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Farming the Future: An Approach to Precision Agriculture through UAS-based Thermal Scanners

**Names are listed in alphabetical order by first name. All authors contributed equally to this project.*

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This report is available in electronic form at

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Abstract

Food waste is a global issue, and it is extremely prevalent in the United States (U.S.) where one-third of the food produced goes to waste. The most common item found in landfills is food waste, which is why it is one of the most significant contributors to global warming with 8%. These negative environmental impacts also return to affect agriculture, as global warming changes climate patterns and adversely affects farming practices. In addition, the resources that were used to grow the produce are also wasted, including money, water, and time. To tackle this problem at its roots, this paper includes a design of an unmanned thermal drone that can be a farmer's third eye. This drone will scan over farms and provide data to the farmers about the health, ripeness, and moisture content of their crops through mounted thermal cameras and artificial intelligence. The information provided via these drones will help farmers to make more informed decisions about their crops, decreasing the chances that the crops will go bad in the field. These drones will be one of the first steps in preventing food waste, which will, in turn, help to reduce global emissions that result from farming.

Problem Statement

Due to a lack of comprehensive farm efficiency, food waste is a significant problem in agriculture [1]. In many instances, without sufficient agricultural observation, farms are notorious for spoiling some of their yield [2]. The food waste accumulates rapidly over time and ends up in landfills. While the landfills may be the waste's final destination, its impact is far from over. In the landfills, the food waste creates methane, contributing even more towards climate change. Throughout our research about food waste and its connection to many global issues, our team created a goal to prevent food waste at its core. With the help of aviation, the solution to this problem becomes more realistic. Applying aviation to solve the task at hand, the utilization of drones could monitor farmland to create the best yield. In contrast to current less technical monitoring methods, including testing the soil temperature and moisture directly, drones can monitor where humans cannot with better applications. Ultimately, reaching this goal could help reduce crop waste, increase yield, feed more families, reduce global emissions, and positively impact the economy.

Background

Main

An overwhelming third of the food produced in the U.S. goes to waste [3]. The lack of awareness and financial incentive to reduce food waste has allowed food waste to expand from landfills into environmental, economic, and humanitarian issues. Food waste is linked with the build-up of methane in the environment from not being appropriately distributed or disposed of. This food waste primarily comes from surplus food in different types of produce, both at the farm level and in grocery stores:

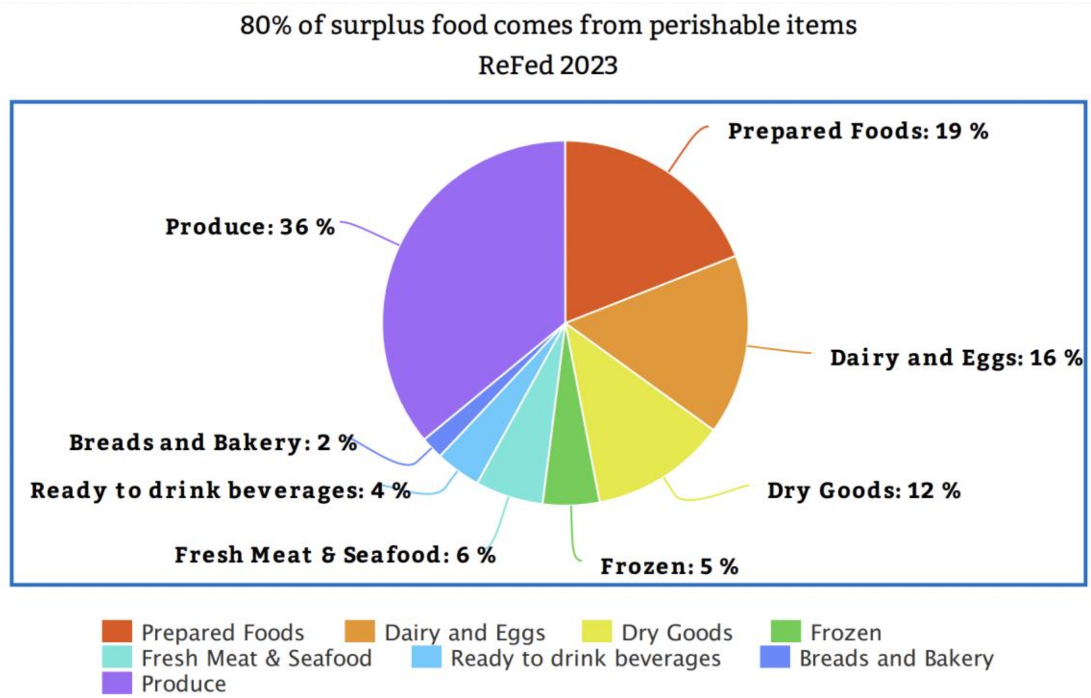

Figure A: Surplus food by type. Redrawn from ReFed 2023 [4].

