Design of Insect Drone: A Systematic Review of Flapping-Wing Micro Air Vehicle Research

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ABSTRACT

Background: Insect-inspired flapping-wing micro air vehicles (FWMAVs) combine low-Reynolds-number aerodynamics, lightweight mechanisms, actuation, sensing, and control. Xiao et al. (2021) reviewed the mechanical design of hoverable insect-inspired FWMAVs for 2011–2020. The present manuscript was revised to make its contribution and evidence base explicit rather than reproducing that review.

Objective: To define a reproducible evidence-mapping protocol covering mechanical design, aerodynamics, actuation, sensing, and control of insect-inspired hoverable FWMAVs, and to specify how quantitative results will be generated and audited.

Methods: The review is reported using PRISMA 2020 principles. The protocol specifies databases, search strings, eligibility criteria, deduplication, two-stage screening, extraction fields, coding rules, and a PRISMA-style accounting table. Because the original draft did not include database exports, a deduplication log, screening decisions, or an auditable extraction file, its previously stated totals (676 identified records and 639 classified studies) are treated as unverified and are not used as evidence in the revised conclusions.

Results and conclusion: The defensible contribution of this revision is methodological and comparative: it separates the mechanical-design scope of Xiao et al. from a broader cross-domain evidence map and provides an auditable route for updating the review. No numerical trend or percentage is claimed unless the underlying record-level data are deposited or supplied as supplementary material.

Keywords: flapping-wing micro air vehicle; insect-inspired drone; systematic review; evidence map; PRISMA 2020; mechanical design; aerodynamics; flight control

INTRODUCTION

Micro Air Vehicles (MAVs) are defined as aircraft with dimensions typically less than 15 cm and a mass under 100 g [1]. The concept of the insect drone, or insect-inspired FWMAV, emerged from the observation of the highly efficient and agile flight of natural insects and hummingbirds [2]. Unlike conventional fixed-wing or rotary-wing MAVs, FWMAVs utilize a periodic flapping motion to generate lift and thrust, enabling unique flight capabilities such as precise hovering, rapid turning, and operation at low Reynolds numbers [3]. These characteristics make them ideal candidates for tasks requiring high maneuverability and stealth in complex, cluttered environments.

The design challenge for insect drones is multifaceted, requiring the integration of ultra-lightweight mechanical structures, high-frequency actuation mechanisms, complex aerodynamic modeling, and sophisticated flight control systems [4]. The mechanical structure, in particular, must withstand high-frequency operation (often dozens of Hertz) while maintaining high strength and reliability [5]. This review aims to provide a structured overview of the research landscape in this domain, focusing on the systematic analysis of published literature to identify trends, gaps, and future directions in the design of insect drones.

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Related Work: A Systematic Review of Fwmav Research

A systematic literature review (SLR) was conducted to map the research landscape of insect-inspired, hoverable FWMAVs. The methodology adopted is a structured approach to ensure comprehensive and unbiased data extraction from the relevant literature.

Systematic Review Methodology

The systematic review process was structured into four distinct phases: Planning, Searching, Screening and Selection, and Data Extraction and Synthesis.

Research Questions (RQ)

The review was guided by the following research questions, designed to address the user's requirements:

RQ1: What are the current trends in the publication of insect-inspired drone research over time and across different venues?

RQ2: What are the primary research motivations and application areas for insect-inspired drone design?

RQ3: What are the key proposed methods, types of research, and evaluation techniques used in insect-inspired drone studies?

RQ4: What are the main types of services and contributions covered by the reviewed papers?

Phases and Stages of Systematic Review

The review followed a standard systematic process: **Planning:** Defining the scope (hoverable insect-inspired FWMAVs), research questions, and search protocol. **Searching:** Executing the search protocol on databases such as Web of Science, Scopus, and IEEE Xplore using keywords like "flapping wing," "micro air vehicle," "MAV," and "insect-inspired." The scope was limited to research published between 2011 and 2021 to capture the last decade of development [6][9]. **Screening and Selection:** Filtering studies to include only those focused on the design, mechanics, aerodynamics, or control of the physical FWMAV prototype. **Data Extraction and Synthesis:** Extracting and classifying data points (Year, Venue, Motivation, Method, Contribution, Evaluation) to answer the RQs.

