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A Tracking Method for the Invasive Asian Hornet: A Brief Review and Experiments

SEUNGWON KIM, CHANYOUNG JU, JEONGEUN KIM, AND HYOUNG IL SON, (Senior Member, IEEE)
Department of Rural and Biosystems Engineering, Chonnam National University, Gwangju 61186, South Korea

Corresponding author: Hyoung Il Son (hison@jnu.ac.kr)

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ABSTRACT Radio-telemetry tracking uses a lightweight transmitter and receivers capable of good mobility. This method can be used to track Asian hornets, which have a significant impact on bees and beekeepers. This is because hornet acts as a group and exhibit dangerous aggressiveness. The most efficient way to prevent the invasion of Asian hornets is to destroy their nest. To this end, fire, pesticides, and experts can be used. However, the nest is not destroyed based on the location (e.g., treetops, rocks, urban areas). Therefore, we propose a method for tracking Asian hornets to effectively destroy their nests. Firstly, we investigate the existing insect-tracking methods. Secondly, we select sensors and conduct flight capability and traceability tests. Finally, we analyze and discuss the feasibility of the proposed tracking method using the experimental results.

INDEX TERMS Tracking, Asian hornet, radio-telemetry, flight capability, traceability test.

I. INTRODUCTION

Bees are a medium for the pollination of plants, and they contribute considerably to human society and ecosystems. Numerous crops depend on pollination by bees, and these crops contribute one-third of the world's food production. Besides, they are estimated to be responsible for $14 billion USD of the US economy annually, which is a huge contribution. Moreover, effective pollination improves the quantity and quality of agricultural products, the diversification of plants, and plant resistance to pests [1]. Also, the products produced by bees are used in industries such as cleaning, beauty products, and daily necessities [2], [3]. Therefore, bees are worth preserving as a major contributor to the ecosystem and human society.

However, there has been a critical threat to the bee ecosystem in recent years. Hornets (e.g., the Asian hornet) are a typical example of a foreign species that threaten bees. Global warming is changing the climate of the entire world to temperate and subtropical. This is caused by the use of fossil fuels. Also, this creates a climate suitable for Asian hornets, and it invades various regions [6]. Therefore, various invasive species (e.g., Asian hornet and European hornet) are invading the existing ecosystem and causing damage to bees and beekeepers. Of these invasive species, we study the Asian hornet, Vespa velutina, which is currently causing great damage to Asia and Europe [7].

They also have a strong preference for feeding on Hymenoptera (e.g., bees) [4], [8]. The Asian hornet preferentially catches bee foragers returning to their hives, and they continue their predation activities around their hive. This reduces the number of objects in the bee. As a result, the number of times the bees leave the hive for foraging decreases as the predation pressure increases, and this is progressive. Therefore, the clusters are weakened and destroyed. Up to 80% of hives have been destroyed in places where Asian hornets have settled, although there may be differences [4].

To counter Asian hornets, farmers either set up traps to capture them or directly hunt and capture them using tools (e.g., badminton rackets, dragonfly nets). However, because this does not destroy the nest, it can reduce short-term damage, but it cannot prevent long-term damage. Therefore, early detection and destruction of nests using the homing instinct of the Asian hornet [9], [10] is the most effective method. To use this method, we need to clearly understand the life cycle of the Asian hornet in Fig. 1.

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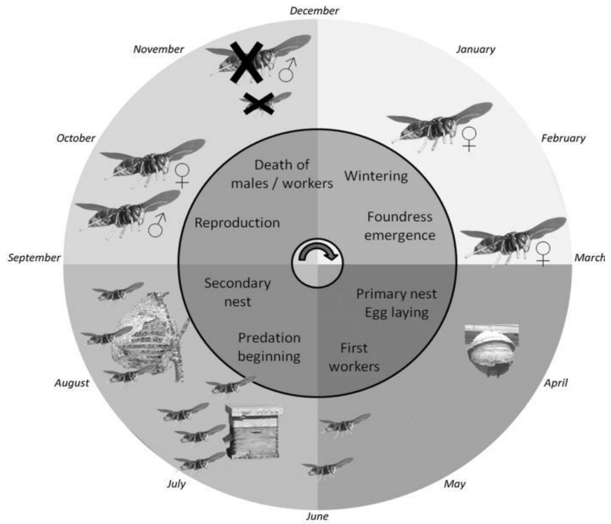


FIGURE 1. The one-year life cycle of the Asian hornet describing its monthly behavior [4].

The queen builds the primary nest for the offspring. Fig. 2 shows that the location is predominantly man-made (76.9%) rather than natural (23.1%). When the breeding succeeds and the number of worker Asian hornets increases, they move to the second nest, which is wood (73.5%), other natural structures (4.4%) and man-made structures (22.1%). Therefore, it is relatively difficult to observe. The secondary nest survives until the males and workers die. However, not all Asian hornets behave this way. Sometimes, the primary nest is expanded to make it a secondary nest, except when the primary nest is damaged or inadequately positioned [4], [5], [11], [12].

Therefore, many researchers track the Asian hornet using a hand-held antenna [12], or track based on signals from a fixed receiver such as a harmonic radar [13]. However, owing to the geographical nature of the hard-to-find Asian hornet nest, it is not easy to track. Thus, we have to track using unmanned aerial vehicles (UAV), which are relatively less susceptible to terrain complexities and obstacles. Thus, this study aims to review promising tracking methods for locating Asian hornet nests using UAV in complex environments.

