Aves Recon: Development of an IoT-Enabled Ornithopter for Covert Aerial Surveillance

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Abstract—**This paper presents Aves Recon, a novel IoT-enabled biomimetic ornithopter designed for covert aerial surveillance. The system mimics avian flapping-wing locomotion using an 84:1 gearbox-driven crank mechanism operating at 5–7 Hz, achieving a measured thrust of 367 g from a 400 g flight-weight airframe constructed from carbon fiber and ripstop nylon. An ESP32 microcontroller integrates dual-core flight control (PID, 100 Hz), LoRa long-range communication (SX1278, 433 MHz, SF9, measured packet loss 1.9% at 500 m), Wi-Fi-based FPV video streaming (ESP32-CAM, 640×480, 15 fps, 120ms latency), MPU6050 inertial measurement (±0.3 static accuracy, 1.8 s convergence), and HC-SR04 ultrasonic obstacle sensing. A cloud-based MQTT dashboard hosted on AWS with Node-RED visualization provides real-time telemetry and remote command capability. Blade Element Momentum (BEM) aerodynamic analysis predicts 488 g lift at 6.5 Hz, providing a 15% margin over the 450 g all-up weight target. Power budget analysis projects 18.5-minute flight endurance on a 3S 2200mAh LiPo battery. MATLAB/Simulink and Gazebo/ROS simulation environments validate the control architecture prior to hardware deployment. The full system component cost is approximately INR 12,740 (USD ~153), demonstrating accessibility for academic research deployment. This paper details the complete design methodology spanning aerodynamics, mechanical design, electronic architecture, firmware, simulation, and experimental observations, addressing identified gaps in IoT integration, cloud dashboards, and payload capacity in existing ornithopter literature.**

Index Terms—**Ornithopter, Biomimetic UAV, IoT Surveillance, ESP32, Flapping-Wing Robotics, LoRa Communication, MPU6050, Covert Aerial Monitoring, Blade Element Method, PID Control.**

I. INTRODUCTION

A. Background and Motivation

Unmanned Aerial Vehicles (UAVs) have become indispensable tools in modern defense, surveillance, agriculture, disaster management, and environmental monitoring. The conventional rotary-wing multirotor and fixed-wing platforms, despite their utility, suffer from significant limitations in covert operations: high acoustic signatures, rigid mechanical silhouettes, and easily identifiable flight patterns render them unsuitable for sensitive reconnaissance environments. Ornithopters aircraft that achieve flight through oscillatory flapping-wing motion analogous to birds and bats offer a compelling alternative paradigm. Their bio-inspired locomotion inherently blends into outdoor environments, produces substantially lower acoustic emissions compared to rotor-driven UAVs, and enables agile, non-linear flight trajectories that rigid-wing platforms cannot replicate. The flapping frequency of natural birds ranges from 2 Hz (large raptors) to 40 Hz (hummingbirds), generating lift and thrust simultaneously through complex aeroelastic interactions.

The integration of Internet-of-Things (IoT) frameworks with bio-inspired ornithopter platforms opens new frontiers in covert aerial intelligence gathering. Real-time sensor telemetry, cloud-based monitoring dashboards, and long-range wireless links transform a mechanical curiosity into a practical surveillance asset. Despite growing interest in flapping-wing robotics, a critical gap remains: no existing ornithopter design fully integrates IoT communication, real-time cloud dashboards, and modular sensor payloads for live surveillance deployment. This paper presents Aves Recon a system name inspired by the Latin classification of birds (class Aves) and aerial reconnaissance developed at Vivekanand Education Society's Institute of Technology (VESIT), Mumbai. The project is a Semester VII capstone effort by Ohm Squad-1 of the Department of Electronics and Telecommunication, under the mentorship of Dr. Monali Chaudhari. Aves Recon addresses identified research gaps by combining a mechanically efficient flapping-wing platform with an ESP32-based IoT architecture, LoRa long-range communication, FPV video streaming, and autonomous IMU-based stabilization.

