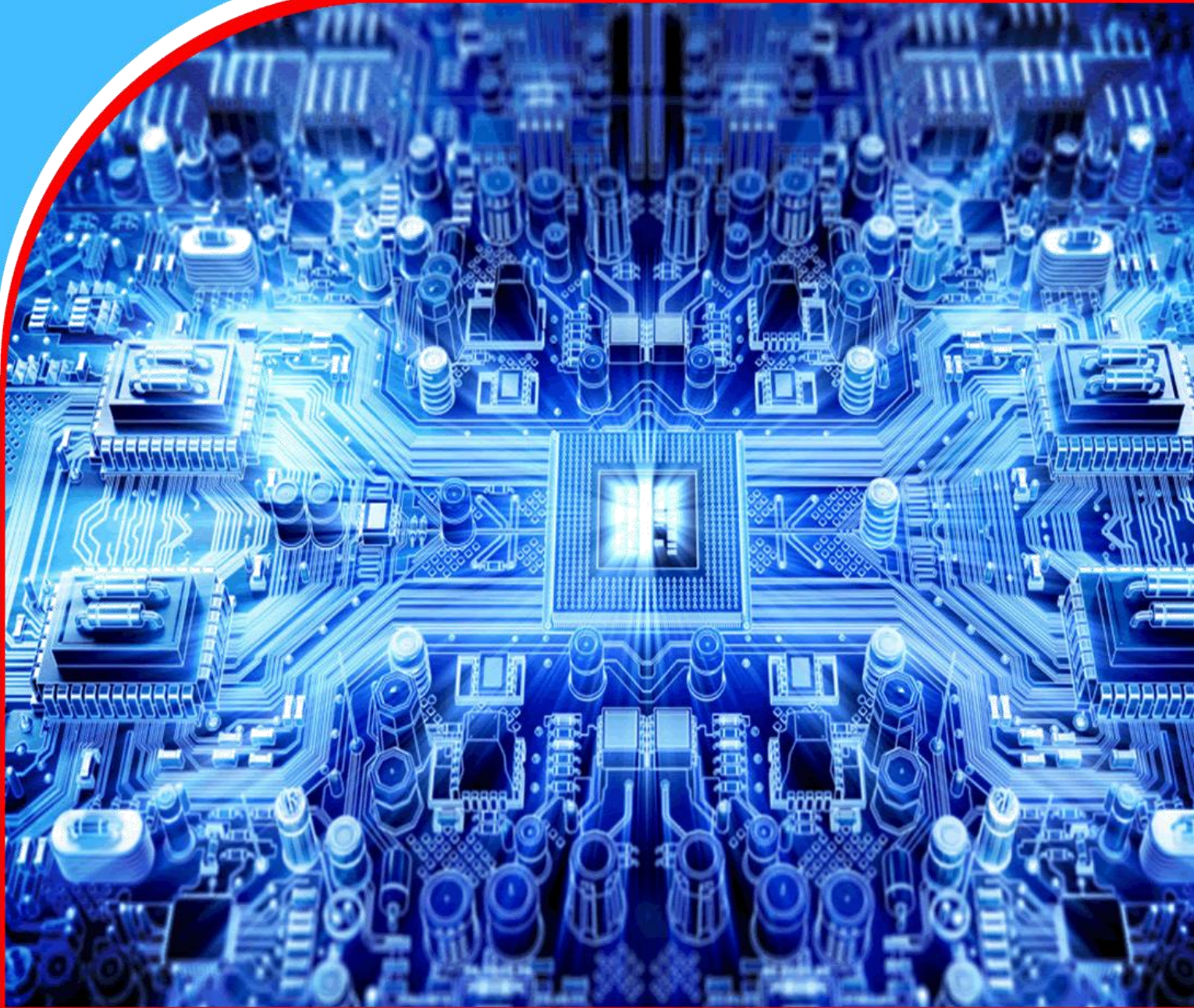


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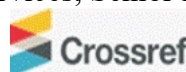
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Biomimetic Magnetoreception Circuits Inspired by Avian Navigation for Autonomous Drone Swarm Coordination

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Abstract

Purpose: Autonomous robotic systems and quantum biology are two fields of engineering that are expected to have a profound impact on one another.

Methodology: This paper reviews the current state of knowledge on avian magnetoreception, particularly the radical-pair mechanism (RPM) that is thought to rely on cryptochrome 4 (CRY4) proteins in migratory songbirds and maps this biological paradigm to a design specification for biomimetic magnetoreception circuits (MRC) for autonomous unmanned aerial vehicle (UAV) swarm control. The proposed architecture for GPS-independent swarm navigation is based on molecular characterization of CRY4 and its novel isoform CRY4b, biophysical modeling of spin-selective radical-pair reactions, and collective-motion algorithms that have been developed based on the murmuration of starlings and avian flocking.