Based on Figure A, it can be concluded that produce creates the largest amount of surplus food, which is the excess of supply over demand. Looking more in-depth at produce, about 13.3% of the world's produce is wasted after harvest and before reaching markets. This issue is further exacerbated by food loss throughout the consumer chain, including retailers and individual households. Approximately 17% of all food is lost at the consumer level [5]. In the U.S. alone, out of 15 million tons of surplus produce generated at the farm level, about 78% was ready to harvest but was left behind [6]. The crops left behind are considered waste because of factors such as rot, insect infestation, or pesticides. There are additional factors as well, such as requirements put forth by companies and restaurants that the crops be aesthetically pleasing and marketable [5]. If produce does not fit a certain high standard, most customers will not reach for it because they can find "healthier-looking" produce at a different market. Due to the requirements for visually appealing food, perfectly edible produce ends up in landfills because they do not sell or were never put on the shelf. Additionally, due to the cost of labor (or lack of laborers), many crops may not be harvested to meet the initial demand, which results in crops dying on the farms because they were not tended to in time. The disconnect between the demand for the produce that is required, and what can be used, adds to landfills in excess.

The accumulation of food waste in landfills is unnecessary and dangerous because it contributes to global warming, while simultaneously misusing resources and food. As stated earlier, through this build-up, about 8% of global emissions can be defined by the food waste that has accumulated in landfills [7]. This 8% contribution impacts the environment immensely, as "organic waste alone accounts for the largest amount of methane emissions and the amount of toxic gasses [derived] from it is equivalent to the one generated by 37 million cars or more than 42 coal-fired power plants" [8]. Food waste is a reliable contributor to global warming because of its mass in landfills. Global warming refers to the rise in global temperature near the Earth's surface. As long as food waste exists at its high, unchecked rates, it will continue to contribute to global warming on a huge scale. In return, global warming will affect agriculture. Increases in heat and changes in the ozone layer and greenhouse gasses impact agriculture significantly since agriculture depends on climate and temperature changes. Due to these temperature changes, habitat ranges, crop rotations, and other farming practices are hindered.

Furthermore, when food is wasted, the resources that go into growing the crops are also wasted. Agriculture uses about 80% of all water, but between 21% and 33% of it is wasted every year in the U.S. [8]. To minimize the water wasted for farming, water must be distributed properly. The more water that is wasted, the less water is available to provide for farming and agriculture which will inevitably decrease yield and production.

As the population increases, food must increase in abundance to keep up with humanity. However, if the food waste continually increases or stays the same, there is a constant loss of valuable produce that could be put to use. In parallel, the less food that is available, the more expensive prices will become due to lower availability. This results in a cycle of poverty, in which individuals of lower economic standing will find it more difficult to purchase enough food to eat which will result in decreased quality of life.

The economy takes the backlash of this food waste too. In 2021, about $444 billion was used to pay for surplus food [9]. This money was distributed between three main categories: donated food, recycled food, and food waste.

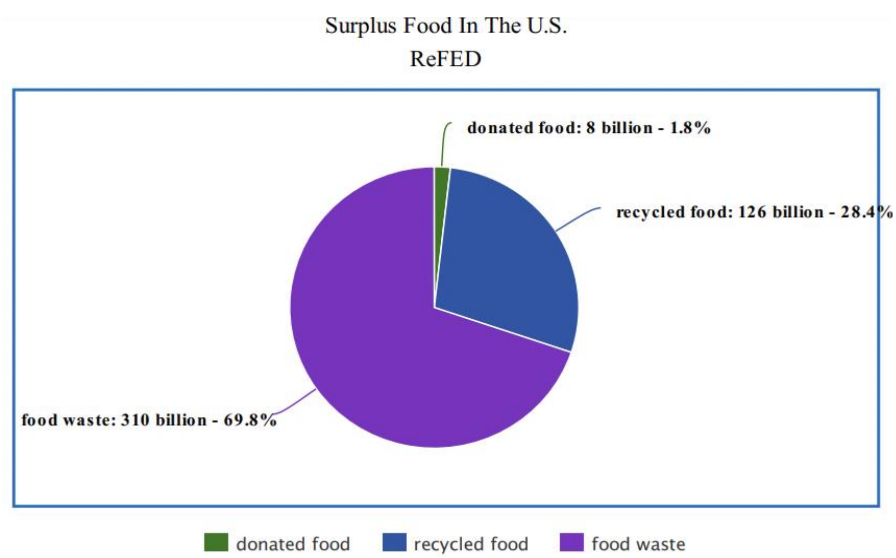

Figure B: Surplus Food In The U.S. Redrawn from ReFed [9].

Figure B shows that spending on food waste accounts for nearly 70% of the total annual amount of money spent on surplus food. Roughly $310 billion of the $444 billion is spent on surplus food that inevitably goes to waste. “According to ReFed, if we recovered about half (46 billion pounds) of the food being wasted, we could feed every hungry person in the United States 3 meals a day, every day” [10]. Studies have shown that when people are adequately nourished, they are more productive at school and work [11]. Not only could more people be fed if food waste is reduced, but global emissions would decrease, landfills would become smaller, and productivity in the economy would improve. Addressing food waste is one of the ways to mitigate global warming and also address food insecurity.