B. Scope and Objectives

The primary objectives of Aves Recon are:
(1) to design and fabricate a lightweight biomimetic ornithopter capable of sustained flapping-wing flight;
(2) to integrate onboard IoT-enabled sensors for covert visual and environmental surveillance;
(3) to implement real-time bidirectional communication using LoRa and Wi-Fi protocols;
(4) to develop a cloud-based dashboard for remote monitoring and control; and
(5) to validate the system through structured simulation and hardware testing phases.

C. Paper Organization

The remainder of this paper is organized as follows: Section II reviews related literature. Section III identifies research gaps. Section IV presents the problem statement. Section V describes the proposed solution. Section VI details the aerodynamic and mechanical design. Section VII presents the electronic architecture. Section VIII covers the firmware and software design. Section IX describes the simulation framework. Section X presents experimental observations. Section XI outlines the project timeline, and Section XII concludes with future work directions.

II. LITERATURE SURVEY

A. Bio-Inspired Flight Control

Ruiz and Acosta [1] developed optimal perching trajectories and a nonlinear adaptive controller for fixed-wing UAVs based on bird dynamics. Their work demonstrated that bio-inspired perching maneuvers can achieve energy-efficient landing with minimal actuation, providing theoretical underpinning for bio-inspired flight control laws. However, the study was limited to simulation and lacked hardware integration or real-time IoT communication.

Haider et al. [4] proposed a dynamic mathematical model and agile control logic for ornithopter UAVs validated in MATLAB/Simulink. Their study showed that PID-based flapping frequency modulation substantially improved attitude stability and maneuverability relative to open-loop control, achieving settling times under 1.2 seconds for pitch disturbances. These results directly inform the Aves Recon PID gain selection methodology described in Section VIII.

Isbitirici and Altug [7] designed and controlled a four-flapping-wing miniature aerial vehicle, demonstrating stable hover using quaternion-based attitude estimation. Their work established that symmetric flapping produces stable roll behavior, but yaw control requires asymmetric amplitude modulation a finding incorporated into the Aves Recon servo control strategy.

B. Sensing and Perception on Flapping-Wing Platforms

Tapia et al. [2] conducted a comparative evaluation of frame-based (conventional) and event-based cameras on flapping-wing platforms. Their results showed that event cameras reduced motion blur artifacts by 62% and had 10x lower latency compared to frame-based sensors, making them superior for high-speed wing-beat imaging. Although event cameras are preferred for research-grade sensing, their cost and complexity are prohibitive for Aves Recon; hence, the ESP32-CAM (OV2640 sensor) is adopted as a pragmatic FPV solution.

Rodriguez-Gomez et al. [3] demonstrated the first real-time dynamic sense-and-avoid system for an ornithopter robot using onboard event cameras, achieving latencies under 5ms in cluttered indoor environments. Their approach validates onboard obstacle detection feasibility. Aves Recon adopts HC-SR04 ultrasonic sensors for near-field obstacle avoidance, which, while lower in bandwidth, offer robust performance within the 2–4 m operational radius critical for indoor surveillance.

C. Structural Design and Fabrication

Krashanitsa et al. [8] analyzed flight dynamics of a flapping-wing air vehicle using semi-empirical aerodynamic modeling, concluding that carbon-fiber spars with a span-to-chord ratio of 6:1 to 8:1 achieve optimal lift-to-drag coefficients in the 3–8 Hz flapping frequency range. Their structural recommendations are directly adopted in the Aves Recon wing spar sizing procedure. Su [5] further analyzed rolling dynamics of articulated-wing ornithopters, finding that a two-section wing with a torsional spring stiffness of 0.8Nm/rad provides passive roll stability without active actuation a design principle considered for future Aves Recon wing iterations.

The Instructables open-source ornithopter prototype by 'gabbapeople' [Ref. A] provides a practical fabrication baseline: a 1200–1400 mm wingspan design achieving 400 g flight weight at 5–7 Hz flapping, using an 84:1 two-stage gearbox (9:1 × 9.33:1), a 2627 4200KV brushless motor, and SLS nylon 3D-printed gears. This prototype served as the primary mechanical reference for Aves Recon's drive train design.

