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RESEARCH ARTICLE

RSSI-Based Autonomous Tracking System for Radio-Tagged Flying Insects Using UAV With Rotational Antenna

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ABSTRACT The escalating effects of climate change have heightened the urgency of ecosystem conservation efforts worldwide. In this context, pollinators such as honeybees play a critical role in maintaining ecosystem health. However, they face appreciable threats, including the proliferation of invasive alien species (IAS) and colony collapse disorder. In this study, we propose a novel tracking system that uses unmanned aerial vehicles (UAVs) equipped with rotational directional antennas and radio telemetry systems. This approach, which represents an improvement over our previous works, aims to protect biodiversity and ecosystem resilience by mitigating the adverse impacts of IAS on pollinator populations. To implement the proposed tracking strategy, a motor-based directional antenna that can rotate 360° is attached to a UAV, and the received signal strength indicator (RSSI) value is used to localize the hornets to which sensors are attached. The proposed tracking system was verified in a simulated field environment that was constructed by considering the RSSI values obtained in a forest. In addition, the robustness and field applicability of the tracking system were improved by applying it to scenarios consisting of different paths that were constructed considering the dynamic nature of hornets.

INDEX TERMS Unmanned aerial vehicle, radio telemetry, tracking, localization, active sensing, rotational antenna, dynamic insect, received signal strength indicator, localization, invasive alien species.

I. INTRODUCTION

The importance of ecosystem conservation is increasing owing to the dramatic effects of climate change. Central to ecosystem health is the critical process of pollination, wherein honeybees play a pivotal role as primary pollinators [1]. The importance of honeybees lies not only in their contribution to pollination but also in their status as key indicators of ecosystem vitality. However, honeybee populations face significant threats, including the spread of invasive alien species (IAS). These threats have caused widespread decimation of honeybee populations, leading to colony collapse disorder [2].

Recognizing the severity of the damage caused by IAS such as the Asian hornet, *Vespa velutina nigrithorax*, we have expanded our efforts beyond traditional capture methods that emply traps or tools. Owing to the rapid reproduction rate of *V. velutina*, conventional trapping methods have proved to be insufficient [3], thereby prompting research into strategies that involve destroying hornet hives. However, hive destruction often requires manual hive inspection by humans, which is a labor- and time-intensive endeavor.

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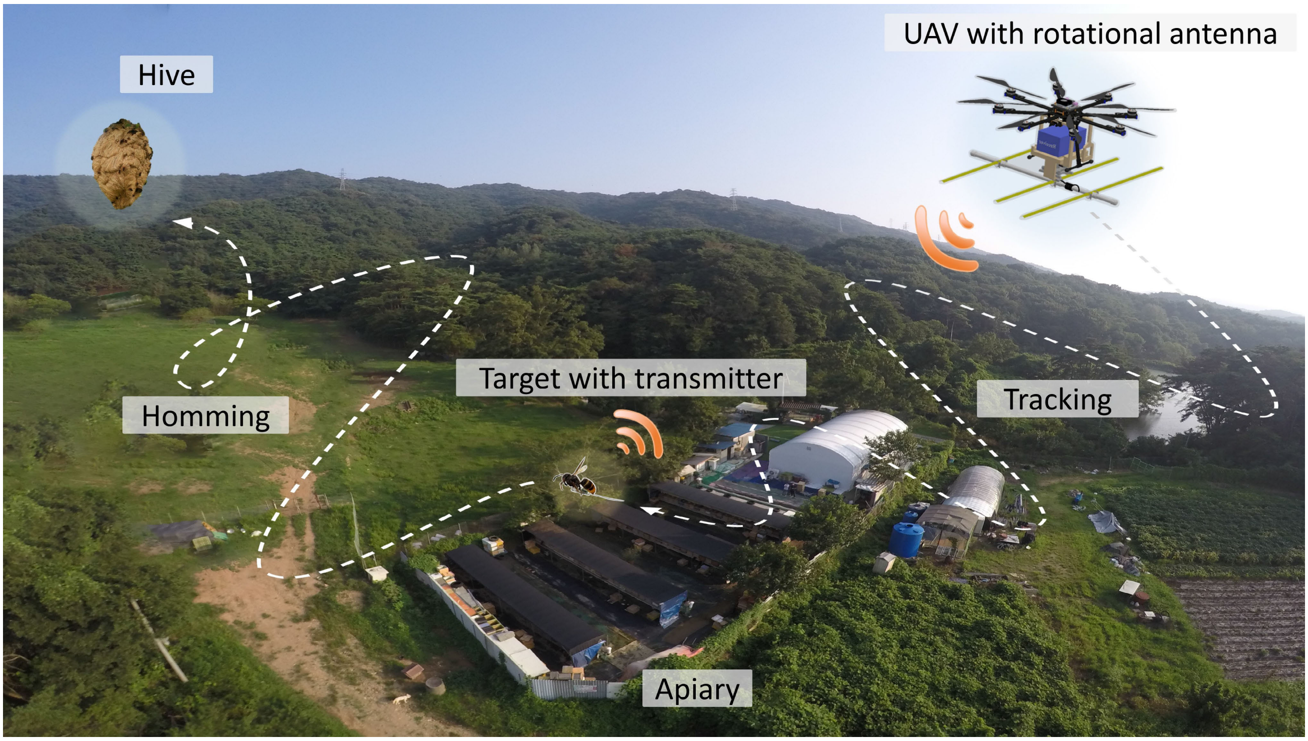


FIGURE 1. **Concept of autonomous tracking system.**

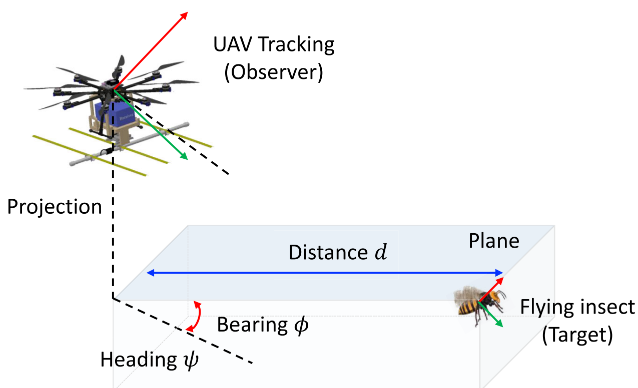


FIGURE 2. **Definition of target tracking problem.**

Moreover, owing to the elusive nature of *V. velutina*, which tend to inhabit elevated locations such as tree canopies or places located at approximately 10 m above the ground [4], tracking their movements is considerably challenging.

The use of unmanned aerial vehicles (UAVs) [5], [6] can be a promising solution for locating hornet hives efficiently (Fig. 1). UAVs provide unparalleled mobility and adaptability, facilitating swift and precise maneuvering in various environments, including dense forests and remote regions where hornets typically establish their hives. This approach reduces reliance on human labor and minimizes the risks associated with traditional hive inspection methods, such as climbing tall trees or scaling steep terrain. Additionally, UAV-based operations help with the implementation of proactive measures for mitigating hornet infestations, thereby reducing the overall effects of hornets on local ecosystems and agricultural activities while minimally disrupting the surrounding wildlife and habitats.

Sensor networks, which use various technologies, such as radio-frequency identification (RFID) [7], harmonic radar [8], and radio-telemetry [9], can serve as versatile platforms for ecological monitoring and tracking. RFID systems use radio waves to identify and track tagged objects or organisms for providing real-time data on their movements and behaviors. Harmonic radar systems emit radio signals that resonate with specific frequencies to facilitate precise localization of targets within a designated range. Meanwhile, radio-telemetry involves the transmission of radio signals from tagged organisms to receivers for realizing remote tracking and monitoring. Among these technologies, radio-telemetry is particularly suitable for tracking hornets because it can provide precise location data over extended periods. Additionally, radio-telemetry can operate in remote and challenging environments, making it suitable for tracking hornets in diverse habitats.

