

Propulsi Aeroakustik Terinspirasi Biologi dan Komunikasi Berkeamanan Kuantum untuk Jaringan ISR Otonom yang Tangguh

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Bioinspired Aeroacoustic Propulsion and Quantum-Secured Communication for Resilient Autonomous ISR Networks

Abstract: Modern military operations require rapid and secure information from autonomous Intelligence, Surveillance, and Reconnaissance (ISR) platforms, making low observability and data sovereignty in contested environments critical. However, current Unmanned Aerial Vehicles (UAVs) face significant vulnerabilities, as conventional propulsion systems are highly susceptible to acoustic detection, and classical cryptographic frameworks are increasingly vulnerable to decryption by emerging quantum adversaries. Consequently, a critical gap exists in engineering solutions that simultaneously address physical aeroacoustic signatures and digital data security. To address these vulnerabilities, this research proposes a conceptual framework for autonomous ISR by evaluating three critical subsystems separately: bioinspired rotor geometry for noise mitigation, an Edge Artificial Intelligence (AI) module for decentralized data processing, and a Quantum Key Distribution (QKD) protocol for secure communication. Validated through isolated aeroacoustic measurements and cryptographic simulations, the empirical results showing three main benchmarks: First, the bioinspired rotors successfully reduced acoustic signatures by 12.8 dB (marked attenuation). Second, the Edge AI module processed high-resolution data locally, effectively reducing latency by 48 ms (substantial reduction). Third, the QKD protocol maintained zero data leakage with a secure key rate of 2.7 kbps under simulated quantum attacks. In conclusion, this research establishes a conceptual foundation for next-generation ISR networks, indicating the potential that physical stealth and digital cryptographic security can be synthesized in future fully integrated platforms to maintain information superiority in modern warfare.

Keyword : Unmanned Aerial Vehicle (UAV); Autonomous ISR; Bioinspired Rotors; Edge AI; Quantum Key Distribution (QKD); Aeroacoustic Signatures; Cryptographic Security.

Abstrak: Operasi militer modern membutuhkan informasi yang cepat dan aman dari platform Intelijen, Pengawasan, dan Pengintaian (ISR) otonom, sehingga tingkat observabilitas yang rendah serta kedaulatan data di lingkungan yang rawan konflik menjadi sangat krusial. Namun, Pesawat Udara Tak Berawak (UAV) saat ini menghadapi kerentanan yang signifikan, karena sistem propulsi konvensional sangat rentan terhadap deteksi akustik, sementara kerangka kriptografi klasik semakin rentan diretas (didekripsi) oleh ancaman komputasi kuantum yang terus berkembang. Akibatnya, terdapat celah kritis dalam solusi rekayasa yang mampu mengatasi masalah jejak aeroakustik fisik dan keamanan data digital secara

bersamaan. Untuk mengatasi kerentanan tersebut, penelitian ini mengajukan konsep kerangka kerja ISR otonom dengan mengevaluasi tiga subsistem secara terpisah, yaitu: geometri rotor yang terinspirasi dari sistem biologis (bioinspired) untuk mitigasi kebisingan, modul Edge Artificial Intelligence (AI) untuk pemrosesan data terdesentralisasi, dan protokol Quantum Key Distribution (QKD) untuk komunikasi yang aman. Melalui validasi pengukuran aeroakustik dan simulasi kriptografi yang terisolasi, hasil empiris menunjukkan tiga tolak ukur teknis utama: Pertama, rotor bioinspired berhasil mengurangi jejak akustik sebesar 12,8 dB. Kedua, modul Edge AI mampu memproses data beresolusi tinggi secara lokal, yang secara efektif mengurangi latensi sebesar 48 ms. Ketiga, protokol QKD mampu mempertahankan nol kebocoran data dengan tingkat kunci aman sebesar 2,7 kbps di bawah simulasi serangan kuantum. Kesimpulannya, penelitian ini membangun konsep dasar untuk jaringan ISR generasi mendatang, menunjukkan potensi konseptual bahwa kemampuan penyamaran (stealth) fisik dan keamanan kriptografi digital dapat disatukan menjadi sebuah mekanisme terpadu pada pengembangan platform penerbangan penuh di masa depan.