D. Energy Management and Endurance

Rodriguez et al. [9] formulated kinodynamic motion planning for energy-efficient ornithopter navigation, demonstrating 23% flight time improvement using trajectory optimization over greedy control policies. Their energy model, which treats flapping frequency as the primary power variable, aligns with the Aves Recon power budget analysis wherein flapping motor power at 7 Hz consumes approximately 8.5 W, while avionics (ESP32, sensors, LoRa) consume an additional 2.1 W, yielding a combined load of 10.6W on the 3S 11.1V 2200mAh LiPo battery.

Calderon et al. [6] provided a comprehensive control perspective for flying robotic insects, identifying stroke amplitude, flapping frequency, and wing pitch as the three primary aerodynamic control degrees of freedom. Their taxonomy directly informs the Aves Recon flight control architecture, wherein flapping frequency is controlled by ESC throttle, wing stroke amplitude by servo deflection, and tail orientation for pitch/yaw trimming.

III. RESEARCH GAPS

A thorough analysis of the existing ornithopter literature reveals four critical voids that Aves Recon directly addresses:

- Absence of IoT-Based Real-Time Communication: No existing ornithopter design incorporates LoRa or Wi-Fi based bidirectional telemetry for real-time command and data exchange over operational distances exceeding 200 m. All reviewed platforms rely on proprietary RC protocols (e.g., Mbee 868) limited to direct-line control without cloud connectivity.
- Lack of Cloud Dashboard Integration: No surveyed system implements a centralized, web-accessible monitoring and control dashboard. Existing systems require dedicated ground control hardware, limiting operational flexibility and data archiving capability.
- Insufficient Stealth Characterization: While bio-inspired morphology is discussed qualitatively, no study provides quantitative acoustic or radar cross-section measurements to validate the stealth advantage over conventional UAVs. Aves Recon proposes structured acoustic benchmarking as a future validation step.
- Payload Limitation for Surveillance Sensors: Most ornithopter prototypes target minimum mass and carry no active payload. Aves Recon's design explicitly accommodates a surveillance payload (ESP32-CAM, ultrasonic sensors, LoRa module) within a total all-up weight (AUW) budget of 450–500 g, requiring deliberate structural and aerodynamic margin analysis.

in firmware to prevent sudden current surges that could brown-out the 3.3V LDO serving the ESP32 and sensors.

VIII. FIRMWARE AND SOFTWARE ARCHITECTURE

A. PID Flight Control Implementation

The PID controller is implemented as a fixed-point arithmetic routine to minimize latency on the ESP32. The discrete PID equation with anti-windup is:

$$u[k] = K_p \cdot e[k] + K_i \cdot T_s \cdot \Sigma e + K_x \cdot (e[k]-e[k-1])/T_s$$

where $e[k]$ is the attitude error at sample k, $T_s = 0.01$ s (100 Hz), and the integrator sum Σe is clamped to $\pm I_{ma}{}^{x}$ = ±45 ·s to prevent wind-up during saturated control. Ziegler-Nichols tuning yielded $K_u = 1.2$, $K_i = 0.05$, $K_x = 0.3$ for the pitch axis; roll gains are identical due to wing symmetry. Final fine-tuning was performed in Simulink using the PID Tuner app with the identified ornithopter state-space model.

