RoboBees - A Novel Adaptive Pollination System

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RoboBees
Precision Pollination

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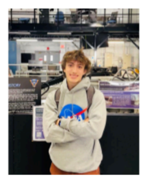

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I. Abstract

Pollination is a fundamental ecological process that enables the reproduction of flowering plants, ensuring biodiversity and the production of crops essential for human diets. The main pollinators of crops are the different bee species. However, bee populations are declining and alternative solutions must be explored to maintain the pollination rate. Current mechanically assisted pollination is expensive, labor intensive and does not achieve the same quality as pollination carried out by bees. The use of Unmanned Aerial Systems (UAS) as artificial pollinators to increase crop yield has been a growing field of research for a long time and has the potential to maintain or increase current pollination rates. However, there still remain many issues that need to be solved first in order to ensure a large-scale swarm of drones can be autonomously deployed to facilitate pollination on a farm. This solution aims to develop a UAS that mimics pollinator function, complementing bees work, while providing improved environmental and health conditions for natural pollinators.

II. Nomenclature

RoboBee	=	lightweight autonomous drone designed for pollination
BeeHive	=	central hub for the RoboBee swarm, providing recharging and coordination capabilities
UAS	=	unmanned aerial system, used for pollination tasks
CO2	=	carbon dioxide, used in the spray-on pollination system for pressurized air delivery
SIFT	=	Scale-Invariant Feature Transform, a feature-based detection algorithm
YOLO	=	You Only Look Once, a object detection and image segmentation model
Mask R-CNN	=	Mask R-CNN, an object detection, image segmentation, and mask generation framework
PI	=	Pollen Injector, part of the spray-on pollination system
AI	=	Artificial Intelligence used in navigation, detection, and optimization of the RoboBee system
ML	=	Machine Learning, used in vision-based algorithms for flower detection and flight control
BVLOS	=	Beyond Visual Line of Sight, a regulatory term for autonomous drone operations
FAA	=	Federal Aviation Administration, the agency that governs drone operations in the U.S.
TRL	=	Technology Readiness, scale to measure the development progress of the RoboBee system

III. Situation Assessment

Pollination is one of the main pillars of crop production, as it provides a link between agriculture and the cycle of life [1]. It can be defined as the process of moving pollen from the male anthers to the female stigmata. Pollen is also considered to be a super food due to its indispensable nutritional and medicinal properties [2]. The average global economic value of pollination is 161 billion US dollars. Particularly in the United States, its value amounts to 16 billion US dollars [1]. Additionally, pollination provides ecosystem services such as enhancing biodiversity, carbon sequestration, soil retention and increasing food production without threatening the environment [3]. Among the main pollinators are bats, moths, overflies, birds, bees, butterflies, wasps, thrips, and beetles [1]. One pollinator of particular importance is the Western honey bee (Apis mellifera L.) which is widely available, effective, and improve both quality and quantity of crops [1]. Honey bees are native to Europe, Northern Africa and Western Asia but have become naturalized on almost every continent. They have a natural sucking proboscis and mandibles for chewing [4]. When doing pollination work, bees attract pollen grains using weak electrostatic fields between flowers, which are negatively charged, and the bee body, which is positively charged [2]. Bees are vital pollinators with specific environmental and health characteristics. They thrive in environments that provide abundant floral resources for nectar and pollen, nesting sites, and suitable climatic conditions [5]. A healthy bee population depends on access to diverse and uncontaminated food sources, absence of diseases and parasites, and minimal exposure to harmful chemicals [5]. Despite their importance, bee populations are declining due to several factors. Urbanization, agriculture, and deforestation reduce the availability of natural habitats and floral diversity necessary for bees. The use of pesticides, particularly neonicotinoids, adversely affects bee health by impairing their nervous systems and foraging abilities. Altered climate patterns such as the ones that occur due to climate change disrupt flowering times and reduce the availability of food resources, challenging bees' ability to forage effectively. Parasites such as the mite *Varroa destructor* and microspordian *Nosema ceranae* [5] and diseases weaken bee colonies, making them more susceptible to other stressors.

Bee population decline poses a severe threat to humanity as they decrease food security [1]. The latter is strengthened by a growing human population that will reach 10 billion in 2050 [6]. The long term decline of honey bee colonies can be seen in Fig. 3.

