

Experimental Flight Validation of a Rocket-Assisted Reusable UAV Platform

Simulation and parameter-identification basis for early rocket-assisted UAV flight validation

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01

Motivation and Research Objective

02

System Architecture and Validation Metrology

03

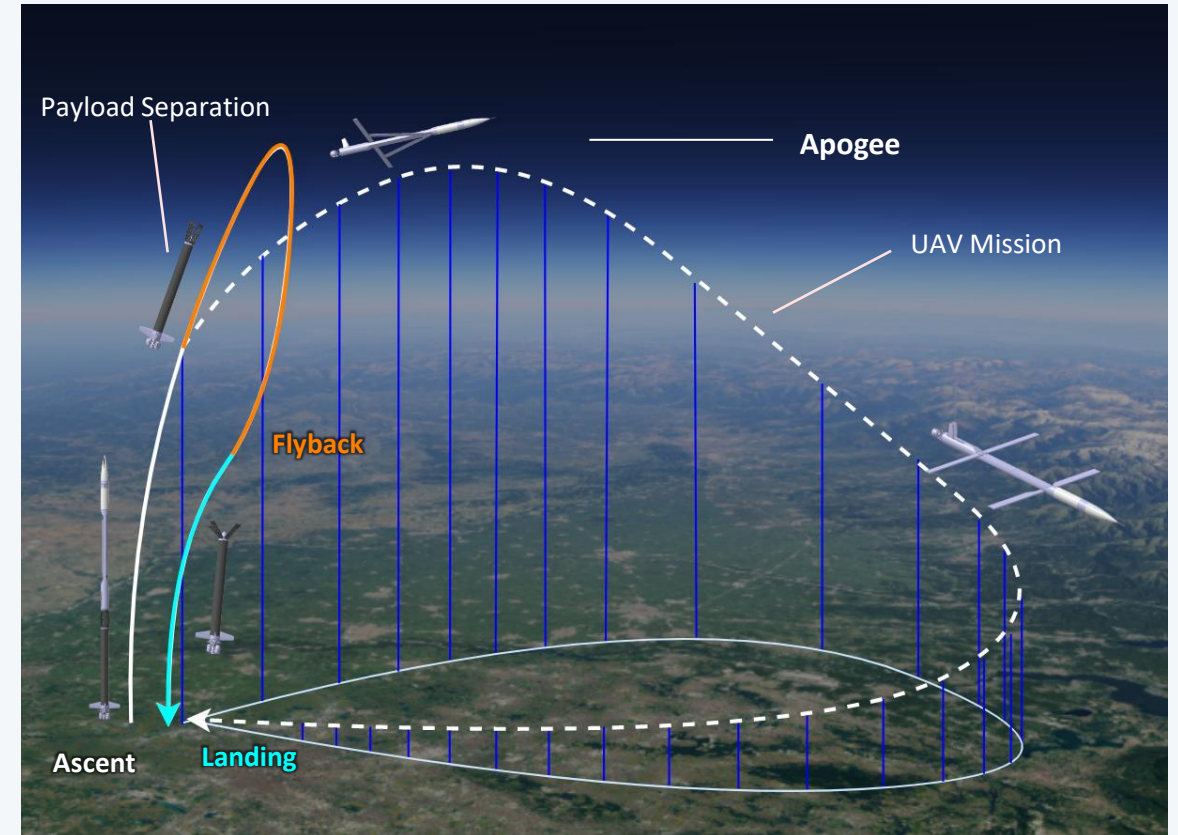
Modeling, Control, and Parameter Identification

04

Simulation Results

05

Conclusion



Mission concept and flight profile

Reusable access as an enabling platform for stratospheric data acquisition

- Fine dust (PM) and hazardous gases (NO_x, SO_x, etc.) disperse from power plants, industrial complexes, and agricultural zones via wind.
- Pollutants migrate into residential and neighboring areas, requiring close-range atmospheric monitoring of inflow, spread, and fluctuation.

1
Growing Demand

Accurate weather forecasting is increasingly critical in the era of global warming.

2
Remote-Sensing Gap

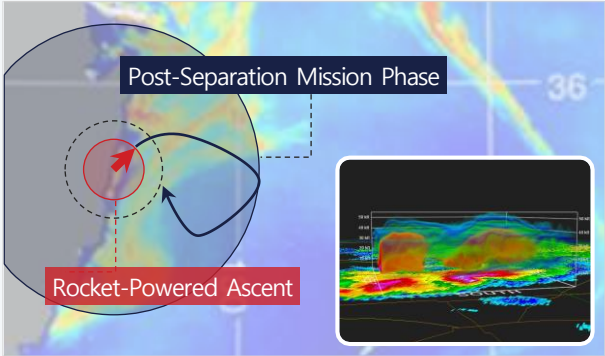
Satellite data, though continuous, must be **periodically calibrated with in-situ observations**.¹

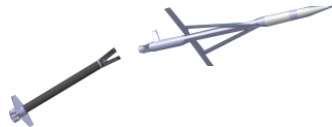
3
In-Situ Constraints

Accessing the stratosphere for direct measurements is costly compared with ground stations.

