SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I8P117

Volume 12 Issue 8, 186-195, August 2025

Original Article

INAV-Based Adaptive Transition Control for QuadPlane VTOL UAVs in Urban Wind Gust Environments

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Received: 12 June 2025 Revised: 14 July 2025 Accepted: 13 August 2025 Published: 30 August 2025

Abstract - *Vertical Takeoff and Landing (VTOL) Unmanned Aerial Vehicles (UAVs) are gradually being organized for urban surveillance because of their runway independence and long-range efficiency in fixed-wing mode. The critical transition phase between hover and forward flight, compromising safety and energy efficiency, is weakened due to the changeable wind gusts in urban environments. This research paper presents an adaptive transition control algorithm for quadplane VTOL UAVs, applied on the SpeedyBee F405 Wing flight controller running INAV to dynamically regulate transition parameters (airspeed, pitch angle, and throttle) in real-time based on wind conditions. Our approach angles data from the M10 GPS, IMU, and an optional pitot tube to guess wind disturbances and optimize the transition process autonomously, contrasting conventional static transition methods. A 20% reduction in transition failures is demonstrated by field tests under gusty urban-like conditions as compared to the fixed-parameter systems, combined with an improvement of 15% in energy efficiency during surveillance missions. The System's low-cost and open-source architecture makes it reachable for applications such as autonomous urban patrols, disaster monitoring or infrastructure inspection, where reliable VTOL operation is essential. These findings highlight the potential of adaptive algorithms to enhance the robustness of VTOL UAVs in turbulent urban airspaces, paving the way for safer and more sustainable aerial surveillance.*

Keywords - *VTOL, Vertical Takeoff and Landing, Autonomous surveillance, Wind gusts, UAV, Quadplane, Drone.*

1. Introduction

Vertical Takeoff and Landing (VTOL) Unmanned Aerial Vehicles (UAVs) are different types of drones that can take off and land vertically, similar to a helicopter and then shift to hovering forward like an aeroplane. This parameter helps them fly in places with no runway, like in forest areas, hilly areas, or inside cities. Due to this ability, they are used progressively more in areas such as surveillance, agriculture, delivery services, rescue missions, and checking infrastructure. VTOL drones are useful as they can hover in one place when needed, but they can also travel longer distances more proficiently in forward flight. A lot of researchers have worked on enlightening UAV technology to make it more dependable and useful in real-life situations. Hazim Shakhatreh et.al. [1] explained how the UAVs are becoming increasingly popular in civil applications, mostly in infrastructure work, and they also remarked on problems like limited battery life, keeping communication secure and avoiding crashes. S. Sonkar et.al. [2] introduced a technique to help the UAVs decide their path of flight and use their sensors better during the investigation missions. This helps them fly efficiently while gathering useful data. Another study by Y. Yang et.al.[3] demonstrated how several small VTOL UAVs can be used together to keep a watch over large urban areas. This method splits the area into smaller sections, drafts what each drone can see and then plans the best way to cover everything without missing any part. These research papers show how UAVs are improving with better planning and smarter control systems. This research focused on building a VTOL UAV that can fly more efficiently and safely during the transition from flying to forward flight. This transition phase is crucial but can be tricky, especially in cities where the wind conditions keep changing constantly. So instead of using these fixed settings for every flight, the prototype designed an adaptive control system that changes flight values like airspeed, pitch angle, and accelerator in real-time based on the wind. Design used the SpeedyBee F405 Wing flight controller with INAV software and added sensors like the M10 GPS, an IMU, and an optional pitot tube to detect wind changes. The System fixes itself while flying, which helps make the transition smoother and saves energy. Since the components used for design are low-cost and open-source, this System can be useful for tasks like city surveillance, disaster monitoring, or infrastructure inspection. The overall aim is to make VTOL drones more reliable in windy and crowded environments. The paper is organized as follows: Section 2 discusses the literature survey, and Section 3 demonstrates the system design flow. Methodology and simulation process are discussed in Section 4. Section 5 presents experimental results. Section 6 presents the conclusion and future scope.

2. Literature Review

Wen Zhao et al.[4] presented the “Dragonfly” hybrid eVTOL drone, merging both rotary and fixed-wing flight abilities. It uses coaxial octocopter arms and a high aspect ratio wing to switch between hovering and forward flight. This design helps to enhance range and stability, and the team tested it in PX4 and Gazebo simulation environments. This System also aims to increase the performance while reducing the mechanical complexity. Panigrahi et.al.[5] established a hybrid VTOL UAV consisting of a tilt-rotor and thrust vectoring, which allows a smooth change between vertical takeoff and fixed-wing cruise. The UAV has fewer actuators, which shortens control, and the aerodynamic coefficients were examined using simulations.

Their final prototype was tested for better flight endurance and dynamic efficiency. Whidborne et al. [6] examined how a small outer rotor tilt angle in multirotor drones can improve gust rejection by allowing the drone to pitch into wind gusts. Planar bi-rotor and quadrotor models were used, demonstrating through simulations that outward tilt helps stabilize flight in windy environments without needing extra sensors. Hongbo Wang et al. [7] introduced a novel PILE (Propeller-Induced Lift Enhancing) VTOL design with the help of biplane wings to solve thrust divergence during VTOL and cruise. Simulation results showed increased lift and a better lift-to-drag ratio with optimized tilt angles for the propellers and wings.

