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Exterminator for the Nests of *Vespa velutina nigrithorax* Using an Unmanned Aerial Vehicle

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Abstract: *Vespa velutina nigrithorax*, a species of hornet, is spreading globally, with increasingly negative effects on human health. To effectively eliminate *V. velutina*, its nest should be destroyed and its queen removed; however, the nests are difficult to reach. Thus, we analyzed the requirements for a drone-assisted hornet exterminator using field observations and physical tests on a sample hornets' nest, and based on these, a UAV exterminator equipped with a nest-perforating device (based on an airsoft rifle) and pesticide-spraying system was designed and manufactured. Pesticides and bullets were manufactured using ecofriendly materials. An actuator at the rear of the device adjusted the pitch of the perforator and sprayer, and a monitoring system was installed to aid the operator in targeting. The operating parameters of the UAV exterminator were evaluated in laboratory tests, with a spray distance of 5 m deemed suitable. To evaluate the system's pest-control performance, several *V. velutina* nests were targeted in field tests. An insecticidal effect of over 99% was achieved using two pyrethrum-based pesticides (15% pyrethrum extract and 10% pyrethrum extract with additives). In addition, compared to conventional nest-removal methods, the UAV exterminator reduced the work time by 85% and the cost by 54.9%.

Keywords: Asian hornet; pest control; drone; pyrethrum; spraying system; *Vespa velutina nigrithorax*

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1. Introduction

Vespa velutina nigrithorax, also known as the Asian hornet, is a subspecies of *Vespa velutina Lepeletier* [1]. As its name suggests, it is also known as the yellow-legged hornet because of the black coloration of its thorax and yellow coloration of its legs [2]. The worker hornet ranges in size from 22–25 mm, falling into the "medium" size classification among hornet families. However, compared to other hornets, it has a large impact on its surroundings because of the large number of swarms that comprise a single nest [3].

V. velutina is native to south China and parts of Southeast Asia [4]. Since the early 2000s, *V. velutina* has been introduced into Asia and Europe, thereby expanding its colonies [5,6]. Although *V. velutina* hunts insect pests, it has a particular preference for honeybees. This puts them in direct conflict with beekeepers, whose livelihoods are damaged by their presence [7,8]. *V. velutina* also occupy urban areas and can attack people [9]. In Republic of Korea, these hornets are estimated to cause damage to the value of more than KRW 175 billion; thus, the government has designated them as an ecosystem-disturbing species [10,11]. In China, hornets have caused a 79% reduction in bee activity [12]. In Europe, *V. velutina* was first discovered in France in 2004 and has since spread to Spain, Portugal, Belgium, Italy, Germany, and the United Kingdom, causing great harm [6,13–18]. In particular, the rate of spread in France is five to six times higher than that in Republic of Korea [19]. Global warming is expected to worsen this situation by increasing the activity of *V. velutina* [20]. Therefore, efforts are needed to mitigate and prevent the damage caused by *V. velutina*.

Typically, damage by *V. velutina* is prevented by removing their nests from sensitive areas; however, this method tends to be costly [21] because nests are usually located atop large trees, at heights of more than 10 m, making them difficult to detect and remove from the ground [22]. Various studies have used image processing to detect hornet nests [23,24] by tagging or baiting [25,26] and using unmanned aerial vehicles (UAVs) [27,28]. With improvements in detection technologies, new approaches have been developed to control *V. velutina* [15]. The trap method is commonly used because of its simplicity; however, its capture rate is low [29,30]. In this method, traps or baits containing toxic substances are typically placed around apiaries (places where beehives are kept), with the expectation that the hornets will be drawn there by the honeybees and will return home with the bait, transferring the toxic substance to other hornets [31]. However, this method can contaminate the environment with toxic substances, kill hornets during transfer, and fail to reach the hornet queens. Alternatively, manual removal of hornets by hand or by spraying chemicals to kill the queen are quicker and more direct; however, as mentioned above, in most cases, nests are difficult to access, and workers are exposed to wasp attacks. Thus, new technologies are required to address the shortcomings of the existing methods.

UAVs are small flying devices that are flown using a remote control or path planning and automatic flight control [32]. UAVs have the advantage of operating at a wide range of altitudes, particularly low altitudes, and can be equipped with various attachments for to suit specific purposes [33]. Among the common applications of UAVs, unmanned aerial spraying systems (UASSs) comprise the attachment of a spraying system, such as nozzles and pumps, to a UAV to deliver pesticides to crops using the wind generated by the rotors [34,35]. Pest control using UASSs has recently found active use on farms [36–39]. The use of UAVs for tree spraying is also becoming more common because they can achieve less drift than ground sprayers, and they can more easily deliver chemicals to the treetops [40–42]. In terms of hornet control, these characteristics may enable a small number of operators to control UASSs from a distance to spray agents on hornet nests located at high altitudes. This is expected to improve the worker safety, reduce operational costs, and increase control effectiveness. Consequently, using this method, efficient control of *V. velutina* may be achieved. However, to ensure effective control of *V. velutina* using such a system, the targets and coverage of the proposed UASS must be analyzed.

In this study, we investigated an exterminator with an agent-spraying function that could be mounted on a UAV to efficiently control Asian hornet nests. We first conducted a requirement analysis for the system design through a field survey. Based on this, we designed and manufactured an Asian hornet nest exterminator that can be mounted on a UAV. Finally, we applied the developed system to control real nests, observed the results, and conducted an economic analysis of the proposed hornet-control method.

