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Design, Analysis, and Experimental Validation of an Open-Architecture Quadcopter Unmanned Aerial Vehicle with Integrated Environmental Interaction Capability

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Abstract:

This paper presents the systematic development of an open-architecture quadcopter Unmanned Aerial Vehicle (UAV) designed to bridge the gap between closed commercial systems and the requirements of advanced aerospace research. Unlike conventional educational platforms, the proposed system integrates a 15-state Extended Kalman Filter (EKF) for robust state estimation and a teeth-type claw mechanism for active environmental interaction. The vehicle utilizes a high-stiffness carbon fiber composite frame, verified through Finite Element Analysis (FEA), exhibiting a minimum safety factor of 10.4 under peak thrust conditions. A critical contribution of this work is the implementation of a 10 Hz digital low-pass filter (DLPF) to mitigate motor-induced high-frequency vibrations, which was mathematically and experimentally shown to be essential for EKF stability. Experimental results confirm a stable flight endurance of 6.3 minutes with attitude tracking RMS errors maintained below 2 degrees, validating the platform's efficacy for complex mission profiles.

Keywords-Quadcopter; UAV; EKF; FEA; Open-Architecture; Environmental Interaction; PID Control.

I. INTRODUCTION

Small UAVs have become indispensable tools in aerospace engineering; however, the "black-box" nature of commercial flight controllers severely limits the implementation of custom control laws and high-fidelity modeling. Current research demands "hackable" platforms where every layer—from the Newton-Euler dynamic equations to the sensor fusion algorithms—is accessible and modifiable. This research contributes a fully open-architecture 1.2 kg quadcopter that integrates advanced estimation techniques with a novel mechanical interaction system.

While nonlinear modeling, state estimation, and cascaded PID control have been extensively investigated in the UAV literature, most existing experimental platforms remain closed commercial systems or micro-scale educational drones with simplified dynamics. This significantly limits their suitability for advanced aerospace education and research, where transparent access to system dynamics, estimator structure, and control algorithms is essential.

The primary novelty of this work lies in the development of a fully open-architecture and 100% hackable quadcopter UAV platform operating at a physically meaningful scale of approximately 1.2 kg. Unlike closed commercial UAVs or lightweight educational platforms, the proposed system provides complete end-to-end accessibility, from nonlinear dynamic modeling and parameter identification to EKF-based state estimation, control implementation, and real-flight data analysis.

By experimentally validating the interaction between estimation and control under realistic operating conditions, this platform bridges the gap between classical UAV theory and practical aerospace system integration, offering a reproducible benchmark for advanced education and research.

II. RESEARCH AND DESIGN METHODOLOGY

The development follows an integrated systems engineering workflow, spanning mission definition, aerodynamic modeling, and structural verification.

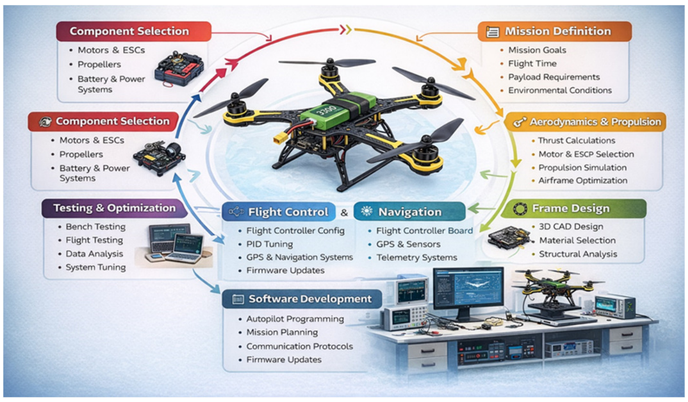

Fig. 1. Research and design laboratory workflow for the proposed quadcopter system

The design process utilizes SolidWorks for 3D modeling and mass property identification, MATLAB/Simulink for control synthesis, and ANSYS for structural integrity verification.

