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Integrating Manned Aircraft and UAVs for the Prediction, Tracking, and Eradication of Desert Locust Swarms

** All authors contributed equally to this research paper. Order listed alphabetically by surname.*

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Summary

Desert locusts (*Schistocerca gregaria*) present an acute threat to the agriculture of certain regions, capable of annihilating vast expanses of farmland and destabilizing food security. In this paper, an aviation-based framework concept is introduced that integrates both manned aircraft and Unmanned Aerial Vehicles (UAVs) to preemptively forecast, localize, and eliminate locust swarms efficiently. The framework begins by leveraging predictive modeling methods to refine search areas and pinpoint high-value Points of Interest (POIs) where locust swarms are most likely to materialize. From there, the proposed two-step model uses optical, infrared, and hyperspectral sensors onboard manned aircraft to conduct long-range surveying of probable swarm locations. Upon detection of a swarm, UAVs equipped with sophisticated sensors, including pheromone detectors, thermal and optical imaging systems, are deployed directly from the aircraft to carry out targeted biopesticide applications. This approach, which capitalizes on the combined strengths of both vehicles, provides the rapid response and large-scale intervention necessary to control locust outbreaks. By targeting locust swarms during their most destructive phase, this paper aims to disrupt the locust life cycle and mitigate their severe agricultural impact, offering a scalable and sustainable solution for food security in afflicted regions.

Keywords: Schistocerca gregaria; UAV deployment; metarhizium acridum; hyperspectral imaging; pheromone sensors; predictive modeling; biopesticide delivery; locust control strategy; locust monitoring systems

Contents

1 Introduction

Across large regions of Southwest Asia and Eastern Africa, the desert locust, *Schistocerca gregaria* (Orthoptera: Acrididae), poses a significant threat to agricultural productivity, directly impacting the agrarian livelihoods of millions (Ref. 1). Globally recognized as “the most destructive migratory pest” (Ref. 1), desert locusts are a persistent source of anxiety and economic strain for those residing in affected areas, which encompass an estimated 10% of the world’s population (Ref. 2). The species’ propensity for gregarious behavior, evidenced in the formation of swarms that can number in the trillions, renders them particularly difficult to control and exacerbates the threat they present (Ref. 3). An average locust swarm consumes enough food in a single day to feed up to 35,000 people (Ref. 1). When this voracious appetite is coupled with the sheer scale of these swarms—often exceeding 80 million insects per square kilometer—and their ability to travel over 90 miles per day (Ref. 1)), the devastating potential of locusts becomes alarmingly clear. Within a matter of hours, these swarms can decimate billions of dollars worth of crops and fertile land (Ref. 1).

The year 2020 witnessed the largest locust swarms in half a century, with some reaching sizes three times those of New York City (Ref. 4). These swarms afflicted dozens of countries in storms described as almost ”biblical” in scale (Ref. 5). Spanning multiple continents and covering thousands of square miles, the crisis marked the most severe outbreak in recent memory (Ref. 5). The unprecedented scale of the 2020 locust surge intensified pre-existing issues of food insecurity and poverty. In Ethiopia alone, locusts devastated 200,000 hectares of cropland, resulting in the loss of over 3 million quintals of cereal and driving a 50% increase in cereal prices compared to years prior (Ref. 6). A study estimated that nearly 35% of global grain production was heavily impacted by the locust upsurge, with losses amounting to 5.5% in 2020 and 14.9% in 2021 within the disturbed regions (Ref. 6). Furthermore, the World Bank found that damages and losses in East Africa and Yemen alone reached as much as $8.5 billion during this period (Ref. 1).

The 2020 locust infestations, despite their devastating impact, did lead to one positive outcome: a significant surge in global interest in combating and developing comprehensive solutions to these destructive insects. In March 2020, public interest in locusts reached an all-time high (Ref. 7), catalyzing increased investment in modern technologies for control and elimination. This heightened focus on locust management has persisted beyond the immediate crisis, as evidenced by the ongoing efforts of the Food and Agriculture Organization’s (FAO) Locust Hub, which continues to maintain a state of caution regarding these insects even today (Ref. 8). Addressing this issue is particularly challenging due to the regions where desert locusts thrive. These insects often inhabit some of the most difficult and remote areas of the world, where traditional methods of pest control are hard to employ. The rugged terrain, limited infrastructure, and vast, inaccessible landscapes make it challenging to conduct large-scale operations (Ref. 6)

This paper presents a novel aviation-based framework concept for the prediction, location, and eradication of desert locust swarms. In doing so, this paper offers a contribution to the advancement of more effective and sustainable strategies that can be rapidly deployed to mitigate the impact of locust outbreaks, thereby helping to safeguard global food security.

2 Related Works

The approaches proposed in this paper, as well as the continued solution concept, build upon a foundation of existing technologies and methodologies developed in the field of locust control. Various innovative strategies have been implemented in recent years to address the growing threat posed by locust swarms, particularly in regions such as East Africa and South Asia.

In East Africa, the FAO deployed UAVs for real-time surveillance, utilizing both rotary and fixed-wing models (Ref. 9). These UAVs were complemented by public data-sharing tools, which facilitated the monitoring of locust swarms and allowed for more coordinated responses (Ref. 9). The integration of satellite imagery and drone technology has become crucial in tracking locust movements and predicting potential outbreaks. Additionally, Geographic Information Systems (GIS) and machine learning algorithms have been incorporated into locust control efforts, as demonstrated by India's Locust Warning Organization (Ref. 10). These technologies have been used to map environmental conditions and forecast swarming patterns, enabling timely and preemptive actions (Ref. 10).

On the active front, pesticides and chemicals remain cornerstones of the battle against the desert locust. Whether sprayed from the ground, the air, or anywhere in between, this technique remains the most effective method for eliminating these insects. Pakistan's Department of Plant Protection exemplified this, coordinating ground and aerial pesticide spraying during the 2019–2020 outbreak, covering over 300,000 hectares with 150,839 liters of pesticides and effectively curbing the spread of locusts in the region (Ref. 11).

Despite the success of these methodologies, the field remains ripe for further innovation. Due to the inherent disparity between these ground-based approaches and their airborne targets, current research and interventions are primarily reactive and often face challenges in difficult terrains where locusts thrive. Furthermore, most current research and interventions have focused predominantly on targeting locust breeding grounds (Ref. 12), an interim solution that overlooks the significant threat posed by mature locust swarms, which degrade farmland and actively reproduce. The need to address locust swarms directly during their most destructive phase to mitigate the damage to farmlands and reduce the likelihood of subsequent outbreaks is therefore critical. By focusing efforts on these in-flight swarms, it is possible to mitigate the damage to farmlands and reduce the likelihood of subsequent outbreaks.

3 Concept Overview

To address this issue, this paper proposes the implementation of a parent-child aviation-based model. Integrating two specialized types of aircraft, this dual-stage locust mitigation strategy leverages the complementary strengths of both manned aircraft and UAVs in a streamlined process designed to effectively and precisely deal with locust swarms. Figure 1 depicts a simplified visual representation of our method in action.

- **Step 1: Long-Range Survey Aircraft (Parent)**
  The first stage of the solution involves the deployment of a manned aircraft, which acts as

the "parent" in this model. The aircraft is equipped with optical, infrared, and hyperspectral imaging systems to detect and localize locust swarms over vast areas. Its extensive range and payload capacity enable it to visit specific Points of Interest (POIs) identified as high-probability locust sites. These POIs are derived from real-time data sources such as satellite imagery, GIS systems, and predictive models, targeting areas where locust swarms are most likely to form.

- **Step 2: UAVs for Eradication (Children)**
  Once a locust swarm is detected and localized, the second stage involves the deployment of a fleet of UAVs, or "children," from the aircraft. Onboard these UAVs are a combination of pheromone sensors, thermal and optical imaging systems, and biopesticide sprayers. These aircraft are capable of autonomously navigating to the precise locations of the swarms, hovering at optimal altitudes, and deploying the chemicals. Designed for high maneuverability and control, the UAVs utilized will have the capacity to track and target locust swarms across even challenging terrain.

