System-Level Optimization and Validation of a Small Suborbital Launch Vehicle with Rocket and Jet Propulsion.

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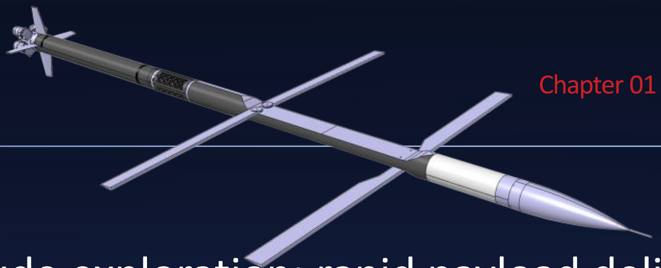
Outlines

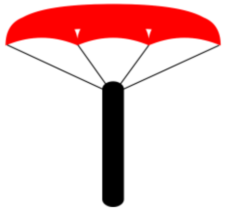
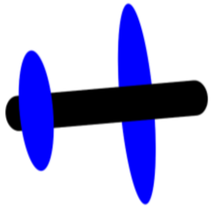
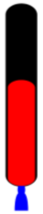
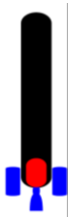
- Chapter 1: Motivation and Research Objective
- Chapter 2: Methodology and Validation Approach
- Chapter 3: Results and Discussion
- Chapter 4: Conclusion and Future Work

Chapter 1: Motivation and Research Objective

Motivation

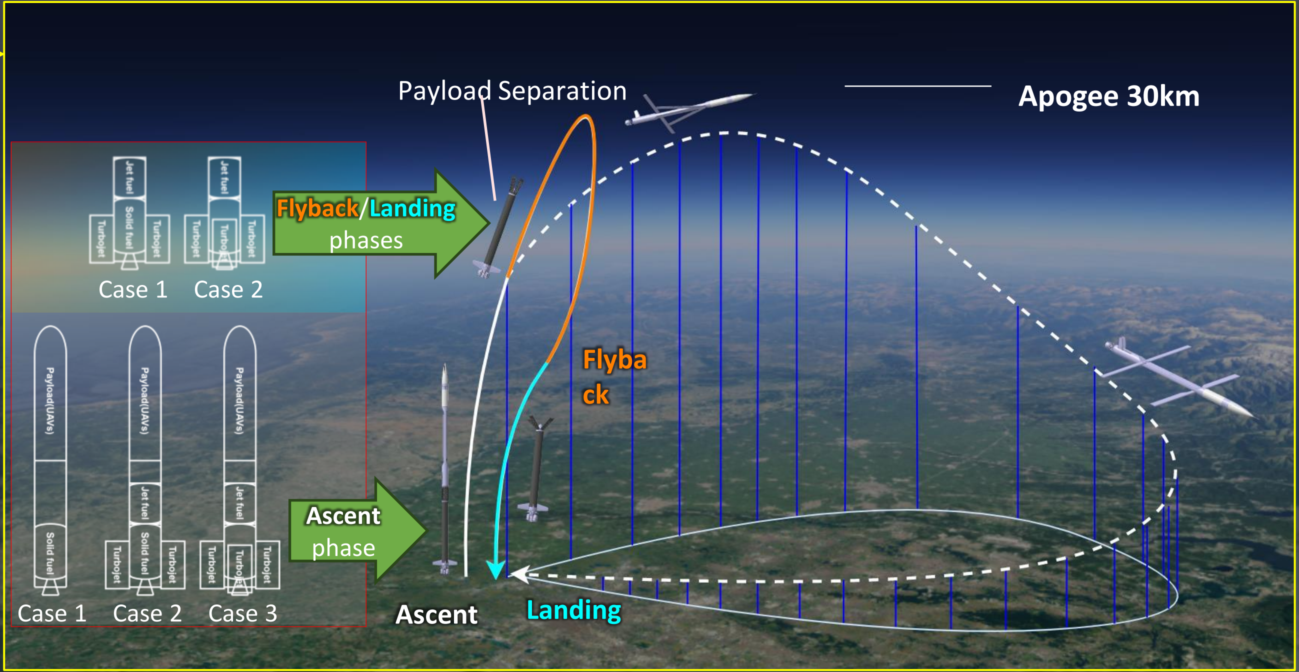


- **Small Suborbital Launch Vehicle**
  - Mission for microgravity experiments; high-altitude exploration; rapid payload delivery.
  - Benefits of reuse: repeatable operations; lower operating cost => sustainable high-altitude mission.
  - Reusable solutions:

	Unpowered Landing		Powered Landing		
	Parachute/Parafoil	Winged Gliding	Liquid Propellant	Hybrid Propellant	Solid Propellant +Turbojet Fuel
Recurring consumable & Recovery method					
Additional weight in ascent	Canopy	Wing	Fuel and oxidizer margin for landing	Fuel and oxidizer margin for landing	Fuel margin for landing
Landing facility	Landing zone	Runway	Landing pad	Landing pad	Landing pad
Recurring consumables	Chute repack	-	-	Reinstall solid fuel	Reinstall solid fuel

Research Objective

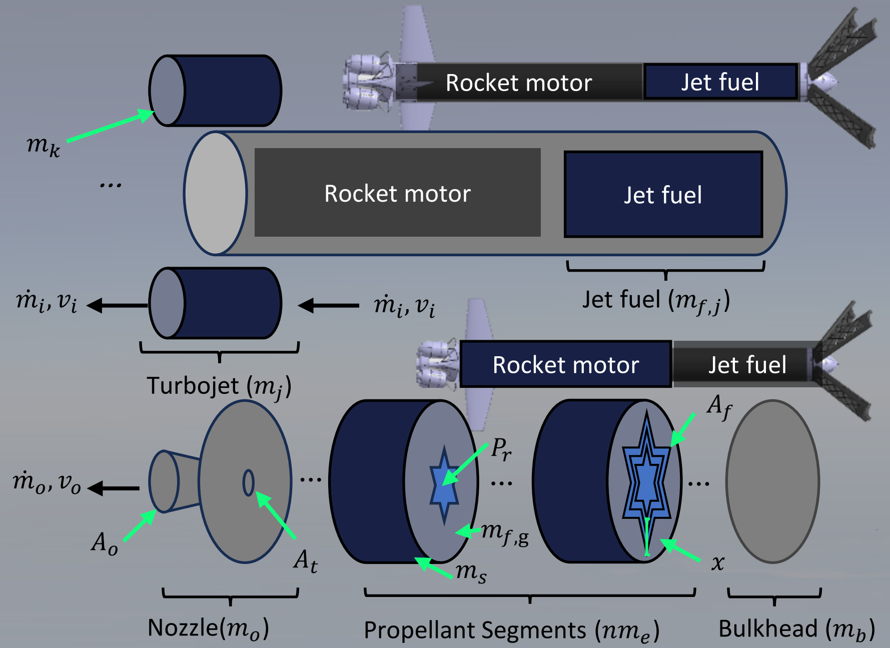
- Rocket and Turbojets Propulsion.
  - Air-breathing turbojet → less onboard oxidizer.
  - Low thrust-to-weight(TWR) → gravity losses.
  - Solid rocket booster has high TWR → cover turbojet's disadvantage.
- Constraints
  - Optimize trajectory to gain required momentum in dense air.
  - Strong nonlinearity and coupling disrupt optimization of rocket and turbojet scale, control law.
- Prior works
  - Simulation-based SQP used to avoid local-minima and optimize configuration.
  - Limitation: simplified motion; fixed controller gains; unverified under model mismatch.
- System-Level Optimization and Validation
  - Goal: co-optimize controller gain and hardware configuration.
  - This study performs 6DoF SQP controller optimization and verifies under model mismatch.

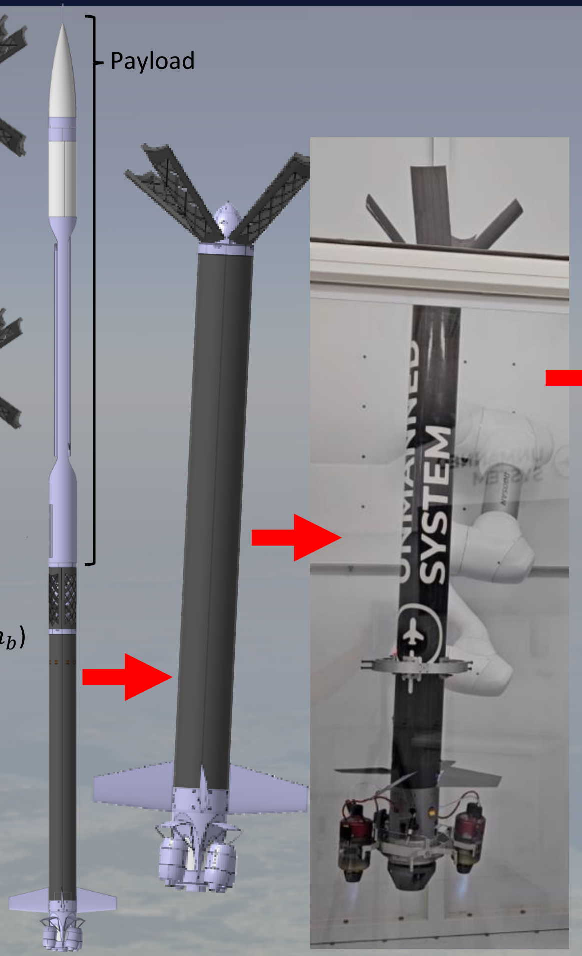


Chapter 2: Methodology and Validation Approach

Methodology

- System-Level Manipulate Variables(Prior study)





