Workshop on Next Generation Transport Aircraft

Development of Hybrid Flight Simulator with Multi Degree-of-Freedom Robot

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Background (1)

■ **Unsteady Aerodynamics**

・The field of use of aircrafts are dramatically expanding

・Unmanned aerial vehicles (UAVs) have a capability of acrobatic flights (Hovering, Turn-around flight, Post-stall maneuver)

・The conventional linear theory based on stability derivatives can not be applied

⇨ **Unsteady aerodynamics**

UAV
(Uchiyama Lab, Tohoku univ.)

Post-stall maneuver

Background (2)

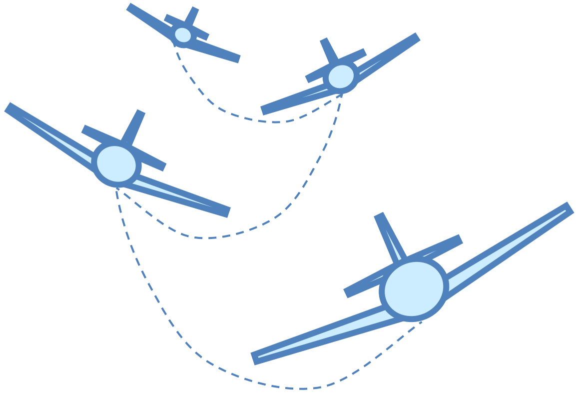
■Experimental Fluid Dynamics (EFD)

- Dynamic Wind-tunnel testing (DWT)
- Free Flight

MPM(DNW)

■Flight Dynamics

- Calculate behavior of the aircraft



Dutch Roll Motion

EFD + Flight Dynamics = Hybrid Motion Simulation

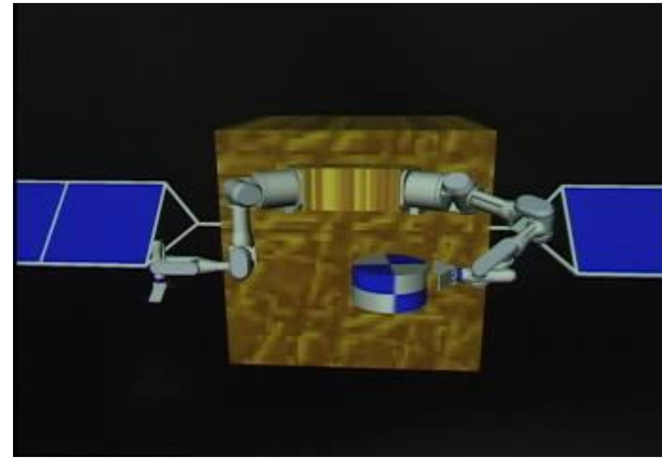
■Hybrid Motion Simulation

- Merge experimental fluid dynamics and numerical simulation
- Arbitrary flights can be demonstrated in the wind tunnel

Past Researches

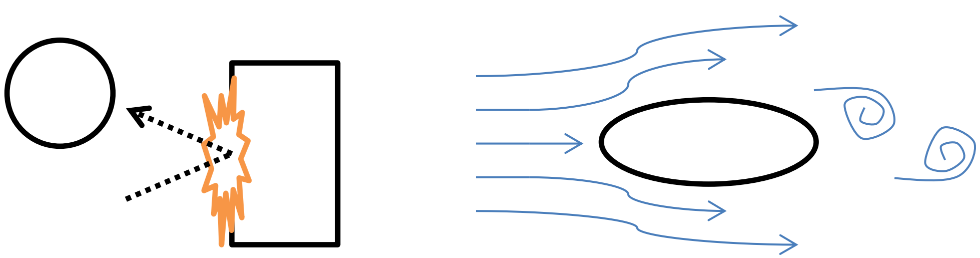
■ Contact phenomena of a satellite

- Only contact phenomena are taken out as a physical model
- Since movement of a model is determined by numerical computation, mass, moment of inertia, etc. can be set up arbitrarily
- This approach can replace other physical models



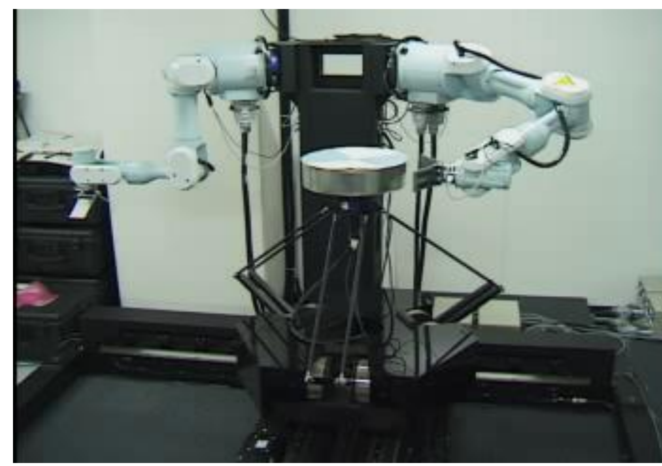
Numerical model

■ Hybrid Flight Simulation



Contact phenomena ⟶ Aerodynamic phenomena

⇨ **New application**



Physical model

Objectives

Development of Hybrid Flight Simulator with Multi-Degree-of–Freedom Robot

Reproduce simulated flight tests in Wind-tunnel using a multi degree-of-freedom robot

- 1-DOF Hybrid motion simulation
  - ex.) Wing rock(limited 1-DOF)
- Multi-DOF Hybrid motion simulation
  - ex.) Wing rock, Dutch roll

Hybrid Motion Simulator

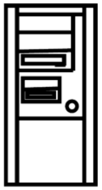
■Outline of Hybrid Motion Simulator

- EFD (Experimental model)
- Flight dynamics (Numerical model)

Experimental model

Servo mechanism
Model positioning

Numerical model



Dynamics calculation
position and attitude

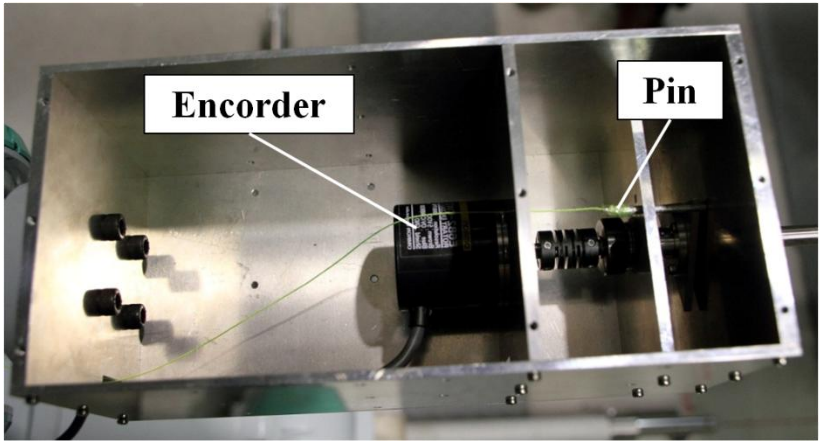
Force and Torque(F/T) Sensor
Measuring force and torque

1-DOF Hybrid Motion Simulation (1)

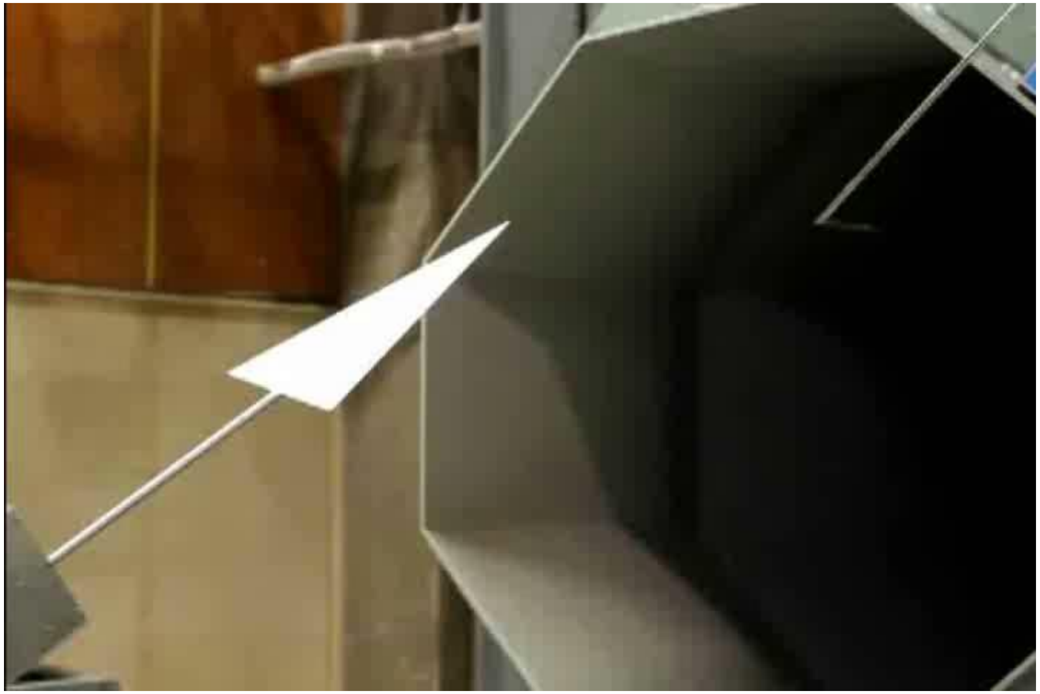
■1-DOF Wing Rock Motion (Free Roll)

- Wing Rock is a dynamic behavior of delta wing model at high angle of attack
- Self-induced limit cycle oscillation
- AoA=35 [deg], *u*=10 [m/s]

f=3.2 [Hz]



Free Roll Device



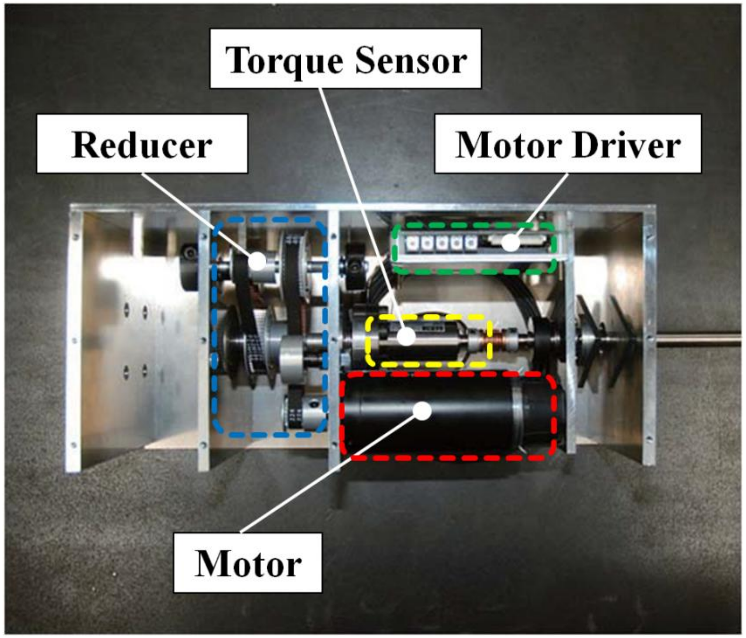
Free Roll(Wing Rock)

