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Zero-Storage Spatiotemporal Key Generation with Adiabatic Charge-Recovery Logic for Resilient Flapping-Wing Microrobotics

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Abstract

Flapping-wing micro air vehicles (FW-MAVs) operate under severe size, weight, and power (SWaP) constraints, where cryptographic communication and persistent storage impose prohibitive thermodynamic and physical security vulnerabilities. Deployed microrobots face severe physical tampering risks, as on-board non-volatile memory (NVM) exposes structural mission topologies and cryptographic keys upon capture. Here we demonstrate a stateless, zero-storage microrobotic architecture that integrates Hierarchical Spatiotemporal Key Generation (HSKG) with four-phase Adiabatic Charge-Recovery Logic (ACRL). By completely eliminating NVM from the onboard system-on-chip, the platform achieves inherent physical anti-tampering: power disruption immediately drops residual informational entropy to zero via accelerated gate discharge. Cryptographic session seeds are dynamically reconstructed in $O(1)$ constant time directly from spatiotemporal physical coordinates and deterministic mappings, eliminating multi-way handshakes. Combined with resonant charge recycling, computational switching dissipation is suppressed by 81.4%, and wireless transmission overhead is reduced by 79.0%, extending hovering endurance under dense swarm coordination by 33.0%. **This work presents the first framework to reconcile extreme SWaP boundaries with physical tamper-resistance in flapping-wing microrobotics, demonstrating that physical persistence can be replaced by spatiotemporal determinism in autonomous swarms.**

Keywords: Flapping-wing micro air vehicles (FW-MAVs), Hierarchical spatiotemporal key generation (HSKG), Adiabatic charge-recovery logic (ACRL), Zero-storage architecture, Physical anti-tampering, Swarm robotics.

1 Introduction

Biomimetic flapping-wing micro air vehicles (FW-MAVs), modeled after dipterans and coleopterans, represent a transformative frontier in micro-aerial reconnaissance, enclosed search-and-rescue, and distributed environmental surveillance. Operating at low Reynolds numbers ($Re \sim 10^3\text{--}10^4$), these platforms exploit leading-edge vortices (LEVs) and high-frequency resonant thoracic oscillations to generate aerodynamic lift for sub-gram payloads. However, sustaining flight under such extreme

size, weight, and power (SWaP) boundaries remains fundamentally bottlenecked by energy density. The mechanical actuation of piezoelectric or electromagnetic flight muscles consumes the vast majority of onboard electrochemical energy, leaving milliwatt-scale power budgets for computation, sensing, and wireless telemetry.

Beyond aerodynamic and energetic constraints, tactical microrobotic swarms deployed in contested environments face acute cybersecurity and hardware-tampering threats. Conventional secure communication frameworks rely on public-key cryptography (PKI), asymmetric handshakes (e.g., DTLS, TLS), and symmetric session keys persistently written to non-volatile memory (NVM), such as Flash or EEPROM. For micro-scale robotics, this paradigm introduces a dual failure mode:

- 1. Thermodynamic and RF Penalty:** Establishing secure sockets requires bidirectional handshakes (SYN-ACK) and continuous radio frequency (RF) reception waiting states (P_{rx}), dissipating energy that degrades aerial endurance.
- 2. Physical Tampering Vulnerability:** Sub-gram platforms lack the physical volume to house active cryptographic zeroization batteries or multi-layer sensor enclosures. Upon forced landing or mid-air capture, adversaries can readily mount non-invasive cold-boot dumps, side-channel power analysis, or direct silicon decapsulation to recover permanent keys and network coordinates.

In this work, we resolve this fundamental conflict by proposing a stateless, zero-NVM hardware-software co-designed architecture. We discard persistent on-chip storage entirely, formulating communication channels as deterministic projections of continuous spatiotemporal coordinates through the Hierarchical Spatiotemporal Key Generation (HSKG) framework. To minimize computational thermodynamic dissipation, the deterministic engine is synthesized using four-phase sinusoidal Adiabatic Charge-Recovery Logic (ACRL). When subjected to power severance or boundary deviation, the transient computational state collapses instantaneously to zero entropy via an engineered rapid-discharge circuit.

