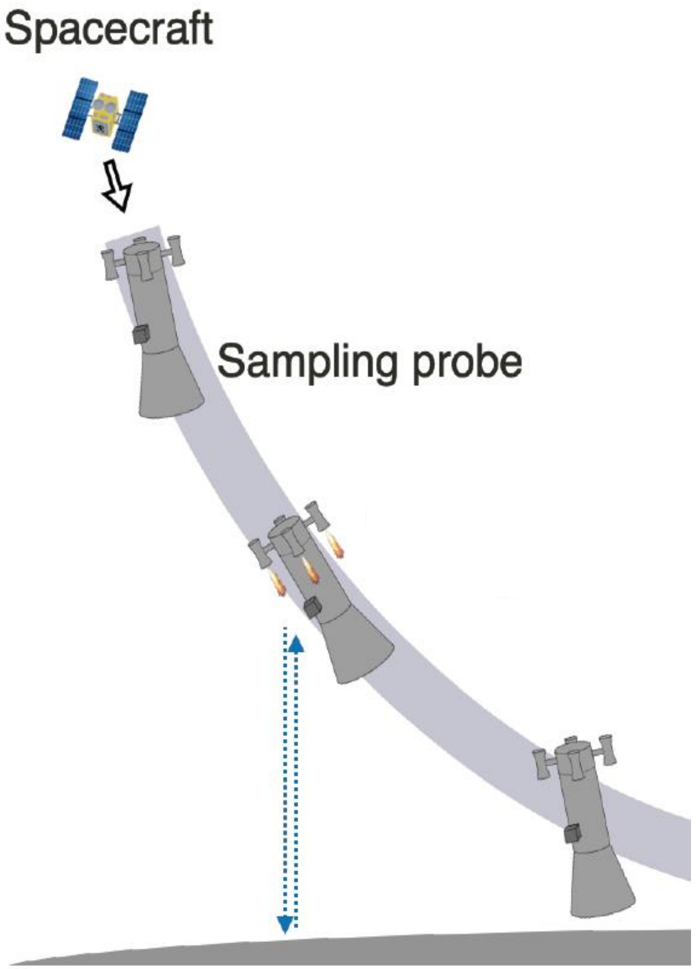
◆ Twist direction

⇒ More degrees of freedom

Table of Contents

Design Concept

Problem statement: descend

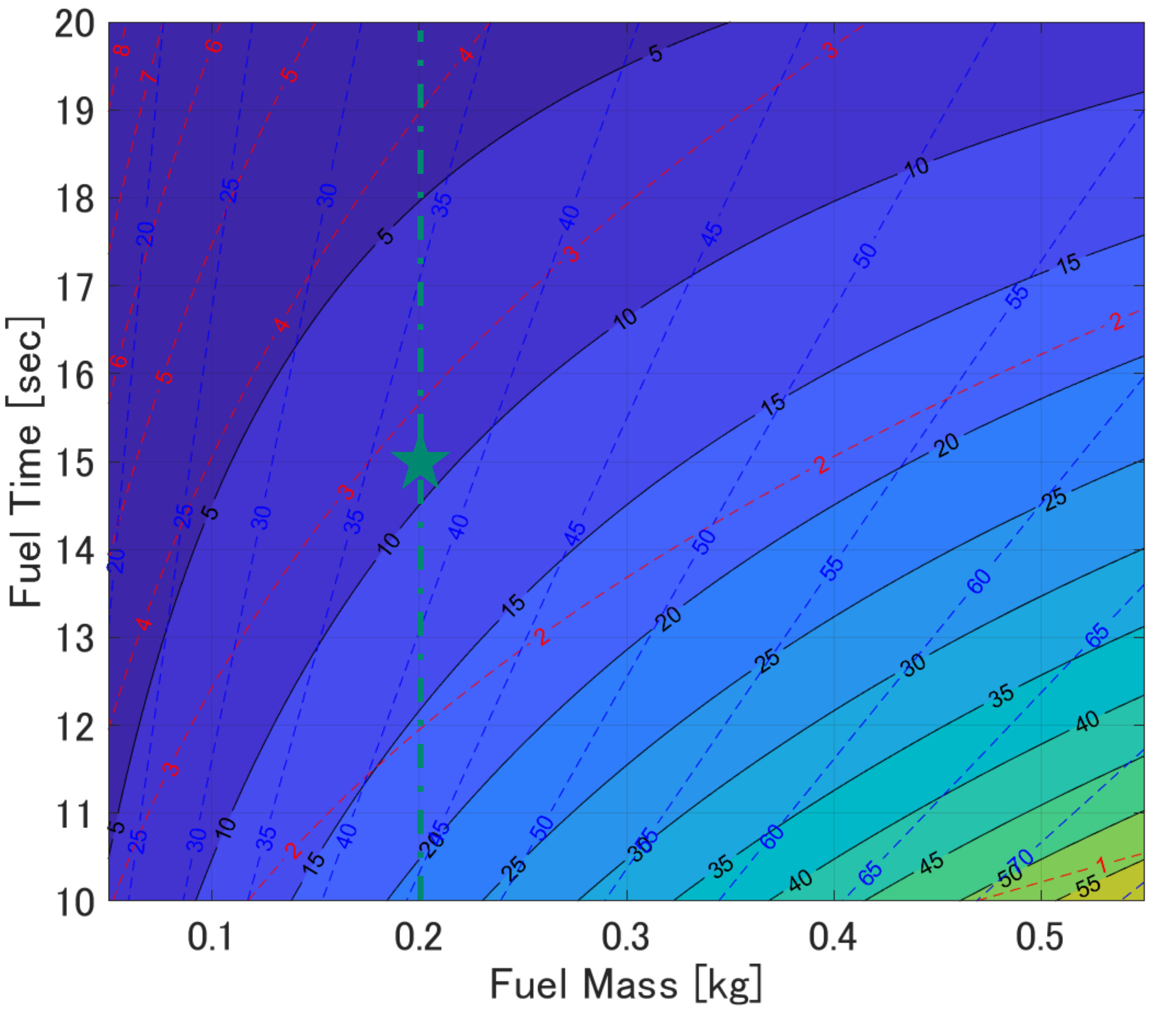


Design concept

Assumption: 0.3G

1. Set parameters of thruster
    - Fuel's mass
    - Time of combustion
2. Compute other parameters
    - Motor's size
    - Thrust
3. Design whole system
    - System's properties