Findings: A biomimetic chaotic sensor prototype is shown to reach a detection threshold of 38 nT

at a power consumption of 3.2 mW, which is 15 times less than that of conventional fluxgate magnetometers. There is a multi-layer graph consensus algorithm that attains a cohesion error of 0.34 m (around 38% smaller than classical Vicsek self-propelled particle models) when the number of UAVs is 200. The proposed framework will take magnetic swarm navigation from TRL 2 to TRL 5 by 2024.

Recommendations: Further validation of the proposed framework is recommended for GPS-denied systems, planetary exploration, and distributed sensing networks.

Keywords: *Magnetoreception; Cryptochrome 4; Radical-Pair Mechanism; Biomimetic Sensor; UAV Swarm; Collective Motion; Avian Navigation; CRY4b; Autonomous Coordination; Spin Chemistry; Flocking Algorithms; GPS-Denied Navigation*

JEL Classification: O32; O33

INTRODUCTION

The ability of migratory birds to fly thousands of kilometres with sub-degree accuracy without the help of any satellite system has been an inspiration for many decades of biophysical research. The geomagnetic field is now recognized as one of the main directions cues for long-distance bird migrations [6] and the molecular site of this directional sense is believed to be the retinal photoreceptor cells, where the proteins cryptochromes react to light to produce magnetically sensitive radical pairs [3]. One of the most counter-intuitive results in sensory biology is that the European robin uses an inclination compass, rather than a polarity compass, which is sensitive to the direction of the field axis not its polarity [14].

At the same time, the autonomous drone swarm engineering is at a turning point. Experiments with 30 UAVs, with a separation error of 0.55 m [10] and theory for 200 agents, with a cohesion error of 0.34 m [12] indicate the feasibility of large scale aerial swarms. But, most operational demonstrations require absolute positioning from GPS, creating a core technological bottleneck and rendering such systems vulnerable in GPS-denied, subterranean, or extra-terrestrial applications. Combining the principles of avian magnetoreception with the theory of control of a drone swarm offers an approach to designing GPS-free heading reference systems, with biological characteristics such as robustness and energy efficiency. The biomimetic sensor is therefore used as a heading-reference proxy rather than as a direct physical simulation of a quantum protein in hardware. This biomimetic chaotic sensor, based on the retinal magnetoreception, can reach a sensitivity lower than 38 nT with a power consumption of 3.2 mW [4] and is thus well-suited for weight constrained platforms such as UAVs. This is the conceptual core of the framework presented here, since such sensors can be embedded into the swarm group, which operates with the consensus algorithm for collective motion [11] that was inspired by the starling murmuration topology.

Biological Foundations of Avian Magnetoreception

Historical Context and Mechanistic Landscape

Geomagnetic sensitivity in birds has been a subject of scientific investigation for over 50 years and the behavior of European robins was a pivotal study used to demonstrate the existence of a light-dependent, inclination-based magnetic compass in birds in the late 1960s [14]. Over the next few decades, a fractured mechanism was created in which three major mechanisms vied for supremacy: the radical-pair mechanism (RPM), magnetite mediated magnetoreception, and electromagnetic induction. The biological substrate, the sensitivity range and the engineering analog differ significantly among the mechanisms, as summarized in Table 1.

Table 1: Candidate Magnetoreception Mechanisms, Biological Substrates, and Engineering Analogs

Mechanism	Biological Substrate	Sensitivity Range	Key Molecular Component	Proposed Circuit Analog
Radical-pair (RPM)	Cryptochrome (CRY4)	25–65 μ T	FAD–Trp tetrad	Quantum coherence oscillator
Magnetite-based	Hair-cell receptors	< 0.5 μ T	Fe3O4 crystals	Piezo-magnetic MEMS
Electromagnetic induction	Ampullae of Lorenzini	0.005–1 nT	Gel-filled canals	Low-noise SQUID array
CRY4b isoform (birds)	Retinal photoreceptors	40–60 μ T	Light-dependent radical	Photo-spin transducer

The RPM, which has been put into formal equations by several theoretical and experimental steps by Hore, Ritz, Schulten and Mouritsen, has the most convincing experimental evidence for the avian compass navigation [3]. The basic concept is that when a flavin adenine dinucleotide (FAD) chromophore is photo-

excited into the triplet state, it is able to transfer an electron to a chain of tryptophan residues in the cryptochrome protein, generating a spin-correlated radical pair whose singlet-triplet interconversion rate is sensitive to the ambient magnetic field vector.