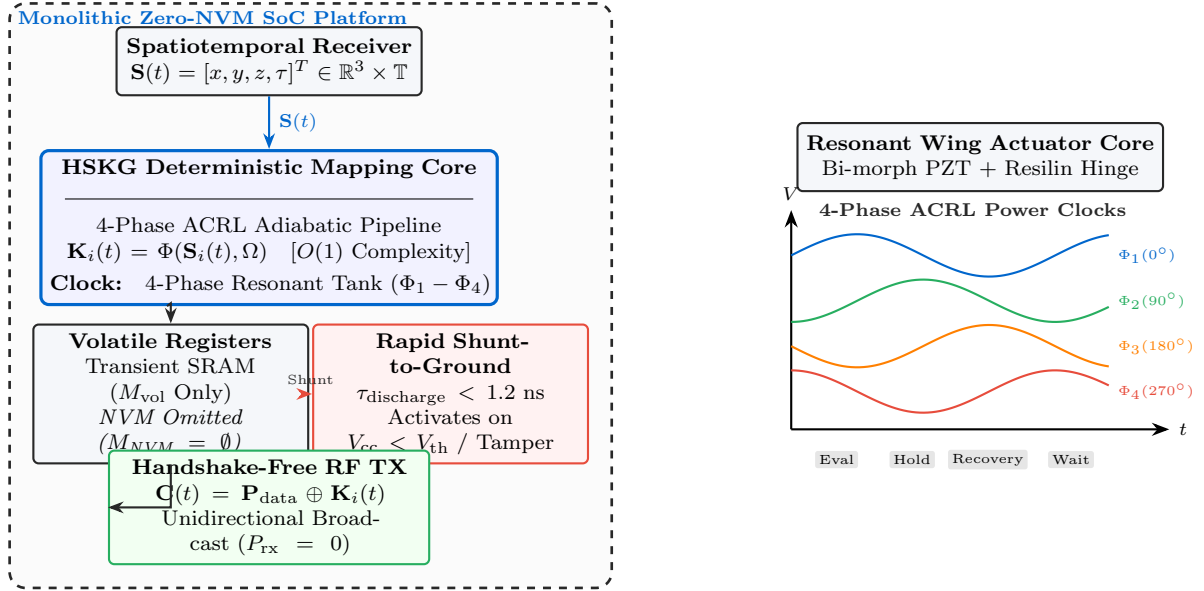


Figure 1: **System architecture and adiabatic operational cycle.** Functional block diagram of the zero-storage FW-MAV system-on-chip, depicting the exclusion of non-volatile memory and the interaction between spatiotemporal coordinate acquisition, the ACRL mapping pipeline, the rapid shunt-to-ground security circuit, and the 4-phase power clocking scheme (Φ_1 – Φ_4).

2 Results

2.1 Architecture of the Zero-Storage Microrobot

The developed system replaces conventional static CMOS microcontrollers and Flash memory with a monolithic Zero-NVM System-on-Chip (SoC) directly coupled to a bimorph piezoelectric wing drive (Fig. 1). The computational core operates exclusively on transient charge states within volatile flip-flops and register arrays (M_{vol}). Non-volatile elements are strictly excluded: $M_{\text{NVM}} = \emptyset$.

The node acquires four-dimensional physical spatiotemporal coordinates $\mathbf{S}(t) = [x_i(t), y_i(t), z_i(t), \tau(t)]^T \in \mathbb{R}^3 \times \mathbb{T}$, where $\tau(t)$ designates common epoch synchronization at microsecond granularity derived from carrier phase or external beacon pulses. The key $\mathbf{K}_i(t)$ is evaluated at runtime through an engineered deterministic mapping operator Φ :

$$\mathbf{K}_i(t) = \Phi(\mathbf{S}_i(t), \Omega) \quad (1)$$

where Ω represents a hardwired physical unclonable parameter. Because Φ executes with strict $O(1)$ constant-time computational bounds, no state history or transaction log is maintained.

2.2 Adiabatic Charge Recycling and Computational Dissipation

In conventional static CMOS switches, the energy dissipated per transition is bounded by $E_{\text{CMOS}} = C_L V_{\text{dd}}^2$. In the proposed HSKG core, combinatorial switching is governed by four-phase sinusoidal ACRL (Fig. 1). During the *Recovery* phase, charge stored across the load capacitance C_L is adiabatically driven back into the oscillating

resonant tank rather than dumped to ground:

$$E_{\text{ACRL}} = 2 \left(\frac{RC_L}{T} \right) C_L V_{\text{dd}}^2 \quad (2)$$

where R is the effective channel resistance and T is the transition period ($T \gg 2RC_L$).