Solution

This team's solution utilizes thermal cameras on drones to monitor crops and aims to solve food waste at its source by optimizing what is already on farms and reducing food waste at its roots. To optimize the harvest, what is grown on the farms must align with what is ultimately harvested. Overproduction and waste should be minimized while the yield is maximized. Food waste results in a waste of resources, time, and money that could be prevented with the right technology. By employing this solution, drones can collect the data that farmers need to give their farms the proper care. Many companies that are currently in the market have created drones to scan for search and rescue, agriculture, and more. However, this drone is special because of its usage of artificial intelligence and quick retrieval of data, which reduces the cost of labor and time constraints for farmers to collect information manually.

Food waste reduction can be achieved with the help of unmanned thermal imaging drones. These drones will use thermal scanners to collect data about crop health because heat is an excellent indicator of crop health and maturity. The mounted thermal cameras can detect different levels of infrared waves and using AI, these images can be converted into data that could help farmers locate issues on their farms. The different levels of heat can tell farmers whether a plant is healthy or unhealthy if there are bugs or pesticides, and the moisture content of the soil, which could warn them to save their crops before they reach their maturity levels. Depending on the farmer's decisions, these drones can scan either multiple times a year, month, or week. The more often they can obtain this new data about their farms, the farmers should be able to convert their original (unplanned) food waste into efficiency and production. Over time, this decrease in food waste should positively impact the environment and economy. The resources that were originally lost through food waste will be put to better use and efficiency as well.

Though the current design of unmanned thermal drones has not been put to the test, many other commercial companies have put together their version of agricultural drones. DroneDeploy is one company that has applied its drones to agriculture and has collected data and seen significant improvement in their farms. DroneDeploy's agricultural drones, "use Crop Health Maps to generate variable rate prescriptions and quantify the benefit of your services pre- and post-treatment applications" [58]. The continual retrieval of new data from their unmanned drones has given farmers the ability to provide all their crops that extra care. This attention to detail has not only saved crops but also increased revenue by preventing the loss of revenue from waste).

Previously, the cost of labor and the vastness of farms has created a barrier between what should and should not be harvested. With these drones, optimization of production will become far more achievable.

FAA Regulations

However, to have drones operated on farms, many rules and restrictions need to be followed. The drone is subject to the Federal Aviation Administration (FAA) Small Unmanned Aircraft Systems Regulations, Part 107 [12]. These regulations apply to commercial and non-recreational use of drones weighing less than 55 pounds (25 kilograms). The key provisions of Part 107 are:

1. Operators of the drones must receive a Remote Pilot Certificate by passing an aeronautical test. This certificate ensures that the user knows the proper rules and requirements to use the drone.
2. Drones must weigh less than 55 pounds, inclusive of payload and cargo, and they should be registered with the FAA with a proper registration number.

3. The drone must stay within visual line of sight operations.
4. The drone can only fly during daylight operations.
5. The drone cannot exceed 100 miles per hour or 400 feet above the ground to stay within the maximum speed and altitude regulations.
6. Operators are required to do preflight inspections.
7. Only one aircraft per operator.

For more information about local, state, and federal regulations, see the Code of federal regulations.

Staying within these stated aviation regulations, the goal is to utilize drones to survey agricultural farms. Equipped with a thermal signaling camera, the drones can survey fields to create an overall summary of the yield. To produce a greater yield, farmers require a consistent level of moisture and maintenance of pests. Furthermore, harvesting the crops at the right time is essential. With a drone equipped with a thermal signaling camera, it can scan the field for these variables. Variations in temperatures can signal differences in moisture levels.

Drone Requirements

Introduction

Drones are a step toward the future and can aid or even replace tasks done by workers. In the agriculture and farm industry, drones can provide valuable information to a farmer. Drones are the most applicable for many reasons. Unmanned drones could be launched at any time that still abides by aviation regulations, making them much more flexible than manned aircraft that may require a runway and much more restricted airspace. Furthermore, unmanned aircraft have precise mapping and decision-making abilities due to their maneuverability, often making fewer errors than manned aircraft make. In the absence of a GPS on farms, drones can easily adapt to the farm layout with a "Highly mechanized process with an accuracy usually exceeding that…" of manned aircraft [13]. With the data obtained from the mapping, the farmers can then designate their resources to create the best yield and also discover when it is best to harvest. Therefore, unmanned drones are more efficient than manned aircraft in many ways for this project.