1-DOF Hybrid Motion Simulation (2)

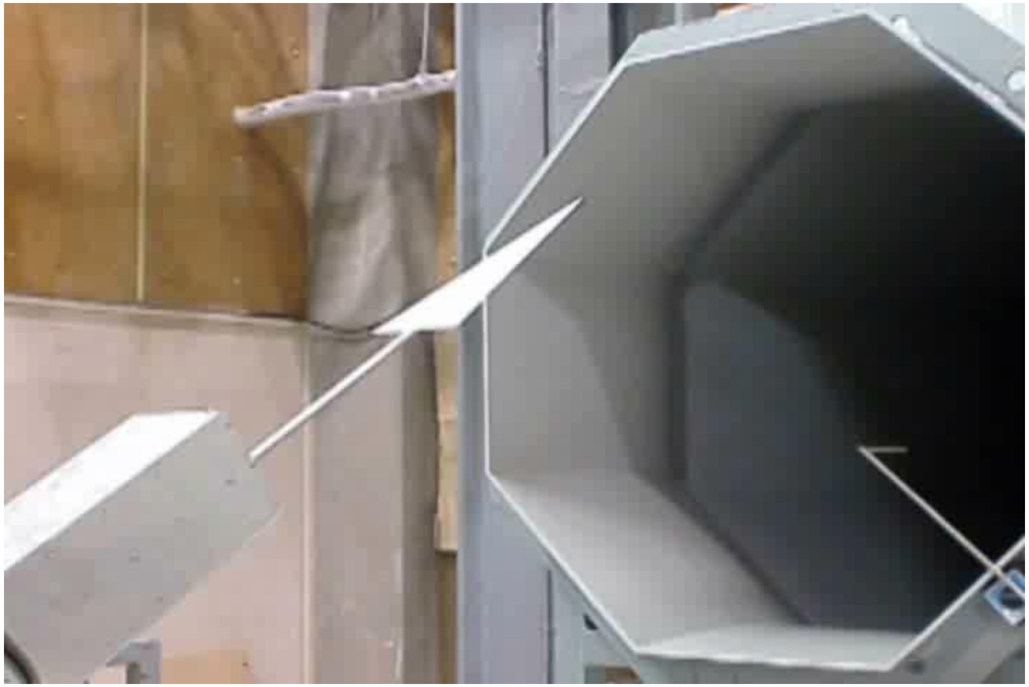
■1-DOF Wing Rock Motion (Hybrid Motion Simulation)

- Compared Hybrid Wing rock motion with free roll motion
- AoA=35 [deg], *u*=10 [m/s]

***f*=1.15 [Hz]**



Rolling motion device



Hybrid Motion Simulation

⇨ Need to increase the accuracy

Cause of the problem

- **Process hold-up time of Hybrid Motion Simulator**

<u>Calculation delay</u>

Dynamics calculation

position and attitude

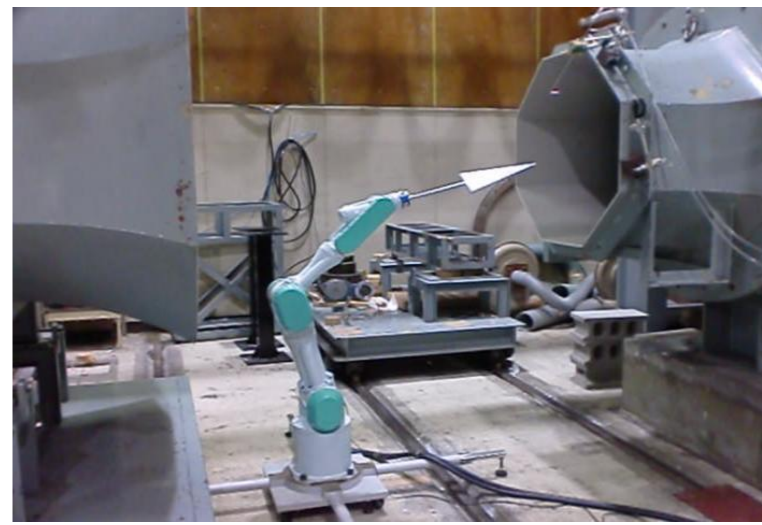
<u>Sensor delay</u>

F/T Sensor

Measuring force and torque

Servo mechanism

Model positioning

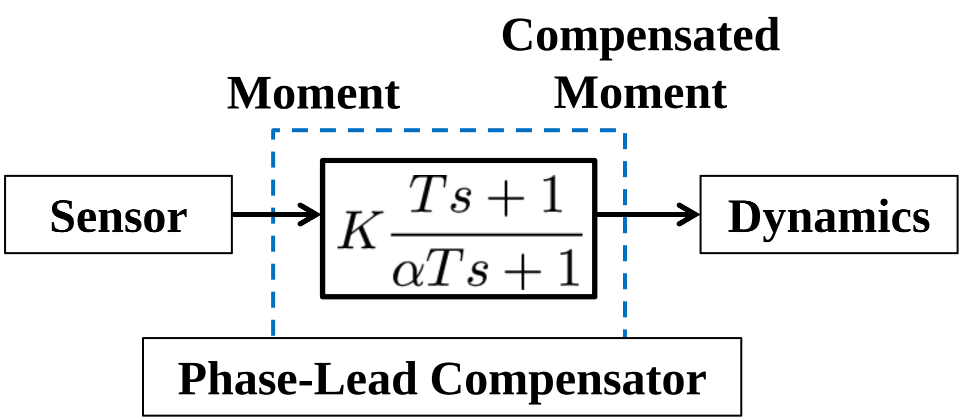


<u>Servo delay</u>

1-DOF Hybrid Motion Simulation (3)

■Phase-Lead Compensation

- Phase-lead compensation (PLC) is introduced
- Compensate for the sensor delay
- AoA=35 [deg], *u*=10 [m/s]



⇨ Compensate for other delays

***f*=1.95 [Hz]**

Hybrid Motion Simulation(PLC)

Multi-DOF Hybrid Motion Simulation

■Multi-DOF

- Using 6-DOF robot manipulator
- Evaluates as compared with R/C model

Get flight data from R/C model

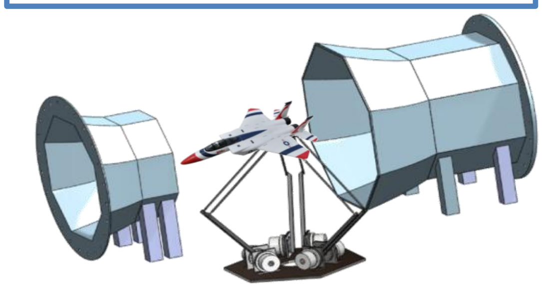
Hybrid Motion Simulation

Numerical model

Evaluate model position & attitude

Dynamics simulation

Experimental model



Exercise experimental model

Measure aerodynamic force

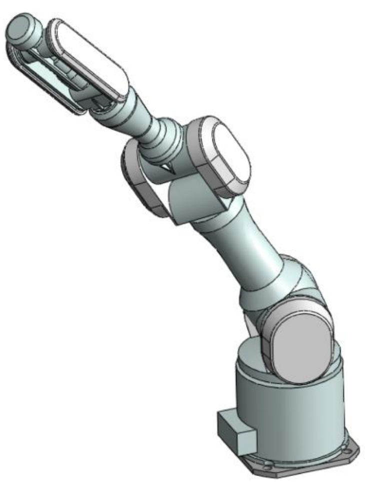
Development of 6-DOF Robot Manipulator

■HEXA-X2

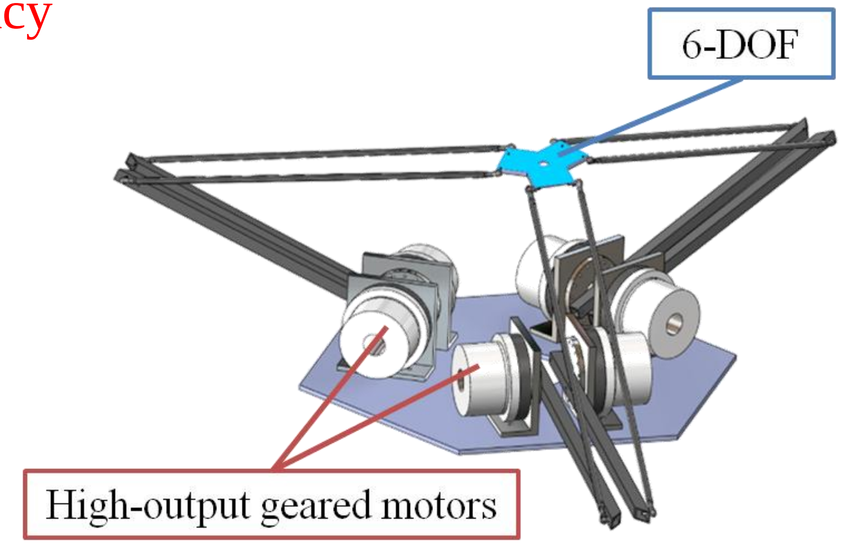
- Uchiyama Lab. in Tohoku University developed HEXA-X2
- HEXA-X2 is a Parallel link robot manipulator

■The merit of HEXA-X2

- Supported by multiple arms → High rigidity
- Light weight arms → High frequency



PA-10 (Serial Robot)



HEXA-X2 (Parallel Robot)