4
Proposed Solution

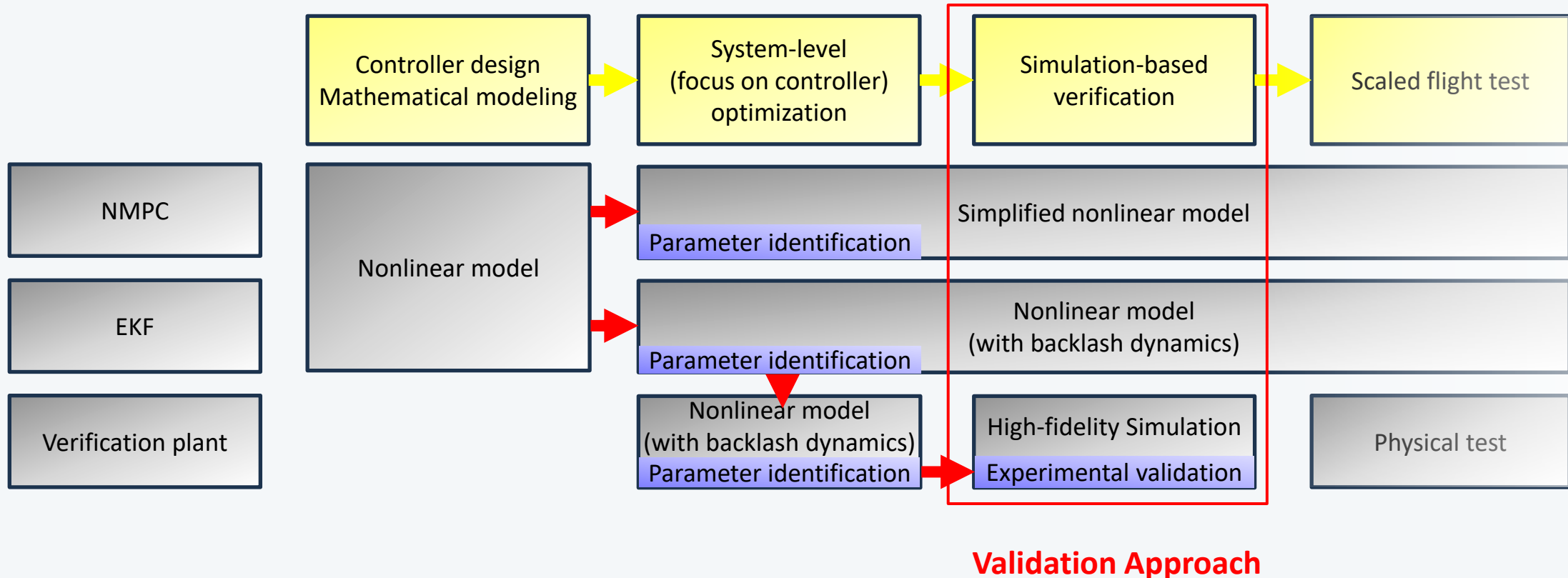
Combine the advantages of rockets and small UAVs: **a rocket-launched, foldable unmanned aircraft***.



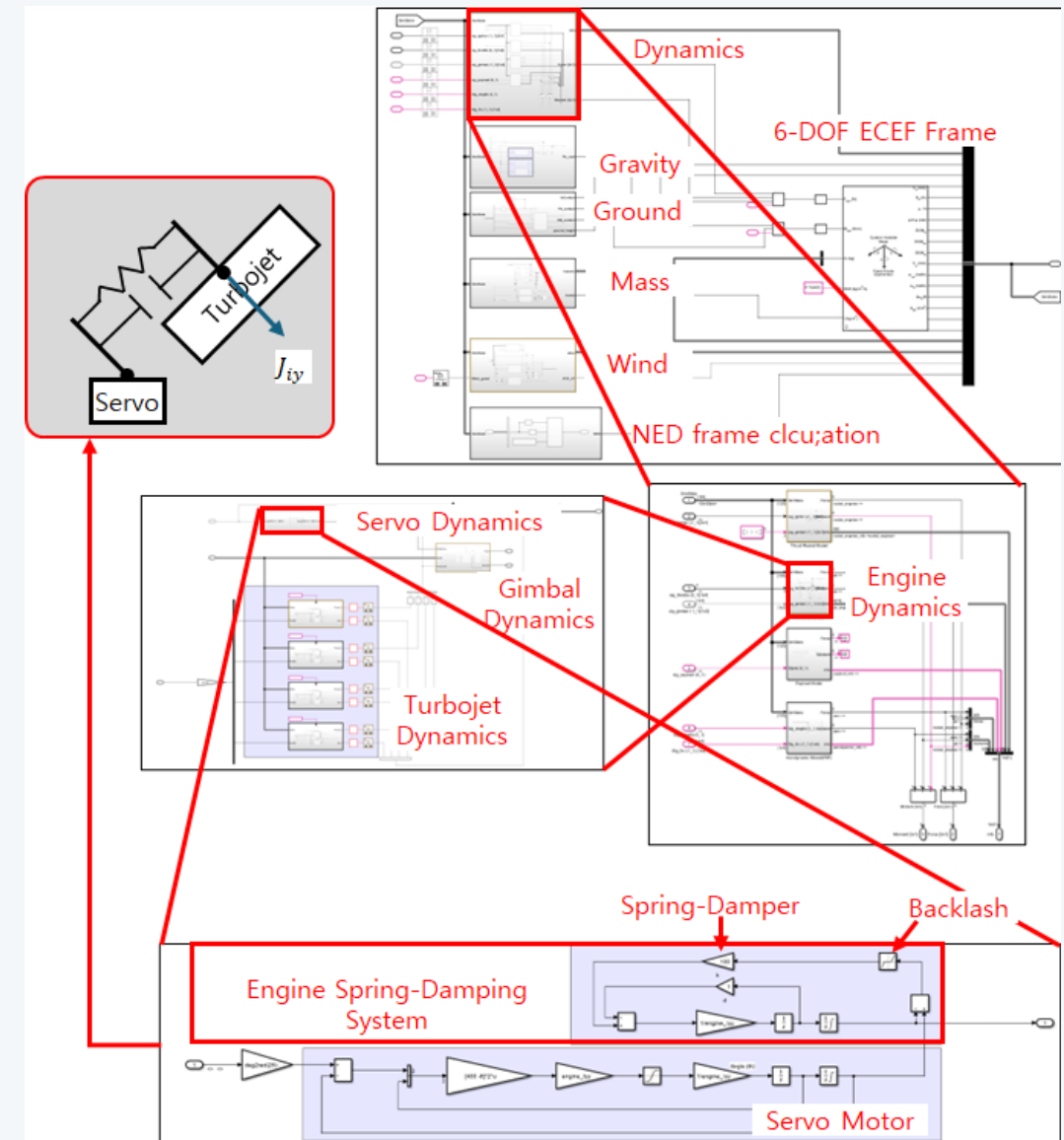
Platform	Observation Aircraft	Observation Balloon	Expendable Sounding Rocket	Reusable Sounding Rocket	*Proposed Method
					