When deciding what camera to use, thermal cameras best fit the purpose. Thermal imaging is helpful as it allows the user to detect minuscule levels of temperature differences that are not visible through the naked eye, or, in this instance, through a visible light camera. Whether it be the heat signature from pests or even just moisture levels, thermal cameras enable drones to pick up on those signals. Heat patterns picked up by thermal cameras provide valuable information into agriculture health which may not be nearly as effective through visible light cameras. The thermal camera would have a multi-faceted purpose with these heat patterns. These purposes range from "...detecting and controlling pre-symptomatic pest and disease issues, pinpointing common issues in both drip and pivot irrigation systems—including leaks, clogged emitters, pressure issues, evaluating soil fertility and salinity…" to even "...optimizing irrigation scheduling and system design for terrain and soil conditions…" [14]. For instance, using thermal imaging to find differences in levels of pests allows farmers to designate their pesticides and resources accordingly. Additionally, finding differences in moisture levels would allow the farmers to tweak and refine their irrigation systems and ultimately achieve the best fertility of their yield.

Knowing that a thermal camera is most suitable, it is vital to know the price point and how the camera will tie in with the drone. To start, these thermal drones range from roughly $5,000-$15,000 per drone [15]. Additionally, thermal drones operate how one might expect: a thermal camera is mounted to a drone with high-definition equipment to allow the user to see the heat signatures of objects, plants, and animals. This, however, may be highly inaccurate while the drone is moving at a high rate of speed; as thermal images have longer wavelengths, this can cause thermal blur, where the heat signatures are distorted. This makes it vital to operate at a slower speed to ensure image quality; the drone(s) would have to fly at 1-6 meters/sec to allow for more precise and accurate readings, due to the frequency of the camera [16]. Thus, it is essential to use a drone that is efficient at moving at this rate of speed. For this project, the team decided to use a multirotor drone, which can fly at the necessary speed and can hover in place, should further inspection of the area be needed.

However, since the thermal imaging camera is of significant size and weight, it is also important that the drone is large and strong enough to have a payload sufficient to efficiently carry and utilize the camera, while staying within FAA regulations, keeping the drone under 55 pounds. Therefore, one problem faced when designing the drone was how to ensure the longest flight time while still being able to carry and utilize the camera payload and minimize weight. In designing the drone, careful consideration was required. In pursuit of surveying the fields as fast as possible, an increased flight time of one drone isn't the only solution.

Another way to cover the farms faster is by having a larger number of drones surveying the farm. With large farms, regardless of how efficient the drone design is, it is unlikely to be able to survey the entire farm on one charge. Although a charging station with which the drone can use may mitigate the issue, multiple drones may be needed. With multiple drones, the surveying tasks required could be divided among the drones, and the entire farm surveyed more efficiently. On large fields, surveying the land in a short period would prove to be difficult while using a single drone. Thus, using multiple drones may be the solution. With a single drone, not only is the mission time lengthened but there is higher uncertainty when mapping with constant charges needed. On the other hand, "...with multiple drones or a fleet of drones, it is possible to identify a globally optimized solution to reduce the total required mission time" [17]. However, the cost of a single drone, much less a fleet of drones, may nonetheless be prohibitive. A solution to this price point is having a team that the farmers can hire to survey with drones. This approach eliminates many barriers for farmers such as price, piloting licenses, drone maintenance, and overall time consumption for the farmers.

An additional factor to take into account when theorizing about drones is how to combat challenges with the weather. However, since crop surveillance is not as time-sensitive as other challenging problems such as forest fires, weather is not a focused problem. For example, if there is rain or high winds one day, the deployment of the drones can wait until one of the following days when the weather conditions are more suitable for drone surveillance.

State-of-the-Art Drone Model Options

Two common possible drones for this application are the DJI Matrice 30T and the Mavic 3T. DJI is a Chinese-based technology company, well known for quality drones. The report follows the plan to use DJI drones, for the reliability, advanced and convenient software, and accessibility of spare parts and repair services. The data collected would be displayed in the DJI Thermal Analysis Tool Software, and other third-party software [18].

The Mavic 3T is a thermal drone based on the ultra-popular Mavic family, used by photographers and fire departments around the globe [19]. The drone comprises a durable, commercial-grade lightweight polymer-plastic construction, and features a camera with 3 sensors, the shutter, the thermal sensor, and the lens. The camera offers a 56x zoom, a 640x540 resolution thermal camera, and a 48MP wide-angle camera. A key feature - the thermal camera can be used as an option - by using the regular wide-angle 4K 60 FPS camera, and overlaying it with the thermal highlights. The Mavic 3T has around 40 minutes of hovering and flight time with a 2.3-pound takeoff weight. To add, the DJI Intelligent Flight Battery has a 5,000 mAh capacity and a Lithium-Ion battery. These cost around 200 dollars per battery pack.

A farmer could use the regular camera for just regular use - surveying the field, and the thermal capabilities to detect thermal signatures in crops that need more water/fertilizer/etc., and detect pests. As the drone already comes with a 56x zoom, they would also be able to see further, act as binoculars, monitor livestock, etc.