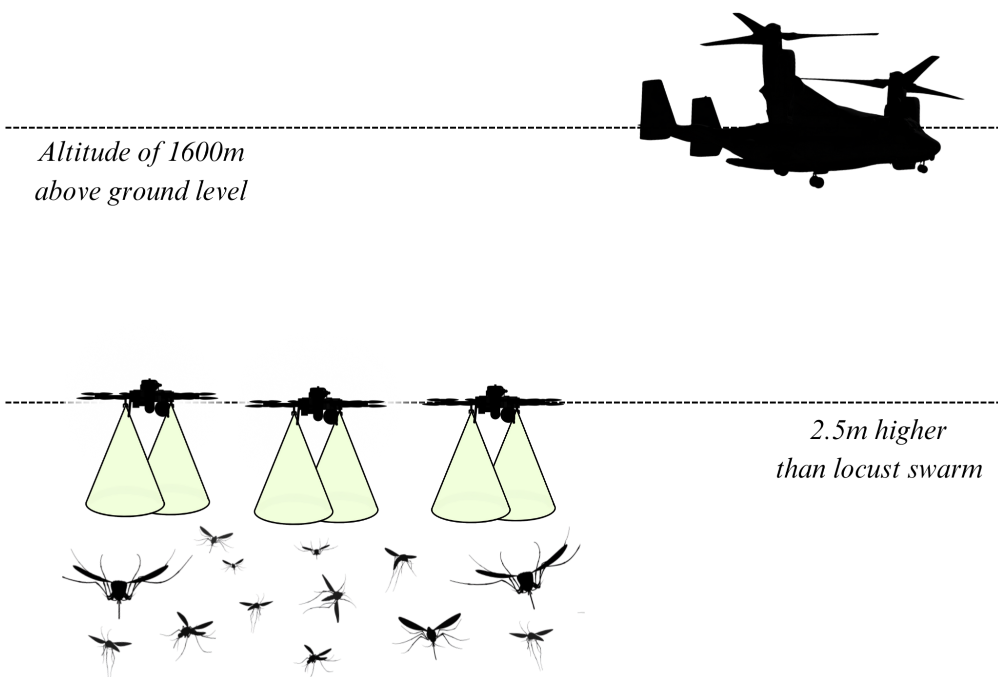

Figure 1.—Simplified Depiction of Parent-Child Aviation Model

Unlike traditional methods that focus on controlling locust populations at breeding grounds (Ref. 12), this approach targets actively migrating swarms that pose immediate threats to agricultural lands. By addressing swarms directly, this system not only mitigates the current threat but also prevents further reproduction, effectively disrupting the locust life cycle. The deployment of child UAVs from a parent aircraft allows for rapid response and coverage over vast areas. The aforementioned combined solution surpasses the capabilities of its individual components: if only planes were used in a concept like this, the lack of precision in spraying pesticides would result in significant waste and difficulty in targeting and maneuvering around locust swarms (Ref. 13); if only UAVs were used, their limited range and payload capacity would make it challenging to cover large areas or carry sufficient biopesticides for widespread eradication (Ref. 14). By employing both aircraft types in tandem, both their individual constraints are effectively overcome.

3.1 Surveying Aircraft

For the initial phase, four key requirements were identified that the surveying aircraft must fulfill:

1. The aircraft must have an extensive range, as locust habitats cover vast areas, and the swarms can traverse considerable distances, necessitating a plane capable of surveying large swathes of land on a single tank of fuel.
2. The aircraft must have a substantial payload capacity; the more drones that can be carried, the more effective they are in combating locust swarms.
3. The aircraft must be able to carry the necessary instruments for tracking locust swarms.
4. The aircraft must be capable of taking off from poorly maintained airfields—common in the regions where it will operate.

Given these requirements, Advanced Air Mobility vehicles—known colloquially as air taxis—were ruled out. While air taxis offer benefits such as quick deployment, vertical takeoff and landing capabilities, and potentially lower operational costs for short-range missions, their current range and payload capacity limitations are insufficient for this operation. Currently, most air taxis are limited to ranges of just over 150 miles on a single charge. However, as technology, particularly battery capacity, continues to advance, air taxis may become viable options for this venture in the future.

There were four main aircraft that satisfied the criteria: the King Air 360, the Cessna Grand Caravan, the C-23 Sherpa, and the V-22 Osprey.

Aircraft:	Range:	Payload:	Cruising Speed:	Configuration:
C-23 Sherpa (Ref. 15)	2,500 nm	8,800 lbs	218 mph	Fixed
King Air 360er (Ref. 16)	2,539 nm	7174 lbs	349 mph	Fixed
Cessna Grand Caravan (Ref. 17)	912 nm	3,532 lbs	212 mph	Fixed
V-22 Osprey (Ref. 18)	2,100 nm	20,000 lbs	318 mph	Tilt-Rotor

Table 1.— Compares the Capabilities of Aircraft Considered for this Mission:

Among these general aviation vehicles, the C-23 Sherpa and V-22 emerged as the top contenders due to their superior range and payload capacities. Of these two, the C-23 was ultimately deemed the best fit for a fixed-wing plane, thanks to its rear loading door and nearly 2,000 pounds of additional payload capacity.

However, despite the advantages offered by the C-23 Sherpa, standard fixed-wing aircraft as a whole still present significant limitations for this specific operational scenario. Although a typical plane offers a wide range and substantial payload capacity, it lacks flexibility in landing and takeoff and cannot retrieve a UAV that lacks the range to return (Ref. 15). To pick up the drones, the UAVs would need to either land at an airfield that the C-23 can land at or get picked up by some other vehicle (which would prevent multiple deployments per flight, slow down operations, and increase cost). To overcome these limitations, our solution is the Bell Boeing V-22 Osprey. With an impressive range of 2,100 nm, auxiliary fuel tanks, and a useful load of 20,000 pounds, it surpasses the capabilities of most planes (Ref. 18). Although its cruising speed is a modest 317 mph and costs a hefty amount, the V-22 Osprey's vertical takeoff and landing capabilities provide significant advantages (Ref. 18). Boeing, the manufacturer, highlights the benefits of tilt rotors: "The V-22 is equipped with complete runway independence technologies, allowing it to take off and land wherever it's needed most," enabling operations from poorly maintained fields and the ability to land and retrieve UAVs almost anywhere (Ref. 19).

With a 20,000-pound payload capacity, the Osprey can be configured to meet various operational needs. Since each UAV weighs under 65 pounds, the aircraft can deploy multiple UAVs per survey while accommodating additional fuel and bio-pesticides for extended missions. Even accounting for the weight of the UAVs, at least 5,000 pounds of the payload can be allocated to extra fuel, extending both flight range and surveying time. Along with internally carried equipment, the plane will be equipped with three sensors: a sensor, an optical camera, and a hyperspectral camera, enhancing its precision in tracking locust swarms.

Overall, the Osprey integrates the most advantageous features of both air taxis and traditional aircraft, offering a versatile solution that maximizes UAV deployment efficiency without compromising performance. The C-23 could work as a different option, requiring more infrastructure and planning. So, based on our mission requirements, the Osprey is the recommended aircraft to fulfill the operation's objectives, offering the most practical combination of range, payload, and control among the available options.

3.2 UAV Solution

When selecting the appropriate UAV for the project, the team acknowledged the necessity of adhering to specific criteria for successful execution. Key considerations include:

1. The UAV must possess low-altitude capabilities to effectively deliver biopesticide to locust populations
2. The UAV must maintain controlled speed to adeptly track and monitor the movements of locusts
3. The UAV must have a substantial payload capacity for cameras, sensors, a parachute, and biopesticides

4. The UAV must exhibit adept maneuverability for tracking and locating locusts
5. The UAV must be capable of hovering for precise spraying during locust swarming
6. The UAV must be able to fly for extended times to allow for targeted spraying at optimal intervals

Upon initial consideration, the team evaluated the YANGDA Sky Whale Max hybrid (Ref. 20) as a potential candidate. However, upon a more thorough review of the UAV, it was determined that it would not be the most optimal choice for the study. The aircraft's design is intended for higher altitudes, rendering it less effective for the task of spraying locusts, which requires application at close range to ensure the optimal delivery of biopesticides.

In research of the requirements, hybrid multi-rotor UAVs offer distinct advantages, as they are capable of operating at lower altitudes and accommodating larger payloads in comparison to various other types of UAVs. The search was narrowed down to three UAV models: FlyDragon's Fire Fighting Drone (Ref. 21), the DragonFly Precision Spray Drone (Ref. 22), and the Skyfront's Perimeter 8+ (Ref. 23). FlyDragon's Fire Fighting Drone was excluded from review due to its limited maximum endurance of 35 minutes, which is insufficient for locating, tracking, and spraying locusts at optimal times. Similarly, the DragonFly Precision Spray Drone was ruled out due to its shorter flight time and higher maximum speed in comparison to Skyfront's Perimeter 8+.

As such, the Perimeter 8+ is recommended as the foundational model for the UAV design outlined in this paper, based on its substantial payload capacity of 22 lbs, extended flight times of approximately 1 hour, low cruising altitudes, and lower cruising speeds. Enhancements to the UAVs will include the integration of an optical camera combined with an infrared sensor, a pheromone sensor for detecting locust scent, and a biopesticide sprayer. Additionally, biodegradable parachutes will be equipped to facilitate controlled descent.

4 Pre-Flight Calculations

4.1 Prediction Methodologies

Desert locusts inhabit semi-arid and arid deserts across Africa, the Near East, and South-West Asia that receive less than 200 mm of rainfall annually, which the FAO estimates collectively cover an area of approximately 16 million square kilometers (Ref. 24). Unfortunately, this vast and difficult expanse is far too extensive to be surveyed in its entirety. As such, before any attempts for the interception and eradication of locust swarms can be made, there arises a critical need for accurate and precise techniques in predicting and forecasting locust swarm movements, so as to establish clear POIs and narrow down the intended search area. Many varied approaches for this purpose have been proposed; however, the monitoring and analysis stack developed by the FAO's Locust Hub division emerges as the frontrunner in this sector:

- **eLocust3** — The eLocust3 technology package is the first stage of the FAO's locust monitoring lifecycle, enabling national survey officers across the globe to record and transmit real-time data from the field via satellite (Ref. 25). This data is crucial for confirming the presence of locusts and forms the basis for further forecasting and monitoring efforts. Featuring a

Panasonic ToughPad and a SkyWave IDP680 antenna, the system is specifically designed for harsh desert conditions and efficient data transmission (Ref. 25). Since its introduction in 1985, the FAO has collected nearly 38,000 records of confirmed locust sightings using this technology (Ref. 26). During periods of exceptionally high locust presence, such as in 2019, 2020, and 2021, the eLocust3 database was updated an average of 17.43 times per day, with a median of 10.5 daily additions (Ref. 26). The eLocust system's consistent influx of data keeps the database current and comprehensive. By outsourcing the manual aspects of locust detection to individual agents across affected regions, the FAO leverages the advantages of a decentralized system, making large-scale monitoring not only feasible but also highly effective.