Reusability	Yes	Limited	No	Yes	Yes
Operational Altitude	< 37.7 km	< 53 km	> 50 km	> 50 km	> 30 km
Station-Keeping	Yes	Limited	No	No	Yes
Precision Recovery	Yes	No	No	Yes	Yes

1. G. Balsamo et al., "Satellite and In situ Observations for Advancing Global Earth Surface Modelling : A review, "Remote Sensing, vol. 10, no. 12, pp. 2038-2109, Dec. 2018

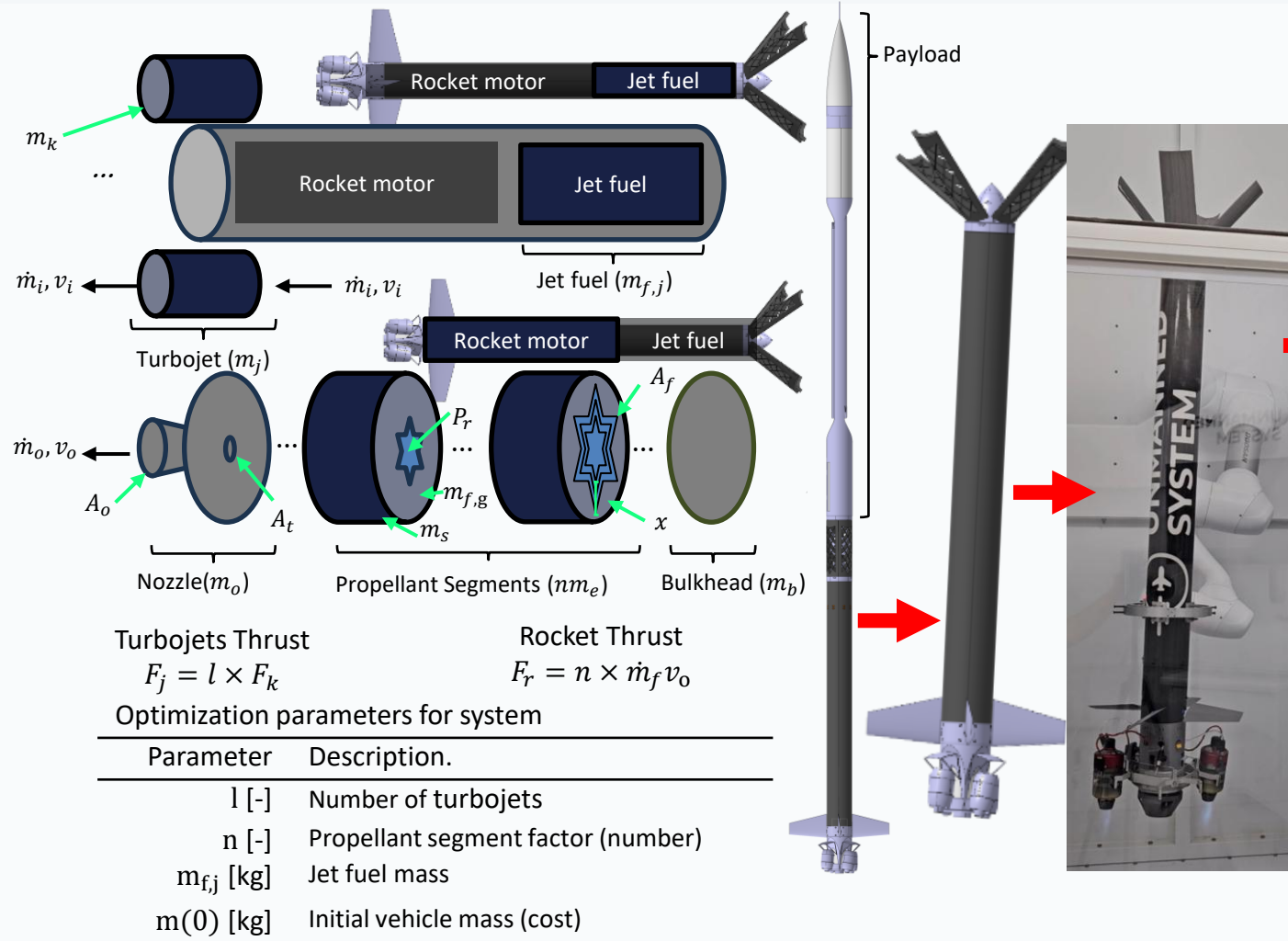
- High-fidelity simulation for controller verification
 - Experimentally identified parameters, validated models



- High-fidelity simulation for controller verification
 - ECEF coordinate based simulation
 - Gimbal reaction torque
 - Aerodynamic forces
 - Wind disturbance
 - Additional state 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.

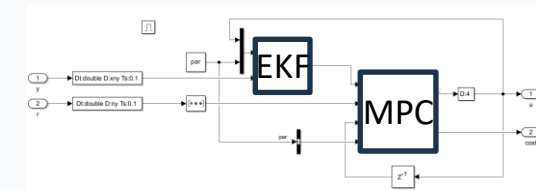
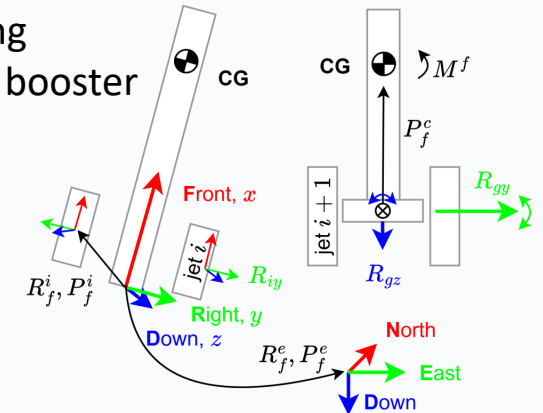


System-Level Manipulate Variables(Prior study)



Controller weights(This study)

