Article

Biomimetic route planning for micro-UAVs using honeybee-inspired optimization

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Abstract

A biomimetic route optimization framework for micro-UAV systems is proposed in this work, which is inspired by the foraging process of honeybees (Apis mellifera) and employs AI. The research is field documented, expert interviews were held, and in combination with supporting microscopic evidence on the morphology of honeybees. The hive entry-exit processes, weather parameters, activity intensity and the environment were registered at three observation points in Goygol and Dashkasan regions of Azerbaijan at 10-minute intervals in the field. These data were analyzed as behavioral indices of adaptive resource search, route choice and group organization. Expert interviews about the behavior of honeybees revealed that honeybees select feeding sites based on distance, availability of nectar/pollen, odor, sight, and energy conservation; and that the information about promising feeding sites is transmitted within the colony through their movement. At the same time, the scientific community of artificial intelligence (AI) confirmed the validity of the use of swarm intelligence and bee colony modelling for routing, resource allocation and real-time adaptation problems in complex systems. From this the paper suggests a conceptual model to translate the searching logic of the honeybee to micro-UAV route optimization idea, such as decentralized search, adaptive path selection, exploration-exploitation balance and environmental responsiveness. Biomimetic evidence is provided by the presence of compound eyes and wing structures, in the form of the microscope images, to the concepts of multi-sensor perception and lightweight mobility. The results indicate that the bioinspired AI models can help to improve the energy efficiency, adaptiveness, and resilience of micro-UAVs, especially in the fields of environmental monitoring, search and rescue missions, and distributed observation systems.

Keywords: honeybee foraging behavior, biomimicry, artificial intelligence, micro-UAV, route optimization, swarm intelligence

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1. Introduction

The importance of using micro-unmanned aerial vehicles (micro-UAVs) for environmental monitoring, precision agriculture, disaster response, infrastructure inspection, border observation, and search-and-rescue operations has been growing. Their small size, mobility and ability to function in areas difficult or dangerous to humans, make them useful tools in modern engineering and applied science. But, despite these merits, there are a number of limitations associated with micro-UAV systems. They still have challenges with extensive and sustainable use due to limited battery capacity, route inefficiency, environmental uncertainty, communication constraints, and the need for real-time decision making.

In the technical aspects of micro-UAV operations, route optimization is one of the most critical issues. An inefficient route leads to higher energy use, shorter missions and less quality of data collection. Conventional methods for planning routes rely on preprogrammed routes or central logic. In such environments, where weather, obstacles, mission priorities and resource availability can vary during operation, these approaches may be inadequate. Hence, the utilization of more adaptive, decentralized and energy-efficient route optimization models is required for micro-UAV systems.

AI models based on nature can be a great conceptual approach to the challenges. One of the most pertinent approaches is the swarm intelligence. It teaches the reader how simple agents, following simple local rules, can yield complex and adaptive behavior of the group as a whole, without any central control. Various classical research studies on swarm intelligence have demonstrated the ability to translate collective systems inspired by insects, birds, or other biological systems into computational models for various optimisation, routing, coordination, and resource allocation problems (Bonabeau et al., 1999). In this respect, the honeybee colony is one of the most significant biological systems used as a model for artificial intelligence and biomimetic optimization.

For the micro-UAV route optimization, the foraging behaviour of honeybees is particularly relevant. Honeybees in natural situations base their search for food sources on distance, quality of the food, smell, color, conditions and energy budget. When a good food source is found, the information is passed on to other colony members by movement and coordinated behavioral reactions. This results in a balance of exploration and exploitation of bees as they try out new food sources and also focus activity on already known high value areas. The Artificial Bee Colony algorithm modeled this biological logic into an optimization model based on the employed bees, onlooker bees, and scout bees and with adaptive search behavior (Karaboga, 2005; Karaboga & Basturk, 2007).

Together with multi-agent systems and decentralized control, the relevance of honeybee-inspired optimization is further emphasized. Micro-UAVs are frequently deployed as single vehicles in a larger mission scenario. Like bees in a colony, every UAV can gather information from its area, assess its local situation, send out information it chooses and alter its path depending on mission requirements. The resemblance of this behavior to the honeybee's foraging strategy suggests it as a biomimetic model for the design of adaptive route selection, distributed decision making, and energy-aware navigation strategies. Another trend of biologically inspired methods, like ant colony optimization and flocking models, also shows the promise of decentralized biological principles for movement planning and routing problems (Dorigo & Stützle, 2004; Reynolds, 1987).