2. Materials and Methods

2.1. Determination of Exterminator Requirements

A field survey of the hornet nests was conducted to analyze the requirements of a hornet nest exterminator. Hornet nests around apiaries in Hamyang and Damyang were observed, and UASS spraying methods and applicability for the hornet nests were investigated. A small camera drone (Mavic, DJI, Shenzhen, China) was used to observe the hornet nests.

After the field survey, five hornet nests were collected by a human on a truck-mounted ladder. These were analyzed to determine a suitable delivery channel for the toxic agent. Two main delivery routes were identified: through holes in the hornet nest walls generated by the spray pressure and through seepage. To verify the feasibility of the first route, the force required to puncture the hornet nests was evaluated in compression tests using a precision universal testing machine (AG-Xplus, Shimadzu, Kyoto, Japan), as shown in Figure 1. To verify the delivery of the solution through seepage, the fragments of hornet nest were sprayed continuously with the solution, and the delivery of the solution inside the fragments was recorded every thirty seconds by observing inside the fragments. The pressure of the sprayed solution was 0.35 MPa.

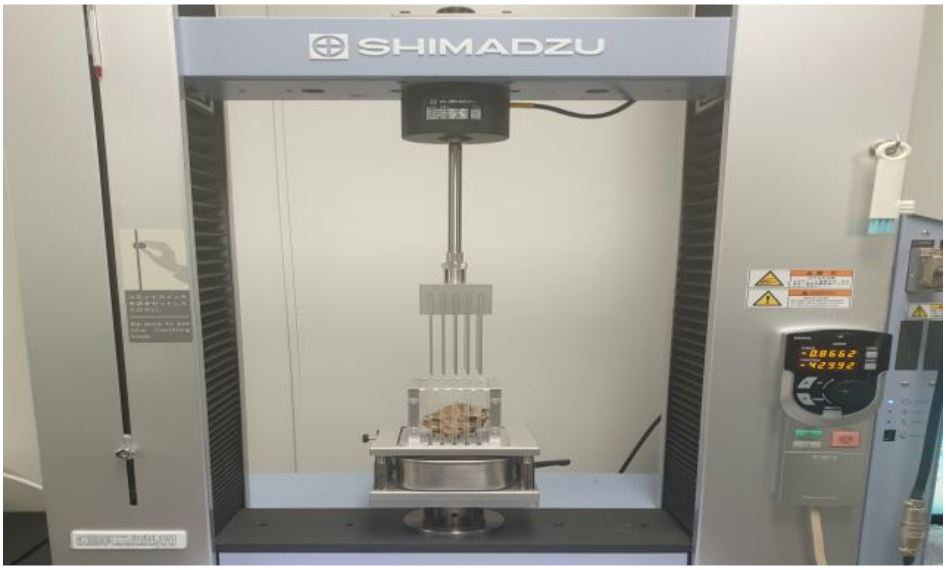


Figure 1. Hornet nest compressive strength test setup.

2.2. System Design and Development

The UAV hornet nest exterminator was constructed by adding spraying, perforating, and monitoring systems to the UAV (Figure 2). The components of each part are described in more detail below, and 3D models of the proposed product were designed using a CAD program (NX, Siemens, Munich, Germany).

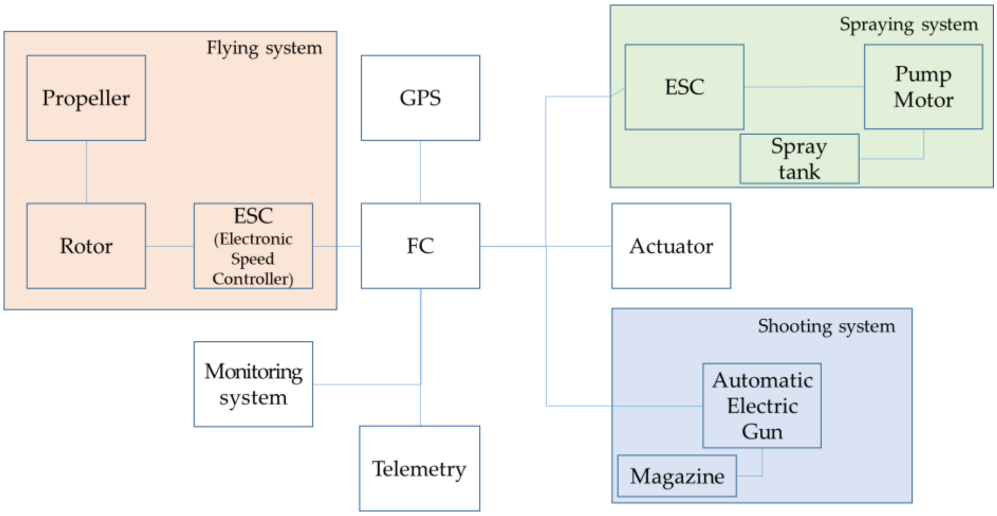
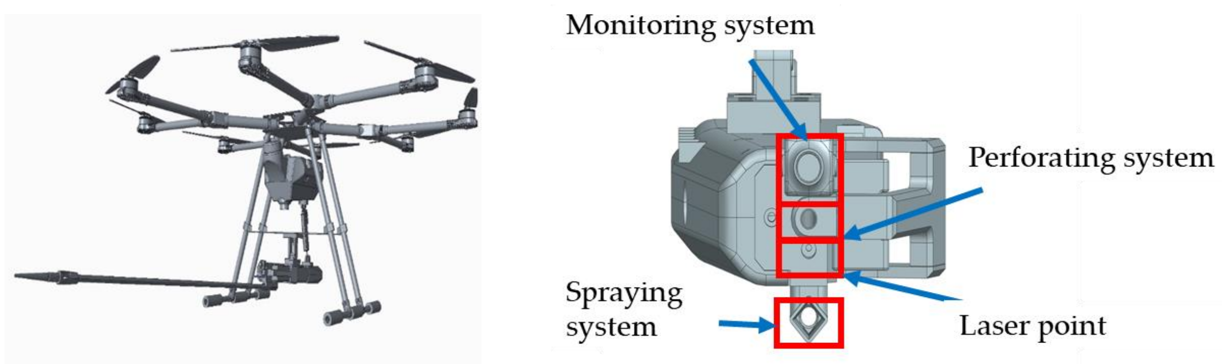


Figure 2. Structural diagram of the proposed UAV exterminator for *Vespa velutina nigrithorax* nests.