- Precision landing
- Without rocket booster



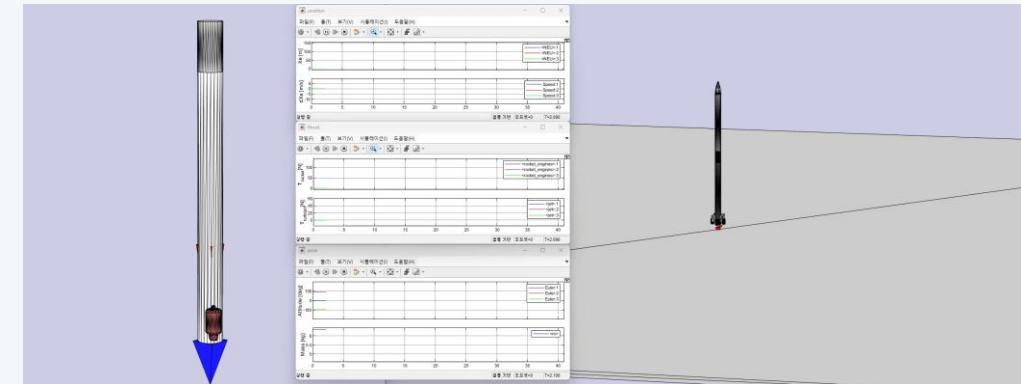
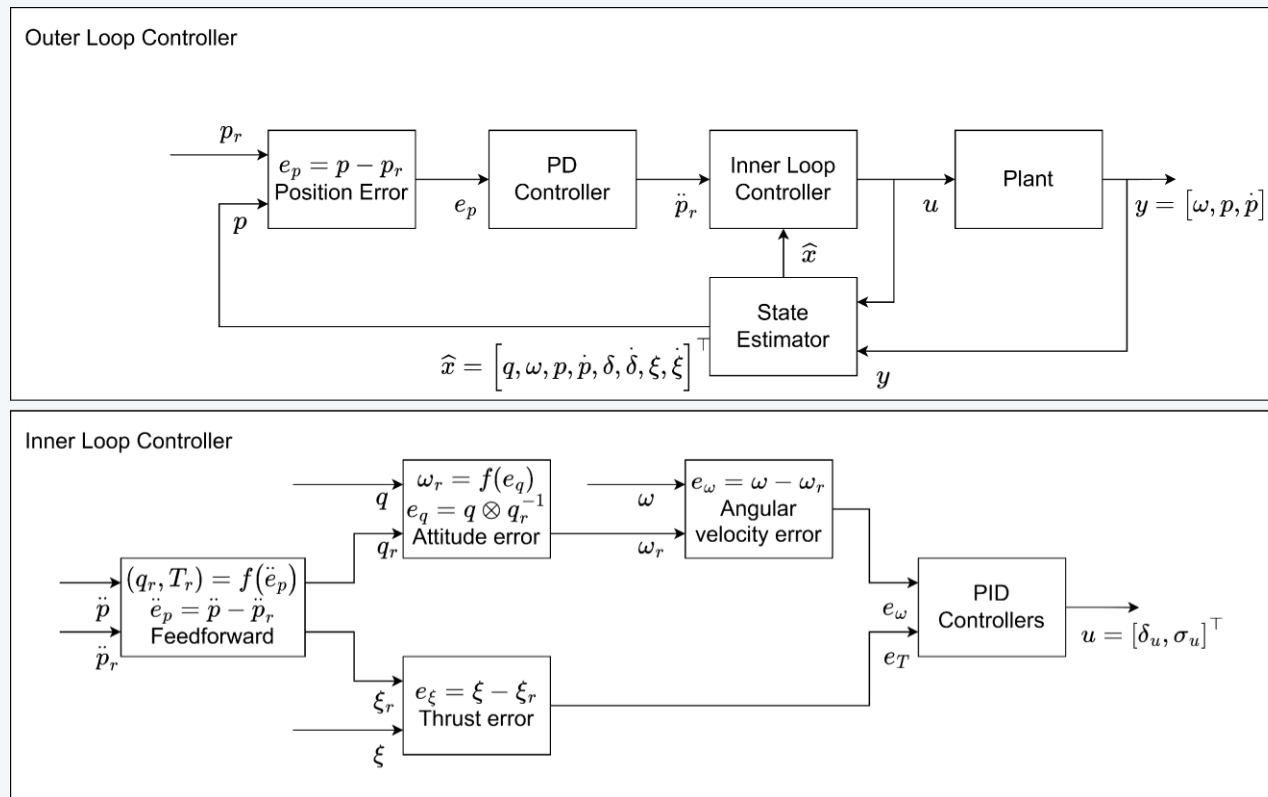
Manipulated Variables(MV) Output Variables (OV)

$$u_k = [g_x, g_y, g_z, T]^T \quad y_k = [\omega, p, \dot{p}]^T$$

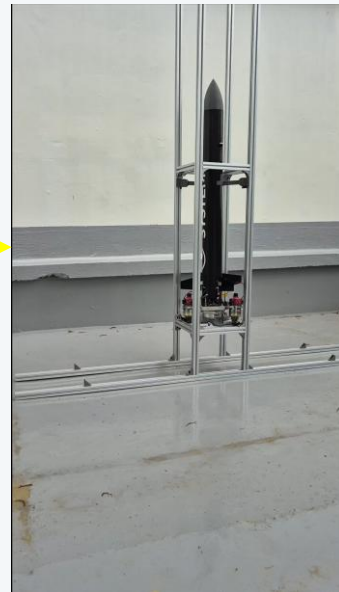
Optimization parameters for controller

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

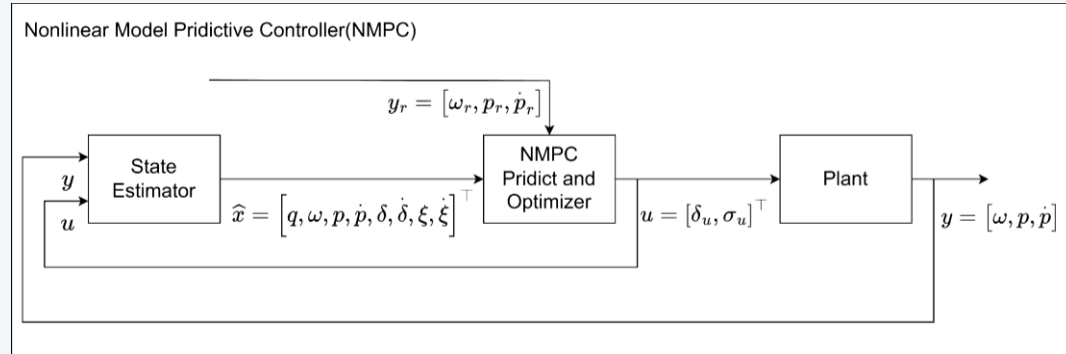
- Controller Design
 - PID controller(Prior study)
 - Outer-loop PD generates reference acceleration
 - Feedforward + PID computes gimbal angles and thrust