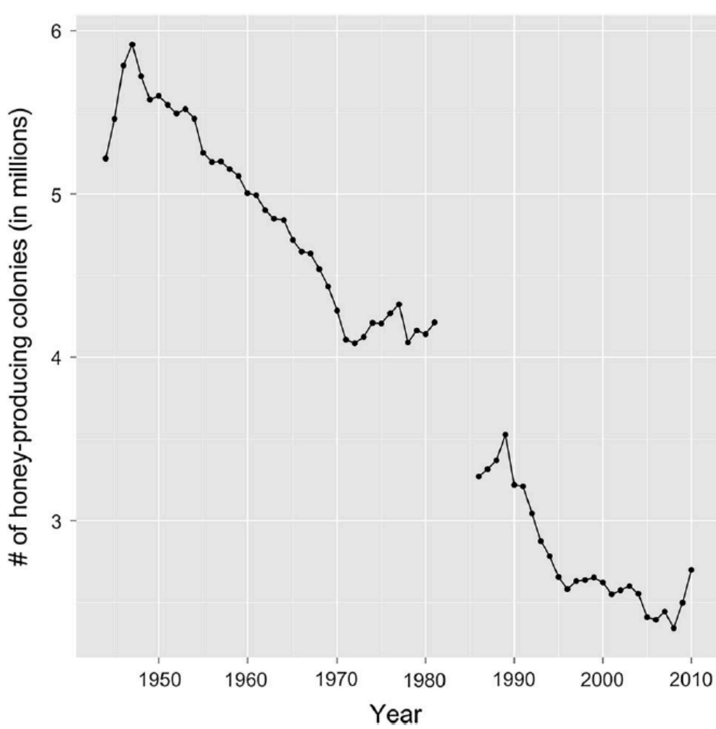

Fig. 3 Long-term decline of honey bee colonies

Bees are ectothermic and rely on external temperatures to regulate their body heat. The optimal temperature range for bee activity is between 60°F and 100°F (15°C to 38°C). Within this range, bees can efficiently forage, communicate, and maintain hive functions. Temperatures below 50°F (10°C) can cause bees to become lethargic, while extreme heat above 113°F (45°C) can be lethal. Due to climate change, agriculture will have to find alternatives to cope with that. Lower temperatures will also decrease the bee pollination rate which will increase the need for a solution that can complement bee's activity. This becomes particularly important in cold springs which are becoming more frequent due to climate change. The latter reduces the available hours for bees to work resulting in less fruit than expected. An automated solution that's able to complement bees pollination work while also providing improvements.

Aided pollination mechanisms exist to collect pollen such as trap-tray at the entrance of the bee hives. If used to spray pollen mechanically, machines are available from certain vendors [7], [8]. This makes the process labor intensive, expensive and time consuming. For those reasons, it's used for emergencies only and it is not economically sustainable in the long term. In nature proboscis can be found in vertebrates such as elephants and monkeys. Invertebrates also have them (bio-inspired) and typical examples are bees, butterflies and moths. Proboscis can be defined as an elongated appendage from an animal head. Some of the benefits of artificial proboscis are extensible, shock absorbing, lightweight, inexpensive and compliant with the environment.

Over the past few years, the growing concerns about the decline in bee populations have led people to propose many solutions that might alleviate the strain this situation will impart on the agricultural community. Research has also resulted in the creation of robotic bee like systems with varying morphologies [9]. Due to the varied shape that flowers have for different crops, we would need a diverse system that can help pollinate as many flower types as we can. To help address this challenge, we propose the RoboBee System, a swarm of small, lightweight micro-drones designed to carry out pollination alongside the natural bee population. The RoboBee system will carry out the pollination duties of the bees without interfering with the lifestyle of the natural pollinators. In order to minimize the effect that the system has on natural pollinators, it will be in operation during times when the natural pollinators are least active.

The heart of the RoboBee system is the BeeHive, a central hub for the swarm that coordinates the drones when they are in range and provides recharging capabilities mid-mission, allowing for extended mission duration and pollination coverage. Each drone itself can be fitted with one of two pollination methods depending on the crop's specific requirement:

- Spray-on Pollination which uses a pressurized canister on board the drone to spray pollen onto the flowers.
- Contact-based Pollination meant for more precise pollen delivery using a flexible proboscis-like attachment that mimics the way that bees transfer pollen by brushing up against the inside of the flowers. An electrostatic tip at the end of the proboscis attracts pollen for further improvements in pollen collection

The two pollination methods enable farmers to choose which method would be most efficient and suitable for their pollination needs. Benefits of the proposed system include the ability to work at lower temperatures than common pollinators, or any time throughout the night. The latter implies very little to no environment condition alteration.

IV. Economic Analysis

An analysis was conducted to understand the supply and demand dynamics of bee hives for almond pollination in California, focusing on the 2025 season. This crop is particularly important for the economic value for the state but also is completely pollination dependant.

A. Supply curve estimation

An analysis of U.S. honey bee colony data from 1944 to 2009 revealed a significant decline in managed colonies, with a linear regression model yielding a strong fit ($R^2 = 0.97$). Extrapolating this trend projected approximately 1.36 million colonies available for pollination services by 2025.

The supply curve was modeled as:

$$Q_s = 1.360 * P \tag{1}$$

where Q_s represents the number of hives supplied (in millions), and P is the rental price per hive (USD).