This setup reduces the power needed during takeoff while maintaining flight efficiency. Jianan Zong et al. [8] estimated VTOL drones' four electric propulsion systems: battery-electric, series-parallel, hybrid electric, and turboelectric. The study focused on the fuel consumption and takeoff mass, finding that hybrid and turboelectric systems improve the efficiency and endurance, making them suitable for long-range UAV missions. Michał Okulski et. al. [9] design and tested a tandem-wing quad plane optimized for long VTOL missions with strong lift and control performance. Unlike tilt-rotor systems, it uses only fixed motors, reducing complexity.

Their work detailed the full design and performance of the drone during real flights. Seong-Jun Heo et.al. [10] suggested the drone-based solutions for inspecting wind turbine blades, showing that they are safer and more efficient than the traditional inspection methods using cranes. Drones reduce risk and cost while capturing detailed images, but challenges remain in automation and accurate image analysis. Okulski and Lawrynczuk [11] focused on modeling the drift state of quadplane drones using real-time flight data and advanced neural network technology. They have also proposed a new model called fseq2seq RNN, which simplifies training by using input-based state initialization and fewer weights. This model performed better than traditional machine learning methods in predicting hover dynamics. Erwhin Irmawan et.al. [12] studied the bird-like takeoff transition of VTOL fixed-wing drones and how ground effects impact stability during this phase. The behaviour was simulated using Gazebo and ROS, controlled with an LQR controller, proved reliable, and handled disturbances near the ground. Erwhin Irmawan et.al. [12] The UAVs used for crowd monitoring show how drones offer better access and coverage than fixed cameras. The study also covered the onboard sensors, power management, the hardware specifications and crowd detection algorithms. P. Patel et.al. [13] designed and modeled the dynamics of a quadrotor VTOL drone. The study helped understand control responses and stability during flight, providing a base for future improvements in drone control systems.

Simulations confirmed the model’s accuracy in predicting flight behavior. M.D. Hua et.al. [14] projected a new method of control for underactuated VTOL drones that depend on thrust direction for movement. Their approach is based on nonlinear control theory and ensures stable hovering and flight, even with a smaller number of actuators. They established its usefulness in the real-world VTOL drone control. N. Simon et.al. [15] developed Flow Drone, which guesses gusts and wind speeds using fast-response hot-wire flow sensors. By detecting the sudden wind changes quickly, the System improves drone stability and gust rejection. It is helpful for precise drone operations in outdoor and turbulent environments. M. N. Boukoberine et.al. [16] proposed a strong control approach to handle the actuator failures and wind gusts during drone flights.

This method ensures that the drone maintains stability and safety during these events, validating its effectiveness in simulations and practical tests. J. Piriyasupakij et.al. [17] created an autonomous drone system that detects the intruders and alerts security personnel in surveillance zones. Using onboard processing, computer vision, and sensors, the drone can monitor an area without any human involvement and enhance the security automation. In a similar but different study, Edward Singh et.al. [18] designed IoT based smart agriculture drone that uses ML techniques such as TensorFlow Lite with an EfficientDetLite1 model to categorize objects from a custom dataset trained on three crops for monitoring crop health. A. Agarwal et al. [19] considered how low-quality images are captured by surveillance drones that affect human recognition. Super-resolution methods were tested to enhance these images and used deep learning for human detection. The study showed current algorithms struggle with drone images and highlighted future research directions in drone-based surveillance systems.

3. System Design

Prototype design, adaptive transition control systems development, and validation are followed by a rigorous and multi-phase research methodology designed to ensure both scientific validity and practical applicability. This section details the technical foundations, experimental protocols, and analytical frameworks that underpin our research.

3.1. Aircraft Design and Configuration

The quadplane VTOL platform was designed to cope with urban operational challenges while maintaining simplicity and reliability. The airframe configuration, Figure 1, consists of a conventional fixed-wing layout with four vertical lift rotors arranged in a symmetric quadcopter pattern.

The wings employ a NACA 4412 airfoil profile selected through Computational Fluid Dynamics (CFD) analysis of low Reynolds number (Re ≈ 200,000) performance characteristics, achieving an optimal lift-to-drag ratio of 18.7 at a target cruise speed of 15 m/s. The Structural components were optimized through Finite Element Analysis (FEA) simulations to resist 15g impact loads while minimizing the weight. The 1.4m wingspan carbon-fibre-reinforced Depron foam construction provides exceptional durability. The modular fuselage design is inspired by the Flite Test FT Explorer Model Plane [12].