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



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



- Predict model

$$\begin{aligned} x_{k+1} &= f(x_k, u_k) \\ y_k &= h(x_k) \end{aligned}$$

- Model states

$$\begin{aligned} x &= [q \ \omega \ p \ \dot{p} \ \delta \ \dot{\delta} \ \xi \ \dot{\xi}]^T, & u &= [\delta_u \ T_u]^T \\ y &= [\omega \ p \ \dot{p}]^T \end{aligned}$$

- Control objective

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

- Tuning 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

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

$$g_0 = [0 \ 0 \ 9.8]^\top$$

- Rotational dynamics

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

- Actuator dynamics

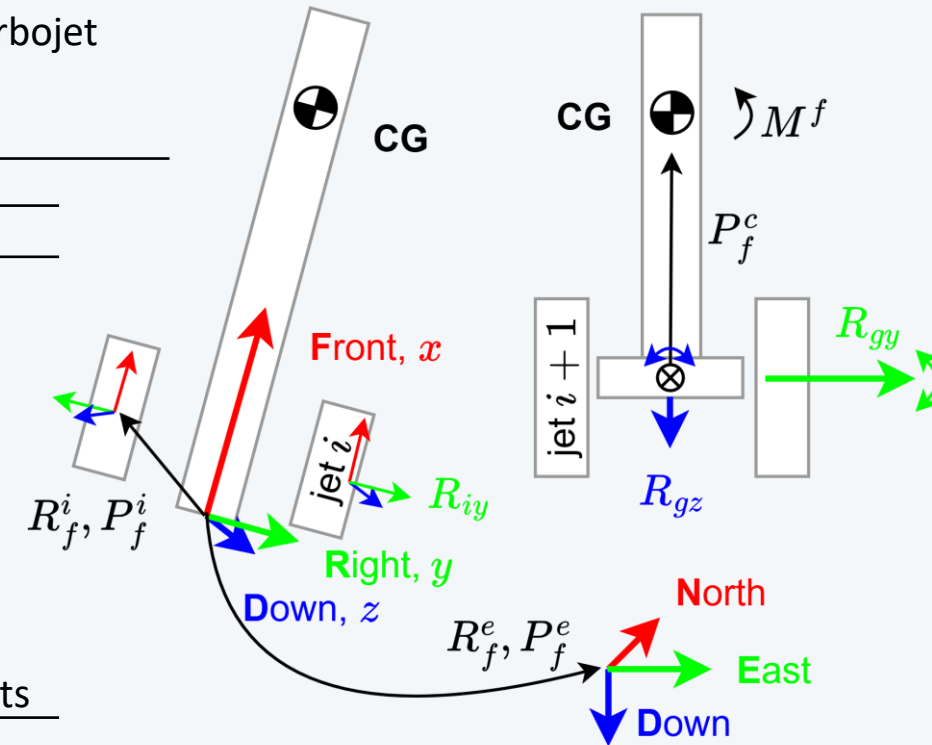
$$F^f = \sum_{i=1}^n R_i^f F^i + F_D^f, \quad F^i = [T \sigma_i, 0, 0]^\top$$

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

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

$$R_i^f = R_{\delta_y}^f(\delta_y)R_{\delta_z}^{\delta_y}(\delta_z)R_{i_y}^{\delta_z}(\delta_{i,x})$$

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

$$\delta = [\delta_x \ \delta_y \ \delta_z]^T$$

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

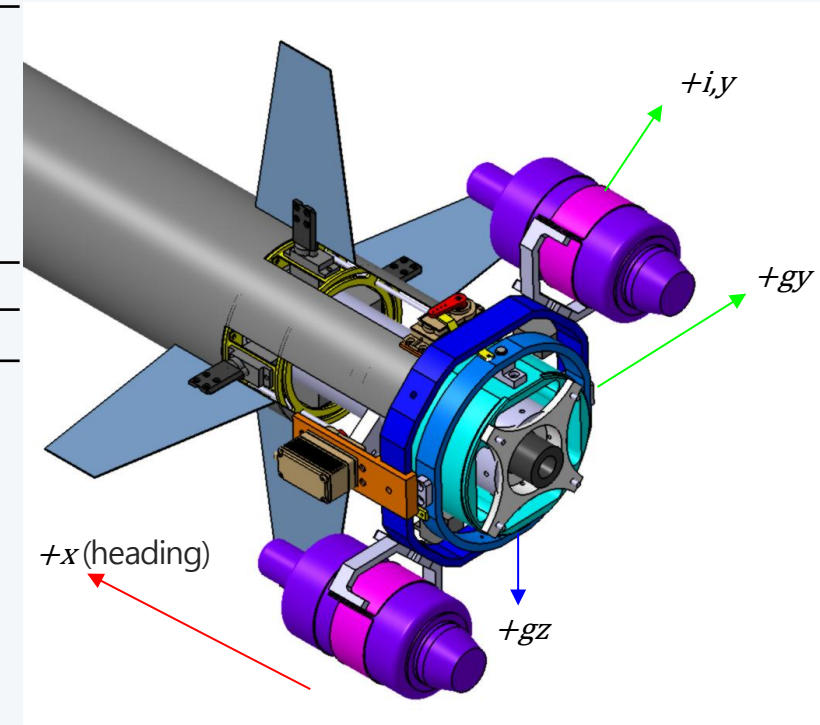
- Turbojet model

$$\sigma_i = \frac{e^{k_1 \xi_i} - 1}{e^{k_1} - 1}$$

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

where k_1, k_2 , and k_3 represent turbojet
turbine coefficients

Index	Description.
f	Body-fixed frame
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- Extended Kalman Filter (EKF)