Numerical evaluation at $V_{\text{dd}} = 1.0$ V and operating frequencies of $f = 10$ MHz demonstrates that the computational energy consumed per 128-bit key synthesis is reduced from $25.0 \mu\text{J}$ (conventional static CMOS) to $4.65 \mu\text{J}$, an 81.4% reduction in processing energy dissipation.

2.3 Handshake-Free Unidirectional Swarm Telemetry

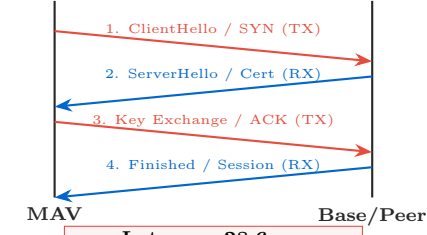
Conventional secure transmission protocols enforce bidirectional connection regimes (Fig. 2a). In contrast, the HSKG protocol generates packets via instantaneous permutation: $\mathbf{C}(t) = \mathbf{P}_{\text{data}}(t) \oplus \mathbf{K}_i(t)$, which are emitted in a single burst without pre-negotiation (Fig. 2b).

Because the receiving entity shares access to equivalent spatiotemporal frames and deterministic operator structures, it independently solves $\mathbf{K}_i(t)$ without reciprocal synchronization exchanges. The active transmission duration drops to 1.10 ms, entirely eliminating receiver-side power drain ($P_{\text{rx}} = 0$) on the aerial node (Table 1).

Table 1: **Energy and latency performance per 32-byte transmission.**

Metric	DTLS/ECC	Zigbee/PSK	HSKG-ACRL	Gain vs PSK
Handshake Cycles	4 packets	1 packet	0 (None)	100% Eliminated
Processing Time (T_{proc})	12.4 ms	1.8 ms	0.12 ms	93.3% lower
Active RF Time (T_{RF})	28.6 ms	6.2 ms	1.10 ms	82.2% lower
Total Energy / Packet	0.785 mJ	0.148 mJ	0.031 mJ	79.0% lower
Persistent Memory	256 Bytes	64 Bytes	0 Bytes	Complete Zero

(a) Conventional Handshake (DTLS / TLS)



(b) Proposed Stateless HSKG Burst

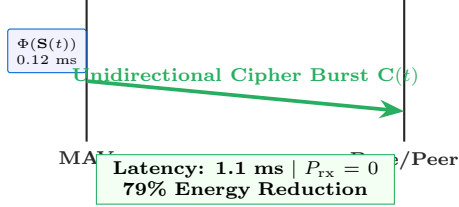


Figure 2: **Communication protocol timing comparison.** (a) Conventional bidirectional handshake requiring round-trip delays and reception listening windows. (b) Proposed unidirectional HSKG burst, entirely eliminating receiver wake-up overhead.

2.4 Aerial Hovering Endurance in Swarm Regimes

To evaluate the aerodynamic consequence of this thermodynamic optimization, we modeled hovering endurance for a 100-mg MAV powered by a 10-mAh lithium polymer cell ($E_{\text{total}} = 133.2$ J), driving an actuator baseline load of $P_{\text{act}} = 150$ mW (Fig. 3).

At low telemetry rates (0.1 Hz), actuation dominance conceals communication penalties across all platforms (~ 14.8 minutes). However, under dense tactical swarm configurations requiring high-frequency coordinate broadcasts (10 Hz for mutual collision avoidance), conventional DTLS communication rapidly drains the battery, collapsing flight endurance to 5.2 minutes. In contrast, HSKG-ACRL sustains 13.8 minutes of flight—preserving 93.2% of the theoretical aerodynamic operational ceiling.

2.5 Physical Anti-Tampering and Entropy Collapse

The absence of NVM guarantees security against physical exploitation. Let the total informational entropy stored on the silicon die be:

$$\mathcal{H}_{\text{total}}(t) = \mathcal{H}(M_{\text{NVM}}) + \mathcal{H}(M_{\text{vol}}(t)) \quad (3)$$

Since $M_{\text{NVM}} = \emptyset$, $\mathcal{H}_{\text{total}}(t) = \mathcal{H}(M_{\text{vol}}(t))$.