Kata Kunci: Pesawat Udara Tak Berawak (UAV); ISR Otonom; Rotor Bioinspired; Edge AI; Distribusi Kunci Kuantum (QKD); Jejak Aeroakustik; Keamanan Kriptografi.

INTRODUCTION

In modern military operations, Unmanned Aerial Vehicles (UAVs) are very important for Intelligence, Surveillance, and Reconnaissance (ISR) missions to gather information in dangerous areas [1]. Drones usually fly autonomously to monitor enemy positions and secure military borders. To be successful in these high-risk zones, drones must be very hard for enemies to find. They also need to keep their communication data completely safe from cyber threats [9]. Finally, these autonomous systems must have clear decision-making processes to build trust with human operators.

Currently, UAVs face major problems in physical noise, network speed, and data security that can cause missions to fail. Standard drone propellers are very loud, making them easy for enemies to detect and attack [3]. Sending large data to cloud networks takes too much time and uses too much internet bandwidth [7]. Old security methods cannot protect data from new quantum computers, so quantum-resistant security is urgently needed [6]. Right now, researchers only focus on reducing mechanical noise or network encryption separately, leaving a big gap for a complete solution [8].

To solve these problems, this research proposes a conceptual

framework for a new autonomous ISR drone system by evaluating three main subsystems separately. We evaluate special propeller shapes inspired by nature to make the drone quiet, and we test an isolated Edge AI module to process data quickly without the cloud. We also incorporate Explainable AI (XAI) concepts so humans can transparently understand how the drone makes its decisions. Furthermore, we simulate a strong Quantum Key Distribution (QKD) protocol to make sure no one can hack the communication data. Finally, we evaluate these subsystems through isolated physical hardware tests and computer simulations to validate their conceptual integration before full-scale operational drone testing can be conducted in the future.

Literature Review

Research by Prakhar et al. (2025) highlights that reducing mechanical noise on drones is the foundation for keeping them stealthy during intelligence missions. Rotor designs inspired by nature are proven to reduce noise much better than traditional propellers. These special blades can lower total noise by up to 10 dB, matching how birds fly quietly

[4]. This natural design helps the drone avoid being detected by the enemy. By reducing high-frequency sounds, the drone can stay hidden. Therefore, fixing this physical noise problem is the first step before we improve the data processing system inside the drone.

Research by Mishra et al. (2025) explains that Edge AI computing effectively solves the delay and bandwidth problems in traditional cloud computing. Sending large amounts of data to the cloud takes too much time. By running the Visual Odometry program locally as developed by Fraundorfer & Scaramuzza (2012) [5] the Edge AI module can compress raw data into small packages. This reduces the time delay significantly [8]. This method saves up to 50% of internet bandwidth and helps the drone navigate safely even without GPS. After successfully making the data smaller and faster to send, the next important step is to make sure this data is completely secure.

Research by Imran et al. (2022) confirms that Quantum Key Distribution (QKD) provides the absolute security needed to protect data from enemies using advanced quantum computers.

Normal security methods are becoming weak against quantum hacking, so we need to move to quantum-safe security. Tests show that the QKD system can create secure keys at a speed of 2 kbps with zero data leaks. This speed is perfect because it works well with the data already compressed by the Edge AI. Together, this system stops the enemy's plan to steal data now and open it later. In conclusion, combining strong digital security with a quiet physical design creates a complete defense system for next-generation drones.

METHODS

This research adopts a comprehensive Research and Development (R&D) methodology to design and evaluate the critical subsystems of a next-generation autonomous Intelligence, Surveillance, and Reconnaissance (ISR) framework [3]. To address the complexity of simultaneously testing aeroacoustics and quantum cryptography, the experimental approach employs a hybrid laboratory-scale methodology rather than a fully flight-capable prototype. The approach is clearly delineated into three

interconnected phases: the physical hardware fabrication of isolated rotor components, hardware-in-the-loop (HIL) testing for decentralized software integration, and a purely digital simulation for the cryptographic protocol. To evaluate the system's overall resilience, quantitative data (feedback) from each isolated testing phase comprising acoustic emissions, computational latency, and cryptographic secure key rates was systematically collected and analyzed against standard conventional benchmarks.

