Computers and Electronics in Agriculture 227 (2024) 109616

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Unmanned Aerial Vehicle-based Autonomous Tracking System for Invasive Flying Insects

Jeonghyeon Pak [a,b,1], Bosung Kim [a,b,1], Chanyoung Ju [d,1], Hyoung Il Son [a,b,c,*]

[a] Department of Convergence Biosystems Engineering, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea
[b] Interdisciplinary Program in IT-Bio Convergence System, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea
[c] Research Center for Biological Cybernetics, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea
[d] Automotive Materials & Components R&D Group, Korea Institute of Industrial Technology, 6 Cheomdangwagi-ro 208 beon-gil, Gwangju 61012, Republic of Korea

ARTICLE INFO

Keywords:
Unmanned aerial vehicle
Autonomous tracking
Flying insect
Radio-telemetry
Received signal strength indicator

ABSTRACT

The Asian hornet or yellow-legged hornet, *Vespa velutina nigrithorax*, is a global predator of honeybees (*Apis mellifera* L.) that has become widespread owing to rapid climate change. Herein, we propose a localization system for tracking radio-tagged hornets and discovering hornet hives by combining unmanned aerial vehicles with a trilateration system. By leveraging the homing instinct of hornets, we systematically structured our experiments as a behavioral experiment, ground-truth experiment, and localization experiment. According to the experimental results, we successfully discovered the hives of two of the five hornets tested. Additionally, a comprehensive analysis of the experimental outcomes provided insights into hornet flight patterns and behaviors. The results of this research demonstrate the efficacy of integrating UAVs with radio telemetry for precision object tracking and ecosystem management, offering a robust tool for mitigating the impacts of invasive species on honeybee populations.

1. Introduction

Climate change (Villemant et al., 2011), with its far-reaching effects on ecosystems, has significantly affected vital ecological services. Particularly, pollination is a crucial ecological service that sustains the reproduction of many plant species, including numerous crops on which humans rely for food. Beyond agriculture, pollination contributes to the overall biodiversity and health of ecosystems. The majority of pollinators are insects, and the majority of these insects are honeybees (*Apis mellifera* L.) (Keeling et al., 2017; Rojas-Nossa et al., 2023b). Therefore, a decline in honeybee populations can severely affect agricultural productivity and ecosystems (Calderone, 2012; Arca et al., 2015). For instance, the worldwide phenomenon of colony collapse disorder (CCD) in honeybees has had substantial economic impacts on crops and caused widespread pollination failures in ecosystems (Johnson, 2010). *Vespa velutina*, commonly called the Asian hornet, is expanding its habitat in an optimal ecological environment in response to climate change. This is one of the main causes of CCD, and it stands out as a particularly concerning example (Monceau et al., 2014).

V.velutina is estimated to have entered through Busan port around 2003 and spread across Korea at a rate of 12.4 km/yr (Jung et al., 2012; Choi et al., 2012). In addition to Korea, *V.velutina* has spread to France (Rortais et al., 2010), Spain López et al. (2011), Portugal (Grosso-Silva and Maia, 2012), Belgium (Rome et al., 2012), Italy (Demichelis et al., 2013), and Germany (Rome et al., 2015). Owing to different climate change scenarios, South Korea (Kim et al., 2021) and Europe (Barbet-Massin et al., 2013) are habitats for *V.velutina*, and many other regions may become suitable in the future (Robinet et al., 2017). The rapid spread of this invasive species across diverse regions has substantially damaged local apiaries and disrupted ecological balances. The threat of *V.velutina* extends beyond the direct harm they cause to other species because they are particularly dangerous for honeybees and, consequently, the pollination processes that is critical for crop production (Dong et al., 2023). Compounding the challenge is the unique reproductive behavior of *V.velutina*, which is characterized by concentrated breeding during specific, relatively short periods, as illustrated in Fig. 1. Therefore, a targeted and time-sensitive approach to curb the population explosion of *V.velutina* is required to effectively address this issue.

Various methods have been used to control *V.velutina* populations. As individual capture methods, traps baited with food (carbohydrates

* Corresponding author at: Department of Convergence Biosystems Engineering, Chonnam National University, Yongbong-ro 77, Gwangju 61186, Republic of Korea.
E-mail addresses: jhpak@jnu.ac.kr (J. Pak), kbms9807@jnu.ac.kr (B. Kim), cyju@kitech.re.kr (C. Ju), hison@jnu.ac.kr (H.I. Son).
URL: https://hralab.jnu.ac.kr (H.I. Son).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.compag.2024.109616
Received 19 June 2024; Received in revised form 24 September 2024; Accepted 31 October 2024
Available online 22 November 2024

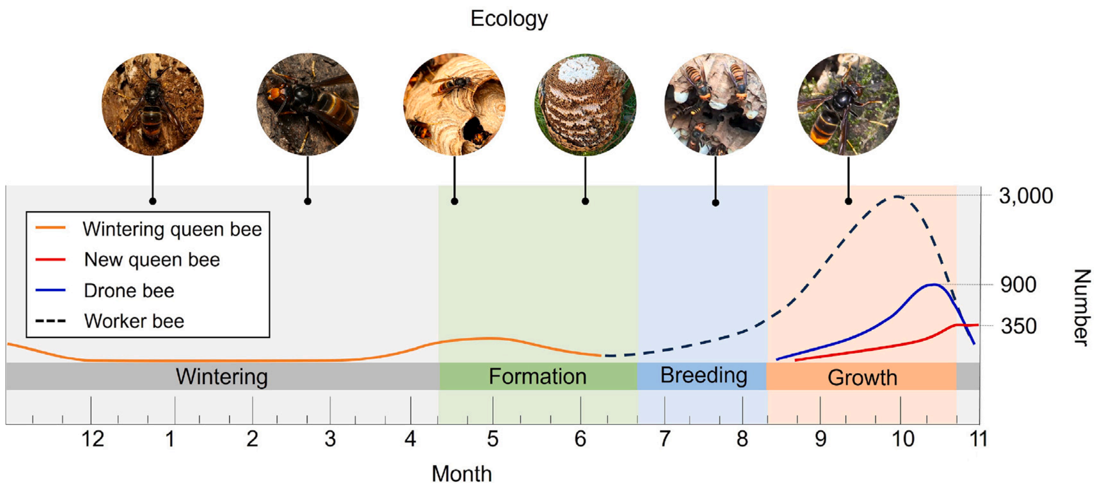

Fig. 1. The plot represents the lifecycle of *V.velutina*. *V.velutina* undergo wintering from late November to early April, followed by formation until the latter half of June. Breeding continues until early August, with approximately two months of growth from early August to late October. During the growth period, numerous *V.velutina* emerge from the eggs, especially worker bees, causing significant damage to honeybee colonies. Moreover, the production of drone bees and queen bees is also a serious problem, with thousands of *V.velutina* being produced in each hive.

or proteins) or insecticides, as well as manual capture using tools, have been utilized (Monceau et al., 2014; Lioy et al., 2020; Rojas-Nossa et al., 2023a). These methods are favored for their simplicity and cost-effectiveness, which make them accessible for widespread use. However, individual capture methods serve only as localized preventive measures to restrict the spread of *V.velutina*. Therefore, collective destruction for removing detected hives is essential to mitigate damage to apiaries and curb the propagation of *V.velutina* (Kennedy et al., 2018). To eradicate *V.velutina* hives, research on tracking to locate targets is being conducted actively. Historically, animal and insect tracking has relied heavily on visual observation, often supplemented by tools such as compasses and binoculars, followed by manual pursuit. However, these tracking methods are susceptible to the limitations imposed by human visual acuity and environmental conditions, leading to reduced accuracy. Considering the mobility and habitat of the target, tracking methods that rely on manual pursuit may have limited performance.

These limitations of traditional methods necessitate the exploration of innovative solutions, particularly robotics-based solutions. Among such innovative solutions, target tracking using unmanned aerial vehicles (UAVs) has been researched extensively (Pak and Son, 2022; Cao et al., 2022; Li et al., 2023, 2024). The use of UAVs in biological sciences has shown promising because of their unrestricted mobility and ability to cover vast areas efficiently (Chen et al., 2024). UAVs are particularly well-suited for targeting dynamic biological entities, such as *V.velutina*, within short timeframes. To effectively employ UAVs for insect localization and tracking, it is crucial to develop localization mechanisms that overcome the inherent challenges associated with dynamic insect behavior. On the back of technological advancement, many studies have been conducted using sensor network-based tracking methods. In general, when tracking animals, it is possible to solve problems such as population identification and extermination of natural enemies by deploying a GPS-based sensor network. However, it may be difficult to mount a GPS sensor on flying insects, and the condition of these insects may be affected by the weight of the sensor or the location and method of attachment. The representative sensors used for tracking insects include radio-frequency identification (RFID) sensors, harmonic radar, and radio telemetry. An RFID sensor is a lightweight and compact transmitter with high accuracy compared to the accuracies of other sensor networks. However, owing to the use of low frequencies (approximately 130 kHz) (Floyd, 2015), the reception distance between the RFID transmitter and receiver is extremely short. Therefore, they have been used to study the ecology of limited spaces (Schneider et al., 2012; Doornweerd et al., 2023). Harmonic radars can transmit over a wider reception area by using a signal with a frequency of approximately 5.96 GHz (Psychoudakis et al., 2008), which expands the research range. However, a harmonic radar records all tags of flying hornets within its detection range (Lioy et al., 2021). Radio telemetry has the longest reception distance between the transmitter and receiver (Bontadina et al., 2002; Wang et al., 2019). In addition, radio telemetry records independently the tracks of all flying hornets on specific frequencies from a transmitter within its detection range. Real-time analysis of the recorded tracks helps us understand the main flying directions. Therefore, for ecosystem management, radio telemetry-based tracking is the most promising technology.