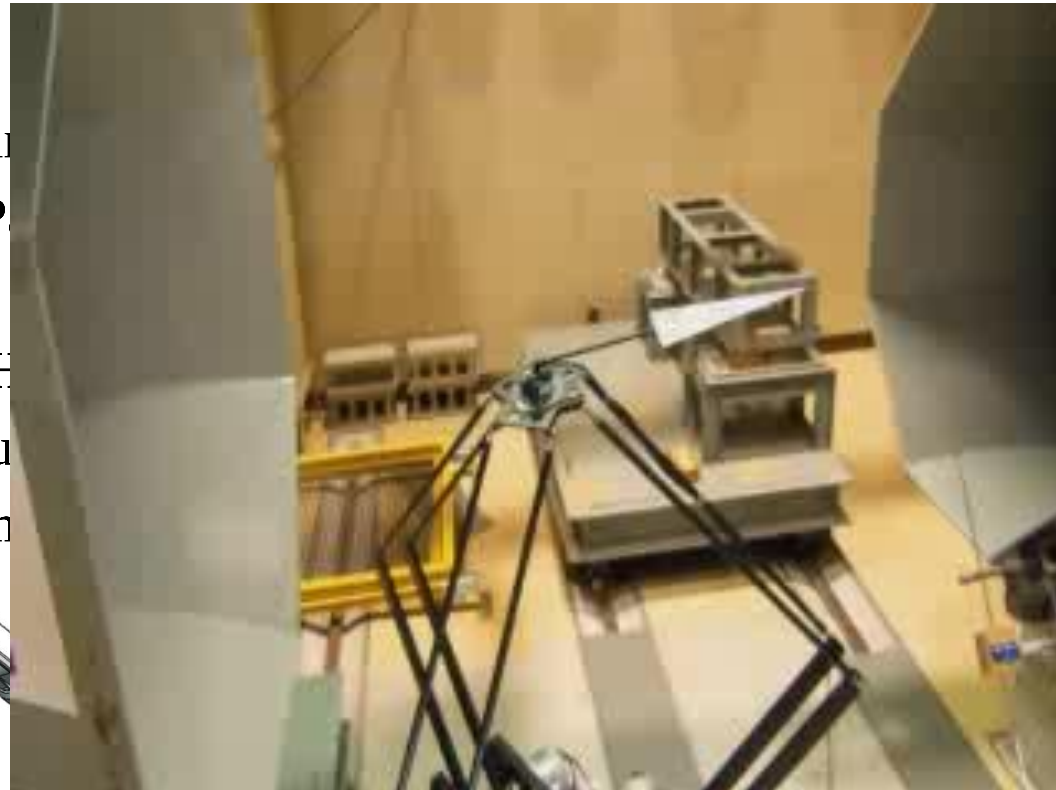
Development of 6-DOF Robot Manipulator

■ **HEXA-X2**

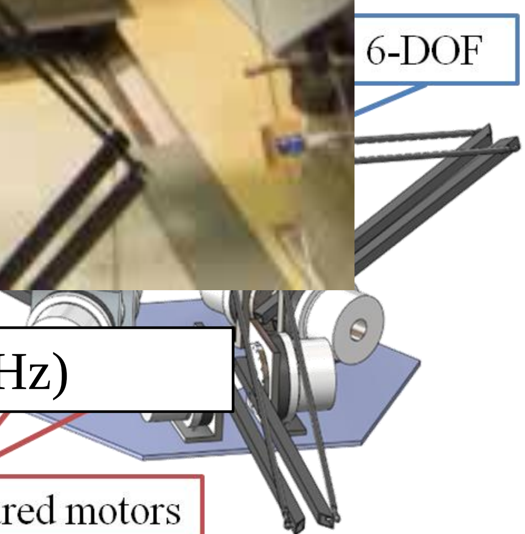
- Uchiyama Lab. i
- HEXA-X2 is a P

■ **The merit of H**

- Supported by mu
- Light weight arm



Dutch Roll Motion (3Hz)



PA-10 (Serial Robot) **HEXA-X2 (Parallel Robot)**

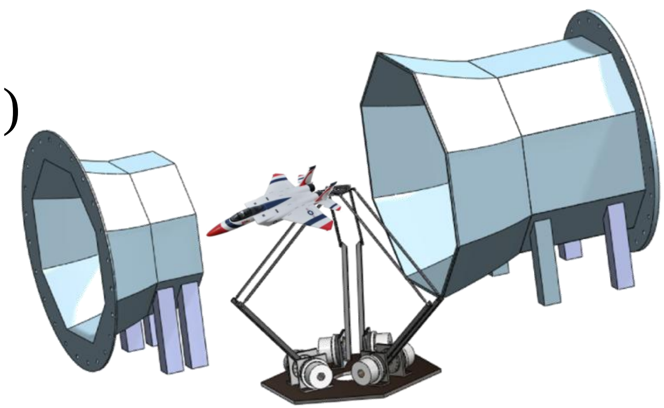
Summary and Future Works

■Summary

- We are developing Hybrid Motion Simulator
- 1-DOF Hybrid Motion Simulator is feasible
- HEXA-X2 is under development for Hybrid Flight Simulator

■Future Works

- Get the flight data from R/C model
  →Model position, attitude, velocity (IMU, GPS)
- Wind tunnel testing
- Validation of Hybrid flight simulation
- Visualization



Hybrid Flight Simulator

Thank you for your attentions!

Significance of Hybrid Flight Simulator

■**The simulation in an actual phenomenon**

・The power from a fluid phenomenon is measured using a physical model

■**The action of an aircraft is reproducible**

・The Hybrid Motion Simulator can reproduce an action, unlike a compulsive shaking test

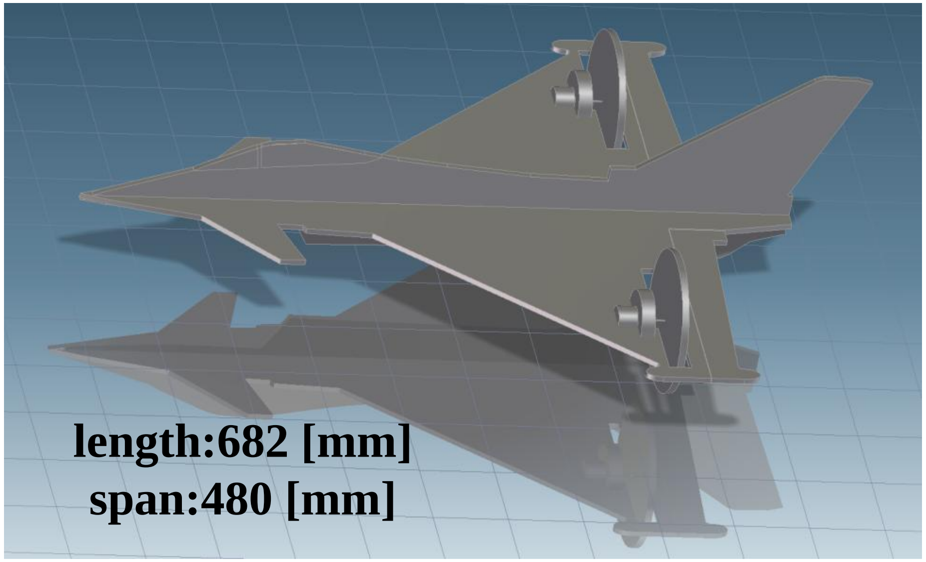
■**A dangerous action is safely reproducible**

・ Since the aircraft is moved using a robot manipulator , there no worries about crash and contact which may take place by actual flight

Flight Test (2)

■R/C model

Propeller model



EDF(Electric Duct fan) model

■Get Flight Data

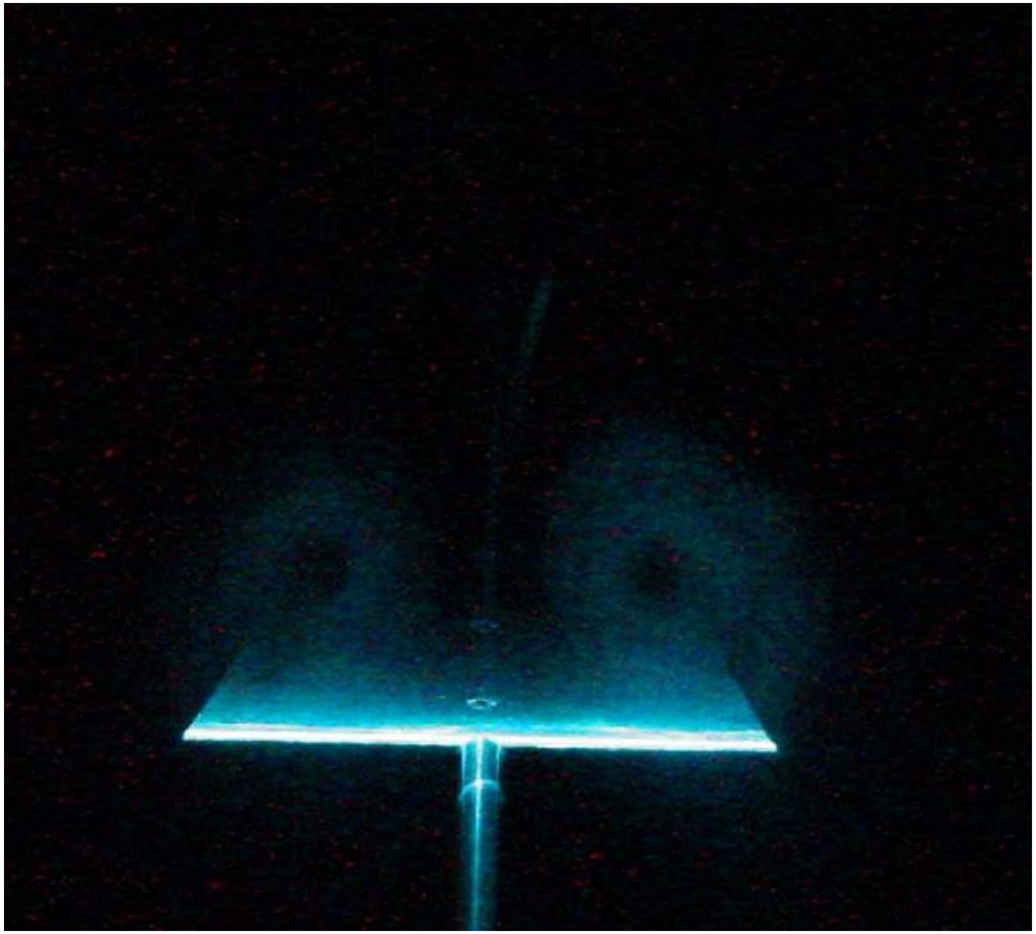
- Model Position
- Model attitude
- Velocity

⇨ **Gathering data from IMU & GPS**

Flow Visualization for dynamic model (1)