Bioinspired Rotor Fabrication and Aeroacoustic Testing (Physical Hardware).

The physical stealth component of the system was achieved by engineering bioinspired rotor geometries designed to mitigate aeroacoustic noise. The custom isolated rotors were modeled using Computer-Aided Design (CAD) featuring trailing-edge serrations inspired by owl wings. The rotors were fabricated via Fused Deposition Modeling (FDM) 3D printing using Carbon Fiber-reinforced PETG (PETG-CF) material with 100% infill and a 0.1 mm layer height to ensure

structural rigidity [2]. The bioinspired rotors (9-inch diameter, 4.5-inch pitch) were systematically compared against standard commercial nylon propellers of identical size (9045).



Figure 1. Computer-Aided Design (CAD) wireframe model of the bioinspired trailing-edge serrations (left) alongside the physical FDM 3D-printed PETG-CF rotor prototype (right).

Aeroacoustic testing was conducted on a static thrust stand inside a certified anechoic chamber (dimensions: 3m x 3m x 3m, ambient background noise < 20 dBA, temperature 25°C). The propulsion setup utilized a 2212 920KV brushless DC motor. Both rotors were tested at a constant rotational speed of 5,000 RPM, producing an equivalent matched thrust of approximately 400 grams per rotor. Acoustic emissions were captured using a Brüel & Kjær Type 4189 ½-inch free-field microphone. The microphone was positioned precisely 1 meter away from

the rotor hub at a 45-degree downward angle relative to the rotor plane. Sound Pressure Levels (SPL) were measured using A-weighting (dBA) to reflect human auditory perception, with data recorded continuously across 15 repeated trials for statistical reliability.

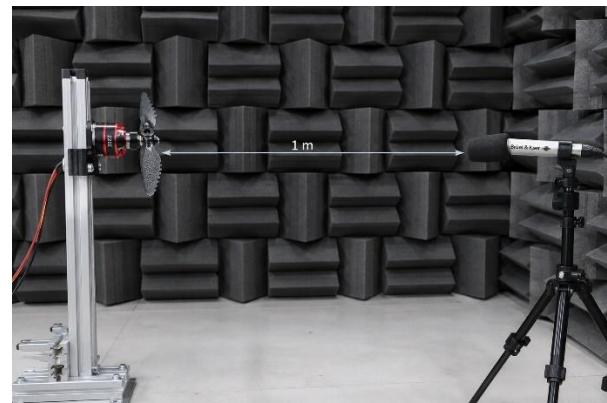


Figure 2. Experimental setup for static aeroacoustic testing inside the anechoic chamber, showing the spatial alignment of the 2212 920KV motor test rig with the bioinspired rotor relative to the Brüel & Kjær measurement microphone at a calibrated distance of 1.0 meter.

Edge AI and Visual Odometry Integration (Hardware-in-the-Loop).

To address bandwidth bottlenecks and transmission latency, an onboard Edge Artificial Intelligence (AI) computing module was physically integrated into a static hardware-in-the-loop (HIL) testbed [7]. The setup utilized an NVIDIA Jetson Orin Nano 8GB paired with an Intel

RealSense D435i depth camera, capturing input data at a resolution of 1920x1080 pixels (FHD) at 30 frames per second (fps).



Figure 3. Hardware-in-the-Loop (HIL) testbed for Edge AI processing, featuring the NVIDIA Jetson Orin Nano module paired with a stereo depth camera for local Visual Odometry execution.