In response to the need for innovative solutions to accurately localize and autonomously track dynamic targets such as flying insects, we present a systematic approach, as depicted in Fig. 2. To the best of our knowledge, there are no studies on the use of UAVs to track dynamic insects by using radio telemetry. In the proposed approach, a trilateration system is used for localizing and autonomously tracking radio-tagged flying insects. The system is designed as a UAV-based tracking system to specifically address the limitations of the existing wireless telemetry systems, particularly when tracking small species over short tracking ranges. In addition, we conduct UAV-based field experiments to validate the feasibility of the proposed localization and autonomous tracking strategy for radio-tagged targets.

2. Trilateration-based localization system

2.1. Problem description

Observations indicate that *V.velutina* return to their habitat after dislodging the thorax of honeybees, showcasing a strong homing instinct. This behavior underscores the significance of understanding the movement patterns of hornets, particularly their flights from apiaries back to their hives. Given the compact size and dynamic nature of *V.velutina*, which often inhabit elevated locations such as treetops or locations at heights of approximately 10 m or higher from the ground (Kishi and Goka, 2017), tracking them is considerably challenging. To address this challenge, we leverage their homing instinct and employ a trilateration-based approach rooted in radio telemetry to accurately track hornet hives (Sedira et al., 2023).

The primary challenge of achieving reliable detection over long distances while using antennas with wide vertical field coverage necessitates innovative solutions. In our preliminary research (Kim et al.,

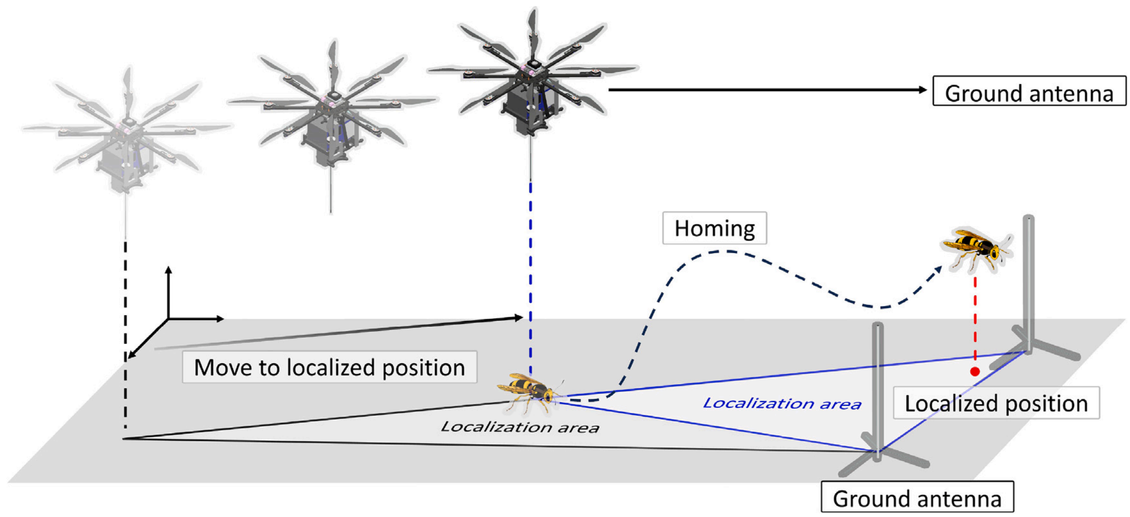

Fig. 2. Overall concept of proposed system, where a UAV equipped with motorized directional antennas approaches the estimated location of hornets as they fly toward beehives.

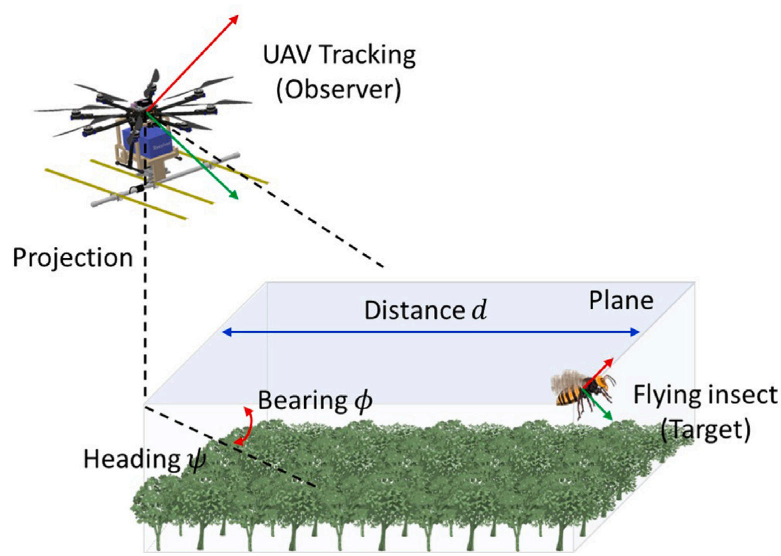

Fig. 3. Concept for simplifying UAV-based hornet tracking by projecting the three-dimensional (3D) behavioral range of hornets into a two-dimensional (2D) space. This reduces the complexity of UAV control and facilitates UAV-based hornet tracking.

2022b), we quantified the size, behavior, traceability, and field performance of insects to assess the feasibility and effectiveness of our tracking system. Additional experiments were conducted to address the biological characteristics of insects, with a focus on practical tracking considerations. Notably, an investigation was conducted to assess the tracking performance of the system by projecting 3D motion onto a 2D plane from the perspective of a UAV. To perform this task effectively, we projected a 3D space inhabited by hornets onto a 2D plane (Fig. 3), which allowed us to focus on capturing the movements of hornets while tracking them by using UAVs flying at high altitudes. By condensing spatial dimensionality, we aimed to streamline the tracking process and increase the precision of our observations. In this regard, the above-described projection method helped us to overcome the inherent complexities associated with tracking flying insects over vast distances. Moreover, the projection of 3D space onto a 2D plane facilitated easier data processing and analysis. This simplification increased the efficiency of the proposed tracking system, allowing for more effective extraction of meaningful insights from the collected data.

In a previous study (Ju and Son, 2022), we attempted to track radio-tagged flying insects by using a single directional antenna. However, this method had limitations, including the need for rotation time and low tracking accuracy. Furthermore, because hornets often inhabit tall trees or buildings, which may affect tracking accuracy, we contemplated tracking at high altitudes or implementing noise-resistant filters. To address the shortcomings of our previous approach, we use a trilateration system consisting of multiple omnidirectional antennas and a finite impulse response (FIR) filter. This enhanced approach is more effective for tracking *V.velutina* and exploring their habitat.

2.2. Autonomous trilateration system

2.2.1. Localization strategy

The UAV-based tracking algorithm is described in Algorithm 1. We use a trilateration system to track radio-tagged flying insects. By seeking the common range S of the transmitters and receivers of the three antennas, we determine the central value C of S at the expected UAV position $\mathcal{O}_d$. This information, combined with trilateration by using three receivers, allows us to estimate and track the movement of a hornet from an apiary to its hive. The strategy of the proposed tracking system comprises four steps (Fig. 4). In Step 1, two ground antennas and an antenna attached to the UAV measure the RSSI

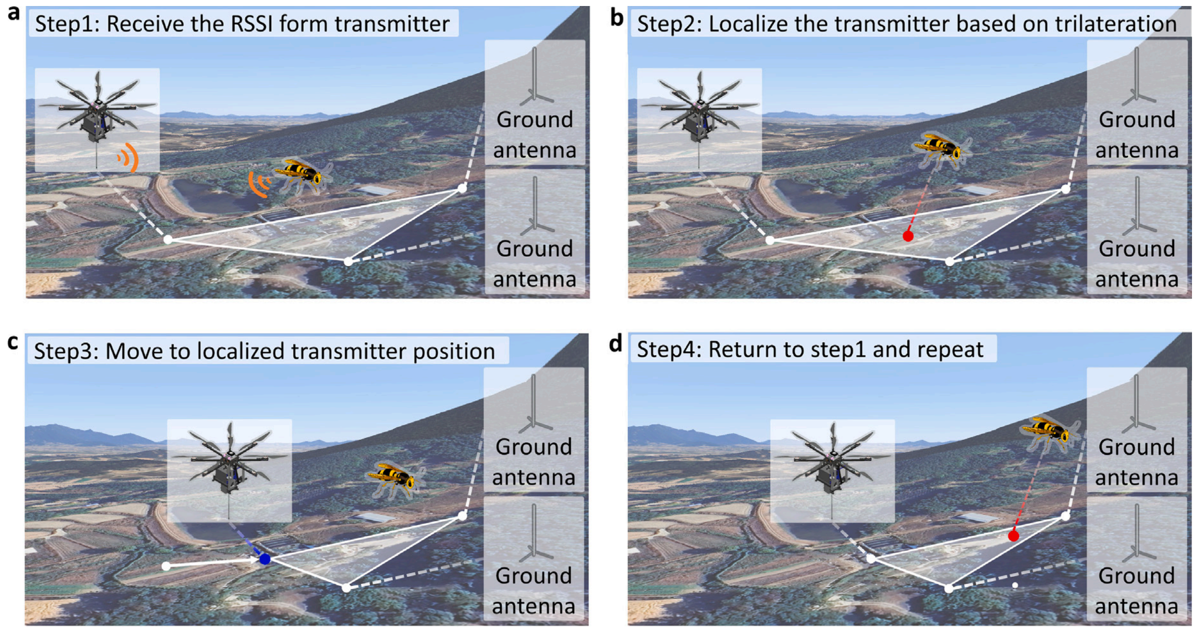

Fig. 4. Tracking strategy of multi-antenna system. (a) Initial states. (b) Collection of RSSI from ground and aerial antennas. (c) Position estimate of moving target based on collected RSSI values. (d) Movement to estimated position.