Parameter Design



—— : System's mass

- - - - : Thruster's diameter

- - - - : Thruster's L/D

⬇

Fuel's mass: 0.2 kg

Time of combustion: 15 sec

Thruster's L/D: 2.8

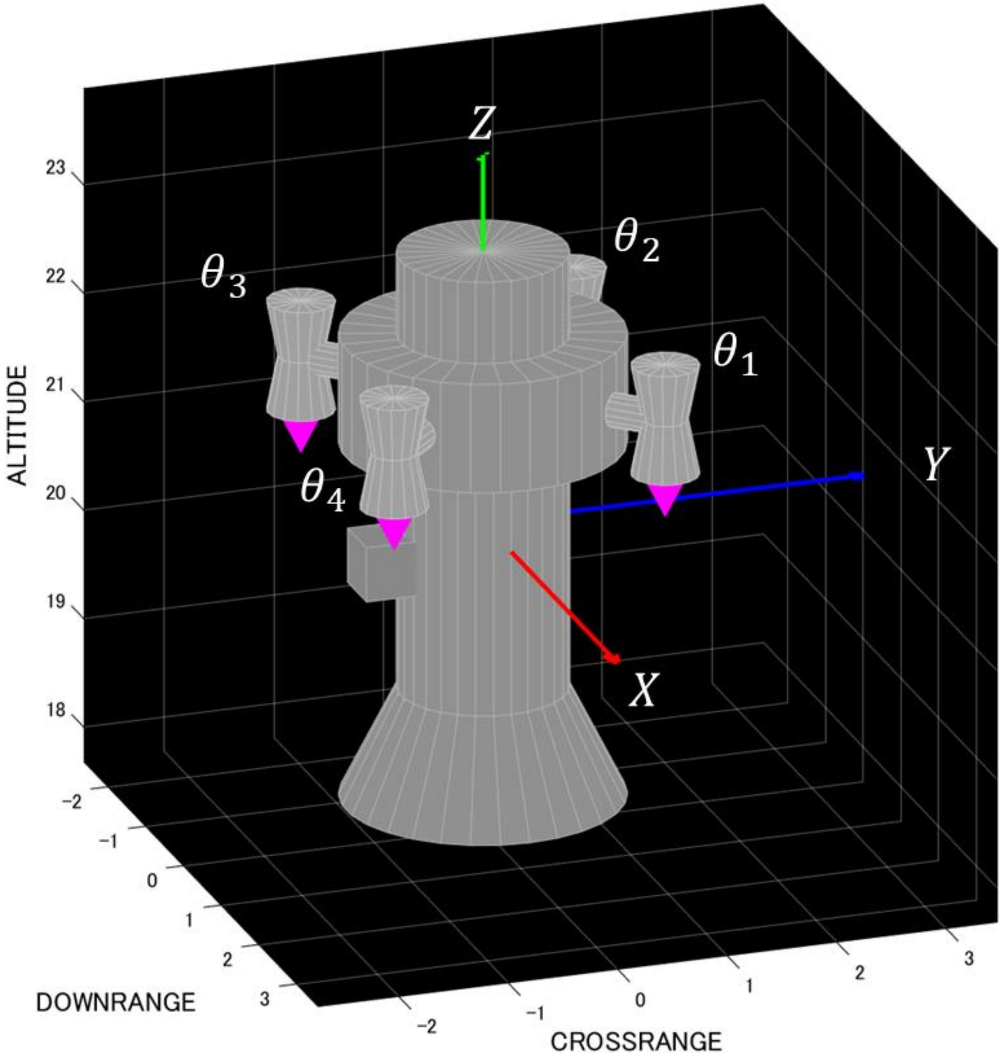
System's weight: 9.14 kg

Parameter of TAG Probe

System	
Mass	9.14 kg

Thrusters	
Fuel	0.20 kg
Mass	4.00 kg
Thrust	26.16 N

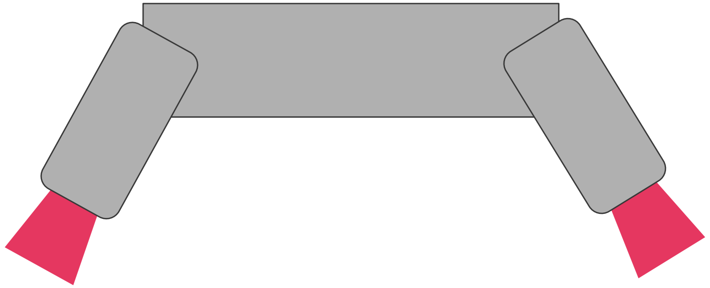
Whole	
Mass	25.14 kg
Balanced angle	45.0 deg