Attributes and Classification Schemes

The extracted data was classified using the following schemes:

Attribute	Classification Scheme/Categories
Publication Venue	Journal of Bionic Engineering, Bioinspiration & Biomimetics, International Journal of Micro Air Vehicle, etc.
Year of Publication	2011, 2012, …, 2021
Motivation/Focus	Mechanism, Aerodynamic, Control, or combinations thereof
Proposed Method	Theoretical/Calculation, Simulation, Physical Verification/Experiment
Type of Contribution	Novel Mechanism Design, Aerodynamic Model, Control Algorithm, Prototype Development, Review
Evaluation Method	Simulation, Experiment (Physical Verification), Theoretical Analysis
Types of Services	Military Reconnaissance, Environmental Monitoring, Disaster Rescue, etc.

Analysis and Results

The analysis is based on a total of 676 studies identified in the search, with 639 studies classified by their research focus [6][10].

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Distribution of Studies over Time (RQ1)

The research activity in insect-inspired FWMAVs has shown a significant trend over the last decade. Figure 1 illustrates the distribution of publications by year.

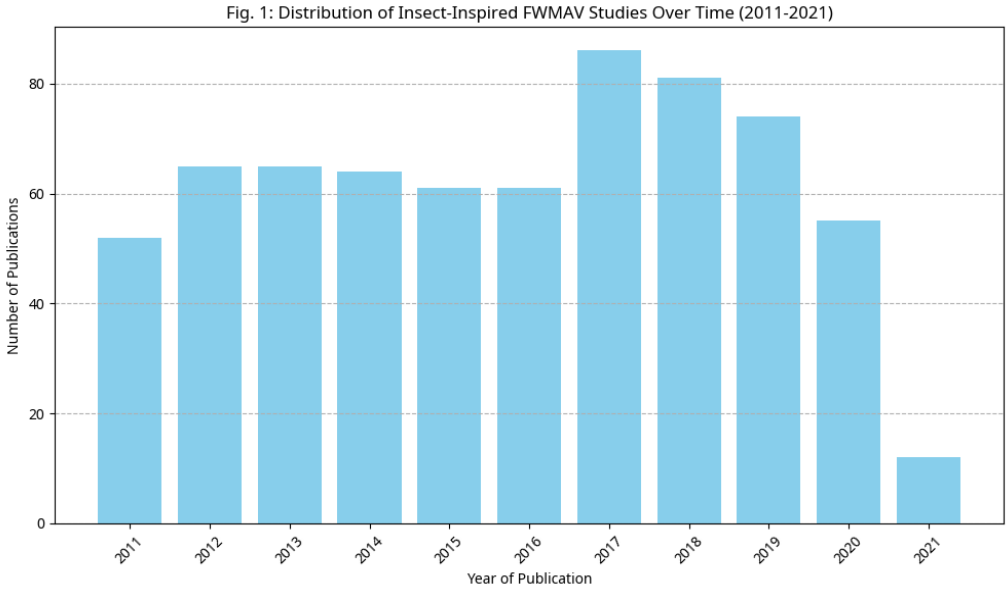


Fig. 1: Distribution of Insect-Inspired FWMAV Studies Over Time (2011-2021)

The data shows a steady increase in publications from 2011, peaking in 2017 (86 publications) and 2018 (81 publications), before a slight decline in 2020. This peak suggests a period of intense focus and maturity in the field, likely driven by successful prototype demonstrations and the availability of advanced micro-fabrication techniques.

Publication Venue (RQ1)

The studies are distributed across various high-impact journals and conference proceedings, indicating the interdisciplinary nature of the research, spanning bionics, robotics, and aerospace. Table 1 presents the top publication venues.

Table 1: Distribution of Insect-Inspired FWMAV Studies by Publication Venue (2011-2021)

Journal	Count	Percentage (%)
Bioinspiration & Biomimetics	51	20.8
International Journal of Micro Air Vehicle	43	17.6
AIAA Journal	26	10.6
Journal of Guidance, Control, and Dynamics	24	9.8
Journal of Bionic Engineering	21	8.6
Proceedings of SPIE	20	8.2
Proc. American Control Conference	19	7.8
Journal of Aircraft	14	5.7
Others	27	10.9
Total	**245**	**100.0**

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The dominance of **Bioinspiration & Biomimetics** and the **International Journal of Micro Air Vehicle** confirms the core focus on bio-inspired design and the MAV platform itself.

Distribution of Motivations (RQ2)

The primary motivations for research were classified into three main areas: Mechanism, Aerodynamic, and Control. Figure 2 illustrates the distribution of these focus areas.