In this study, you will learn how to create an AI-Based Biomimetic Route Optimization Framework for Micro-UAV Systems, inspired by the Honeybee Foraging Behavior. The article relies on theoretical literature of international character and original empirical materials, previously documented by the authors. The empirical basis consists of field observations of the activity of honeybees from the Goygol and Dashkasan regions of Azerbaijan, an expert interview on honeybee food selection and environmental adaptation, and a microscopic morphology report on the structures of Apis mellifera. The field observations include hive entry and exit, intensity of activity, time of observation, weather conditions, temperature, humidity, wind speed and UV index at three locations. These data are taken as behavioral expressions of adaptive movement, environmental responsiveness, and activity related to resources. The expert interview about the behaviour of honeybees describes how bees chose the food sources based on the principles of proximity, the nectar and pollen source and the olfactory sense, visual perception and energy saving. The AI expert interview validates the applicability of swarm intelligence and bee-colony based models for routing, resource allocation, real-time adaptation and multi-agent coordination problems. Moreover, microscopic analyses of the compound eye of the honeybee and its wing morphology serve as supporting biomimetic data for multi-sensor perception and lightweight mobility concepts. While the main theme of this article is behavioral route optimization, morphological evidence is provided to add weight to the biomimetic argument. In Apis mellifera, the compound eye is an example of parallel visual perception and distributed sensory input and the wing design exemplifies lightweight design and functional optimization. Such properties do not form the focus of the research, but they do go towards explaining the potential of using honeybees as a general biological model for micro-UAV design, perception and adaptive navigation.

This study aims to convert the honeybee's foraging logic and perform a conceptual AI-based route optimization model for micro-UAV systems. The research aims to answer the question: What is the biomimetic interpretation of the honeybee foraging behaviour for the design of adaptive and energy-efficient route optimisation of micro-UAVs? In order to answer this question, the article first gives the theoretical background of swarm intelligence and bee-inspired optimization, then provides the data sources from the empirical observation and expert-based knowledge and finally proposes the conceptual framework which links the honeybee foraging principles with the micro-UAV route planning. The scientific contribution of the study is the integration of biological behavior, artificial intelligence and applied engineering in a single interdisciplinary model. The article is not a theoretical discussion of biomimicry, but rather utilizes field-based data on honeybee activity and expert-based qualitative evidence to construct a real-world route optimization logic for micro-UAV systems. Applications of the proposed framework could include environmental monitoring, distributed observation, search missions, precision agriculture and energy-efficient flight planning of UAV. In that respect, more adaptive, resilient and resource-saving micro-UAV systems could be developed with the help of the honeybee-inspired AI-based route optimization.

Biomimicry as a research method, is known as learning from nature and transferring nature-tested principles to technological solutions (Benyus, 1997). Small drone and micro-UAVs are now frequently mentioned as potential flexible platforms for monitoring, inspection and observation of the environment, with their performance being largely driven by energy efficiency, autonomy and adaptive route planning in the case of autonomous aerial systems (Floreano & Wood, 2015).

2. Methodology

The approach in this study is a mixed conceptual-empirical one to create a biomimetic route optimization framework for micro-UAV systems based on honeybee foraging behavior using an AI-based scheme. The methodological design involves field observation data, expert interview evidence, microscopic biomimetic evidence and conceptual AI-based modelling. The goal of this step is not to develop a fully implemented UAV navigation algorithm at this stage, but to derive a route optimization logic based on the honeybee foraging principles that can be simulated and studied with prototypes.

2.1. Research design

The study was a biomimetic modelling one which was planned as an interdisciplinary study. It is an integrated approach of biology, artificial intelligence, swarm intelligence and applied aerospace engineering. The adaptive foraging behaviour of honeybees, particularly in finding food sources, assessing the quality of the environment, passing on useful information and optimising collective movement with minimal energy expenditure, forms the biological basis of the study.