We researched existing small insects for the selection of effective tracking methods (e.g., harmonic radar, radio-frequency identification (RFID), and radio-telemetry). Then, we selected the sensor (e.g., transmitter, receiver, antenna) based on flight-capability tests, and verified it through traceability tests (i.e., received signal strength). Based on the data obtained from the experimental results, we discuss the various limitations and algorithms that could eliminate noise and optimize the position estimation. Moreover, we researched the use of a mobile robot (e.g., UAV) to locate the nest.

II. A BRIEF REVIEW ON TRACKING METHODS FOR SMALL INSECTS

Animals and insects have been tracked in various ways (e.g., visual tracking, global positioning system (GPS) [14], harmonic radar [13], [15]–[18], RFID [19]–[25], radio-telemetry [12], [26]–[28]). However, visual tracking covers only a short viewing distance and is prone to low persistence. Although GPS has a high positional trace, it has no small tag for insect attachment. Thus, small insects are typically tracked using harmonic radar, RFID, or radio-telemetry with lightweight transmitters (e.g., tags). This section presents the comparison results of the effectiveness of these three methods for tracking small insects, and the findings are summarized in Table 1. Also, we discuss the practical availability of each method for mobile tracking at the end of each section.

TABLE 1. Comparison of tracking methods for small insects.

Method	Object	Purpose	Range	Ref
Harmonic radar	Asian hornet	Flight trajectory	125 m	[13]
	Bee		900m	[15]
		Flight range	700 m	[16]
		Effect of disease	900 m	[17]
		Flight navigation	1,000 m	[18]
RFID	Bee	Influence of pesticide	-	[19]
				[20]
				[21]
		Influence of disease		[22]
		Object identification		[23]
		Mating flight duration		[24]
		Flight behavior		[25]
Radio - telemetry	Asian hornet	Find nest	375 m	[12]
	Bee	Monitoring	-	[26]
		Biological pattern	-	[27]
		Flight trajectory	-	[28]

A. HARMONIC RADAR

Harmonic radars are used to track small insects because of their lightweight tagging, as shown in Fig. 3. A harmonic radar consists of two low-height Schottky barrier diodes and a wire antenna. The tag re-emits or reflects the incoming signal. Therefore, the battery is not needed because it does not emit a signal [29].

The harmonic radar has been used to locate Asian hornet nests [13], and the flight trajectory and behavior of bees [15]–[17] changes under various conditions (e.g., pathogens, drugs, diseases, new environment). After capturing the Asian hornet, they approached the hive for hunting activities and conducted to trace nest. To improve traceability in tree and shrub environments, the nest was found by repeating the acquisition several times in the direction of the strong signal using a larger receiver [13].

Tracking was carried out using the homing instinct after the bee's pollination reconnaissance activity. An experimental environment with no obstacles was set for ease of tracking, training the ability of the bee to return home through artificial prey. The bees with pollination activity were captured, the transmitter installed, and the return process confirmed

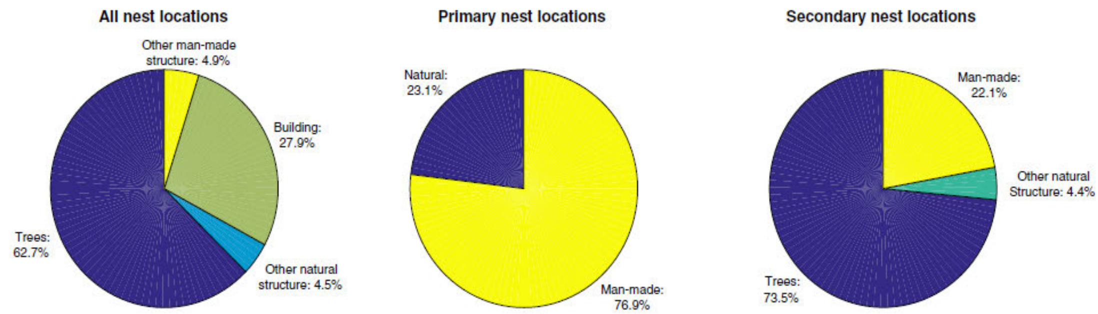


FIGURE 2. The diagram of overall net locations, primary nest locations, and secondary nest locations in case of the Asian hornet [5].

(a) (b) (c)

FIGURE 3. Examples of harmonic radar tracking. (a) Asian hornet with tag [13] (b) tagged honey bee [16] (c) typical receiver [13].

(i.e., flight trajectory) in the new environment they were then returned successfully [15].

The bees fly repeatedly around the beehive before they mature, returning in a stable manner. This behavior enables the bee to learn about the surrounding area, and experienced bees were able to fly further. Thus, to confirm the effects of bee behavior on the transmitter's attachment, experiments were conducted by separating the normal bee and the attached transmitter. It has been verified that there are no affects [16]. Tracking was conducted to observe flight characteristics and trajectory changes due to infections of bee pathogens (i.e., Nosema ceranae). The experiment result found that the rate of return to the home of disease bees was significantly lower than that of normal bees. Moreover, the transmitter was designed to be lighter than honey and pollen to not affect the bees flight [17].