As shown in Figure 3, the UAV exterminator was designed as an octocopter and had a long axis length of 1640 mm between motors and height of 720 mm. A flight controller (FC) with K++ (JIYI, Shanghai, China), rotor (XRotor Pro X6, Hobbywing, Shenzhen, China), and propeller (XRotor 2388 propeller, Hobbywing, Shenzhen, China) were selected. The weight balance and rotor settings of the UAV were adjusted through experimentation. The weight of the UAV with batteries was 21.5 kg. The two batteries (Herewin, Dongguan, China) had a capacity of 12,000 mAh each and were configured in series. When flying with full load, the flight time was about eight minutes. Detailed specifications of the UAV are listed in Table 1.



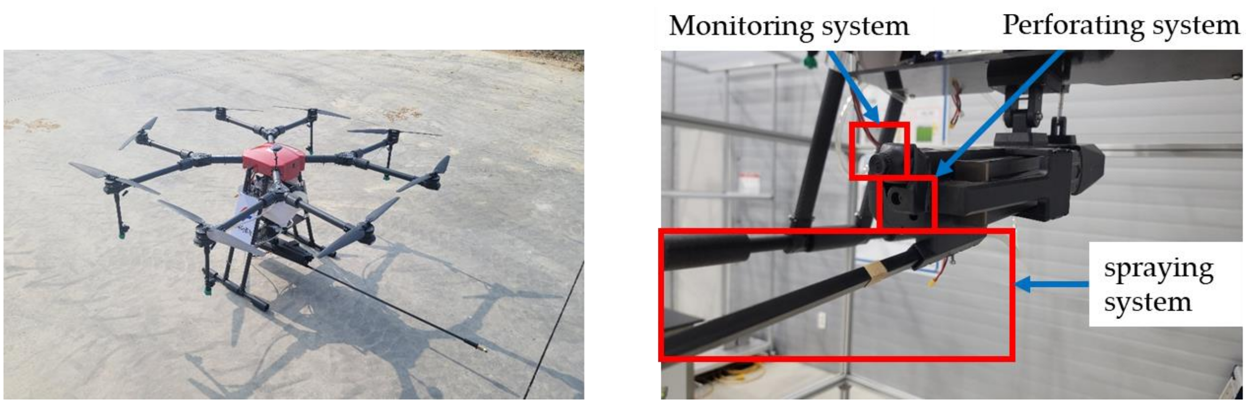
(**a**) Integrated system (**b**) Spraying and perforating system

Figure 3. Three-dimensional modeling of the exterminator for *Vespa velutina nigrithorax* nest.

Table 1. Specification of the UAV.

Parameter	Value
Length (mm)	1510
Width (mm)	1510
Height (mm)	750
Weight (with battery) (kg)	21.5
FC	K++
Rotor	XRotor Pro X6
Number of rotors	8
Size of propeller (cm)	58.42
Maximum take-off weight (kg)	36
Capacity of the solution tank (L)	10
Flight time (min)	8

Figure 4 presents the final system for extermination of the *Vespa velutina nigrithorax* nests. The agent-spraying system comprised a small water pump (COMBO-PUMP-5L-brushless-10A-14S-V1, Hobbywing, Shenzhen, China) with a direct injection nozzle (2 mm orifice diameter) and tank to hold the toxic agent. The pump had a flow rate of 5 L/min with a pressure of 0.35 MPa. For testing and field applications, the spray was applied at a pressure of 0.3 MPa and a flow rate of 3 L/min. To extend the spraying distance, a long pipe (carbon, with a diameter of 10 mm and length of 1 m) was designed. A nozzle for spraying the solution was mounted at the end of the pipe and coupled to a tube to transfer the solution inside the pipe. The water tank was designed to have a capacity of 10 L to comply with the maximum allowable landing load of the UAV.



(**a**) Integrated system (**b**) Spraying and perforating systems

Figure 4. Exterminator of the *Vespa velutina nigrithorax* nest.

The perforator was designed to create holes in the outer wall of the nest. Among the various possible methods to achieve this, we introduced an airsoft gun, which is lightweight and can produce a force greater than the relevant strength of the hornet honeycomb [15]. The small electric air-compression cylinder and magazine were extracted from an airsoft gun (FN P90, Kingarms, Taiwan) and assembled in a 3D-printed container (Figure 5). The bullet energy of the small electric air compression cylinder was 1.2 J. The envelope of the container was 470 mm × 90 mm × 60 mm. Using this system, bullets could be fired continuously at a rate of up to 300 rounds/min.