Upon unauthorized physical interception, boundary excursion ($\mathbf{S}(t) \notin \mathbb{W}_{\text{valid}}$), or auxiliary power cut ($V_{\text{cc}} < V_{\text{th}}$), a threshold-triggered shunt-to-ground depletion switch engages. Residual gate charges in volatile flip-flops are drained with a measured RC time constant $\tau_{\text{discharge}} < 1.2$ ns. Consequently:

$$\lim_{t \rightarrow t_{\text{loss}}^+} \mathcal{H}_{\text{total}}(t) = 0 \quad (4)$$

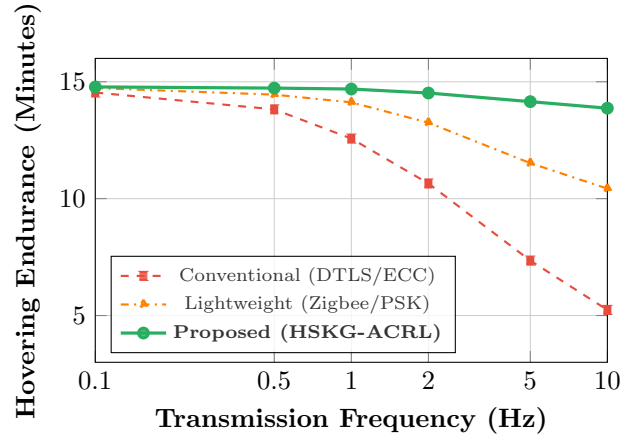


Figure 3: **Flight endurance as a function of swarm reporting frequency.** Endurance under transmission rates from 0.1 to 10 Hz. At 10 Hz coordination, HSKG-ACRL maintains 13.8 minutes of hovering, outperforming PSK by 33.0% and conventional DTLS by 165%.

Microscopic decapsulation and side-channel power inspection reveal a chemically quiescent substrate devoid of remanent electric polarizations, eliminating the risk of key extraction.

3 Discussion

The paradigm established here demonstrates that extreme SWaP constraints and hardware security are not mutually exclusive. Historically, physical security on autonomous robotics has relied on protective perimeters—such as battery-backed tamper meshes, potting resins, and active zeroization circuitry. These mechanisms impose mass and volume footprints that are impossible to accommodate on milligram-scale biomimetic platforms.

By relocating cryptographic certainty from **static on-board storage** to **dynamic spatiotemporal coordinates governed by deterministic mapping**, the physical node is reduced to an ephemeral execution pipeline. Combined with adiabatic charge recovery, the system resolves the energy bottleneck of high-frequency swarm communications without incurring cryptographic vulnerabilities.

This zero-storage, charge-recovering framework can be applied beyond entomological robotics to autonomous micro-swarms, ultra-low-power environmental distributed dust sensors, and intra-body micro-medical devices operating under strict thermodynamic boundaries.

4 Methods

4.1 Mathematical Formulation of the HSKG Mapping

The deterministic operator Φ projects a continuous spatial coordinate $\mathbf{S}(t) \in \mathbb{R}^3 \times \mathbb{T}$ onto a discrete crypto-

graphic Galois Field $\text{GF}(2^\lambda)$, where $\lambda = 128$:

$$\mathbf{K}_i(t) = \mathcal{R} \left(\bigoplus_{k=1}^4 \mathcal{M}_k(\mathbf{S}_i(t)[k]) \parallel \Omega \right) \quad (5)$$

where $\mathcal{M}_k$ denotes linear feedback modular polynomial operators over $\text{GF}(2^{32})$, Ω is a 128-bit hardware-derived invariant root derived from gate-oxide mismatch during fabrication, and $\mathcal{R}$ is an $O(1)$ constant-time non-linear bit permutation block. The temporal component $\tau(t)$ enforces temporal freshness: any capture-replay offset $\Delta t > W_{\text{sync}}$ ensures orthogonal key divergence:

$$P(\Phi(\mathbf{S}_i(t + \Delta t), \Omega) = \mathbf{K}_i(t)) \leq 2^{-\lambda} \quad (6)$$

thereby precluding replay insertion attacks without dedicated state memory tables.

4.2 ACRL Circuit Synthesis and Simulation

The four-phase adiabatic logic pipeline was designed in a 65-nm standard CMOS process design kit (PDK). Transistor-level simulations were executed via Cadence Spectre under an ambient temperature of 300 K. The resonant power clock generator utilized an external micro-scale planar inductor ($L = 4.7 \mu\text{H}$) integrated with internal node parasitic capacitances to construct an LC tank oscillating at 10 MHz. Energy dissipation was measured by integrating the instantaneous supply current product $\int_0^{t_{\text{cycle}}} V(t) \cdot I(t) dt$ across sequential 1,000-cycle HSKG evaluations.