The engineering issues addressed in this research are micro-UAV route optimization. The underlying assumption of the main method is that the behavior of honey bees when they forage for food can be interpreted as a natural model of adaptive route planning. In this model, the food source is analyzed as a mission target, the movement of the hive is analyzed as the route activity, other environmental factors are analyzed as an external constraint, and the collective decision making behavior is analyzed as a decentralized AI-based route selecting behavior.

The study is divided into four phases of methodology:

1. Collection and systematisation of honeybee field activity data;
2. Expert interviews on honeybee behaviours and biomimetic applications using AI;
3. application of the data of the microscopic morphology as supporting biomimetic evidence;
4. conceptual route optimization development of a framework for micro-UAV systems.

2.2. Field observation data

The empirical basis of the study is the field observations made in 3 places of Azerbaijan – Uchtepe and Topalhasanli villages of Goygol region and Bayan village of Dashkasan region. A 10 minute period was used to record honeybee activity at each site. The observations included hive entry/exit activity, local flight activity, cases of collisions near the hive entrance, type of hive, number of hives, and environmental parameters. The different field variables employed in this study are shown in Table 1.

Table 1. Observed variables in the field for interpretation of route optimization.

Variable group	Observed indicators	Interpretation for micro-UAV route optimization
Activity dynamics	Hive entry, hive exit, total activity	Movement intensity and route demand
Environmental conditions	Temperature, humidity, wind speed, UV index, weather condition	External constraints affecting route efficiency
Location data	Observation point, altitude, coordinates	Spatial mission environment
System density	Number of hives, activity per hive, collision cases	Congestion and coordination pressure
Time factor	Observation hour and observation duration	Time-dependent route variation

The data of the field was not used as a statistical sample for predictive modelling, but as an empirical basis for identification of behavioural patterns. The comparative observations revealed that the activity of the honey bees varied with time and weather conditions. The highest total activity was found at Topalhasanli where there was a relatively balanced activity in hive entry and exits and lowest activity was found at

Bayan under rainy and colder weather conditions. It was concluded that these differences are a sign of adaptation to the different environmental constraints.

2.3. Expert interview evidence

Structured expert interview items are also included in the study. The first expert interview centered on the selection of food by honeybees, the coordination of the colony, division of labor, signaling communication and adaptation to the environment. This interview was conducted to identify biological sense of foraging behaviour. The interpretation of the experts is that honeybees choose forage sources according to the distance, the amount of nectar and pollen they can harvest, the smell, the sight, and the amount of energy they can use. The expert also highlighted the importance of movement-based signals and coordinated colony responses in communication of promising sources by bees.

The second expert interview was on how biomimicry and artificial intelligence are being used in the systems of aerospace. This interview was prepared to aid in the computational interpretation of the behavior of the honeybee. The expert reported that routing, resource allocation, real-time adaptation, and decentralized coordination are some of the applications where swarm intelligence models can be helpful. These ideas served as the foundation for making links between the foraging behaviour of the honeybee and route planning of a micro-UAV.

Thematic analysis was used for the expert evidence. Table 2 provides an overview of the main themes that emerged from the interviews.

Table 2. Themes derived from experts that explain behaviours and AI modelling.

Expert evidence theme	Biological meaning	AI-based interpretation	Micro-UAV application
Food source selection	Bees prefer nearby and resource-rich sources	Objective function based on distance and resource value	Selection of high-priority mission points
Odor and visual perception	Bees use sensory cues to identify targets	Sensor-based target recognition	Multi-sensor route adjustment
Movement-based signaling	Bees transmit information to the colony	Agent communication and information sharing	UAV-to-UAV coordination
Exploration and exploitation	Bees search for new sources and reuse valuable ones	Balance between global search and local optimization	Adaptive mission route planning
Environmental adaptation	Bees reduce or change activity under unfavorable conditions	Dynamic route adjustment under constraints	Weather-aware UAV navigation

2.4. Microscopic biomimetic evidence

The study was primarily on the foraging behaviour of honeybees, but microscopic morphology information was provided as biomimetic support. The compound eyes, wings, legs and body segmentation of Apis mellifera were studied under the

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microscope. It was thought that these structures were natural examples of functional optimization.