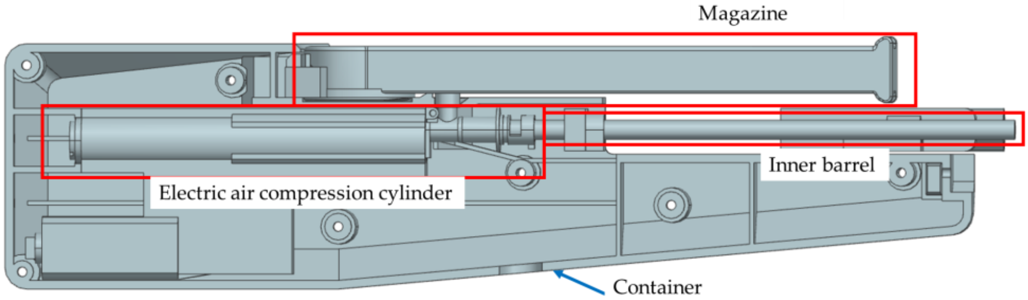


Figure 5. Inner view of perforator.

In addition, the UAV was designed to enable integration of the spraying and perforating systems. A small actuator (12Lf-27PT-90, iRRobot, Bucheon, Republic of Korea) was installed at the rear of the spraying system to control the nozzle's vertical position such that the pitch angle could be adjusted while the drone was hovering when spraying the hornet nest.

A video-based monitoring system was installed to enable drone operators to remotely observe the hornet nests and the progress of spraying with the drone in flight. It consisted of a wireless video transmission device (Skydroid mini camera, Skydroid, Quanzhou, China) connected to the FC and was capable of capturing 720 p 30 fps video and transmitting that video up to a distance of 20 km. Operators could monitor the video through an application on their mobile phones, thereby enabling them to check the location of hornet nests and the spraying status. A laser pointer was installed on the perforator container to assist in aiming the spraying and perforation systems: through the video feed, the operator could see where the laser pointer was pointing and thus identify the likely (and actual) trajectory of the spraying liquid. A test device was constructed based on the designed system, and flight tests were conducted.

2.3. Experimental Test

Prior to the field trial, basic indoor experiments were conducted to evaluate the performance of the spraying and perforation systems. Since global positioning systems (GPSs) have poor indoor reception, indoor experiments were conducted with the UAV exterminator fixed to an aluminum profile holder (and thus not actively flying). A hornet nest collected in the field was installed as the target, and the performances of the perforation and spraying devices were evaluated (Figure 6). The distance between the target and spraying system was increased from 3 m to 5 and 7 m, and the hit point of the sprayed droplets and target point of the laser pointer were measured. The same experiment was conducted using the perforator. However, for the perforator experiments, the coincidence of the target and impact points was measured by recording the distance between the position of the laser pointer and position of the marks created on the paper by the airsoft bullet.

After the indoor experiments, the exterminator was operated in the field on real hornet nests, and its performance was analyzed. The pest-control evaluation was conducted in the autumn of 2022 in the mountainous areas of Buan and Wanju. The toxic agent and airsoft bullets for the tests were manufactured using eco-friendly materials based on the positive list system (PLS). The PLS originated in Japan and has since spread to Europe, Taiwan, and Republic of Korea. It provides a list of crop-protection agents that are suitable for various crops and prohibits the use of other agents for pesticide management [43]. This system is similar to the "Zero Tolerance" system implemented in the United States. In Europe, aerial spraying has been banned because of concerns regarding drift; therefore, pesticides that are not harmful to the environment should be introduced [44], especially in UASS operations. Thus, for the pesticide, we used pyrethrum extract mixed in three different concentrations: 10% pyrethrum extract, 15% pyrethrum extract, and 10% pyrethrum with additives (10% sugar, 10% formic acid, and 1% bee shred); for the bullet, we used cornstarch [45,46].

Figure 6. Performance test of the spraying and perforation devices: (**left**) UAV exterminator fixed to aluminum profile holder and (**right**) nest condition after experiment.

Experiments were conducted on three hornet nests found in the field. All three hornet nests were located at heights of over 10 m. Each hornet nest was treated with one of the three different agent mixtures. To ensure a safe experiment, a preliminary flight was conducted to determine the approach route. Thereafter, the exterminator UAV flew at an altitude similar to that of the target nest and approached it from the upper part of the tree, with the operator being careful to avoid obstacles. Once in position, the UAV used the perforator system to create a hole in the nest before spraying the pesticide solution towards the nest. As the exterminator approached the tree, the operator used a monitoring device to observe the situation in front of the exterminator. During the experiment, the wind speed at ground level was less than 1 m/s.

Due to the height of the hornet nests and resulting difficult access, it was not possible to collect the nests for further internal observations. As a result, the effectiveness of the control was evaluated indirectly based on evidence from aerial photography. The number of *V. velutina* entering and exiting the nest for one minute was counted one week after the treatment. The pest-control operation was determined to be effective if there were no individuals entering or exiting the nest during that period.

2.4. Economic Feasibility of the Proposed Method

The economic feasibility of the drone-based hornet nest exterminator was analyzed. A comparison was made between the control tasks performed by conventional devices and the developed exterminator. The conventional method was assumed to be manual nest removal, with the remover wearing beekeeper suit and utilizing a vehicle-mounted ladder or extending platform to remove hornet nests using a net and sprayer.

The cost was calculated considering the price of the equipment, working hours, and labor costs. Equipment for conventional work included beekeeping suits and tools (including sprayer and nest), while equipment for work using the proposed exterminators included UAVs and sprayers. The cost of the equipment was divided by its lifetime to calculate depreciation. The annual usage time was calculated from the working hours of actual hornet-nest-extermination workers (determined from interviews). The durability of the equipment in each method was determined through literature review [47]. Expenses included the cost of repairs and the interest on the loan for the purchase. Labor costs were calculated based on daily wages in rural Republic of Korea.