In this paper, we propose a rotational-antenna-based localization system to track *V. velutina*. The contributions of this work are the development of a tracking algorithm, evaluation of the developed algorithm, and system setup for field experiments involving radio-tagged flying insects. In sum, our main contributions are as follows:

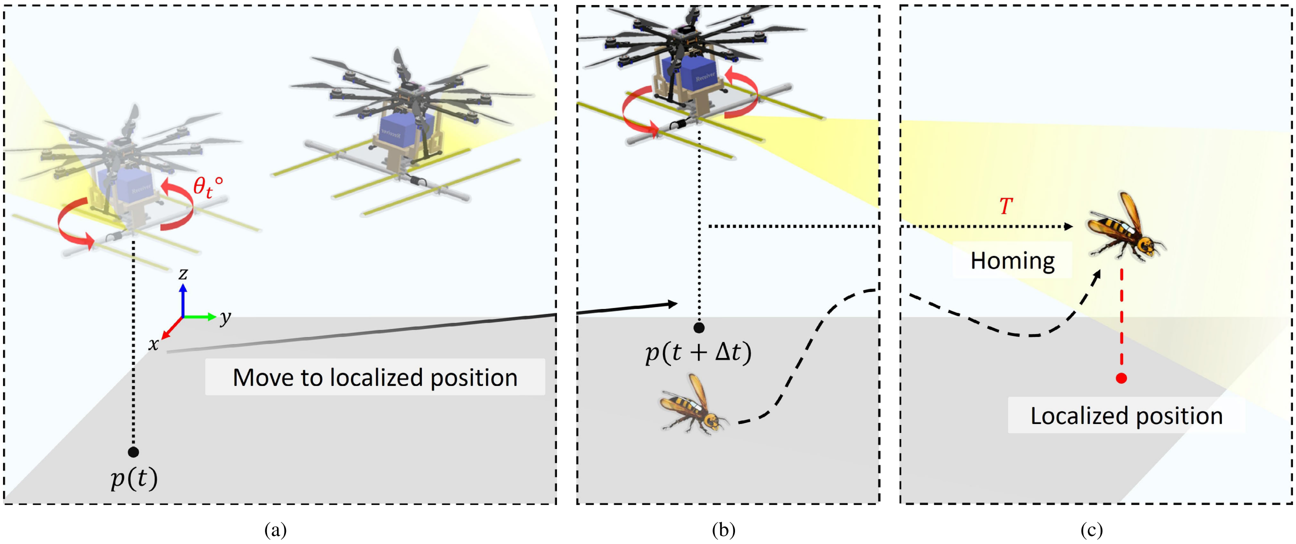


FIGURE 3. Autonomous tracking strategy: (a) Rotating a motor-driven antenna in steps of $\theta°$ at time t, (b) estimating the target's position based on the direction of the strongest received signal strength indicator, and (c) UAV movement toward the estimated target position; steps (a) to (c) are repeated until the UAV and target are within a threshold T.

- We propose a novel systematic approach based on nonlinear model predictive control (NMPC) to localize and autonomously track radio-tagged flying insects.
- We design a UAV-based tracking system that overcomes the limitations (e.g., small species and short tracking range) of the existing radio telemetry systems.
- We validate the feasibility of the proposed strategy for localizing and autonomously tracking radio-tagged targets by conducting UAV-based simulation.
- We conduct experiments in the field environment (a forest) and use the results to demonstrate and discuss the real-world traceability of the system.

The remainder of this paper is organized as follows. In Section II, our previous research is described. The proposed rotational antenna-based tracking algorithm is presented in Section III, in addition to the problem description and system models. The experimental setup is described in Section IV, and the experimental results are presented in Section V. The challenges associated with tracking dynamic targets are discussed in Section VI. Finally, the conclusions of this study are provided in Section VII.

II. RELATED WORK

In this section, various systems and methodologies used to track dynamic and small targets such as insects are discussed. In addition, the authors' previous research efforts to enhance localization and tracking accuracy are reviewed to highlight the strengths and limitations of different approaches.

A. TRACKING SYSTEM FOR DYNAMIC TARGETS

Tracking small, dynamic targets such as insects is challenging on several fronts owing to the need for miniaturized but precise sensors. The low weights and rapid movements of insects complexify consistent tracking because the weight of even a small additional sensor can disrupt their behavior. Additionally, environmental factors such as variable terrain and fluctuating signal conditions further complicate the tracking process. Therefore, effective tracking solutions need to be developed to address these issues by selecting technologies that can manage the specific needs of the target and environment.

Modern technological advancements have led to more efficient and precise tracking solutions based on sensor networks. For short-range tracking, RFID technology is commonly used because of its high accuracy, low power consumption, and ease of integration. By contrast, long-range tracking applications typically use harmonic radar and radio telemetry, which provide extensive coverage and real-time monitoring capabilities. Harmonic radar systems have inherent limitations, including reduced effectiveness in densely vegetated environments and constrained operational range owing to their line-of-sight requirement. For instance, [8] in diverse environments, achieving an average range of 96 ± 65 m and a maximum range of 300 m and [10] developed a wide-field harmonic radar capable of tracking hornets to distances of up to 500 m. Similarly, [11] designed a low-cost harmonic radar optimized for hilly and vegetated terrains, they achieved a detection range of 125 m by employing clutter suppression techniques. References [12] and [13] implemented tracking and monitoring, but the communication distance ranged from as little as 3 m to a maximum of 20 m.

By contrast, radio telemetry offers several advantages over harmonic radar, particularly in challenging environments. Its long operational range allows for tracking wide-ranging or migratory species and its receivers are portable. This characteristic makes it suitable for supporting large-scale ecological studies. Moreover, the radio waves used in

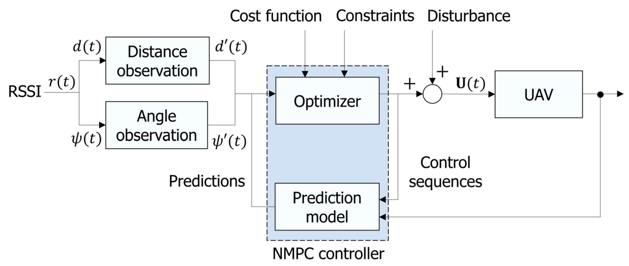


FIGURE 4. Block diagram of proposed controller rooted in nonlinear model predictive control illustrating the prediction and optimization processes based on received signal strength indicator.

telemetry can penetrate vegetation, soil, and even water, facilitating signal reception in obstructed or rugged terrains where harmonic radar may fail. Reference [14] effectively tracked *V. velutina* workers for up to 1.33 km by using 0.28 g radio tags. Reference [15] demonstrated a similar approach to locate *Vespa mandarinia* nests, where tagged hornets led the researchers to nests located up to 650 m away. Reference [16] improved localization accuracy to ±30 m by incorporating habitat-specific factors in telemetry models. Reference [17] minimized localization errors from up to 1929 m to as low as 0.4 m by employing data smoothing and signal selection. These advancements highlight the potential of using refined tracking and localization methods in ecological research and invasive species management.

B. SENSOR NETWORK SYSTEM FOR SMALL TARGETS

Tracking dynamic targets is considerably challenging because of their rapid and, often, unpredictable movements. Traditional methods such as manual trapping and identification are labor-intensive, time consuming, and have limited scalability in terms of tracking insects in their natural habitats. Various tracking systems incorporating sensor networks for dynamic small targets have been studied. One study [6] employs UAV rotation to perform angle of arrival measurements combined with RSSI, which significantly increases measurement time and reduces tracking efficiency, particularly for dynamic targets. Furthermore, in [18] and [19], the particle filter (PF) utilized discrete sampling to determine localization, whereas NMPC performs continuous optimization to generate more efficient UAV trajectories. While PF suffers from sample scarcity when particle numbers are limited, leading to lower tracking accuracy and unreliable performance, NMPC can adapt to real-time changes in the target's motion.