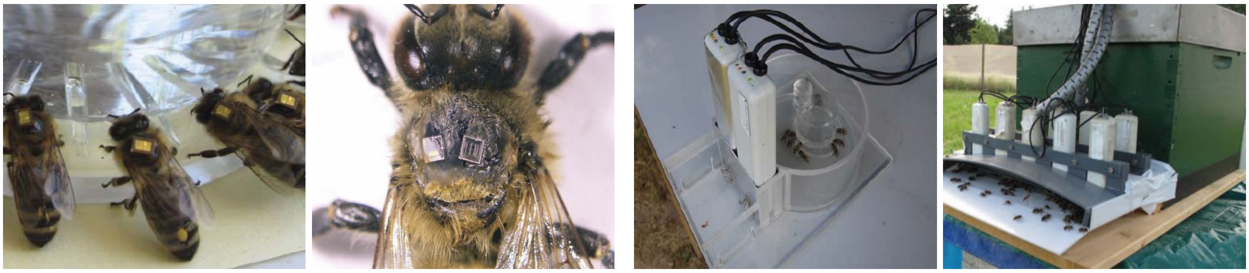
In addition, the fed syrup contaminated with neonicotinoids was tracked to observe changes in the bees navigation due to certain pesticides. It has been found that it reduces the beehive return to the origin, but does not affect the performance itself. A transmitter was installed on the chest for stable bee flight and used a low-noise preamplifier and a parabolic antenna with a downstream amplifier to prevent noise. Experiments were conducted [18].

The detection range of the harmonic radar is affected by the beam angle (e.g., 1°, 20°) and the receiver distance. On average, it requires a huge receiver to detect a wide range, but the development of a portable version can greatly reduce the size of the receiver and it uses passive tags [31]. However, the detectable range (less than 100 m) is reduced, allowing the only trace at close range. In this case, it can use the vehicle to keep track of the nests of the Asian hornets that fly for a long time and make numerous stops [32]. Since Asian hornet nests are located where the vehicle cannot be reached (e.g., forest, treetop, cliff). Therefore, the small detection range requires proximity to the Asian hornet, which is not suitable because it may affect the behavior of Asian hornet. To increase the tracking efficiency, it is very important to find nests quickly and destroy them.

B. RFID

Depending on the tags attached to them, RFIDs can be classified as passive, semi-passive, or active. Passive tags do not have internal power rather, they supply power to their internal circuits using electromagnetic fields. The semi-passive type has a power supply, but no transmitter. Active RFIDs have both internal power supplies and tag transmitters. RFID is used to track insects, because of its lightweight tag, as shown in Fig. 4.

RFID can be attached to a wide variety of insects using lightweight, small tags. Further, multiple objects can be identified simultaneously. Therefore, it was used to analyze the mortality and behavior of bees according to insecticide [19]–[22], and to analyze the behavior of



(a) (b)

FIGURE 4. Examples of RFID tracking. (a) Bees with RFID tags [19], [25] (b) RFID readers and tracking systems [19], [21].

parameters such as mating frequency [23]–[25]. Moreover, there is an example of RFID tracking of the Asian hornet's return ability and hunting activity rhythm [9]. A tag with a weight of 4 to 5 mg was used to keep the bee behavior from affecting, and the RFID reader was mounted in front of the hive entrance. The reading distance was approximately 3 to 4 mm, and their lethal dose of insecticides was analyzed by aligning them with the reader fixed to the hive for accurate readout [19]–[22].

In addition, RFID can be used semi-permanently, and it can obtain huge amounts of data through the identification of many objects. Bee behavior can be observed by installing readers for various beehives and analyzing their data over approximately a week for behavior analysis. This can be used instead of direct observation or video recording, which have traditionally been used to analyze the behavior of bees [23]–[25]. It can analyze their behaviors by searching for the Asian hornet in advance and installing a reader. Behavior analysis has been successful, but it has the disadvantage of finding the Asian hornet's nest before installing the reader [9].

RFID has a high tracking success rate in a limited space, and many objects can be identified simultaneously. Moreover, since the detection range is very narrow, from 1 to 5 m, it is very easy to precisely trace the behavior analysis of the bee at a point with a known range of activity and return location. However, in the case of Asian hornets, the goal is to find and destroy their nest, and thus we need a wide tracking range. Besides, tracking using RFID is not suitable because it can affect the behavior of the Asian hornet because it is conducted at a very short distance and the Asian hornet nest must be located in advance.

C. RADIO-TELEMETRY

Radio-telemetry is considered an indicator of direction and location and is determined by triangulation. The weight of the transmitter is sufficiently small to attach it to the insects, and thus it is suitable to track the Asian hornet. In addition, the receiver weight is part of the light. However, in the other method, the harmonic radar receiver is heavier depending on the detection distance (1 kg to several hundred kgs). Moreover, RFID has a lightweight reader (it varies from 0.3 g), but its availability is inferior because of its very short tracking distance. Therefore, radio-telemetry with low weight and a relatively wide detection range is suitable for attachment to a UAV and is considered the most promising way to track Asian hornets [12], bee [26]–[28].