Turbojets Thrust

$F_j = l \times F_k$

Rocket Thrust

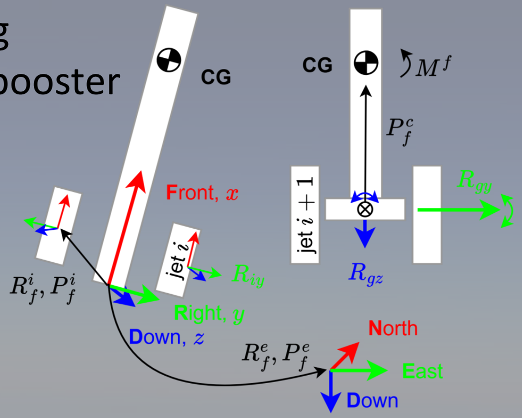
$F_r = n \times \dot{m}_f v_o$

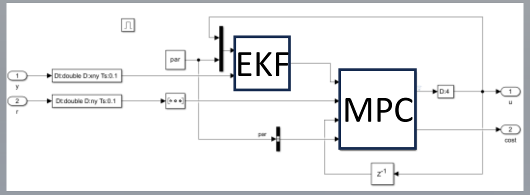
Optimization parameters for system

Parameter	Description.
l [-]	Number of turbojets
n [-]	Propellant segment factor (number)
$m_{f,j}$ [kg]	Jet fuel mass
m(0) [kg]	Initial vehicle mass (cost)

- Controller weights(This study)

- Precision landing
- Without rocket booster





Manipulated Variables(MV)

$u_k = [g_x, g_y, g_z, T]^{\mathrm{T}}$

Output Variables (OV)

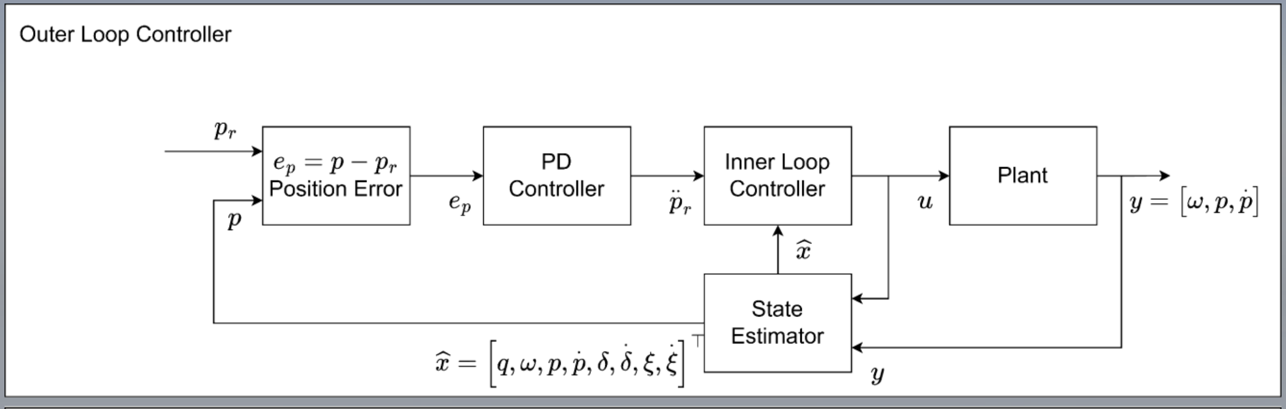
$y_k = [\omega, p, \dot{p}]^{\mathrm{T}}$

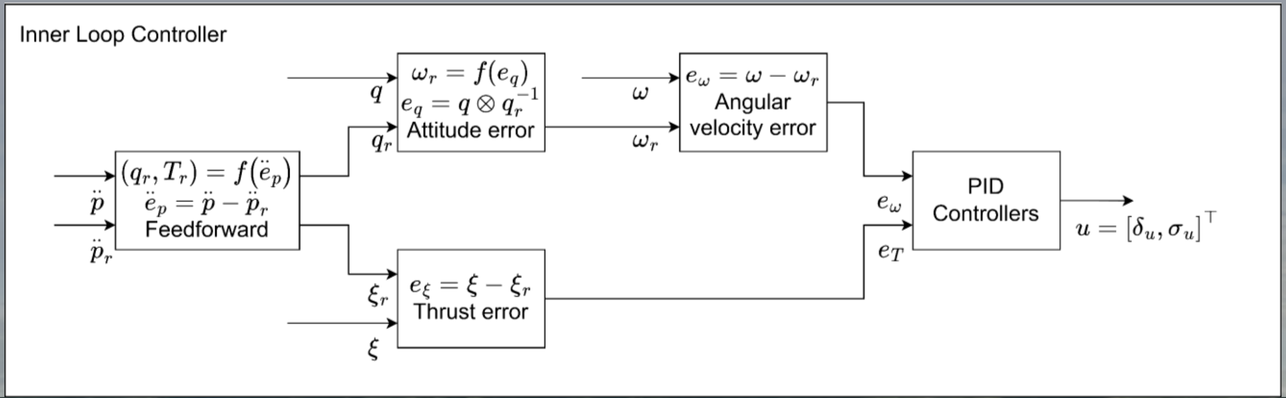
Optimization parameters for controller

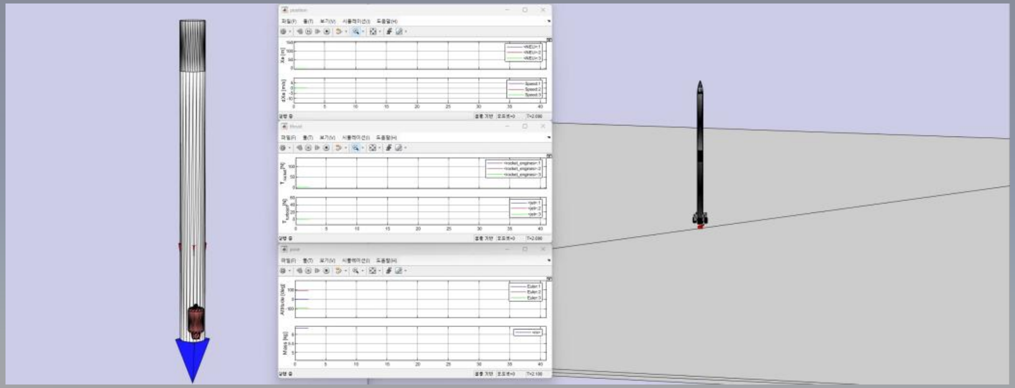
Parameter	Description.
W_o [-]	OV weights
W_M[-]	MV weights
$V(y, y_r)$	Cost function

Methodology

- Controller Design
  - PID controller(Prior study)
    - Outer-loop PD generates reference acceleration
    - Feedforward + PID computes gimbal angles and thrust

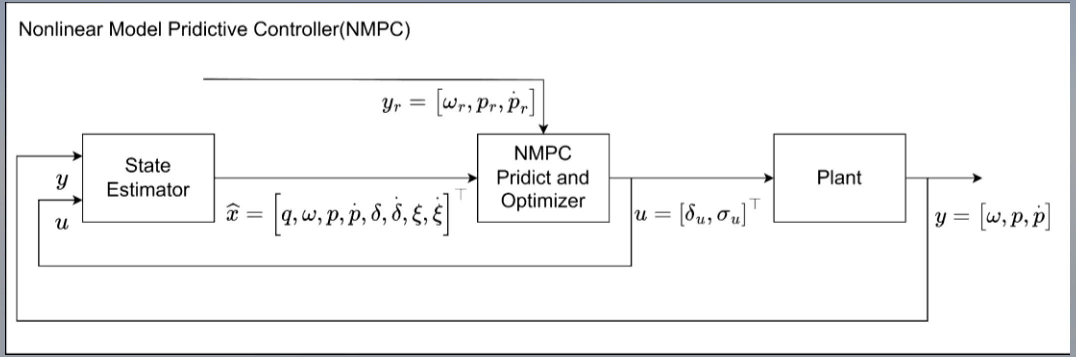






- Simulation result
  - Stable tracking
- Experiment(landing phase)
  - Oscillation under backlash & rate limits
- Optimize hardware -> configuration changed -> gain tunning lack guarantees.

- Controller Design
  - Nonlinear model predictive controller(NMPC)
    - Enforce constraints
    - Improve robustness to model-plant mispatch



  - Predict model

$$x_{k+1} = f(x_k, u_k)$$
$$y_k = h(x_k)$$

  - Model states

$$x = [q\ \omega\ p\ \dot{p}\ \delta\ \dot{\delta}\ \xi\ \dot{\xi}]^\top, \qquad u = [\delta_u\ T_u]^\top$$
$$y = [\omega\ p\ \dot{p}]^\top$$

  - Control objective

$$\min_{u_k} \sum_{k=0}^{N_p-1} \left(\|y_k - y_{r,k}\|_{W_O}^2 + \|u_k\|_{W_M}^2 + \|\Delta u_k\|_{W_{M,\Delta}}^2 \right)$$

  - Tunning objective in this study

$$W \in \{W_O, W_M, W_{M,\Delta}\}$$

    - The prediction horizon N_p was manually tuned (timing profile) to meet 10 Hz; fixed during optimization.

State	Description.
q	Unit quaternion (rotation FRD to NED frame) [-]
ω	Angular rate in FRD. [rad/m]
$p, \dot{p}$	Position and velocity in NED [m, m/s]
$\delta, \dot{\delta}$	Gimbal deflection and rate in FRD [rad, rad/s]
$\xi, \dot{\xi}$	Turbojets throttle state and rate (scalar) [-]
δ_u, T_u	Gimbal and thrust command [rad, N]