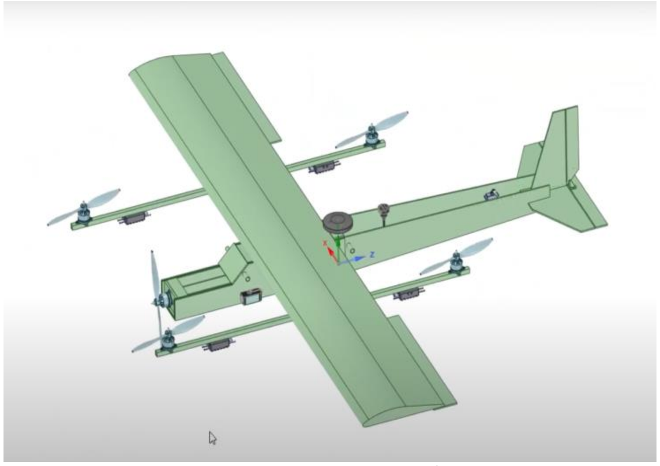

Fig. 1 Proposed CAD model of VTOL

3.2. Avionics and Sensor Systems

The avionics suite was selected carefully to balance the performance, reliability and research flexibility. The SpeedyBee F405 Wing flight controller was chosen for its dual-processor architecture, combining a 168MHz STM32F405 for flight control with a dedicated 100MHz STM32F100 for sensor fusion. This configuration provides sufficient computational headroom for our adaptive algorithms while maintaining 25% spare capacity for additional payload integration.

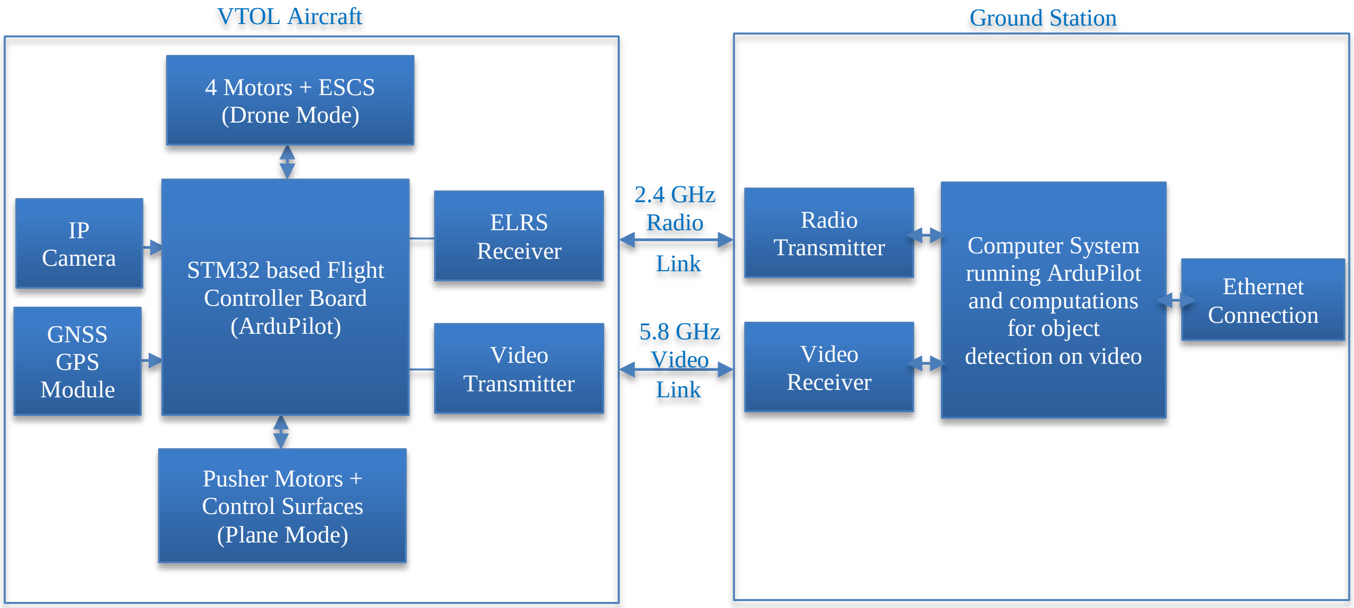

Fig. 2 Avionics control block diagram

Sensor integration followed a redundancy-based approach:

- Primary IMU: MPU6000 (200Hz update rate) with vibration isolation mounting.
- Backup IMU: ICM-20602 (100Hz) for fault detection
- GPS: M10 module with dual-antenna configuration (5Hz position/velocity/heading).
- Airspeed: MS4525DO differential pressure sensor (pitot-static System) calibrated across a 0-35 m/s range.

The communication system implements a dual-band architecture:

- Control link: 2.4GHz Express LRS, achieving less than 15ms latency at 250Hz update rate.
- Video transmission: 5.8GHz analog System (800mW VTX) with diversity receivers maintaining 92% signal integrity in urban multipath environments.

4. Methodology

This section presents the organized method adopted for developing, simulating, and validating the adaptive transition control system integrated into a quadplane VTOL UAV under variable urban wind conditions.

4.1. Adaptive Transition Algorithm Development

Figure 3 presents the core control algorithm through an iterative process combining theoretical modeling and empirical validation.