The compound eye structure is a good support to the concept of distributed and parallel visual perception that could be applied in multi-sensor perception of the micro-UAV system in this study. Wing morphology serves as a lightweight mobility and aerodynamic efficiency, whereas leg structure and body segmentation serve as additional biomimetic references for adaptive contact, modularity, and system-level design.

The main route optimisation logic was not based on the microscopic evidence. Rather, this was used to bolster the overall biomimetic case that the honeybee offers both behaviour and structure-based models for engineering applications.

Table 3. Use of microscopic biomimetic evidence in the study

Honeybee structure	Observed biomimetic principle	Relevance to micro-UAV systems
Compound eye	Parallel visual perception	Multi-sensor environmental scanning
Wing	Lightweight and stable movement	Energy-efficient flight design
Leg	Adaptive contact and gripping	Landing and surface interaction mechanisms
Body segmentation	Modular biological architecture	Modular UAV system design

2.5. Optimization model for conceptual route.

The last step of the methodology was to translate the honeybee foraging behaviour into a conceptual route optimisation model for micro-UAV systems. The model is based on the following biomimetic logic:

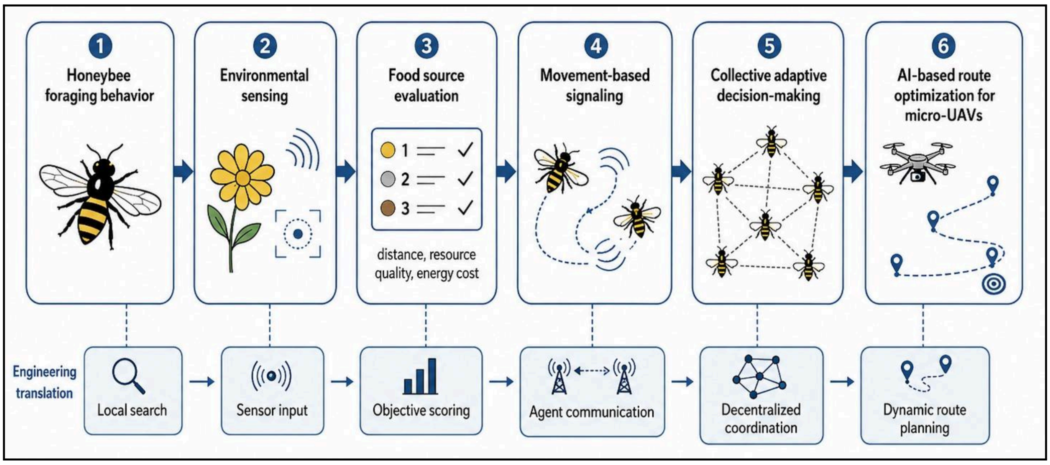
- The scout bees are understood to be UAV reconnaissance forces;
- food sources are mission targets or observation points;
- mission value/information value is interpreted as nectar/pollen quality;
- Route cost is approximated as distance to the food source;
- Operational constraints are interpreted as: weather and environmental conditions are interpreted as operational constraints;
- waggle-dance-like communication is considered to be inter-agent information exchange;
- The foraging efficiency at colony level is considered as system level route optimization.

The proposed conceptual model contains five main stages:

1. environmental scanning;
2. target identification;
3. route evaluation;
4. adaptive selection;
5. updating of routes via inter-agent communication.

This process is presented in Figure 1.

Figure 1. The transformation of a conceptual model, from a foraging behaviour of honeybees to route optimization of micro-UAVs with the use of AI.