- Controller Design
  - Rigid-body model
    - Translational dynamics

$$\ddot{p} = g_0 + \frac{1}{m} R_f^e(q) F^f$$

$$g_0 = [0\ 0\ 9.8]^{\mathsf{T}}$$

    - Rotational dynamics

$$\dot{q} = \frac{1}{2} \omega \circ q, \qquad \dot{\omega} = J^{-1} M^f$$

    - Actuator dynamics

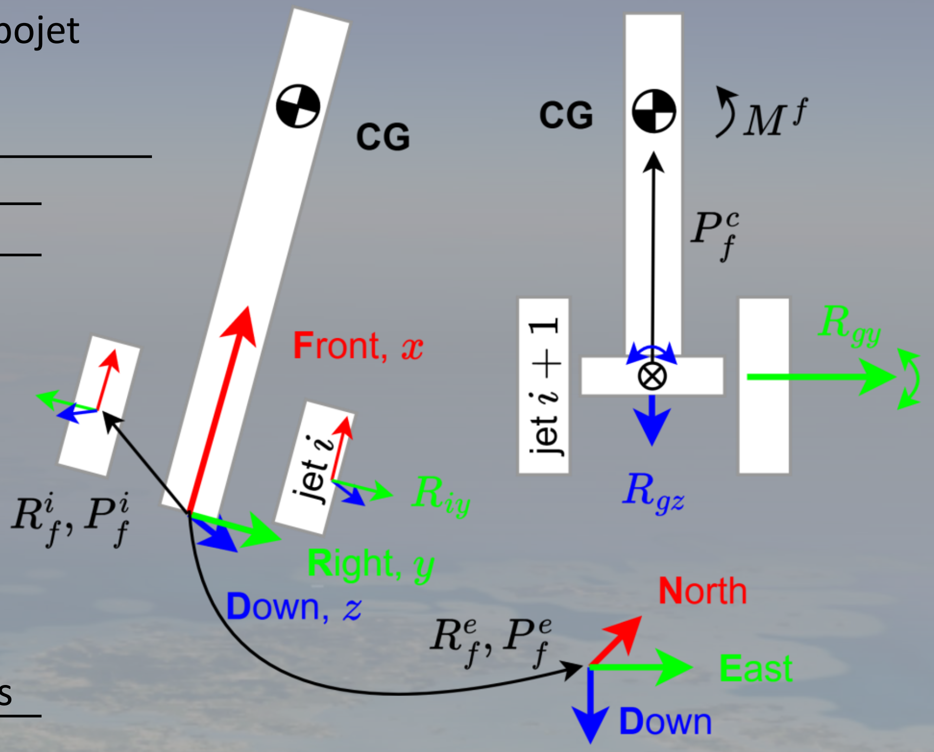
$$F^f = \sum_{i=1}^{n} R_i^f F^i + F_D^f, \ \ F^i = [T\sigma_i, 0, 0]^{\mathsf{T}}$$

$$M^f = \sum_{i=1}^{n} P_c^i \times F^i + M_D^f$$

where disturbances F_D^f and M_D^f including aerodynamics assumed 0.

Index	Description.
f	Body-fixed frame
e	Earth-fixed NED frame
i	Local frame of i^{th} Turbojet
c	Center of gravity
δ	Gimbal for TVC

Symbol	Description.
P	Position vector
R	Rotational matrix
F	Force vector
M	Moment vector
T	Max thrust
σ	Throttle fraction
J	Inertia matrix
m	mass
n	number of Turbojets



- Controller Design
- Gimbal model

$$R_i^f = R_{\delta y}^f(\delta_y) R_{\delta z}^{\delta y}(\delta_z) R_{iy}^{\delta z}(\delta_{i,x})$$
$$\ddot{\delta} = J_\delta^{-1}(k_p e_\delta - k_d \dot{\delta})$$
$$\delta = [\delta_x\ \delta_y\ \delta_z]^{\mathrm{T}}$$

where $\delta_r = [\delta_{r,x} \delta_{r,y} \delta_{r,z}]^{\mathrm{T}}$ is input δ_u, $J_\delta^{-1} = diag(J_{iyy}, J_{\delta yy}, J_{\delta zz})$ denote gimbal moment of inertia, and k_p, k_d denote gimbal servo PD gains

- Turbojet model

$$\sigma_i = \frac{e^{k_1 \xi_i} - 1}{e^{k_1} - 1}$$
$$\ddot{\xi}_i = k_2\left(\frac{T_u n}{T} - \sigma_i\right) - k_3 \dot{\xi}_i$$

where k_1, k_2, and k_3 represent turbojet turbine coefficients

Index	Description.
f	Body-fixed frame
e	Earth-fixed NED frame
i	Local frame of i^{th} Turbojet
c	Center of gravity
δ	Gimbal for TVC

Symbol	Description.
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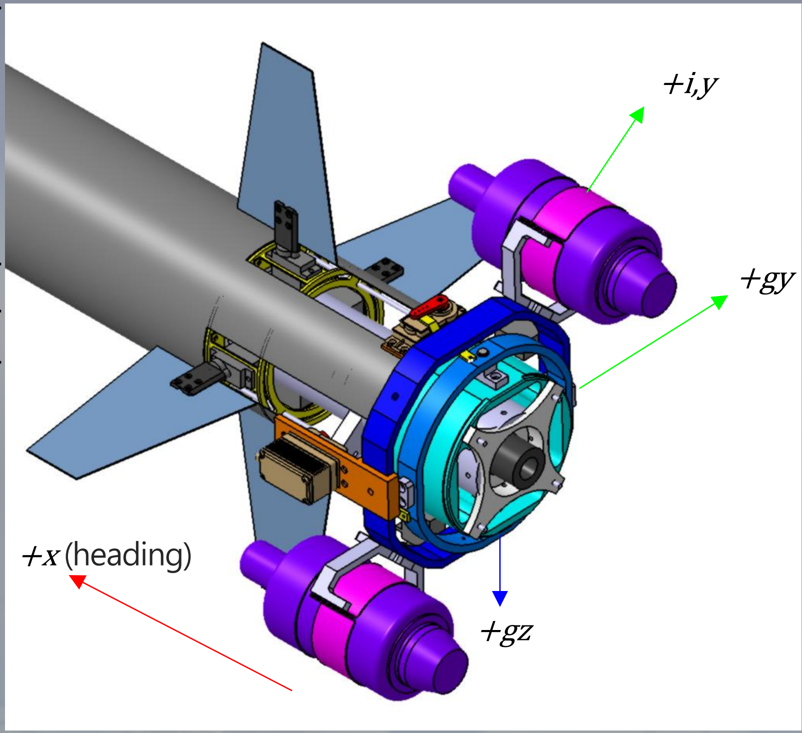


- Extended Kalmal Filter (EKF)

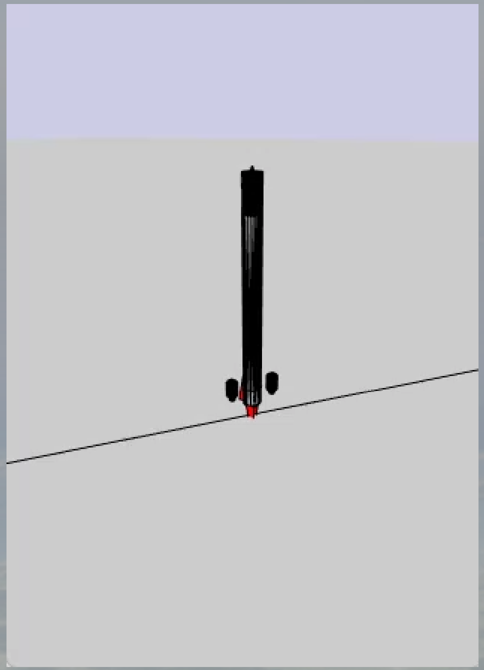
- Model mismatch
  - From gimbal model,

$$\ddot{\delta} = J_{\delta}^{-1}\left(k_p z(e_\delta) = -k_d \dot{\delta}\right)$$

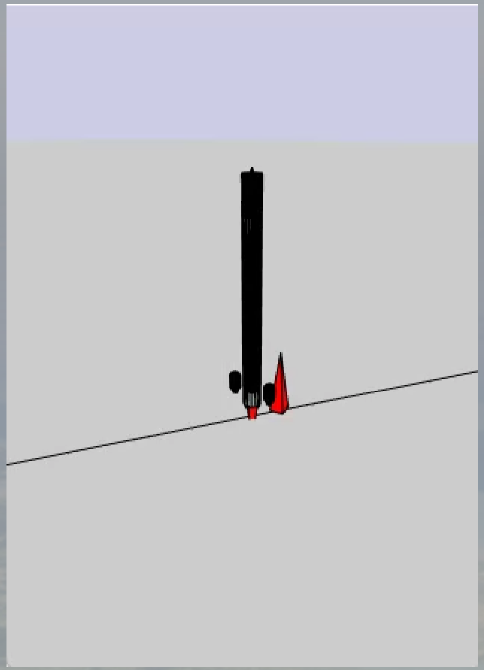
where $z(e_\delta) = DeadZone(e_\delta, d)$, d represent dead zone width.

- Extended Kalmal Filter (EKF)
  - If simulation model's $d > 0$: model mismatch
  - EKF with mismatch in state model: Control failure
  - NMPC prediction model using $z(e_\delta)$: loose of real-time feasibility
  - Solution: $d > 0$ in EKF, simplified $d = 0$ in NMPC

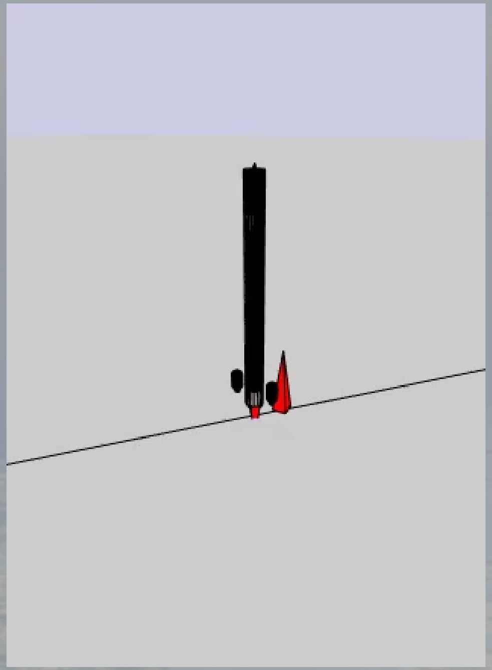
Same NMPC weights



Ideal model(MPC, EKF)