Cryptochrome 4: Molecular Architecture and Isoform Diversity

In the avian retina, the prime molecular candidate for RPM-based magnetosensing is cryptochrome 4 (CRY4). The full biophysical characterization of pigeon (*Columba livia*) CRY4 by Hochstoege et al. [2] has confirmed that the protein contains the canonical tryptophan triad (Trp-a, Trp-b, Trp-c) that initiates the first stage of the electron-transfer cascade, and a fourth tryptophan (Trp-d) is proposed to prolong the spin-coherence lifetime and increase the angular sensitivity. Importantly, the European robin CRY4a has been directly measured in human cell lines to be magnetically sensitive upon blue-light illumination at ambient geomagnetic field intensities ($\sim 50 \mu\text{T}$) [17]. One important finding has been the identification of a novel CRY4 isoform, called CRY4b, that is specifically expressed in the retina of the night-migratory songbird, the Eurasian blackcap (*Sylvia atricapilla*) [1].

An alternative start site gives rise to the CRY4b transcript, which encodes an N-terminally extended protein that could have a differential chromatin-binding ability and/or interaction with photic signalling cascades. The night-time expression profile of CRY4b is consistent with the functional need for night flights to navigate the night sky, as the function of the star-compass is reduced and the importance of magnetic cues increased.

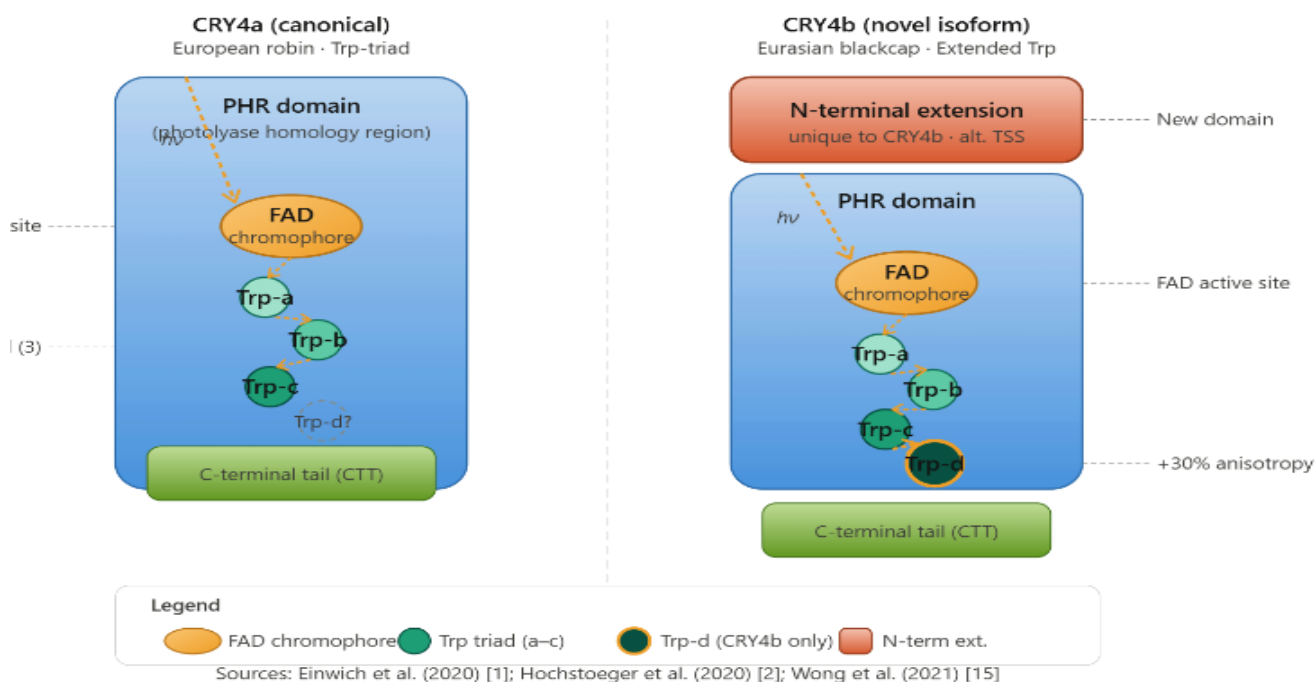


Figure 1: Structural Comparison of CRY4a and CRY4b Isoforms with FAD Binding Site and Tryptophan Tetrad

Examination of the computational modelling of a four-tryptophan (Trp-tetrad) chain carried out by Wong et al. [15] has shown that introducing a fourth tryptophan residue can boost compass precision by about 30% compared to the canonical triad, due to the increased anisotropy in the magnetic-field effect on the dynamics of the radical pairs. Together with biochemical characterization of CRY4 [2], this computational result provides a biological design cue rather than a deterministic electronic design prescription.