- Model mismatch

- From gimbal model,

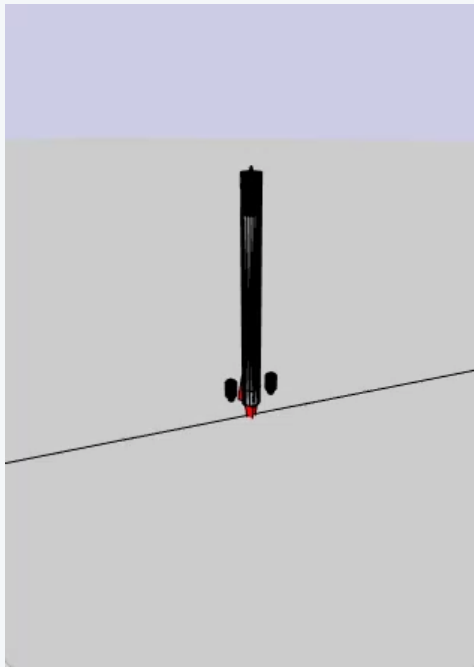
$$\ddot{\delta} = J_{\delta}^{-1}(k_p z(e_{\delta}) = -k_d \dot{\delta})$$

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

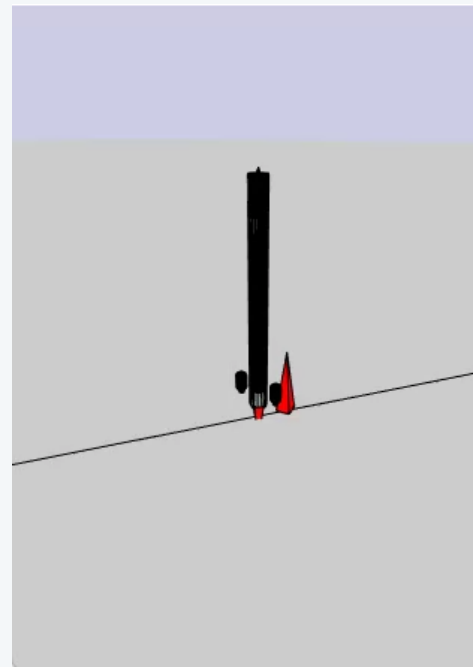
- Extended Kalman Filter (EKF)

- 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

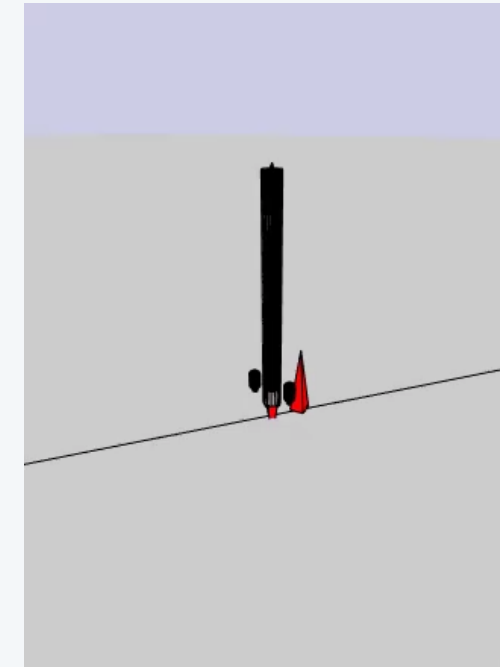
Same NMPC weights



Ideal model(MPC, EKF)