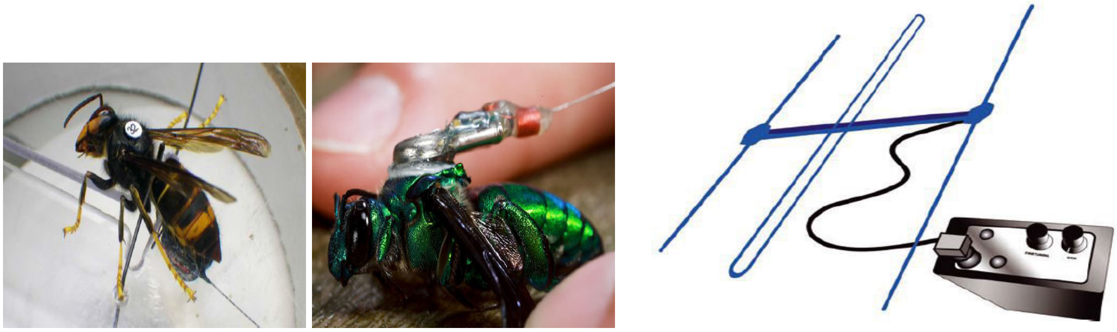
Tracking has been conducted to locate the nest after capturing and tracing the Asian hornets to the beehive. The weight of the attachable tag differs according to the size of the Asian hornet. Thus, the flight-capability test was conducted according to the size. It took approximately 55 to 129 minutes to navigate the nest, and it used radio signals to navigate the nest by directly moving to the roads [12].

A trace was performed to monitor the bee. Tracking was performed in an attachable weight transmitter of a bee in a limited laboratory environment, using a low-noise amplifier to reduce noise. Moreover, they used received signal strength indication (RSSI) to estimate and track their location [26]. Similarly, a trace was conducted on the bee's ability within a limited range of a garden. It was directly received and tracked using a hand-held antenna [28]. The other case tracked the bees moving a long distance. They set up a transmitter for bees that freely pollinate a wide range of forests, such as rain forests, and track them using a helicopter to understand the bee's path and forest pollination [27].

In the tracking method of radio-telemetry, the weight of the tag and the location of its attachment to the trace in small insects (e.g., the Asian hornet and bee) is important. Therefore, tags should be attached to the stomach or back of bees and hornets, such as in Fig. 5. Also, for optimal results, the receiver should be attached quickly to avoid stress. In some cases, radio-telemetry supports a receiver that is lighter than a harmonic radar. Moreover, it can measure distances farther than RFID, and it has sufficient detection distance. Radio-telemetry is the most promising way to track using mobile robots on the nest, which are located in relatively high or geographically inaccessible places.

III. EXPERIMENTAL RESULT ON RADIO-TAGGED TRACKING SYSTEM

The flight capability of the Asian hornet should be tested to further ascertain the effectiveness of the radio-telemetry. To this end, a transmitter with a suitable lifetime should be selected, and the receiver and the corresponding antenna



(a) (b)

FIGURE 5. Examples of radio telemetry tracking. (a) Asian hornet and bee with transmitters [12], [27] (b) receiver and Yagi antenna [30].

(a) (b) (c)

FIGURE 6. The flight-capability experiments. (a) Test group (b) tagged Asian hornet (c) capture tool.

should be selected. Based on the selected sensors, traceability should be tested to verify that there is optimal connectivity between the transmitter and receiver as well. In this section, we present the validation of the radio-tagged tracking system.

A. FLIGHT CAPABILITY TEST

Flight-capability tests are very important in insect tracking. The sensor must be selected to ensure that it is of appropriate weight to not hinder the flight or behavior of the insects. Moreover, the adhesive used to attach the transmitter could accidentally trap the wings and body of the insects, restricting their flight. Thus, threads are used instead, as shown in Fig. 6.

1) SET-UP

A test group with a total of six weights (i.e., 0.1 g, 0.13 g, 0.15 g, 0.20 g, 0.25 g, and 0.30 g) was selected to identify the flight capability of the Asian hornet. The test group was constructed by wrapping the wire according to the weight of the common transmitter, which was attached. The test group was attached as soon as possible so that the Asian hornet could achieve optimal flight conditions. We then proceeded immediately to the experiment to reduce the accumulated fatigue and stress of the Asian hornet. In the process of attaching the test group, a thread was used instead of glue to minimize the impact on Asian hornet behavior. The detailed experiment sequence is as follows. Step 1: Bind the test group to the Asian hornet; Step 2: Check the flight availability of the Asian hornet; Step 3: Steps 1 and 2 were repeated according to different weights.

2) RESULTS

We captured the results through a trap captured at the apiary in July (when the Asian hornet is most active), and a nearby laboratory conducted a flight-capability test. In the course of the experiment, the Asian hornet was strapped to the capture frame made of acrylic plates (as shown in Fig. 6) using a thread, and a test group was attached. In addition, 50 Asian hornets were captured and tested. During the flight-capability test, we investigated the average weight that could be carried by an active Asian hornet worker, that hunts honeybees without considering the weight and size. The experiment confirmed that weight in the range of 0.2 to 0.25 g did not hinder the flight. However, the flight was affected by weights exceeding 0.25 g. Based on the experiment, we found transmitters (PicoPip, LB-2X, and NTF-1-1) with a suitable weight (see Table 2). In Table 2, the symbols for the 'available' column are as follows: (◯) Transmitter that can be attached to an Asian hornet for tracking,

TABLE 2. Specifications of small and light transmitter.