The Matrice 30T is a commercial-grade drone specifically made for emergency response, search and rescue, fire rescue, and other extreme situations [20]. It is much larger than the Mavic, as it has been designed for rugged situations. These are both controlled with the DJI RC Plus Controller, which allows them to switch between camera modes and the functionalities of a regular drone remote. The Matrice offers a higher resolution 4K 30FPS camera that comes with 40x optical zoom, and 4x digital zoom, on the Zenmuse H20N camera. Although the camera setup is not as high definition on paper, the Matrice offers more stable thermal imaging, capable of producing high-quality thermal signatures at a speed of 6-10 m/s, as well as having a much clearer heat map, around 20 times more precise and accurate and much more detailed enlarged and zoomed in images than the Mavic. The laser rangefinder allows for relatively precise distance measurements of up to 1,200m and features a tracking feature, which we can use in conjunction with AI to hover the drone and monitor the heatmaps. The Matrice is also designed for extensive fire and search and rescue operations, as the plastic is much more durable, and weather resistant. The Matrice has a max takeoff weight of 8.8 pounds and a flight and hover time of 36 and 42 minutes.

As the Matrice 30T is much more weather resistant, and durable, it would be suitable for harsher conditioned farms, while the Matrice 30T could suit most farms, being around $9,000 cheaper, as well as being lighter, faster, and more user-friendly, having more flight and hover time than the Matrice.

The DJI Agras T30 is an agriculture drone currently under consideration, intended for farmers to spray crops with chemicals [21]. It is the largest spray drone in the world, has a max speed of 7 m/s, and is the size of a desk. This drone has a max t/o weight of 66.5 kg and can be programmed with the DJI software to follow a flight path. This flight path may be used in conjunction with the findings of the thermal imaging map, to provide fertilizer and pesticides in a more targeted manner. Working with thermal drones, agricultural drones would allow farms to be much more efficient, and cleaner - as drones do not produce any emissions by themselves, and free up the workload on the farmer [22].

Thermal Scanner

Introduction

The most vital component of this solution is the thermal camera that will be attached to the drone. The thermal camera is what will capture all of the necessary details about crop health, pests, moisture, and more information for use by farmers. That data is essentially what the farmers will be purchasing through the drone, so it is necessary to ensure that the camera is efficient and implemented effectively. There are many factors to consider including the wavelength, mounting, and resolution of the camera.

Wavelength

When considering the composition of a thermal camera, one would notice that the most important factor is the thermal scanner. In general, there are three different types of thermal scanners: short-wavelength, mid-wavelength, and long-wavelength [23]. Each type serves its specific purpose. Shorter-wavelength thermal scanners are meant to work more efficiently in higher temperatures while longer-wavelength thermal scanners work better in lower temperatures [23]. Short-wavelength scanners detect light between 0.9 and 1.7 μm, mid-wavelength scanners detect light between 2 and 5 μm, and long-wavelength scanners detect light between 7 and 12 μm [23]. Everything in the universe emits light, though the wavelength of these emissions varies, which is why selecting the right type of thermal scanner is important. It is necessary to know what exactly is being scanned before selecting the range of detection so that the desired information can be collected in high resolution. At lower temperatures (cold, dry, 30 degree weather), the energy emitted is mainly detectable at long wavelengths, and at high temperatures (tropical, humid, 90 degree weather), the energy emitted is mainly detectable at short wavelengths. An example of this phenomenon can be seen when one observes that metal glows as it heats up because the thermal energy shifts from longer wavelengths to shorter ones, therefore entering the visual light spectrum, and becoming visible to the human eye [24][25]. The existence of the three types of thermal scanners provided the team with an opportunity to create multiple drone products, one with each type of scanner. This way, depending on the climate conditions of each farm, they could purchase the drone they need (e.g., A farmer in southern California might want to purchase a drone with a short-wavelength scanner due to the high temperatures, while a farmer in a colder area like Canada would need to account for pests during the dormant season and would need a long-wavelength scanner). Unfortunately, it is not possible to take advantage of this opportunity as the main factor in this project is to maintain usability for an average farmer, so the most viable and efficient option is to use a mid-wavelength camera. This type of camera would allow the user to get the widest spectrum of wavelength and the most adaptability regarding temperature capability for the drone. It would provide for the most widespread application of the drone. If thermal imaging drones provide a great enough benefit, the next move would be to expand horizons and provide different models focused on different wavelengths, so farmers can have more accuracy.