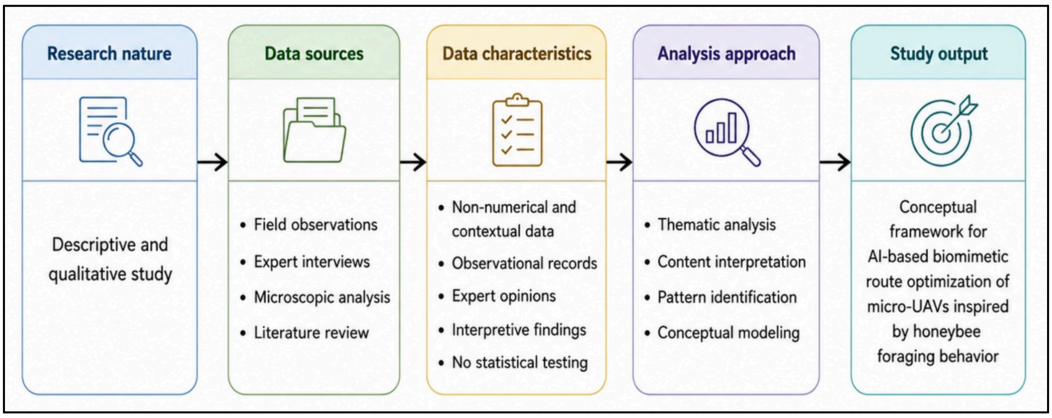


2.6. Analytical procedure

Comparative interpretation was used for the analysis instead of statistical testing of hypothesis. Field observation data were first categorised by: Location, Environmental conditions, Activity indicators. Second, the content of the expert interviews was coded in terms of behavioral and computational themes. Thirdly, micro observations were categorized based on their biomimetic significance. Lastly, all evidence groups were merged into a micro-UAV route optimization conceptual framework.

The analytical logic of the study is presented in Figure 2.

Figure 2. The study is descriptive and qualitative in nature.



2.7. Scope and limitations of the methodology

The methodology has a number of drawbacks. First, the field observations were run in three different locations and in short, 10-minute time blocks and should be seen as exploratory behavioral data, not large-scale ecological data. Second, the proposed micro-UAV optimization model is conceptual and has not yet been validated with simulation and real flight UAV experiments. Thirdly, the expert interviews offer a qualitative interpretation but not an experimental validation. Fourth, although microscopic observations have been used to bolster the biomimetic aspect of the argument, the primary route optimization model involves mostly behavioural foraging logic.

The methodology opens the door to an AI-based route optimization framework, despite these limitations, as it offers a practical interdisciplinary foundation to transform the honeybee foraging behavior and advance its use in this context. The method can be

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extended to simulation, algorithmic testing and application of micro-UAVs by prototypes.

3. Results

Study findings indicate that the honeybee foraging behavior can be regarded as a biomimetic model for adaptive route optimization for a micro-UAV system. Because of the descriptive and qualitative nature of the study, the study results are presented through comparative interpretation, expert-based analysis, field observation evidence and conceptual modelling.

The field observations in Uchtepe, Topalhasanli and Bayan revealed that the activity of the honeybee was different depending on time, weather and the surrounding environmental factors. The hives in Topalhasanli had relatively balanced hive entry and exit indicators and were the most active. This pattern could be a sign of an active foraging and route exchange phase. The activity of Uchtepe was also high, though the entry indicator was much higher than the exit indicator, which might be a return-flow phase following resource collection. Honeybee movement, however, proved to be very sensitive to environmental constraints and In contrast, Bayan showed very low activity under rainy and colder conditions.

Table 4. Micro-UAV route optimization based on integrated interpretation of honeybee foraging data.

Evidence source	Main finding	Biomimetic interpretation	Micro-UAV route optimization implication
Field observation data	Honeybee activity changed across Uchtepe, Topalhasanli, and Bayan according to weather, time, and hive activity intensity	Foraging behavior is adaptive and context-dependent	UAV routes should be dynamically adjusted according to weather, mission time, and environmental constraints
Honeybee behavior expert interview	Bees select food sources based on distance, nectar/pollen availability, odor, visual cues, and energy-saving principles	Route selection is based on cost-benefit evaluation	UAVs should prioritize mission points by distance, target value, risk, and energy cost
AI and biomimicry expert interview	Swarm intelligence is useful for routing, resource allocation, decentralized coordination, and real-time adaptation	Bee-colony behavior can be transformed into multi-agent optimization logic	UAV systems can use decentralized communication and adaptive route planning
Microscopic morphology evidence	Compound eyes, wings, legs, and body segmentation show functional optimization	Honeybees provide both behavioral and structural biomimetic models	Sensor perception, lightweight mobility, landing stability, and modular UAV design can be improved

The expert interview about the behavior of honeybees proved that the honeybees are not random in selecting food sources. They're influenced by their nearness, the quality of the food they eat, smell, sight, and energy spent. Valuable and energy-efficient path is the most important thing to be considered in route optimization of micro-UAVs, as shown in this section. In this way, the foraging behaviour of the honeybees is a good natural model of multi-criteria route choice.