B. Demand curve estimation

In 2024, California's bearing almond acreage was estimated at 559,720 hectares [10] at a stocking rate of 5 hives per hectare, the maximum potential demand (at zero price) is therefore:

$$Q_d = 559.720 * 5 = 2.798.600 \quad (2)$$

To derive the linear demand curve, we identify the choke price—the rental fee at which demand falls to zero. Industry surveys report that pollination fees have reached up to (USD) 225 per hive in recent seasons [11].

$$Q_d = 2.798.600 - 2.545,5 * P \quad (3)$$

Equilibrium is determined by setting the supply and demand curves equal to find the market-clearing price and quantity, where the amount producers are willing to sell matches what consumers want to buy. Mathematically:

$$Q_d = Q_s \quad (4)$$

$$1.360 * P = 2.798.600 - 2.545,5 * P \quad (5)$$

$$P = 717 \quad (6)$$

$$Q = 975.120 \quad (7)$$

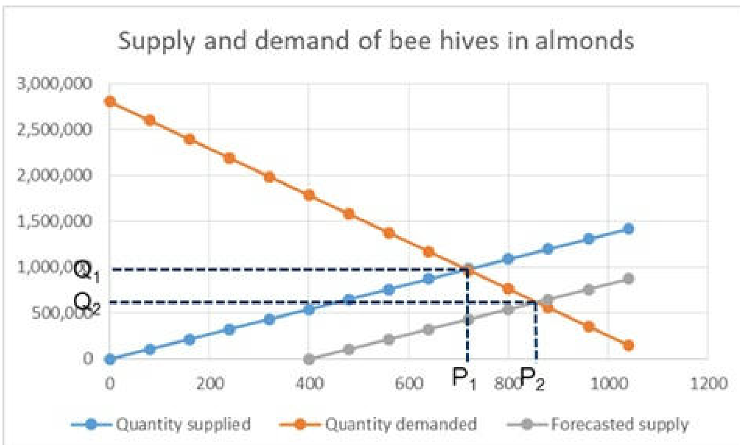

Fig. 4 Supply and demand curve estimation

C. Market dynamics under declining supply

If the downward trend in hive populations continues beyond 2025, the supply curve of bee hives for pollination services will shift to the right, reflecting fewer hives available at any given price. This contraction in supply results from ongoing pressures such as colony collapse disorder, pesticide exposure, habitat loss, and disease—all of which have been documented to negatively impact honey bee populations in the U.S.A. A rightward shift in the supply curve would cause a new market equilibrium where the service of renting a beehives per hectare will increase to around 856 and the total number of hives available for pollination decreases to 620.000. This adjustment leads to a higher cost burden for almond growers who are already heavily reliant on bee pollination services for productivity. From an economic standpoint, a tighter supply of hives would not only raise pollination costs but could also reduce crop yields if the quantity of rented hives falls short of optimal levels. Given that almonds are highly dependent on bee pollination and account for a substantial portion of California's agricultural revenue—over (USD) 5 billion annually. This scenario would carry significant economic consequences. Higher input costs could reduce profit margins for growers, potentially resulting in higher consumer prices for almonds and related products. Additionally, the strain on bee populations may ripple through other pollination-dependent crop sectors, highlighting the broader agricultural vulnerability tied to pollinator health.

D. Cost Analysis of Almond Pollination Services

A framework to assess almond profitability for one hectare at full production is presented. Three years are evaluated according to the development of the RoboBee. A typical almond orchard produces 1360 kilograms per hectare. The model consider irrigation and fertilization, utilizing micro-sprinkler systems and standard nitrogen application. Water is applied twice weekly from mid March through mid October. Harvest operations, encompassing mechanical shaking, sweeping, and hauling are also considered. Pruning services for annual canopy management is included. Herbicide applications for weed control are also added. Additional field operations, including disease control and miscellaneous tasks. A stocking density of five hives per hectare is used varying the prices from 200, 400 and 600.

	2025	2030	2035
Revenue	$ 11,871	$ 11,871	$ 11,871
Pollination cost	$ 1,000	$ 2,000	$ 3,000
Cultural costs	$ 6,344	$ 6,344	$ 6,344
Harvest	$ 1,693	$ 1,693	$ 1,693
Interset on operating capital	$ 156	$ 156	$ 156
Cash overhead costs	$ 1,636	$ 1,636	$ 1,636
EBITDA	$ 1,044	$ 44	$ (956)

Fig. 5 Economic evaluation of one hectare of almonds at full production

V. Innovation

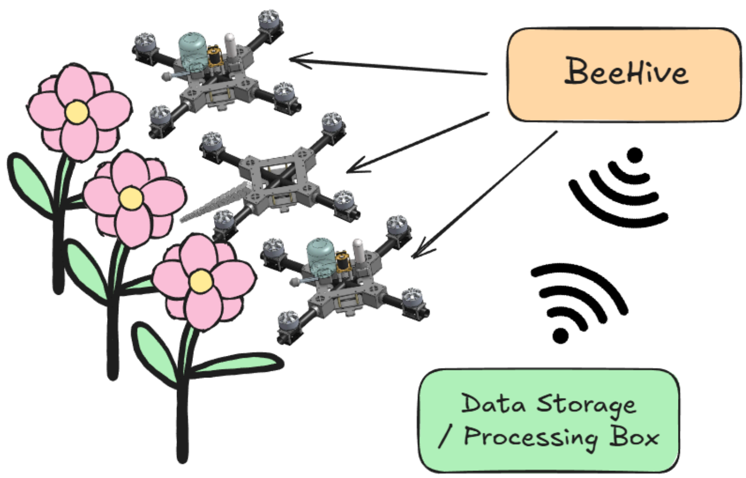

Fig. 6 Diagram of proposed system

A. Mechatronic Design

1) *BeeHive:*

The RoboBee system integrates multiple key mechatronic components to ensure precise, efficient, and scalable artificial pollination. The design encompasses the BeeHive Mother-ship, RoboBee micro-drones, and their specialized pollination mechanisms, as shown in Fig. 6. Each of these elements is engineered to optimize pollination efficiency while ensuring seamless integration with existing agricultural practices.