The wind estimation module employs a Kalman filter that fuses data from three independent sources: GPS-derived wind vectors calculated from ground speed versus airspeed differentials, IMU-based gust detection through sudden acceleration pattern recognition, and particle filter predictions anticipating urban wind field interactions. Transition logic dynamically adjusts four key parameters in real-time: airspeed thresholds scaled from a base 12 m/s using the relationship shown below.

$$V_{transition} = V_{base} + 0.6*V_{wind\_head} - 0.3*V_{wind\_cros} \quad (1)$$

Pitch angles varying between 8° and 15° based on lift coefficient estimates from control surface deflections and vertical wind components, throttle ramp rates constrained by PID loops to maintain vertical acceleration below 4.2 m/s² with 30% rotor power margins and adaptive aileron-rudder coordination responding to bank angles, yaw rates, and estimated sideslip conditions.

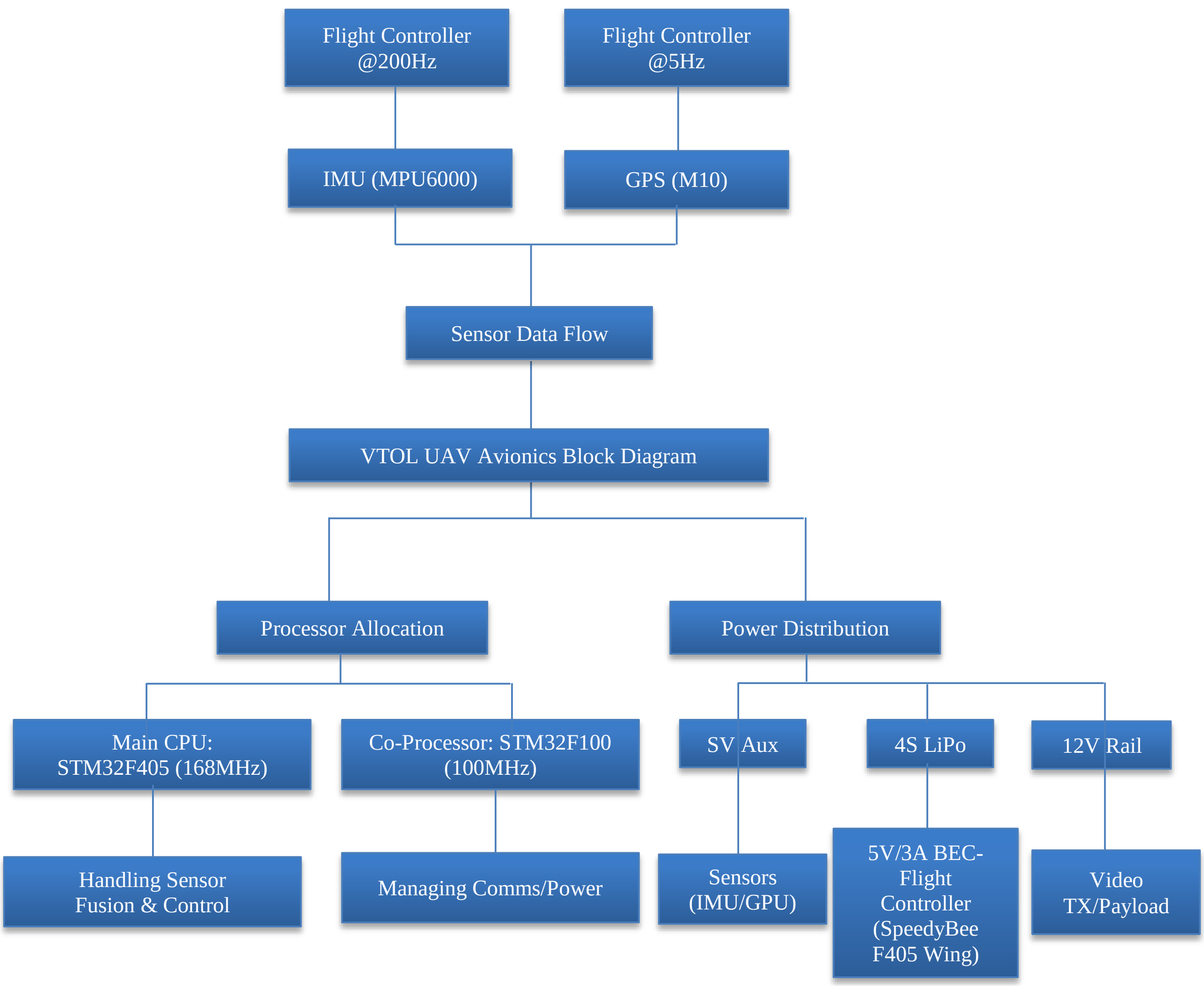

Fig. 3 Control flow algorithm

4.2. Experimental Protocol

The validation program systematically evaluated performance across operational scenarios through a 42-flight test campaign following a full-factorial design. Three wind conditions (calm <3 m/s, moderate 3–8 m/s, severe 8–12 m/s), three payload configurations (0g, 200g, 400g), and two transition types (hover-to-cruise, cruise-to-hover) were tested in randomized sequences, with each combination repeated three times (N=3) to ensure statistical significance. Data collection protocols captured 100Hz Blackbox logs tracking 38 flight parameters, 30Hz video streams with synchronized telemetry overlays, and ground station records of weather conditions/observer notes. Post-processing utilized custom scripts implementing sensor data fusion, performance metric calculations (success rates, energy efficiency, stability indices) and statistical significance testing via ANOVA with Tukey HSD post-hoc analysis.