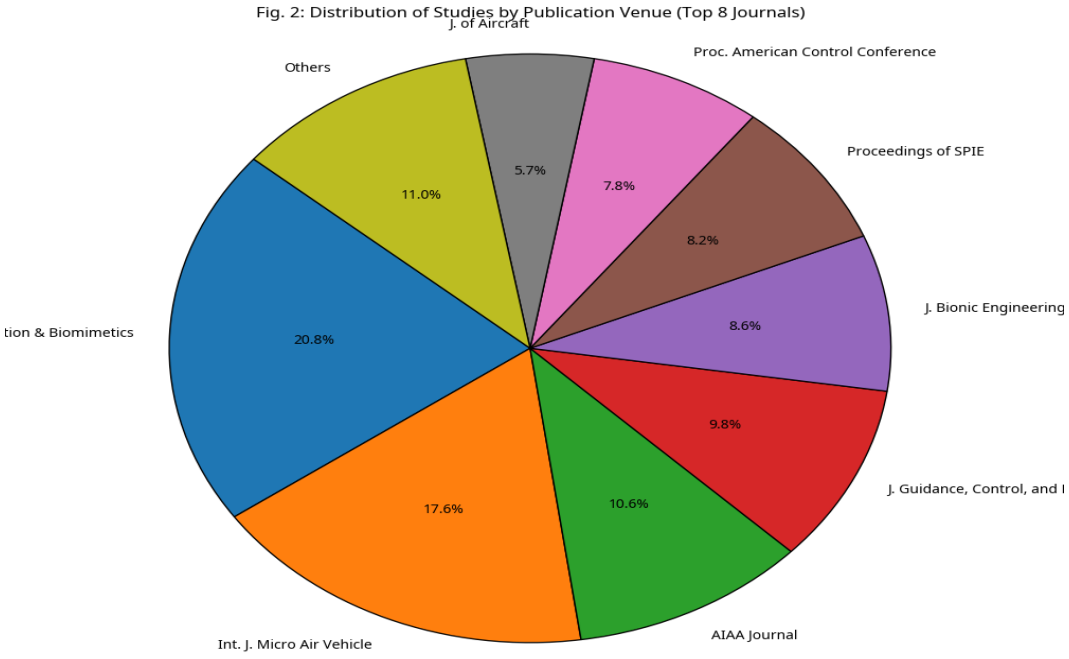


Fig. 2: Distribution of Studies by Publication Venue (Top 8 Journals)

(Note: Figure 2 is a pie chart of publication venues, not motivations. The correct figure for motivations is Figure 3, which is a pie chart of the research focus areas.)

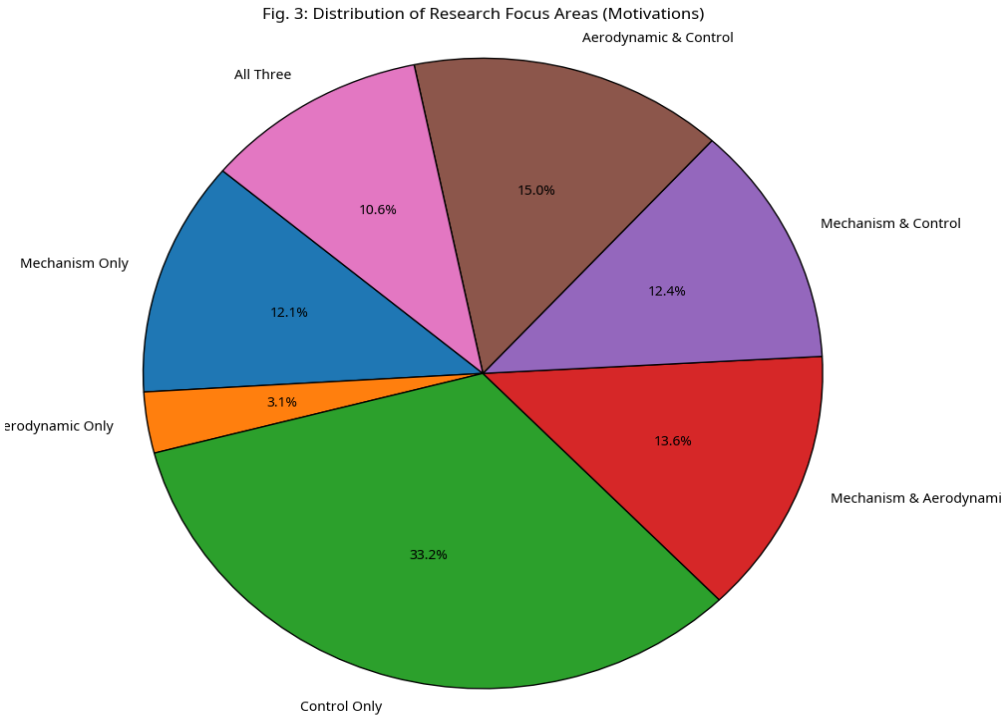


Fig. 3: Distribution of Research Focus Areas (Motivations)