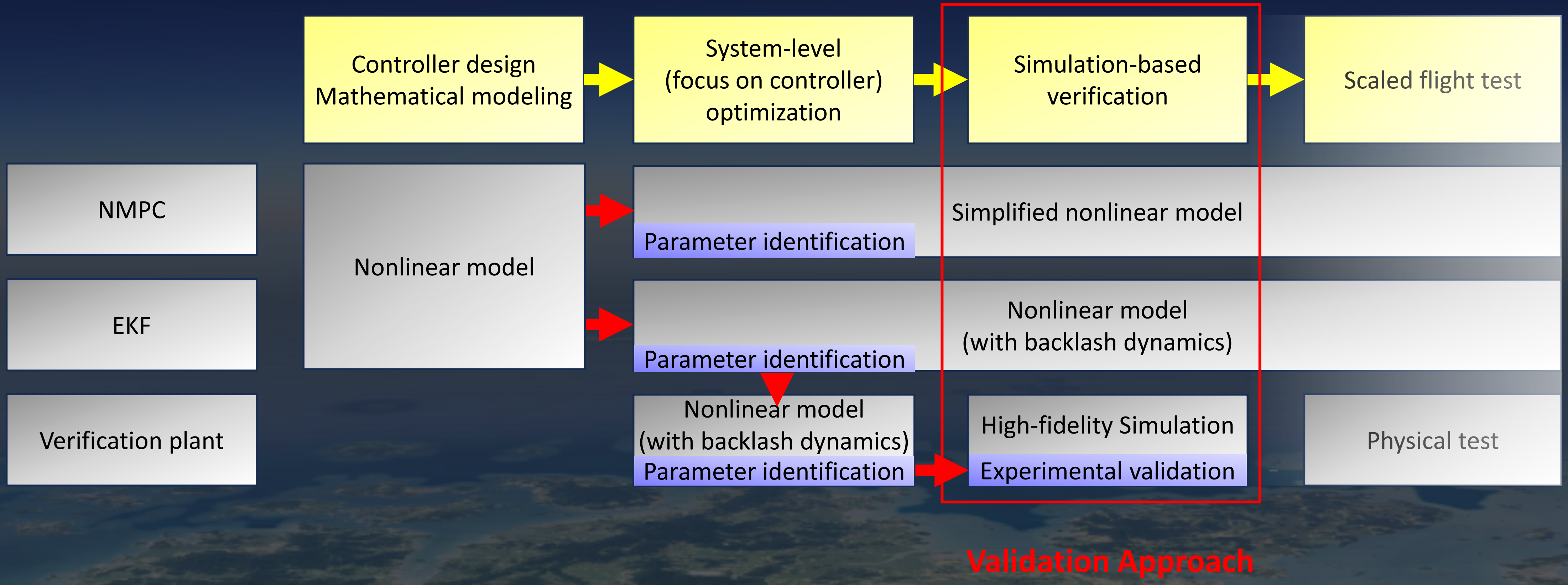
MPC, EKF Model mismatch



MPC Model mismatched

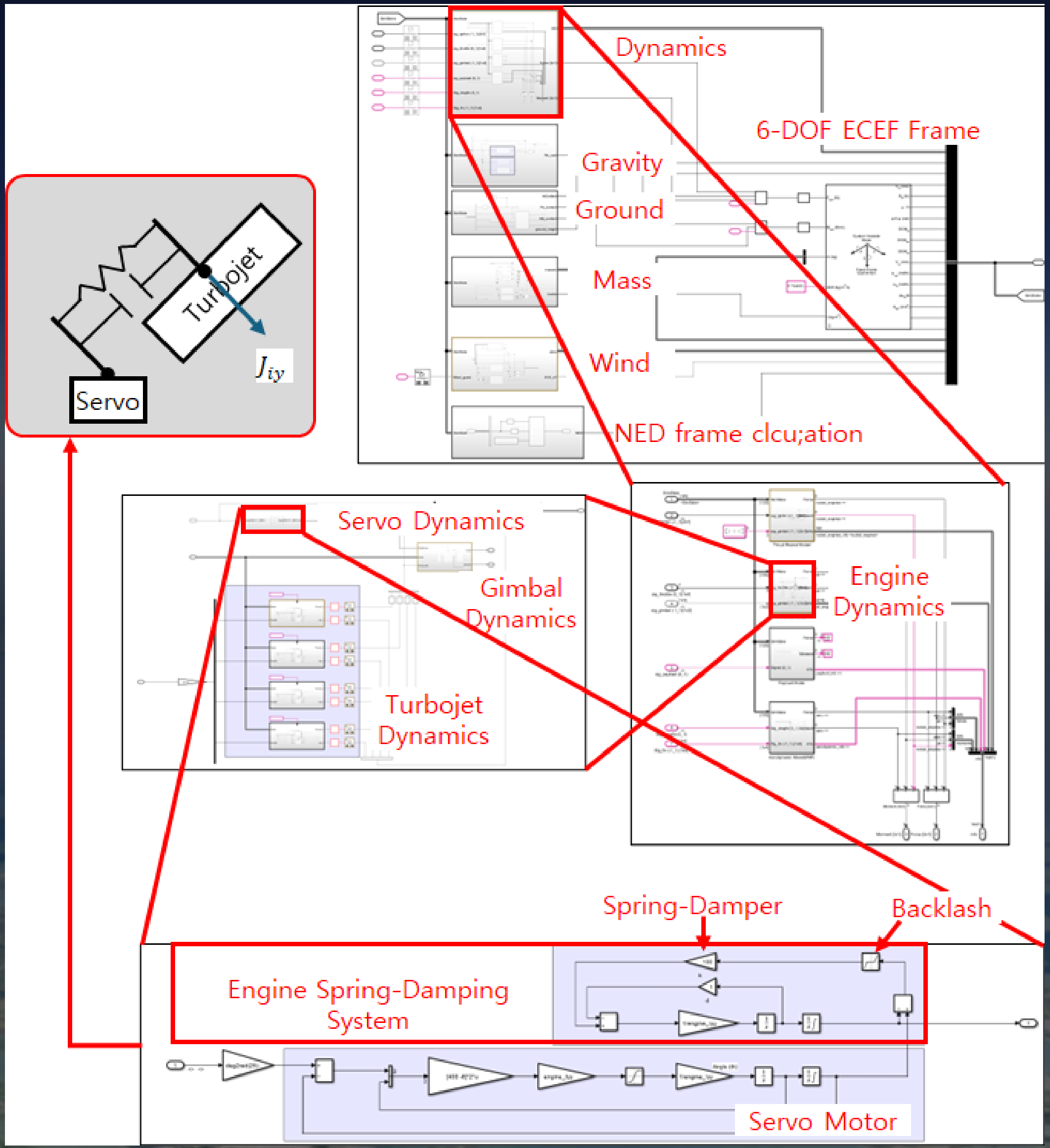
Validation Approach

- High-fidelity simulation for controller verification
  - Experimentally identified parameters, validated models



Validation Approach

- High-fidelity simulation for controller verification
  - ECEF coordinate based simulation
  - Gimbal reaction torque
  - Aerodynamic forces
  - Wind disturbance
  - Additional sate for gimbal spring-damping system →
  - Turbojet performance modeled as a nonlinear function
    - Air density, Mach number.
  - Variable mass, moment of inertia and CG due to fuel consumption.

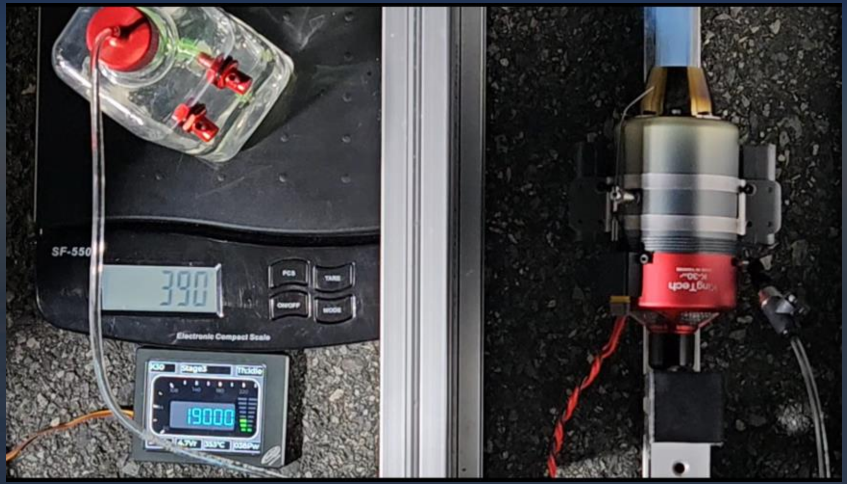


Chapter 3: Results and Discussion

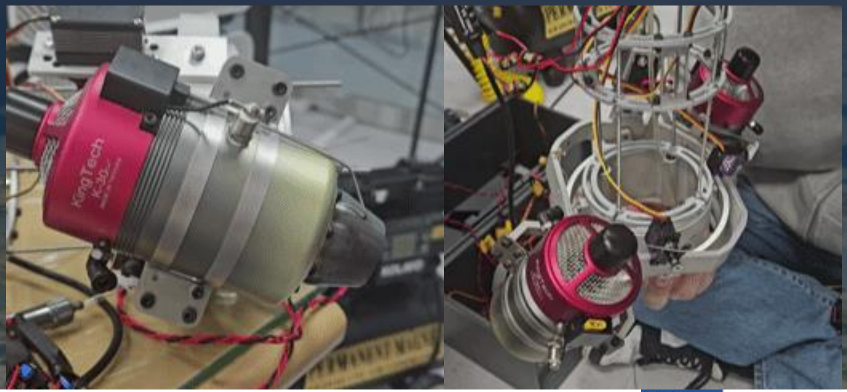
Parameter identification

- Rigid body model experiment
  - Mass (m) and moment of inertia (J_{iyy}, J_{xx}, J_{yy})
  - Center of gravity Position (P_f^c)

- Turbojet model experiment
  - Maximum thrust(T), fuel consumption ($\dot{m}_f$)
  - Turbojets turbine coefficients (k_1, k_2, k_3)



- Gimbal model experiment
  - Gimbal moment of inertia ($J_{\delta xx}, J_{\delta yy}$)
  - Gimbal servo PD gains (k_p, k_d)
  - Backlash width (d)
  - Saturation angles, spring damper paratmers



Parameter identification

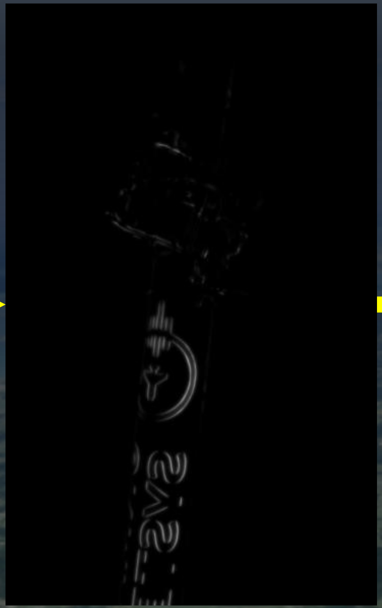
- Rigid body model experiment
  - Bifilar pendulum method

$$J = \frac{m g_0 b^2 T^2}{16\pi^2 L}$$

where b [m] denote distance between rope, L [m] represent length of rope, and T [s] denote oscillation period.