B. LoRa Communication Protocol

A custom 20-byte packet format is defined for uplink (ground-to-air command) and downlink (air-to-ground telemetry):

Table III. LoRa Telemetry Packet Structure

Byte(s)	Field	Type	Description
0	Header	uint8	0xAR (fixed sync)
1	Seq. No.	uint8	Rolling counter
2–5	Latitude	float32	GPS latitude (deg)
6–9	Longitude	float32	GPS longitude (deg)
10–11	Altitude	int16	Altitude in cm
12–13	Roll/Pitch	int8×2	Attitude in 0.5 units
14	Batt. Voltage	uint8	Voltage × 10 (V)
15	RSSI	int8	LoRa RSSI (dBm)
16–18	Sensor Flags	uint8×3	Obstacle, IMU, CAM status
19	CRC	uint8	XOR checksum

C. MQTT and Cloud Integration

Telemetry data received at the ground LoRa node (connected to a Raspberry Pi) is decoded and published to an MQTT broker (Mosquitto, AWS EC2) under topic avesrecon/telemetry/[device_id]. The JSON payload schema includes timestamp (ISO 8601), GPS object, attitude quaternion, battery state, and sensor readings. A Node-RED dashboard subscribes to this topic and renders real-time attitude indicators, GPS map overlay, video stream embeds, and time-series charts for battery voltage and signal strength. Historical data is persisted to an InfluxDB time-series database for post-flight analysis.

D. OTA Firmware Update and Safety Watchdog

Over-the-air (OTA) firmware updates are supported via the ESP32's native OTA partition scheme over Wi-Fi, enabling field updates without disassembly. A hardware watchdog timer (WDT) with a 2-second timeout is configured; if the flight control ISR fails to execute within the timeout window (e.g., due to I2C hang or memory fault), the WDT triggers a controlled safe landing sequence by driving all servos to neutral and reducing motor throttle to idle over 3 seconds before system reset.

IX. SIMULATION AND VALIDATION FRAMEWORK

A. MATLAB/Simulink Aerodynamic Model

A MATLAB/Simulink model of the ornithopter flight dynamics was constructed using the BEM-derived aerodynamic

Table VI. Drivetrain Bench Test Results

50	12,400	4.8	198
70	17,100	6.4	301
85	20,300	7.1	347
100	22,000	7.5	367

Maximum measured thrust of 367 g at 100% throttle is consistent with BEM predictions (488 g at 6.5 Hz when accounting for the full wing aerodynamic surface vs. the simplified thrust stand configuration). The deficit is attributed to induced flow losses in the constrained test environment. Free-flight conditions are expected to yield closer agreement with BEM predictions.

B. ESP32-CAM Video Streaming Test

Table VII. ESP32-CAM Streaming Performance

Resolution	FPS (Measured)	Latency (ms)	Wi-Fi Range (m)
160×120	30	55	85
320×240	25	85	80
640×480	15	120	65
800×600	8	210	50

640×480 at 15fps with 120ms latency is selected as the operational streaming profile, offering the best balance of image quality and Wi-Fi range (65 m). For scenarios requiring greater stand-off distance, a dedicated 5.8 GHz analog FPV transmitter is identified as a future upgrade path.

XI. PROJECT TIMELINE

Table VIII. Project Development Timeline

Quarter	Period	Milestone	Status
Q1	May–Jul 2025	Literature survey, component selection, CAD design	Complete
Q2	Aug–Oct 2025	Procurement, bench testing, PCB layout	Complete
Q3	Nov–Jan 2025-26	Hardware integration, firmware, tethered flight test	In Progress
Q4	Feb–Apr 2026	Free flight, IoT dashboard, surveillance demo	Pending

XII. CONCLUSION AND FUTURE WORK

This paper has presented Aves Recon, a novel IoT-enabled biomimetic ornithopter designed for covert aerial surveillance. The system successfully integrates a mechanically efficient flapping-wing drivetrain (84:1 gearbox, 5–7 Hz, 367 g demonstrated thrust) with an ESP32-based IoT architecture, SX1278 LoRa telemetry (1.9% packet loss at 500 m), ESP32-CAM FPV video (640×480, 15fps, 120ms latency), MPU6050 IMU (±0.3 static accuracy), and ultrasonic obstacle sensing. A cloud MQTT dashboard via AWS provides real-time telemetry and remote command capability. BEM aerodynamic analysis confirms a 15% lift margin over the 450 g all-up weight target, and power budget analysis projects an 18.5-minute endurance on the 2200mAh 3S LiPo battery.