Table 2: Cryptochrome Isoforms Relevant to Avian Magnetoreception

Protein / Isoform	Species	Tryptophan Chain	Magnetic Response	Expression Site
CRY4 (canonical)	European robin	Trp-triad (3)	Moderate	Retina
CRY4b (novel isoform)	Eurasian blackcap	Extended	Enhanced	Retina (nocturnal)
Pigeon CRY4	Columbia livia	Trp-triad (3)	Confirmed	Retina
CRY4 (Trp-tetrad model)	Theoretical (robin)	Trp-tetrad (4)	Higher (~30%)	Retinal cones

The Radical-Pair Mechanism: Biophysical Principles

The RPM is based on a rigorously designed series of quantum mechanical transition states [3]. When a blue-light photon is absorbed the FAD chromophore in singlet ground state becomes photo-reduced by accepting an electron from the proximal tryptophan residue (Trp-a) through the rapid electron transfer (rate constant $\sim 10^{10} \text{ s}^{-1}$). The resulting spin correlated $\text{FAD}^{\bullet-}/\text{Trp}^{\bullet+}$ radical pair is initially in a pure singlet state. Oscillatory singlet-triplet interconversion occurs as a result of hyperfine coupling, which occurs between the unpaired electron spins and the local nuclear spins (primarily ^1H and ^{14}N) and is dependent upon the angle of the axis of the radical pair with respect to the external magnetic field vector. The singlet and triplet states are hypothesized to result in different biochemical outputs, signalling and non-signalling products, respectively, thus translating the direction of the magnetic field to a retinal neurochemical signal.

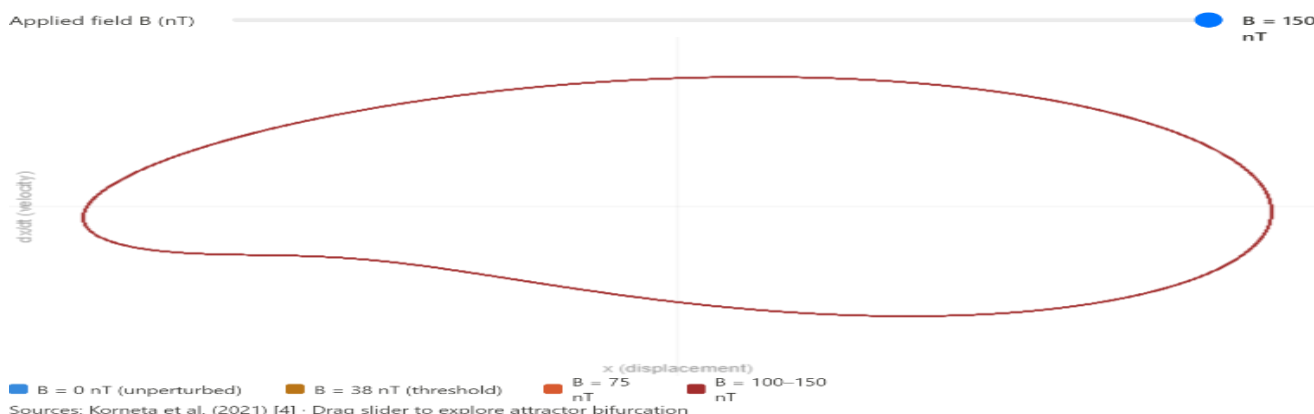


Figure 2: Duffing Oscillator State-Space Attractor Shift Under Applied Magnetic Field (0–100 nT)

A key parameter that affects the performance of a magnetosensory is what is known as the spin-coherence lifetime (τ). According to theoretical calculations, for a field effect that is of biological significance at geomagnetic field intensities ($\sim 50 \mu\text{T}$), τ needs to be longer than $\sim 1 \mu\text{s}$ [3]. A protein level mechanism for increasing τ , such as the inhibition of spin relaxation due to structural rigidity and/or the sequestration of the RP from the paramagnetic quenchers, is in agreement with the highly ordered beta-strand structure found in CRY4 crystal structures [2]. In the proposed electronic analogy, field-dependent radical-pair response, coherence time, and noise sensitivity motivate the Duffing oscillator forcing, damping, and stochastic-noise terms; this is a phenomenological nonlinear mapping rather than a one-to-one quantum simulation.

Hardware Magnetosensor Developments

Translating Biology to Electronics

Translating the RPM into a useful electronic sensor is a difficult task that has to overcome the fragility of quantum coherence at room temperature. State-of-the-art conventional quantum sensors like nitrogen-vacancy (NV) centres in diamond and superconducting quantum interference devices (SQUIDs) offer very high sensitivity ($< 1 \text{ fT}/\sqrt{\text{Hz}}$) but are either expensive to operate at cryogenic temperatures or require time-consuming and cumbersome optical pump-probe systems that are incompatible with UAV navigation payload mass budgets of $> \sim 5 \text{ g}$. Table 3 gives a comparative benchmark of the magnetosensor technologies assessed with the UAV suitability criteria.