Algorithm 1 Tracking algorithm.

input: Antenna current position $\mathcal{O}_n$, desired distance D_o, initial constant I, number of antennas $\mathbf{N}$
UAV position input $\mathcal{O}_d \leftarrow \mathcal{O}_1$
Target position $\mathbf{x} \leftarrow I$
procedure TRACKING $(\mathbf{x}, \mathbf{O})$
compute $D(\mathbf{x}, \mathbf{O})$
while $D(\mathbf{x}, \mathbf{O}) > D_o$ **do**
    for $i = 1$ to N **do**
        compute $\mathbf{h}(\mathbf{x}, \mathbf{O}_i), \mathbf{D_i}(\mathbf{x}, \mathbf{O}_i)$
        compute estimation space $\mathbf{S}(\mathbf{O}_i, \mathbf{D_i}(\mathbf{x}, \mathbf{O}_i))$
    compute intersection space of S
    if intersection space ≥ 0 **then**
        compute center position $\mathbf{C}$
    else
        continue
    $\mathcal{O}_d \leftarrow C$
end procedure

(Yang et al., 2013) at the current position. Step 2 involves trilateration of the RSSI values obtained from the three antennas to estimate the position of the target. In Step 3, the UAV tracks to the estimated position of the target through flight control. Finally, in Step 4, even if the target stops flight at the habitat, the tracking process continues until the relative distance between the UAV and the target decreases by a certain threshold distance D_o. That is, the tracking process is complete when the relative distance is sufficiently small. Owing to its efficiency and accuracy, this tracking approach provides valuable insights into the behaviors and migration patterns of hornets, thereby contributing to effective hornet management strategies.

2.2.2. Localization model for tracking flying insect

We propose a signal propagation model for accurately tracking the strength of the signals emitted by radio tags, particularly in challenging field environments such as forests and non-urban areas. The model leverages the log-distance path loss model, which is suitable for measuring RSSI, a crucial metric in radio frequency signal analysis; the proposed model is expressed as follows:

$$\mathbf{h}(\mathbf{x}, \mathbf{O}) = P_{d_0} - 10n \log \frac{D(\mathbf{x}, \mathbf{O})}{d_0}, \quad (1)$$

where $\mathbf{h}(\mathbf{x}, \mathbf{O})$ is the RSSI measurement function between the target's position $\mathbf{x}$ and UAV's position input $\mathcal{O}$. P_{d_0} is the RSSI at the reference distance d_0, n is a path-loss exponent ranging from 2 to 4, and $D(\mathbf{x}, \mathbf{O})$ is the Euclidean distance between x and $\mathcal{O}$. The quantum of change in RSSI depending on the change in distance between the signal strength at a given location and the UAV location is given as follows:

$$f(\mathbf{x}, \mathbf{O}) = \Delta \mathbf{h}(\mathbf{x}, \mathbf{O}). \quad (2)$$

To account for noise, particularly in environments with significant interference such as forests, we introduce the concept of white Gaussian noise. Assuming that the noise in the RSSI measurements conforms to white noise, the total RSSI measurement $\mathbf{z}$ can be expressed as follows:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}, \mathbf{O}) + v, \quad (3)$$

where v follows a zero-mean Gaussian distribution with covariance σ_R^2, which denotes the white noise term. Despite potential deviations from the ideal white noise characteristics in field environments, this assumption provides a practical means for characterizing the received noise.

2.2.3. FIR-filter-based localization

FIR filters are widely used in various applications, including digital signal processing, communications, audio processing, and image processing, owing to their simplicity, stability, and linear phase-response characteristics. The FIR filter is a type of causal filter that utilizes both past and present input data to compute the output signal. The basic form of an nth-order FIR filter (Wu et al., 1996; Chang et al., 2008) is expressed as follows:

$$y[n] = \sum_{k=0}^{M} b_k x[n-k], \quad (4)$$

where $y[n]$ represents the output signal of the filter at a discrete time instant n, and $x[n]$ denotes the input signal. M and b_k are the order and kth coefficient of the filter, respectively. The filter order M dictates the number of coefficients used in the filter, thereby influencing its frequency-selective properties and computational complexity. The

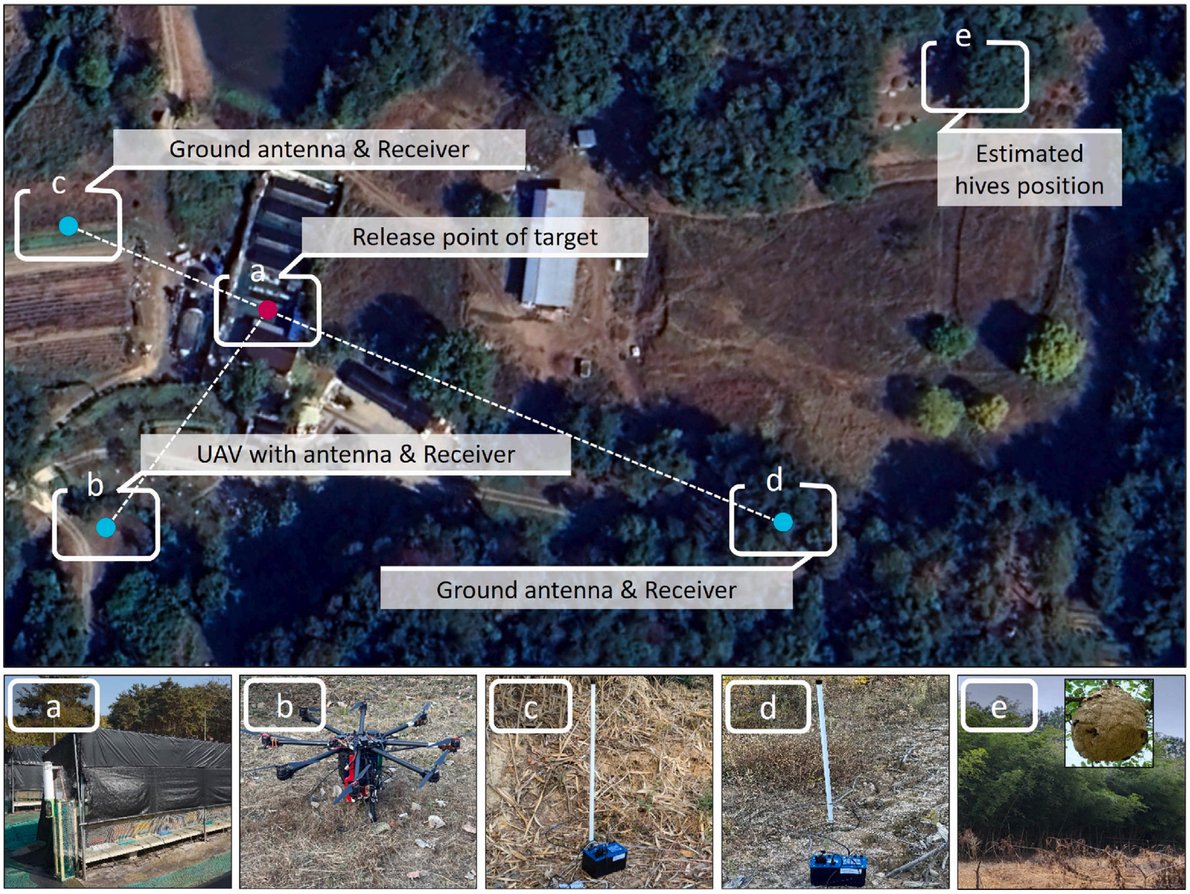

Fig. 5. Experimental setup for apiary field experiment in urban mountains. (a) The field environment illustrates the apiary located within urban mountains, providing a realistic setting for testing and data collection. (b) An octocopter equipped with specialized receivers, antennas, and additional field experiment apparatus is essential for aerial data acquisition and monitoring. (c) and (d) Ground station equipment includes the two ground-based antennas and receivers, in addition to the onboard and LTE modules installed for trilateration. This setup ensures accurate position tracking and data transmission during the experiment. (e) Visualization of the computed positions of the hives, derived through the trilateration process facilitated by the coordinated efforts of the octocopter and ground stations.

coefficients b_k play a crucial role in determining the filter's frequency response characteristics, including its magnitude and phase responses. Higher-order FIR filters can provide sharper frequency responses, but they may require more computational resources.

One of the key advantages of FIR filters is their inherent stability owing to the lack of feedback loops, which can lead to instability. This characteristic makes them suitable for use in real-time signal processing applications, where reliability is essential. Additionally, FIR filters offer precise control over frequency response through the selection of appropriate coefficients. These design methods help optimize the filter coefficients for achieving the desired frequency response characteristics, such as low-pass, high-pass, band-pass, or band-stop filtering. FIR filters play crucial roles in diverse signal processing tasks, offering flexibility, stability, and precise control over the filtering operation.

2.2.4. Trilateration system

An omnidirectional antenna transmits and receives power uniformly in all directions, thereby ensuring comprehensive coverage and facilitating effective signal capture regardless of the orientation or movement pattern of a dynamic target. To increase tracking accuracy, we propose a multi-antenna-based trilateration system that employs three omnidirectional antennas (Pak et al., 2023). This system estimates the position of a target by analyzing the RSSI acquired from each omnidirectional antenna, allowing for the assumption of at least three positions. The proposed trilateration system is expressed as follows:

$$d_i = \sqrt{\left(x - a_i\right)^2 + \left(y - b_i\right)^2 + \left(z - c_i\right)^2}, \tag{5}$$

where d_i denotes the distance from the target-attached transmitter to each receiver as computed using Eq. (1). a_i, b_i, and c_i are already known because they denote the positions of static receivers. This system allows us to track targets with greater precision and reliability. Kim et al. (2022a) verified this trilateration system by conducting a simulation. In this study, we utilize the trilateration system to estimate the position of a dynamic target.