3. Results and Discussion

3.1. Exterminator Requirements

Most of the hornet nests observed during initial sample collection were in the largest trees, which were more than 10 m above the ground and within 1 km of the apiary. This was consistent with the findings of previous studies [1,48]. Because of the heights of the hornet nests and the limited visibility owing to the branches, relative positioning of the drone and hornet nests was difficult to achieve (Figure 7). Although typical UASSs are not equipped with monitoring systems, it was determined that a remote monitoring device should be added to the extermination system to improve the remote control performance of the drone and overcome the visual limitations of the operator on the ground, thus likely improving the spraying accuracy.

Figure 7. A nest of *V. velutina nigrithorax*: (**left**) position and (**right**) closeup view of the nest.

Hornet nests consist mainly of pulp. Hornets create nests under the leaves of the host broadleaf tree, normally 1–2 m below its top to avoid rain. If a pest-control agent is sprayed from the top of the hornets' nest, as in conventional UASSs, the leaves are likely to protect the nest and reduce the amount of agent delivered to it. Thus, this application requires a system that can directly spray solution from the side. In addition, as the wind speed increases with altitude, so does the sway of the branches, which increases the chance of the UAV crashing into the branches. Therefore, during operation, the drone should maintain a distance of 3–5 m between it and the nest to prevent damaging the system. Considering the safe distance between the hornets' nest and drone, the horizontal spraying distance of the agent should be greater than 5 m.

As previously mentioned, two main potential delivery routes were identified, namely through holes in the hornet nest walls and through seepage. From the compression test, the compressive strength of the honeycomb was found to be 3.5 $\pm$ 0.25 MPa. The pump used in ordinary UASSs has a pressure of 0.3–0.5 MPa and was thus determined to be unlikely to be able to penetrate the hornet nest through spraying. When testing the feasibility of seepage, it was found to take 2.2 min for the water to penetrate the nest to a depth of 1 cm and 5 min to reach 2 cm (Table 2). However, no water reached a depth of 3 cm, even with continuous, prolonged spraying. The water (representing the pest-control agent) thus penetrated only up to 2 cm from the nests outer wall, and it was concluded that agent delivery through seepage would be difficult to achieve. Hence, the penetration method was chosen, with a second device required to perforate the hornet nests and enable the agent to be sprayed inside. In addition, a function to adjust the working angle of the drilling device was necessary to enable fine adjustment of the angle of the spraying device when aiming at the hornet nest.

Table 2. Results of seepage test for hornet nest wall.

Depth from Nest Wall (cm)	1	2	3
Time to seepage (min)	2.2	5	No seepage

3.2. Exterminator Performance

The results of the indoor exterminator performance evaluations showed that the target point and the impact point of the projectile coincided well at distances of 3, 5, and 7 m. The spray droplets reached the target point at distances of 3 and 5 m; however, at 7 m, the droplets landed below the target point (Figure 8). Since increasing the length of the spray pipe would increase the likelihood of collisions with trees during flight, it was determined that the system should be operated at a distance of 5 m from the target hornet nest. At this distance, the maximum measured position error between the target point and the bullet fired from the perforator was less than 1 cm, indicating high precision. However, even if the bullet impact points are not densely concentrated at the precise target point, they are considered to have sufficient strength to damage the hornets' nests for spray penetration; i.e., the system could efficiently deliver the agent by firing the bullets in a shotgun style and creating holes in the hornet nest at various locations.

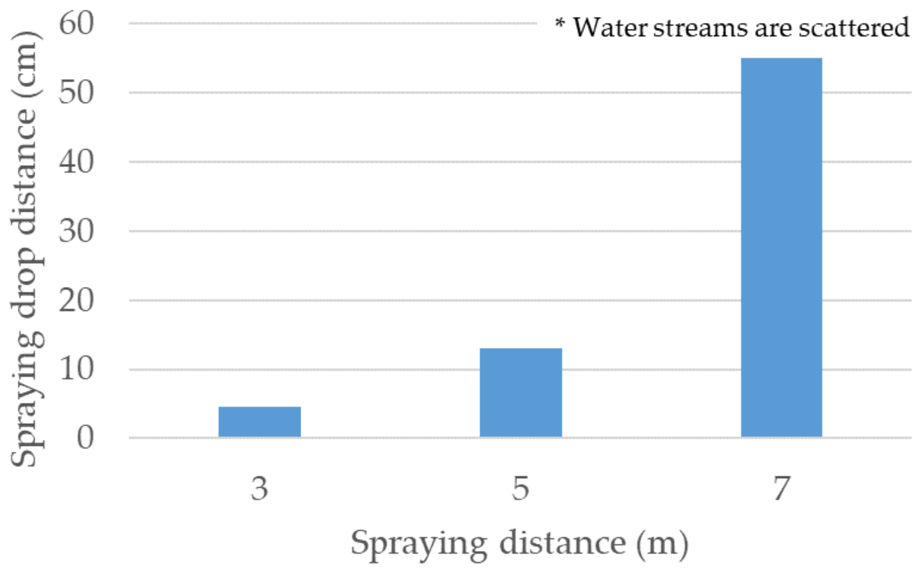


Figure 8. Distances between target point and water-stream drops at various spray distances. * When the agent was sprayed from 7 meters away, the water stream split into multiple streams before reaching the target.

In field tests, after pest-control operations by the exterminator UAV, video footage seemed to indicate that the hornet nests had been destroyed. Figure 9 shows photographs taken during the actual experiments using the UAV exterminator for the control of *V. velutina*. The insecticidal rate of 15% pyrethrum extract and 10% pyrethrum extract plus additives in the treatment sites was found to be 99% (Table 3). In the nests sprayed with these agents, no hornets were observed entering or repairing the nests even one week after the control (Table 2). In the nest sprayed with 10% pyrethrum extract without additives, however, several hornets were observed entering and leaving the nest a week after operations.