■Laser light sheet method

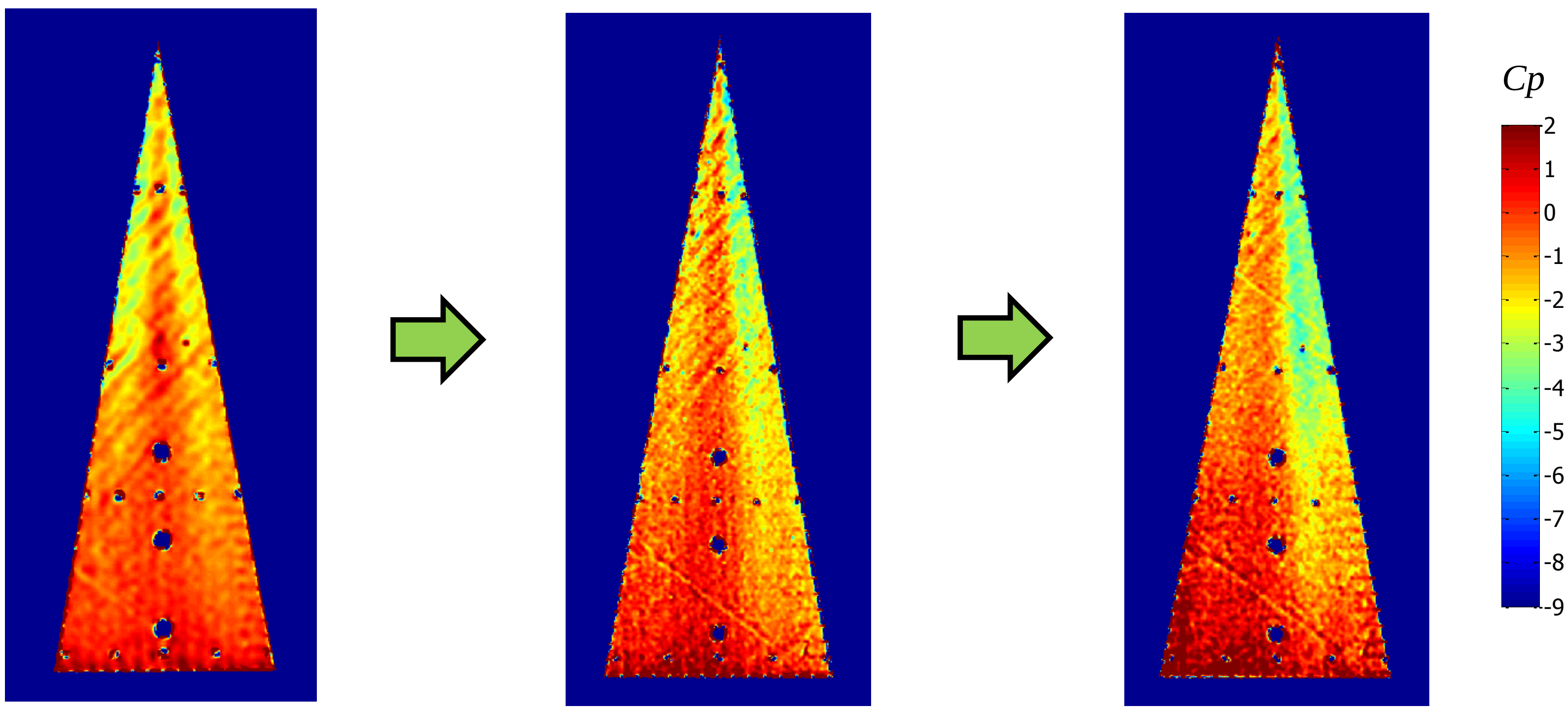
・Flow phenomena upper the model can be visualized



Flow Visualization for dynamic model (2)

■PSP (Pressure Sensitive Paint)

- PSP is a pressure distribution sensor
- Pressure field on the model can be visualized

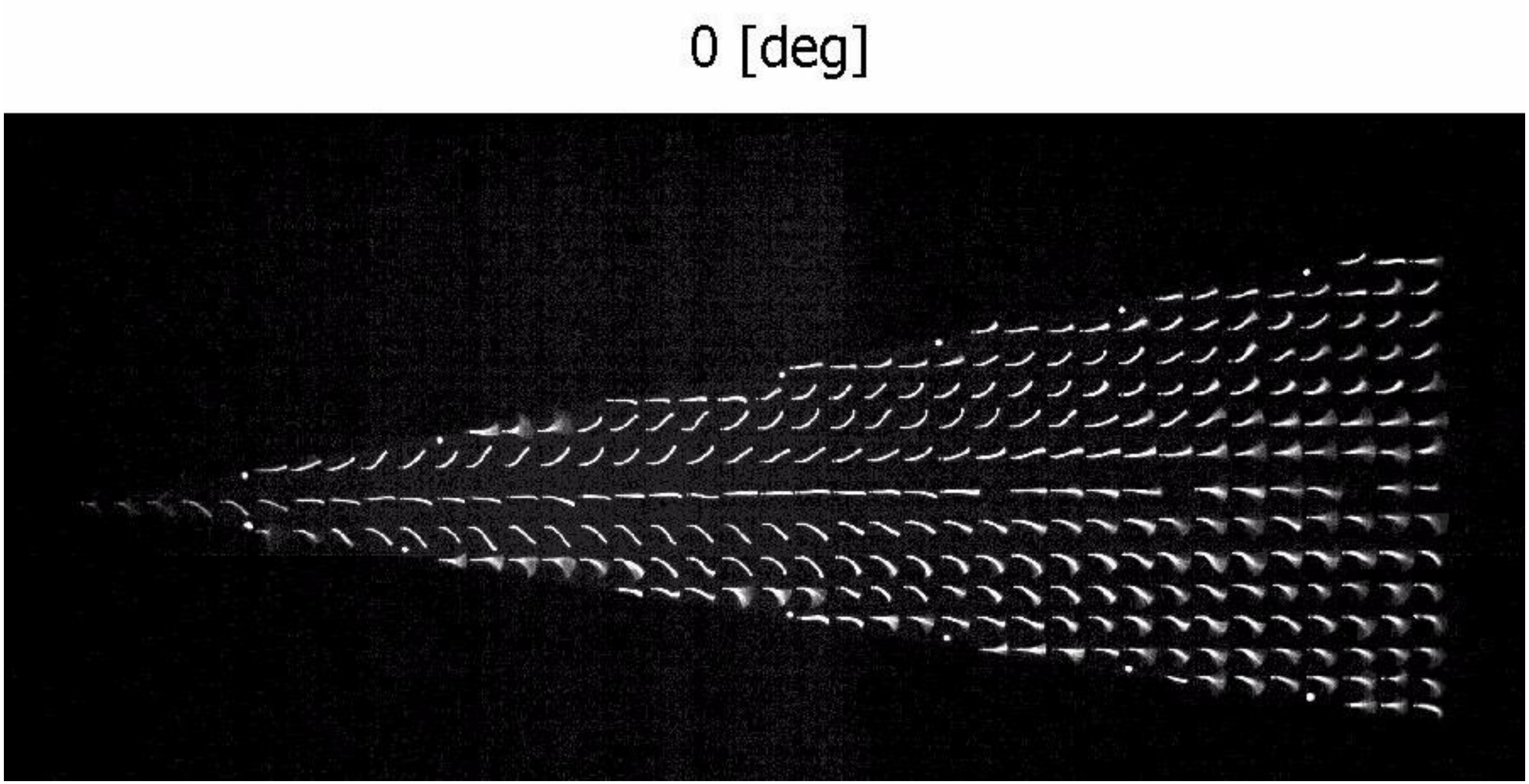


ϕ = 0 [deg]　**ϕ = 10 [deg]**　**ϕ = 20 [deg]**

Flow Visualization for dynamic model (3)

■ **Fluorescence minituft method**

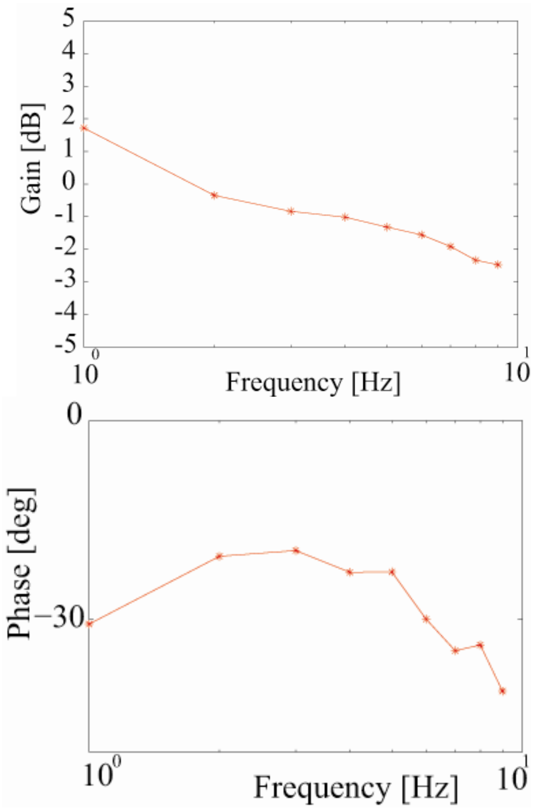
- Fluorescence monofilaments are glued to the model surface
- Flow direction and unsteady region on the model surface can be visualized



Phase lead compensation

■ PLC for the sensor delay

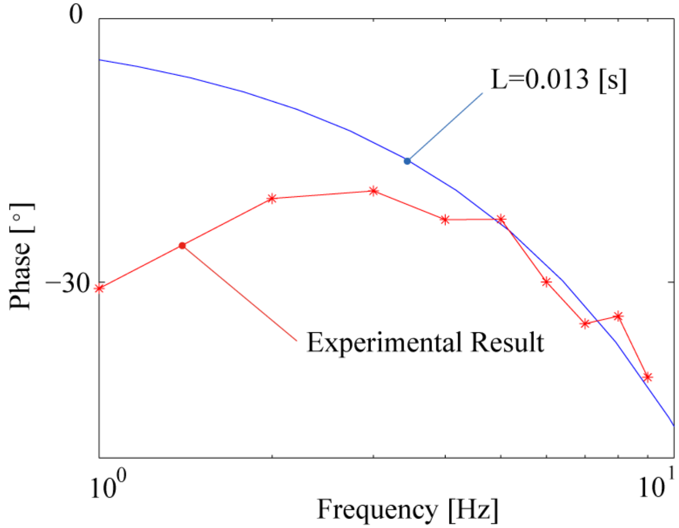
- Identifies from the Bode diagram of a force/torque sensor