The BeeHive acts as a central hub for the RoboBee swarm, enabling drone coordination, recharging, and refilling functionalities. It serves as the core of the system, ensuring continuous pollination cycles. Key features include:

- Tractor-mounted or stationary platform: The BeeHive can be attached to a tractor for mobile deployment across large farms or placed as a standalone station.
- Autonomous charging station: Enables drones to recharge via wireless induction or contact-based docking, extending operational flight time.
- Pollen refilling system: The BeeHive replenishes pollen reservoirs within the drones, ensuring continuous pollination without manual intervention.
- Swarm coordination module: A communication system that manages drone flight paths, prevents collisions, and optimizes swarm efficiency based on real-time environmental data.

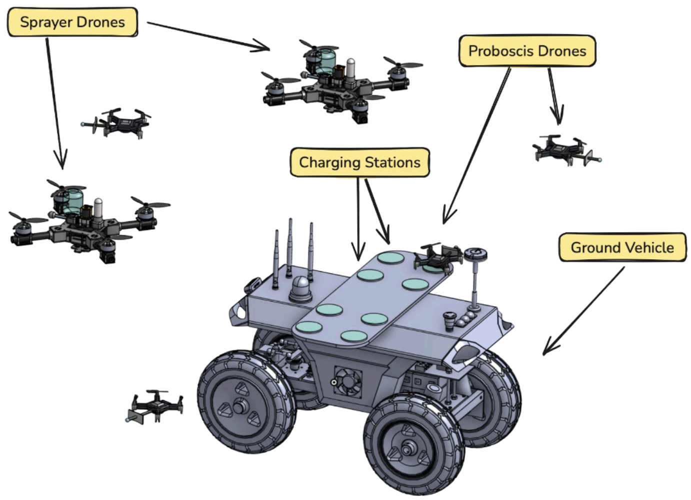

Fig. 7 Integrated system with multiple drone types & ground vehicle.

2) ***RoboBee Micro-Drones:***

The RoboBee micro-drones are lightweight, autonomous UAVs designed to mimic natural pollinators. Their compact form factor enables precise navigation through crop fields with minimal environmental disruption. Each drone is equipped with one of two pollination methods:

Spray-on Pollination System: This system is designed for efficient pollen distribution across large crop areas using a pressurized mechanism. Key components include:

- Pressurized CO2 canister - Provides controlled airflow for precise bursts
- Pollen storage chamber - Meters out appropriate amount per spray
- Pollen delivery tube - Channels Pollen from storage to the sprayer
- Movable & adjustable nozzle - Allows dynamic control of spray location and patterns.
- Will be used for pollinating large acreage crops with shallow, open blossoms such as almonds.

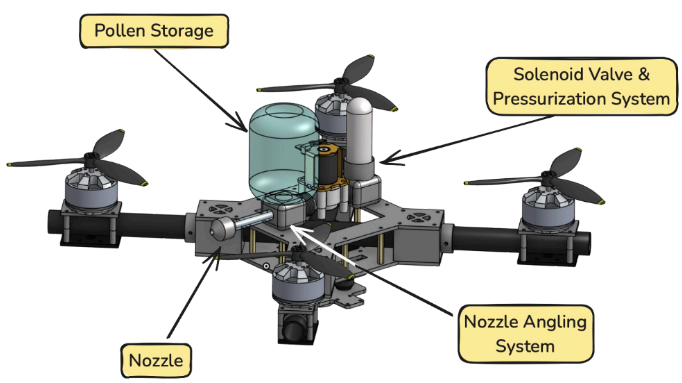

Fig. 8 Sprayer-equipped RoboBee

Contact-Based Pollination System: Inspired by the natural behavior of bees, the contact-based pollination system physically transfers pollen between flowers using an artificial proboscis. Key features include:

- Flexible "soft robotic" mechanism that can extend out and mimic bee-like interactions with flowers
- Electrostatic pollen attraction - Uses a charged tip to enhance collection and deposition efficiency by exploiting electrostatic forces.
- Proboscis end shielded to prevent prop-wash from interfering with pollination
- Will be used primarily for research and crops that require precise stigma contact for blossoms such as pumpkins.