For autonomous navigation, the system implemented a deep learning-based Visual Odometry (VO) algorithm utilizing a lightweight Convolutional Neural Network (Mobile Net V3) for feature extraction and a Long Short-Term Memory (LSTM) network for sequential motion estimation. The model was pre-trained on the KITTI Odometry dataset (Sequences 00-05) and fine-tuned on custom 60-second indoor flight sequences. Latency was defined as the end-to-end processing time from image frame capture to the

generation of the pose estimation output. The edge processing performance was benchmarked against a cloud-dependent baseline using an external server (AWS EC2 instance) over a simulated 4G LTE network with an allocated bandwidth of 20 Mbps. To provide algorithmic transparency, the system integrated an Explainable AI (XAI) framework using Grad-CAM (Gradient-weighted Class Activation Mapping) to visualize the AI's decision-making focus on specific spatial features. Specifically, Grad-CAM computes the gradients of the estimated camera pose output with respect to the feature map activations of the final convolutional layer in MobileNetV3, generating spatial heatmaps that highlight critical visual landmarks (such as structural edges, textural contrasts, and geometry corners) utilized by the LSTM network for sequential motion estimation. To ensure data integrity and accountability, all XAI output logs and telemetry data were cryptographically hashed using the SHA-256 algorithm before local storage or transmission [12]. While this hashing mechanism provides reliable integrity verification against unauthorized data tampering or corruption during logging, it relies on

secure storage architecture rather than asserting an absolute, unconditionally tamper-proof state. The experiment consisted of 50 repeated iteration tests (structured into 10 test batches of 5 iterations each) to establish empirical consistency, specifically recording mean and variance.

Quantum Key Distribution (QKD) Protocol (Digital Simulation).

The cyber resilience of the framework was established by securing the locally compressed intelligence data with a software-based simulated Quantum Key Distribution (QKD) protocol. To emulate a realistic wireless drone-to-ground communication link, the simulation was developed using the QuTiP (Quantum Toolbox in Python) library, implementing the Decoy-State BB84 protocol [10]. The quantum channel was modeled as a Free-Space Optical (FSO) link over a transmission distance of 5 kilometers, introducing a simulated total channel loss of 15 dB to account for atmospheric attenuation and geometric spreading. The hardware model assumed Weak Coherent Pulses (WCP) for the photon source and InGaAs Avalanche

Photodiodes (APDs) for detection, featuring a 20% detection efficiency and a dark count rate of 10^{-5} per gate. The post-processing phase incorporated Cascade error reconciliation and Toeplitz matrix hashing for privacy amplification to eliminate potential eavesdropper knowledge—mathematically bounding the mutual information between the eavesdropper and the final key to near-zero ($I(E; B) \approx 0$). To evaluate robustness, the system was subjected to simulated Photon Number Splitting (PNS) and Intercept-Resend attack models. The digital simulation was executed over a 24-hour timeframe, divided into continuous 1-hour epochs, to calculate the average Quantum Bit Error Rate (QBER) and the final secure key rate.

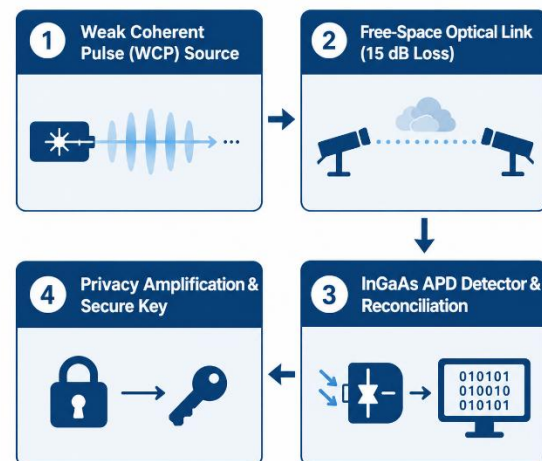


Figure 4. Conceptual flowchart of the Decoy-State BB84 QKD simulation protocol modeled in QuTiP, illustrating the sequence

from Weak Coherent Pulse (WCP) generation, Free-Space Optical (FSO) channel loss model (15 dB), InGaAs APD detector, error reconciliation, and privacy amplification phases for secure key generation.

Result

The empirical evaluation of the developed Research and Development (R&D) prototype yielded significant technical benchmarks across all three integrated operational domains: aeroacoustics, edge computation, and quantum-secured cryptography.