3. Field experiments

3.1. Experimental setup

3.1.1. Field environment

The trilateration system for tracking hornets was implemented in an apiary located in Gwangju, South Korea, to mitigate the spread of hornets in the region (Fig. 5). Owing to the dependence of hornets on honeybees as a food source, it is strategically prudent to focus our tracking efforts on apiaries. We conducted the experiment in apiaries located between forested and urban areas to account for the diverse topographical challenges associated with hornet tracking. The presence of high hills or buildings in these environments necessitates the use of innovative tracking methods, such as high-altitude tracking or the development of robust sensor networks, to obtain accurate and reliable tracking results. Furthermore, the ability of the proposed system to track hornets in challenging environments such as forests, despite obstacles such as signal interference and dense vegetation, demonstrates its robustness and versatility, suggesting that it would be even more

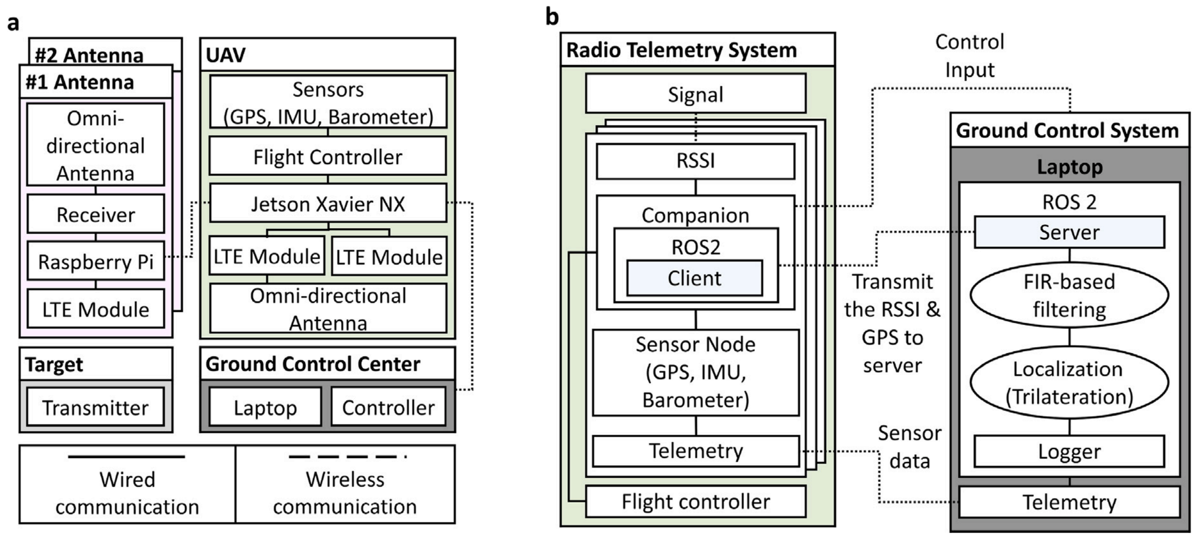

Fig. 6. System architecture. (a) Hardware architecture of proposed trilateration system. The antenna and UAV communicate through raspberry Pi and Jetson Xavier NX. Then, localization data are received by the ground control center (GCS) through Jetson Xavier NX and a laptop. (b) Software architecture of proposed trilateration system. The radio telemetry system and GCS are the client and server, respectively, in ROS2-based communication.

efficient in less obstructive environments and have broad applicability under various types of conditions.

Our observations of hornet behavior patterns and activity trends from the field experiments are as follows. Most of the flight activity of hornets occurred between 07:00 a.m. and 08:00 p.m. Kennedy et al. (2018). We consistently conducted experiments between 10:00 a.m. and 7:00 p.m. Hornets hunt honeybees indiscriminately, showing little interest in the surrounding events. Attempts to capture hornets with tools or traps cause them to move suddenly and erratically or change direction abruptly. Despite this, they pursue honeybees persistently. Furthermore, the field experiments were conducted multiple times in November, when the maximum temperature was stable at approximately 18 °C, and the mean humidity was around 57%. Hornets tend to be active within a certain temperature range, and the experimental conditions were suitable for their activity and foraging. These environmental conditions provided valuable insights into hornet behavior and activity patterns, contributing to a comprehensive understanding of hornet ecology and management strategies.

3.1.2. *UAV system*

The multi-antenna-based trilateration system was configured as follows. The solid black lines and dotted black lines in Fig. 6a represent wired and wireless communication, respectively. The radio-tagged tracking targets emitted periodic radio signals, which were captured by each omnidirectional antenna, collected by the receiver, and transmitted to the companion computer. To build this setup, we designed an octocopter by using the Tarot T15 platform, which is known for its high payload capacity of up to 12 kg. We used Pixhawk 2 by Holybro as the flight controller to directly manage the UAV's flight operations. Additionally, a Raspberry Pi 4 was used as the companion/on-board computer, to integrate the upper controller functionalities. The RSSI data generated by the transmitter attached to the insect were transmitted sequentially to the antenna, receiver, and companion computer.

We utilized a receiver sourced from Advanced Telemetry Systems, Inc., USA, to measure the radio signals emitted by the transmitters attached to the flying insects. This receiver is equipped with advanced digital signal processing (DSP) technology, which enhances its sensitivity by digitizing audio signals. It features adjustable RF gain values, which are crucial for accurately estimating the distance between the transmitter (i.e., flying insects) and receiver (i.e., UAVs). Additionally, the receiver incorporates a dial-type gain regulator, which allows us to adjust reception sensitivity through a variable resistor that controls the voltage input to the receiver controller. This adjustment facilitates precise control over the receiver gain by outputting the desired voltage through the analog output channel of the controller. The frequency range of the receiver is divided into 4-MHz-wide segments within a specific range. We selected the 145–149 MHz and 148–152 MHz segments and communicated in the 148 MHz band. We used omni-directional antennas in conjunction with the receiver to capture the radio signals emitted by the transmitters. These antennas emit electromagnetic waves uniformly in a 360-degree horizontal space, covering all directions. The frequency range covered by the selected antennas aligned with the receiver specifications. The height of the ground antennas was 123 cm, while the height of the UAV-mounted antennas was 73 cm. As the transmitter attached to the flying insects, we opted for the T15 model, which is known for its compactness and reliability. In choosing this sensor among the sensors that weigh less than 0.25 g and have been validated in prior studies, we considered factors such as lifespan, pulse rate, and compatibility with the selected receiver. The transmitter weighed 0.15 g and measured 11 mm×3.4 mm, and it offered a usable lifespan of 7 to 27 days.

3.1.3. *Communication*

To establish smooth wireless communication between the ground control station (GCS) and the three companion computers, an LTE-based communication protocol was developed. This protocol was designed specifically to facilitate seamless data exchange and command transmission over long distances with the aim of ensuring reliable communication even in challenging environments.

The solid and dotted black lines in Fig. 6b represent wired and wireless communication, respectively. To develop the software architecture, we used the robot operating system 2 (ROS2) framework, which provides a comprehensive suite of tools and libraries for building complex robotic systems. Additionally, we used the real-time publish–subscribe (RTPS) protocol of data distribution service (DDS), a communication middleware that guarantees real-time performance in distributed systems. By incorporating ROS2 and DDS, we were able to realize efficient and reliable communication between the components of our robotic system. To establish a secure and reliable communication network, we deployed a virtual private network (VPN) configuration. This allowed us to create a remote communication environment in which each local IP address was configured as a separate network, which ensured that data transmission was secure and isolated from external interference.

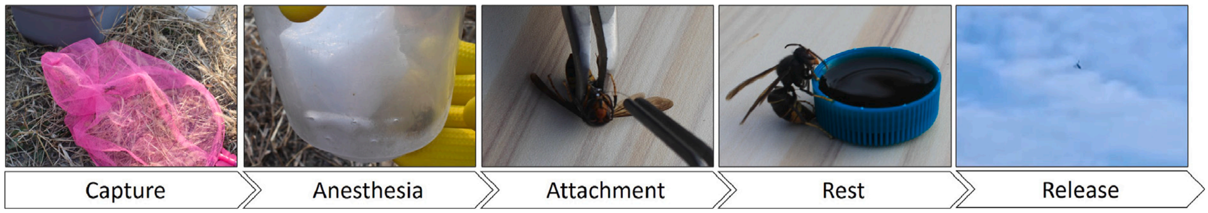

Fig. 7. Experimental process for attaching sensors to *V.velutina*. This process involved the following sequence: Capture, anesthesia, attachment, rest, and release.

The combination of LTE-based communication, ROS2, RTPS protocol, and VPN configuration allowed us to establish a robust communication infrastructure for our UAV system. This infrastructure played a crucial role in facilitating seamless coordination and control of the UAV's operations, enhancing its overall performance and reliability in real-world scenarios. Through preliminary testing and optimization, we verified the effectiveness and efficiency of our communication protocol and network architecture to ensure that the proposed UAV system could reliably transmit data and commands between the GCS and onboard computers in various operational environments.