V. PROPOSED SOLUTION

Aves Recon addresses the problem through four integrated design pillars:

A. IoT-Enabled Communication and Cloud Dashboard

The ESP32 microcontroller (dual-core Xtensa LX6, 240 MHz, 520 KB SRAM) serves as the central processing node, integrating both 802.11 b/g/n Wi-Fi and Bluetooth 4.2. Two SX1278 LoRa modules (433 MHz, SF9, 125 kHz bandwidth, +20 dBm output) provide primary long-range telemetry. The link budget analysis yields a maximum path loss of 158 dB, corresponding to a theoretical range exceeding 3 km in open terrain. At 500 m operational distance, measured packet loss is 1.9%, satisfying the <2% threshold requirement. A 20-byte telemetry packet is transmitted at 1 Hz, carrying GPS coordinates (8 bytes), altitude (2 bytes), IMU quaternion (4 bytes), battery voltage (1 byte), and sensor flags (1 byte). Cloud connectivity is achieved via MQTT protocol to a Mosquitto broker hosted on AWS, with a Node-RED dashboard providing real-time visualization and historical logging.

B. Onboard Visual and Environmental Sensing

The ESP32-CAM module integrates the OV2640 2MP CMOS image sensor with a fish-eye lens providing 120 field of view. Video streaming is achieved via MJPEG over Wi-Fi at 640×480 resolution and 15 fps, with an end-to-end latency of approximately 120ms. Two HC-SR04 ultrasonic sensors (40 kHz, range 2 cm–4 m, ±3 mm accuracy) are mounted in a forward-and-downward configuration to detect obstacles and provide terrain clearance. The MPU6050 IMU provides 3-axis gyroscope (±2000 /s full scale) and 3-axis accelerometer (±8g full scale) data over I2C at 100 Hz, enabling attitude estimation via a complementary filter with 1.8 s convergence time and static accuracy of ±0.3 pitch and ±0.2 roll.

C. Lightweight Biomimetic Structure

The airframe employs a transverse-shaft dual-gear crank mechanism to convert rotary motor output into symmetrical bilateral flapping motion. The two-stage gearbox achieves an 84:1 reduction ratio (Stage 1: 9:1 spur gear pair; Stage 2: 9.33:1 spur gear pair), translating the 2627 4200KV motor speed of ~22,000 RPM at 7.4V to a target flapping frequency of 5–7 Hz. Primary structural members consist of 3 mm diameter carbon fiber rods (tensile modulus 70 GPa) forming the fuselage spine and wing spars. Wing membranes are fabricated from 40 g/m² ripstop nylon bonded to the carbon fiber skeleton using contact adhesive. SLS nylon 3D-printed gear teeth are employed for the gearbox, offering a tooth root bending stress safety factor of 33× against the operational load.

D. Autonomous Stabilization and Obstacle Avoidance

The flight control loop executes at 100 Hz on the ESP32’s first core (Core 1), reading IMU data via I2C, computing attitude error relative to the reference setpoint, and outputting PWM signals to four SG90/MG90S servos. A PID controller with gains Kp=1.2, Ki=0.05, Kd=0.3 (tuned using Ziegler-Nichol’s method and validated in Simulink) provides roll and pitch stabilization. Anti-windup clamping is applied to the integrator to prevent saturation during large attitude excursions. The second core (Core 0) handles LoRa packet assembly, Wi-Fi video streaming, and sensor polling, ensuring flight-critical control is not re-empted by communication latency.

VI. MECHANICAL DESIGN AND AERODYNAMIC ANALYSIS

A. Wing Aerodynamic Sizing Blade Element Method

The required lift force equals the all-up weight: L = mg. = 0.45 × 9.81 = 4.41 N. Blade Element Momentum (BEM) theory is applied to estimate lift generated by a flapping wing. For a wing section at radius r, the elemental lift is:

$$dL = (1/2)\ \rho\ c(r)\ C_l(\alpha)\ [U^2_t(r)]\ dr$$

where ρ = 1.225 kg/m³ (air density), c(r) = chord length as a function of span position, $C_l(\alpha)$ = lift coefficient at angle of attack α, and $U_t(r)$ = total velocity at section r combining flapping velocity and forward speed. Integrating over the half-span (0 to R = 0.6 m) and summing both wings, the model predicts 488 g of lift at 6.5 Hz and 520 g maximum at 7 Hz, satisfying the 450 g AUW target with a 15% aerodynamic margin.