- **eLocust3D** — A separate application, eLocust3D, builds upon the NASA-developed World Wind planetary globe 3D engine to superimpose the data collected by the eLocust3 system onto Landsat imagery, rainfall data, and greenness maps (Ref. 25). By integrating these multiple layers, eLocust3D allows for the easy identification of areas that are likely to contain locust infestations.

- **SWARMS/RAMSES** — To post-process the data from the eLocust systems, the FAO developed the Reconnaissance and Management System of the Environment of Schistocerca (RAMSES) and Schistocerca WARning Management System (SWARMS) GISs (Ref. 27). These systems enable locust information officers to analyze field results, query locust data and overlay it on various static and dynamic maps to corroborate findings. Static maps include layers such as country boundaries, wadis, lakes, roads, elevation contours, towns, Landsat imagery, and Tactical Pilotage Charts. Dynamic imagery includes rainfall estimates, vegetation indices (NDVI and EVI) from SENTINEL-2, soil moisture data, weather conditions, and climate forecasts (Ref. 27). Accessible on the web via ESRI's ArcGIS Online, this approach allows for real-time analysis and forecasting (Ref. 27).

- **NOAA HYSPLIT** — As an additional tool adding to the FAO Locust Hub method, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by NOAA, is used to track the movement and dispersion of locust swarms (Ref. 28). Originally designed to track the atmospheric diffusion of airborne pollutants, a partnership with the FAO adapted the HYSPLIT model to predict locust swarm movements by modeling the passive flight patterns of locusts, which are highly influenced by wind flows in the area (Ref. 29). The model integrates high-quality data from NOAA's National Weather Service, allowing for accurate forecasts of locust trajectories and, through retrodiction, potential source areas (Ref. 29).

Using a varied assortment of approaches and technologies, these methods offer a comprehensive approach to the monitoring, prediction, and management of locust outbreaks. For the purposes of the aviation-based framework concept outlined in this paper, it is recommended that the FAO Locust Hub model be utilized to identify POIs with a high probability of locust presence, thereby enabling more efficient and targeted interventions.

4.2 Path-Planning

Merely identifying the thousands of POIs across afflicted regions, however, is insufficient for effective control initiatives. In this aviation-based solution, aircraft are deployed to survey as many

POIs as possible before requiring restocking and refueling. Unfortunately, these aircraft are constrained by factors such as range, maximum altitude, and fuel/battery capacity, which limit the number of POIs they can visit in a single sortie. Consequently, optimizing the flight path is critical to maximizing coverage and efficiency.

This optimization problem can be conceptualized in two forms, both of which are variations of the Prize-Collecting Traveling Salesman Problem (PCTSP) (Ref. 30). Unlike the traditional Traveling Salesman Problem (TSP) , where the objective is to find the shortest route that begins and ends at the same location, visiting every node exactly once in a Hamiltonian cycle, in PCTSP the goal is to maximize the number of nodes visited within a certain travel range constraint (Ref. 30). Optimizing this pathing would, in this context, determine the most efficient route that maximizes POI coverage while adhering to the aircraft's limitations.

1. In the original variant of PCTSP, the starting node must be returned to. This algorithm is applicable when the aircraft has to land at its initial airfield after completing the survey mission.

2. The second variant is a modified version of the PCTSP, where the journey is allowed to end at a different location than where it started. This approach is used when the pilot has alternative landing options after completing the survey.

In both variants—PCTSP and the modified PCTSP—it is essential to determine an optimal or reasonably efficient path before the aircraft takes off. To achieve this, various path-finding algorithms, incorporating the necessary constraint of flight range, can be employed. Figure 2 illustrates a sample of solved survey pathing with both single landing and multiple landing options.

In this example, the path planning method employed is the greedy nearest-neighbor heuristic (Ref. 31), an intuitive yet effective algorithm for addressing the PCTSP problem under the given constraints. Greedy is a class of pathfinding methodology that tries to find the most optimal solution by making the best local choice at each step. The two graphs presented simulate a 100x100 surveying area, featuring an aircraft with a maximum range of 300 units and X's marking Points of interest. In the second graph, additional randomly placed green X's represent alternative landing nodes. This approach begins at the designated origin point—the aircraft's departure location—and calculates the Euclidean distance between the current node and all neighboring nodes. The nearest unvisited POI is then selected as the next destination. The process continues iteratively, selecting the closest unvisited node until the remaining range in the journey is less than the distance required to travel to the next nearest node and return to the closest landing zone. At this point, the journey concludes. Although the greedy heuristic may not guarantee the absolute optimal path in all scenarios, it is estimated to achieve solutions within approximately 25% of the optimal route in the vast majority of cases (Ref. 31). This generation of near-optimal solutions, combined with its computational simplicity, makes it highly suitable for this application. A similar approach should be leveraged to plan the flight path of the aircraft and ensure that the maximum number of POIs are surveyed within the operational constraints.

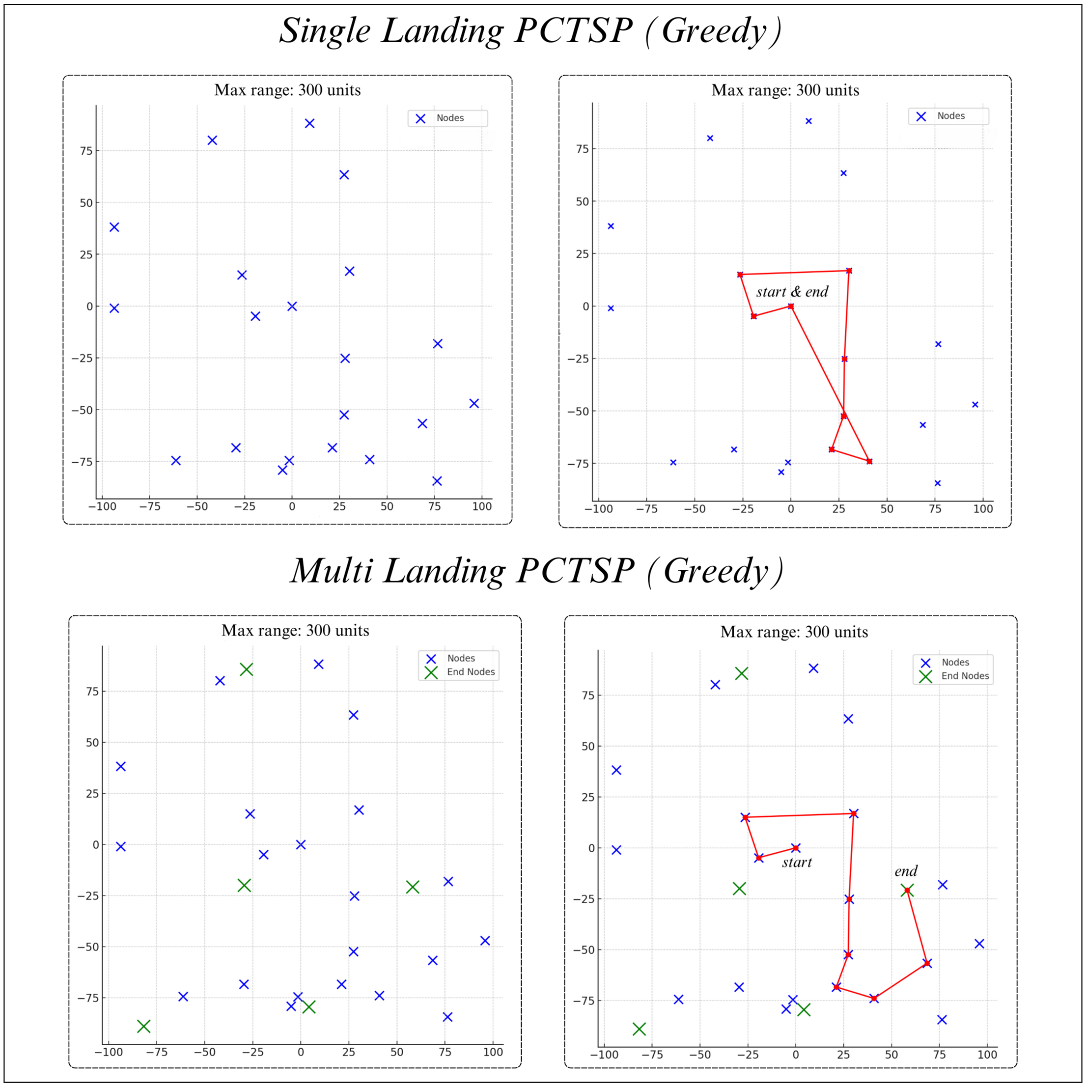

Figure 2.—Solved Examples of Greedy Nearest-Neighbor Heuristic

5 Deployment of UAVs

To deploy the UAVs from the Osprey, it was necessary to determine how to launch the vehicles from the plane without burning valuable fuel by landing each time. Initially, launching the UAVs from the deck of the Osprey and flying them out the back was considered. However, this approach proved unfeasible due to the significant wake generated by the large propeller blades, which could reach "gale force winds" and exceed the UAV's maximum wind speed of 25 mph (Ref. 32)(Ref. 23).