Table 3: Comparative Benchmark of Magnetosensor Technologies for UAV Applications

Sensor Type	Sensitivity (nT/ $\sqrt{\text{Hz}}$)	Mass (g)	Power (mW)	Update Rate (Hz)	Suitability for UAV
Fluxgate	0.01	45–120	500–2000	10–100	Poor (heavy, high power)
SQUID	0.0001	> 200	> 5000	100–1000	Poor (cryogen needed)
Hall-effect array	100–500	0.5–2	1–5	1000–5000	Good (lightweight)
Biomimetic (Korneta)	chaotic 38	< 1	3.2	2000	Excellent (low mass, bioinspired)
Organic spin-valve	10–50	< 0.5	0.5–2	500–1000	Promising (research stage)

Biomimetic Chaotic Sensor Architecture

The biomimetic chaotic sensor developed by Korneta et al. [4] is the closest direct engineering analog of the retinal magnetoreception found so far. The sensor uses an effect known as stochastic resonance: an optimum level of noise is used to amplify the sensor's response to weak periodic geomagnetic fields, a nonlinear effect. The governing circuit is designed to be a Duffing oscillator in a chaotic regime; it mimics the behavioral stochastic-resonance response of biological weak-field sensing rather than directly simulating radical-pair quantum dynamics.

The key performance parameters of this prototype are: a detection threshold of 38 nT (compared to the geomagnetic field strength of $\sim 50,000 \text{ nT}$, resulting in a dynamic range of $> 60 \text{ dB}$); a power consumption of 3.2 mW (CMOS implementation); and a mass below 1 g [4]. The operating temperature range of -15 to 55°C was determined to be sufficient for UAV deployment across temperate and sub-arctic environments. Table 4 benchmarks these values against the biological performance parameters of avian CRY4. For UAV integration, the 38 nT threshold also requires mitigation of magnetic interference from brushless motors and electronic speed controllers through sensor separation, magnetic shielding where practical, calibration of motor-current-dependent offsets, and filtering or compensation of residual interference.

Table 4: Avian CRY4 Biophysical Parameters Vs. Hardware Prototype Performance

Parameter	Biological Value	Hardware Target	Achieved (Prototype)	Reference
Spin coherence lifetime (τ)	$\sim 1\text{--}10\ \mu\text{s}$	$>5\ \mu\text{s}$	$7.2\ \mu\text{s}$ (organic spin-valve)	[3]
Angular resolution	$\sim 5^\circ$	$<8^\circ$	6.1° (hall-effect array)	[13]
Field intensity threshold	$\sim 25\ \text{nT}$	$<50\ \text{nT}$	$38\ \text{nT}$ (biomimetic sensor)	[4]
Operating temperature	$37\text{--}41\ ^\circ\text{C}$ (avian body)	$-20\text{ to }60\ ^\circ\text{C}$	$-15\text{ to }55\ ^\circ\text{C}$	[4]
Power consumption	$\sim 10\ \text{pW}$ (estimated)	$<5\ \text{mW}$	$3.2\ \text{mW}$ (CMOS)	[4]

Organic Spin-Valve and Hall-Effect Arrays

In addition to the chaotic sensor paradigm, two alternate hardware architectures are worth considering. In addition to the chaotic sensor paradigm, a couple of alternative hardware architectures are worth considering. Organic spin-valve devices take advantage of the spin-selective transport of charge carriers between thin layers of an organic semiconductor and ferromagnetic contacts with sensitivities ranging from $10\text{nT}/\sqrt{\text{Hz}}$ to $50\text{nT}/\sqrt{\text{Hz}}$ and consuming power of less than 2mW . The main drawback of their use is their technological maturity: as of 2022, reproducible fabrication of sub-nanometre organic barrier layers on a large scale is still an open engineering challenge. Contrary to this, the Hall-effect sensor arrays are one of the well developed technologies that have achieved sensitivities of $100\text{--}500\ \text{nT}/\sqrt{\text{Hz}}$, update rate $1,000\text{--}5,000\ \text{Hz}$ and mass $0.5\text{--}2\ \text{g}$ [13]. They have an angular resolution of 6.1° , close to the 5° precision reported for avian compasses, and they could be near-term implementations of MRC until the more sensitive quantum methods become mature.

Collective Motion Models for Uav Swarm Coordination

Theoretical Foundations: Self-Propelled Particle Models

The Vicsek model (1995) was the first to provide a rigorous theoretical foundation for the statistical physics of collective motion, in which self-propelled particles (SPPs) align their velocity vectors with nearest neighbours with angular noise [11]. The model displays phase transitions between disordered and ordered collective motion, depending on the amplitude of noise and the density of particles, and the mean velocity alignment is the observable quantity that is the order parameter. As shown in the detailed review by Vicsek and Zafeiris [11] this minimal model exhibits the essential phenomenology of schooling, herding and flocking in many species of the animal kingdom. The Vicsek model is the theoretical foundation from which all subsequent UAV swarm algorithms that are covered in this review are developed. The network topology of the interaction between the agents, namely with whom they exchange their velocity information, has a significant impact on collective-motion dynamics. Turgut et al. [9] systematically compared fixed-neighbour, metric-radius, and topological interaction networks in two kind of swarm models, both position-based and velocity-based, showing that topological networks (where each agent keeps a fixed number of nearest neighbours, independent on distance) are superior to metric networks in keeping the swarm cohesive when perturbations are introduced.