Electronically switchable parasitic array radiator antennas [20] provide electronic beam steering but suffer from limited beam resolution, slow response time, and signal instability, making them unsuitable for fast-moving dynamic targets. In contrast, mechanically controlled directional antennas offer higher tracking accuracy and signal consistency, making them more effective for precise localization. In [21], electronically switchable antennas operating in the high-frequency (HF) band encounter challenges such as greater susceptibility to atmospheric noise, solar activity, and ionospheric disturbances compared to the very high frequency band. In addition, due to its longer wavelengths, the HF band requires larger antennas for efficient transmission, making deployment challenging in portable applications.

To improve mobility and coverage, radio telemetry research has been expanded to include UAV-based systems. Traditional handheld receivers, limited by human mobility and terrain constraints, have been replaced by UAVs equipped with receivers and antennas for automated tracking. According to [22], in mountainous landscapes, UAV-based radio tracking can cover up to four times the area covered by handheld tracking systems. Additionally, [18] reported an average position estimation accuracy of 56 m with an average tracking distance of 66 m. Similarly, [6] introduced ConservationBots, which are autonomous aerial robots designed for rapid and robust wildlife tracking in complex terrains by using radio telemetry. However, these systems are constrained by their ability to detect only one peak signal in each radio-tag transmission period, short tracking range in long-distance monitoring, and high estimation error.

C. OUR PREVIOUS RESEARCH

Previously, we developed a received signal strength indicator (RSSI)-based localization and tracking system for *Vespiae* by following two distinct approaches: UAV rotation and trilateration. Each approach aimed to address the challenges of accurately tracking dynamic and fast-moving insects, but both approaches had limitations that affected their overall effectiveness.

In our initial study [23], we developed a radio telemetry-based system and implemented it in a simulation environment, where the UAV was rotated at regular intervals to acquire RSSI data from four orientations: 0, 90, 270, and 360 degrees. Our experimental results indicated that the localization error at the end of the tracking was 20 to 50 m. In this method, a directional antenna was used to focus signal transmission and reception along specific directions, thereby increasing signal accuracy in targeted areas. However, the need to rotate the UAV introduced operational delays, and the use of a single antenna limited the overall tracking accuracy because the system could not capture real-time changes in insect movements.

In a second studies [24] and [25], we introduced an enhanced UAV-based localization algorithm based on a trilateration system with multiple omnidirectional antennas and conducted field tests. The system was able to track real hornets by integrating signal measurements from two fixed ground antennas and one UAV-mounted antenna. This multi-antenna setup improved the tracking accuracy and reduced the time required for localization compared to those of the rotating UAV system. Our experimental results indicated that two nests were found, and the average errors

(a) (b)

FIGURE 5. Field environment: (a) Forest road near an apiary, and (b) an apiary damaged by hornets.

Algorithm 1 Autonomous Tracking Algorithm

Input: Orientation $\Psi = \{\psi_1, \psi_2, \ldots, \psi_\alpha\}$, UAV current position $\mathbf{P}$, UAV current heading ψ, desired distance D_d, waiting time threshold T, received signal strength r, control input vector $\mathbf{U}$, observation vector $\mathbf{O} = [d, \psi]^T$
UAV position input $\mathbf{P}_d \leftarrow \mathbf{P}$
UAV heading input $\psi_d \leftarrow \psi$
$d \leftarrow D_d + C$
while $d \geq D_d$ **do**
  $\alpha \leftarrow 0$
  for $i = 1$ to α **do**
    $\psi_{\mathbf{d}} \leftarrow \psi_i$
    Received RSSI r_{ψ_i}
    $\alpha \leftarrow \max(\alpha, r_{\psi_i})$
    if $r_{\psi_i} = \alpha$ **then**
      Calculate distance d_{ψ_i} by (3)
      $d \leftarrow d_{\psi_i}$
      Normalize r_{ψ_i} by (5)
      Calculate pattern correlation ψ_i by (6)
      $\psi \leftarrow \psi_i$
    end if
    Optimize d and ψ by (7)
  end for
  $\mathbf{P}(t+1) \leftarrow \mathbf{P}(t) + \mathbf{U}(t)$
  $\psi(t+1) \leftarrow \psi(t) + \dot{\psi}_k$
  Time.sleep(T)
end while
Output: Updated UAV position $\mathbf{P}(t+1)$ and heading $\psi(t+1)$

were 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. Despite these advancements, the addition of three antennas led to inefficiencies, particularly in terms of tracking range and economy. These limitations reduced the system's effectiveness in tracking rapidly moving hornets over larger areas, thereby highlighting the need for further refinement of the tracking technology.

III. ROTATIONAL ANTENNA BASED TRACKING ALGORITHM

In this work, we aim to track dynamic small insects to which only a transmitter can be attached. Tracking depends solely on the RSSI signal emitted from the transmitter. To this end, we propose a motor-driven rotational-antenna-based tracking system.

The proposed system integrates NMPC with RSSI-based tracking to facilitate robust and adaptive localization of flying targets, such as *V. velutina*, in complex and dynamic environments. Traditional RSSI-based localization systems typically rely solely on signal strength measurements, which are prone to inaccuracies owing to environmental uncertainties such as multipath effects, signal degradation, and target mobility. By contrast, the proposed approach uses NMPC to dynamically adjust the UAV's trajectory in real time by accounting for these uncertainties and optimizing tracking performance. This integration considerably increases the tracking precision and system responsiveness, particularly in challenging settings such as forested and obstructed areas.

A. PROBLEM DESCRIPTION

V. velutina, commonly called the Asian hornet, prefers habitats characterized by low forests and mountainous regions, typically avoiding higher-altitude climates. The habitats in which these hornets reside typically feature an average forest canopy height of 10 to 15 m. Interestingly, *V. velutina* localization is primarily a two-dimensional problem rather than a three-dimensional problem from the resolution perspective, as depicted in Fig. 2. This study revolves around an observer tracker system, where a UAV operates at altitudes surpassing those of Asian hornets. Consequently, from a technical standpoint, the altitude dimension introduces an additional degree of freedom in terms of tracking resolution. Therefore, the primary focus

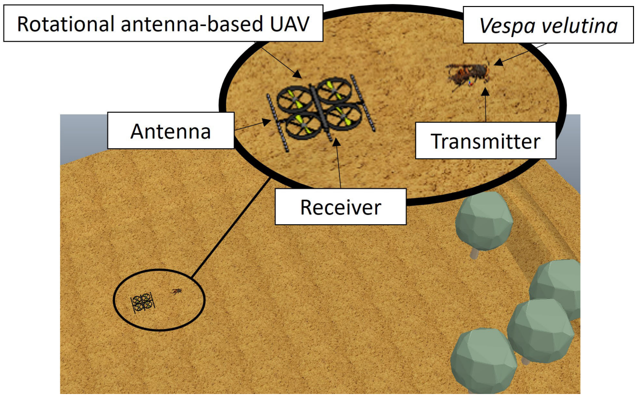


FIGURE 6. Simulation setup: A physics-based simulation using CoppeliaSim, featuring an unmanned aerial vehicle equipped with an antenna and receiver, and a hornet with a transmitter attached to it.

of this investigation is estimating the relative distance and bearing of a flying target within a two-dimensional plane to realize effective tracking.

B. AUTONOMOUS TRACKING STRATEGY

We present a *V. velutina* tracking strategy in Fig. 3. Here, d is the distance between a UAV and a target hornet. α is a counter variable for the number of orientations. The four-step *V. velutina* tracking strategy is summarized as follows:

1) The directional antenna attached to the UAV is rotated using a motor-driven system in steps of θ_t from its current position (Fig. 3(a)).
2) The direction with the strongest RSSI is considered the direction in which the target is located (Fig. 3(b)).
3) The UAV tracks the target based on its relative distance to the dynamic target and RSSI (Fig. 3(c)).
4) Steps 1)-3) are repeated, and the mission is ended when the distance between the UAV and target is less than T.