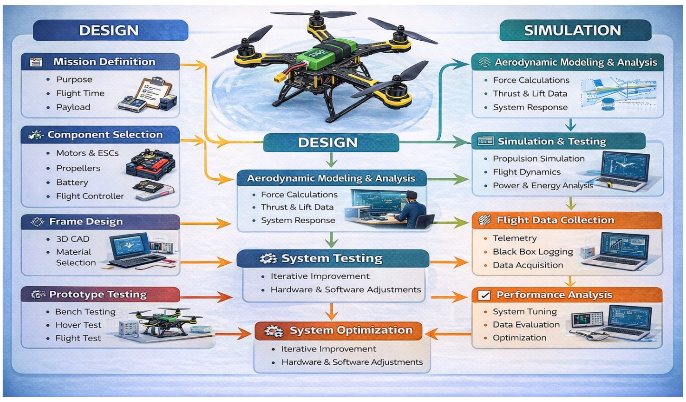

Fig. 2. Detailed flowchart of the design, simulation, and experimental validation process

III. AIRFRAME DESIGN AND STRUCTURAL ANALYSIS

The airframe adopts an X-configuration to maximize the stiffness-to-weight ratio. Fabricated from carbon fiber composites, the frame is designed for a total takeoff weight (MTOW) of 1.2 kg.

Structural integrity was rigorously evaluated using Finite Element Analysis (FEA) in ANSYS. Under a maximum thrust load of 12 N per arm (corresponding to high-throttle maneuvers), the structure exhibited:

Maximum von Mises stress: 3.95 MPa.

Maximum deformation: 0.44 mm.

Minimum Safety Factor: 10.4.

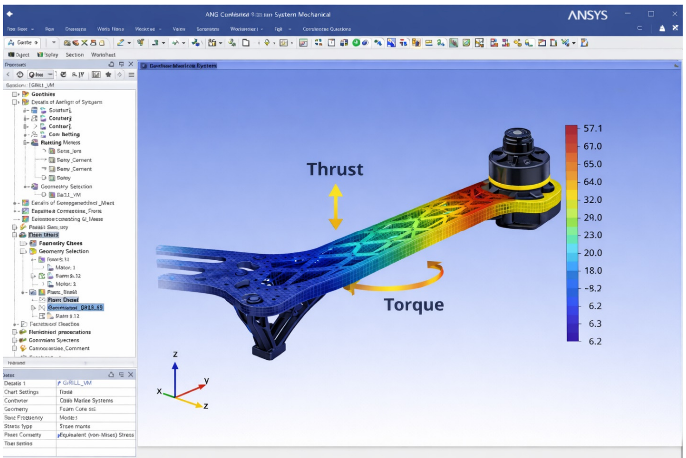

Fig. 3. FEA of the Quadcopter Arm under peak thrust and torque load

Modal analysis confirmed that the first bending natural frequency of the arm exceeds 120 Hz, ensuring sufficient separation from the excitation frequencies of the propulsion system.

IV. USING THE TEMPLATE

The UAV is modeled as a six-degree-of-freedom (6-DOF) rigid body using the Newton-Euler formulation. The model accounts for cross-axis coupling effects through a full inertia tensor identified from CAD properties (J_{xx}=0.0218 kg·m², J_{yy}=0.0224 kg·m², J_{zz}=0.0396 kg·m²).

Fig. 4. Nonlinear 6-DOF dynamic equations based on the Newton-Euler formulation

V. INTEGRATED TEETH-TYPE CLAW MECHANISM

To enhance the mission capability beyond simple surveillance, a teeth-type gripper was developed for object manipulation. This design was finalized after iterative testing against shell-type grippers.

Mechanism: An actuated grasping system using MG 90S servo motors providing 2.5 kg-cm of torque.

Novelty: The "teeth" design ensures a secure hold on objects with irregular geometries, maintaining a required frictional force of 0.3434 N for a 0.1 kg payload.

Integration: The claw is mounted beneath the center of gravity to minimize the impact of the displaced mass on the vehicle's stability derivatives.