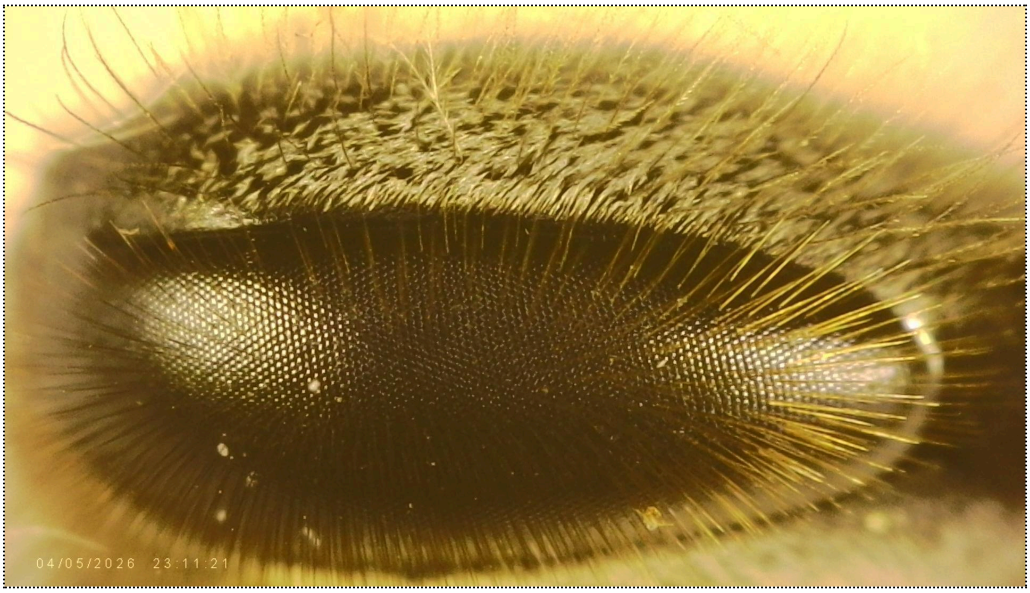
The results of the artificial intelligence and biomimicry expert interview confirmed the concept of using swarm intelligence to solve routing and resource allocation problems. The expert interpretation indicates that bee-colony inspired models are particularly pertinent to decentralized systems, where each agent makes local decisions and is an efficient member of the entire system. This logic can be directly applied in micro-UAV operations when multiple UAVs are deployed to monitor environment, search or distributed observation.

Biomimetic evidence was acquired by observations made with the microscope. In Apis mellifera the visual perception of the compound eye can be correlated to a parallel perception and multi-sensors scanning. The overall design of the wing structure is based on the principle of lightweight and stable mobility; the leg structure and the segmented body structure are used as reference designs to guide the adaptive landing and modular system design. These micro observations are not the primary criteria on which the route optimization model is based, but they do bolster the overall biomimetic argument put forth by the study.

Figure 3. During the recording of honeybee activity, field observation process was carried out.

One of the field observation stages was performed during the process of recording the activity of honeybees and is shown in figure 3. Empirical support for the study is provided by the images and direct field observations support the proposed biomimetic interpretation.

Figure 4. Morphology of Apis mellifera on a microscopic level as supporting biomimetic evidence



Microroscopic evidences from Apis mellifera morphology are shown in Fig. 4. It can be interpreted that this image represents the use of honeybee constructions as models of perception, mobility and functional optimisation in micro-UAV systems.

In general, the results show that it is possible to adapt the honeybee foraging behavior and apply it as a route optimisation logic for micro-UAV systems using a conceptual approach of AI. This model is proposed to be composed of five key fundamental principles: energy-aware route selection, adaptive route updating, decentralized coordination, exploration-exploitation balance, and environmental responsiveness. These principles have the potential of leading to more efficient, resilient and context sensitive micro-UAV operations.