Instead, parachutes would be the most effective method for offloading the UAVs for this framework. With a maximum weight of 62 pounds for the UAV and payload (Ref. 23), a parachute with a radius of 1.475 meters would be required. By employing a static line, the UAVs will be pushed off the plane, and the parachute will automatically deploy, allowing the vehicle to slow its descent until cruising altitude is reached, after which it activates and sheds the parachute and proceeds with its mission. Although the UAV's parachute is not centered, differential thrust of the propellers will correct its off centered descent.

The parachute is constructed from a polyvinyl alcohol (PVOH)-based film, designed to dissolve upon contact with water and fully biodegrade within a few weeks. Originally developed for deploying sonar buoys, this technology relies on water for biodegradation, which presents a challenge in certain environments (Ref. 33). Luckily, the desert locusts found in eastern Africa and surrounding areas are triggered by the wet season, which comes with large amounts of rainfall that can properly dispose of the parachutes, preventing ecological harm (Ref. 34). Given an object of mass m = 28.2 kg or 62 pounds, find the radius of the parachute needed to provide a terminal velocity of V = 7.5 m/sec. Assume Cd = 1.2. Math modeled off of UIdaho math to size a parachute (Ref. 35)

$$r = \sqrt{\frac{2 \times m \times g}{\pi \times c_d \times p \times v}}$$

$$r = \sqrt{\frac{2}{\pi \times 1.2} \times 28.2kg \times (9.8m/s^2) \times \left(\frac{m^3}{1.28kg}\right) \times \left(\frac{1}{7.5^2} \times \frac{s^2}{m^2}\right)}$$

$$r = 147.5 \text{ cm or } 58.07 \text{ in}$$

The value provided is not the value that would be required if it were cut from a sheet of fabric, which would be larger. It is for the radius of a three-dimensional object (Ref. 35).

6 Sensors

To facilitate the tracking and perusal operations outlined in this concept framework, both the surveying aircraft and the deployed UAVs will contain various sensors and cameras centered around the locust swarms.

6.1 UAV Sensors

6.1.1 RTK GNSS Module

A GNSS (Global Navigation Satellite System) will be needed to accurately track the drones and recover them when fuel is depleted (further details of the deactivation process are provided in section 10). The Perimeter 8 UAV is equipped with RTK (Real-time kinematic) GNSS compatibility(Ref. 23), but requires an additional module to perform position-tracking operations. RTK GNSS is superior to traditional GNSS because it employs the use of a base station. The station corrects the RTK GNSS receiver on the UAV, leading to an accuracy within a few centimeters(Ref. 36). An existing network of base stations can be utilized for the project; organizations such as AFREF (African Geodetic Reference Frame) have established RTK base stations networks across Africa(Ref. 37). If out of range from a base station, traditional GNSS capabilities can still function and receive an accuracy within a few meters (Ref. 38). Thus, the system is not reliant on base stations and can function with lower accuracy if the UAV operations exceed the range of such stations. The Reach M2 RTK module best suits our needs, as it is a lightweight, high accuracy device and it will work with the Perimeter 8 UAV. The Reach M2 weights 35g, or about 0.08 lbs(Ref. 39). Altogether, the RTK GNSS system is essential for the success of the mission.

6.1.2 UAV Thermal Imaging

An infrared (IR) camera mounted on the UAV will be employed to detect locust body heat and assess the efficacy of the fungus-based biopesticide on the affected insects (details on this biopesticide are provided in the subsequent section). Accurate results have been obtained by using a wavelength of 7.5–13.5 μm with a sensitivity of 85 mK (Ref. 40). The IR camera operates on an uncooled system to minimize the payload requirements, ensuring that the UAV remains agile and efficient (Ref. 40). This study has demonstrated that thermal cameras with these specifications can effectively capture locust activity (Ref. 40). Object-tracking software or a gimbal stabilizer will be required to ensure smooth locust capture. Following the application of the fungus biopesticide, locusts typically exhibit an increase in body temperature as a physiological response to the pathogen. Thermal imaging can detect the influx of locust heat, allowing for confirmation of the biopesticide's effectiveness in eliminating the insects (Ref. 41). Infrared imaging offers a reliable method for tracking locusts, as it excludes non-target elements such as rocks and dirt from the thermal scan. Suitable thermal imaging systems for this application include the FLIR T1020 (Ref. 42) and the FLIR VUE TZ20-R (Ref. 43).

6.1.3 UAV Color Imaging

A color zoom camera paired with the infrared sensor will be mounted to the UAV as well. Color cameras offer the benefit of rapid data processing of the locust swarm footage. A shutter speed of around 1/2000s–1/4000s is the most optimal for this purpose (Ref. 44). High shutter speeds will ensure smooth capture of the moving locust swarm from the UAV. Additionally, the camera should not sacrifice weight for extra, unnecessary resolution. Similarly, the device should be paired with object-tracking software or a gimbal stabilizer. The Octopus Epsilon 140LC was selected for this project due to its integrated design, which combines both a color zoom camera and an infrared camera, thereby eliminating the need for two separate systems(Ref. 45). Additionally, the installation process is streamlined, as this camera is pre-compatible with the modular payload system of the Perimeter 8+ drone. An alternative to this instrument is the DJI Zenmuse P1, a color camera that also meets the project's requirements (Ref. 46).

6.1.4 UAV Pheromone Detection

The plane will be equipped with a nucleic aptamer sensor to detect 4-vinylanisole (4VA), a pheromone that locusts emit when they begin swarming. As the number of locusts in a group increases, the concentration of 4VA also rises, making it detectable by the nucleic aptamer sensor (Ref. 47). The sensor is constructed by linking DNA aptamers to a metal-organic framework (UiO-66-NH2) via gold nanoparticles (AuNPs) and coating the structure with a silicon-based IDE. The integration of UiO-66-NH2 and AuNPs makes it easier for the DNA aptamers to bind to 4VA. The approach of leveraging the nucleic aptamer proves superior to standard gas sensors because of, as the study corroborates, the "unique binding ability of DNA to 4VA" (Ref. 47). Thus, the sensor can specifically detect locust swarms by measuring 4VA concentrations in the surrounding air. Additionally, it has a quick response time and exhibits a linear relationship to surrounding

4VA levels. The combination of specificity, quickness, and accuracy makes the nucleic aptamer sensor the most optimal to include on the UAV. Unfortunately, nucleic aptamer sensors specific to 4-vinylanisole are not yet readily available for sale, as this remains a relatively new and emerging technology.

6.1.5 Camera Footprint on the Locust Swarm

The camera footprints on the locust swarm needs to be calculated to determine the spacing of the UAVs when they are deployed. The Octopus Epsilon 140LC will be utilized to track identified locust swarms, ensuring that the biopesticide is sprayed efficiently and accurately. To calculate the footprint of this camera, the formula $\mathrm{L} = 2\mathrm{H}\tan\left(\frac{\mathrm{FOV}}{2}\right)$ will be used. In this equation, H is the camera height, FOV is the field of view in a singular dimension, and L is the camera footprint. The UAV will be flying at a height of 2.5 m above the locust swarm to optimize biopesticide dispersion (Ref. 48); thus, H can be replaced by 2.5 in the equation. The color zoom camera on the Octopus Epsilon 140LC has a maximum vertical FOV of 37.9° and a maximum horizontal FOV of 62.9° (Ref. 45). The updated equations for the color zoom camera of the Octopus Epsilon 140LC are included below.

Vertical Footprint

$$L = 2H\tan\left(\frac{\mathrm{FOV}}{2}\right)$$
$$L = 2(2.5)\tan\left(\frac{37.9}{2}\right)$$
$$L = 1.72$$

Horizontal Footprint

$$L = 2H\tan\left(\frac{\mathrm{FOV}}{2}\right)$$
$$L = 2(2.5)\tan\left(\frac{62.9}{2}\right)$$
$$L = 3.06$$

When solved, the color zoom camera's vertical footprint is 1.72 m and the horizontal footprint is 3.06 m, amounting to 5.25 m^2. A similar approach is taken for the infrared camera, which has a maximum vertical FOV of 18.9° and a maximum horizontal FOV of 25°. The updated equations are included below for the infrared camera of the Octopus Epsilon 140LC.