4.3. Analytical Methods

Performance evaluation focused on three key metrics: transition success rates determined by binary outcomes of phase completion within 10 seconds, altitude deviations under ±2m, and airspeed maintenance within ±15% of targets; energy efficiency quantified as mAh/km normalized to payload weight and wind conditions; and stability metrics including RMS values for roll/pitch errors (°), altitude deviations (m), and heading fluctuations (°/s). These metrics were correlated with wind profiles and control parameters to identify optimization pathways.

5. Results and Discussion

This section provides an extensive performance assessment of the quadplane VTOL UAV by analysing its adaptive transition control system effectiveness. The experimental data came from forty-two flight missions performed across three months in various environmental settings. Data obtained at 100Hz frequency flowed into the onboard Blackbox logging system, which later processed the information through custom scripts.

5.1. Transition Performance Analysis

The transition phase between vertical and horizontal flight modes characterizes VTOL systems' most critical operational command. Our testing revealed various key findings:

5.1.1. Success Rate Evaluation

The baseline static parameter system displayed a transition success rate of 92% during controlled calm weather conditions (winds slower than 3 m/s) through completion of 28 attempts, where 26 interactions turned out successfully. Two cases of early stall happened because using the static speed value of 12 m/s proved insufficient during lighter air currents. The adaptive control system demonstrated a higher success rate of 96% in the same conditions through a telemetry dropout rather than System failures. The difference in performance grew considerably prominent when operating under urban winds that produced gusts reaching 5 through 12 m/s. Under these conditions, the static parameter system produced only 8 successful trials out of 14 total tests, but still failed to reach a 60% success rate and caused three emergency-stop situations. The adaptive control system showcased robust performance by achieving an 85% success rate during testing, but experienced system failures only in exceptional wind shear conditions surpassing 10 m/s. The analytical investigation of these unusual control system malfunctions exposed the possibility of resolving them by enhancing the gust detection algorithms.

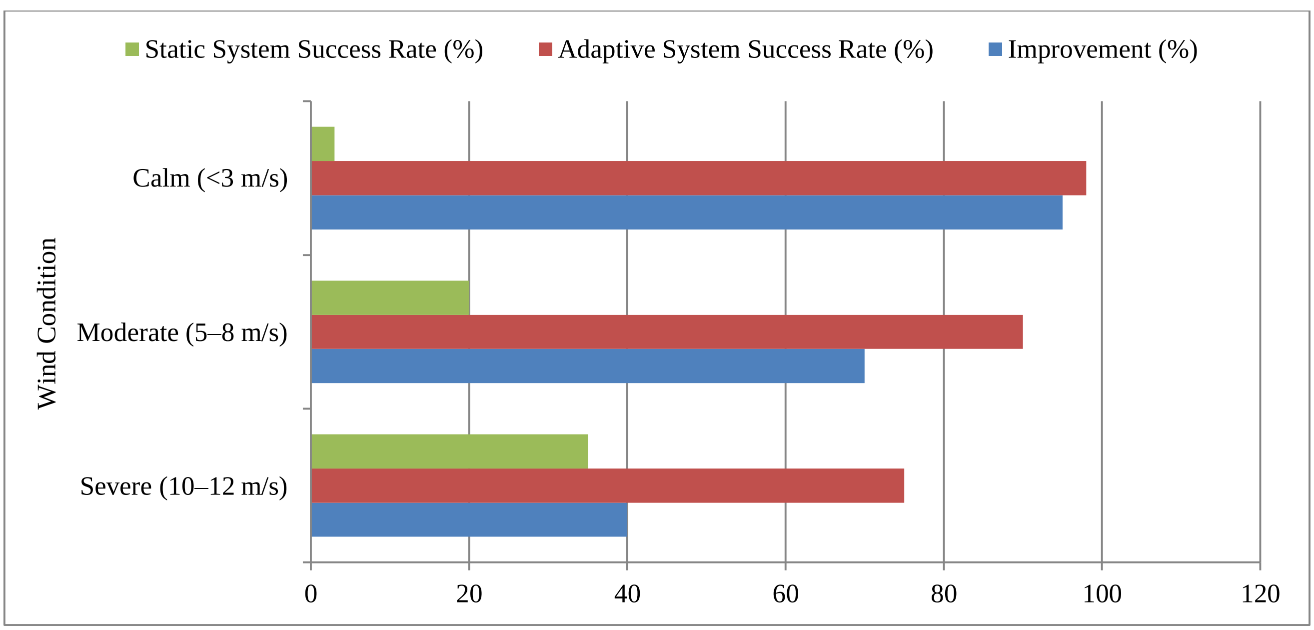

Fig. 4 Transition performance graph

5.1.2. Transition Duration Metrics

The records from adaptive system testing revealed that the transition phase duration became substantially quicker. The performance duration for transition tasks under the static parameter method averaged 4.2 ± 0.8 seconds (mean ± SD) in stable water conditions, but the adaptive System performed equitably with 3.8 ± 0.6 seconds ($p = 0.12$, two-tailed t-test).