3.2. Behavioral experiment

Flying insects, such as *V.velutina*, possess limited payload capacity owing to their lightweight anatomy, which highlights the criticality of determining their load-carrying capabilities. The flight capability experiment, detailed in our preliminary research (Kim et al., 2019), was performed using a test group of *V.velutina* loaded with weights ranging from 0.10 g to 0.30 g to assess their flight capabilities. The results indicated that weights of 0.20 to 0.25 g did not impede flight, while weights exceeding 0.25 g adversely affected flight performance. Notably, the entire process of hornet tagging was completed in less than 1 min per hornet, and the tag weight was 3 to 4 times lower than the typical weight of prey pellets transported by this species. Rojas-Nossa et al. (2022) suggested the use of color paints or conspicuous nail polish to mark individuals for ensuring visibility and easy identification from distances of 1.5 to 2 m, which are typical observer distances from bait stations. However, we developed a specific harness-based sensor attachment method suitable for arthropods to avoid the use of chemical substances (Jirinec et al., 2021; Buck et al., 2021). The proposed attachment method involves forming a loop with a thread and fastening it onto a hornet by hooking it around two segments of the insect and pulling until it fits snugly.

The experimental process involved the following sequence: capture, anesthesia, attachment, rest, and release (Fig. 7). Capturing *V.velutina* was relatively straightforward because they primarily target honeybees. Dry ice was used as anesthesia to avoid residues that could interfere with the sensors. However, it was crucial to ensure a short sedation time to prevent prolonged unconsciousness, which could be fatal for hornets. Sensors were attached swiftly by using the proposed harness technique in view of the sensitivity of hornets to touch. After the *V.velutina* awakened from anesthesia, efforts were made to help them regain strength, typically by providing a warm environment or sugar water. Finally, after practicing with mock sensors, the actual tagging procedure was executed. We conducted experiments to confirm that the sensors attached to the hornets did not affect their flight. Preliminary experiments were conducted by attaching clips of the same weight as that of the actual transmitters to multiple hornets by using the harness technique. Ethical considerations were paramount in our experiments, and the hornets were not harmed, injured, or retained in captivity after tagging.

3.3. Ground truth experiment

The diminutive size of *V.velutina* is a formidable obstacle in directly attaching GPS devices onto them to determine their location. To address this challenge, we used a small drone as a surrogate to replicate the swift movement characteristic of dynamic insects and understand their behavioral tendencies. By strategically integrating a transmitter onto the small drone, we acquired ground-truth data, which served as a benchmark for tracking *V.velutina*. Our approach involved transitioning the target of interest from hornets to the small drone to facilitate application of the trilateration system under conditions that closely resemble real-world scenarios. To assess the performance of the localization system, we compared GPS-derived positions with those estimated through trilateration in both linear and nonlinear flight scenarios, and the results revealed distinct patterns in trajectory estimation of the small drone. This methodological adaptation underscores our commitment to use innovative solutions for unraveling the complexities of insect behavior and advancing our understanding of ecological dynamics.

3.4. Localization experiment

To determine the positions of hornets, experiments were conducted within an apiary. Sensors were attached to the hornets, and the, preliminary behavioral trials were conducted to assess the hornets' activities. To evaluate the effectiveness of the proposed algorithm tailored for small insects such as hornets, a small drone was used in the experiments. Following these evaluations, practical experiments involving live hornets were conducted. Three antennas were positioned strategically in a triangular formation approximately 60 m apart from the point of origin of the hornets' flight. Notably, one of these antennas was mounted on a UAV. Each antenna was connected to a receiver equipped with a companion computer. As the hornets commenced flight, the RSSI data originating from each companion board were transmitted to the central computer. The three companion boards and the central computer facilitated real-time information transmission through the ROS2 framework. The transmitters affixed to the tracking targets emitted radio signals at regular intervals. These signals were collected by each antenna, filtered, and transmitted to a microcontroller unit mounted on the UAV. Subsequently, the trilateration system was used to estimate the hornets' positions by using the RSSI signal data.

4. Experimental results

4.1. Harness-based behavior of V.velutina

Insects generally have a segmented structure composed of a head, thorax, and abdomen, and their legs are attached to the thorax. We took advantage of this structure to develop a harness-based sensor attachment method. To start creating the harness neck loop, we cut approximately 20 cm of thread and tied a loose figure-eight knot at approximately a quarter of the way down the strand (Fig. 8a). Once the harness neck loop was formed, we slide it onto the transmitter, ensuring that the knot was positioned correctly. Then, we tightened the knot securely around the top of the transmitter by pulling the thread

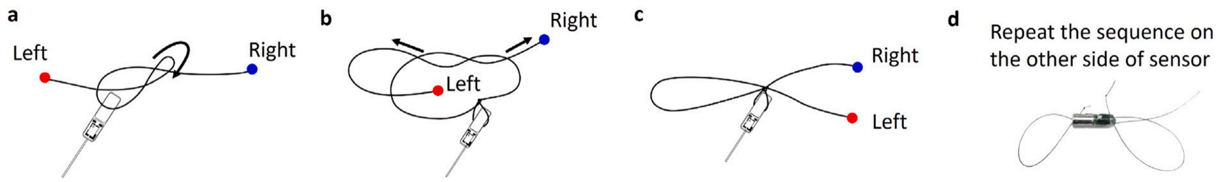

Fig. 8. The flow depicts a harness-based sensor attachment method suitable for small segmented insects such as hornets. A slightly elastic thread of appropriate thickness is used to minimize interference with hornet movement. (a) and (b) The thread is tied securely with a knot to prevent unraveling at approximately one-quarter of its length. (c) A slipknot is tied to loop the ring around the hornet's segment for quick and secure attachment. Finally, in (d), the procedure is repeated in the direction opposite to that of the sensor to create two loops.

tightly and applied a small amount of super glue for additional security, ensuring that any excess glue did not adhere to the harness (Fig. 8b). Next, we fashioned a loop to secure the transmitter onto an actual hornet by tying a slipknot, which is a stopper knot that can be undone easily by pulling the tail (Fig. 8c). To create a slipknot, the yarn should be crossed by twisting one's fingers, and a loop should be formed. Then, two fingers should be inserted into the loop to expand it. Thereafter, the working yarn should be grasped and pulled partially through the loop. The knot should be tightened halfway by pulling the tail end of the yarn. A hornet should be placed into the loop, and both ends of the yarn should be pulled snugly. This process should be repeated on the bottom of the transmitter, too (Fig. 8d).

We developed a harness suitable for hornets and conducted preliminary experiments involving actual hornets. To imitate the actual sensor, we used a clip to create a sensor model with dimensions identical to those of the sensor. By using the above-described harness technique, we captured a real hornet and attached the sensor model to it by using a thread. We tested approximately 15 *V.velutina* and found that they were able to fly well. For visibility, we stretched the harness end threads and added white tissue paper. Although the long threads and pieces of tissue paper were easily visible, they made the insects vulnerable to the external environment. When the released hornets rested on a tree, they were caught in a spider's web or tangled in a tree branch, failing to reach the hive. Therefore, we decided that it would be efficient to attach only the sensor to the hornet without any additional materials.

4.2. Ground-truth acquisition of small UAV

The experimental evaluation involved subjecting a small drone to a variety of flight scenarios, encompassing both linear and nonlinear trajectories. These scenarios were crafted carefully to simulate real-world conditions and emulate the dynamic flight patterns of insects. The results yielded a position estimation accuracy of 100%, thereby highlighting the robustness and reliability of the proposed localization system. A comparative analysis was conducted between the GPS-derived positions and those estimated through trilateration, across linear and nonlinear flight scenarios. This analysis revealed distinct patterns in the trajectories estimated using the small drone, further validating the system's ability to track dynamic targets accurately.

In Fig. 9, the cumulative tracking results of six experiments conducted using the small drone are depicted; the color bar denotes the path of the target over time, ranging from blue (start point) to red (end point). In each experiment, the latitude and longitude of a transmitter and the GPS attached to the small drone were compared. The average position estimation error in terms of altitude was 0.0000($\pm$0.0001) and that in terms of longitude was 0.0000($\pm$0.0002) across the six experiments. These findings provide compelling evidence of the efficacy of our tracking system in diverse flight scenarios, underscoring its potential utility in insect behavior research and related fields. Through methodical experimentation and rigorous data collection, we provide valuable insights into the accuracy and dependability of the proposed tracking approach. These insights contribute to a deeper understanding of the capabilities and practical implications of our proposed localization system for studying the behaviors of dynamic insects.

4.3. Localization of *V.velutina*

The main experiments were conducted in an apiary located between a forest and a city, the same location as that used for ground-truth testing. Field evaluations of the trilateration-based localization system for radio-tagged *V.velutina* were conducted assuming that the hives in which the target *V.velutina* live were their last known locations owing to their homing instinct. We conducted position estimation by using five hornets. These hornets, equipped with a transmitter each, initiated flight and moved out of sight quickly. The trilateration system recorded information about the tagged *V.velutina*, including their tracking longitude and altitude. The results yielded a position estimation accuracy of 100%.

The tracking results of individual *V.velutina* are presented. The latitude and longitude of a transmitter attached to an individual *V.velutina* are depicted in Fig. 10. The color bar indicates the estimated paths of the targets over time, ranging from blue (start point) to red (end point). By using the merged data, the primary locations of two *V.velutina* hives were identified, as depicted in Fig. 11. The coordinates in decimal degrees of these two hives, A and B, were latitude 35.1815, longitude 126.7558 and latitude 35.1812, longitude 126.76675, respectively. The average localization error of three hornets in terms of altitude and longitude were 0.0006($\pm$0.0002) and 0.0023($\pm$0.0015), respectively, for hive A, and the average localization error of two hornets in terms of altitude and longitude were 0.0012($\pm$0.0001) and 0.0004($\pm$0.0011), respectively, for hive B, in decimal degrees. Among the potential failure factors, no signal detection failures were observed. Nonetheless, based on the insights gleaned from the preliminary experiments, external factors such as periods of rest, presence of spider webs, and sticky plants in the vicinity may have influenced the tracking process.