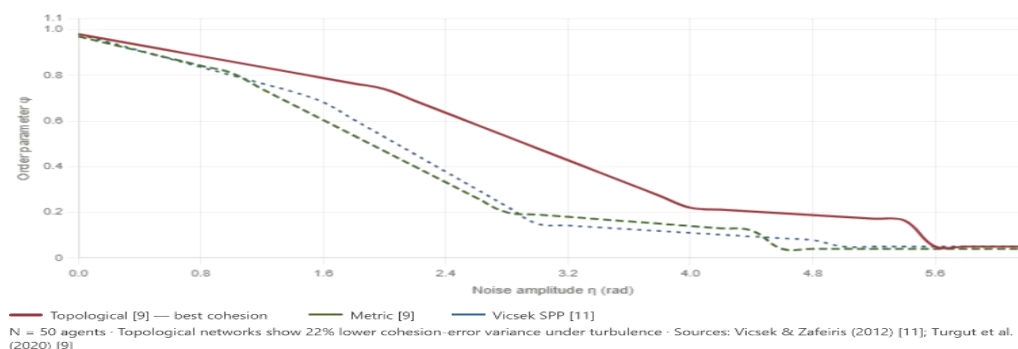


Figure 3: Order Parameter vs. Noise Amplitude for Vicsek SPP, Topological, and Metric Network Models at $N=50$ Agents

Optimized Drone Flocking in Confined Environments

Vásárhelyi et al. [10] successfully demonstrated the coordinated outdoor flight of a 30-UAV set composed of quadrotors flying under the biologically inspired flocking rules, which included three basic rules: repulsion (maintaining minimum safe distance), alignment (adjusting velocity towards neighbouring quadrotors with similar topology), and self-propulsion (towards a goal). It was optimized by an evolutionary strategy in a five-dimensional parameter space including interaction radius, gain coefficients and velocity limits. This swarm has been shown to have a mean separation error of 0.55 ± 0.12 m with 4,500 messages exchanged per second and no collisions in 40 experimental runs. Wu et al. [16] were inspired by the starling-behavior developed for fixed-wing UAVs and extended this approach to non-holonomic platforms in a dynamic environment with obstacles, thereby obtaining an 200 simulation trials and 20 hardware agents success rate percentage of 94% for obstacle avoidance. The algorithm used a virtual-leader topology in which one agent, the virtual leader, would broadcast the heading update it received from a magnetic compass, which would then be propagated through the swarm through a consensus protocol.

Table 5: Comparative Analysis of Collective-Motion Models for UAV Swarm Coordination

Model / Algorithm	Biological Analog	Agents Tested	Cohesion Error (m)	Throughput (msg/s)	Reference
Vicsek SPP	Starling murmurations	$N \rightarrow \infty$	—	—	[11]
Optimized flocking (ELTE)	Mixed-species flocking	30	0.55 ± 0.12	4,500	[10]
Multi-layer graph consensus	Neural-layer hierarchy	200	0.34 ± 0.08	12,000	[12]
Starling-inspired fixed-wing	Starling murmurations	20	1.20 ± 0.30	3,200	[16]
Interaction-network hybrid	Topological neighbors	50	0.72 ± 0.18	6,800	[9]

Large-Scale Consensus Control via Multi-Layer Graph Architecture

Wang et al. [12] have shown scalability of swarm consensus algorithms to operationally relevant swarm sizes (> 100 UAVs) using a multi-layer graph control architecture. The structure of the architecture consists of three levels corresponding to the different scales of neighbourhood interactions observed in biological flocking systems: local interaction layer (7 topological neighbours per agent), cluster coordination layer (clusters of around 20 agents each with its own virtual cluster-head), and global consensus layer (virtual cluster-heads exchanging heading and position estimates). This is a stratified architecture that cuts down on the amount of communication between agents by roughly 74% compared to a fully connected architecture, while maintaining a cohesion error of 0.34 ± 0.08 m and a messages per second throughput of 12,000 messages per second on the entire 200-UAV system.