C. UAV MODELING

UAV position $\mathbf{p}(t)$ denotes the position vector of the UAV at time t. This vector is expressed as $\mathbf{p}(t) = [px(t), py(t), pz(t)]$, where $px(t)$, $py(t)$, and $pz(t)$ denote the UAV coordinates along the x, y, and z axes, respectively. The UAV orientation $\mathbf{po}(t)$ is given by its orientation vector at time t. This vector is expressed as $\mathbf{po}(t) = [\phi(t), \theta(t), \psi(t)]$, where $\phi(t)$, $\theta(t)$, and $\psi(t)$ denote the UAV coordinates along the x, y, and z axes, respectively.

D. SYSTEM MODELING

Let us consider the system as a discrete-time stochastic linear system:

$$\begin{aligned} \mathbf{S}(t+1) &= A_t\mathbf{S}(t) + B_t\mathbf{U}(t) + \mathbf{z}(t), \\ \mathbf{O}(t) &= C_t\mathbf{S}(t) + \mathbf{w}(t), \end{aligned} \tag{1}$$

where $\mathbf{S}(t)$ represents the vector of the state variables of the system, $\mathbf{U}(t)$ represents the vector of the control inputs, and $\mathbf{O}(t)$ represents the vector of the measured outputs available for feedback. A_t and B_t denote the state transition matrices, and C_t denotes the state-to-observation transformation matrix. $\mathbf{z}(t)$ and $\mathbf{w}(t)$ denote system noise and observation noise, respectively, at time t. We set $\mathbf{O}(t)$ as the observation vector and define $\mathbf{O}(t) = [d(t), \psi(t)]^T$. Here, $d(t)$ is a distance observation, and $\psi(t)$ is an angle observation. In Fig. 4, each observation is designed to be calculated using the RSSI vector $r(t)$, optimized using NMPC, and fed into the UAV control input.

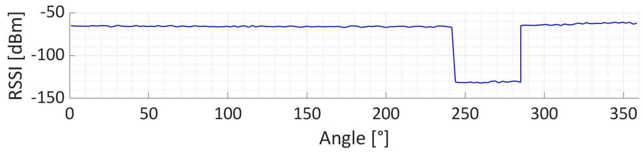


FIGURE 7. Received signal strength plot of a directional antenna using the signal strength data obtained in a real forest and implemented in a simulation.

E. DISTANCE OBSERVATION

Distance observation is used in the general path loss model to estimate the distance between the receiver and transmitter based on the RSSI value [26].

$$r \propto \left(\frac{d}{d_0}\right)^n, \tag{2}$$

where r is the mean received power in dBm, n is the mean path loss exponent that indicates the rate of increase in path loss with distance, d is the distance between the receiver and transmitter, and d_0 is a reference distance. The log-distance path loss model is expressed as follows in equation (2):

$$r = \overline{r}(d_0) + 10\, n \log_{10}\left(\frac{d}{d_0}\right), \tag{3}$$

where $\overline{r}(d_0)$ can be attributed to free-space propagation from the transmitter to a reference distance d_0. In this system, we assume that the UAV possesses information about the initial distance to the *V. velutina* d_0. The UAV performs an RSSI scan by rotating the antenna assembly to generate $r(t)$ and uses information about the mean received power to estimate the environment exponent n, as follows:

$$n = (r - \overline{r}(d_0))/10 \log_{10}\left(\frac{d}{d_0}\right). \tag{4}$$

F. ANGLE OBSERVATION

When targeting dynamic insects, the only data we can obtain are the $r(t)$ values emitted by the transmitter. The first method for estimating the target's angle entails identifying the direction with the highest signal strength in terms of the $r(t)$ value and estimating the angle corresponding to the peak RSSI value. The assumption underlying this method is that the direction with the strongest signal reception is likely to be related to the insect's current orientation. In the second method, the principles of triangulation and trilateration are used to infer the insect's angle based on its relative position,

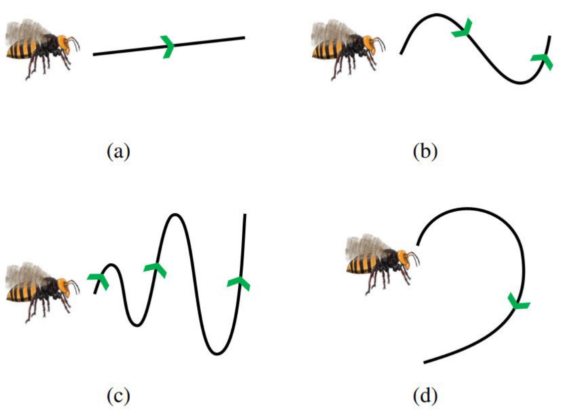


FIGURE 8. Experimental scenario: (a) Linear path, (b) simple curved path, (c) complex curved path, and (d) semicircular path.

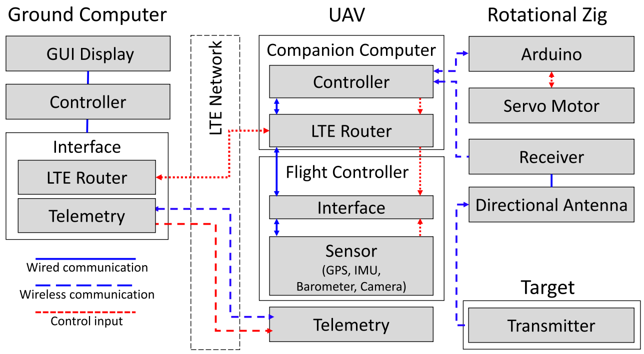


FIGURE 9. Hardware architecture.

which is obtained using multi-directional antennas. In the third method, $r(t)$ is compared to pre-obtained signal patterns to estimate the angle.

We cannot guarantee communication stability in the forest, which is the main habitat of *V. velutina*. In addition, the use of multi-antennas is not cost-effective and offers limited tracking range. Therefore, we match the radiation pattern obtained in advance in the forest with the radiation pattern obtained in real time. This approach allows the system to respond to unpredictable situations in which communication is delayed or lost owing to the dynamic nature of the targets. Pattern correlation proceeds through normalization and correlation. Normalization is performed to map the range of data into a specific interval to ensure that all features have a consistent scale. In the proposed approach, we perform data normalization based on the maximum $r(t)$ value by using the distinctive features of directional antennas. The signal patterns of directional antennas exhibit specific characteristics, and the maximum value of $r(t)$ often corresponds to the direction of the strongest signal. By performing normalization based on this maximum value, the normalization strategy is aligned with the inherent properties of directional antennas to extract meaningful insights from the received signal strength. The UAV performs a 360° sweep to generate $r(t)$, and the generated $r(t)$ is then normalized as follows:

$$r'_a(t) = r(t) - max(r(t)), \tag{5}$$

where a is the number of antennas. Next, we perform pattern correlation. Various pattern correlation methods are available such as Pearson's correlation coefficient, L_2 distance, and clustering. The observed $\dot{\psi}$ represents the L_2 distance, which is defined as follows [27]:

$$\psi' = arg \min_{\psi' \in \Psi} \sum_{k \in \Psi} \omega_k \cdot \left\| r'_k - g_{(k+\theta_t)} \right\|_2 \cdot \eta_{r'_k}, \tag{6}$$

where Ψ is the set of possible angles considered during optimization. ω_k is the weight of each point or measurement k in the summation. r'_k is the transformed point or measurement corresponding to point k after application of the relative angle $\dot{\psi}$. $g_{(k+\theta_t)}$ is the corresponding point on the ground, as obtained by applying the relative angle $\dot{\psi}$ to point k. $\left\| r'_k - g_{(k+\theta_t)} \right\|_2$ is the Euclidean distance between the transformed point r'_k and its corresponding ground point $g_{(k+\theta_t)}$. $\eta_{r'_k}$ is the uncertainty or weight associated with the transformed point r'_k.