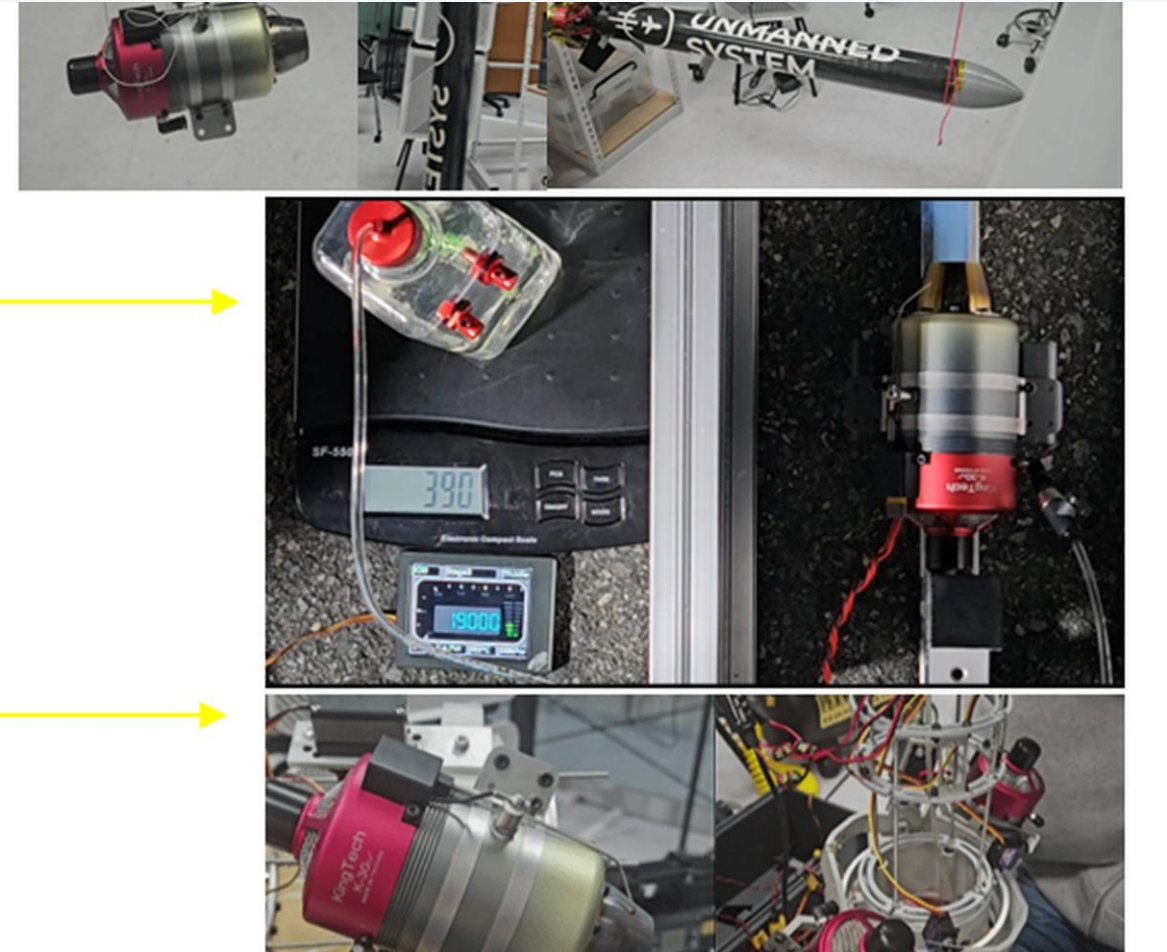


MPC, EKF Model mismatch



MPC Model mismatched

Parameter-identification evidence



Measured-parameter summary

Bifilar-pendulum inertia relation

Role: parameter closure

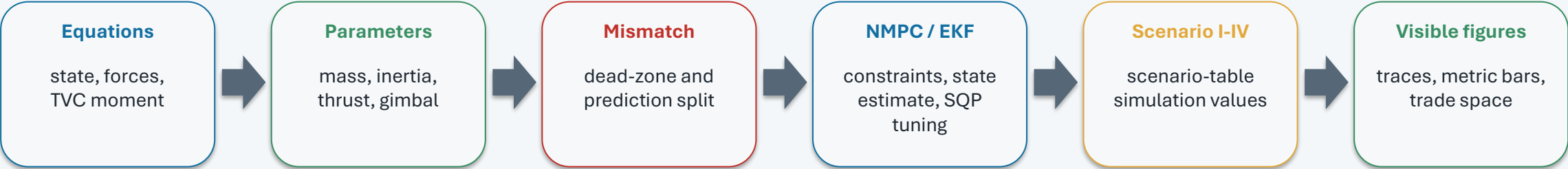
$$J = m g b^2 T^2 / (16 \pi^2 L)$$

measured inertia closes the dynamics parameter chain

Final-grade notation for visible talk use; derivation and assumptions are preserved in speaker notes.

Parameter inputs to simulation model

Group	Terms	Model / result role
Rigid body	m, CG, J_B	state dynamics
TVC / gimbal	J_g, K_p, K_d, d	actuator mismatch
Propulsion	T_max, fuel, coeff.	force model
Scenario values	landing, fuel, RMS	result comparison
Source table	scenario metrics	result provenance



Result slides are interpreted through the chain of equations, parameters, mismatch assumptions, controller settings, and Scenario I-IV metrics.

Result object	Source basis	Use in talk	Limit
Scenario II traces	original trace images	mismatch behavior	simulation
Metric bars	scenario table values	comparison plot	table-derived values
Trade-space plot	scenario table values	interpretation	additional simulation runs required for stronger validation
Hardware photos	local project files	context	hardware context only

Scenario	Plant model	Controller weights	Purpose	Interpretation
I	ideal	initial	baseline	nominal response
II	mismatch	initial	mismatch baseline	recovery-control stress case
III	mismatch	SQP optimized	tuned mismatch	fuel/RMS improvement; landing remains unvalidated
IV	ideal	SQP optimized	optimized ideal reference	ideal reference

Key comparison

The useful comparison is sensitivity to mismatch and tuning.

Interpretation

Scenario IV is an ideal-model reference.

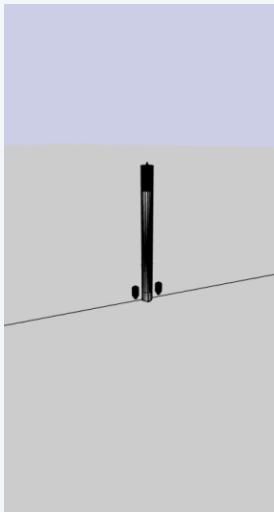
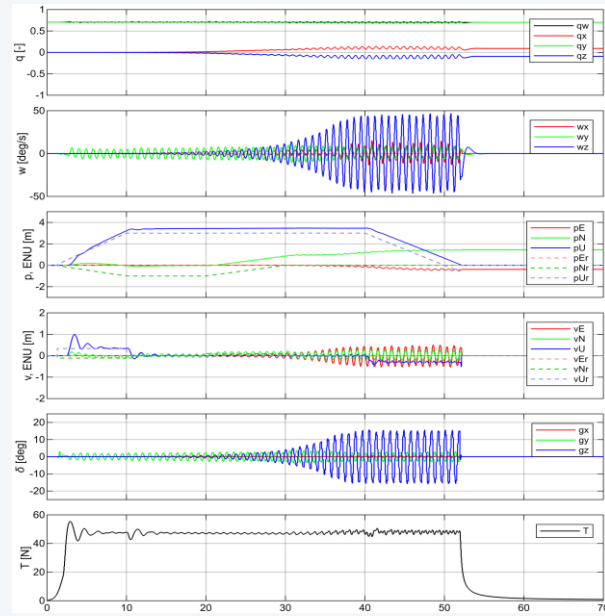
Current technical basis

Scenario results quantify model response under simulation assumptions.