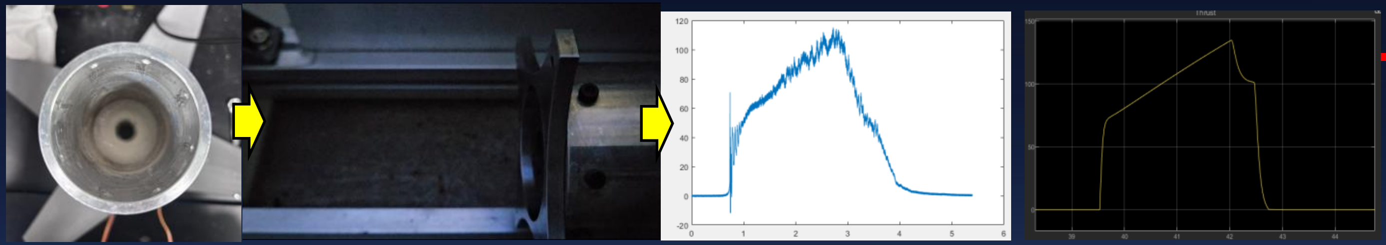
- Oscillation period

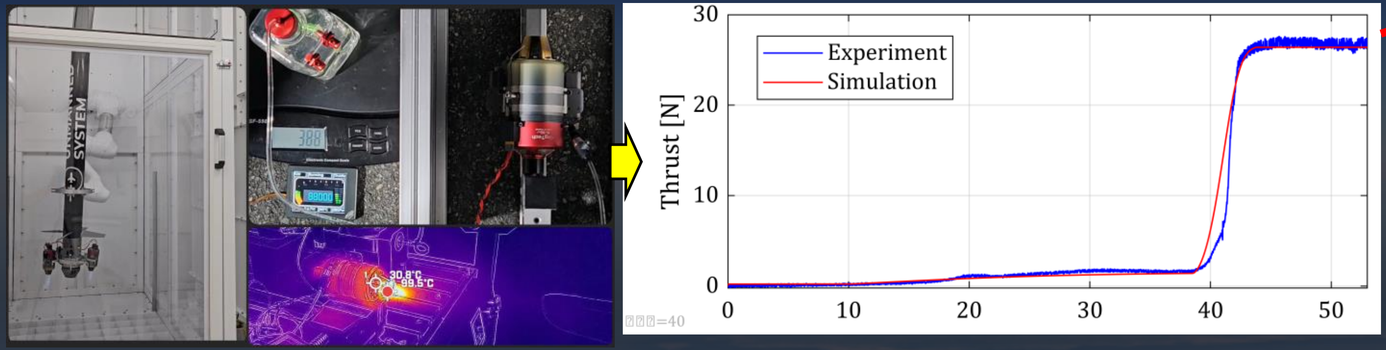
Optical flow

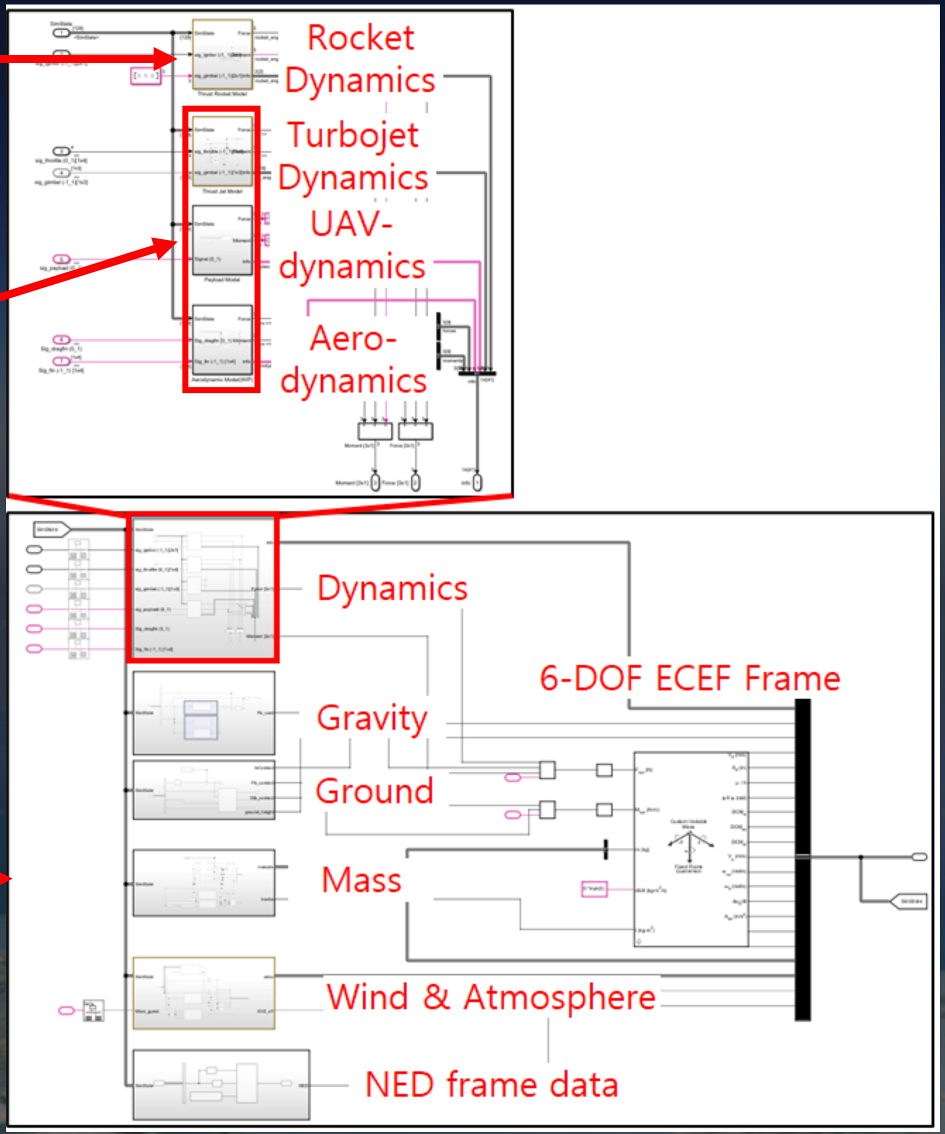


Sum &
FFT analysis

Experimental Validation



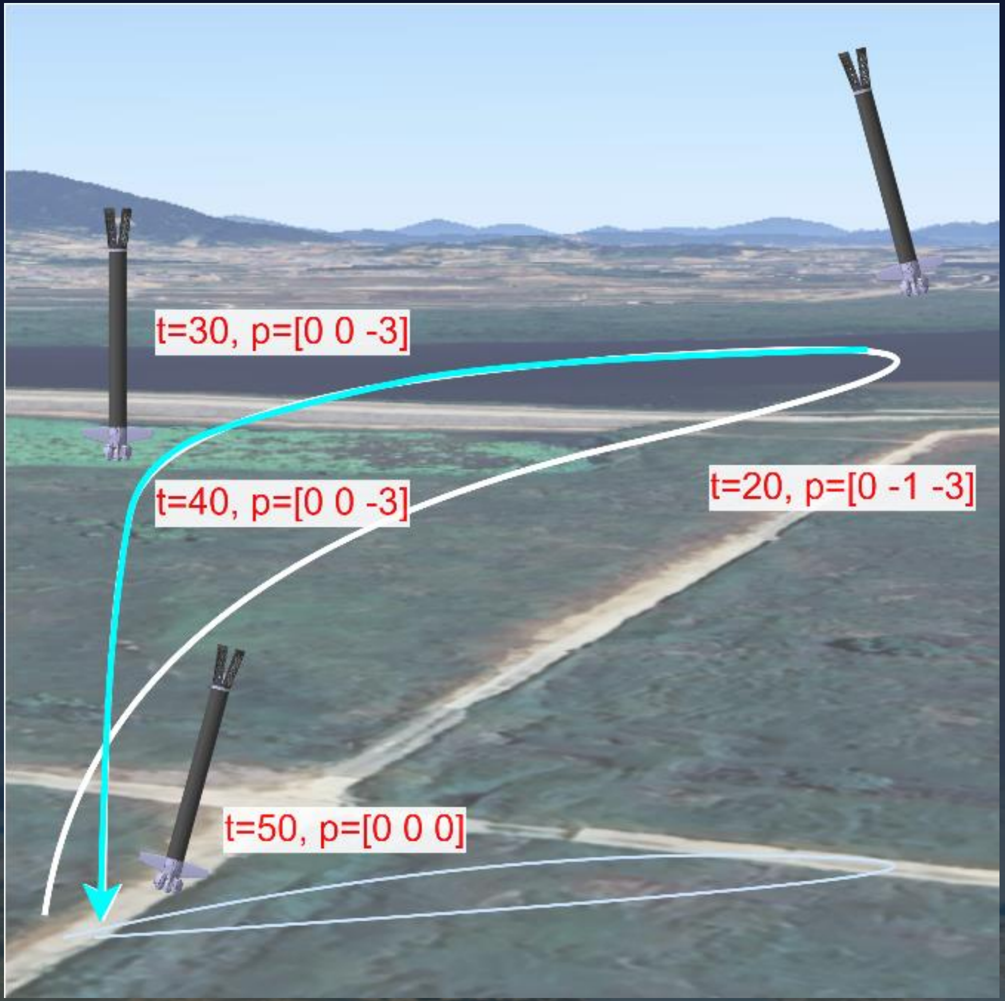




Scenarios

- Common mission profile for verification of optimization
  - Demonstrate landing phase, max 3 m altitude
  - About 60 s flight time

- Scenario I
  - Ideal model(zero backlash $d = 0$)
  - NMPC with initial weight
- Scenario II
  - Mismatched model(with backlash $d = 1 - 2\ deg$)
  - NMPC with initial weight
- Scenario III
  - Mismatched model(with backlash $d = 1 - 2\ deg$)
  - NMPC with optimized weight
- Scenario IV
  - Ideal model(zero backlash $d = 0$)
  - NMPC with optimized weight