5. Discussion

We demonstrated the feasibility of UAV-based tracking of radio-tagged objects by using a trilateration system. This validation of the proposed UAV-based tracking system highlights its potential for use in various fields, including wildlife monitoring, asset tracking, and search and rescue operations. Owing to the inherent advantages of UAVs, such as mobility, versatility, and accessibility, the proposed system can potentially be used for tracking in diverse environments and scenarios. Furthermore, the proposed localization system can be applied not only to dynamic targets such as flying insects but also to static objects with limited mobility. This suggests that the proposed tracking system can be applied to diverse objects, regardless of their size or movement characteristics (Wikelski et al., 2007; Kays et al., 2015). In Kim et al. (2022b), we defined small insects based on size, and any insect larger than this threshold can be tracked effectively by using the proposed method. Although insects smaller than this threshold may currently pose challenges, technological advancements will likely allow us to track them in the future. The scalability of the proposed tracking approach highlights its adaptability and flexibility, thereby paving the way for practical experiments involving diverse objects. As we continue to advance and optimize our system, we anticipate its widespread adoption and impact across various sectors, ultimately contributing to

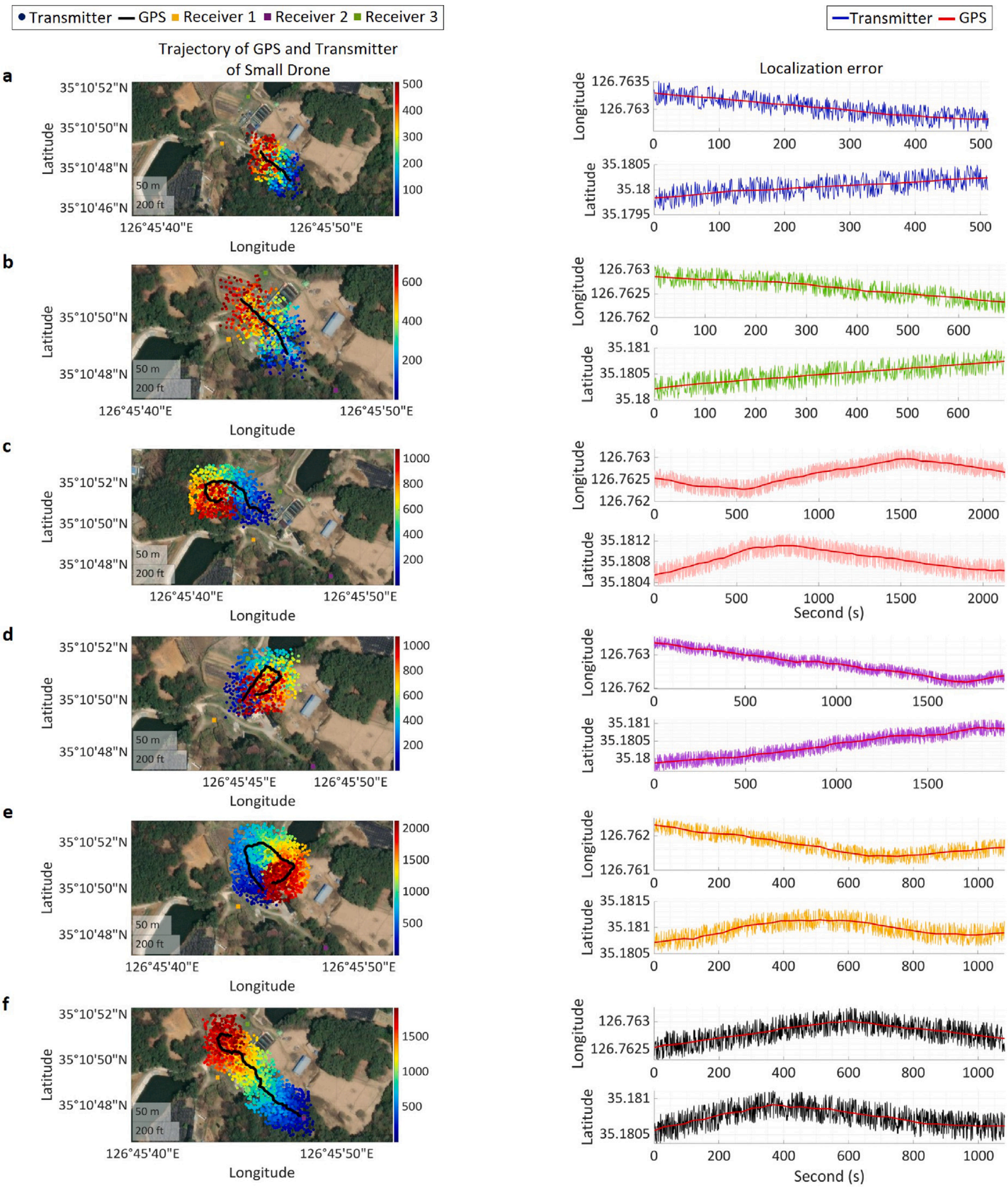

Fig. 9. A map illustrating the transmitter and GPS module attached to the small drone. Scattered points of various colors represent the estimated localization coordinates calculated through trilateration by using the RSSI data acquired from the transmitters attached to the small drone in conjunction with the proposed algorithm. The color bar at the top shows the movement of the small drone tracked over time. The black lines represent the GPS data of the small drone. The coordinates of the three receivers installed for trilateration are indicated as well. Receiver 1 is mounted on the UAV, while receivers 2 and 3 are fixed to the ground. (a), (b), and (c) Estimated straight-line paths of hornets; (d), (e), and (f) nonlinear paths incorporating circles, considering the dynamic nature of hornets.

advancements in environmental monitoring, wildlife conservation, and beyond.

Destruction of honeybee colonies leads to economic losses at the national scale (Lima et al., 2022; Requier et al., 2023), and therefore, methods to explore hornet habitats sustainably are needed. The use of UAVs to track hornets and locate their hives offers significant economic advantages over traditional methods such as tools, traps, and manual search. UAVs provide high mobility and efficiency, allowing for rapid coverage of large areas within short timeframes. Moreover, automated UAV systems optimize resource utilization, thereby reducing the labor costs associated with manual efforts. Furthermore, the precision and real-time capabilities of UAV-based tracking systems facilitate swift identification of hornet nests, minimizing the potential damage caused by hornets. By contrast, removing hornets using conventional methods involves expenses such as purchase and maintenance of traps, upkeep of equipment, and cost of labor required for manual search and removal (Barbet-Massin et al., 2020). While these costs may initially appear lower than investing in UAVs and the related equipment, the

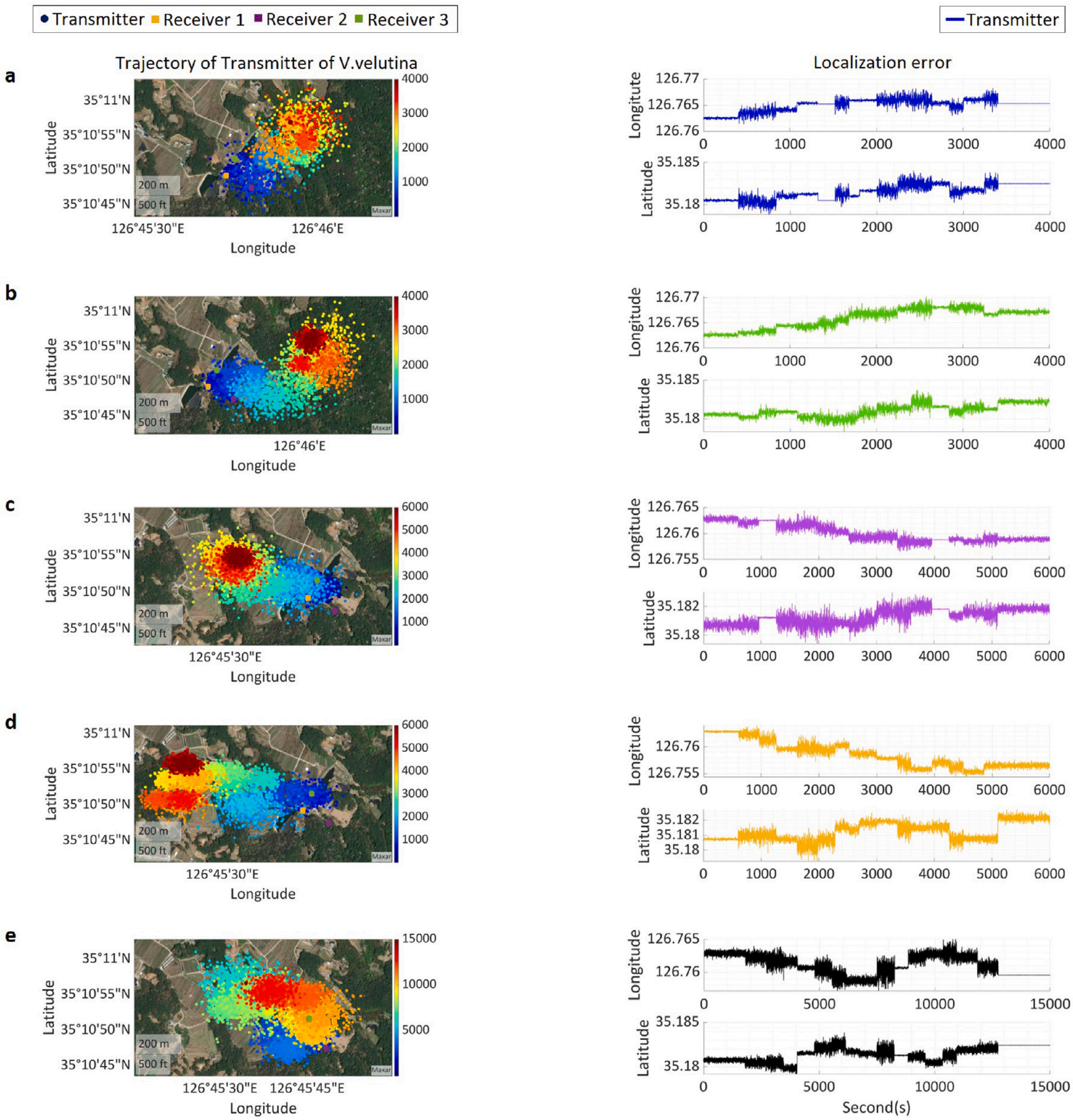

Fig. 10. Maps showing the localization estimation results of *V.velutina*. The scattered points of various colors represent the localization coordinates estimated through trilateration by using the RSSI data acquired from the transmitters attached to *V.velutina* in conjunction with the proposed algorithm; The color bar at the top represents hornet movement over time. Lines of similar colors represent the paths estimated using the scattered points with respect to time. The coordinates of the three receivers installed for trilateration are indicated as well. (a), (b), and (c) Results of hornets assumed to live in hive A. (d) and (e) Results of hornets assumed to live in hive B.