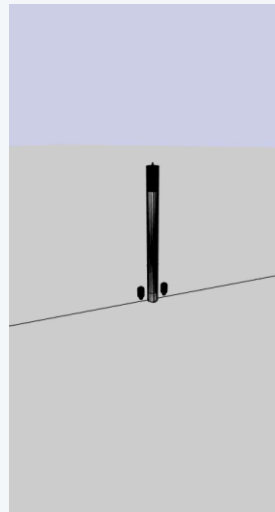
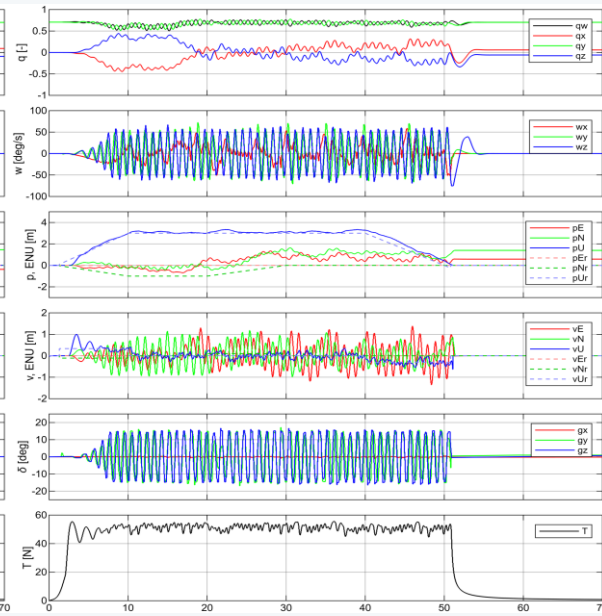
Section IV | Simulation Results

04/04 | Simulation Results and Validation Outlook

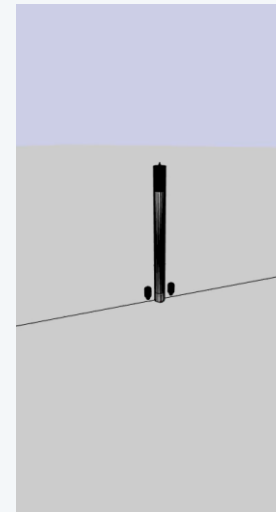
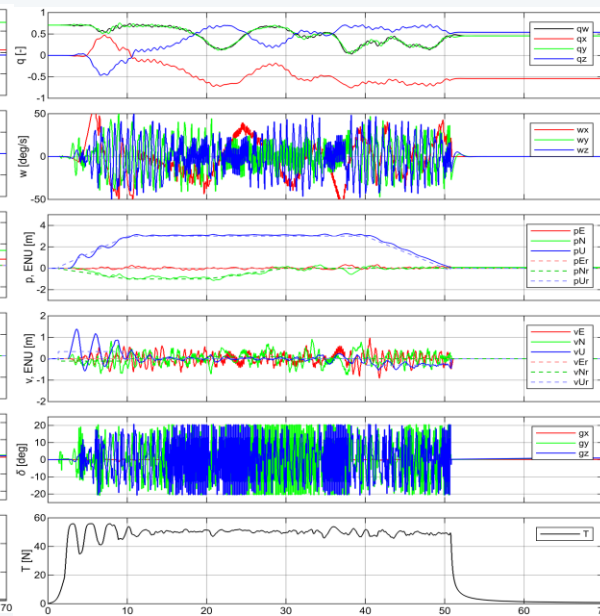
Scenario I



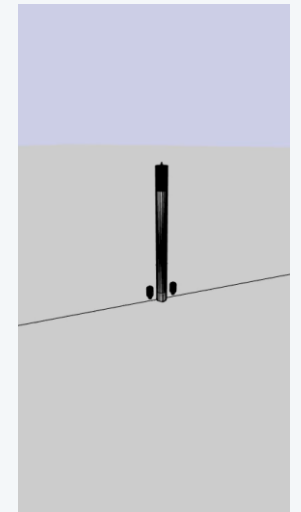
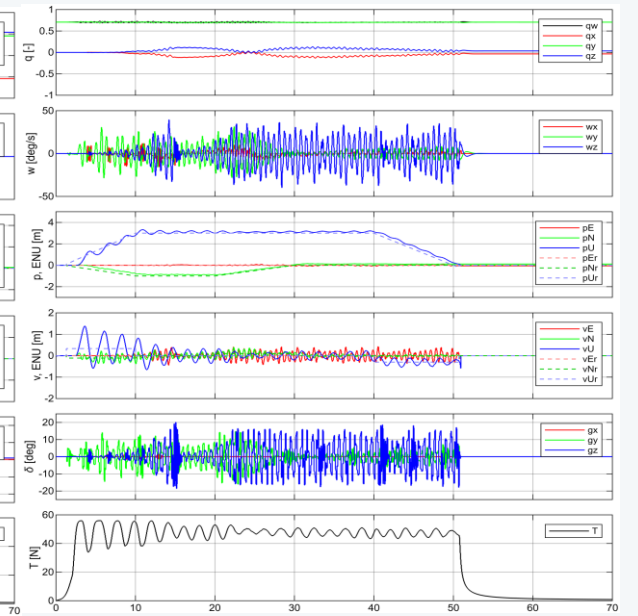
Scenario II



Scenario III



Scenario IV



Scenario	e_{RMS} [m]	e_{land}^{xy} [m]	ϕ_{t_∞} [kg]
I	5.6062e-1 (0.00%)	2.2193e-0 (0.00%)	1.6951e-1 (0.00%)
II	6.2011e-1 (+10.61%)	1.2814e-0 (-42.26%)	1.7786e-1 (+4.93%)
III	1.4430e-1 (-74.26%)	2.5789e-2 (-98.84%)	1.7355e-1 (+2.38%)
IV	1.2440e-1 (-77.81%)	1.7344e-2 (-99.22%)	1.6644e-1 (-1.81%)

Values in parentheses denote relative change versus Scenario I: $\Delta[\%] = 100 (m_s - m_I)/m_I$.

Reusable high-altitude access using a rocket-assisted UAV requires a defensible link between model-based analysis and flight-test evidence before full mission demonstration.

This work built a hardware-informed 6-DOF simulation basis using identified parameters, propulsion/TVC modeling, actuator-mismatch assumptions, and NMPC/EKF scenario evaluation.

The Scenario I-IV results indicate that actuator mismatch and controller tuning affect recovery-response metrics, fuel use, and landing-error trends under simulation assumptions. These results support control-sensitivity interpretation, not completed flight validation.

Planned validation will proceed through a 2026 rocket-mounted upper-stage UAV separation flight test, followed by the design, manufacture, and flight test of a 10 km-class vehicle in 2027 to compare measured flight data against the current model, parameter-identification, and simulation results.

Thank you for your attention.