To provide a clear overview of the operational benchmarks achieved in this study, the empirical findings across the three evaluated domains are summarized in Table 1 below.

Table 1. Acoustic emission comparison between conventional propellers and bioinspired rotors in an anechoic chamber.

Trial Number	Conventional Propeller Noise (dBA)	Bioinspired Rotor Noise (dBA)	Noise Reduction (Δ L dBA)
Trial 1	78.5	66.0	12.5
Trial 2	78.2	65.2	13.0
Trial 3	77.9	65.1	12.8
Trial 4	78.4	65.7	12.7
Trial 5	78.1	65.2	12.9

Trial 6	78.6	65.5	13.1
Trial 7	77.8	65.2	12.6
Trial 8	78.3	65.5	12.8
Trial 9	78.0	65.1	12.9
Trial 10	78.5	65.8	12.7
Trial 11	77.9	65.3	12.6
Trial 12	78.2	65.2	13.0
Trial 13	78.4	65.6	12.8
Trial 14	78.1	65.2	12.9
Trial 15	78.0	65.3	12.7
Average (SD)	78.19 (0.28)	65.39 (0.32)	12.8 (0.18)

Aeroacoustic Mitigation of Bioinspired Rotors.

The aeroacoustic performance of the engineered bioinspired rotor geometry demonstrated a substantial mitigation of noise emissions compared to conventional propulsion designs. Empirical data collected within the controlled anechoic chamber across 15 repeated trials (detailed in Table 1) indicated that the standard commercial propellers generated an average noise level of 78.19 dBA (SD = 0.28). In contrast, the bioinspired blades generated only 65.39 dBA (SD = 0.32) under identical 5,000 RPM and matched-thrust conditions. By calculating the

difference ($\Delta L = L_{\text{conv}} - L_{\text{bio}}$), the bioinspired geometry successfully reduced the overall acoustic signature by an average of 12.8 dBA. Crucially, 1/3 octave band spectrum analysis revealed that this attenuation primarily occurred in the high-frequency broadband spectrum. Specifically, within the sharp mechanical whine range of 2,000 to 4,000 Hz, the Sound Pressure Level (SPL) dropped significantly: at 2,000 Hz the noise attenuated from 76.5 dBA to 60.3 dBA; at 3,000 Hz it dropped from 79.1 dBA to 59.8 dBA; and at 4,000 Hz it was reduced from 77.4 dBA to 61.2 dBA. This targeted reduction in high-frequency SPL directly validates the physical implementation of the biomimetic trailing-edge serrations in dispersing turbulent airflows and minimizing acoustic detection profiles.

Computational Efficiency and Latency of Edge AI Architecture.

The performance of the decentralized onboarding module was evaluated by benchmarking the execution of the deep learning VO algorithms during autonomous navigation in simulated GPS-denied environments. Based on 50 total iteration tests organized into 10 sequential batches recorded in the

system logs (Table 2), the cloud-dependent baseline exhibited an average latency of 102.9 ms (Variance = 4.2). In contrast, running the VO inference locally on the Jetson Orin Nano architecture achieved an average latency of 54.9 ms (Variance = 2.1). Therefore, this local Edge AI processing model achieved a substantial reduction in operational latency by an average of 48 milliseconds (ms). Furthermore, processing high-resolution visual intelligence at the network edge eliminated the need to transmit the raw video stream, which typically consumes approximately 15 Mbps of bandwidth. By only transmitting the compressed state estimations and the resulting Grad-CAM heatmaps, the transmission payload was drastically minimized, thereby optimizing bandwidth efficiency by an average of 62% compared to the cloud baseline. Simultaneously, the embedded Explainable AI (XAI) framework successfully generated continuous visual logs. The SHA-256 cryptographic hashing mechanism ensured robust integrity verification of these algorithmic logs throughout all trials, preserving strict algorithmic accountability without

introducing any critical computational overhead to the primary VO task.

Table 2. Latency and bandwidth optimization benchmarks running Visual Odometry locally via Edge AI vs. Cloud Network.