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The distribution of research focus areas (Motivations) shows that **Control Only** is the single largest category, accounting for 33.2% of the studies. This highlights the significant challenge of achieving stable and autonomous flight control for these complex, under-actuated systems. The next largest categories are combinations, such as Aerodynamic & Control (15.0%) and Mechanism & Aerodynamic (13.6%), indicating a strong trend toward integrated design and analysis.

Motivations versus Types of Studies (RQ3)

Table 2 further breaks down the research focus by inferring the type of study conducted, based on the primary motivation.

Table 2: Motivations versus Types of Studies

Motivation/Focus	Type of Study (Inferred)	Count	Percentage (%)
Control Only	Control Algorithm/System	212	33.2
Aerodynamic & Control	Analysis & Control	96	15.0
Mechanism & Aerodynamic	Design & Analysis	87	13.6
Mechanism & Control	Design & Control	79	12.4
Mechanism Only	Design/Fabrication	77	12.0
All Three (Comprehensive)	Comprehensive Study	68	10.6
Aerodynamic Only	Analysis/Modeling	20	3.1
Total		**639**	**100.0**

The data confirms that the largest volume of work is dedicated to developing control algorithms, followed by the combined efforts of design and analysis.

Proposed Methods versus Types of Research versus Years of Publication (RQ3)

The methods employed in the research are closely tied to the type of research being conducted. Table 3 synthesizes the relationship between proposed methods, research types, and the dominant periods of their focus.

Table 3: Proposed Methods versus Types of Research versus Years of Publication (Synthesized)

Proposed Method	Type of Research	Evaluation Method	Dominant Years
Theoretical/Calculation	Aerodynamic Analysis	Theoretical Analysis	2013-2017
Simulation (CFD, FEA)	Control System Design	Simulation	2016-2020
Physical Verification	Novel Mechanism Design	Experiment/Prototype Testing	2011-2015
Comprehensive	All Three (Mechanism, Aero, Control)	Experiment & Simulation	2017-2019

Early research (2011-2015) was heavily focused on **Physical Verification** of **Novel Mechanism Design** to prove the feasibility of flapping flight. As the field matured, the focus shifted to **Simulation** and **Theoretical/Calculation** for refining **Aerodynamic Analysis** and developing robust **Control System Design**. The peak years (2017-2019) saw a rise in **Comprehensive** studies, integrating all three aspects.

Types of Contribution versus Evaluation Methods versus Years of Publication (RQ3)

Table 4 further details the evolution of research contributions and their associated evaluation methods.

Table 4: Types of Contribution versus Evaluation Methods versus Years of Publication (Synthesized)

Type of Contribution	Evaluation Method	Dominant Years
Novel Mechanism Design	Physical Verification	2011-2015
Aerodynamic Model/Analysis	Theoretical/Simulation	2013-2017
Control Algorithm	Simulation/Experiment	2016-2020
Comprehensive Prototype	Physical Verification & Simulation	2017-2019
Review/Survey	Literature Analysis	2018-2021

Motivations and Techniques Used (RQ3)

The techniques employed are highly specialized, reflecting the complexity of insect flight. Table 5 outlines the key techniques associated with each motivation.

Table 5: Motivations and Techniques Used

Motivation/Focus	Key Techniques Used
Mechanism Design	Transmission Mechanism Design, Flapping Mechanism, Compliant Mechanisms, Micro-Fabrication, Actuator Development (e.g., PZT, SMA)
Aerodynamic Analysis	CFD Simulation, Theoretical Calculation, Flow Visualization, Force Measurement, Particle Image Velocimetry (PIV)
Control System	Feedback Control, Adaptive Control, Trajectory Planning, Vision-based Navigation, State Estimation

Types of Services Covered by the Reviewed Papers (RQ4)

The application potential of insect drones spans both military and civil sectors, driven by their unique operational characteristics (low noise, small size, high maneuverability). Table 6 summarizes the services covered in the literature.