Mounting

The mounting of the camera is a very important facet of the situation to consider to ensure the product works properly. If the mounting is not stable, the pictures could be shaky, or worse, the camera could fall off. There are two types of mounts possible for thermal cameras: fixed mounts and attachable payloads [26]. As the name suggests, fixed mounts are camera mounts that do not allow for cameras to be switched out [26]. The large benefit of this type of mount is that it guarantees stability as the camera is locked out with no moving parts. On the other hand, attachable payloads are mounts that allow for cameras to be swapped depending on the situation [26]. For this case, this sensor generally does not need to be changed as the drone is only meant to gather thermal data for the farmers, but is capable of utilizing an attachable payload mount. Flexibility is always beneficial, and if a farmer were to need to use a multi-spectral camera, having the option to mount it onto this drone would be very helpful. Using an attachable payload also allows for better functioning in coherence with a gimbal. Gimbals are another necessity regarding mounting that allows for steady images. Gimbals are stabilizers that move with the drone to hold the camera in the same place, regardless of external influences [26]. Gimbals are also extremely useful in the way that they are automated, but can also be controlled manually, meaning that the camera can be moved in any direction wanted by the farmer. This allows them to get the best angle to see the health of their farm effectively. Most gimbals are built along with thermal sensors and are sold together as a whole product. Regarding the camera to implement alongside a fixed mount, a dual-sensor camera (ex. Zenmuse XT2) would be best for this implementation. A dual-sensor camera combines a thermal sensor and an RGB sensor to get both types of input for data collection [27]. In addition to the thermal sensor, the RGB sensor can help the farmer operate the drone as it will provide a visual and it can also provide generic aerial images of the farm so farmers can have that information as well.

Resolution

As mentioned earlier, most thermal cameras maintain a lower resolution, but we chose to vie for something better. Despite it being the most expensive of all of the options, a 1024x768 resolution thermal sensor for the drone is most useful. The reasoning for this is that to collect information that is useful to farmers, the camera needs to produce clear images. Things like crop moisture and harvest readiness can only be detected in high definition in thermal cameras. With thermal resolution, there are 3 stages: detection range, recognition range, and identification range [28]. Detection range level sensors are only capable of creating images that allow the human eye to identify that there is an object present [28]. Recognition range sensors create images that are clear enough for someone to identify the object that is visible in the photo [28]. Lastly, identification range level sensors are capable of creating images so clearly that one can discern minute characteristics of the object shown [28]. For thermal cameras, 1024x768 is considered a resolution that falls under the identification range umbrella, which is why it is vital for farmers [28]. It allows for specific crop health qualities to be visualized and analyzed.

Software Components

Navigation

To ensure optimal convenience and efficiency for the UAS (Unmanned Aircraft System), picking the right algorithm for navigation is crucial. The "Navigation" section discusses four algorithms, three of which were considered top contenders, which one was chosen, and for what reasons. It discusses Dijkstra's Algorithm, as many of the algorithms found a basis in this algorithm, the A* algorithm, Rapidly Exploring Random Trees (RRT), and Probabilistic RoadMap (PRM).

It is important to acknowledge that using artificial intelligence in unmanned drones is still strictly controlled, and as such they must abide by certain regulations. For example, all drones must be overseen by a licensed drone operator, and must operate within visual line of sight. These restrictions do limit the capabilities of our drone, however, changes in FAA regulations may open new avenues for the software discussed in this section. However, considering the current regulations, the unmanned navigation portion of the report will discuss hypothetical applications of the algorithm, and the speculative side of it will be further discussed in "Future Advancements".

Dijkstra's Algorithm

Conceived by Dutch computer scientist Edsger W. Dijkstra, Dijkstra's Algorithm is a popularly used algorithm to find the shortest distance between two points, or nodes [29]. The algorithm starts at a source vertex and selects the next closest vertex. It will then visit the next node's neighbors and update its tentative distance if there are shorter paths found. This process will repeat until a path is found or all vertices have been visited. As observed in other algorithms, this basic skeleton is repeated with small changes in many path-finding algorithms.

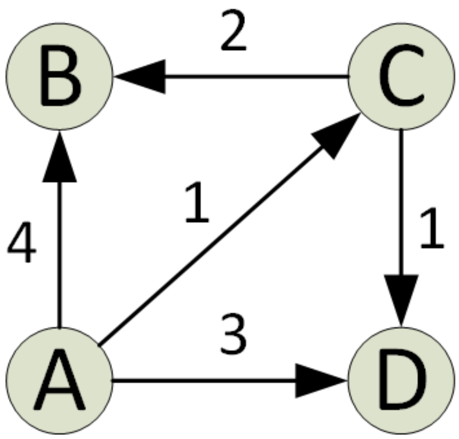

Figure [C]: Visualization of Dijkstra's Algorithm [30].

The distances between the nodes are labeled along the arrows. Figure [C] takes the start vertex as "A" and the end vertex as "C". In this example, going from A to C directly is the quickest path, compared to going from A to B to C, A to D to C, or any other configuration. An understanding of the functionality of Dijkstra's Algorithm is important before moving on to pathfinding algorithms that will be used in the field.

A* (A-Star)

A* is a popularly used algorithm in pathfinding [31]. To begin, the algorithm stores nodes that have yet to be explored and those that have already been explored. The algorithm starts with the starting node in the open list and sets the "f" value representing the cost of reaching the goal from that node to zero. While the open list contains nodes, A* will continue to run through it, calculating the "f" value for every node and its neighbors to find the ideal path, eventually it will arrive at either a heuristic path or no path at all. The main goal for A* is to reach the defined goal with the least cost possible, giving the algorithm its reputation for a heuristic solution [32]. Figure [D] shows a visualization of the A* Algorithm. The green box labeled "0" is the start vertex, and the blue box labeled "19" is the goal. The boxes colored red in between are labeled with numbers that represent the cost of going from one "box" to another [33].