Difficulty of TAG Probe

Thrusters are heavy ⇒ Some effects on the behavior

1. The speed of motor

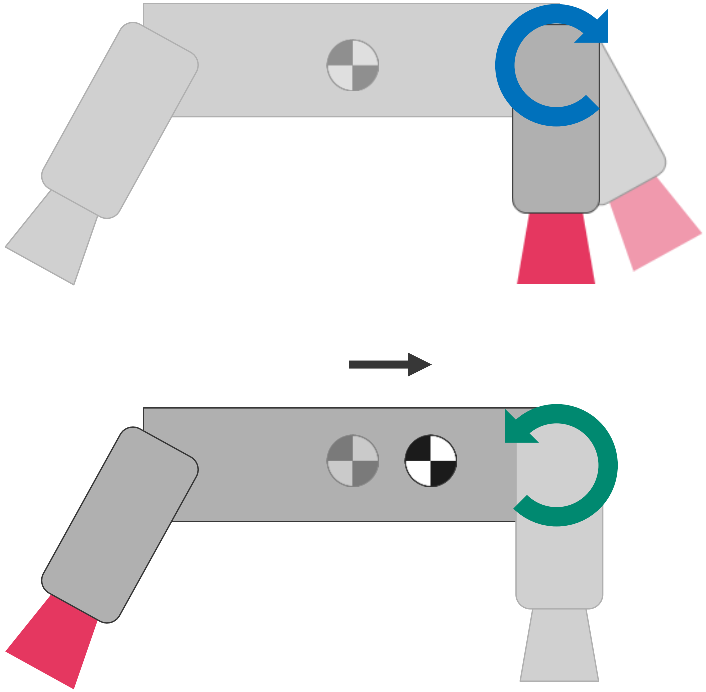


mass

0.5 ×2 : 1 : 0.5 ×2

⇒ Poor response speed (<90 deg/s)

2. The multi-body dynamics



Model: Multi-body Dynamics

Whole dynamics of TAG probe = …

The **rigid-body** dynamics
(The center of gravity)

+

The **multi-body** dynamics
(Around center of gravity)