Vertical Footprint

$$L = 2H\tan\left(\frac{\mathrm{FOV}}{2}\right)$$
$$L = 2(2.5)\tan\left(\frac{18.9}{2}\right)$$
$$L = 0.83$$

Horizontal Footprint

$$L = 2H\tan\left(\frac{\mathrm{FOV}}{2}\right)$$
$$L = 2(2.5)\tan\left(\frac{25}{2}\right)$$
$$L = 1.11$$

When solved, the vertical footprint is 0.83 m and the infrared camera's horizontal footprint is 1.11m, amounting to 0.92 m^2.

6.1.6 Total Area Coverage of the Octopus Epsilon 140LC

Using the camera footprint, the total area coverage will be calculated with the following equation, $A = \int_a^b (GS \cdot L)\,dt$, in which A is the total area coverage, GS is the ground speed, and L is the camera footprint. In this case, the starting flight time of the UAV, which is zero, will replace a and the maximum flight time is b. The UAV will match the ground speed of the locusts, which is 1.5 m/s (Ref. 49) , or 5400 m/h. In the previous section, the footprint of the color zoom camera was calculated as 5.25 m^2, and the footprint of the infrared camera was calculated as 0.92 m^2. The maximum flight time of the UAV with the given payload is one hour (Ref. 23). The updated equations are included below.

Octopus Epsilon 140LC Color Camera

$$A = \int_a^b (GS \cdot L)\, dt$$

$$A = \int_0^1 (5400 \cdot 4.25)\, dt$$

$$A = 28,350$$

Octopus Epsilon 140LC Infrared Camera

$$A = \int_a^b (GS \cdot L)\, dt$$

$$A = \int_0^1 (5400 \cdot 0.92)\, dt$$

$$A = 4968m^2$$

The total area coverage of the color camera is 28,350 m^2, while the infrared camera covers 4,698 m^2. With these capabilities, the UAV is capable of capturing a large area of the locust swarm during its one-hour battery life. This, in turn, will aid in the accurate spraying of the biopesticide.

6.2 Aircraft Sensors

6.2.1 Aircraft Color Imaging

Similar to the UAVs, the surveying aircraft will be outfitted with an optical camera. A high-speed shutter is required to capture fast-moving locust swarms effectively (Ref. 44). Additionally, a gimbal stabilizer or object-tracking software will be necessary to ensure smooth and accurate image capture. Given the aircraft's high payload capacity, weight constraints are not a concern, allowing for the use of high-resolution cameras optimized for long-distance imaging. High-resolution will be required because of the distance from the V-22 Osprey to locusts; the aircraft will cruise at an altitude of 1600m while gregarious locust swarms travel at an altitude of 300-1000m (Ref. 50). The IXM 100 color camera, made by Phase One, is recommended for this purpose. Specifically designed for aerial systems, the IXM100 offers high shutter speeds and exceptional resolution (11,664 x 8,750 pixels), making it ideal for capturing detailed images during flight (Ref. 51).

6.2.2 Aircraft Hyperspectral Imaging

Finally, a hyperspectral camera will be mounted on the plane as well. With the ability to accurately detect many wavelengths of light, this sensor will be the best for the high altitude of the plane. Research has shown that locusts have a distinct reflectance of light from 710 nm to 900 nm

(Ref. 52). Using spectral unmixing, the plane will determine a locust swarm against a backdrop of greenery or vegetation. Desert backdrops are a drawback of hyperspectral imaging of locusts. The reflectance of sand does not significantly differ from that of locusts (Ref. 52). Hyperspectral imaging can accurately capture locusts up to 1000 hectares, exceeding the detail of satellite imagery (Ref. 52). Additionally, weight is not a deciding factor when choosing a hyperspectral camera because the plane has greater payload capacities. The preferred hyperspectral camera is the Specim-AFX10 (Ref. 53). This sensor has a range of 400-1000 nm, which includes the optimal range of 710 nm to 900 nm. The Specim AFX10 is specifically made for aerial systems, and it comes with an included gimbal stabilizer.

6.2.3 Camera Footprint on the Locust Swarm

The same equation, L=2H tan $\left(\frac{\text{FOV}}{2}\right)$, will be used to calculate the footprints of the cameras on the V22 Osprey. The aircraft will be cruising at 1600m, and gregarious locust swarms travel at an altitude of 300–1000m (Ref. 50). For this calculation, the average is taken for locust swarm altitude, which is 650 m. Thus, the aircraft will cruise 950 m above the average altitude of the locust swarms, and H is replaced with 950 m. The IXM-100 color camera has a vertical FOV of 64.1° and a horizontal FOV of 50.3°(Ref. 51). The updated equations are included below for the IXM-100 color camera.

Vertical Footprint

$$L = 2H\tan\left(\frac{\text{FOV}}{2}\right)$$
$$L = 2(950)\tan\left(\frac{64.1}{2}\right)$$
$$L = 1189.55$$

Horizontal Footprint

$$L = 2H\tan\left(\frac{\text{FOV}}{2}\right)$$
$$L = 2(950)\tan\left(\frac{50.3}{2}\right)$$
$$L = 892.05$$

When solved, the color camera's vertical footprint is 1189.55m and the horizontal footprint is 892.05 m, amounting to an area of 1,061.14 km^2. For the Specim-AFX10 hyperspectral camera, the vertical FOV is 30.37° and the horizontal FOV is 38°(Ref. 53). Similarly, the updated equations are included below for the Specim-AFX10 hyperspectral camera.

Vertical Footprint

$$L = 2H\tan\left(\frac{\text{FOV}}{2}\right)$$
$$L = 2(950)\tan\left(\frac{30.37}{2}\right)$$
$$L = 654.22$$

Horizontal Footprint

$$L = 2H\tan\left(\frac{\text{FOV}}{2}\right)$$
$$L = 2(950)\tan\left(\frac{38}{2}\right)$$
$$L = 337.37$$

When solved, the hyperspectral camera's vertical footprint is 515.68 m and the horizontal footprint is 654.22 m, amounting to an area of 337.37 km^2. These calculations show that, at any given moment, both cameras on the V-22 Osprey will detect a large area of the locust swarms.

6.2.4 Total Area Coverage of the Aircraft-Based Cameras

The same equation, $A = \int_a^b (GS \cdot L)\, dt$, will be used to calculate the total area coverage of the cameras on the V-22 Osprey. The flight time required to achieve maximum range is b, and the starting flight time, which is zero, will replace a. Given that the V-22 Osprey has a range of 1100 nautical miles (Ref. 18), or 2037.2 km, and the cruise speed is 240 kts (Ref. 54), or 444.48 km/h, the time required to achieve a maximum range of 2037.2 km is calculated as 4.58 hours. In the previous section, the footprint of the color camera was calculated at 1,061.14 km^2, and the footprint of the hyperspectral camera was calculated at 337.37 km^2. The updated equations are included below.

IXM100 Color Camera

$$A = \int_a^b (GS \cdot L)\, dt$$

$$A = \int_0^{4.58} (444.48 \cdot 1,061.14)\, dt$$

$$A = 2,160,182.23$$

Specim AFX10 Hyperspectral Camera

$$A = \int_a^b (GS \cdot L)\, dt$$

$$A = \int_0^{4.58} (444.48 \cdot 337.37)\, dt$$

$$A = 686,790.3166$$

The total area coverage of the color camera is 2,160,182 km^2 while the hyperspectral camera covers 686,790 km^2. The aircraft will most likely not achieve the stated area coverage, because payload and velocity changes can influence range. However, this difference will be minimal; the UAVs and the sensors are relatively lightweight compared to the total weight of the aircraft, and the V-22 Osprey will change velocity only when necessary.

Altogether, the total area coverage of the aircraft-based cameras display the capability to accurately track large areas of locust swarms. Extensive locust capture in multiple wavelengths is crucial for the deployment of UAVs and the success of the swarm extermination.

6.2.5 Locust Swarm Route Mapping Using Geo-Referenced Imaging

Images taken from the plane will be compared to existing data from maps in order to map out the flight path of the locust swarms. The cameras on the V-22 Osprey will geo-reference the locust swarm footage. Given the large area of coverage, locust swarms will be extensively and accurately mapped with the detailed cameras on the aircraft. This study utilized cameras on an Unmanned Aerial System (UAS) to geo-reference images (Ref. 55). "[I]nformation about the camera sensor, mounting characteristics, and attitude and position of the UAS in the geographic frame is used" (Ref. 55). The need for ground control points is eliminated with this method. This is crucial for the accuracy of the geo-referencing because desert and rural environments often lack ground control points. Geo-referencing will aid in studying swarm behavior as well, determining their affinity or aversion for specific crops, weather, soil conditions, etc.

7 CAD Model of UAVs

To prototype the proposed UAV and sensor framework, a complete 1:1 scale 3D model was created in CAD, complete with all the most important components outlined in the previous specifications. Standard, non-custom components that a physical device might incorporate—including but not limited to electronics, wires, nuts, screws, and bolts—were excluded from the model. The base drone is modeled using top-down bleuprints of the Perimeter 8+ aircraft available online. As there was no provided 3D file, the base drone is not an exact replica of the Perimeter 8+, but it is more than accurate enough for this purpose. The final model went through iterative design processes, keeping in mind practical tolerances and capabilities. Figure 3 depicts multiple angles of this CAD design.