Results

- Parameter identification

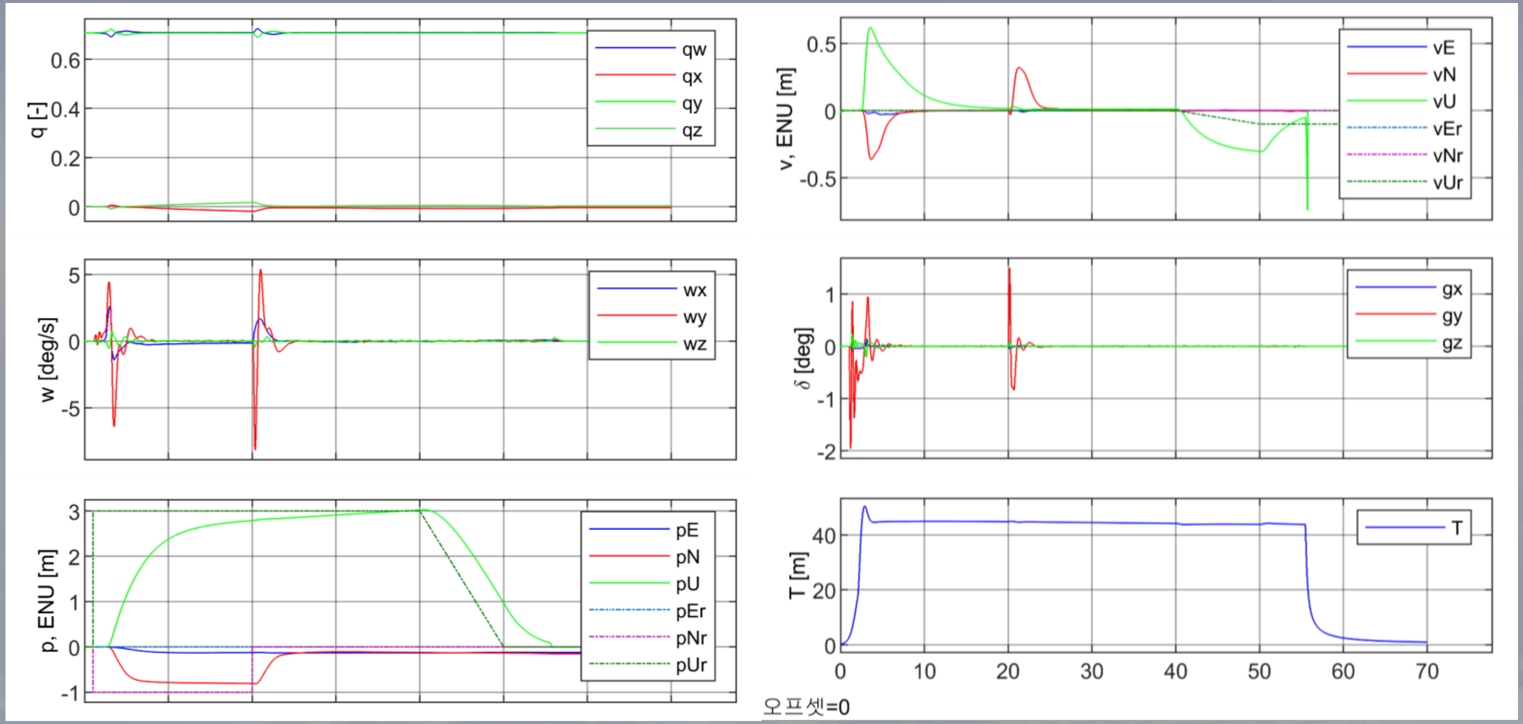
Symbol	Description	Value	Unit
T	Maximum thrust	52	N
k_1, k_2, k_3	Turbine coefficients	5.0e+0, 2.0e+1, 2.0e+1	-
$k_{p,\delta x}, k_{p,\delta y}, k_{p,\delta z}$	Gimbal servo P gains	5.1e-1, 1.5e+1, 1.5e+1	-
$k_{d,\delta x}, k_{d,\delta y}, k_{d,\delta z}$	Gimbal servo D gains	7.6e-3, 4.2e-1, 4.2e-1	-
$J_{iyy}, J_{\delta yy}, J_{\delta zz}$	Gimbal moment of inertia	6.4e-4, 3.8e-2, 3.8e-2	kg·m^2
J_{xx}, J_{yy}, J_{zz}	Body moment of inertia	3.1e-2, 5.2e-1, 5.2e-1	kg·m^2
m_f	Body mass (Dry mass)	4.1e+0	Kg
P_f^c	CG position vector	(4.0e-1; 0.0e+0; 0.0e+0)	m
P_f^1	Turbojet 1 Position	(1.0e-2; 8.8e-2; 8.8e-2)	m
P_f^2	Turbojet 2 Position	(1.0e-2; -8.8e-2; -8.8e-2)	m
R_f^1	Turbojet 1 Attitude (x,y,z)	(π/4, 0, 0)	rad
R_f^2	Turbojet 2 Attitude (x,y,z)	(5π/4, 0, 0)	rad

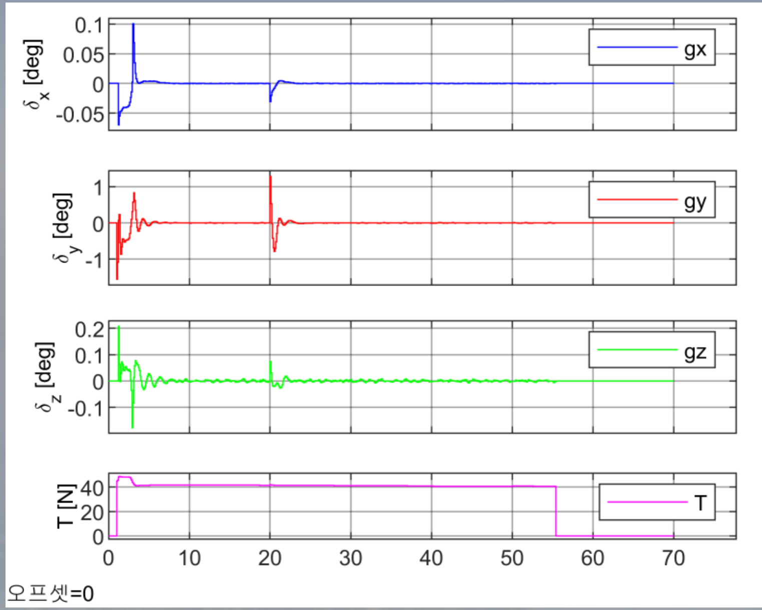
- Controller weights

Description	Initial value	Optimal value
Number of state	21	
Number of output	9	
Number of input	4	
Prediction horizon	8	
Control horizon	[4, 2]	
Output constants, ω	±[2 15 15]	
Output constants, p_z	[0,-inf]	
Output constants, $\dot{p}_x$, $\dot{p}_x$	±[2 2]	
Output weight, $W_{y,\omega}$	[1 1 1]	[1.00 1.65 1.65]
Output weight, $W_{y,p}$	[3 3 2]	[3.00 3.00 2.15]
Output weight, $W_{y,\dot{p}}$	[2 2 2]	[1.77 1.77 1.85]
Input weight, $W_{u,\delta}$	[0.1 1 1]	[2.00 0.02 0.02]
Input weight, W_{u,T_U}	[1]	[0.00]
Input weight, $W_{u\Delta,\delta}$	[5 1 1]	[0.30 0.25 0.25]
Input weight, $W_{u,\Delta T_U}$	[1]	[0.10]

Results

- Scenario I
  - Ideal model (no mismatch effects)
  - Used to verify NMPC baseline operation