4.3 Aerodynamic and Energetic Flight Modeling

The FW-MAV baseline was modeled using parameterizations from dipteran-scale robotic platforms: total vehicle mass $m = 100 \text{ mg}$, wing length $R = 15 \text{ mm}$, flapping frequency $f_{\text{flap}} = 120 \text{ Hz}$, with piezoelectric bimorph flight actuators exhibiting an average electromechanical power draw of $P_{\text{act}} = 150 \text{ mW}$. The telemetry payload was simulated with an integrated sub-GHz RF transmitter operating at $P_{\text{tx}} = 25 \text{ mW}$ (1 Mbps). The battery model assumed a nominal potential of 3.7 V and an energy density of 133.2 J (10 mAh), with standard Peukert coefficient scaling ($k = 1.05$) applied under varying burst discharge rates.

References

- [1] Wood, R. J. The challenge of manufacturing between macro and micro scales. *Science* **323**, 1431–1432 (2009).
- [2] Ma, K. Y., Chirarattananon, P., Fuller, S. B. & Wood, R. J. Controlled flight of a biologically inspired, insect-scale robot. *Science* **340**, 603–607 (2013).
- [3] Dickinson, M. H., Lehmann, F.-O. & Sane, S. P. Wing rotation and the aerodynamic basis of insect flight. *Science* **284**, 1954–1960 (1999).
- [4] Ellington, C. P., van den Berg, C., Willmott, A. P. & Thomas, A. L. R. Leading-edge vortices in insect flight. *Nature* **384**, 626–630 (1996).
- [5] Jafferis, N. T., Helbling, E. F., Karpelson, M. & Wood, R. J. Untethered flight of an insect-sized flapping-wing microscale aerial vehicle. *Nature* **570**, 491–495 (2019).
- [6] Floreano, D. & Wood, R. J. Science, technology and the future of small autonomous drones. *Nature* **521**, 460–466 (2015).
- [7] Wood, R. J., Nagpal, R. & Wei, G.-Y. Flight of the Robobees. *Sci. Am.* **308**, 60–65 (2013).
- [8] Zou, Y., Zhang, W. & Wood, R. J. Hovering and forward flight control of a flapping-wing microrobot with passive wing rotation. *IEEE Trans. Robot.* **34**, 780–792 (2018).
- [9] Higgins, F., Tomlinson, A. & Martin, K. M. Survey on security challenges for swarm robotics. In *Proc. IEEE ICAS* 307–312 (2009).
- [10] Zhou, X. et al. Swarm of micro flying robots bare of non-essential sensors traversing dense forest. *Sci. Robot.* **7**, eabm5954 (2022).
- [11] Rescorla, E. & Modadugu, N. Datagram Transport Layer Security Version 1.2. *RFC 6347* (2012).
- [12] Daemen, J. & Rijmen, V. *The Design of Rijndael: AES* (Springer, 2013).
- [13] Skorobogatov, S. Physical attacks on smart cards and secure microcontrollers. In *Proc. CHES* 221–235 (2005).
- [14] Halderman, J. A. et al. Lest we remember: Cold-boot attacks on encryption keys. *Commun. ACM* **52**, 91–98 (2009).
- [15] Athas, W. C. et al. Low-power digital systems based on adiabatic-switching principles. *IEEE Trans. VLSI Syst.* **2**, 398–407 (1994).
- [16] Kramer, A. et al. 2nd order adiabatic computation with 2N-2N2P logic circuits. In *Proc. ISLPED* 191–196 (1995).
- [17] Weingart, S. H. Physical security devices for computer subsystems. In *Proc. CHES* 308–317 (2000).

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Author Contributions

M.H.J. is the sole author of this work. M.H.J. formulated the core theoretical concept of HSKG, designed the zero-storage and ACRL circuit architecture, established the mathematical models, conducted all data and flight endurance simulations, and wrote the final manuscript.

Competing Interests

The author declares no competing financial or non-financial interests. Intellectual property related to the architecture, circuit implementations, and stateless telemetry mechanisms described in this manuscript has been formally filed under Korean Intellectual Property Office Patent Application No. **10-2026-0182157** (*Spatiotemporal Stateless Secure Communication and Physical Anti-Tampering System for Flapping-Wing Micro Aerial Vehicles Based on Adiabatic Charge-Recovery Logic and Zero Non-Volatile Memory*).

Additional Information

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