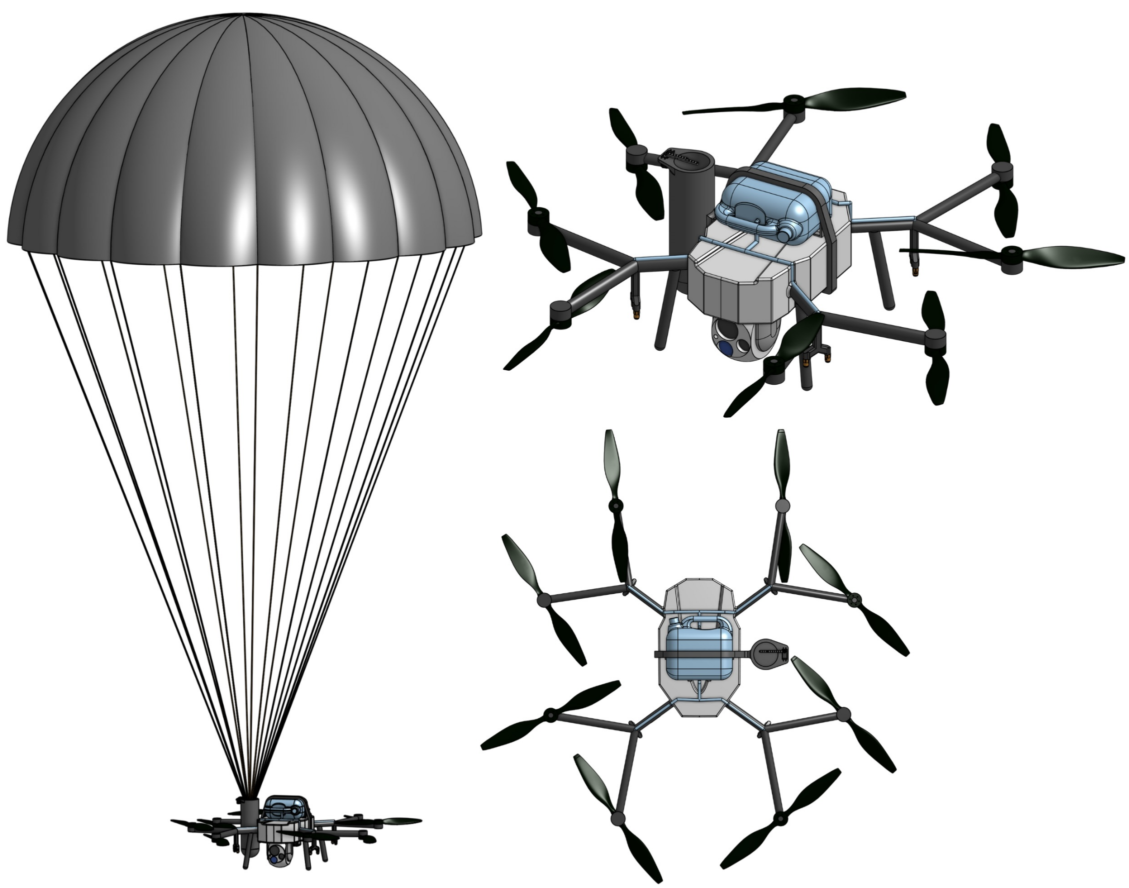

Figure 3.—Multi-angle 3D View of Proposed UAV; Parachute Deployed, Isometric, Top

Figure 4 is a drawing of the proposed CAD model with the critical dimensions of components outlined to the nearest millimeter.

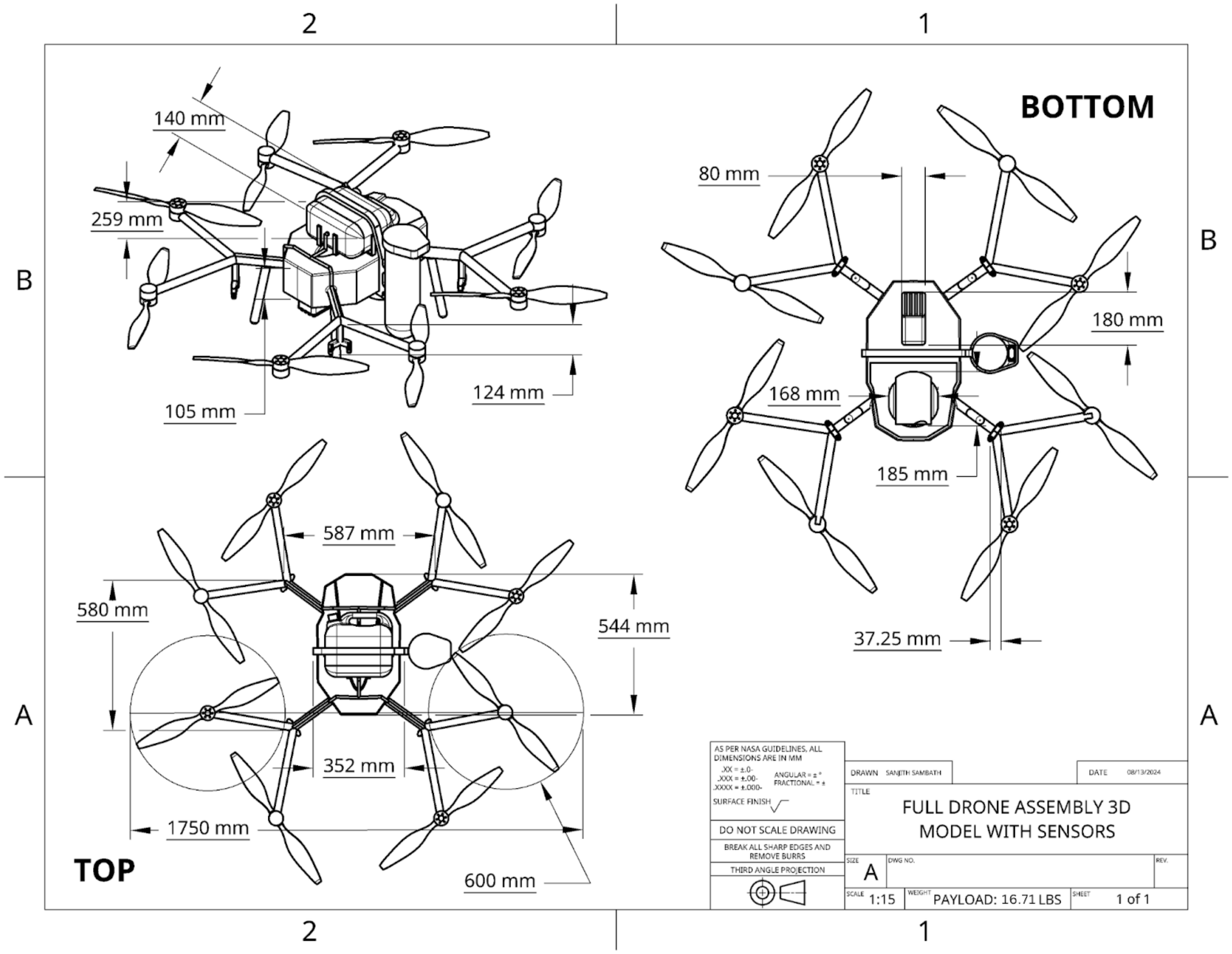

Figure 4.—Proposed UAV Drawing Dimensions

7.1 Weight of Pesticide Deployment Mechanism

1. **5L Pesticide Tank (Empty) - 1.06 lbs (HDPE Polyurethane)**
   The pesticide container's rigidity is vital. It will have to endure hot weather conditions without having a major impact on the bio-pesticides inside. HDPE Polyurethane is food-safe, UV-resistant, and very durable. The tank with this material would weigh 1.06 lbs.

2. **Pesticide Pumping Tubes - 0.41 lbs (CPVC)**
   The tubing also needs to be durable and lightweight, leading to the selection of CPVC, a material widely used globally for similar applications. This choice ensures the smooth transfer of biopesticides and weighs a total of 0.41 lbs.

3. **Liquids - 9.26 lbs (5 Liters of Diesel + Bio-Pesticides)**
   The total weight of the liquid components (diesel and bio-pesticides) is 9.26 lbs. Calculated with the density of diesel (0.832 kg/L) and the negligible weight of the pesticide.

4. **Spray Nozzle - 0.45 lbs (303 Stainless Steel)**
   The spray nozzle for the deployment of bio-pesticides is made from 303 stainless steel (Ref. 56), which is highly resistant to high temperatures and resists oxidation, ensuring reliable performance. This nozzle is also designed to spray in a conic pattern, maximizing coverage. The total weight of all 8 nozzles is 0.45 lbs.

5. **Spray Nozzle Mounts - 0.62 lbs (PLA Filament)**
   The four spray nozzle mounts weigh a total of 0.62 lbs. Designed to be 3D printed with PLA filament, these mounts will be more rigid and lighter compared to other materials like PETG and nylon. Additionally, PLA has less warping and shrinkage during the printing process, which ensures the precise fabrication of the custom designs created by the team.

6. **Pesticide Tank Mounts - 0.18 lbs (Aluminum 6061)**
   The pesticide tank mounts are designed to be custom-cut from angle stock. The total weight is 0.18 lbs.