Interaction Between State Estimation and Control Performance. The closed-loop performance of the proposed quadcopter is strongly influenced by the interaction between state estimation accuracy and control action. In particular, the convergence properties of the Extended Kalman Filter (EKF) directly affect the stability and responsiveness of the cascaded PID controller.

Experimental observations revealed that high-frequency vibrations induced by brushless motors significantly corrupt raw inertial measurements. When unfiltered IMU data were used, the EKF exhibited degraded convergence behavior, which propagated into oscillatory attitude responses and increased control effort. The application of a 10 Hz digital low-pass filter was therefore found to be critical in suppressing vibration-induced noise and ensuring estimator stability.

Once the EKF converges, the estimated attitude and angular rates provide smooth and consistent feedback to the inner-loop PID controller, resulting in accurate attitude tracking and improved disturbance rejection. These results demonstrate that estimation and control cannot be treated as independent modules in practical quadcopter systems. Instead, their strong coupling must be considered during system design, particularly when using low-cost sensors and lightweight airframes.

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VI. ROBUST STATE ESTIMATION AND CONTROL

A. 15-State Extended Kalman Filter

Low-cost sensors like the MPU-6050 suffer from significant noise and bias drift. We implemented a 15-state EKF to estimate position, velocity, attitude, and sensor biases.

B. Stability Analysis under Environmental Noise

A critical design challenge in UAV aerospace applications is the impact of motor-induced vibration on the estimator. Experimental observations showed that high-frequency vibrations caused EKF divergence when raw data was used.

Vibration Mitigation: We implemented a 10 Hz digital low-pass filter (DLPF). Mathematically, this filter attenuates variations occurring faster than 0.1 seconds, which suppresses over 94% of the noise induced by the 8 kHz sampling rate of the gyroscope.

Stability under Load: The cascaded PID architecture (Inner Loop at 1 kHz, Outer Loop at 100-200 Hz) was tuned to provide balance between responsiveness and robustness. The derivative term (D=0.0032) provides essential damping against the flexibility of the carbon fiber arms.

VII. EXPERIMENTAL RESULTS AND ANALYSIS

Physical flight tests were conducted to validate the framework. The powertrain (930KV motors, 10x4.5 propellers) provided a measured endurance of 6.3 minutes.

Attitude Tracking: Flight log analysis showed roll and pitch RMS tracking errors of 1.6° and 1.4°, respectively, even during aggressive maneuvers.

Altitude Stability: Autonomous hovering tests constrained altitude errors within ±0.5 m, demonstrating the effectiveness of the EKF in maintaining vertical velocity.

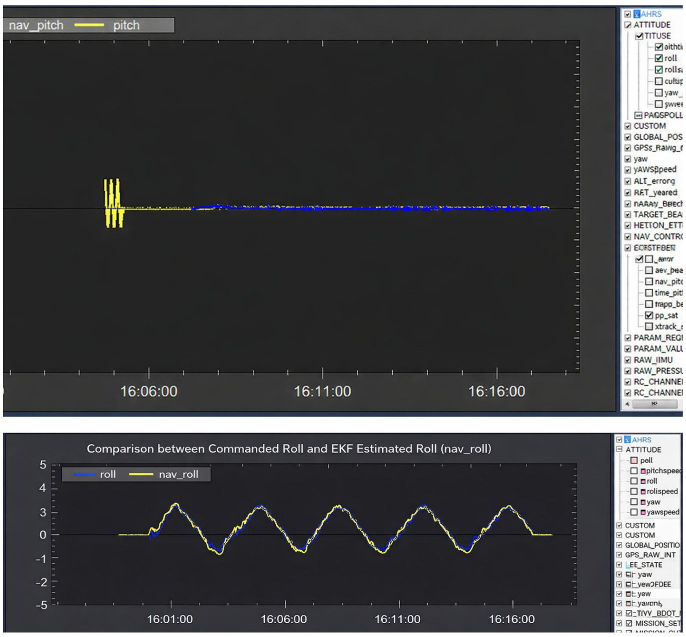

Fig. 5 & 6. Comparison between Commanded Attitudes and EKF Estimated Attitudes during flight.