Rigid-body Dynamics

19

Translational/Rotational motion

Dynamics

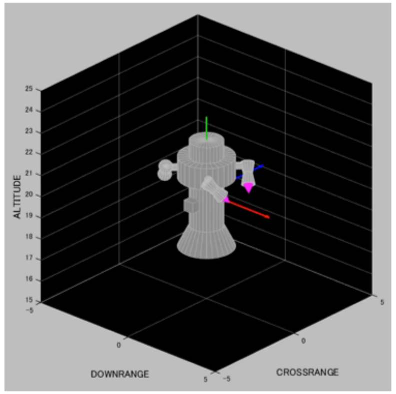
$$\dot{\boldsymbol{v}}^{\mathrm{I}}_{\mathrm{B/I}} = \boldsymbol{F}^{\mathrm{I}}$$

$$\dot{\boldsymbol{\omega}}^{\mathrm{B}}_{\mathrm{B/I}} = \left(I^{\mathrm{B}}_{all}\right)^{-1}\left(\tau^{\mathrm{B}} - \boldsymbol{\omega}^{\mathrm{B}}_{\mathrm{B/I}} \times I^{\mathrm{B}}_{all}\boldsymbol{\omega}^{\mathrm{B}}_{\mathrm{B/I}}\right)$$

Kinematics

$$\dot{\boldsymbol{r}}^{\mathrm{I}}_{\mathrm{B/I}} = \boldsymbol{v}^{\mathrm{I}}_{\mathrm{B/I}}$$

$$\dot{\boldsymbol{q}}_{\mathrm{B/I}} = \frac{1}{2}\boldsymbol{\omega}^{\mathrm{B}}_{\mathrm{B/I}} \otimes \boldsymbol{q}_{\mathrm{B/I}}$$



Multi-body Dynamics

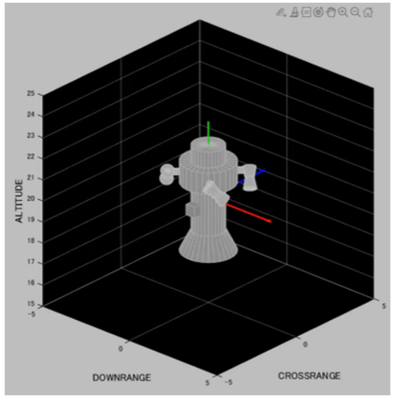
20

Linear/Rotational momentum

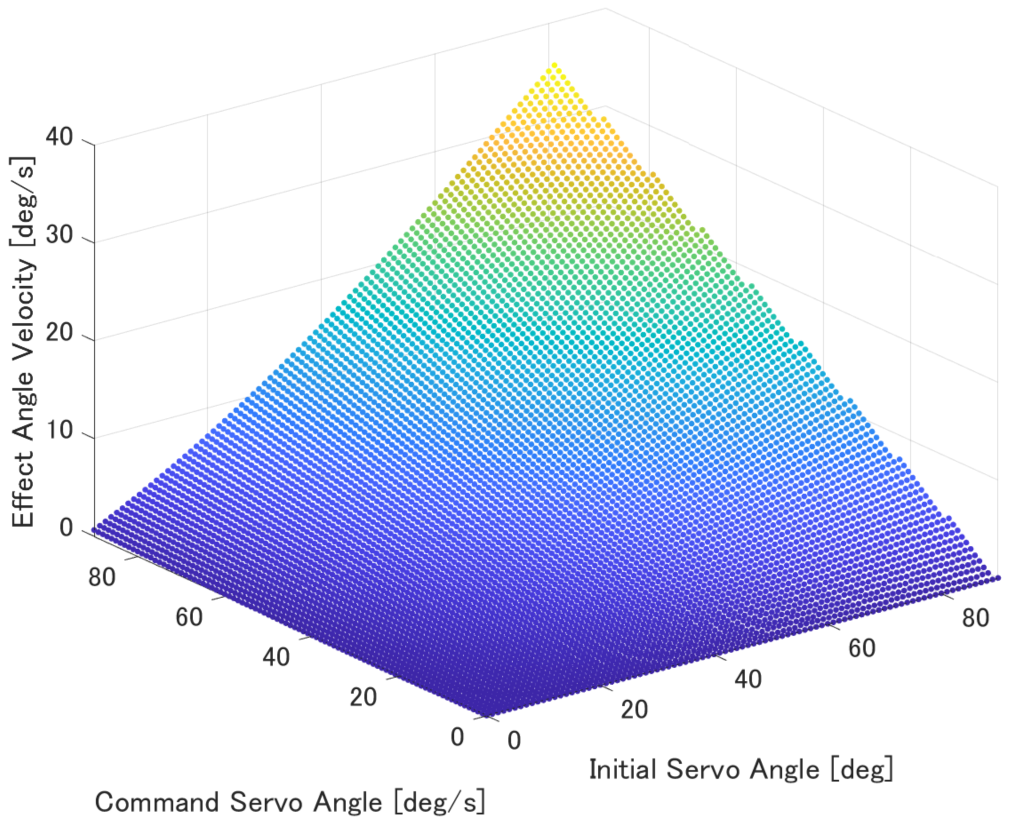
$$\begin{bmatrix} \boldsymbol{P}^{\mathrm{I}} \\ \boldsymbol{L}^{\mathrm{I}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_V & \boldsymbol{H}_{V\Omega} \\ \boldsymbol{H}_{V\Omega}^{\mathrm{T}} & \boldsymbol{H}_{\Omega} \end{bmatrix} \begin{bmatrix} \boldsymbol{v}^{\mathrm{I}}_{\mathrm{B/I}} \\ \boldsymbol{\omega}^{\mathrm{I}}_{\mathrm{B/I}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{H}_{Vq} \\ \boldsymbol{H}_{\Omega q} \end{bmatrix} \dot{\boldsymbol{\varphi}} + \begin{bmatrix} 0 \\ \boldsymbol{r}^{\mathrm{I}}_{\mathrm{B/I}} \times \boldsymbol{P}^{\mathrm{I}} \end{bmatrix}$$