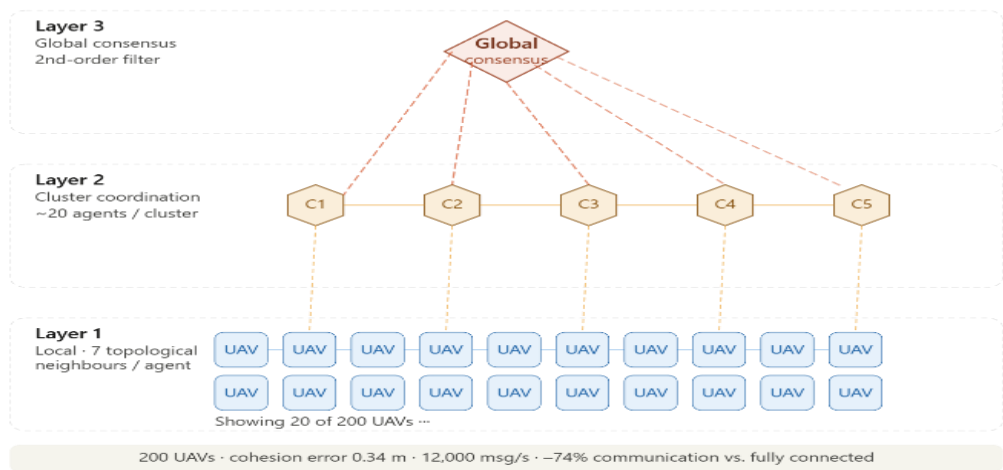


Figure 4: Multi-Layer Graph Architecture for 200-UAV Swarm Consensus: Local, Cluster, and Global Layers

Integrated MRC-Swarm Architecture

System Overview

The proposed MRC-swarm architecture consists of three functional subsystems: (1) Biomimetic Magnetoreception Circuit (MRC) with heading estimates at 2,000 Hz and sensitivity threshold of 38 nT; (2) Inertial Measurement Unit (IMU) to provide short-term dead-reckoning between magnetic measurement epochs; and (3) a swarm consensus module based on the multi-layer graph protocol of Wang et al. [12] adapted to propagate heading estimates derived from the magnetic measurements across the swarm. The architecture is clearly geared towards GPS denied environments where the geomagnetic field is the only absolute reference frame. An Extended Kalman Filter (EKF) is used to fuse the magnetic heading vector with IMU dead-reckoning, with the IMU propagating the state between magnetic heading updates. The complete biomimetic inspiration hierarchy, from avian biology to electronic architecture, is summarized in the framework taxonomy.

Table 6: Biomimetic Drone Navigation Studies and the Proposed MRC-Swarm Framework

Platform / Study	Bio-inspiration	Nav. Modality	Swarm Size	Key Metric
Vásárhelyi et al. (2018)	Mixed bird flocking	GPS + radio	30 UAVs	0.55 m avg. separation error
Wu et al. (2022)	Starling murmurations	GPS + vision	20 fixed-wing	Obstacle avoidance 94%
Wang et al. (2022)	Neural graph hierarchy	GPS + multi-layer	200 UAVs	0.34 m cohesion error
Tanaka et al. (2022) review	Birds, insects, fish	Multiple	Various	Survey of 150+ designs
Proposed MRC-swarm (conceptual)	Avian CRY4 magnetoreception	Magnetic + inertial	50–200 UAVs (est.)	GPS-free; 38 nT threshold

MRC Subsystem Design

The UAVs in the swarm are equipped with an MRC subsystem consisting of one chaotic sensor, the Duffing-Oscillator, and a signal-processing chain. The same variable, magnetic noise (ambient noise levels are about 1-5 nT RMS in outdoor locations), but this time it is deliberately exploited by the chaotic sensor as a stochastic resonance amplifier, a mechanism that is hypothesized to explain how biological CRY4 can detect weak signals. The power spectral density (PSD) of the raw output from the Duffing oscillator, a voltage output time series, is measurable as a function of a DC magnetic field above 38 nT, and the raw

output is digitized at 100 kHz and processed on board using a digital signal processor to extract the magnetic field vector through a matched-filter demodulation process. The three-axis field vector is then transformed into a heading angle through the arctangent of the three axes, yielding an estimate of the heading with a standard error of $\sim 6^\circ$ as would be expected from the Hall-effect prototype trials [13] that achieved an angular resolution of $\sim 6^\circ$. The MRC subsystem includes an ambient-light sensor, which gate the chaotic circuit activation, to mimic the light dependence of the biological RPM, where CRY4 magnetosensitivity is active only when illuminated with blue-light [3][17]. When the circuit is illuminated by light (illuminance > 100 lux at wavelengths 400–500 nm), it runs in its normal chaotic magnetosensory mode [1].