(**a**) Firing and spraying of the nests (**b**) Nest conditions after spraying

Figure 9. Control experiment with exterminator for *V. velutina*.

Table 3. Effect of the concentration and additives on the control effect.

Treatment	Number of Hornets Entering the Nest per Minute 1 Week after Spraying	Control Effect
10% pyrethrum extract	4 ± 2.5	x
15% pyrethrum extract	0	o
10% pyrethrum extract + 10% sugar + 10% formic acid + 1% bee shred	0	o

3.3. Economic Feasibility of the Proposed Method

The price of the exterminator was calculated to be KRW 20 million with a lifespan of 5 years and annual usage time of 100 h (Table 4). Repair costs were calculated at 6% of the equipment price and interest at 5% of half the equipment price. The time required for the control work with the conventional device was 2 h per hornet nest, whereas the exterminator required 0.3 h, representing a reduction in labor time of 85%. The calculations showed that the cost for using the exterminator was 54.9% lower than that of conventional device.

Table 4. Economic analysis of the exterminator.

Classification	Control	Exterminator
Equipment price (won)	1,000,000	20,000,000
Lifetime (years)	5	5
Annual usage time (hour)	100	100
Labor cost (won/h)	24,165	24,165
Expense (won/h)	27,015	81,165
Working time per session (h/session)	2.0	0.3
Cost (won/session)	54,030	24,350

4. Conclusions

Vespa velutina nigrithorax, a hornet species native to Asia, is spreading globally, with devastating effects for beekeepers (who experience a loss of income) and crop yields (which are reduced due to decreased pollination). To effectively eliminate a *V. velutina* colony, their nest should be destroyed and the queen removed. However, the heights at which *V. velutina* nests generally occur make them difficult to access. To address these issues, we designed and developed a drone-assisted exterminator of *V. velutina*. Thereafter, we evaluated the system's spraying performance and determined its operating parameters, conducted field trials, and finally, analyzed its economic feasibility.

To determine the system requirements of a drone-based hornet exterminator, we first surveyed hornet nests in the field. We thus determined that the UAV hornet nest exterminator would need to be able to laterally spray pesticides from a distance of more than 5 m. Based on the measured strength of a sample hornet nest and the rated spray pump pressure, a separate perforation device was deemed necessary. Preliminary tests indicated that pesticide delivery through seepage was insufficient. In addition, remote-monitoring and angle-adjustment devices were proposed to overcome the visibility limitations of the operator experienced in preliminary field observations and thus to improve the remote control performance of the drone and accuracy of the perforating and spraying devices.

Based on the analyzed requirements, a hornet-nest-exterminating UAV was designed and manufactured. The spraying system comprised a pump and direct injection nozzle. A spray pipe was added to increase the horizontal spraying distance of the agent, and an airsoft gun was installed to destroy the outer wall of the nest. An actuator was installed at the rear of the device to adjust the pitch of the spray nozzle and perforator while the drone hovered. A remote monitoring system was also installed to improve the targeting and adjustment accuracy of the operator.

To evaluate the system performance, field pest-control tests were conducted against *V. velutina* in Buan and Wanju. Three different mixtures of pyrethrum extract (PLS-compliant) were used as the pesticide agent, and cornstarch airsoft bullets were used. A week after pest-control operations, no hornet activity was observed at nests targeted with the 15% pyrethrum extract solution or the 10% solution with additives, indicating an insecticidal rate of over 99%. Compared to conventional manual nest removal, the UAV exterminator reduced the work time by 85% and the cost by 43%, indicating significant advantages compared to human labor.

It is thus concluded that the developed UAV exterminator can be used to perform pest-control work quickly and affordably, and it is also expected to increase the safety of workers. In the future, combined with technology for the detection of hornets' nests, extermination can be performed more efficiently to prevent the spread of *V. velutina*. Further research is needed to develop alternative solutions for areas in which airsoft rifles are banned.

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References

1. Archer, M.E. Taxonomy, distribution and nesting biology of species of the genera Provespa Ashmead and Vespa Linnaeus (Hymenoptera, Vespidae). *Entomol. Mon. Mag.* **2008**, *144*, 69–101.
2. Jung, C.; Kim, D.; Lee, H.-S.; Baek, H. Some Biological Characteristics of a New Honeybee Pest, *Vespa velutina nigrithorax* Buysson, 1905 (Hymenoptera: Vespidae). *J. Apic.* **2009**, *24*, 61–65. (In Korean)
3. Rome, Q.; Perrard, A.; Muller, F.; Villemant, C. Monitoring and control modalities of a honeybee predator, the yellow-legged hornet *Vespa velutina nigrithorax* (Hymenoptera: Vespidae). *Aliens* **2011**, *31*, 7–15.
4. Carpenter, J.; Kojima, J. Checklist of the species in the subfamily Vespinae (Insecta: Hymenoptera: Vespidae). *Nat. Hist. Bull. Ibaraki Univ.* **1997**, *1*, 51–92.
5. EPPO. EPPO Global Database. Available online: https://gd.eppo.int/taxon/VESPVE/distribution (accessed on 20 April 2023).