Bode diagram

$$G(s) = e^{-Ls}$$

The transfer function of a dead time element



Curve fitting by a dead time element

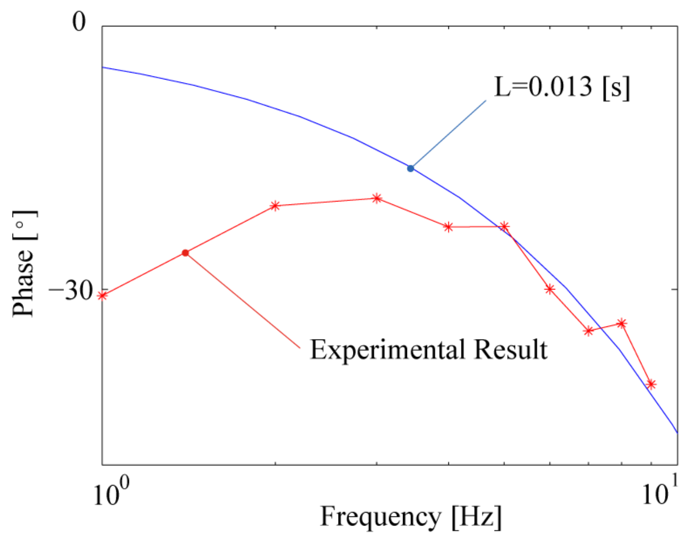
Phase lead compensation

■ PLC for the sensor delay

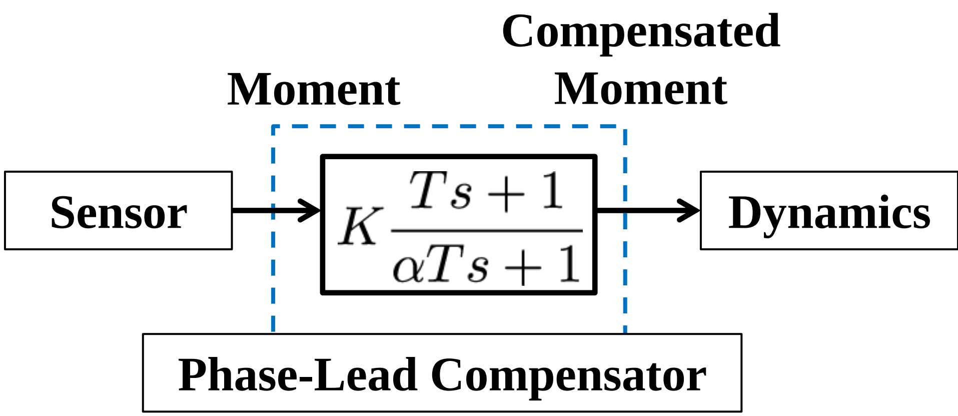
- Identifies from the Bode diagram of a force/torque sensor

