Vision Based Nonlinear Control for UAVs

Reactive + Predictive + CBF Fusion for Safety-Critical Flight

Abstract: I propose a UAV obstacle avoidance framework that integrates Lyapunov-based control, predictive trajectory sampling, and control barrier function (CBF) safety projection. Implemented on the Holybro X500 v2 with PX4–ROS–Gazebo pipeline, the system demonstrates real-time feasibility and qualitative safety guarantees, bridging simulation and indoor flight validation.

System Architecture

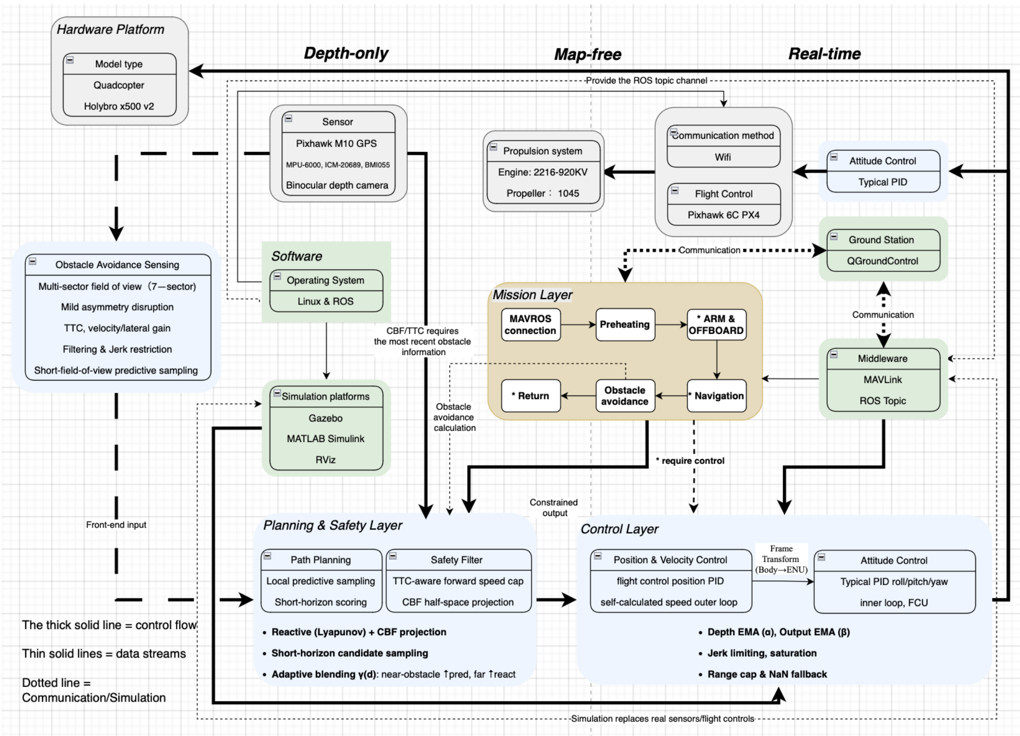

Figure 1. Closed-loop pipeline integrating sensing, planning, safety, and control.

Key Methods

Reactive velocity field: 7-sector vision-based depth sensing with time-to-collision metrics. **Predictive sampling:** Short-horizon candidate trajectories scored by progress + safety.Local trajectory set $u_i(t)$, scored by $J(u_i) = \alpha \cdot progress(u_i) + \beta \cdot safety(u_i)$. **CBF safety projection:** Provable forward invariance guarantees via quadratic programming. Safety filter: $u^* = \arg\min |u - u_{nom}|^2 \quad \dot{h}(x,u) + \alpha(h(x)) \geq 0$. **Fusion strategy:** Distance-adaptive blending of predictive and reactive commands. Adaptive weight $\gamma(d) = e^{-\lambda d}$ blends predictive foresight and reactive safety. **Jerk limiting:** Filtering ensures smooth actuation and safe PX4 execution.

Results Highlights

Real-time onboard feasibility at **30 Hz** control update rate. Corridor simulation trials (**10 runs**) achieved **over 90% success rate**. Consistently maintained minimum clearance > 0.35 m; no collisions observed. Fusion approach improved **smoothness vs. reactive** and **efficiency vs. predictive**.

Limitations

Error metrics (attitude error, velocity tracking, path overhead) not yet quantitatively measured.
Validation restricted to a single simulated corridor and small-scale indoor tests

Implementation Details

- **Software:** ROS + PX4 + Gazebo + MAVROS + Ubuntu 20.04
- **Hardware:** Holybro X500 v2, Pixhawk 6C PX4, Stereo Depth Camera
- **Update rate:** 30Hz

Future Research Directions

1. **Extend to large-scale cluttered environments (indoor/outdoor).**
2. **Quantitative evaluation of tracking error, safety margin, and path efficiency.**
3. **Real-world deployment under wind, GPS-denied conditions, and dynamic obstacles.**
4. **Explore multi-UAV swarm extensions and RL-based adaptive controllers.**

Takeaway: This framework showcases a safety-critical, map-free UAV navigation pipeline, where CBF-based guarantees and the fusion module stand out as core innovations. While preliminary, it provides a solid basis for rigorous follow-up studies in both simulation and real-world UAV deployment.

References

- A. D. Ames, X. Xu, J. W. Grizzle, and P. Tabuada. “Control barrier function based quadratic programs for safety critical systems.” *IEEE Trans. on Automatic Control*, 62(8):3861–3876, 2017.

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