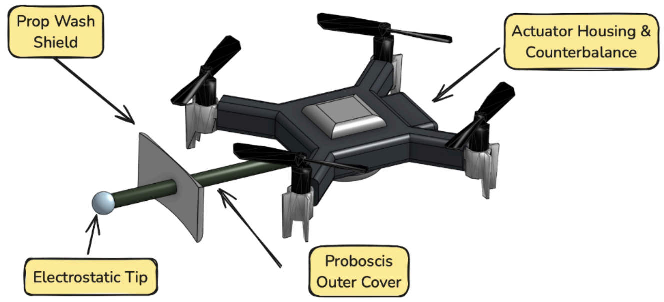

Fig. 9 Proboscis-equipped RoboBee

B. Computer Vision

1) *Flower detection:*

In order to target individual flowers, the RoboBee system needs to be able to detect if there are flowers, and find where they are relative to the drone. This starts with the coprocessor (such as a Raspberry Pi or Jetson Nano) on the RoboBee taking a picture of its environment. The image would get handed off to an image segmentation algorithm such as YOLOv11 [12] or MASK-RNN [13]. It's quite feasible to run image detection on the drone at 30Hz, and maintain a high enough accuracy for live flower pose/ position estimation. There are other, non-machine learning algorithms that can be implemented as well for object detection such as SIFT [14], however it suffers in variable light conditions, motion blur, and other imperfections in the field.

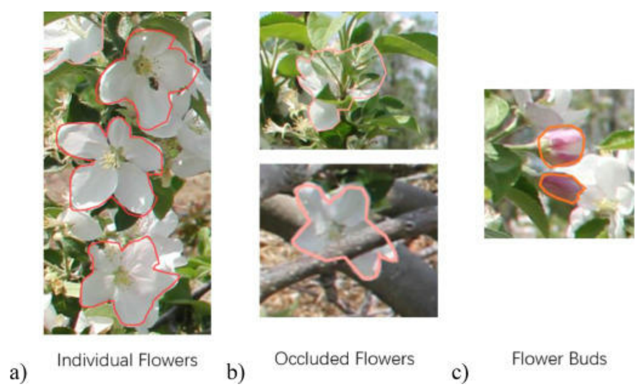

Fig. 10 Sample output from Mask R-CNN ([15])

Once the flower positions, and other obstacles like branches or other drones, are extracted from the image, that data can be used to further inform the path planning and obstacle avoidance algorithms. In addition to supplying that information, it can also be used to evaluate individual plant health, and analyze the whole field on a smaller scale, rather than requiring labor intensive spot checks.

2) *Localization / April tags:*

April Tags [16] are a visual fiducial system designed for autonomous systems to find the 6 DOF pose of an object accurately with computer vision alone. Its heavily used in these environments because they are robust to high variablity in light conditions, and are cheap and easy to place, increasing reliability in the case of occlusion or blocking. There's a large variety of tuning and tools to work with them, and companies that specialize in printing high quality tags.

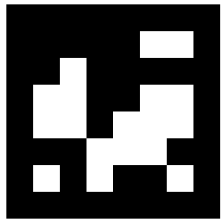

Fig. 11 April Tag from the 36H11 family

The tags can be placed on the drones so we know where they are relative to the truck, and can also be placed on the truck so the drones can see where the truck and charging zones are. This is a valuable addition to the GNS data for the drones because its a low-cost, high accuracy way of determining all of their positions and feeding that data into the collision avoidance and path planning algorithms.

VI. Concept of Operations Overview

While agricultural pollination drones already exist, the RoboBee system is significantly more complex, incorporating specialized mechanisms for pollen delivery, autonomous navigation, swarm behavior, and more. These features need more sophisticated hardware, software algorithms, and higher complexity compared to pollination drones used today. However, the system also produces vital benefits, particularly for crops that are struggling to receive adequate pollination due to changing environmental factors or the declining natural pollinator population.

The two systems that the RoboBee drone can be equipped with, the contact-based pollination system and the spray-on pollination system, enable precise pollination that goes beyond what is currently capable through existing means of artificial pollination in terms of precision and automation. By delivering only the necessary amount of pollen to each crop, the RoboBee system minimizes waste and reduces the likelihood of cross-pollination between different plants. Less waste translates to lower operational costs and promotes more sustainable farming practices overall.

In order to make complete use of the potential of the system and increase its durability, the RoboBees will be built with lightweight frames that balance robustness with agility. This will help them deal with wind, fog, rain, extreme temperatures, or other environmental scenarios that can impede flight or damage drone components. However, they still need to be deployed strategically during windows of acceptable weather in order to reduce risk of damage to the system.

Like any piece of sophisticated technology, tending to the maintenance of the RoboBee system is essential to support its functionality. Each system will require periodic inspections to ensure that the propulsion systems, sensors, and onboard pollen dispensers remain in working order. The drones must also be calibrated to handle different pollen types, humidity conditions, and flight altitudes to maintain accuracy which will most likely happen when the system is initially set up the farm. The BeeHive system that functions as a home base for the drones will also require maintenance from a trained professional so that the charging stations, autonomous flight planning software, and data management systems are operating smoothly. The farmers would also need to be trained in order to understand when and how to use the system, and to know what is wrong if common problems arise. While some simple fixes like replacing standard parts could be done by the farmers/consumers themselves, more complex issues will require the assistance of trained field engineers. The data collected from onboard the systems will also help the farmers and engineers diagnose the issues at hand.