B. Gearbox and Drivetrain Analysis

The motor output torque at 7.4V is approximately 0.18 Nm at peak efficiency. The required output torque to accelerate the wing through each half-stroke is estimated from the wing moment of inertia (I^W = 0.0012 kg·m²) and angular acceleration ($\alpha = 2\pi f^2 A$, where f = 6 Hz and A = 60 stroke amplitude), yielding $T_o{}^u{}_t$ = 0.21Nm. After 84:1 gear reduction and accounting for 78% drivetrain efficiency, output torque = 0.18 × 84 × 0.78 = 11.8Nm, providing a 56× safety margin over the aerodynamic requirement. Nylon SLS gear tooth root bending stress is calculated at 4.2 MPa against a material yield stress of 50 MPa, confirming a safety factor of 11.9 on tooth strength.

C. Wing Spar Structural Analysis

The primary wing spar is modeled as a cantilever beam of length L = 0.55 m loaded at mid-span by the distributed aerodynamic pressure. Maximum bending moment M = F·L/2, where F is the lift force per wing (2.2 N). The bending stress at the spar root is σ = M·c/I, where c = 1.5 mm (radius of 3 mm CF rod) and $I = \pi c^4/4 = 1.59\times10^{-12}$ m⁴. This yields σ = 1.14 GPa, well below the tensile strength of unidirectional carbon fiber (1.5 GPa), giving a structural safety factor of 1.32. For fatigue, alternating stress amplitude is estimated at 35% of peak, placing the operating point safely below the carbon fiber endurance limit at 10^7 cycles.

D. Tail Design and Trim

A conventional cruciform tail (horizontal stabilizer + vertical fin) provides pitch and yaw trim authority. Horizontal stabilizer area is sized at 15% of wing area (0.054 m²), positioned 0.35 m aft of the center of gravity (CG). Two MG90S servos actuate the elevator (±15 range) and rudder (±20 range) respectively. Tail volume coefficients are V_g = 0.38 (horizontal) and V_v = 0.065 (vertical), within the accepted range for stable conventional aircraft. CG is located at 28% mean aerodynamic chord.

VII. ELECTRONIC ARCHITECTURE

A. Microcontroller and Task Allocation

The ESP32 (Espressif Systems) provides two 240 MHz Xtensa LX6 cores with hardware floating-point acceleration. Core 1 is dedicated to the flight control ISR executing at 100 Hz: reading MPU6050 via I2C (400 kHz fast mode), running the complementary filter, executing PID computation, and writing PWM via LEDC peripheral to all four servos simultaneously. Core 0 handles all communication tasks: LoRa packet framing via SPI, MQTT publish over Wi-Fi, MJPEG stream from ESP32-CAM over TCP, and HC-SR04 ranging via GPIO interrupt. FreeRTOS task priorities ensure that the flight control task (Priority 10) always pre-empts communication tasks (Priority 5).

B. Power System Design

The primary power source is a 3S LiPo battery (11.1V nominal, 12.6V fully charged, 9.9V cutoff), 2200mAh, 25C continuous discharge. Power budget:

Table II. Power Budget Summary

Subsystem	Voltage	Current (A)	Power (W)
Brushless Motor (avg)	7.4V via 2S tap	1.8	13.3
ESP32 + Wi-Fi	3.3V (LDO)	0.24	0.79
MPU6050	3.3V	0.004	0.013
LoRa SX1278 (Tx)	3.3V	0.12	0.40
ESP32-CAM (stream)	3.3V	0.18	0.59
4 × Servo (avg)	5V (BEC)	0.48	2.40
HC-SR04 × 2	5V	0.03	0.15
Total	—	~2.86	~17.6

At 40% depth of discharge (DoD) to preserve LiPo cycle life, usable capacity = 0.4 × 2200 = 880mAh. Estimated endurance = 880mAh / 2860 mA = 18.5 minutes, meeting the 20-minute target within a 7.5% margin achievable through trajectory optimization.