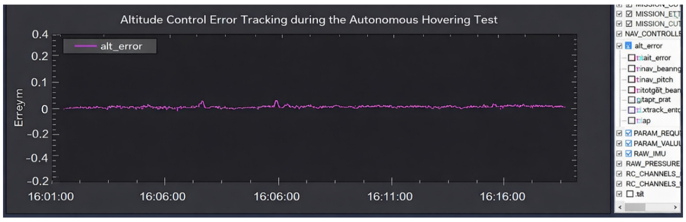

Fig. 7. Altitude control error tracking during the autonomous hovering test.

VIII. EDUCATIONAL IMPACT AND LIMITATIONS

To highlight the advantages of the proposed open-architecture design, a comparative analysis was performed against popular educational and research UAV platforms based on cost, weight, architectural openness, and tracking performance. While commercial systems like the DJI Mini (Edu) and Parrot ANAFI provide high flight stability, they are fundamentally "closed systems" that restrict access to internal dynamic models and control architectures. Conversely, micro-scale platforms such as the Crazyflie 2.1 are fully open-source but are limited by their physical scale (0.027 kg) and typically exhibit higher attitude tracking RMS errors (>3°). The proposed platform maintains a physically meaningful scale of 1.2 kg, provides full access to all control and estimation layers, and achieves superior attitude tracking with RMS errors below 2°, all while maintaining a competitive cost under $600.

TABLE 1. COMPARISON WITH EDUCATIONAL UAV PLATFORMS

Platform	MTOW (kg)	Open Architecture	Control Access	Cost (USD)	Attitude RMS Error
DJI Mini (Edu)	0.249	No	No	>400	N/A
Parrot ANAFI	0.32	Limited	Limited	>700	N/A
Crazyflie 2.1	0.027	Yes	Yes	~250	>3°
Proposed Platform	1.2	Yes	Full	<600	<2°

Limitations. Despite the positive experimental validation, the current research identifies specific limitations that should be noted for future development. First, the navigation system is currently reliant on GPS measurements for outdoor positioning; this dependency can introduce noise or latency that impacts the Extended Kalman Filter's (EKF) velocity estimation accuracy, especially in signal-degraded environments. Second, the aerodynamic modeling utilized in this study involves deliberate simplifications, such as treating the airframe as a slender body and neglecting higher-order drag effects. While these assumptions are acceptable for standard hovering and low-speed maneuvers, unmodeled aerodynamic disturbances may become more pronounced under high-wind conditions. These limitations offer valuable educational opportunities for future work, focusing on the refinement of robust control under uncertainty and the implementation of concurrent learning adaptive algorithms to compensate for such modeling gaps.

Specifically, these modeling inaccuracies—stemming from the slender body approximation and the neglect of higher-order drag—directly influence the performance of the cascaded PID controller when subjected to environmental wind. In such conditions, unmodeled aerodynamic forces manifest as persistent disturbances that primarily task the integral (I) term of the PID loops. While the I-gain is designed to compensate for steady-state errors caused by asymmetries or constant wind, it is intentionally limited to 400 µs to prevent integrator wind-up. Consequently, in strong or sustained winds, this constraint may lead to residual tracking offsets as the controller reaches its predefined integration limits. Furthermore, wind gusts introduce high-frequency perturbations; although the derivative (D) term provides necessary damping against structural flexibility, the required 10 Hz digital low-pass filter (DLPF)—while essential for EKF stability—introduces a subtle phase lag. This lag can limit the effective bandwidth of the controller, potentially reducing its ability to reject very rapid turbulence and leading to the observed RMS tracking errors during aggressive maneuvers.

IX. CONCLUSION

The developed platform demonstrates that a 100% hackable, open-architecture UAV can achieve industrial-grade performance. By integrating a 10 Hz DLPF to stabilize the 15-state EKF and a specialized teeth-type claw mechanism, this research provides a validated baseline for advanced autonomous environmental interaction tasks in the aerospace domain. Future work will explore concurrent learning adaptive control to further reduce error under varying payload masses.

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