A* is advantageous for several reasons. As it is a general-use algorithm, it can be implemented in any environment, so long as the domain is capable of being represented as a graph structure. The algorithm can be used in various search space representations and dynamic environments. In addition, A* guarantees a feasible solution due to its heuristic approach, and while this trait may have its downsides, this ensures a complete and tangible path. However, as it is a heuristic, A* depends heavily on the calculation of "f" and subsequent values, meaning that in a more complex environment, A* may not find the most optimal path or may take too long to converge to the goal. A*'s memory requirements may also increase significantly in complex environments. Given the above, it can be concluded that A* is suited to find optimal paths in grid-based, largely static environments.

7	6	5	6	7	8	9	10	11		19	20	21	22
6	5	4	5	6	7	8	9	10		18	19	20	21
5	4	3	4	5	6	7	8	9		17	18	19	20
4	3	2	3	4	5	6	7	8		16	17	18	19
3	2	1	2	3	4	5	6	7		15	16	17	18
2	1	0	1	2	3	4	5	6		14	15	16	17
3	2	1	2	3	4	5	6	7		13	14	15	16
4	3	2	3	4	5	6	7	8		12	13	14	15
5	4	3	4	5	6	7	8	9	10	11	12	13	14
6	5	4	5	6	7	8	9	10	11	12	13	14	15

Figure [D]: A* Algorithm visualization [33].

Rapidly Exploring Random Trees (RRT)

In Figure [E], a visual depiction of Rapidly Exploring Random Trees, or RRT, demonstrates how the algorithm functions. RRT starts with an initial configuration and forms a tree from that root node. As it travels in the search space, RRT will randomly sample a configuration, representing a new position for the UAS, and find its nearest neighbors, aptly named parent nodes [34]. If the UAS collides with an obstacle, RRT will discard that configuration and sample a new one. However, if there was no collision, the configuration is added to the RRT as a new node, and these steps are repeated until a goal configuration is reached.

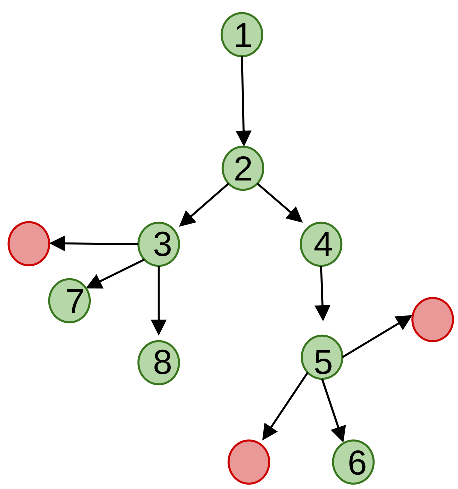

Figure [E]: Visualization of how RRT explores the space around it. Green-colored circles indicate safe nodes, while red indicates unviable nodes.

Due to its explorative nature, RRT is well suited for complex, multi-dimensional environments as it can adapt to many circumstances. It is well suited for exploration in previously unexplored areas, as it can navigate around dynamic obstacles. It is also computationally efficient, due to its random sampling [35]. RRT is best for its scalability, as the efficiency does not degrade much if the search space is increased. However, RRT does not ensure an optimal solution the way A* does and instead focuses on just finding feasible paths. Its main purpose is exploration, and this goal is reflected by the paths and trees formed by the algorithm. Overall, it is observed that RTT is generally well-suited for exploratory purposes.

Probabilistic RoadMap (PRM)

The third algorithm explored is Probabilistic RoadMap or PRM [36]. This algorithm begins by initializing start and end positions, search boundaries, iterations, max number of nearest neighbors for each node in the roadmap, and more as variables. It checks if the specified number of iterations have been completed, and if this is not the case, PRM will randomly select points from the search area. A K-Dimensional tree is formed, where points will be grouped into a tree to perform nearest-neighbor queries on points. The neighbors of each node in the K-D tree will be identified, and collision-free nodes will be connected. When all nodes in the K-D tree have been connected, a roadmap will be formed, giving the vehicle a pathway to follow. Figure [F] illustrates the decision-making process and the K-D tree formed from the algorithm.