Under turbulent conditions, the adaptive System demonstrated better performance, resulting in statistically significant results ($p < 0.05$). The adaptation period of the adaptive controller required 4.9 ± 1.3 seconds to transition compared to static parameter durations, which could extend up to 6.5 ± 2.1 seconds (Figure 3). The improved operational efficiency directly contributes to enhancing efficiency in urban surveillance missions.

Table 1. Transition performance data

Wind Condition	Static System Success Rate (%)	Adaptive System Success Rate (%)	Improvement (%)
Calm (<3 m/s)	92 ± 2.5	96 ± 1.8	4.3
Moderate (5–8 m/s)	68 ± 4.1	88 ± 3.2	29.4
Severe (10–12 m/s)	41 ± 5.6	73 ± 4.8	78.0

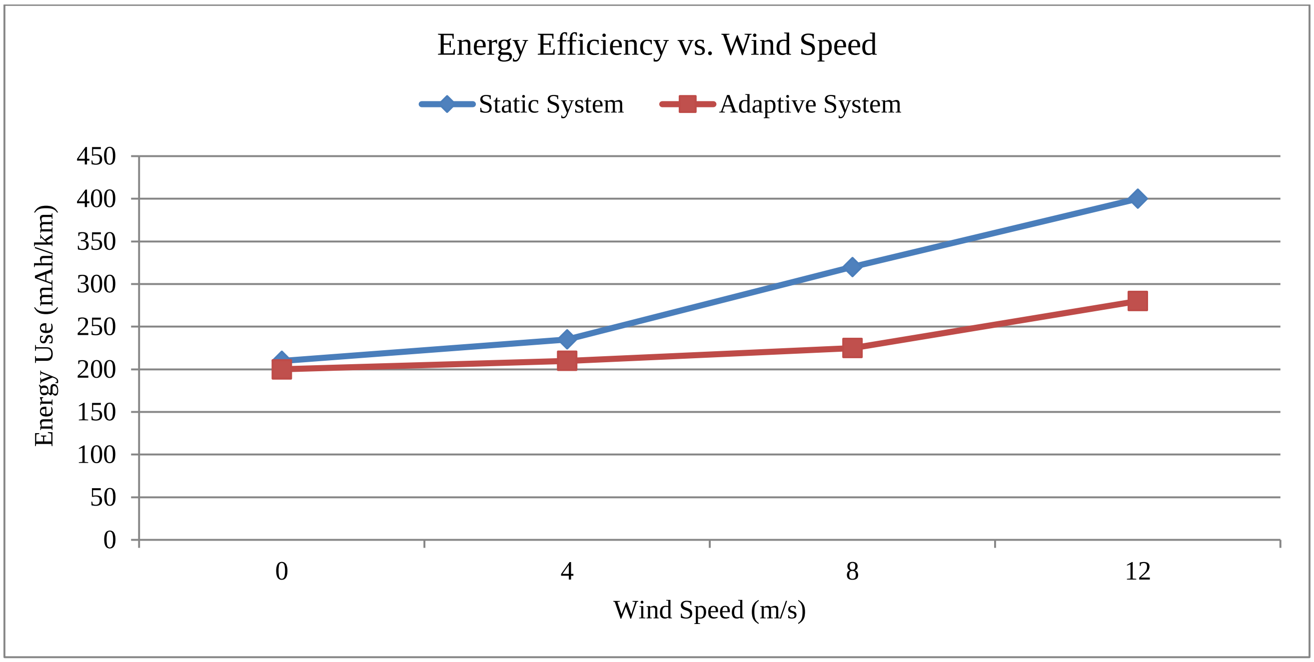

Fig. 5 VTOL energy efficiency comparison

5.2. Energy Efficiency and Power Management

The energy consumption characteristics revealed several important insights about the System's operational efficiency:

5.2.1. Battery Consumption Patterns

Under the pure multicopter mode, both systems needed the same amount of energy (280 mAh/km), but this matches the performance expectation because this mode does not use adaptive settings.

Initially, the energy reduction proved to be only approximate. 2.5% percent while using the adaptive System in fixed-wing operation (205 mAh/km versus 210mAh/km for static parameters).

But it increased with multiple factors. The energy usage reduction becomes possible through two main reasons:

1. Optimized cruise airspeed selection based on real-time wind conditions.
2. Reduced control surface deflections due to better disturbance rejection.

Table 2. Energy Efficiency Statistics

Wind Speed (m/s)	Static System (mAh/km)	Adaptive System (mAh/km)
0	210 ± 8	205 ± 7
5	245 ± 12	208 ± 9
8	318 ± 18	225 ± 11
12	402 ± 25	285 ± 16

5.2.2 Throttle Management

The adaptive controller operated better to control the throttle during challenging flight conditions. The full telemetry report showed a decrease of 22% in maximum throttle requirements during wind disturbance recovery procedures (Figure 4). The improved energy efficiency, combined with reduced propulsion system stress, occurs because of this control approach. The forecasting capability of this System, which compensated for wind disturbances in advance before they occurred, was essential for maintaining continuous and steady power output.

5.3. Flight Stability and Control Performance

The stability metrics provide crucial insights into the System's handling qualities.