G. NONLINEAR MPC

The proposed system is an NMPC-based optimal formulation of the movement control problem for dynamic insects [28], [29]. NMPC outperforms the most fundamental optimal control problem, that is, LQG control, which is the combination of a Kalman filter and a linear quadratic regulator (LQR) [30].

NMPC optimizes the following cost function with constraints on system dynamics and input bounds to determine the optimal control input sequence u:

$$\mathbf{J}(u) = \sum_{k=0}^{N-1} d_k^2 + \omega_d \sum_{k=0}^{N-1} \dot{d}_k^2 + \omega_\psi \sum_{k=0}^{N-1} \dot{\psi}_k^2, \tag{7}$$

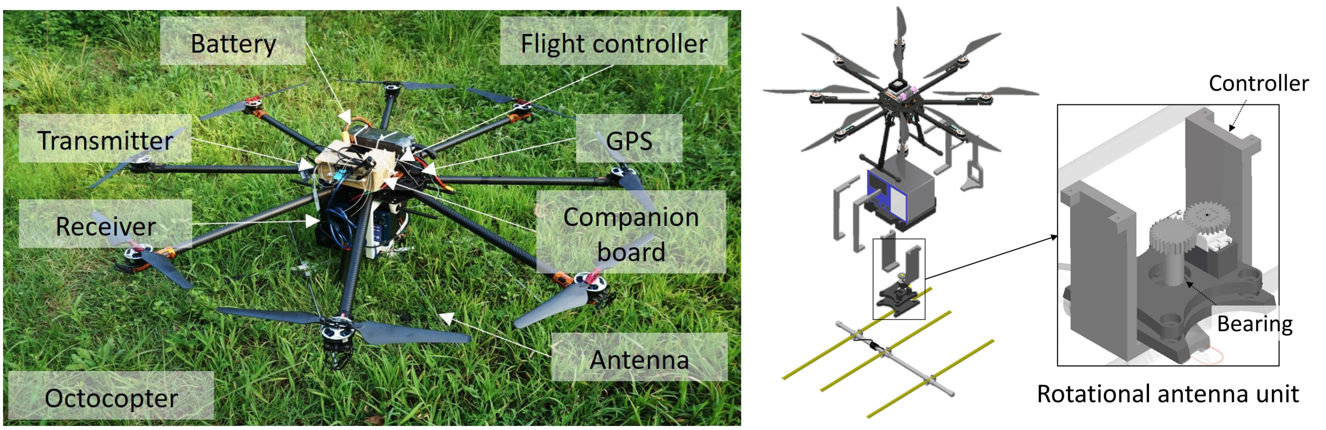
where k denotes the prediction step, and N is the total number of prediction steps. ω_d and ω_ψ denote the weights of the velocity and angle penalties of the UAV, respectively. The proposed algorithm is presented in Algorithm 1.

IV. EXPERIMENTAL SETUP

In this section, we describe the experimental setup used to evaluate the proposed system. These components are integral to ensure that the system performs robustly in complex and dynamic environments.

A. ENVIRONMENT

Before pattern correlation, it is essential to verify whether radio telemetry communication functions effectively in densely wooded areas (Fig. 5(a)), which represent the typical habitat of *V. velutina*. To this end, we conducted a field study in the mountainside of Gwangsan-gu, Gwangju Metropolitan City, South Korea, where actual apiaries are located (Fig. 5(b)). We collected RSSI data at 20 m intervals from the mountainside to the summit to confirm the radiation pattern. Through this data-acquisition step, we aimed to



(a) (b)

FIGURE 10. **Hardware system: (a) Hardware configuration, and (b) rotational antenna structure.**

assess the reliability and effectiveness of radio telemetry communication in densely wooded terrain.

We conducted simulations using CoppeliaSim and MATLAB, which are widely used in robotics and control systems research. In Fig. 6, we established a tracking environment in CoppeliaSim that resembled real-world conditions. The UAV is equipped with a rotating antenna and receiver, while a transmitter is attached to the hornet. In the simulation, given that RSSI of the directional antennas is not supported, we devise a directional radiation pattern that increases the signal strength as the UAV rotates and approaches the transmitter based on the positions of the UAV, target, and forest radiation pattern. Consequently, the antenna rotates by a certain angle and transmits and the signals received at specific angles (Fig. 7).

B. SCENARIO

To validate the rotating-antenna-based tracking algorithm for flying insects, we constructed linear and nonlinear path scenarios. As depicted in Fig. 8, dynamic objects exhibit diverse movements rather than simply flying in straight lines. Therefore, under the same parameter conditions, we evaluated the UAV's tracking capability in various scenarios. The experimental parameters included $\overline{r}(d_0) = -60$, $d_0 = 1$, $\omega_d = 0.00005$, $\omega_\psi = 0.7$, and the number of antennas a was set to 1. These parameters were selected to ensure comprehensive testing and assessment of the algorithm's performance in different dynamic scenarios.

C. HARDWARE

The overall system architecture is illustrated in Fig. 9. We selected an octocopter by considering the payload of the entire device, as depicted in Fig. 10(a). To measure the radio signals emitted by the transmitters attached to flying insects, we used a receiver sourced from Advanced Telemetry Systems, Inc., USA. To ensure compatibility, the receiver, antenna, and transmitter were sourced from the same company. The receiver featured advanced digital signal processing technology, which enhances sensitivity by digitally converting audio signals. Additionally, it incorporated adjustable RF gain values, which are crucial for accurately estimating the distance between the transmitter (i.e., flying insects) and receiver (i.e., UAVs).

Moreover, the receiver was equipped with a dial-type gain regulator to facilitate reception sensitivity adjustment through a variable resistor that controlled the input voltage to the receiver controller. This regulator allowed for precise control over receiver gain by outputting the desired voltage through the controller's analog output channel. The receiver's frequency range was segmented into 4 MHz–wide segments within a specific range. We utilized the 145–149 MHz and 148–152 MHz ranges, and employed directional antennas alongside the receiver to capture the radio signals emitted by the transmitters.

Three-element folding Yagi antennas were used in conjunction with the receiver to measure the radio signals emitted by the transmitters. Custom-tuned to the user-specified 4 MHz range, we selected the 145–152 MHz frequency range to ensure alignment with the receiver's specifications. The antenna dimensions were as follows: maximum height of 81 cm, maximum length of 106 cm, weight of approximately 0.71 kg, isotropic gain of 7.7 dBi, and dipole gain of 5.6 dBi. Based on these parameters, the radiation pattern of the Yagi antenna was simulated, as shown in Fig. 11. Furthermore, the S-parameter was calculated as -4.9753 dB, while the voltage standing wave ratio was determined to be 3.5865, indicating efficient impedance matching and signal transmission characteristics.

As the transmitter attached to flying insects, we selected the T15 model, a crystal-controlled single-stage design that is known for its compact size and reliability. Various sensors weighing less than 0.25 g were considered, all of which had been validated in previous study [31]. Key factors such

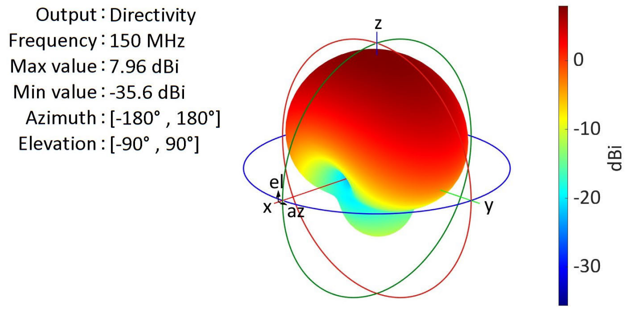


FIGURE 11. Radiation pattern of Yagi antenna.

as lifespan, pulse rate, and compatibility with the selected receiver were considered in the selection process. The chosen transmitter weighs 0.15 g, measures 11 mm×3.4 mm, and offers a usable lifespan of 7–27 days. It operates at a pulse rate of 15–30 ppm and maintains frequency stability of ± 0.5 kHz within the temperature range of -20°C to +40°C.