6. Kishi, S.; Goka, K. Review of the invasive yellow-legged hornet, *Vespa velutina nigrithorax* (Hymenoptera: Vespidae), in Japan and its possible chemical control. *Appl. Èntomol. Zoöl.* **2017**, *52*, 361–368. [CrossRef]
7. A Shah, F.; Shah, T.A. Vespa Velutina, a Serious Pest of Honey Bees in Kashmir. *Bee World* **1991**, *72*, 161–164. [CrossRef]
8. Laurino, D.; Lioy, S.; Carisio, L.; Manino, A.; Porporato, M. *Vespa velutina*: An Alien Driver of Honey Bee Colony Losses. *Diversity* **2019**, *12*, 5. [CrossRef]
9. Feás, X. Human Fatalities Caused by Hornet, Wasp and Bee Stings in Spain: Epidemiology at State and Sub-State Level from 1999 to 2018. *Biology* **2021**, *10*, 73. [CrossRef]
10. Jung, C. Initial Stage Risk Assessment of an Invasive Hornet, *Vespa velutina nigrithorax* Buysson (Hymenoptera: Vespidae) in Korea. *J. Apic.* **2012**, *27*, 95–104. (In Korean)
11. Choi, M.B.; Martin, S.J.; Lee, J.W. Distribution, spread, and impact of the invasive hornet *Vespa velutina* in South Korea. *J. Asia-Pac. Èntomol.* **2012**, *15*, 473–477. [CrossRef]
12. Tan, K.; Hu, Z.; Chen, W.; Wang, Z.; Wang, Y.; Nieh, J.C. Fearful Foragers: Honey Bees Tune Colony and Individual Foraging to Multi-Predator Presence and Food Quality. *PLoS ONE* **2013**, *8*, e75841. [CrossRef] [PubMed]
13. Bertolino, S.; Lioy, S.; Laurino, D.; Manino, A.; Porporato, M. Spread of the invasive yellow-legged hornet *Vespa velutina* (Hymenoptera: Vespidae) in Italy. *Appl. Èntomol. Zoöl.* **2016**, *51*, 589–597. [CrossRef]
14. Chauzat, M.-P.; Martin, S. A foreigner in France: The Asian hornet. *Biologist* **2009**, *56*, 86–91.
15. Turchi, L.; Derijard, B. Options for the biological and physical control of *Vespa velutina nigrithorax* (Hym.: Vespidae) in Europe: A review. *J. Appl. Èntomol.* **2018**, *142*, 553–562. [CrossRef]
16. Arca, M.; Mougel, F.; Guillemaud, T.; Dupas, S.; Rome, Q.; Perrard, A.; Muller, F.; Fossoud, A.; Capdevielle-Dulac, C.; Torres-Leguizamon, M.; et al. Reconstructing the invasion and the demographic history of the yellow-legged hornet, *Vespa velutina*, in Europe. *Biol. Invasions* **2015**, *17*, 2357–2371. [CrossRef]
17. de Haro, L.; Labadie, M.; Chanseau, P.; Cabot, C.; Blanc-Brisset, I.; Penouil, F. Medical consequences of the Asian black hornet (*Vespa velutina*) invasion in Southwestern France. *Toxicon* **2010**, *55*, 650–652. [CrossRef] [PubMed]
18. Rodríguez-Flores, M.S.; Seijo-Rodríguez, A.; Escuredo, O.; Seijo-Coello, M.D.C. Spreading of *Vespa velutina* in northwestern Spain: Influence of elevation and meteorological factors and effect of bait trapping on target and non-target living organisms. *J. Pest Sci.* **2018**, *92*, 557–565. [CrossRef]
19. Jung, C. Spatial Expansion of an Invasive Hornet, *Vespa velutina nigrithorax* Buysson (Hymenoptera: Vespidae) in Korea. *J. Apic.* **2012**, *27*, 87–93. (In Korean)
20. Barbet-Massin, M.; Rome, Q.; Muller, F.; Perrard, A.; Villemant, C.; Jiguet, F. Climate change increases the risk of invasion by the Yellow-legged hornet. *Biol. Conserv.* **2013**, *157*, 4–10. [CrossRef]
21. Barbet-Massin, M.; Salles, J.-M.; Courchamp, F. The economic cost of control of the invasive yellow-legged Asian hornet. *Neobiota* **2020**, *55*, 11–25. [CrossRef]
22. Robinet, C.; Suppo, C.; Darrouzet, E. 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.* **2016**, *54*, 205–215. [CrossRef]
23. Braga, D.; Madureira, A. Towards a decision support system for the automatic detection of Asian hornets and removal planning. *Int. J. Comput. Inf. Syst. Ind. Manag. Appl.* **2020**, *12*, 239–247.
24. Lioy, S.; Bianchi, E.; Biglia, A.; Bessone, M.; Laurino, D.; Porporato, M. Viability of thermal imaging in detecting nests of the invasive hornet *Vespa velutina*. *Insect Sci.* **2020**, *28*, 271–277. [CrossRef]
25. Kennedy, P.J.; Ford, S.M.; Poidatz, J.; Thiéry, D.; Osborne, J.L. Searching for nests of the invasive Asian hornet (*Vespa velutina*) using radio-telemetry. *Commun. Biol.* **2018**, *1*, 88. [CrossRef] [PubMed]
26. Leza, M.; Miranda, M.; Colomar, V. First detection of *Vespa velutina nigrithorax* (Hymenoptera: Vespidae) in the Balearic Islands (Western Mediterranean): A challenging study case. *Biol. Invasions* **2017**, *20*, 1643–1649. [CrossRef]
27. Reynaud, L.; Guérin-Lassous, I. Design of a force-based controlled mobility on aerial vehicles for pest management. *Ad Hoc Netw.* **2016**, *53*, 41–52. [CrossRef]
28. Gao, P.; Lee, K.; Kuswidiyanto, L.W.; Yu, S.-H.; Hu, K.; Liang, G.; Chen, Y.; Wang, W.; Liao, F.; Jeong, Y.S.; et al. Dynamic Beehive Detection and Tracking System Based on YOLO V5 and Unmanned Aerial Vehicle. *J. Biosyst. Eng.* **2022**, *47*, 510–520. [CrossRef]
29. Goldarazena, A.; de Heredia, I.P.; Romon, P.; Iturrondobeitia, J.C.; Gonzalez, M.; Lopez, S. Spread of the yellow-legged hornet *Vespa velutina nigrithorax* du Buysson (Hymenoptera: Vespidae) across Northern Spain. *EPPO Bull.* **2015**, *45*, 133–138. [CrossRef]
30. Rojas-Nossa, S.V.; Novoa, N.; Serrano, A.; Calviño-Cancela, M. Performance of baited traps used as control tools for the invasive hornet *Vespa velutina* and their impact on non-target insects. *Apidologie* **2018**, *49*, 872–885. [CrossRef]
31. Sackmann, P.; Rabinovich, M.; Corley, J. Successful Removal of German Yellowjackets (Hymenoptera: Vespidae) by Toxic Baiting. *J. Econ. Èntomol.* **2001**, *94*, 811–816. [CrossRef]
32. Mohsan, S.A.H.; Khan, M.A.; Noor, F.; Ullah, I.; Alsharif, M.H. Towards the Unmanned Aerial Vehicles (UAVs): A Comprehensive Review. *Drones* **2022**, *6*, 147. [CrossRef]
33. Del Cerro, J.; Ulloa, C.C.; Barrientos, A.; Rivas, J.D.L. Unmanned Aerial Vehicles in Agriculture: A Survey. *Agronomy* **2021**, *11*, 203. [CrossRef]
34. *FDIS 23117-1*; Agricultural and Forestry Machinery—Unmanned Aerial Spraying Systems—Environmental Requirements. ISO: Geneva, Switzerland, 2021.