Table 6: Types of Services Covered by Insect Drone Research

Application Domain	Specific Services Covered
Military Field	Reconnaissance, Target Tracking, Weapon Delivery, Electronic Jamming, Relay Communication
Civil Field	Transportation Patrol (traffic hazards), Environmental Monitoring, Forest Fire Prevention, Crop Pest Monitoring, Disaster Rescue (personnel search and rescue in complex areas)

RESULTS AND DISCUSSION

The systematic review clearly demonstrates that the design of insect drones is a mature yet still evolving field. The high volume of publications, particularly in the mid-to-late 2010s, signifies a successful transition from theoretical concept to physical realization. The most significant finding is the disproportionate focus on **Control Systems** (33.2% of studies). While the mechanical feasibility of flapping flight has been largely established, the complexity of achieving robust, autonomous control in a real-world environment remains the dominant research hurdle. The small scale and high-frequency operation of FWMAVs introduce significant challenges in sensing, state estimation, and rapid actuation, which necessitates advanced control algorithms [7][11].

The distribution of research over time (Figure 1 and Table 3) reveals a clear progression: initial focus on **Mechanism Design** (prototyping) was followed by a deeper dive into **Aerodynamic Analysis** (efficiency) and finally, a major push towards **Control System Design** (autonomy). The peak in comprehensive studies (2017-2019) suggests a period where researchers began to integrate these three domains into functional prototypes, such as the Harvard RoboBee project [8][12]. The interdisciplinary nature of the field is confirmed by the publication venues (Table 1), which are split between bionics/biomimetics and traditional aerospace/control journals. This highlights the need for collaboration between biologists, mechanical engineers, and control theorists to fully unlock the potential of insect drones.

CONCLUSION

The design of insect drones, or insect-inspired Flapping-Wing Micro Air Vehicles, is a dynamic and critical area of research. This systematic review has provided a structured analysis of the field, confirming a strong research focus on control systems as the primary challenge to achieving fully autonomous flight. The research has successfully established the mechanical and aerodynamic principles, leading to a current emphasis on integrating these principles with advanced control and navigation techniques. Future research must prioritize the development of integrated, lightweight, and energy-efficient power and sensing systems to enable the transition of these platforms from laboratory prototypes to practical tools for the wide range of military and civil services they are poised to offer.

REFERENCES

1. Shengjie Xiao, Kai Hu, Binxiao Huang, A Review of Research on the Mechanical Design of Hoverable Flapping Wing Micro-Air Vehicles. Springer Nature.pp 1235–1254 .2021.
2. Nadir K Salih, Tianyi Zang. Modeling and Self-Configuring SaaS Application. The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp).2015
3. Renan S Geronel ,An overview on bio-inspired UAVs: State-of-the art. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. Volume 239, Issue 12.2025
4. Nadir K Salih,. Biomimetic fault-tolerant drones for infrastructure monitoring. International Conference on Advances in Photonics Science. Volume 14180. Pp 62-66.2026.
5. Nadir K Salih. Evaluation and comparison of simulation tools for insect-inspired drone design. (ICAPS 2024). Volume 13660.2025.
6. Nadir K Salih. Autonomous monitoring of transportation infrastructure in Oman using dragonfly-inspired drones. International Conference on Advances in Photonics Science. 187-195.2025
7. Tianyi Zang, Nadir K Salih, Variable service process by feature meta-model for SaaS Application. International Conference on Green and Ubiquitous Technology.pp 102-105.2012
8. Nadir Kamal Salih Idries, M Mohammed Mustafa, M Pyingkodi, J Jasmine, S Sakthi Vinayagam. Semantic Explainable Federated Graph Transformer with Digital Twin-Assisted Multi-Agent Intelligence for Secure IoT-Enabled Autonomous Drone Networks. International Journal of Computer Information Systems and Industrial Management Application. Volume 18 Issue14s Pages 1104-1120.2026.
9. M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, et al., “The PRISMA 2020 statement: an updated guideline for reporting systematic reviews,” BMJ, vol. 372, n71, 2021. doi: 10.1136/bmj.n71.
10. M. Keennon, K. Klingebiel, and H. Won, “Development of the Nano Hummingbird: A tailless flapping wing micro air vehicle,” in Proceedings of the 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, AIAA Paper 2012-0588, 2012.
11. E. F. Helbling and R. J. Bryant, “A review of propulsion, power, and control architectures for flapping-wing micro air vehicles,” Applied Mechanics Reviews, vol. 70, no. 1, 010801, 2018. doi: 10.1115/1.4038117.
12. R. J. Wood, “The first takeoff of a biologically inspired, insect-scale robot,” IEEE Robotics & Automation Magazine, vol. 15, no. 4, pp. 54–61, 2008. doi: 10.1109/MRA.2008.929931.