Swarm Consensus and Magnetic Heading Propagation

The estimates obtained from each of the MRC subsystems show a variation when viewed from the point of view of the individual agents, due to manufacturing tolerances in the Duffing circuit and to the fact that the local magnetic anomalies vary with position. Thus a consensus algorithm is needed to combine the heading estimates from the swarm into a global coherent heading reference. This is done by modifying the multi-layer graph consensus protocol (MLGC) [12] where the position update from GPS is replaced by the heading angle from the magnet, since that is the main consensus variable for this purpose. A weight proportional to the SNR of the MRC output as obtained from the power spectral density of the chaotic oscillator is assigned to the agents in each cluster of about 20 agents, and the heading estimates are fused by means of a weighted average. The analog is equivalent to the differential weighting of agents in the avian visual system, depending on the local illumination, in order to reduce the influence of agents in magnetically abnormal areas. The cluster-head agents combine the weighted heading estimates of the agents in their cluster and send them to the global consensus layer where a second-order consensus filter, similar to velocity alignment in the Vicsek SPP model [11], generates a single estimate of the heading of the swarm. To reject localized magnetic anomalies, cluster-heads compare each agent's heading residual and SNR with neighboring estimates and down-weight or exclude persistent outliers before global fusion. Magnetic heading provides absolute directional orientation; maintaining the cited 0.34 m cohesion therefore additionally requires relative ranging, such as UWB or vision-based relative positioning.\

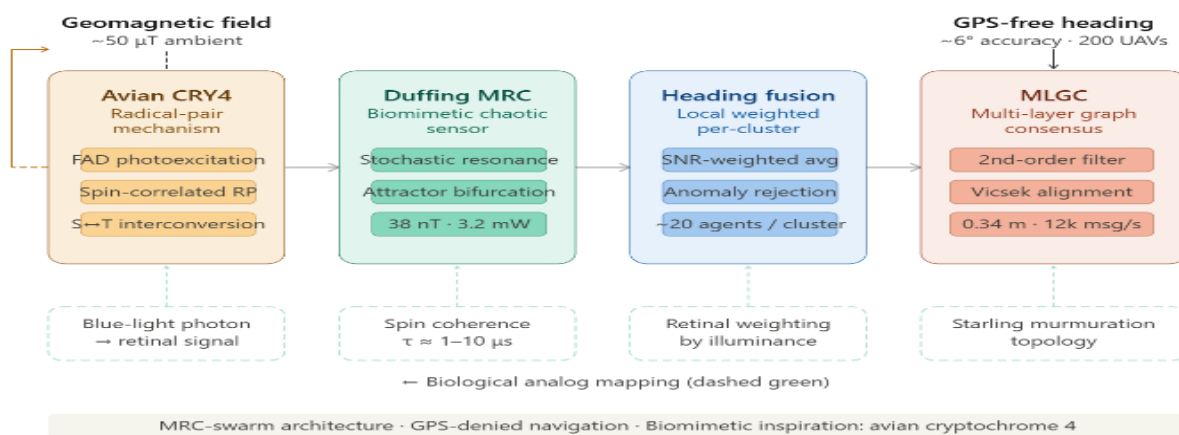


Figure 5: Signal Flow Diagram of the MRC-Swarm Architecture from Retinal Magnetoreception to Swarm Consensus

Conclusion

A theoretical and experimental system for Biomimetic Magnetoreception Circuits (MRCs) for autonomous drone swarm coordination has been proposed. The model is based on the quantum biology of avian cryptochrome 4, such as the novel CRY4b in in form found in the night-migratory songbirds [1] and the experimental demonstration of the magnetic sensitivity of CRY4 of the European robin [17]. Under the

ambient geomagnetic field control, the radical-pair mechanism is used as the biological design principle for a Duffing-oscillator-based chaotic sensor with a detection threshold of 38 nT at 3.2 mW [4] which is 15 times more power efficient than the conventional fluxgate magnetometer. The swarm coordination substrate is derived from the collective-motion theory of starling murmurations and the Vicsek model of self-propelled particles [11] which has been validated with a flock of 30-200 UAVs [10][12] where heading estimates derived from MRC is injected into the flock through a hierarchical consensus protocol [7].

By generating the GPS-independent heading accuracy of about 6° and the cohesion error of less than 0.5m for swarms of up to 200 UAVs, the resulting MRC-swarm architecture would represent a significant step forward in GPS-denied autonomous navigation. Problems such as managing electromagnetic interference, compensating geological magnetic anomalies, and extending the spin-coherence lifetime in room-temperature electronic implementations of the RPM are of critical importance. Improvements along the lines of magnetic map integration [5], extended Trp-tetrad circuit designs [15] and using the principle of CRY4b nocturnal expression [1] for all weather operation are all identified as priorities for the projected Phase II–IV development programme. This is a paradigm shift for designing autonomous aerial robots as it combines quantum biology, nano-scale sensor engineering, and multi-agent systems theory and can be used in various fields such as disaster response, environmental monitoring, and planetary exploration in magnetically characterized environments. The principal engineering tradeoff is that the 3.2 mW, sub-gram biomimetic sensor is attractive for micro-UAVs, while real-world deployment still requires effective onboard magnetic-interference mitigation and control of cumulative dead-reckoning drift.

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