The collected data can also be fed into broader crop management platforms and will contribute significantly to the systems ability to use data synergistically with other platforms. Farmers and ag-tech companies already use sophisticated tools for soil analysis, irrigation scheduling, and disease detection. By integrating RoboBee data with these existing solutions, agriculture professionals gain a deeper and holistic understanding of crop needs. Data collected from other sources such as local environmental monitoring systems can also be used in order to refine the navigation and pollination strategies employed by the RoboBee system, increasing efficiency and promoting data interoperability.

The system can operate around the clock in various environmental conditions where natural pollinators might be less active. Over time, these drones can give farmers a consistent and predictable yield by delivering dependable pollination to the flowers. This reliability will then translate into sustainable long term gains in crop productivity and profit.

VII. Implementation Analysis

A. Pathway Analysis

The readiness of Machine Learning and Machine Vision technologies for RoboBees is currently not yet commercially available, with several key areas under active development. These areas include AI-driven navigation, computer vision for environment interaction, and real-time data processing systems that are critical for autonomous operations. The convergence of advancements in Machine Learning and Machine Vision has enabled significant improvements in the precision and reliability of autonomous vehicles and drones, however the system as a whole still needs a few more years of research and development to get to a usable point before RoboBees can be deployed at scale in the field. A key area of focus will be improving precision controllability in real-world environments where variable factors such as weather conditions, plant density, and terrain complexity affect performance.

For instance, while significant advancements in drone battery technology have been made, more efficient power management and higher energy densities are still required for longer flight times. Future battery technologies, such as solid-state batteries and advanced lithium-polymer/lithium-ion chemistries, promise to extend drone flight times, offering a potential leap in energy storage solutions for commercial and agricultural drone systems [17]. As battery technology improves, we can expect RoboBees to operate longer in the field, minimizing the need for frequent recharging and maximizing the productivity of our autonomous system in pollination.

Sourcing of pollen is also essential to the proper function of the spray-based pollination system. Multiple vendors currently sell pollen for systems that deal with automated and hand pollination [18]. Proboscis based pollination on the other hand does not need to rely on pre-sourced pollen, and is an advantage of the system.

The adaptation of a proboscis-like tool from medical applications to agricultural use presents notable challenges. Literature search and discussions have led us to consider using a modified cable driven prothetic finger deign for the proboscis. Prosthetic fingers provide multi-joint bending using antagonistic cables pairs, allowing the proboscis to steer into narrow flowers. This design closely mimics hand pollination which is a pollination method that is already widely used for certain crops such as vanilla where pollinators are scarce. Early-stage prototypes will be iterated upon to improve pollination efficiency using the proboscis for common flower types; 1-2 years will be required to optimize these systems for full deployment.

B. Technology Readiness Levels (TRL) and NASA Standard

In line with the NASA Technology Readiness Level (TRL) scale, RoboBees are currently at TRL 2 or 3, which corresponds to the early stages of development, with TRL 2 focused on conceptual research and theoretical modeling, and TRL 3 involving experimental proof of concept in a controlled environment, demonstrating feasibility but not yet ready for real-world deployment [19]. By the end of 2032, we project RoboBees will reach a TRL 7 or 8 to ensure that they are ready for full-scale agricultural deployment, meeting the required regulatory and operational standards. Achieving this will involve both substantial technological advances and regulatory approvals, as well as the refinement of agricultural-specific technologies. This then leaves 3 years before the 10 year deadline to put the system on the market and into operation.

C. Limitations

While RoboBees are designed to be autonomous and require minimal human intervention, effective operation will still necessitate certain levels of training for users and stakeholders. Key areas of training include:

- **Vehicle Operation Training**: Farmers and agricultural workers will need training to safely deploy and retrieve drones, manage drone operations, and monitor real-time data from on-board hardware integrated into tractors.
- **Vehicle Maintenance Training**: As with any high-tech equipment, routine maintenance, software updates, and hardware repairs are essential. Training programs will focus on providing farmers and technicians with the necessary skills to maintain the drones in good working order.
- **Customer/Stakeholder Operational Integration**: Successful integration of RoboBees into existing farm operations requires close coordination with stakeholders, particularly farmers, to ensure seamless adoption of new workflows and technologies.