35. Lee, C.-G.; Yu, S.-H.; Rhee, J.-Y. Effects of Unmanned Aerial Spray System Flight Altitude and Collector Height on Spray Deposition Measured Using a Food Dye Tracer. *Agriculture* **2022**, *13*, 96. [CrossRef]
36. OECD. *State of the Knowledge—Literature Review on Unmanned Aerial Spray Systems in Agriculture*; OECD Publishing: Paris, France, 2021.
37. Chen, P.; Douzals, J.P.; Lan, Y.; Cotteux, E.; Delpuech, X.; Pouxviel, G.; Zhan, Y. Characteristics of unmanned aerial spraying systems and related spray drift: A review. *Front. Plant Sci.* **2022**, *13*, 870956. [CrossRef]
38. He, X.; James, B.; Andreas, H.; Jan, L. Recent development of unmanned aerial vehicle for plant protection in East Asia. *Int. J. Agric. Biol. Eng.* **2017**, *10*, 18–30.
39. Morales-Rodríguez, P.A.; Cano, E.C.; Villena, J.; López-Perales, J.A. A Comparison between Conventional Sprayers and New UAV Sprayers: A Study Case of Vineyards and Olives in Extremadura (Spain). *Agronomy* **2022**, *12*, 1307. [CrossRef]
40. Zhang, P.; Deng, L.; Lyu, Q.; He, S.; Yi, S.; Liu, Y.; Yu, Y.; Pan, H. Effects of citrus tree-shape and spraying height of small unmanned aerial vehicle on droplet distribution. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 45–52.
41. Wang, L.; Huang, X.; Li, W.; Yan, K.; Han, Y.; Zhang, Y.; Pawlowski, L.; Lan, Y. Progress in Agricultural Unmanned Aerial Vehicles (UAVs) Applied in China and Prospects for Poland. *Agriculture* **2022**, *12*, 397. [CrossRef]
42. Sarri, D.; Martelloni, L.; Rimediotti, M.; Lisci, R.; Lombardo, S.; Vieri, M. Testing a multi-rotor unmanned aerial vehicle for spray application in high slope terraced vineyard. *J. Agric. Eng.* **2019**, *50*, 38–47. [CrossRef]
43. Lim, D.-J.; Kim, S.-W.; Kim, Y.-E.; Yoon, J.-H.; Cho, H.-J.; Shin, B.-G.; Kim, H.-Y.; Kim, I.-S. Plant-Back Intervals of Imicyafos Based on Its Soil Dissipation and Plant Uptake for Rotational Cultivation of Lettuce and Spinach in Greenhouse. *Agriculture* **2021**, *11*, 495. [CrossRef]
44. *DIRECTIVE 2009/128/EC*; Establishing a Framework for Community Action to Achieve the Sustainable Use of Pesticides. EU: Brussel, Belgium, 2009; pp. 71–86.
45. Casida, J. *Pyrethrum: The Natural Insecticide*; Elsevier Science: Amsterdam, The Netherlands, 2012.
46. Krief, A. Pyrethroid insecticides. Chapter I. Synthesis, structure, biochemistry and biosynthesis of pyrethroids. *ARKIVOC Online J. Org. Chem.* **2021**, *2021*, 55–77. [CrossRef]
47. You, H.-K.; Jeong, U.-S.; Chae, Y.-W.; Kim, S. An Analysis of Economic Feasibility and Perception of Drone for Pesticide Application. *J. Korea Acad. Coop. Soc.* **2021**, *22*, 235–245. [CrossRef]
48. Leza, M.; Herrera, C.; Picó, G.; Morro, T.; Colomar, V. Six years of controlling the invasive species *Vespa velutina* in a Mediterranean island: The promising results of an eradication plan. *Pest Manag. Sci.* **2021**, *77*, 2375–2384. [CrossRef] [PubMed]