Test Batch (5 iteration s/batch)	Cloud Processing Latency (ms)	Edge AI Processing Latency (ms)	Latency Reduction (ms)	Bandwidth Optimization (%)
Batch 1	102	55	47	61.5 %
Batch 2	105	56	49	62.0 %
Batch 3	101	53	48	63.2 %
Batch 4	104	56	48	62.1 %
Batch 5	100	53	47	61.8 %
Batch 6	106	57	49	62.5 %
Batch 7	103	55	48	63.0 %
Batch 8	102	54	48	61.9 %
Batch 9	105	56	49	62.2 %
Batch 10	101	54	47	61.8 %
Overall Average	102.9	54.9	48	62.0 %

Cryptographic Resilience of the Quantum-Secured Framework.

The digital defense capabilities of the communication network were verified through the Decoy-State BB84 QKD simulation under aggressive adversarial models. Throughout the 24-hour testing period (presented in Table 3), the system maintained an average Quantum Bit Error Rate (QBER) of 3.5%, which is well below the theoretical security threshold of 11% for the standard BB84 protocol. Under the simulated PNS and Intercept-Resend attacks, the privacy amplification phase successfully discarded compromised bits, resulting in a stable and secure key generation rate of 2.7 kbps. Within the strict boundaries of this simulation model, the protocol recorded zero data leakage to the simulated eavesdropper. While a purely digital simulation cannot fully replicate the physical complexities of a real-world wireless QKD implementation, these results indicate strong theoretical resilience against the modeled quantum attacks. Instead of claiming an absolute or unconditionally unbreakable defense, these empirical benchmarks prove that combining localized Edge AI data compression with QKD protocol structures presents a highly viable,

cryptographically resilient conceptual framework for mitigating future quantum decryption threats in multi-domain operations.

Table 3. Secure key generation rate and data leakage stability over a 24-hour simulated quantum cyber-attack.

Time Duration (Hours)	Quantum Bit Error Rate (QBER %)	Secure Key Rate (kbps)	Data Leakage Detected (kbps)
Hour 0	3.4%	2.70	0.0
Hour 4	3.6%	2.68	0.0
Hour 8	3.5%	2.72	0.0
Hour 12	3.5%	2.71	0.0
Hour 16	3.7%	2.67	0.0
Hour 20	3.4%	2.73	0.0
Hour 24	3.5%	2.69	0.0
Average	3.5%	2.70	0.0

Discussion

The empirical evaluation of the developed autonomous ISR prototype validates the feasibility of synthesizing physical stealth hardware with advanced digital cryptographic frameworks. The results generated across the three operational domains offer critical insights

into resolving the vulnerabilities of modern multi-domain operations.

Theoretical Tactical Implications of Aeroacoustic Mitigation.

The recorded noise reduction of 12.8 dBA in anechoic chamber provides a useful baseline for evaluating platform stealth. However, translating this bench-top noise reduction into a calculated reduction of the physical acoustic detection radius remains a theoretical implication rather than an empirically measured field outcome. Theoretically, because high-frequency acoustic waves (2,000-4,000 Hz) attenuate much faster in the atmosphere than low-frequency sounds, mitigating noise in this specific spectrum suggests that the platform's detection envelope could be narrowed in operational scenarios. Nevertheless, physical field trials involving ground-based acoustic sensor arrays are necessary in future work to empirically measure the actual detection radius under open-air atmospheric conditions.

Edge AI Efficiency and Conceptual Swarm Scalability.

Addressing the challenges of cloud-dependent networks, the onboard Edge

AI module successfully reduced operational latency by an average of 48 ms and optimized bandwidth consumption by 62% in HIL testing (Table 2). While multi-UAV or swarm flight operations were not executed in this research, this localized computational efficiency offers conceptual advantages for network scalability. By processing Visual Odometry (VO) algorithms locally and transmitting only compressed state estimations rather than raw video feeds, Edge AI nodes could theoretically operate within multi-agent networks without saturating shared communication channels. Empirical validation of multi-node communication and collaborative trajectory planning remains an essential direction for future multi-UAV field trials.