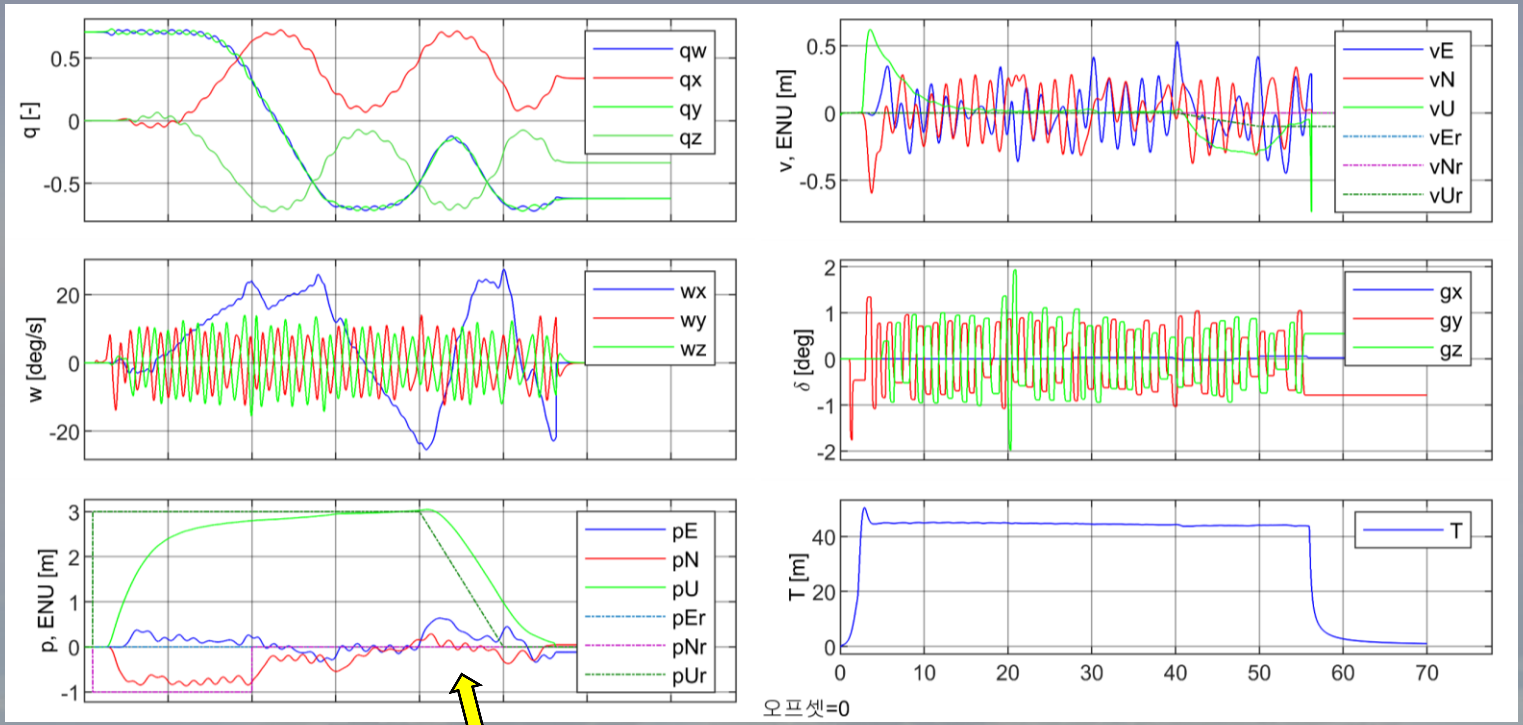


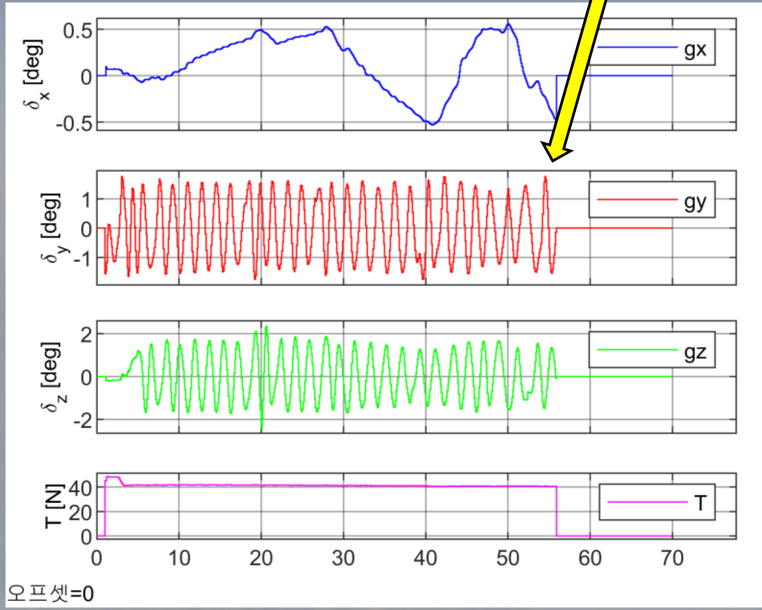


Results

- Scenario II
  - NMPC Prediction model-hardware mismatch

Gimbal oscillation

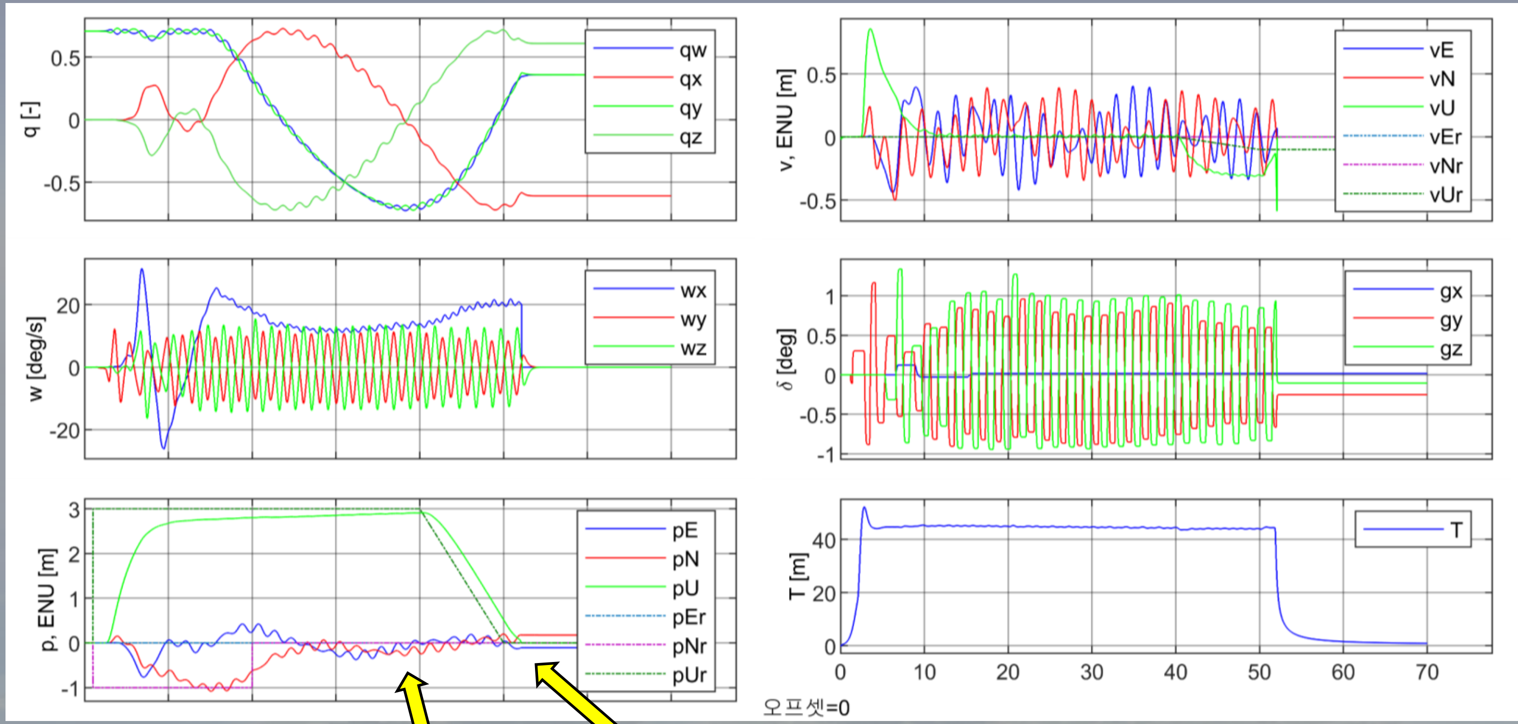


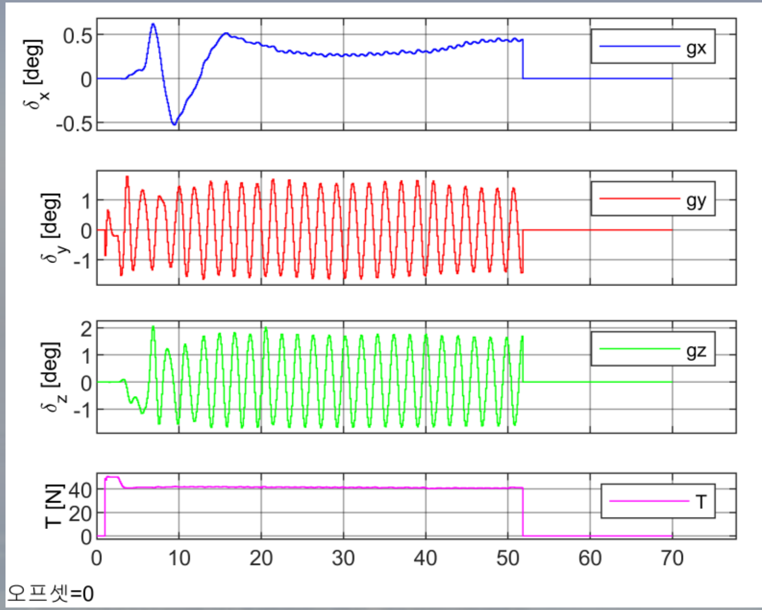


Lateral error increase

Results

- Scenario III
  - NMPC Prediction model-hardware mismatch, with optimized weights