$$\downarrow \boldsymbol{P}^{\mathrm{I}} = \boldsymbol{L}^{\mathrm{I}} = \boldsymbol{0}$$

$$\begin{bmatrix} \boldsymbol{v}^{\mathrm{I}}_{\mathrm{B/I}} \\ \boldsymbol{\omega}^{\mathrm{I}}_{\mathrm{B/I}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_V & \boldsymbol{H}_{V\Omega} \\ \boldsymbol{H}_{V\Omega}^{\mathrm{T}} & \boldsymbol{H}_{\Omega} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{H}_{Vq} \\ \boldsymbol{H}_{\Omega q} \end{bmatrix} \dot{\boldsymbol{\varphi}}$$



Polynomial approximation



Function approximation

$$\dot{\phi}_{\text{eff}} = g(\varphi_{\text{init}}, \dot{\varphi}_{\text{cmd}})$$

$\dot{\phi}_{\text{eff}}$: probe's angular velocity

φ_{init} : initial servo's angle

$\dot{\varphi}_{\text{cmd}}$: servo's angular velocity command

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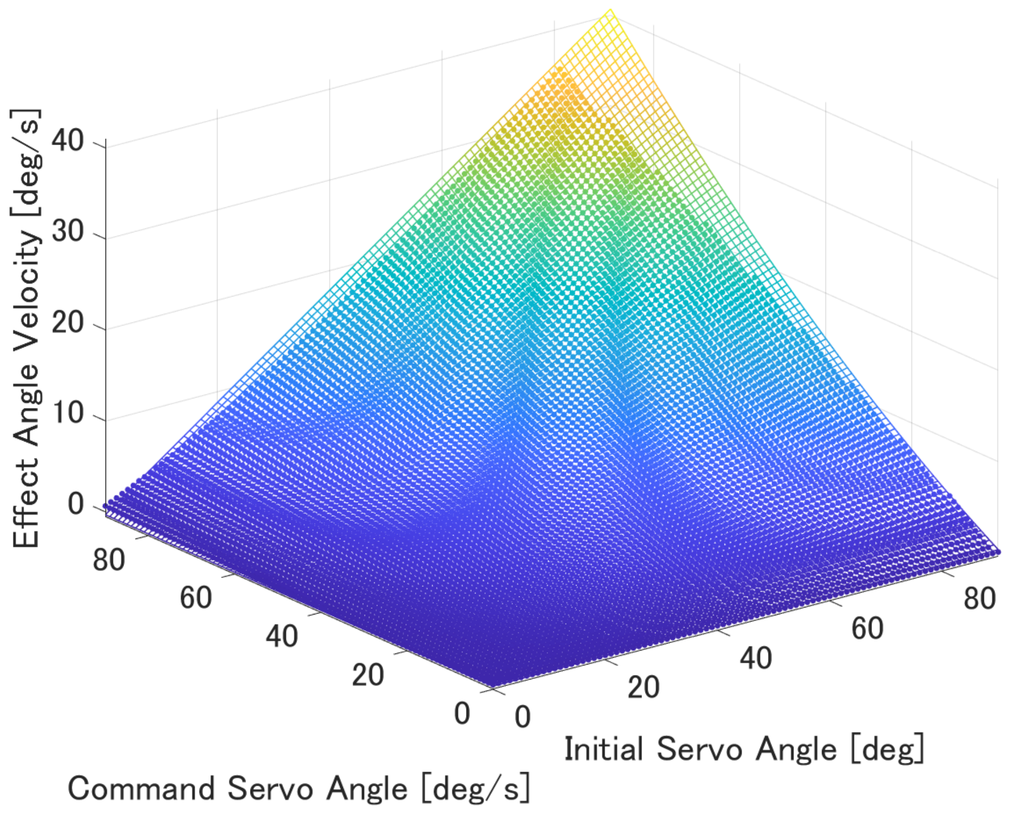
Polynomial approximation