Name	Size	Mass	Frequency	Life	Company	Available
PicoPip	$2 \times 5 \times 10$ mm	0.21g	Need inquiry	2days	Biotrack	○
LB-2X	$2.8 \times 4 \times 8$ mm	0.22g	148, 149, etc. MHz	3∼7days	Holohil	○
NTF-1-1	$3 \times 5 \times 9.6$ mm	0.24g	147 to 168MHz	13days	Lotek Wireless	△
SS300	$2.8 \times 5 \times 10.7$ mm	0.3g	416.7kHz $\pm 0.5\%$	23days	Atstrack	X

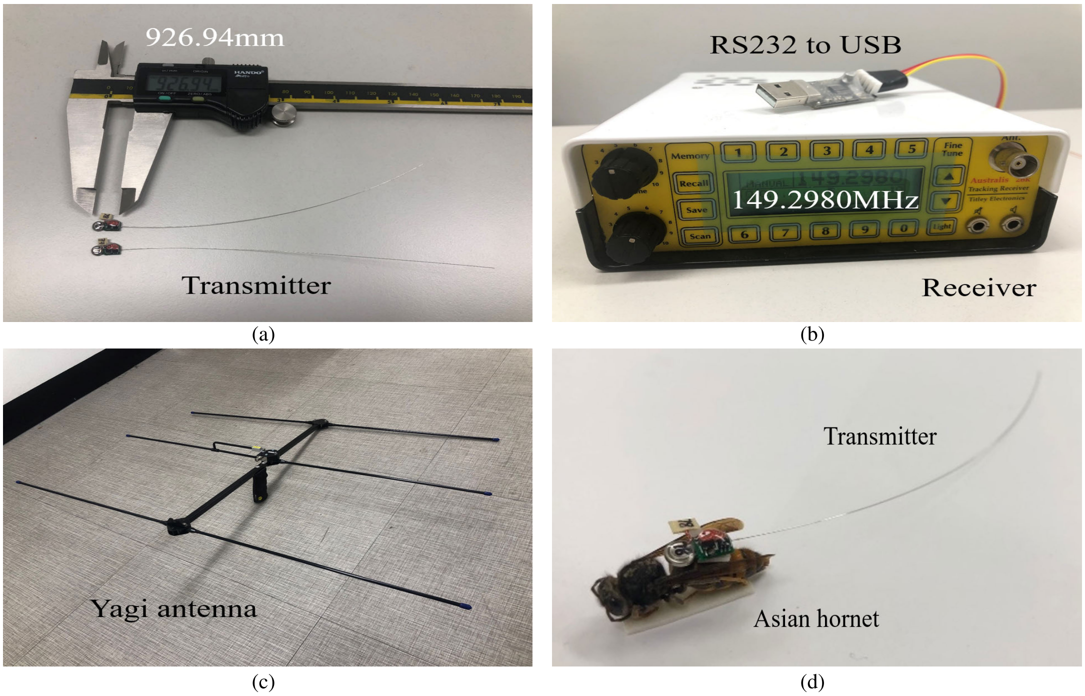


FIGURE 7. Radio telemetry based tracking system. (a) Transmitter (b) receiver (c) Yagi antenna (d) Asian hornet with transmitter.

(△) transmitter with ambiguous weights (X), and transmitter with a weight with which the Asian hornet cannot fly. Of the sensors that met the conditions of mass, the LB-2X with longer battery life was selected as the final sensor (transmitter).

B. SELECTION OF SENSOR

The trade-off between battery life and weight is an important consideration in the use of the active transmitter for small insects. Through a simple experiment, it was confirmed that the maximum load under which the Asian hornet can fly unimpeded is 0.25 g. An active transmitter that satisfies this requirement is available. For this study, a transmitter (LB-2X) from Holohil Systems Ltd., shown in Fig. 7(a), was chosen. The standard LB-2X weighs 0.22 g (available up to 0.3 g with a lifespan range of 13-22 days) and radiates a 150-MHz radio signal (available in only 148, 149, 150, 151, 164, 165, 172, 173, 218, 219, and 220 MHz) at 40 pulses per minute (available from 20-120 ppm) for a 20 ms pulse width [30]. Besides, there are temperature and position options for this transmitter, and the final decision including all conditions can be selected by the customer at the point of ordering. A simple test was performed to verify that the Asian hornet with this attached transmitter (Fig. 7(d)) can fly without hardship.

Fig. 7 also shows the selected receiver and Yagi antenna (from Titley Scientific, Brendale, Australia) used for measuring the radio signal emitted by the transmitter. The frequency range of this receiver with connected Yagi antenna is 4-MHz wide segments within a specific range (i.e., 148.000-151.999 MHz; 149.000-152.999 MHz; 160.000-163.999 MHz; or 170.000-173.999 MHz). Therefore, the selected system can receive the signals without problems because the transmitter frequency is 150 MHz on average. Additionally, the receiver has a dial-type gain regulator that adjusts the reception sensitivity and comprises a variable resistor that ultimately controls the input voltage to the receiver controller. Therefore, the receiver gain can be adjusted by outputting the desired voltage through the analog output channel of the controller.

C. TRACEABILITY TEST

1) SET-UP

The signal received via radio-telemetry has no information, such as coordinate values and relative distance. However, the radio-telemetry-based method provides useful

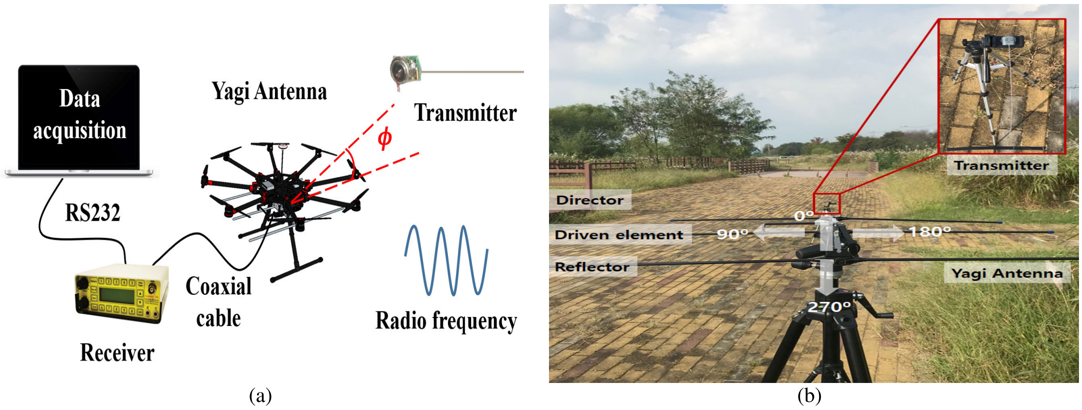


FIGURE 8. **Tracking system. (a) A concept of the proposed system. (b) A field test environment.**