$$G(s) = e^{-Ls}$$

The transfer function of a dead time element

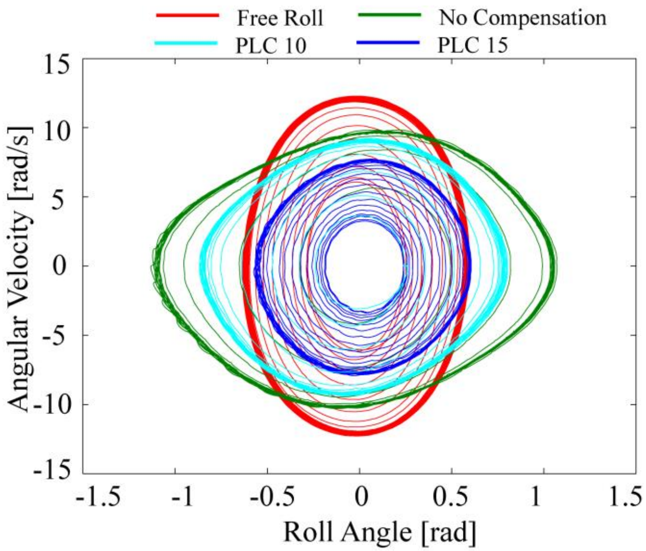


Approximation by a dead time element

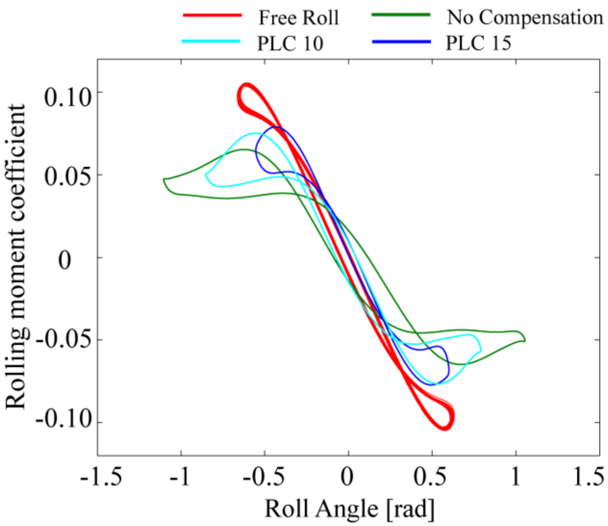


Phase lead compensation

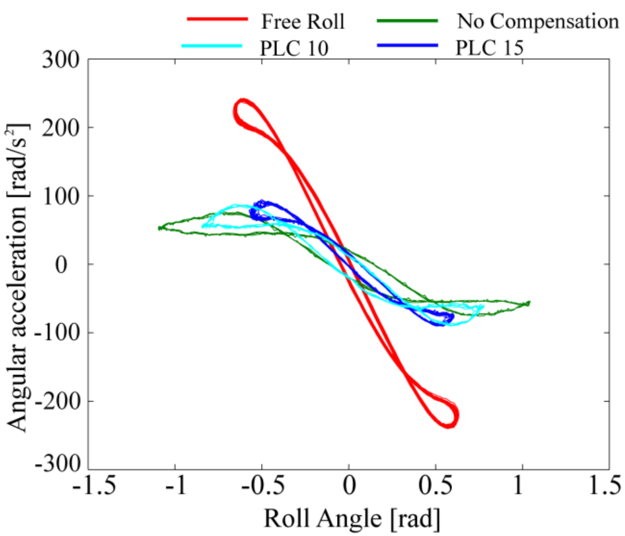
- **The PLC result of sensor delay**



Limit cycle



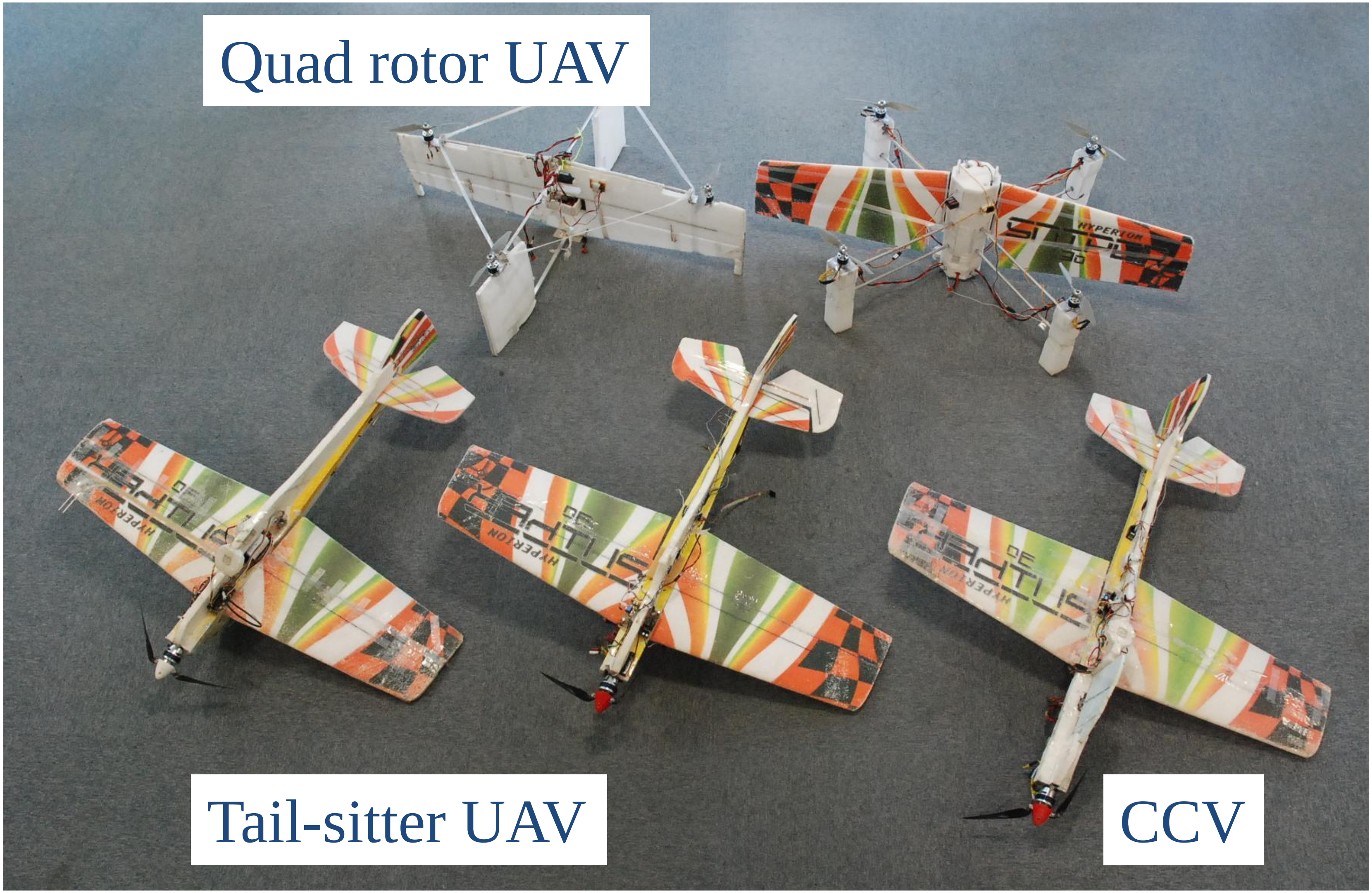
Rolling moment coefficient



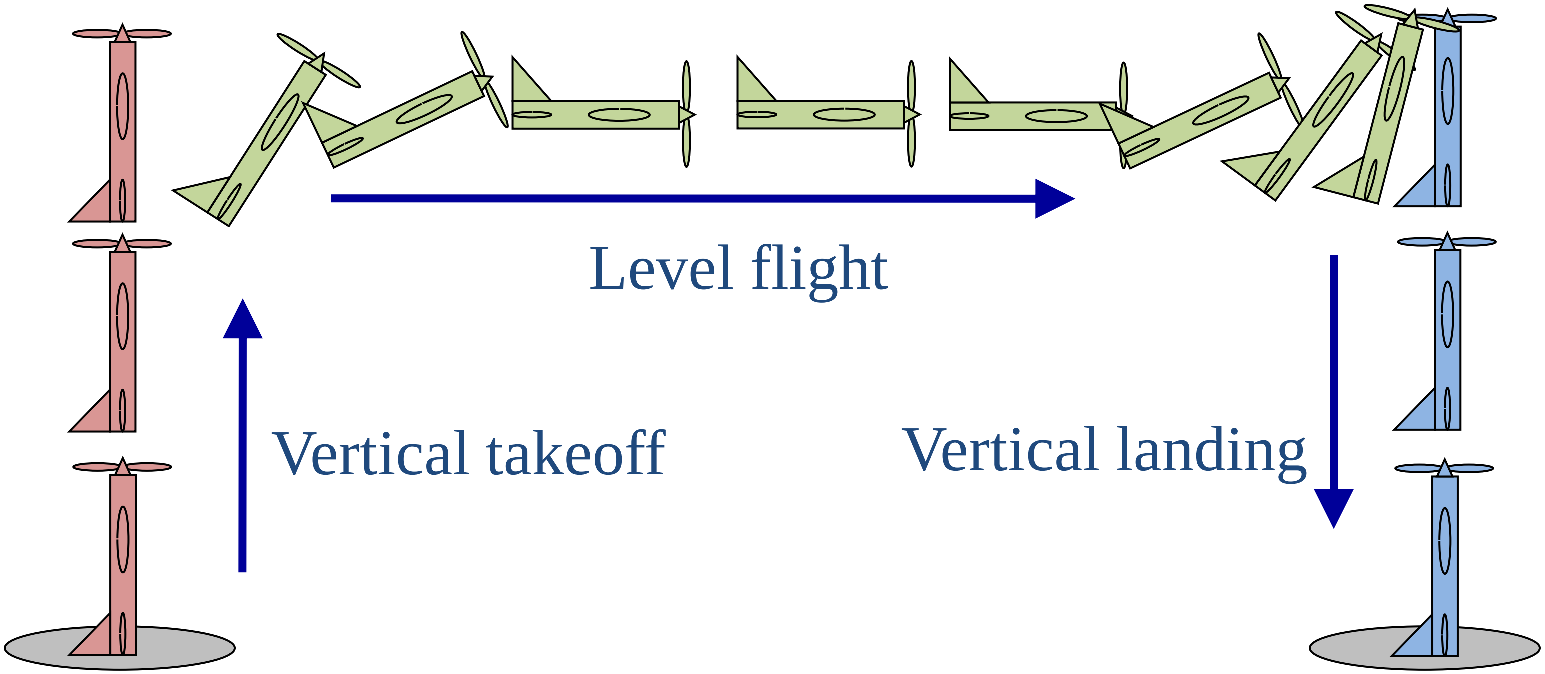
Angular acceleration

Unmanned Aerial Vehicle

UAVs developed in Uchiyama Lab.



Tail-Sitter VTOL UAV



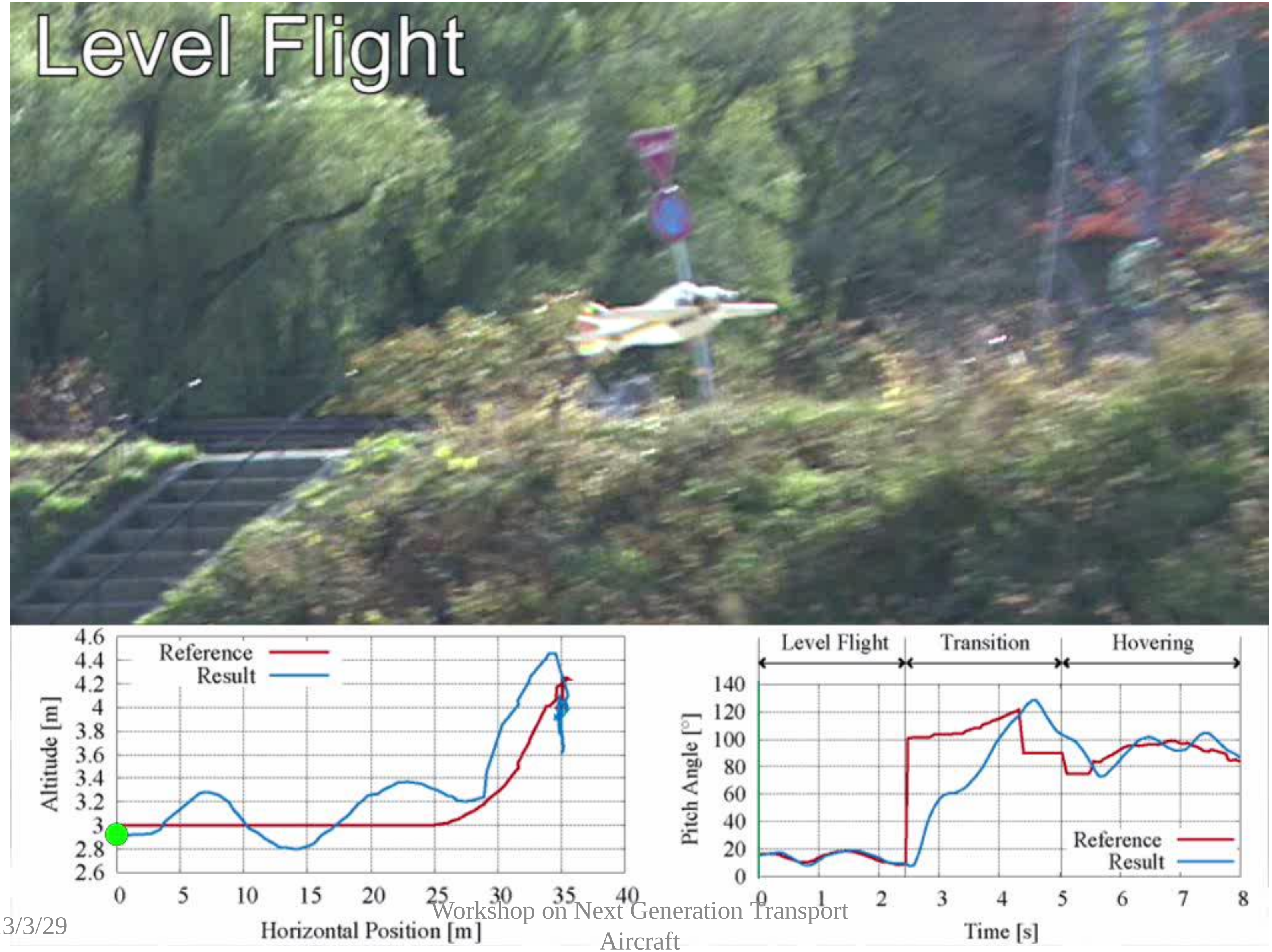
Advantages:

- Long range flight performance
- Simple mechanism

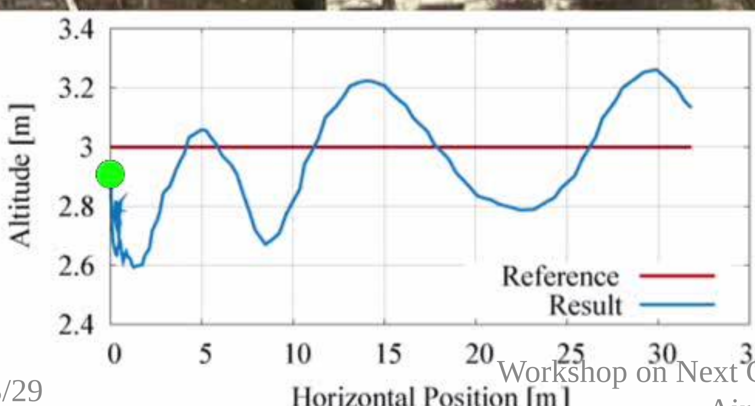
Disadvantages:

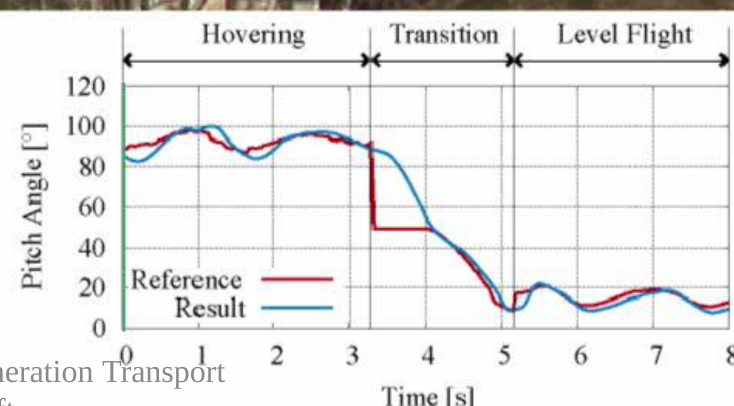
- Difficulty in canceling rotor reaction moment in vertical mode