Polynomial approximation



n^th order approximation

$$\dot{\phi}_{\mathrm{eff}} = g(\varphi_{\mathrm{init}}, \dot{\varphi}_{\mathrm{cmd}})$$

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$$\dot{\phi}_{\mathrm{eff}} \approx \sum_{\substack{0 \le i \le 2 \\ 0 \le j \le 1}} c_{ij}\, \varphi_{\mathrm{init}}^{i} \dot{\varphi}_{\mathrm{cmd}}^{j}$$

Linear about input ($\dot{\varphi}_{\mathrm{cmd}}$)

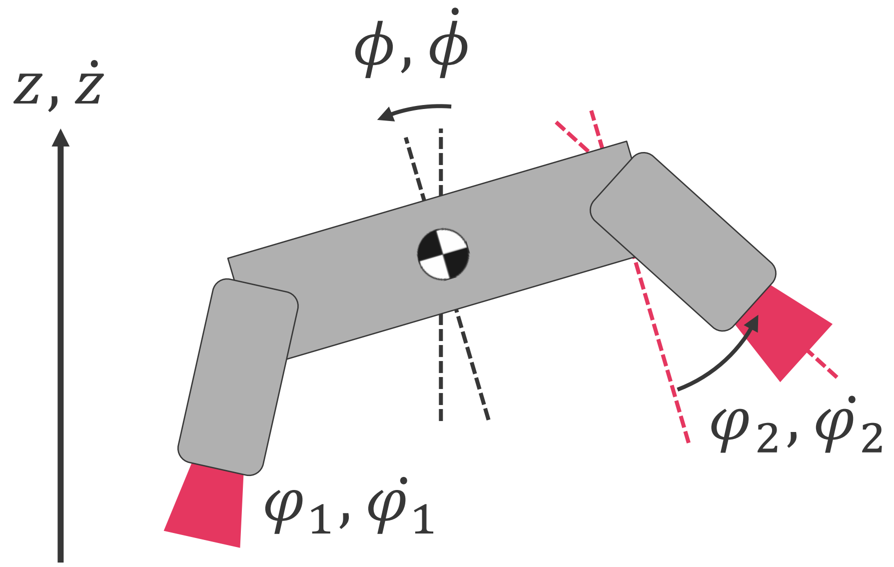
= Affine input system

⇒ Bang-Bang control

Problem Statement (Multi-Body)

State : $\boldsymbol{x} = (z, \dot{z}, \phi, \dot{\phi}, \varphi_1, \varphi_2)$

Input : $\boldsymbol{u} = (\dot{\varphi}_1, \dot{\varphi}_2)$



Equation of Motion

$$\dot{\boldsymbol{x}} = f_A(\boldsymbol{x}) + f_B(\boldsymbol{x})u$$

$$\frac{d}{dt}\begin{bmatrix} z \\ \dot{z} \\ \phi \\ \dot{\phi} \\ \varphi_1 \\ \varphi_2 \end{bmatrix} = \begin{bmatrix} \dot{z} \\ -g + F(\cos\varphi_1 + \cos\varphi_1)\cos\phi\,/m \\ \dot{\phi} \\ Fl(-\cos\varphi_1 + \cos\varphi_1)/I \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ g(\varphi_1), g(\varphi_2) \\ \mathbf{0} \\ 1 \quad 0 \\ 0 \quad 1 \end{bmatrix} \begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix}$$

Conclusion

Touch-and-Go Sampling (TAG) Probe

Avoid the risk of breakdown by touchdown

Systematic Study

Behavior Analysis: Peculiar to TAG probe

Recommendation

Advanced Control Law: Effective way