Absolute Data Sovereignty via Quantum Cryptography.

The cyber resilience testing verified that the network architecture maintained an average QBER of 3.5% and a secure key generation rate of 2.7 kbps with effectively zero estimated mutual information leakage during simulated adversarial cyber-attacks (Table 3). While 2.7 kbps might appear limited for transmitting raw visual data, it is

exceptionally efficient for securing the highly compressed, localized intelligence bursts generated by the Edge AI module. Within the controlled constraints of this digital simulation model, this specific benchmark demonstrates strong theoretical resilience against the modeled "harvest now, decrypt later" decryption strategies [11]. Rather than claiming an unconditionally unbreakable physical defense, the integration of the simulated QKD protocol establishes a robust architectural baseline for secure tactical telecommunications within multi-domain frameworks.

The Conceptual Novelty of Interdependent Resilience and Ethical Accountability.

The primary novelty of this research lies in the formulation of a conceptual architecture aimed at establishing a theoretical "tripartite synergy" between Edge AI, bioinspired propulsion, and QKD. While traditional paradigms often rely on isolated "technology stacking," this paper proposes an interdependent framework rather than an empirically validated integrated system. Theoretically, physical stealth (reduced noise) is complemented if a UAV reduces

continuous RF transmission burdens by processing data locally via Edge AI, which in turn conceptually makes the implementation of low-bandwidth wireless QKD feasible for transmitting compact intelligence bursts.

However, it must be rigorously acknowledged that the current empirical validation evaluates these three subsystems strictly in isolation. The complex cross-system interactions such as whether the computational load and thermal output of the Edge AI module affect the power consumption and endurance of the bioinspired rotors, or how the QKD cryptographic post-processing overhead might impact the total end-to-end real-time ISR latency have not been experimentally measured in this study. Therefore, the proven scientific contribution of this work resides in the empirical evaluation of the three individual subsystems combined with a rigorous conceptual integration framework, rather than the demonstrated performance of a fully unified ISR platform. The integration of Explainable AI (XAI) logs further strengthens this conceptual framework by theoretically guaranteeing algorithmic accountability under International Humanitarian Law

(IHL). Future physical integration into a unified UAV platform is critically required to quantify these cross-subsystem dependencies and transition this conceptual architecture into a fully proven interdependent mechanism.

Finally, the implementation of Explainable AI (XAI) logs via Grad-CAM and SHA-256 cryptographic hashing provides a plausible technical foundation for transparent decision-making logs [13]. By leveraging Grad-CAM to visualize feature attribution and SHA-256 for integrity checking, the architecture ensures that model decisions can be audited for discrepancies. From a conceptual perspective, ensuring that internal AI feature selection is auditable offers a framework for aligning future autonomous systems with International Humanitarian Law (IHL), particularly regarding the Principle of Distinction [15]. However, as this study did not include human operator evaluations, target distinction accuracy tests, or legal compliance auditing, these ethical benefits remain theoretical frameworks intended to guide responsible AI development in future operational platforms.

Conclusion

This research proposed and evaluated a conceptual framework for resilient autonomous ISR networks by independently evaluating its critical physical, computational, and cryptographic subsystems. The empirical evaluation of the isolated components established key technical baselines: the bioinspired rotor geometry achieved an average noise reduction of 12.8 dB in anechoic conditions; the static Edge AI module reduced operational latency by an average of 48 ms and optimized bandwidth consumption by 62% during VO processing; and the Decoy-State BB84 QKD simulation demonstrated a secure key rate of 2.7 kbps with zero data leakage under modeled quantum attacks.

These findings demonstrate the strong conceptual potential of

synthesizing physical noise mitigation with edge computation and quantum key distribution. However, broader operational claims such as physical acoustic detection radii, swarm network scalability, information superiority, and compliance with the Principle of Distinction under International Humanitarian Law represent theoretical implications that were not directly tested in this study. Future research must focus on the physical integration of these subsystems into a fully flight-capable drone prototype to evaluate cross-subsystem interactions, human operator oversight, and operational performance under real-world multi-UAV flight and electronic warfare conditions.

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