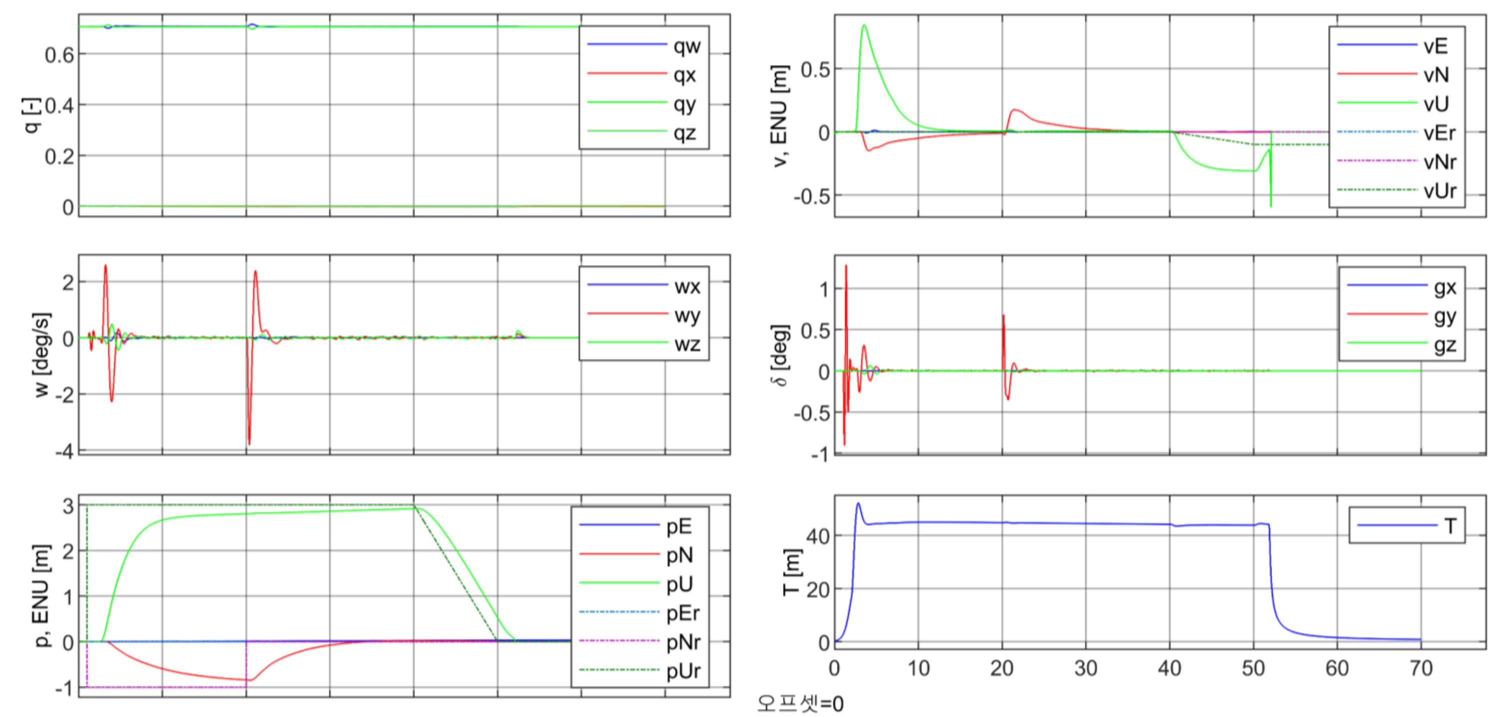


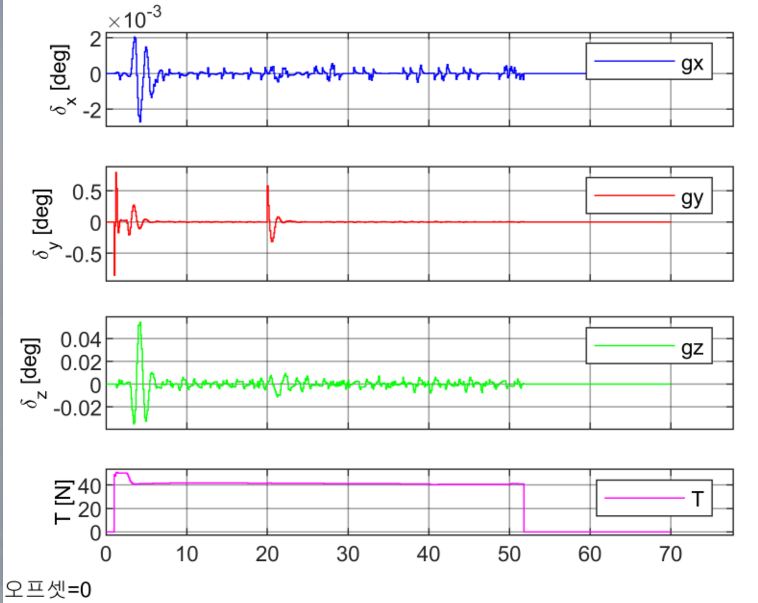
Altitude error decrease

Lateral error decrease

Results

- Scenario IV
  - Ideal model with optimized weights
  - Assuming hardware improvements



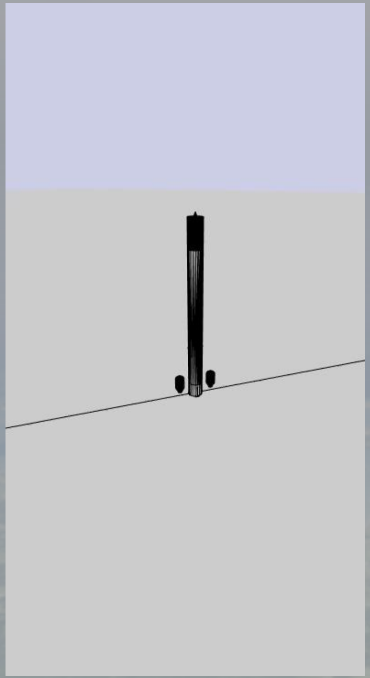
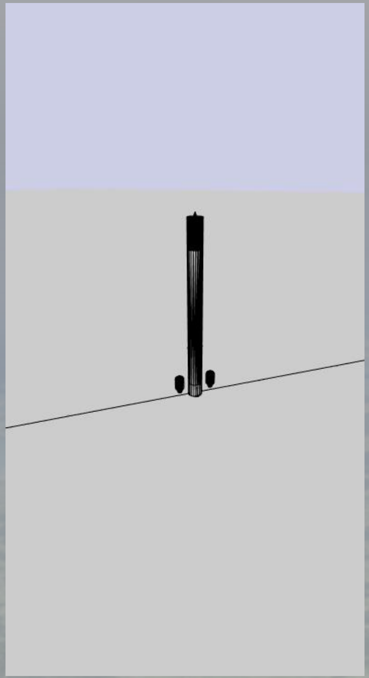
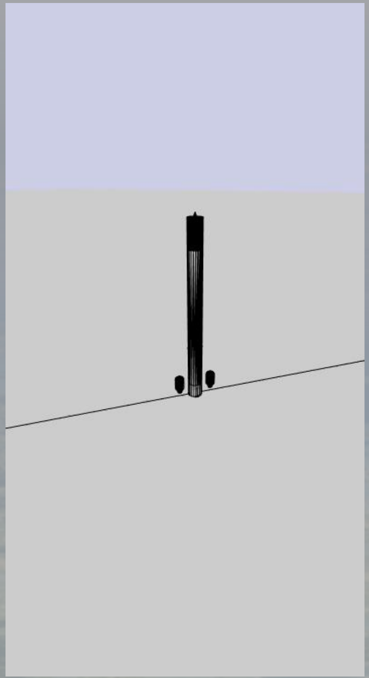
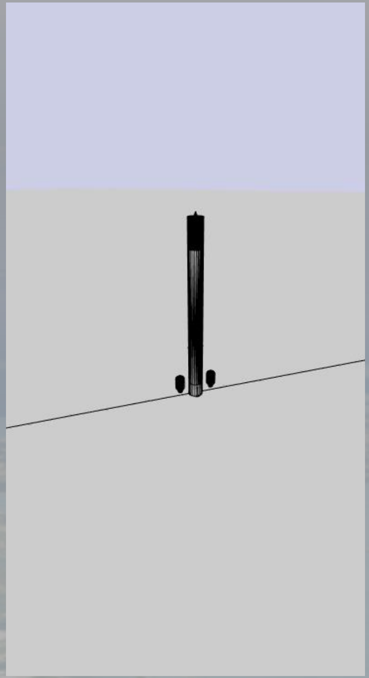


Results

- Verification optimize result

	Scenario I	Scenario II	Scenario III	Scenario IV	
Landing error $e_{xy}(60\text{s})$	1.9387e-01	1.2430e-01	2.0241e-01	3.4680e-02	I→IV, -82.7% II→IV, -72.1%
Fuel consumption $\Delta m(0-60\text{s})$	1.7344e-01	1.7537e-01	1.6294e-01	1.6245e-01	I→IV, -6.3% II→IV, -7.4%
Positon error e_p, RMS	1.1167e+00	9.8689e-01	9.0710e-01	9.3932e-01	I->IV, -15.9% II→IV, -4.8%

Legend
Highest performance
Worst performance

Chapter 4: Conclusion and Future Work

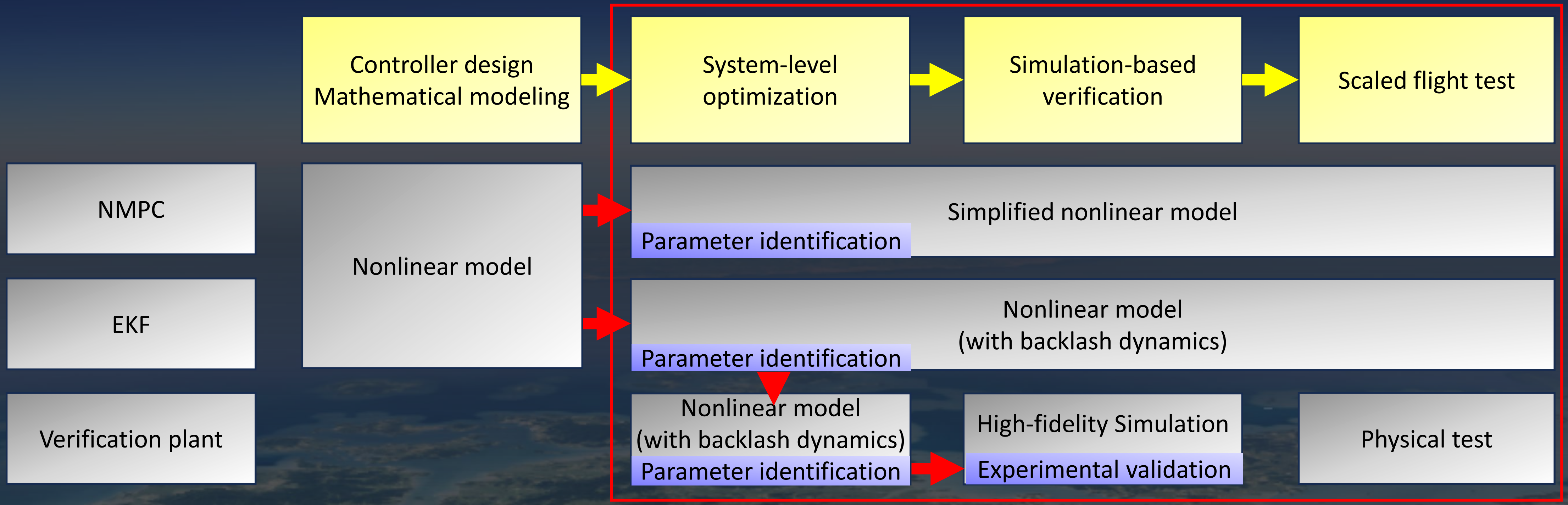
Conclusion

- Foundation for **system-level optimization** and **experimental validation**
- **NMPC** for a reusable suborbital launcher; **SQP** controller weight/constraint tuning in simulation (leveraging prior optimization framework)

- **Prior work**: PID controller performance coupled to **hardware optimization**, limiting system-level improvement. **This work**: **nonlinear MPC** robust to **hardware variation**; controller weights optimized via the **same** framework
- **High-fidelity 6DoF** simulation extended; **experimental model validation and real-vehicle parameter identification**
- **Four-scenario** comparison; optimization yields **up to 7.4%** reduction in fuel consumption

Future work

- **Full system-level optimization and verification.**
- Scaled flight tests of the small suborbital launch vehicle with rocket and jet propulsion with payload (UAV)



Flight test with system-level optimization and verification

Thank you very much

International Astronautical Congress 2025, ICC Sydney, Sydney, Australia, 2 Oct 2025