UAV Suspended Load Control

Pasin Jindadumrongwech — Chulalongkorn University
Email: pasinjnd.job@gmail.com — GitHub: `https://github.com/porhJ`

Problem

Suspended-payload configurations are commonly used in UAV delivery due to onboard space limitations. However, payload swing introduces strongly coupled and underactuated dynamics that are highly sensitive to wind disturbances and sensor noise, posing significant challenges for stable and precise flight control.

Approach

- Derive nonlinear system dynamics using Lagrangian mechanics
- Linearize the dynamics about the hover equilibrium
- Design a local Linear Quadratic Regulator (LQR) to obtain the optimal feedback gain matrix (K_r)
- Implement an Extended Kalman Filter (EKF) for full-state estimation under sensor noise
- Validate the control and estimation framework through Python-based physics simulations

Methods

Model: Planar quadrotor with two actuators, modeled as a rigid body carrying a point-mass payload suspended by a massless rigid link.

Control: LQR designed to minimize payload swing while maintaining locally optimal trajectory tracking.

Estimation: Full-state estimation to suppress sensor noise and infer unmeasured states.

Key Experiments

- Nominal response (no disturbance)
- Disturbance rejection under sinusoidal gusts
- Robustness to elevated sensor noise
- Parameter sensitivity analysis
- Observer performance evaluation

Metrics

- **Settling condition:** $|x - x_{\text{ref}}| < 0.05 \wedge |z - z_{\text{ref}}| < 0.05 \wedge |\dot{x}| < 0.05 \wedge |\dot{z}| < 0.05 \wedge |\theta_p| < 10°$
- **Sensitivity score:** $J = 2\theta_p + \text{RMSE}_x + 0.5\, u_{\text{effort}}$

Results

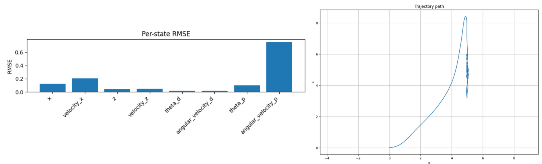

Figure 1: Baseline performance under nominal conditions (no gust, sensor noise at specification level). The controller stabilizes the system with a maximum payload swing of 39.8° and a settling time of 5.3 s.

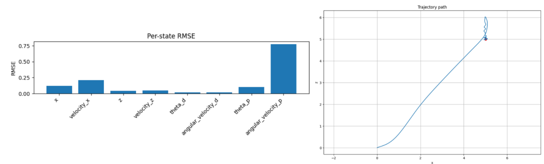

Figure 2: System response under sinusoidal gust disturbance with nominal sensor noise. Despite a 10% equivalent weight disturbance at 1.5 Hz, the controller maintains stability with a maximum payload swing of 64.9° and a settling time of 11.4 s.

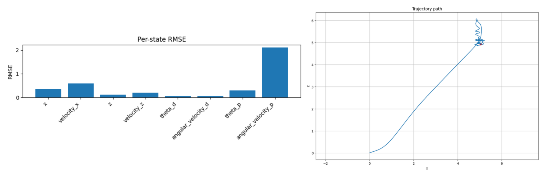

Figure 3: Robustness under elevated sensor noise (three times specification level) without external gusts. The system remains stable with a maximum payload swing of 67.0° and a settling time of 16.3 s, illustrating the estimator–controller trade-off under severe noise.

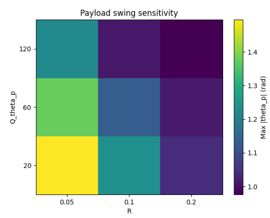

Figure 4: Parameter sensitivity study over Q_θ and R. The optimal configuration is $Q_\theta = 20$ and $R = 0.2$, yielding settling within 7 s, mean control effort of 5.58, and maximum payload swing of 59.99°.

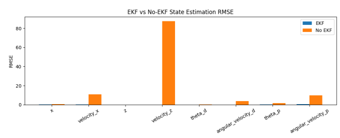

Figure 5: Observer comparison. The naive approach fails due to large velocity estimation errors, while the EKF accurately infers hidden states (e.g., payload swing velocity), enabling stable flight.

Conclusion

The proposed LQR–EKF framework achieves stable control of a suspended-payload UAV under significant wind disturbances and sensor noise, demonstrating robustness and suitability for precision flight tasks.