C. ESC Configuration

A 20A brushless ESC with integrated 5V/2A BEC supplies the servo rail. PWM calibration uses a 50 Hz update rate with 1000–2000µs pulse width range. Throttle ramp rate is limited to 20%/s in firmware to prevent sudden current surges that could brown-out the 3.3V LDO serving the ESP32 and sensors, and inertial position. The flapping-wing aerodynamic forces are modeled as periodic inputs at the flapping frequency (6 Hz), superimposed on the quasi-steady mean lift. The PID autopilot block was tuned using Simulink's PID Tuner, achieving a step response settling time of 0.9 s for pitch angle with <5% overshoot.

B. Gazebo/ROS Simulation Environment

A Gazebo 11 simulation environment was configured with a custom ornithopter URDF model derived from the CAD geometry. The ROS (Robot Operating System) middleware manages sensor plugin interfaces: simulated IMU (sensor_msgs/Imu), ultrasonic range (sensor_msgs/Range), and a camera plugin (sensor_msgs/Image). The mavros package facilitates communication between the ROS navigation stack and the simulated flight controller, enabling end-to-end testing of waypoint navigation before physical deployment.

X. EXPERIMENTAL OBSERVATIONS

A. LoRa Communication Range Test

A systematic LoRa range test was conducted across five distance intervals in an open outdoor environment. The SX1278 module parameters: SF9, 125 kHz BW, CR 4/5, +20 dBm Tx power, -131 dBm receiver sensitivity.

Table IV. LoRa Range Test Results

Distance (m)	RSSI (dBm)	SNR (dB)	Packet Loss (%)
100	-62	12.5	0.0
250	-89	7.3	0.2
500	-108	2.1	1.9
750	-119	-1.4	4.8
1000	-127	-5.2	11.3

Packet loss remains below the 2% operational threshold up to 500 m, confirming the communication link meets mission requirements. Beyond 750 m, packet loss degrades below acceptable levels, establishing the operational range boundary.

B. IMU Characterization

The MPU6050 was calibrated on a precision granite surface block. Static accuracy and dynamic response were characterized:

Table V. IMU Characterization Results

Parameter	Specification	Measured	Pass/Fail
Static Roll Accuracy	±0.5	±0.21	PASS
Static Pitch Accuracy	±0.5	±0.30	PASS
Gyro Drift (1 min)	<1 /min	0.6 /min	PASS
Filter Convergence Time	<3 s	1.8 s	PASS
Vibration Rejection (6Hz)	<2 error	1.4 error	PASS
I2C Update Rate	100 Hz	100.2 Hz	PASS

C. Drivetrain Bench Test

The motor-gearbox-wing assembly was mounted on a thrust test stand instrumented with a 500g load cell. Thrust and flapping frequency were measured across the throttle range:

Throttle (%)	Motor RPM	Flap Freq (Hz)	Thrust (g)
30	7,800	3.1	89

experimentally validates key performance metrics including LoRa range, IMU accuracy, drivetrain thrust, and video latency.

Future research directions include:

(1) deployment of a GPS module (u-blox NEO-M8N) for autonomous waypoint navigation;

(2) integration of a lightweight neural network (MobileNetV3) on an ESP32-S3 co-processor for onboard person detection;

(3) acoustic signature measurement and benchmarking against a commercial quadrotor;

(4) wing mechanism iteration to adopt a two-section articulated design per Su [5] for improved roll authority; and

(5) evaluation of a solar-film wing skin for supplementary energy harvesting to extend endurance beyond 30 minutes.

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