4. Discussion

Based on the results of this research, foraging behaviour of honeybee can be considered as a promising biomimetic model for the AI-based route optimization of micro-UAV system. The biological model is most valuable for its adaptive, decentralized and energy sensitive nature. Honeybees are not random foragers, but their movements are influenced by distance, food-source quality, sensory information, environmental factors, and colony-level organization. These features directly relate to micro-UAV systems where flight routes need to be planned within battery constraints, varying weather conditions, mission priorities, and communication constraints.

The field observation results support the fact that the activity of the honeybees is sensitive to the environment. The differences in Topalhasanli and Uchtepe with high activities and Bayan with low activity exposure indicates that the weather, temperature and the time of observation determine the degree of change in honeybee movement. This means that the problem of route optimization cannot simply be interpreted as a shortest-path problem for micro-UAV systems. Rather, it should be considered as an ongoing process of decision making where route cost and target value are considered in conjunction with safety and weather conditions and energy consumption.

An interpretation that is reinforced by the expert interview about behavior of honeybee. The expert evidence indicates that bees select lower quality food sources if they are easily located (either by smell or sight) and that they are closer to the colony and contain more nectar and pollen. This biological logic can be captured in a route optimization model using AI that prioritizes mission points based on distance, data value, environmental risk and battery cost. In this way, the activity of the honeybee is a natural example of multi-criteria decision-making process.

The expert interview in the field of artificial intelligence and biomimicry also shows the relevance of swarm intelligence for routing and resource allocation problems. Centralized route control may be ineffective or insecure in micro-UAV operations particularly when multiple UAVs are operating concurrently. The proposed Honeybee inspired model allows each UAV to be a independent agent, assess its local situation, exchange pertinent data, and help optimize the entire mission. This can enhance resilience of the system, decrease reliance on a solitary control unit, and help in real-time route adaptation.

Further evidence for the biomimetic interpretation comes from the microscopic evidence. In this article, while the emphasis is on foraging behavior, Apis mellifera's compound eye, wing and leg structure and segmented body illustrate that honeybees are not just behaviorally adaptive, but structurally optimized as well. The compound eye can be used to develop distributed visual perception, and wing morphology can be used to develop lightweight and energy efficient mobility concepts. Hence, it is possible to identify the honeybees as both behavioral and morphological model for micro-UAV design and route optimization.

The proposed framework adds to the interdisciplinary linkage between biology, artificial intelligence and applied engineering. The major contribution of this is the conversion of the principles found in honeybee foraging into a route optimization logic for a micro-UAV system. Five main ideas are incorporated into this logic: (1) energy-aware route selection, (2) adaptive route updating, (3) decentralized coordination, (4) exploration-exploitation balance, and (5) environmental responsiveness. The principles could be of use for environmental monitoring, search and rescue, distributed observation, precision agriculture and other micro-UAV applications.

But there are also limitations in the study. First, the field observations were made from only three sites and for brief observation periods, and the observations can only be regarded as exploratory evidence and not as a comprehensive behavioural data set. Secondly, the proposed route optimization model is only conceptual, and there is no simulation or real flight test of the UAV as yet. Thirdly, although the expert interviews are qualitative, they need to be backed up by engineering simulation and algorithmic testing. Future research will involve formulating a coded optimization model, as per the honeybee foraging logic, and validate the model in simulated micro-UAV mission scenarios.

To conclude, the talk demonstrates that the route optimization of micro-UAVs using AI mimicking honeybee is a viable avenue for further research on micro-UAV systems. The advantage of this way is that it brings together the natural resource-search behavior and the computational optimization and applied engineering needs. Learn from the honey bee foraging behaviour, the micro-UAV systems could be more adaptive, energy efficient and resilient to environment changes.
Furthermore, the proposed framework is relevant as UAV path-planning studies revealed that metaheuristic and swarm-based optimization techniques can enhance route selection in real-time in the presence of operational constraints (Roberge et al., 2013). Thus, the optimization of UAVs navigated using a honeybee approach can be thought of as a member of a larger family of biologically inspired approaches to adaptive UAV navigation.

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