Transition from Level Flight to Hovering

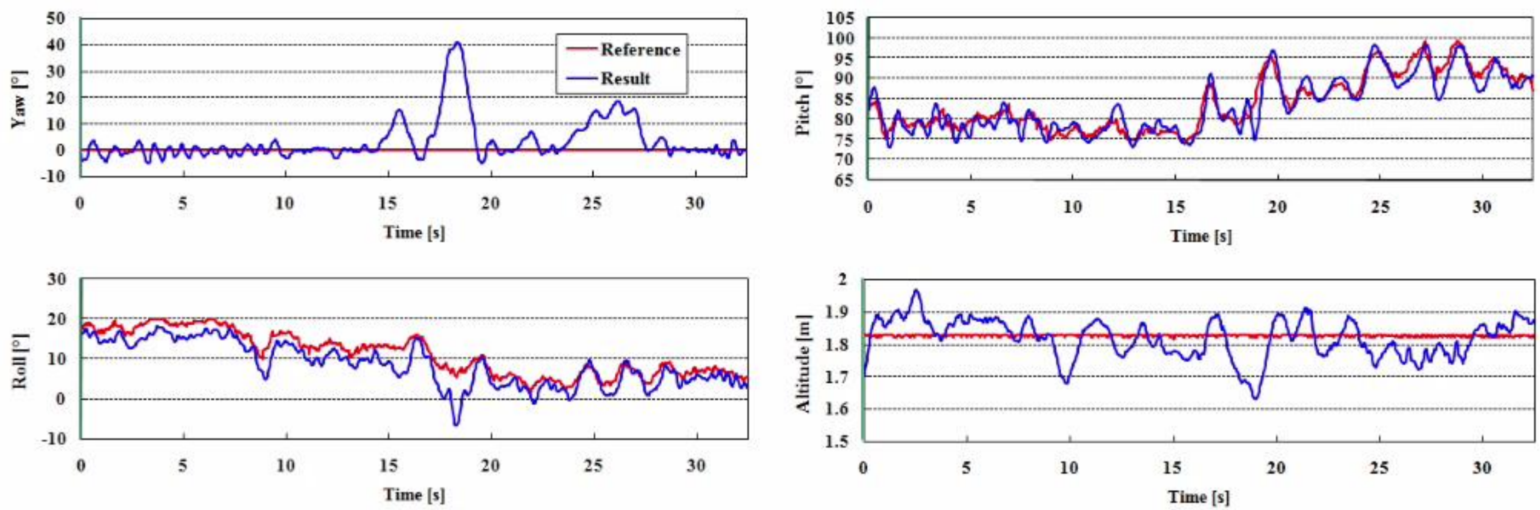


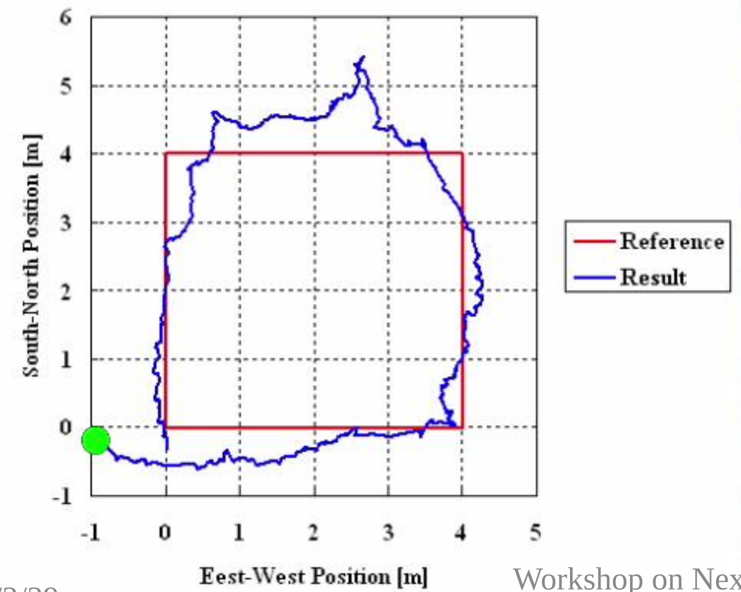
Transition from Hovering to Level Flight





Trajectory Tracking in Hover Mode





Post-stall Maneuver：Minimum distance turn

Post-stall Maneuver : Constant altitude turn

CCV (Control Configured Vehicle)

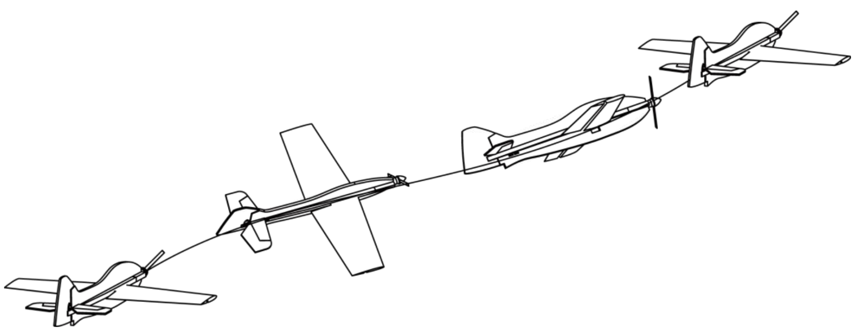
Advantages:

- Turn without rolling
- ultralow flying

Disadvantage:

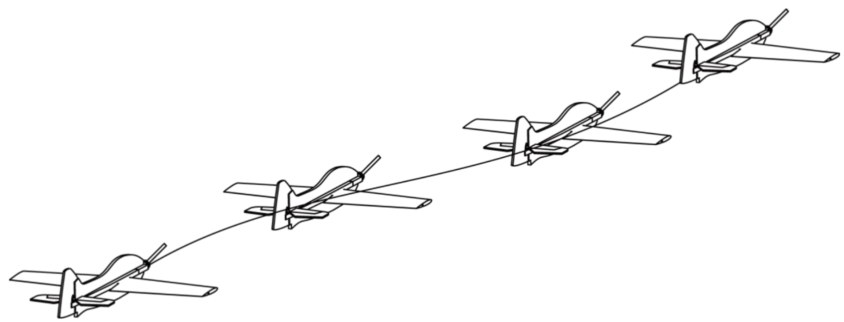
- Computer assist is absolutely imperative