time factor becomes crucial. Given the rapid proliferation of hornets such as *V.velutina*, timely removal of multiple hornets is vital, and eliminating entire hives offers a strategic advantage in preventing hornet breeding. Despite its potentially higher initial costs, the long-term necessity and efficacy of UAV-assisted hornet nest removal are evident, making it a more economically viable solution for managing hornet infestations. As the demand for sensor networks continues to grow, advancements in manufacturing processes will lead to increased production, which will reduce implementation costs, thereby further enhancing the cost-effectiveness and accessibility of UAV systems for hornet tracking and removal.

We have developed an omnidirectional antenna system to solve the problems of turning time and tracking accuracy, which were encountered in previous studies where directional antennas were used. The multiple omnidirectional antenna system proposed herein shortens tracking time and increases tracking accuracy. However, the tracking range and tracking location of this system may be limited depending on the tracked target and UAV movement. The proposed trilateration system involves the deployment of two omnidirectional ground antennas and one omnidirectional antenna attached to a UAV. In spite of the UAV's movement capabilities, the trilateration technique restricts the effective tracking range to a specific triangular area, thereby limiting the overall coverage. In addition, the performance of the proposed system is influenced by the quality of the signal processing algorithms used. While we have developed a trilateration-based tracking system with carefully tuned parameters, it remains highly sensitive to environmental conditions. This highlights the need for more advanced and precise algorithm designs to mitigate these effects, especially in dynamic environments.

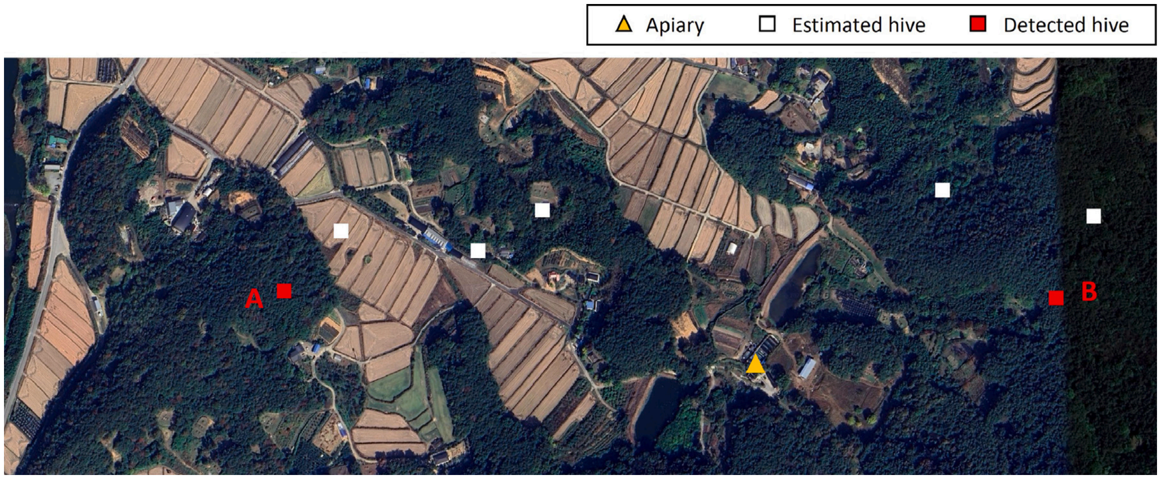

Fig. 11. In the experiment involving five hornets, candidate localization is achieved for five hornet hives, and two hives are discovered by exploring the surrounding area.

Because the proposed system targets various objects, such as flying objects, more advanced tracking technologies are required. We can consider the localization and tracking of UAV-based flying objects by using rotating antennas to overcome these limitations. A rotational antenna system employs a single antenna, and it is economical compared to a multi-antenna system. In addition, because such an antenna is rotated using a motor, its tracking range is not limited, which reduces the tracking time while ensuring 360° coverage. We are developing the proposed UAV-based positioning and tracking system further to reduce its position estimation error and expand its tracking range. Through continuous development and improvement, we aim to establish the proposed system as a reliable approach to object localization and tracking. In addition, we can improve system performance by using improved filters. Furthermore, there is potential for comprehensive expansion, including spraying (Seol et al., 2022a,b) using UAVs.

6. Conclusion

In this study, we demonstrated the feasibility and effectiveness of using a radio telemetry-based tracking system in conjunction with UAVs to locate and monitor the nests of *V.velutina*. By leveraging the homing instinct of hornets and employing a systematic experimental approach, we successfully discovered two out of estimated five hornet hives. Our localization system achieved an average error of 0.0006(±0.0002) in latitude and 0.0023(±0.0015) in longitude for the first hive, and 0.0012(±0.0001) in latitude and 0.0004(±0.0011) in longitude for the second hive. These results underscore the potential of UAV-based trilateration systems for accurately tracking radio-tagged hornets and effectively identifying their nests. The proposed approach not only provides valuable insights into hornet behavior and movement patterns but also serves as a promising tool for managing the impacts of invasive hornet species on local ecosystems and honeybee populations. The ability to monitor hornets and locate hornet nests in real time can substantially enhance our efforts for controlling the spread of this invasive species and mitigating its threat to biodiversity and agriculture.

CRediT authorship contribution statement

Jeonghyeon Pak: Writing – original draft, Visualization, Hardware, Methodology, Formal analysis, Data curation, Conceptualization. **Bosung Kim:** Visualization, Hardware, Methodology, Formal analysis, Data curation, Conceptualization. **Chanyoung Ju:** Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Hyoung Il Son:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Cooperative Research Program for Agriculture Science and Technology Development, Rural Development Administration, Republic of Korea, under Project RS-2023-00232224, Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through the project of Fostering expertise and advancing technologies in digital agriculture, funded by Ministry of Agriculture, Food and Rural Affairs (MAFRA) (project no. RS-2024-00397026), and Regional Innovation Strategy (RIS) through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (MOE) (2021RIS-002).

Data availability

No data was used for the research described in the article.

References

Arca, M., Mougel, F., Guillemaud, T., Dupas, S., Rome, Q., Perrard, A., Muller, F., Fossoud, A., Capdevielle-Dulac, C., Torres-Leguizamon, M., et al., 2015. Reconstructing the invasion and the demographic history of the yellow-legged hornet, Vespa velutina, in Europe. Biol. Invasions 17, 2357–2371.

Barbet-Massin, M., Rome, Q., Muller, F., Perrard, A., Villemant, C., Jiguet, F., 2013. Climate change increases the risk of invasion by the Yellow-legged hornet. Biol. Cons. 157, 4–10.

Barbet-Massin, M., Salles, J.-M., Courchamp, F., 2020. The economic cost of control of the invasive yellow-legged Asian hornet. NeoBiota 55, 11–25.

Bontadina, F., Schofield, H., Naef-Daenzer, B., 2002. Radio-tracking reveals that lesser horseshoe bats (Rhinolophus hipposideros) forage in woodland. J. Zool. 258 (3), 281–290.

Buck, E.J., Sullivan, J.D., Kent, C.M., Mullinax, J.M., Prosser, D.J., 2021. A comparison of methods for the long-term harness-based attachment of radio-transmitters to juvenile Japanese quail (Coturnix japonica). Anim. Biotelem. 9, 1–16.

Calderone, N.W., 2012. Insect pollinated crops, insect pollinators and US agriculture: Trend analysis of aggregate data for the period 1992–2009. PLoS One 7 (5), e37235.

Cao, Z., Huang, Z., Pan, L., Zhang, S., Liu, Z., Fu, C., 2022. TCTrack: Temporal contexts for aerial tracking. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. pp. 14798–14808.

Chang, C.-H., Chen, J., Vinod, A.P., 2008. Information theoretic approach to complexity reduction of FIR filter design. IEEE Trans. Circuits Syst. I. Regul. Pap. 55 (8), 2310–2321.

Chen, F., Nguyen, H.V., Taggart, D.A., Falkner, K., Rezatofighi, S.H., Ranasinghe, D.C., 2024. ConservationBots: Autonomous aerial robot for fast robust wildlife tracking in complex terrains. J. Field Robotics 41 (2), 443–469.

Choi, M.B., Martin, S.J., Lee, J.W., 2012. Distribution, spread, and impact of the invasive hornet Vespa velutina in South Korea. J. Asia-Pac. Entomol. 15 (3), 473–477.

Demichelis, S., Manimo, A., Porporato, M., 2013. Trovato il primo nido di Vespa velutina a Vallecrosia (IM). Communicato Stampa. Università Degli Studi di Torino, Turin.