information regarding the direction of the tagged Asian hornet since the signal strength can be measured through the receiver. Therefore, it is necessary to estimate the traceability by varying the distance of the transmitter. The measurement was conducted in outdoor conditions as shown in Fig. 8. The field is flat and open, which does not affect the transmission of radio-frequency signals. The experimental tests were performed in an environment sufficient to verify the tendency and feasibility of traceability based on radio-telemetry. Traceability was measured for each case with the transmitter located at a distance (10 to 300 m) from the receiver and antenna. The distance of the transmitter was measured using a tape measure.

Also, we measured the traceability in each direction while rotating the antenna at 0°, 90°, 180°, and 270° at each distance. That is, the reference angle is as shown in Fig. 8 and the arrow indicates the direction of the transmitter position. Sample data were obtained by applying four experimental cases (depending on the orientation of the antenna) according to each distance. The detailed measurement procedure is as follows.

1) The transmitter is placed in its position.
2) The receiving antenna is directed toward the transmitter (arrow direction as shown in Fig. 8).
3) The gain is set to a specific constant α.
4) The RSSI is recorded 20 times after varying the direction of the Yagi antenna while maintaining the gain value set in Step 3.
5) If the RSSI is recorded for the four antenna directions, return to Step 1 to increase the distance of the transmitter, and repeat the measurement at 10 m intervals.

Please note that we set the value of gain α to 6.2. The gain was to prevent saturation of the RSSI at long distances, i.e., more than 30 to 50 m. To compare the change in traceability due to the variation in the antenna direction, the direction of the receiver antenna was varied while maintaining a constant gain.

2) RESULTS

Fig. 9 shows the RSSI values measured for each distance and direction. Traceability tests were measured at 10 m increments in the range of 10 to 300 m. The results were expressed as 30 to 300 m. In general, the RSSI decreases with increasing distance. Therefore, if the relative distance increases and the direction of the receiver antenna is different from that of the receiver, the RSSI decreases. This trend can be seen in the experimental results. However, some of the results of the follow-up test show a tendency to bounce. Therefore, we could apply a low-pass filter to get clearer data and results.

Fig. 9 shows the results of the filter and the RSSI value obtained at the transmitter position for four antenna directions in the outdoor environment. The x-axis represents the position of the transmitter and the y-axis represents the value of the RSSI measured by the antenna of the receiver. In addition, traceability gradually decreases with the antenna angle. The antenna direction that is of most interest is 0° because the traceability is measured most strongly in this direction. In this regard, the manual telemetry eventually estimates the direction of the transmitter based on this direction. Thus, the approximate direction of the target can be predicted from the RSSI value, and we can proceed to trace through it.

These results show that the Yagi antenna used in the traceability test has the largest radiation pattern of 0°. They were modeled using Yagi antenna characteristics (e.g., antenna length, dipole number, and frequency) as shown in Fig. 10. The ideal radiation pattern modeled is shown in Fig. 11. However, the results of 180° and 270° should show a similar tendency under ideal conditions. Nevertheless, the experimental results do not follow the desired tendency of the radiation pattern. This is because the actual radiation pattern of the Yagi antenna is different from the ideal radiation pattern, and is influenced by the environment and disturbance. Therefore, the results obtained in the actual environment, such as with the traceability test, will be effective in tracking Asian hornets.

IV. DISCUSSIONS

A. LIMITATIONS

The transmitter for tracking the Asian hornet uses a 0.2 to 0.25 g sensor, based on the flight capability test. However, their average lifespan is very short, approximately