7.2 Sensor Weights

1. **Reach M2 - 0.08 lbs**
   The Reach M2 will be used to track the location of the UAVs. Location info is essential for the decommision and reuse of the UAVs. An existing network of base stations can be relyed on to operate the RTK capabilities. The module will be added to the Perimeter 8 UAV. This is a commercial sold module that weighs 0.08 lbs.

2. **Octopus Epsilon 140LC - 2.8 lbs**
   The Octopus Epilson 140LC is used for its thermal imaging and color zoom camera to effectively recognize locust swarms and their general location in relation to the UAV. Its integration of both types of cameras is an optimal balance of weight and utility. This is a commercially sold camera that weighs 2.8 lbs.

3. **Gas Sensor - 1.92 lbs (ABS)**
   A nucleic aptamer sensor is required to aid the camera in ensuring the presence of a locust swarm. Sensing the pheromone emitted by swarms will enable the UAV to start its autonomous process. This sensor will be created using ABS due to its lightweight and durability in hot conditions. This is not a commercially sold sensor, and making it would result in a weight of 1.92 lbs.

7.3 Additional Components

1. **Parachute Holder - 11.26 lbs (PLA)**
   The parachute holder is constructed from PLA, known for its durability and biodegradable properties. its purpose is to deploy the UAV's parachute while the UAV is in descent. The estimated weight of the parachute holder is 11.26 lbs.

Altogether, the onboard components of the UAV will weigh a combined 16.71 pounds, significantly under the 22-pound threshold for which the Perimeter 8+ is rated. This leaves excess capacity for additional pesticides, sensors, or components if needed. The viewable 3D render of the design can be found here: 3D Render of UAV Design.

8 Optical Detection of Swarms with Machine Learning

Aerial locust detection and identification from the optical sensors onboard both the manned surveying aircraft and the UAVs necessitate the use of machine-learning image-classification models. To achieve this objective, a Conventional Neural Network (CNN) is considered the most appropriate model. This type of network is trained on extensive datasets and excels at discerning intricate shapes and patterns. The CNN will undergo training to identify locust swarms at plane-level altitudes and provide timely alerts to personnel responsible for deploying the UAVs.

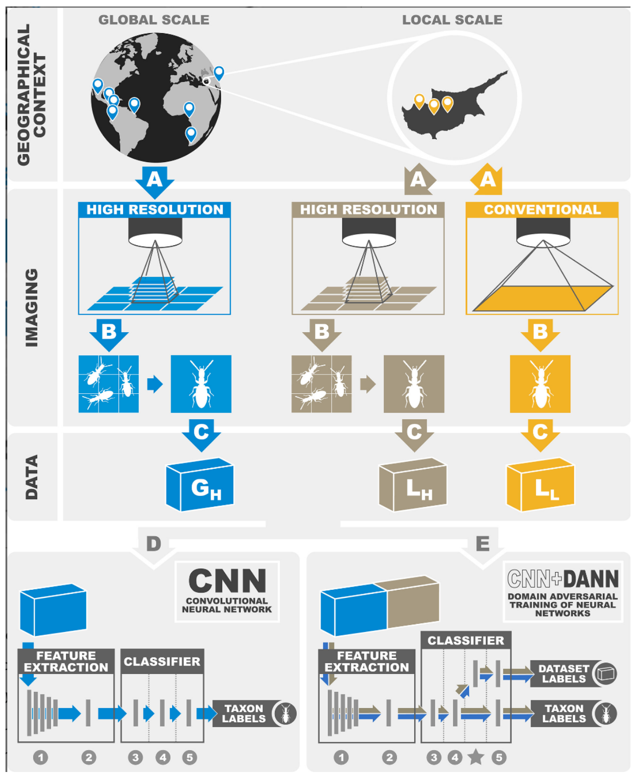

Figure 5.—Example use of CNN model on detecting small insects (Ref. 57)

Figure 5 illustrates the functionality of a CNN by dissecting images into smaller, more recognizable sections and comparing them with a specific animal. The CNN model will operate akin to the depicted scenario, with the aerial vehicle transmitting local data through the CNN model and comparing it with the visual characteristics of swarms of locusts at the specified altitude. It is imperative to acknowledge that CNN models require substantial amounts of training data, which demands additional time and financial resources. Nonetheless, this approach stands as the most precise method for detecting and pinpointing locust swarms from such altitudes. Several proven CNN architectures could be employed for this purpose, including AlexNet (Ref. 58), VGGNet (Ref. 59), and ResNet (Ref. 60), or a novel framework constructed to optimize detection capabilities. The basis of this approach has been validated in concept through multiple studies, such as one that successfully utilized this technology to for this same exact scenario, identifying locusts from UAVs (Ref. 61), and another that demonstrated the effectiveness of CNN techniques in detecting bees from similar airborne platforms (Ref. 62).

9 Extermination of the Locust Swarm

9.1 Metarhizium acridum-based biopesticide

In the extermination phase, locusts will be killed using a solution with a ratio of 50 grams of *Metarhizium acridum* spores from Novacrid® to one liter of diesel oil (Ref. 48). *M. acridum* was selected because it is a fungus that specifically attacks insects in the *Acrididae* family (Ref. 63), which includes the desert locust. In general, biopesticides only target a limited number of species, unlike popular chemical pesticides. Chemical pesticides are often preferred by farmers because they are fast-acting, but can harm non-target organisms as well, including humans and natural predators of locusts (Ref. 64). The effects of chemical pesticides can also be long-lasting, leaching into groundwater and other resources, unlike biopesticides, which biodegrade faster than chemical pesticides (Ref. 65), limiting harmful exposure. Therefore, biopesticides are more environmentally friendly than chemical pesticides, and are the best option for the purpose of this concept.

After *M. acridum* is sprayed on a locust, the fungus begins developing from resources present on the locust's wings. Then, the *M. acridum* fungus starts producing enzymes to break down the chitin and proteins present in the locusts' cuticle, which is a structure that protects insects from environmental harm (Ref. 66). This allows *M. acridum* to enter the insect and sporulate, creating a colony that spreads throughout the entire insect, killing it (Ref. 67). This process takes about 14-20 days (Ref. 68). Unfortunately, this means this biopesticide will not always be completely effective because adult swarms can move quickly. This can be combated in multiple ways. One, by over expressing one of the genes in *M. acridum*, *ATM1*, by using a promoter. This increases the production of an energy-producing enzyme and decreases the amount of time the fungus takes to colonize. The fungus can also become more deadly by inserting genes from other insects to increase or introduce the production of neurotoxins (Ref. 67). These will all increase the efficacy of *M. acridum*.

9.2 Delivery of the biopesticide

Once the UAV arrives atop the locust swarm, or catches up to the locust swarm if needed, it will begin to spray the pesticide. Locust swarms can move at up to 1.5 m/s (Ref. 49), while the Perimeter 8+'s cruise speed is 9.7 m/s (Ref. 23). In order to spray the locust swarm, the UAV will need to slow down, and, in some cases, hover over the locust swarm. Due to the relationship between power and velocity in multirotor drones, as seen in Figure 6, more power will be used to hover, but the Perimeter 8+ will not lose as much power as other high-endurance UAVs because it moves at a slower velocity than them.

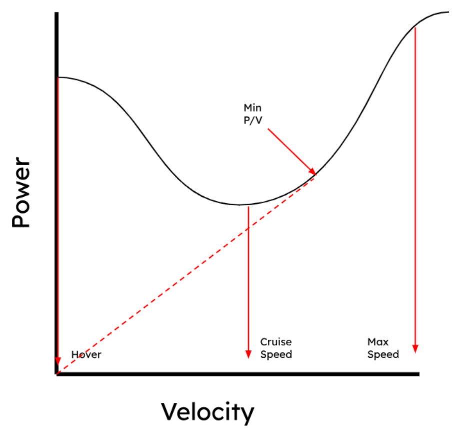

Figure 6.—Bucket curve for optimal power usage

The UAV will position itself 2.5 meters above the locust swarm, which has been found to be the optimal height for spraying the biopesticide solution. At 2.5 m, locusts have much lower survival rates compared to when sprayed at taller heights (Ref. 48). The UAV will spray the biopesticide through its four arms and eight nozzles, effectively covering the locusts. To calculate the theoretical coverage, assuming perfect conditions (absence of wind), the equation $A = \pi\,(D \cdot \tan(2))^2$ is used in Figure 7. The distance from the locust swarm would be 2.5 meters and the spray angle of the FullJet® GG Nozzle is 58° at 20 psi (Ref. 56), so the theoretical coverage area of one nozzle is about six meters squared. Discounting overlaps, the overall coverage of the UAV would be 48 meters squared. The dose rate of *M. acridum* is 50 grams per hectare (Ref. 69), and the UAV can store up to 5 liters of biopesticide, so the UAV will be able to spray up to 5 hectares of a locust swarm at once.