D. Barrier Analysis

Several significant barriers must be overcome to achieve widespread deployment of RoboBees by 2035:

- **FAA Certification**: One of the major regulatory hurdles is obtaining certification from the Federal Aviation Administration (FAA). Ensuring farmer compliance with FAA Part 107 regulations and securing approval for drone swarms operating Beyond Visual Line of Sight (BVLOS) will be necessary for large-scale autonomous operations. The process of obtaining these approvals can be lengthy, requiring both technological validation and regulatory negotiations.
- **Farmer Adoption**: The slow rate of adoption of new technology by farmers presents another barrier. Many farmers are resistant to autonomous systems due to concerns about the high initial cost, potential disruptions to existing workflows, and limited understanding of the technology's long-term benefits. To mitigate this barrier, a multi-faceted approach is necessary:
  - **Demonstrations**: Practical demonstrations that showcase RoboBees' efficiency and effectiveness in real-world agricultural settings can build trust and credibility among farmers.
  - **Incentives**: Financial incentives or government subsidies may help offset the initial investment, encouraging early adoption.
  - **Cost-Benefit Analyses**: Detailed analyses of long-term savings and yield increases can provide farmers with a clearer understanding of the return on investment, making it easier to justify the upfront cost.

E. Technology Restrictions

The potential impact of RoboBees on real bees must be carefully considered. Maintaining the health of natural bee populations is a priority, and strategies must be implemented to minimize any potential negative impacts. These strategies include:

- **Low-Noise Propellers**: Propeller designs that reduce noise emissions are essential in mitigating disturbances to natural bees, which rely heavily on a quiet environment for foraging and navigation.
- **Coordination with Tractor Operations**: It is also crucial to coordinate RoboBees' operations with tractor activities to minimize cumulative environmental disruptions. Since tractors are known to pose a greater threat to natural pollinators, ensuring that drones work in tandem with existing farm machinery can reduce any negative impact on ecosystems.

VIII. Future Prospects

There are many different ways that the RoboBee System can grow and evolve in the future. The most obvious improvement is to integrate the drones with a suite of sensors, such as multispectral cameras and environmental monitoring devices to gather real time data about crop health and weather patterns. These sensors would allow for detailed data-driven decision making in the field from the massive amounts of information about the crops and local environment that they would gather. Advanced analytics could be then used to optimize flight paths, allowing the swarm to improve its pollination strategies over time. Eventually, farmers might be able to use this data for predictive insights, like identifying potential crop diseases before they spread or adjusting the amount of water used for irrigation. The system can also be modified in order to do more than just pollination. Modifications of the Spray-on system on the drone would enable it to deliver targeted treatments of fertilizers or pesticides, reducing the broad application of chemicals and minimizing environmental impact. They could even serve as a first line of defense against pests by detecting early infestations and promptly delivering biological control agents right where they're needed. The Contact-based system can also be modified in the future to have stronger graspers instead of the thin proboscis currently employed; this would enable the micro-drone to interact with their environment by moving branches, grasping fruit, etc. Additionally, the system could be expanded with a variety of specialized UAVs. Some of the larger farms might benefit from bigger drones that can carry more pollen or travel longer distances, while other consumers might have other necessities that would require a modification of the existing system such as a different proboscis type. This kind of flexibility would make the RoboBee System suitable for everything from massive industrial farming operations to small organic gardens.

Bibliography

[1] S. A. Khalifa *et al.*, "Overview of bee pollination and its economic value for crop production," *Insects*, vol. 12, no. 8, 2021, doi: 10.3390/insects12080688.

[2] M. Thakur and V. Nanda, "Composition and functionality of bee pollen: A review," vol. 98. Elsevier Ltd, pp. 82–106, 2020. doi: 10.1016/j.tifs.2020.02.001.

[3] K. L. J. Hung, J. M. Kingston, M. Albrecht, D. A. Holway, and J. R. Kohn, "The worldwide importance of honey bees as pollinators in natural habitats," *Proceedings of the Royal Society B: Biological Sciences*, vol. 285, no. 1870, 2018, doi: 10.1098/rspb.2017.2140.

[4] V. Authors, "Britannica Encyclopedia." [Online]. Available: https://www.britannica.com/animal/western-honeybee

[5] A. Satta *et al.*, "How seasonality, semi-natural habitat cover and compositional landscape heterogeneity affect pollen collection and development of Apis mellifera colonies in Mediterranean agro-sylvo-pastoral systems," *Landscape Ecology*, vol. 39, no. 2, 2024, doi: 10.1007/s10980-024-01826-y.

[6] FAO, "How to Feed the World in 2050."

[7] A. pollen supplies Inc., "Pollination Enhancement and Plant Nutrition Products." [Online]. Available: https://www.antlespollen.com/

[8] O. S. Systems, "Electrostatic Sprayers for Pollen Applications." [Online]. Available: https://ontargetspray.com/pollen/

[9] N. J. Sanket, "Active Vision Based Embodied-AI Design For Nano-UAV Autonomy," 2021. doi: 10.13016/en44-gszf.

[10] T. Hillman, "California almond acreage rises slightly as removals continue." [Online]. Available: https://www.freshplaza.com/north-america/article/9726542/california-almond-acreage-rises-slightly-as-removals-continue/

[11] C. Souza, "Heavy bee mortality puts almond pollination at risk." [Online]. Available: https://www.agalert.com/california-ag-news/archives/february-26-2025/heavy-bee-mortality-puts-almond-pollination-at-risk/

[12] R. Khanam and M. Hussain, "YOLOv11: An Overview of the Key Architectural Enhancements." 2024.