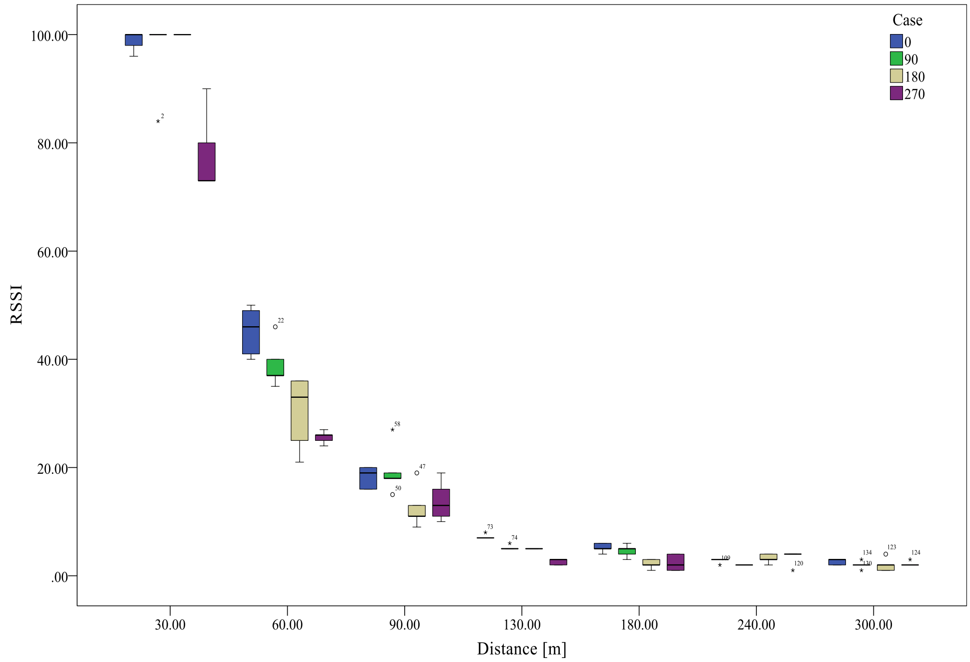


FIGURE 9. Experimental results of the RSSI feasibility test for each distance and angle.

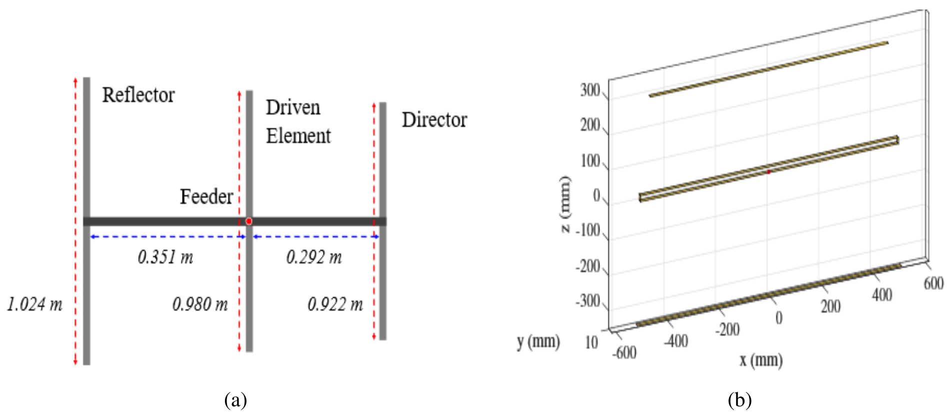


FIGURE 10. Modeling of Yagi antenna for radiation analysis. (a) Size (b) modeling results.

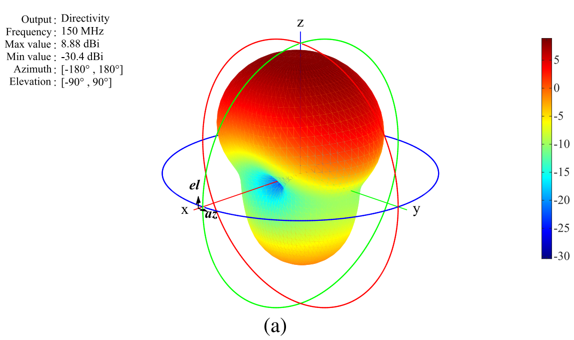


FIGURE 11. Ideal radiation patterns of the Yagi antenna.

three to ten days, and they are expensive at approximately $200 to $300 USD.

The long battery life is good for effective tracking. However, it is difficult to change the battery itself because the weight of the small radio-telemetry transmitter varies depending on the battery. Therefore, it is necessary to solve the battery problem of the transmitter.

Lightweight and long-lasting transmitters enable continuous tracking of long-term Asian hornets. This has many advantages such as improved localization accuracy, identification of active areas, management of introduced species and ecosystems, and protection of apiaries. Moreover, robot-based control systems with high potential and scalability can also be applied to ecosystems.

The traceability test demonstrates that the value of the received signal varies depending on the distance, and the highest value is obtained when the direction of the antenna receiving the data is 90°. However, maintaining the directionality toward a fast-moving Asian hornet with a single antenna is difficult. A tracking method using a multi-antenna is required to solve the following problems.

Many insect studies continue to refer to multi-antennas for effectiveness [33]. When using multi-antennas, it is not necessary to move the antenna to match the direction of the object. Further, it is to track insects more effectively. However, the use of multi-antennas causes reduced maneuverability owing to the antenna size and receiver weight. Therefore, further studies on how to operate multi-antennas effectively are required [34].

In radio-telemetry, the receiver is traced using a mobile robot or handle-type antenna to directly meet the demands of complex environments and to circumvent obstacles. Therefore, when an obstacle is encountered, Simultaneous Localization And Mapping (SLAM) using the LiDAR and camera of mobile robots will be performed to circumvent obstacles and autonomously track the [35]–[37]. In addition, Kalman filters and particle filters should be deployed for the robust tracking of objects under various conditions (e.g., in the presence of animal sounds and environmental noise due to rain) [38].

B. TRACKING ALGORITHM

To improve tracking performance, it is necessary to accurately estimate the position of the Asian hornet. A representative solution is to use the Kalman or particle filter to reduce the noise in the sensor output. The Kalman filter comprises two steps, the prediction step by the input measurements and the update step (i.e., correction step) by sensor observation. Recursive data processing is conducted based on the predicted and observed measurements while estimating the current state variables, and the optimum value is extracted. Therefore, this approach is used to reduce the location error in tracking marine animals [39], and improve animal tracking algorithms [40]. However, the Kalman filter is optimized when the noise model has a Gaussian distribution, which degrades tracking performance depending on the surrounding environment.