Turn of general airplane



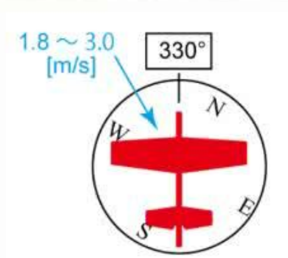
With rolling movement

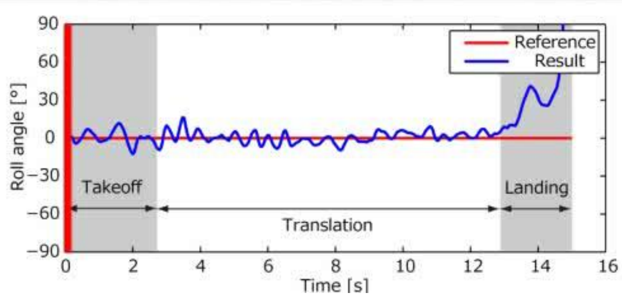
Turn of CCV

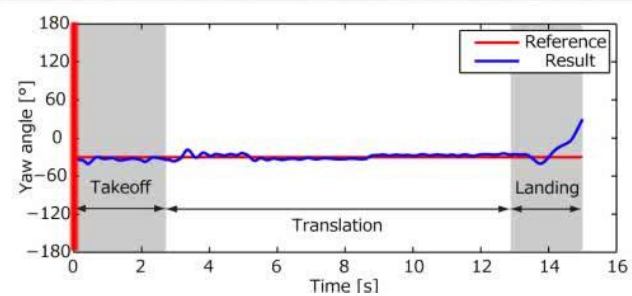


Without rolling movement

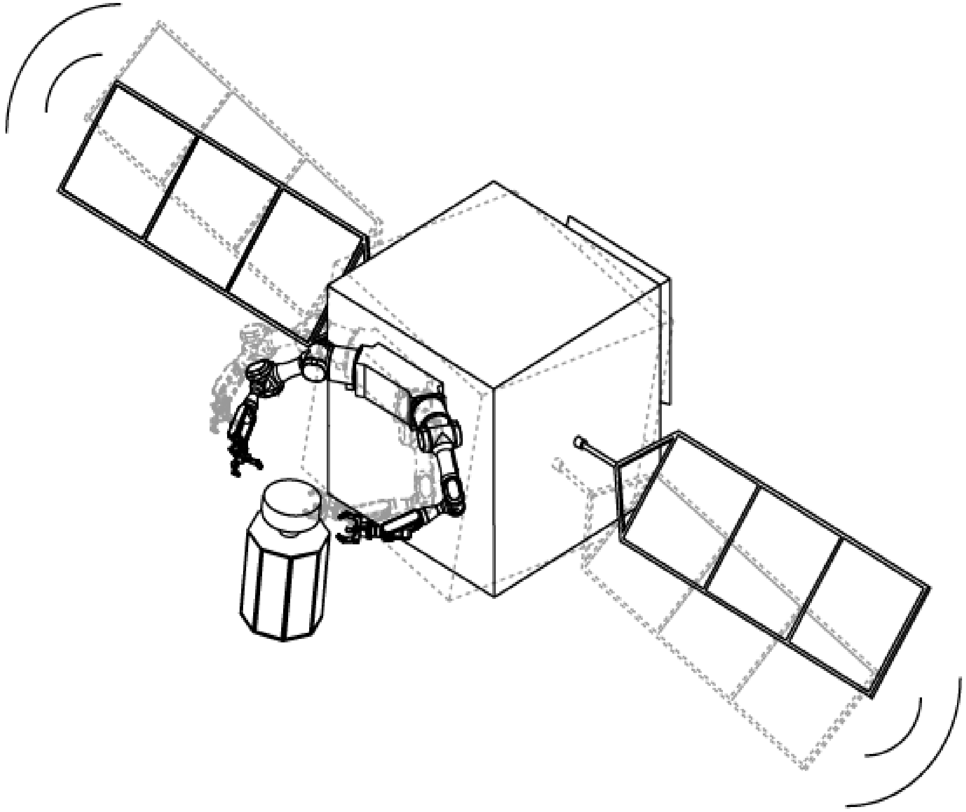
Lateral Translation Flight





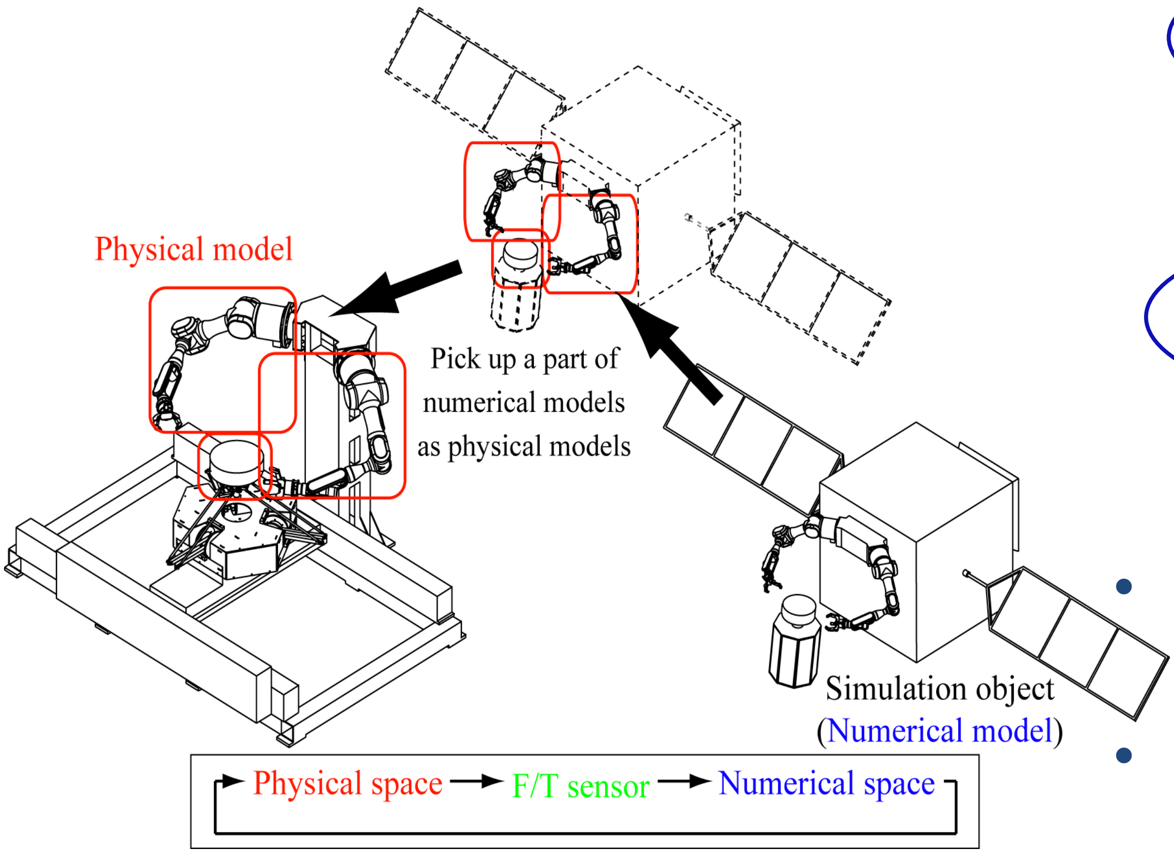


Free-Floating Space Robot



When the robot arm moves, the reaction force affects the attitude of the satellite.

Hardware-in-the-loop Simulator



Physical Model

+

Numerical Model

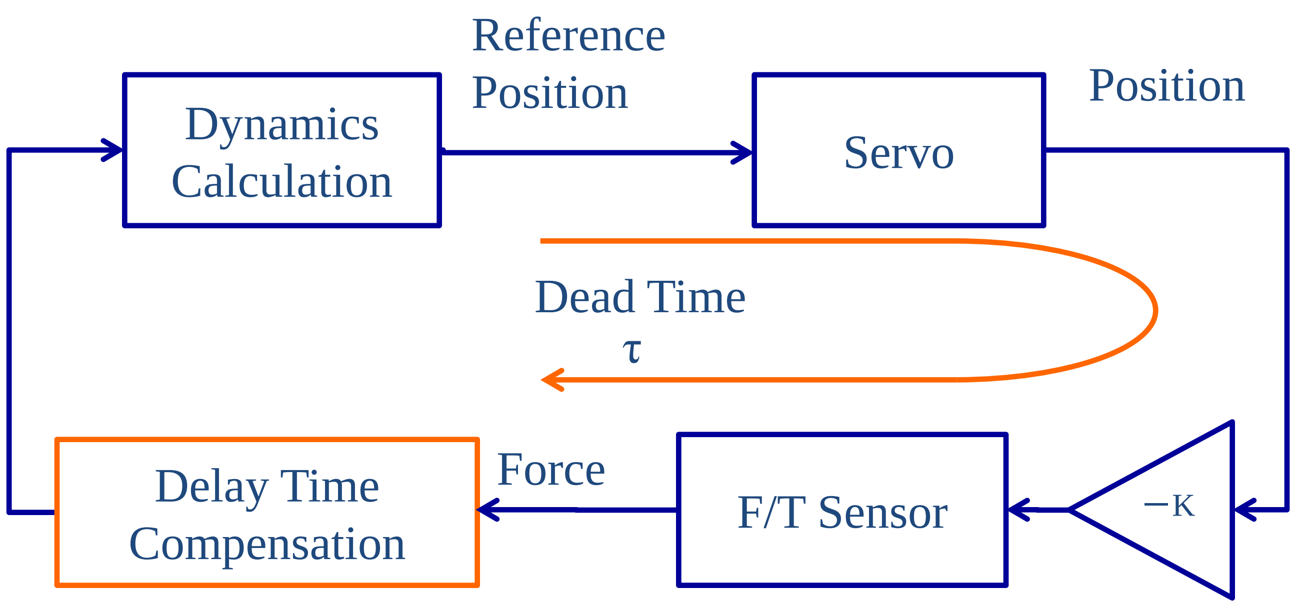
- Simulation on Ground for Space Application
- Precise Reproduction of Complicated Physical Phenomena

Problem in Hardware-in-the-loop Simulation

Time delay exists due to servo delay and low pass filter

Energy Increase during contact or impact

Instability of the system and unrealistic physical phenomena

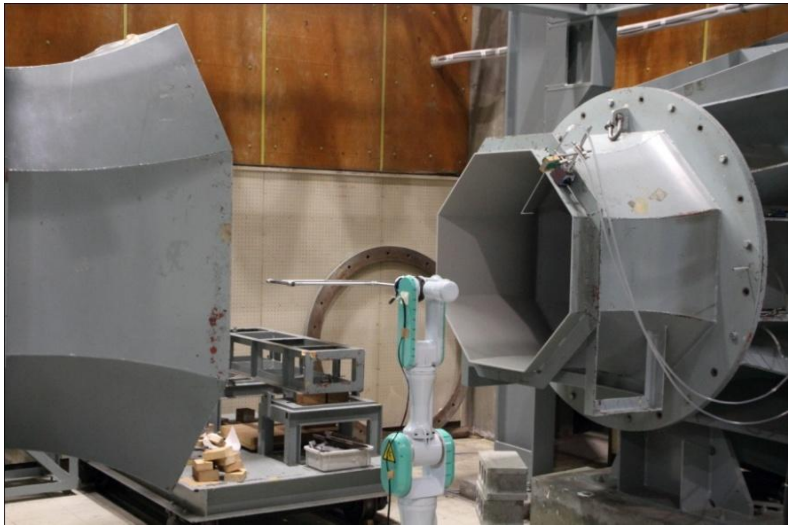


Delay time compensation based on the coefficient of restitution

Experimental Setup and Wind Tunnel

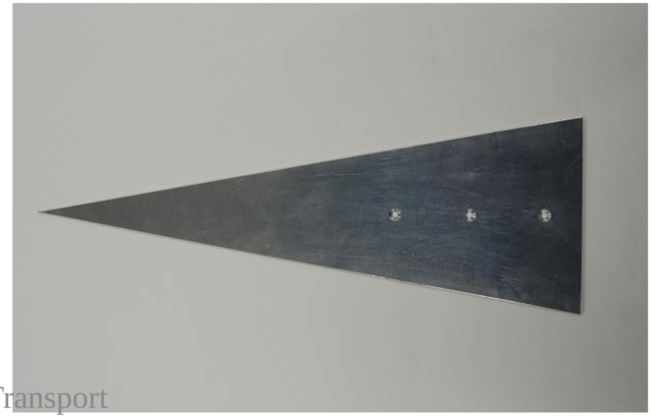
- **Low-Turbulence Heat-Transfer Wind Tunnel @Tohoku Univ.**

  Model : Single-path return-flow type
  Measurement section: open
  2nd nozzle opposite side distance: 0.81m
  Length: 1.42 m
  Flow speed: 5–70 m/s



- **Scaled airplane model: Delta Wing**

Sweepback angle	:	80 [°]
Chord length	:	300 [mm]
Thickness	:	2 [mm]
Leading edge	:	45 [°] sharp edge
Material	:	A2017 (Duralmin)



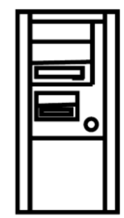
System Configuration

Physical Model

F/T Sensor

Numerical Model

Dynamics Calculation



$$F = m\ddot{x}$$
$$M = I\ddot{\theta}$$

Manipulator：

Servo Mechanism

Motion Demonstration

Verification of Hybrid Motion Simulator

Aerodynamic phenomena in uniaxis

- Wing Rock
- Damped Vibrations

WingRock Phanomena
©Asai/Nagai Lab@Tohoku Univ.

Conventional Method
Free motion around one axis by using bearing

Comparison ⇕ Nondimensional Frequency (Strouhal Number)

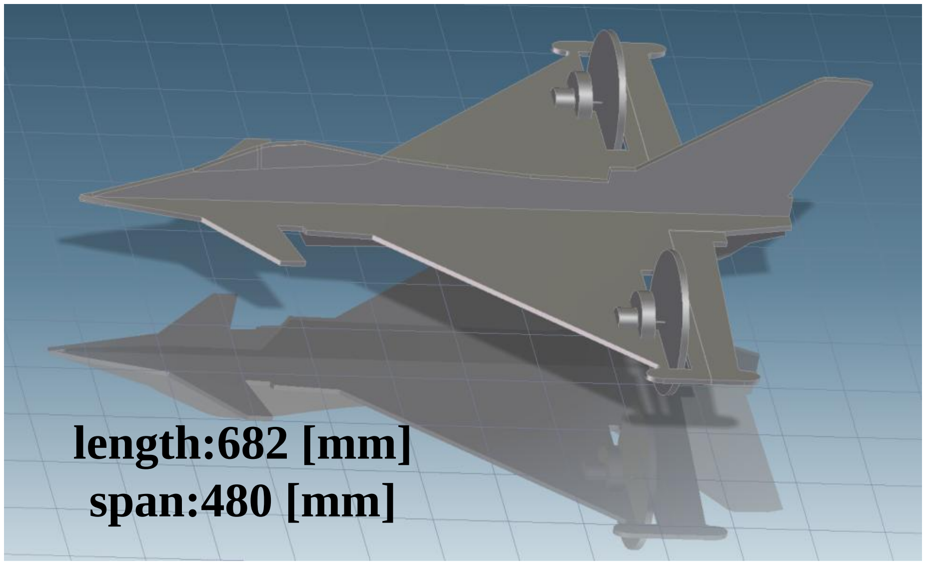
Proposed Method
Motion demonstrated by manipulator system

Damped Vibration Motion demonstrated by Hybrid Motion Simulation

Flight Test (2)

■R/C model

Propeller model



EDF(Electric Duct fan) model

■Get Flight Data

・Model Position

・Model attitude

・Velocity

⇨ **Gathering data from IMU & GPS**