[13] K. He, G. Gkioxari, P. Dollár, and R. Girshick, "Mask R-CNN." 2017.

[14] T. Lindeberg, "Scale Invariant Feature Transform," vol. 7, 2012, p. . doi: 10.4249/scholarpedia.10491.

[15] X. Mu, L. He, P. Heinemann, J. Schupp, and M. Karkee, "Mask R-CNN based apple flower detection and king flower identification for precision pollination," *Smart Agricultural Technology*, vol. 4, p. 100151, 2023, doi: https://doi.org/10.1016/j.atech.2022.100151.

[16] M. Krogius, A. Haggenmiller, and E. Olson, "Flexible Layouts for Fiducial Tags," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2019.

[17] X. Fang, Y. Yuan, Y. Li, and X. Hu, "Optimization of Electric Vehicle Charging for Battery Maintenance and Degradation Management," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 12, pp. 10407–10416, 2020, doi: 10.1109/TIE.2019.2949967.

[18] "Firman Pollen."

[19] NASA, "Technology Readiness Levels." [Online]. Available: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

IX. Appendix

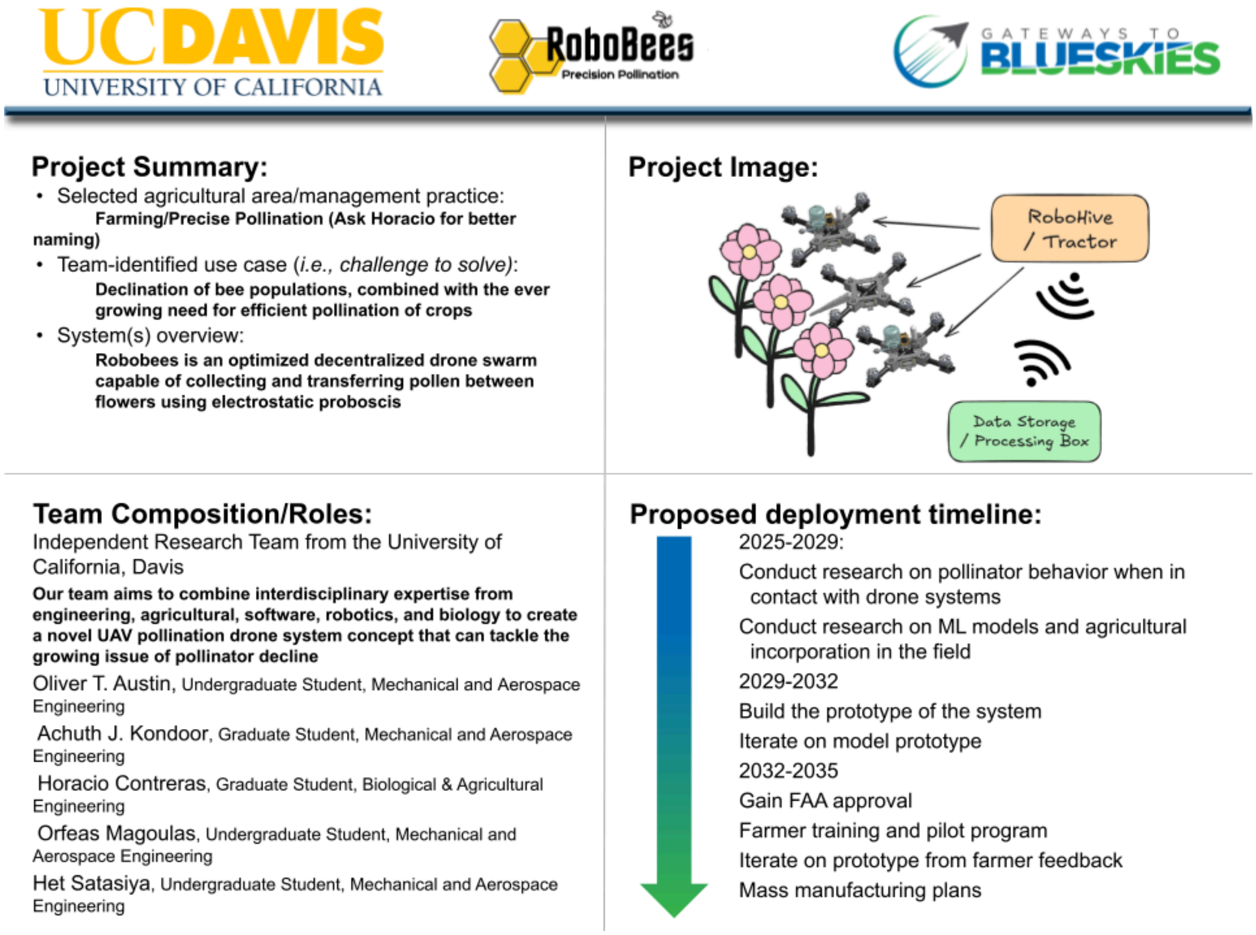

Fig. 12 Quad Chart