The particle filter used in the Monte Carlo method is suitable for estimation and prediction systems based on a non-Gaussian noise model. Particle filtering uses a set of particles (also called samples) to represent the posterior distribution of the stochastic process that provides noisy and/or partial observations. In this process, the accuracy of the filter can be increased by weighing the overlapping probability between the existing samples through resampling. Therefore, this methodology is used to solve nonlinear filtering problems, and track and localize wildlife in ecology [37], [41]. However, because particle filters can cause problems when the number of samples is insufficient, Kalman filters and particle filters have recently been combined [42]. Therefore, it is necessary to filter the sensor noise to more accurately track Asian hornets in our systems, without positioning errors.

C. MOBILE TRACKING

Many of the existing researchers tracked the target by tracing the signal through a handle-type antenna and using a helicopter [12], [27], [28]. However, the handle-type antenna is restricted geographically when tracking objects, and helicopters are expensive to operate. Furthermore, the Asian hornet's nest could be located in a forested area on the top of a tree, which is difficult to locate. Therefore, some researchers use UAV, which has a high-cost efficiency when tracking insects, animals, and other objects [43], [44].

Currently, animals are typically tracked using UAV, and tracking is underway for most birds [43]. Moreover, research continues to identify bumblebee and Asian hornet nests using thermal cameras [44], [45]. In this way, it is easy to determine where the density of trees makes it difficult to find nests with the naked eye. However, tracking efficiency is inferior to price, and further research is needed. If the effectiveness of tracking with a thermal camera is verified, the Asian hornet's nest will be easier to find using a UAV that can easily obtain data from difficult terrain.

In [9] found that the Asian hornet flew within an average of 1 km around the nest, and the maximum distance of the homing instinct was 5 km. Moving 1 to 5 km causes physical fatigue for small tracked objects such as Asian hornets. Also, there are conventional methods (e.g., direct human movement, stationary antennas, RFID), but they are time-consuming and less efficient at tracking. Therefore, we have to use mobile robots such as UAV, which can reduce geographical characteristics and are time-consuming, to track them and destroy their nests.

However, Asian-hornet tracking using UAVs has limited access. Because of the nature of the Asian hornet nest and the dense trees, it is very difficult. There are two ways to track the following locations using UAVs. The first is to use the ability to fly to track the air, which is not affected by obstacles. Since the tracking distance is approximately 300 m in the case of radio-telemetry, the tracking can be conducted by moving up to the sufficient sky height without being affected by obstacles. The second is to introduce SLAM by attaching additional sensors such as cameras, LiDAR, to UAV. This introduction of SLAM not only completely ignores the geographical characteristics of the Asian hornet nest, but also provides faster and more accurate tracking information. Therefore, these two methods can overcome the geographical characteristics of Asian hornet nests.

V. CONCLUSION

Tracking small insects, such as the Asian hornet, is challenging and demanding. In this study, we reviewed three tracking methods, harmonic radar, RFID, and radio-telemetry based on mobility, flight capability, and traceability to identify the most effective method. Of these methods, we identified radio-telemetry as the most suitable for tracking the Asian hornet. Furthermore, based on the flight capability test of the Asian hornet, we determined that the most suitable sensor should weigh less than 0.25 g. Following the experimental results, the tracking system consisted of a transmitter, receiver, and Yagi antenna. We performed the traceability test in the outdoor environment and found that it was necessary to improve the noise performance of the transmitter and receiver. Ultimately, this paper presents the feasibility of various systems for tracking the Asian hornet, and rigorously discusses the challenges that must be addressed to perfect these tracking systems. In future studies, we aim to develop a tracking algorithm and UAV-based autonomous tracking system based on a real environment.

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SEUNGWON KIM is currently pursuing the B.S. degree in biosystems engineering from Chonnam National University. His research interests include agricultural robotics and unmanned aerial vehicle.

CHANYOUNG JU received the B.S. and M.S. degrees from the Department of Rural and Biosystems Engineering, Chonnam National University, South Korea, in 2017 and 2019, respectively, where he is currently pursuing the Ph.D. degree in biosystems engineering. His research interests include agricultural robotics, swarm control, and discrete event systems.

JEONGEUN KIM received the B.S. degree from the Department of Rural and Biosystems Engineering, Chonnam National University, South Korea, in 2019, where she is currently pursuing the M.S. degree in biosystems engineering. Her research interests include agricultural robotics, machine vision, and machine learning.

HYOUNG IL SON (M'11–SM'19) received the B.S. and M.S. degrees from the Department of Mechanical Engineering, Pusan National University, South Korea, in 1998 and 2000, respectively, and the Ph.D. degree from the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), South Korea, in 2010. In 2015, he joined the Faculty of the Department of Rural and Biosystems Engineering, Chonnam National University, Gwangju, South Korea, where he is currently an Associate Professor. Before joining Chonnam National University, from 2012 to 2015, he led the Telerobotics Group, Central Research Institute, Samsung Heavy Industries, Daejeon, South Korea, as a Principal Researcher. He also had several appointments both academia and industry, as a Senior Researcher, with LG Electronics, Pyungtaek, South Korea, from 2003 to 2005, and Samsung Electronics, Cheonan, South Korea, from 2005 to 2009, a Research Associate with the Institute of Industrial Science, The University of Tokyo, Tokyo, Japan, in 2010, and a Research Scientist with the Max Planck Institute for Biological Cybernetics, Tübingen, Germany, from 2010 to 2012. His research interests include field robotics, hybrid systems, teleoperation, and haptics.