A rotational antenna system was installed in the lower part of the UAV by using a jig to facilitate precise directional tracking, as depicted in Fig. 10(b). The system consisted of a controller (Arduino UNO) and a rotational antenna unit comprising a motor, receiver, and directional antenna. Bearings were integrated into the rotational antenna unit to minimize interference during rotation. To achieve precise antenna rotation, gears with identical gear ratios were attached to both the motor and the antenna, which ensured that the motor's output was transmitted directly to the antenna without any motion accuracy loss.

D. COMMUNICATION

The proposed system was built using robot operating system (ROS2), and real-time publish-subscribe (RTPS) and data distribution service (DDS) were used for communication. ROS2 is an open-source framework that supports communication between various robotic software components in a distributed network architecture, and it allows for real-time data exchange through RTPS and DDS.

To ensure secure communication, a virtual private network (VPN) was implemented to encrypt the transmitted data and safeguard the system against external threats. Specifically, we used Husarnet, a VPN designed for low-latency communication in real-time robotic applications. Husarnet establishes peer-to-peer connections and minimizes routing delays by bypassing centralized servers and using a lightweight protocol to reduce communication overhead. This approach enhances security, ensures data integrity, and maintains real-time system performance without significant increases in latency.

V. EXPERIMENTAL RESULTS

We assessed two main aspects of the proposed framework: (i) robustness to the dynamic movements of insects, especially in forests, and (ii) predictive performance.

A. TEST OF RSSI TENDENCY

Our initial research focused on understanding radiation pattern correlation in forest environments for tracking hornets. One of the main challenges encountered was pattern normalization on a hillside, where dense vegetation, including trees and grass, created significant differences compared to open field environments. To address this challenge, a simplified forest-specific radiation pattern was defined based on the results of an RSSI tendency test conducted in the field.

In this test, antenna patterns were created by rotating the antenna in 10 degree increments by using motor-based setups, and the distance between the antenna and transmitter was varied from 20 m to 200 m in increments of 20 m. The average of the five antenna patterns at each position was assumed to represent the radiation pattern at that specific location. The results evidenced the existence of a directional radiation pattern at distances of 60 m and beyond, leading to the conclusion that the accuracy of position estimation improved significantly when the distance between the UAV and the target was at least 60 m.

This approach to normalization of the detected radiation patterns by establishing a reference point—typically peak signal strength—within a single rotation allowed us to align the patterns with reference patterns, which increased tracking accuracy. However, the presence of obstacles such as densely wooded areas and thick foliage complicated the identification of ideal radiation patterns. To mitigate this, basic radiation patterns were defined for forested environments and applied to the hornet tracking system. The radiation pattern created is critical especially in forested environments, where obstacles may interfere with signal propagation. The present study represents an initial step toward exploring how radiation pattern correlation can be used for target tracking in complex forest environments.

B. TEST OF TRACKABILITY FOR DYNAMIC TARGETS

The proposed system models distance and angle observations, and it has been optimized using NMPC. Fig. 12 illustrates the UAV's tracking performance when using the proposed radio telemetry-based control system in comparison to that when using a basic circular motion model. The proposed algorithm generates dynamic and stable trajectories when following moving targets by continuously adjusting the UAV's heading angle and speed on the basis of real-time signal strength data received from the transmitter. By contrast, the basic circular model exhibits limited adaptability, highlighting the proposed system's enhanced ability to track the moving target in various scenarios.

In the proposed system, the UAV relies solely on the signals emitted by the transmitters attached to the targets for tracking, as depicted in Fig. 13. RSSI values fluctuate owing to changes in distance and angular orientation between the UAV and the target. These signal variations drive UAV control decisions, facilitating adaptive tracking through continuous antenna reorientation for maximum signal reception.

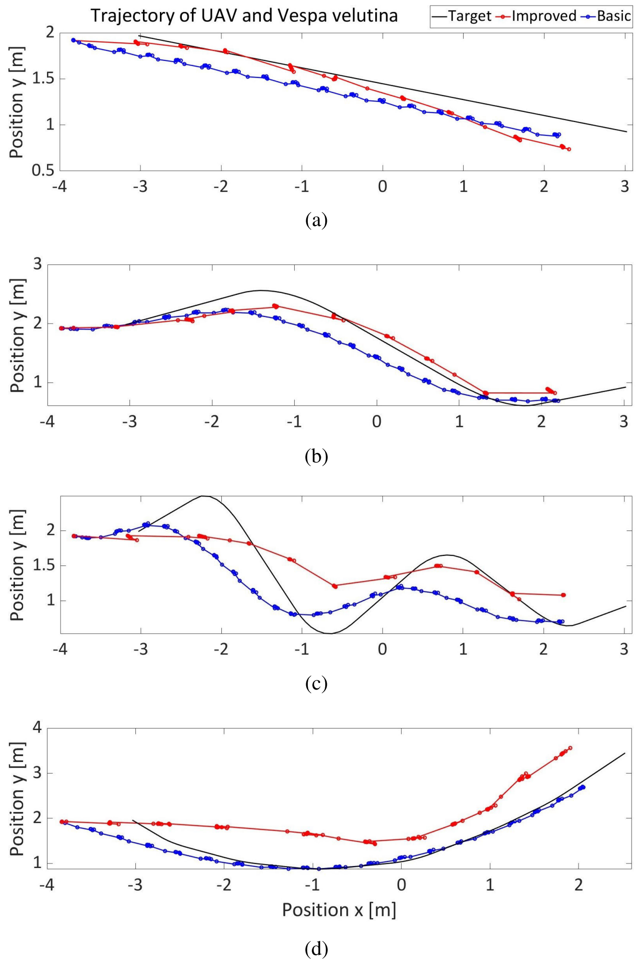


FIGURE 12. Trajectories of UAV and target: (a) Linear path, (b) simple curved path, (c) complex curved path, and (d) semicircular path.

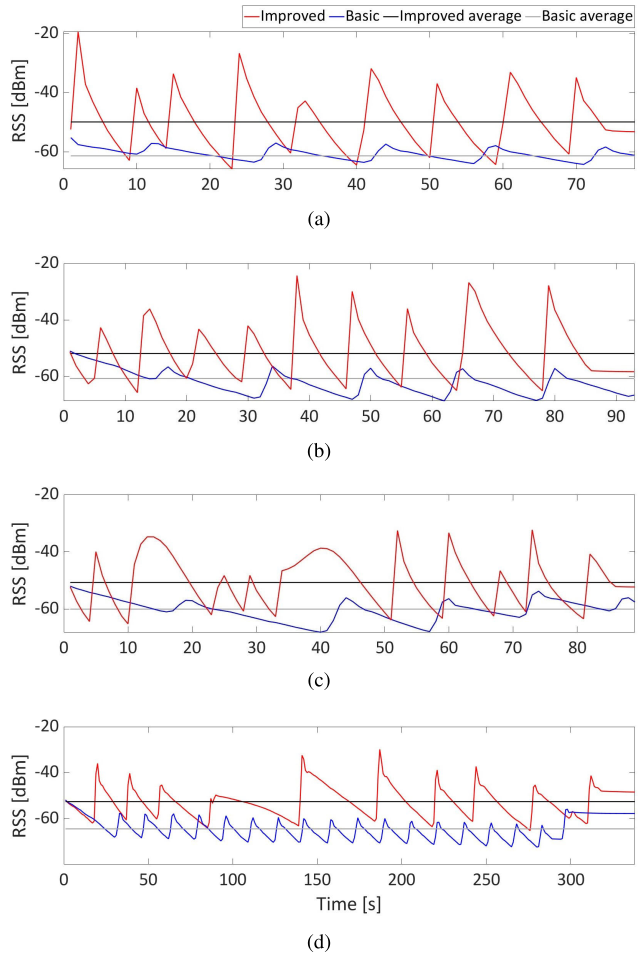


FIGURE 13. RSS of UAV and target: (a) Linear path, (b) simple curved path, (c) complex curved path, and (d) semicircular path.