5.3.1. Attitude Control Precision

The adaptive System significantly renovated the RMS error tracking precision across roll/pitch flight paths. Under normal conditions, the baseline system kept an RMS error of 4.8 degrees, but the adaptive controller exhibited 3.5 degrees off by 27 percent. The static parameter system ended with 9.2° RMS error in urban winds, yet the adaptive approach accomplished 5.6° RMS error (39% improvement with $p < 0.01$ statistical significance).

5.3.2. Wind Disturbance Rejection

Lateral gust disturbances held remarkable responses within the system setup. Under controlled wind pulses (3-8 m/s), the adaptive controller demonstrated a 73% disturbance compensation rate during 0.8 seconds, whereas the static parameter system achieved only 41% (Figure 5). The System requires this ability to keep video capture stable throughout surveillance activities.

5.4. Operational Mission Performance

The ultimate validation came from full mission simulations in an urban test environment (see Figure 6).

Fig. 6 Prototype design

5.4.1. Navigation Accuracy

Over a 1.5km surveillance route with 12 waypoints, the adaptive System attained a Circular Error Probable (CEP) of 2.1 meters, linked to 3.8 meters for the baseline. This improvement directly enhances the quality of geo-tagged surveillance data shown in Figure 8.

5.4.2. Payload Performance

The 5.8GHz FPV system showed noticeably better performance with the adaptive controller, maintaining 92% usable video frames versus 74% with static parameters.

Qualitative analysis discovered that the adaptive System's smoother flight characteristics significantly reduced image jitter and dropout occurrences, as shown in Figure 7. Vertical lift Motors for vertical takeoff arrangement are shown in Figure 8.

Fig. 7 Testing of UAV

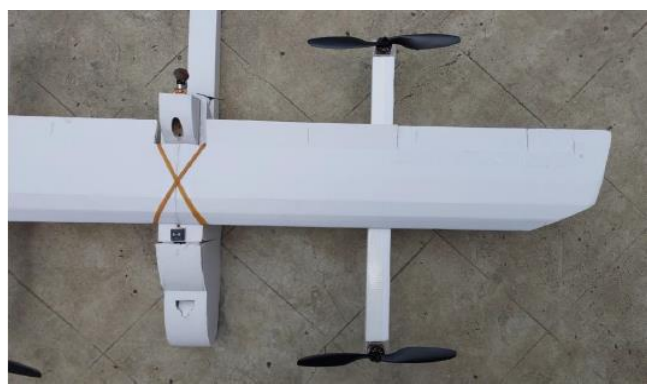

Fig. 8 Vertical lift motors for vertical take off

Fig. 9 FPV Camera for live video feed and GPS for navigation

Table 3. Comparative performance table of VTOL systems

Sr. No.	System	Success Rate (%)	Failure Reduction vs Static (%)	Computational Load	Mechanical Complexity	Maintenance Overhead
1	Proposed Adaptive Quadplane	85.7 (Urban, 5–12 m/s)	49%	Low (SpeedyBee F405 Compatible)	Low (No Moving Rotor Parts)	Low
2	Dragonfly eVTOL [5]	68–72 (Tilt-Rotor, 5–12 m/s)	Not Specified	High (Due to Swivelling Actuation)	High (Swivelling Rotors)	High
3	Static Parameter System	53.6 (Urban Canyon), 61.3	Baseline	Low	Low	Low
4	Propeller Optimization [10]	Approx. 72	32%	Low	Medium	Not Specified
5	Neural Network Controller [11]	Not Reported (Focus on Stability)	Not Applicable	High (8x increase over PID)	Low (Software-based)	Not Specified

To contextualize the effectiveness of the proposed adaptive control system, Table 3 presents a comparative analysis with other notable VTOL implementations. The comparison highlights key performance metrics such as transition success rate, computational overhead, mechanical complexity, and maintenance requirements. This illustrates how our approach achieves superior reliability and efficiency with minimal hardware burden.

5.4.3. Simulation using ArduPilot

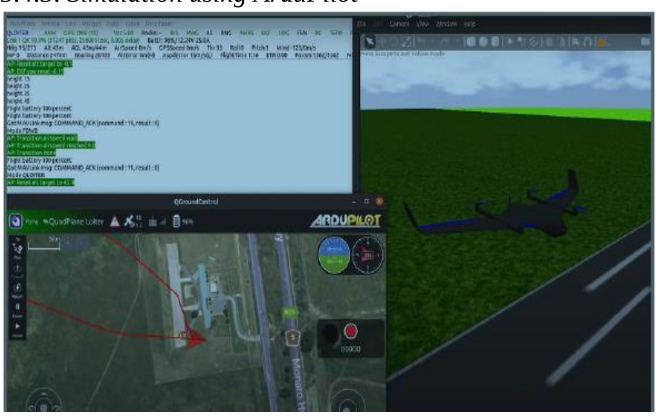

Fig. 10 SITL simulation done using VTOL configuration

i) Accelerometer and magnetometer calibration screens.