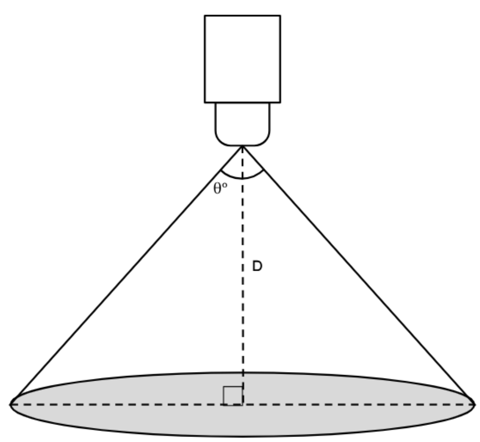

Figure 7.—Theoretical coverage

10 Deactivation of UAVs

10.1 Centralized or Secondary Pickup Point

Upon completing its pesticide delivery or when its range falls below 20%, the UAV will autonomously search for a designated retrieval location. Ideally, it will head to a centralized pickup point, which is a predetermined site within the operational range of multiple UAVs, providing an optimal landing zone for the V-22 Osprey. If within range, the UAV will land at this centralized location and await collection. To maximize efficiency and conserve the manned aircraft's fuel, multiple UAVs will aim to converge at this single location, reducing the number of trips required. In the event of an emergency or malfunction, the V-22 is capable of landing in various environments to recover the UAVs. If retrieval by the Osprey is not feasible, the UAV will navigate to a secondary location, such as a nearby gas station or farm, where it can be refueled. The Perimeter 8+ drone operates on 91-octane fuel (Ref. 23) or higher, which is readily available at most gas stations, ensuring that the UAV can continue its mission with minimal downtime.

10.2 Reuse of UAVs

After the UAVs have arrived at their landing location, they will be retrieved and transported back to the grounded aircraft, where they will undergo examination, refueling, and replenishment of pesticides and their parachute mechanism. This operational process is designed to streamline this operation and maximize efficiency.

11 Current Regulations and Legislation

Limiting factors in the concept are the aviation laws and regulations of the East African countries. For example, international tracking is difficult because of registration laws. Kenya requires every drone to be registered through the Kenya Civil Aviation Authority (KCAA) and stay under the height limit of about 133 m (Ref. 70). UAV imports and exports are banned in this country. Similarly, Somali laws mandate a permit for commercial and research UAV usage (Ref. 71). Rwanda has stricter regulations; registration is required and UAVs cannot fly above 100 meters from the ground (Ref. 72). Most other countries "are still in the early stages of drafting laws, prohibiting usage unless in exceptional circumstances and with strict approvals" (Ref. 73). Similar laws apply to privatized aircraft, with registrations being required in most countries. Altogether, the restriction of UAVs and aircraft in East African countries proves to be one of the most constricting factors in this specific aviation-based framework concept.

In order to effectively execute this paper, regulations will need to be altered or appealed in specific regions. Gregarious desert locusts can travel over 90 miles a day for multiple weeks at a time (Ref. 1). They can potentially migrate across international borders in their destruction of farmland. Current regulations on registration mandates for research UAVs hinder rapid response efforts. This process must be lifted or streamlined in order to avoid wasting time and potentially losing the swarm. Altitude requirements need to be removed as well; locusts cruise at a range of 300m-1000m (Ref. 50), far exceeding the legal maximums of nations like Kenya and Rwanda.

12 Feasibility and Practicality

Although the concept is designed to be as feasible as possible with existing technology of today, it is not inexpensive. Table 2 outlines some of the projected costs, along with proposed alternative technologies:

Equipment Type	**Recommended Technologies**		**Alternative Technologies**	
	Name	**Cost**	**Name**	**Cost to buy new**
Plane	V-22 Osprey	Unknown	AW-609	~$25 million (Ref. 74)
			Cessna 208	~$2.72 million (Ref. 75)
			King Air 360ER	$8.9 million (Ref. 17)
			C-23 Sherpa	Unknown
UAV	Perimeter 8+	$52,400 (Ref. 76)	Perimeter 8	$44,900 (Ref. 76)
RTK GNSS Module	Reach M2	$649 (Ref. 39)		
Thermal Cameras for UAV	Octopus Epsilon 140LC	~$59,000 (Ref. 77)	FLIR VUE TZ20-R	$6000 (Ref. 43)
			FLIR T1020	~$53,000 (Ref. 42)
Color Zoom Cameras for UAV	Octopus Epilson 140LC	~$59,000	DJI Zenmuse P1	$6800 (Ref. 46)
Hyperspectral Cameras for Plane	Specim-AFX10	Unknown		
Color Cameras for Plane	IXM100	$42,000 (Ref. 51)		

Table 2.— Estimated Concept Solution Price Report

The Perimeter 8+ drone costs upwards of $52,400 (Ref. 76), the Bell Boeing V-22 Osprey is a military aircraft. Government entities may have the rights to purchase this aircraft (Ref. 78), but individual agents or organizations cannot. A civilian version of this aircraft is available—the Leonardo AW-609 (Ref. 74)—but its payload is lower, so the duration and range of missions would have to be scaled down. Alternate aircraft, such as the Cessna 208B (Grand Caravan), King Air 360, or C-23 Sherpa, could also be employed, as previously mentioned; however, being fixed-wing planes, they introduce challenges in the UAV retrieval process during operations. On the positive side, these substitutes are much more accessible monetarily and availability-wise, and can be bought or rented. All require a trained pilot, which may also be difficult to find. As for alternative UAVs, Skyfront also produces the Perimeter 8, which has lower endurance (Ref. 23). Other options may include fire-fighting drones or crop-dusting drones, but both have lower flight times at maximum payload (Ref. 22)(Ref. 21). Most sensors and prediction technologies are commercially available and ready to use, but the research conducted in this paper failed to find a price for the nucleic aptamer sensor, as it is a novel technology. *M. acridum* is commercially available (Ref. 79), but it lacks immediate efficacy. The ideal solution entails the development of a rapid-acting, commercial biopesticide. The overall cost of this concept is substantial and likely prohibitive for individual farmers, even when considering alternate technologies. As such, the primary target consumers for this large-scale concept are governments and corporations that have the resources to invest in and benefit from its implementation on a broader scale.

13 Broader Implications

13.1 Effect

With the growing threat of climate change, food shortages have become more common. The World Food Programme goes as far as to say, "Climate shocks destroy lives, crops and livelihoods, and undermine people's ability to feed themselves. Hunger will spiral out of control if the world fails to take immediate climate action" (Ref. 80). For this reason, every bit of food is of the utmost value to the world. To help stop this disaster, the proposed concept seeks to prevent locusts from destroying more food sources. One locust swarm, measuring 150 million locusts per square kilometer, can eat the same amount as 35,000 people in one day (Ref. 81). As climate change continues, experts estimate that locust numbers will continue to mount (Ref. 82) and potentially spread worldwide (Ref. 81). A significant effort is required to prevent locusts from further damaging global food production.

Using the parent-child concept, the aircraft and UAVs are able to protect and survey large areas of land very quickly and eradicating the swarms efficiently. For every swarm the UAVs kill, the proposed concept can save food for 35,000 people daily, especially in areas already facing food scarcity (Ref. 83); with the entire fleet of 20 UAVs in one V-22 at only a 50% kill rate, the proposed concept can protect the food of 350,000 people daily. Not only does this help with food production by killing locusts, as farmers can hold a higher profit margin with increased crop yield. In some areas, 42%–69% of produce is destroyed by locusts (Ref. 81), but by removing these locusts from the equation, farmers can bring more crops to market and turn over more profits. Lastly, having a higher number of crops come to fruition means less water is wasted on crops that will only be killed by locusts, which will help combat droughts and use energy and resources more efficiently.

13.2 Other Uses

The concept also offers a plethora of additional uses aside from purely eradicating locust swarms. With climate change becoming an ever-growing threat, there is a large increase in forest fires ravaging the Earth. Leveraging the long-range capabilities of manned aircraft, this system can be adapted to address these fires by deploying UAVs equipped with fire retardants instead of biopesticides. These UAVs can be used to contain or extinguish fires in their early stages and have the ability to patrol at night when most other aircraft are grounded (Ref. 84). Additionally, the mothership system can be modified to deliver food and medicine to remote communities, a task that is currently resource-intensive due to accessibility challenges (Ref. 85). While this system is specialized for locust control, its adaptable design allows it to tackle a variety of other challenges with minimal retrofitting, offering a solution that can contribute to global efforts in many sectors.

14 Conclusions

Desert locusts pose a significant threat to agriculture and communities in regions such as Southwest Asia and Eastern Africa. Swarms of locusts, which can reach massive sizes, have the potential to cause severe crop losses and economic damage, as evidenced by the devastating outbreaks of 2020. To address this critical issue, this paper proposes an innovative solution utilizing an aviation-based framework for the detection and eradication of locust swarms. The approach integrates a manned aircraft with deployable UAVs to conduct a large-scale and targeted intervention. Once locust swarms are located, the aircraft deploys UAVs equipped with pheromone-detection sensors and thermal imaging systems to precisely target the swarms. The UAVs then apply biopesticides to exterminate the swarms over time.

The proposed aviation-based concept framework has the capacity to aid greatly in the global battle against locust swarms. This paper has combined the research and data from many other sources into one system. Altogether, this concept takes a passive and active approach to managing desert locust swarms—an innovative method that has the potential save countless crops and people throughout stricken regions.

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