The UAV maintains a consistent tracking distance until the target stops moving (Fig. 14). This figure depicts the UAV's ability to maintain a safe, predefined tracking distance while dynamically adjusting to the target's movements. Distance variations occur when the target changes speed or direction, but the UAV compensates by recalculating an optimal path.

The UAV computes speed and movement direction on the basis of the RSSI-derived observations and refines these values through NMPC optimization, as illustrated in Fig. 15. The graph reflects periodic fluctuations owing to UAV path recalculations, particularly when navigating curved paths or reacting to intermittent signal loss. This adaptive control ensures robust target tracking, even in dynamic and unpredictable environments.

We have previously validated the localization and tracking algorithm in the CoppeliaSim simulator [32] and conducted experiments with the proposed system in a real-world apiary environment [24], [25]. In this study, we performed RSSI trend analysis using an actual UAV, confirming that our hardware setup operates as intended without any functional issues. Furthermore, the proposed algorithm has been rigorously validated through simulations, demonstrating its feasibility for real-world applications. While additional field tests are necessary for full deployment, this study primarily focuses on the development and validation of a novel rotational antenna-based radio telemetry system. The findings presented in this paper establish a solid foundation for future real-world implementations.

C. COMPARISON TO OUR PRIOR RESULTS

Our objective is not to merely mimic the path of dynamic targets but to ensure uninterrupted tracking within a certain radius until the targets stop moving. For this reason, trajectory overlap is not necessary. The average position estimation error of 0.80 m (Fig. 16) is a substantial improvement over those of other tracking systems, such as the 23.09 m [23] error of the rotating UAV system and 9.50 m [32] error of the multi-antenna system. Collectively, these figures demonstrate the effectiveness of the proposed system in tracking dynamic targets with minimal error, highlighting its adaptability, accuracy, and real-time applicability. The results of simulations validate the system's performance, showcasing

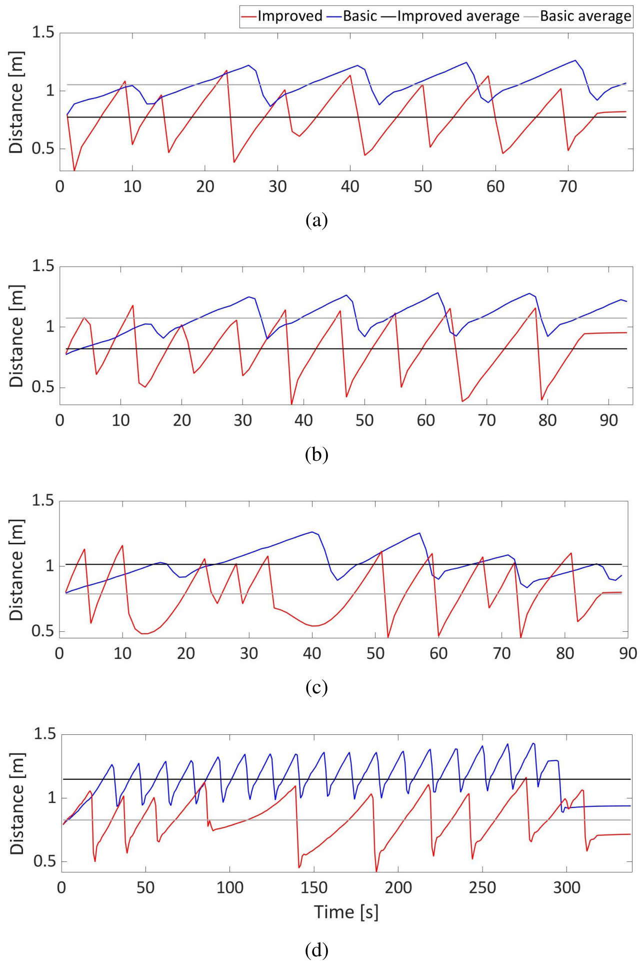


FIGURE 14. Distance between UAV and target: (a) Linear path, (b) simple curved path, (c) complex curved path, and (d) semicircular path.

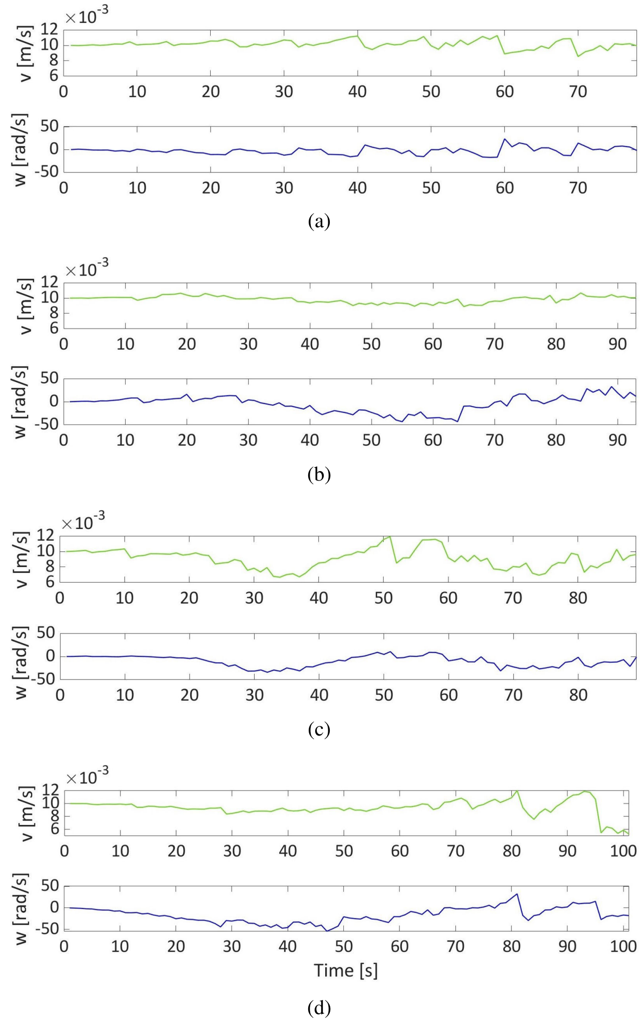


FIGURE 15. UAV's movement speed *v* (m/s) and movement direction *w* (rad/s): (a) Linear path, (b) simple curved path, (c) complex curved path, and (d) semicircular path.

its robustness and potential for implementation in UAV-based tracking applications.

The observed effectiveness of UAVs in tracking dynamic hornets in diverse scenarios highlights the robustness of the proposed control approach. The results of the simulations attests to the robustness and real-time applicability of the proposed control strategy, reaffirming its potential for use in various real-world motor control applications.

VI. DISCUSSION

A. TRACKING ACCURACY

The tracking system must be precise to ensure reliable monitoring, especially in applications that require detailed analysis. Factors such as lighting variations, weather conditions, and physical obstructions can adversely affect sensor performance, leading to inconsistencies. Additionally, the efficiency of the tracking algorithm is a critical factor because as it determines how well the system can adapt to challenging environments. Future studies should focus on enhancing sensor durability and refining algorithms to better manage diverse and unpredictable conditions.