Dong, S., Gu, G., Li, J., Wang, Z., Tan, K., Yang, M., Nieh, J.C., 2023. Honey bee social collapse arising from hornet attacks.. Entomol. Gen. 43 (2).

Doornweerd, J., Kootstra, G., Veerkamp, R., De Klerk, B., Fodor, I., Van Der Sluis, M., Bouwman, A., Ellen, E., 2023. Passive radio frequency identification and video tracking for the determination of location and movement of broilers. Poultry Sci. 102 (3), 102412.

Floyd, R.E., 2015. RFID in animal-tracking applications. IEEE Potentials 34 (5), 32–33.

Grosso-Silva, J.M., Maia, M., 2012. Vespa velutina Lepeletier, 1836 (Hymenoptera, Vespidae), new species for Portugal. Arq. Entomolóxicos (6), 53–54.

Jirinec, V., Rodrigues, P.F., Amaral, B., 2021. Adjustable leg harness for attaching tags to small and medium-sized birds. J. Field Ornithol. 92 (1), 77–87.

Johnson, R., 2010. Honey Bee Colony Collapse Disorder, vol. 444. Congressional Research Service Washington, pp. 1–17.

Ju, C., Son, H.I., 2022. Investigation of an autonomous tracking system for localization of radio-tagged flying insects. IEEE Access 10, 4048–4062.

Jung, C., et al., 2012. Spatial expansion of an invasive hornet, vespa velutina nigrithorax buysson (hymenoptera: Vespidae) in Korea. Korean J. Apic. 27 (2).

Kays, R., Crofoot, M.C., Jetz, W., Wikelski, M., 2015. Terrestrial animal tracking as an eye on life and planet. Science 348 (6240), aaa2478.

Keeling, M.J., Franklin, D.N., Datta, S., Brown, M.A., Budge, G.E., 2017. Predicting the spread of the Asian hornet (Vespa velutina) following its incursion into Great Britain. Sci. Rep. 7 (1), 6240.

Kennedy, P.J., Ford, S.M., Poidatz, J., Thiéry, D., Osborne, J.L., 2018. Searching for nests of the invasive Asian hornet (Vespa velutina) using radio-telemetry. Commun. Biol. 1 (1), 88.

Kim, S., Ju, C., Kim, J., Son, H.I., 2019. A tracking method for the invasive Asian hornet: A brief review and experiments. IEEE Access 7, 176998–177008.

Kim, B., Ju, C., Son, H., 2022a. Design of uav-based multi-antenna system for localization of asian hornet and its simulation study. J. Apicult. 1, 15–24.

Kim, B., Ju, C., Son, H.I., 2022b. Field evaluation of UAV-based tracking method for localization of small insects. Entomol. Res. 52 (3), 135–147.

Kim, S.-H., Kim, D.E., Lee, H., Jung, S., Lee, W.-H., 2021. Ensemble evaluation of the potential risk areas of yellow-legged hornet distribution. Environ. Monit. Assess. 193 (9), 601.

Kishi, S., Goka, K., 2017. Review of the invasive yellow-legged hornet, Vespa velutina nigrithorax (Hymenoptera: Vespidae), in Japan and its possible chemical control. Appl. Entomol. Zool. 52, 361–368.

Li, S., Yang, X., Wang, X., Zeng, D., Ye, H., Zhao, Q., 2024. Learning target-aware vision transformers for real-time UAV tracking. IEEE Trans. Geosci. Remote Sens.

Li, S., Yang, Y., Zeng, D., Wang, X., 2023. Adaptive and background-aware vision transformer for real-time UAV tracking. Proceedings of the IEEE/CVF International Conference on Computer Vision 13989–14000.

Lima, C.G., Vaz, A.S., Honrado, J.P., Aranha, J., Crespo, N., Vicente, J.R., 2022. The invasion by the Yellow-legged hornet: A systematic review. J. Nat. Conserv. 67, 126173.

Lioy, S., Laurino, D., Capello, M., Romano, A., Manino, A., Porporato, M., 2020. Effectiveness and selectiveness of traps and baits for catching the invasive hornet vespa velutina. Insects 11 (10), 706.

Lioy, S., Laurino, D., Maggiora, R., Milanesio, D., Saccani, M., Mazzoglio, P.J., Manino, A., Porporato, M., 2021. Tracking the invasive hornet Vespa velutina in complex environments by means of a harmonic radar. Sci. Rep. 11 (1), 12143.

López, S., González, M., Goldarazena, A., 2011. Vespa velutina Lepeletier, 1836 (Hymenoptera: Vespidae): first records in Iberian Peninsula. EPPO Bull. 41 (3), 439–441.

Monceau, K., Bonnard, O., Thiéry, D., 2014. Vespa velutina: a new invasive predator of honeybees in Europe. J. Pest Sci. 87 (1), 1–16.

Pak, J., Kim, B., Ju, C., You, S.H., Son, H.I., 2023. UAV-based trilateration system for localization and tracking of radio-tagged flying insects: Development and field evaluation. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, pp. 1–8.

Pak, J., Son, H.I., 2022. Semantic SLAM-based autonomous tributary navigation system using 3D LiDAR point cloud for UAV. In: Proceeding of 22nd International Conference on Control, Automation and Systems (ICCAS). IEEE, pp. 1380–1382.

Psychoudakis, D., Moulder, W., Chen, C.-C., Zhu, H., Volakis, J.L., 2008. A portable low-power harmonic radar system and conformal tag for insect tracking. IEEE Antennas Wirel. Propag. Lett. 7, 444–447.

Requier, F., Fournier, A., Pointeau, S., Rome, Q., Courchamp, F., 2023. Economic costs of the invasive Yellow-legged hornet on honey bees. Sci. Total Environ. 898, 165576.

Robinet, C., Suppo, C., Darrouzet, E., 2017. Rapid spread of the invasive yellow-legged hornet in France: The role of human-mediated dispersal and the effects of control measures. J. Appl. Ecol. 54 (1), 205–215.

Rojas-Nossa, S.V., Álvarez, P., Garrido, J., Calviño-Cancela, M., 2022. Method for nest detection of the yellow-legged hornet in high density areas. Front. Insect Sci. 2, 851010.

Rojas-Nossa, S.V., Mato, S., Feijoo, P., Lagoa, A., Garrido, J., 2023a. Comparison of effectiveness and selectiveness of baited traps for the capture of the invasive hornet vespa velutina. Animals 14 (1), 129.

Rojas-Nossa, S.V., O'Shea-Wheller, T.A., Poidatz, J., Mato, S., Osborne, J., Garrido, J., 2023b. Predator and pollinator? An invasive hornet alters the pollination dynamics of a native plant. Basic Appl. Ecol. 71, 119–128.

Rome, Q., Muller, F., Touret-Alby, A., Darrouzet, E., Perrard, A., Villemant, C., 2015. Caste differentiation and seasonal changes in Vespa velutina (Hym.: Vespidae) colonies in its introduced range. J. Appl. Entomol. 139 (10), 771–782.

Rome, Q., Muller, F., Villemant, C., 2012. Expansion en 2011 de Vespa velutina Lepeletier en Europe (Hym., Vespidae). Bull. Soc. Entomol. France 117 (1), 114.

Rortais, A., Villemant, C., Gargominy, O., Rome, Q., Haxaire, J., Papachristoforou, A., Arnold, G., 2010. A New Enemy of Honeybees in Europe: the Asian Hornet, Vespa velutina. Atlas of Biodiversity Risks–from Europe to globe, from stories to maps. Sofia & Moscow: Pensoft 11.

Schneider, C.W., Tautz, J., Grünewald, B., Fuchs, S., 2012. RFID tracking of sublethal effects of two neonicotinoid insecticides on the foraging behavior of apis mellifera. PLoS One 7 (1), e30023.

Sedira, N., Pinto, J., Ginja, M., Gomes, A.P., Nepomuceno, M.C., Pereira, S., 2023. Investigating the architecture and characteristics of Asian hornet nests: A biomimetics examination of structure and materials. Materials 16 (21), 7027.

Seol, J., Kim, J., Son, H.I., 2022a. Field evaluations of a deep learning-based intelligent spraying robot with flow control for pear orchards. Precis. Agric. 23 (2), 712–732.

Seol, J., Kim, J., Son, H.I., 2022b. Spray drift segmentation for intelligent spraying system using 3D point cloud deep learning framework. IEEE Access 10, 77263–77271.

Villemant, C., Barbet-Massin, M., Perrard, A., Muller, F., Gargominy, O., Jiguet, F., Rome, Q., 2011. Predicting the invasion risk by the alien bee-hawking Yellow-legged hornet Vespa velutina nigrithorax across Europe and other continents with niche models. Biol. Cons. 144 (9), 2142–2150.

Wang, Z., Huang, Y., Pierce, N.E., 2019. Radio telemetry helps record the dispersal patterns of birdwing butterflies in mountainous habitats: Golden Birdwing (Troides aeacus) as an example. J. Insect Conserv. 23, 729–738.

Wikelski, M., Kays, R.W., Kasdin, N.J., Thorup, K., Smith, J.A., Swenson, Jr., G.W., 2007. Going wild: what a global small-animal tracking system could do for experimental biologists. J. Exp. Biol. 210 (2), 181–186.

Wu, S.-P., Boyd, S., Vandenberghe, L., 1996. FIR filter design via semidefinite programming and spectral factorization. In: Proceedings of 35th IEEE Conference on Decision and Control, vol. 1. IEEE, pp. 271–276.

Yang, Z., Zhou, Z., Liu, Y., 2013. From RSSI to CSI: Indoor localization via channel response. ACM Comput. Surv. 46 (2), 1–32.