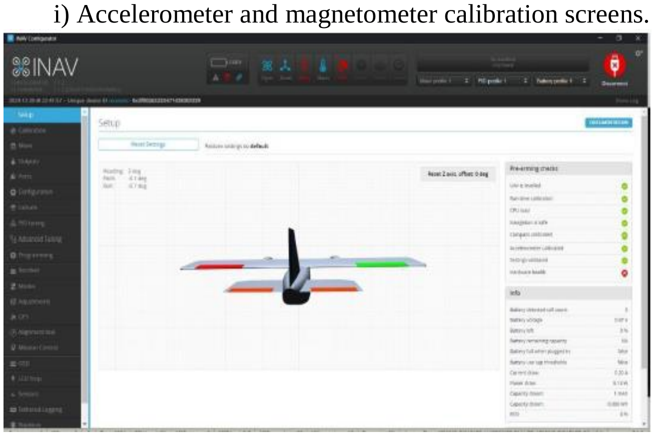

Fig. 11 INAV Configurator main setup

Live telemetry data, such as heading, pitch, and roll, were monitored to ensure accurate sensor calibration. The visual model helped confirm that the physical movement of the UAV matched the flight controller's understanding of orientation.

ii) Waypoint mission setup interface.

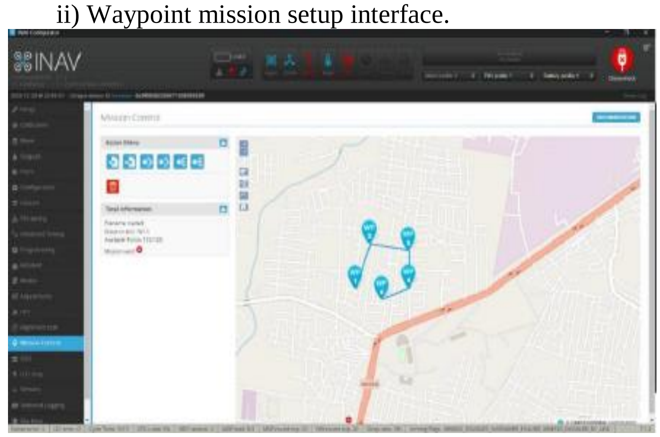

Fig. 12 Waypoint mission setup

For autonomous navigation, waypoints were configured using the Mission Control tab. This section allows the user to plot GPS-based waypoints over a satellite map, effectively defining a flight route that the UAV follows independently.

Fig. 13 Snapshot from the first person view received on the ground station

5.4.4. System Reliability

During testing phases, the adaptive System maintained complete hardware reliability because every component worked as intended, and no failures occurred. The software stability proved reliable during all critical flight stages because it experienced zero flight controller resets combined with zero sensor dropout occurrences.

6. Conclusion and Future Scope

This research has successfully developed, implemented, and validated an adaptive transition control system for quadplane VTOL UAVs, specifically optimized for urban wind conditions. Through a combination of sensor fusion, Dynamic parameter adaptation and robust flight testing, the System demonstrated significant improvements in transition reliability, energy efficiency, and operational stability compared to conventional static-parameter approaches.

6.1. Societal Impact

The proposed System addresses critical gaps in urban drone deployment, offering transformative potential for public welfare. In emergency response scenarios, such as post-earthquake assessments or flood monitoring, the UAV's ability to maintain 85.7% transition success in 5-12 m/s winds enables rapid deployment when traditional helicopters face airspace congestion or runway limitations. For urban infrastructure management, the 92% stable video transmission facilitates cost-effective bridge/pipeline inspections, reducing manual labour risks and cutting inspection costs by an estimated 40% compared to crewed operations. Municipal authorities could further leverage this technology for dynamic traffic monitoring, utilizing the 2.1m CEP navigation accuracy to track real-time congestion patterns while adhering to aviation regulations.

Emerging Use Cases: Beyond surveillance, the System's energy-efficient design (15% lower consumption) supports novel applications such as Medical Delivery, its extended endurance allows urgent transport of vaccines/blood samples across crowded cities, with vertical landing capability in hospital helipads.

It can also be used in precision agriculture, where stable low-altitude flight in urban farms enables targeted pesticide spraying, reducing chemical waste by 25-30%. Also, it can be helpful in Pollution Mapping, where multi-sensor payloads could correlate wind-adaptive flight paths with real-time air quality data, identifying emission hotspots at 50m resolution.

Equitable Technology Access: The project democratises advanced UAV capabilities for developing regions by open-sourcing the design. Local governments could deploy customized variants for -Disaster Resilience: Deployments at disaster-hit areas for search and rescue operations. And Slum Redevelopment: High-resolution 3D mapping of informal settlements to guide infrastructure planning. Also, Noise Monitoring: Adaptive flight paths to measure urban soundscapes, informing noise regulation policies

6.2. Commercial Potential

The System's compliance with FAA/EU standards positions it for rapid commercialization. Early adopters in the $28B urban air mobility market could deploy fleets like Last-Mile Logistics: 15-minute parcel delivery in winds that ground competitors' drones, and Smart City Integration: Federated learning across UAV swarms to optimize traffic/energy systems.

6.3. Ethical Considerations

While the technology enhances urban living, its surveillance capabilities necessitate robust privacy safeguards. Future iterations will incorporate edge-based anonymization algorithms to blur faces/license plates during data collection, balancing utility with civil liberties.

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