In this study, we aimed to correlate the RSSI patterns obtained in mountainous environments to reduce environmental noise and increase tracking accuracy when pursuing dynamic targets. While the application of standardized patterns to dynamic targets offers certain advantages, it is inherently limited owing to the variability in target behavior and environmental conditions. To address these challenges, we propose an adaptive approach in which the target's direction is estimated in real-time based on its current position. By employing an adaptive threshold for the RSSI signal values, we are able to estimate the target's position and track it more accurately, which improves the overall tracking performance.

Furthermore, the proposed system relies on predefined reference patterns established through empirical measurements conducted in similar environments. These reference patterns allow the system to compensate for distortion in radiation signals due to environmental obstructions, thereby ensuring more accurate target localization. Even in the presence of

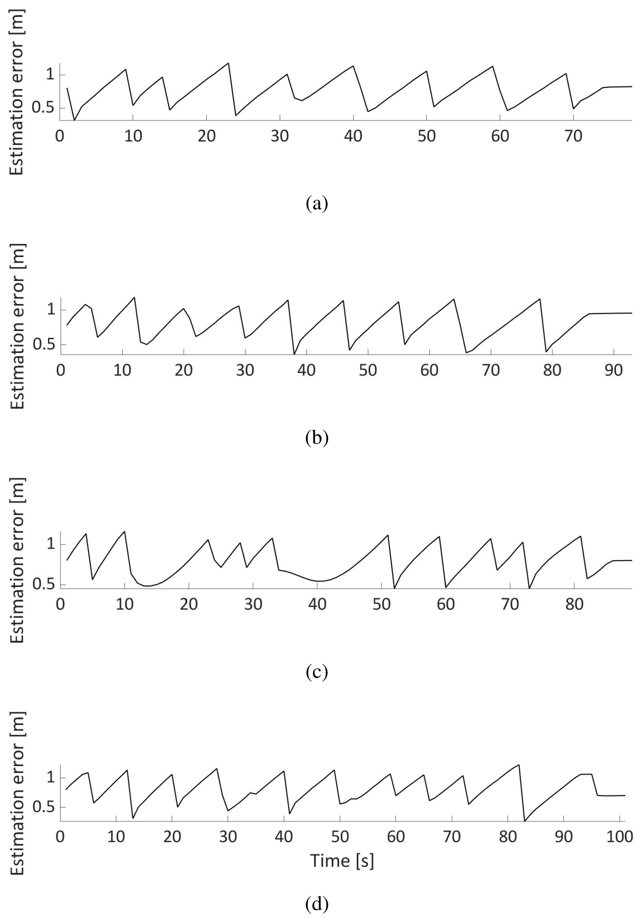


FIGURE 16. Average distance estimation error of improved rotational antenna-based tracking system in various path scenarios: (a) For a linear path, it is 0.77 m; (b) for a simple curved path, it is 0.82 m; (c) for a complex curved path, it is 0.79 m; and (d) for a semicircular path, it is 0.81 m.

significant interference, the system demonstrated consistent and reasonable accuracy by comparing incoming signals to the aforementioned reference patterns. To further enhance the system's robustness, we plan to acquire additional radiation patterns specific to various forested and mountainous environments to better account for environmental variability. In addition, we plan to integrate advanced filtering algorithms, such as the Kalman filter and finite impulse response filter, to reduce noise, correct signal inconsistencies, and improve localization accuracy. The implementation of these enhancements alongside the proposed adaptive tracking approach will help the system to handle signal degradation and environmental interference in a better way, even in extreme and dynamic scenarios.

B. STABILITY

Stability refers to the system's ability to perform consistently over time without experiencing degradation. This aspect is influenced by the reliability of the hardware components and robustness of the software. Ensuring that both elements are resilient to wear and tear, as well as operational stress, is vital for maintaining long-term system effectiveness.

Before conducting field experiments, preliminary testing can be performed to evaluate system performance under controlled yet variable conditions. These tests facilitate the identification and correction of real-time variations, providing valuable evidence of the system's stability. Additionally, they allow us to assess the controller's response to various perturbations, such as dynamic target movements, environmental obstructions, and disturbances that are commonly encountered in forested or rugged terrains. By addressing these factors early on, the system can be better optimized for field deployment while reducing the risk of performance degradation.

Reliable connectivity is another critical factor, particularly for applications requiring real-time data transmission and remote monitoring, such as autonomous robotics and industrial automation. While the proposed system performed well under stable network conditions, it faced issues such as latency and data loss in areas with poor connectivity. To address these limitations, it is important to focus on ensuring secure, robust, and reliable data transmission to maintain system performance even in suboptimal network environments.

To enhance network performance, we incorporated a VPN solution designed specifically for low-latency communication in real-time robotic applications. The selected VPN establishes peer-to-peer connections, thereby reducing routing delays and mitigating the latency caused by centralized servers. Although VPNs inherently introduce some latency owing to encryption and tunneling overheads, we determined that this trade-off was minimal and within acceptable thresholds in view of the system's operational requirements. However, under extreme conditions, such as highly dynamic environments or areas with severe signal interference, additional measures are needed to optimize network performance and ensure reliable communication. This includes implementing techniques such as adaptive communication protocols, signal filtering, and real-time data compression to mitigate latency and packet loss. By enhancing the system's resilience to network disruptions, we can achieve continuous operation and robust system performance in real-world deployments.

C. MINIATURIZATION

Although a quadcopter offers advantages such as reduced weight, low power consumption, and simple control mechanisms owing to its fewer degrees of freedom, it is inherently limited in terms of payload capacity. For applications that require heavier payloads, such as tracking systems, sensors, and additional equipments, a quadcopter's capabilities are insufficient. Based on these considerations, we opted to use an octocopter, which provides increased payload capacity, superior stability, and redundancy in flight control. The greater number of propellers in an octocopter facilitates improved thrust distribution, allowing it to carry heavier payloads while maintaining stable flight performance.

Among the various octocopter models available, we selected one that prioritizes high payload capacity without compromising flight stability or maneuverability. Despite the larger size and greater energy demands of this octocopter compared to those of a quadcopter, significant efforts have been made to miniaturize the equipment components for optimizing efficiency and reducing the overall system weight. This includes the use of lightweight materials and streamlined structural designs.

In the future, we will focus on drone miniaturization to address the current limitations of octocopters, such as high battery consumption and operational costs. On the back of advancements in lightweight materials, efficient power delivery systems, and miniaturized hardware components, we aim to reduce the overall system size and weight. These improvements could eventually allow for a transition to a platform with a greater number of degrees of freedom, which would offer additional benefits in terms of energy efficiency, operational flexibility, and cost-effectiveness, while still meeting the payload and performance requirements of the application.

VII. CONCLUSION

We proposed novel UAV-based tracking system for *V. velutina*, employing directional antennas and radio telemetry technology. The proposed system, which uses rotational antennas, addresses the key limitations of existing research by enhancing economic feasibility, reducing tracking time, and extending tracking range. By integrating physics-based simulators and real-world field data, we developed a system that is both realistic and practical. The system achieved an average localization error of 0.80 m, demonstrating its precision and reliability. Moreover, the proposed tracking system was effective at hornet localization in diverse scenarios, and it was able to adapt successfully to the dynamic behavior of hornets.

In the future, we will focus on refining the proposed tracking strategy by conducting extensive field experiments, wherein we will optimize the hardware, fine-tune the algorithms, and evaluate the system under various environmental conditions. By employing experimental feedback, we aim to iteratively enhance the system's robustness. Furthermore, to achieve high positional accuracy despite the challenges posed by sensor networks, we plan to use small UAVs to explore the surroundings of identified hives, which would enhance our ability to precisely locate and manage hornet hives. Moreover, the proposed system exhibits scalability for application to various targets.

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