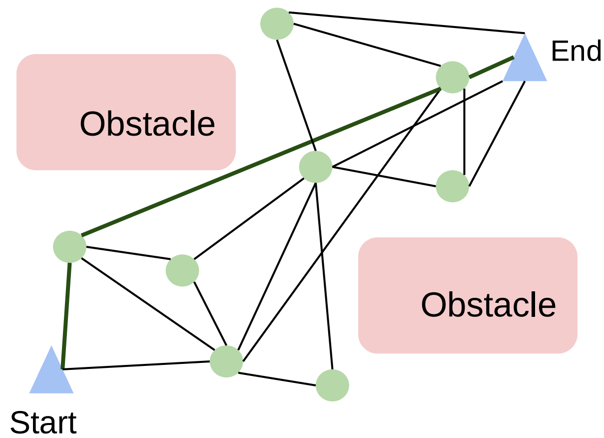

Figure [F]: Sketch of how PRM traces paths between nodes along a path. The bolded path is the most optimal one.

The PRM is flexible and capable of navigating complex environments [37]. Similar to RTT, PRM constructs a roadmap of all feasible paths by sampling various configurations and connecting them. It can also incorporate various kinds of constraints, such as kinematic or dynamic obstacles/constraints, and adapt around them. Like A*, PRM is also probabilistically complete, creating a level of assurance that PRM will be able to find feasible paths. However, these benefits come with a cost. PRM faces high memory requirements, which could create a load on storage. It is also computationally expensive which could get worse if the environment is complex. Given these traits, it is clear that PRM is best suited for complex but pre-processed environments.

Summary

Provided the above discussion, the team concluded that A* is best suited for its purposes. The A* algorithm is ideal for grid-based, static environments, and features that align with the field space. Farm fields are grid-based and static, often following a uniform pattern of rows and columns. They are fairly uncomplex and are often placed in quiet, unobstructed rural areas where complex obstacles and constraints are rare and therefore less of a concern. For this study, a Python implementation of the A* algorithm can be found here: https://github.com/aryaarawat/NASAAF-ThermalScannerswUAS/tree/main [38].

```python
        neighbors = get_neighboring_nodes(current_node, grid)
        for neighbor in neighbors:
            if neighbor in closed_list:
                continue

            #Cost calculation! We can calculate how much each node "costs" us, using the values of g and h
            neighbor.g_cost = current_node.g_cost + 1
            neighbor.h_cost = calc_distance(neighbor, end_node)
            neighbor.f_cost = neighbor.g_cost + neighbor.h_cost
            neighbor.parent = current_node

            if neighbor not in open_list:
                heapq.heappush(open_list, neighbor)
            else:

                index = open_list.index(neighbor)
                if neighbor < open_list[index]:
                    open_list[index] = neighbor
                    heapq.heapify(open_list)
```

Figure [G]: Image of code. Demonstrates how A* is implemented in the Python programming language.

Figure [G] contains an image of the main A* algorithm function code. While this implementation is not what would be used, it allowed the team to understand the limitations and capabilities of this algorithm. For example, while A* is optimized and probabilistically complete, it is still a heuristic solution with limitations. While it returns a feasible path, it may ignore paths that would've been more efficient if they initially seem costly. While this code is a helpful tool, it does not take into account the presence of obstacles or more complex search spaces. A tangible implementation meant for field use would account for those factors as well.

Still, compared to the other options, A* is far more effective. While RTT and PRM are both valuable algorithms, PRM construction can be heavy and memory-intensive, which may cause unnecessary problems for the UAS user. Similarly, RTT's exploratory nature is not needed in the monotonous, generally clear airspace of a farm. With these variables taken into consideration, it has been determined that A* would be the most efficient algorithm for the UAS.

Image Analysis

The second part of this section covers "Image Analysis", or which potential methods could be used in analyzing input from the thermal scanners. Unlike autonomous vehicles, the object or features the UAS is detecting will not be big, boldly colored, or even easily visible. Artificial intelligence should be able to pick up the heat signatures of pests, diseases in plants, and ripeness of crops. Aligned with this, the image analysis model must be capable of detecting and identifying small details. Most importantly, the algorithm should do all the heavy lifting for the farmer so that he does not have to spend too long doing data analysis. This portion will cover the model being used, its implementation, and its various advantages and disadvantages.

Discussion

Three image processing approaches are Scale-Invariant Feature Transform (SIFT), Convolutional Neural Networks (CNN), and You Only Look Once (YOLO). SIFT works by identifying key points and extrema in an image, pinpointing common distinctive points between multiple images taken, assigning an orientation and name to it, and matching that feature to new images [39]. SIFT is robust to changes in scale, angle, and light, which opens it up to various kinds of applications. SIFT has a high accuracy rate, and compared to CNN, it focuses a lot more on key points, rather than key features, which is especially valuable in location detection or place analysis. However, due to its heavy computational cost, and sensitivity to image noise, SIFT may be logistically difficult to implement. In addition, SIFT is very memory-intensive, making storage and analysis that much more complicated and expensive.

Figure [H]: The above image shows how SIFT takes notes of critical points used for image analysis [40].

CNNs are modeled after how neurons in the brain function [41]. It is most clearly identified by the presence of layers, and most importantly, the convolutional layers which contain filters that extract the edges, textures, and shapes from an image. This output is passed through numerous other layers such as connected layers, and pooling layers, which can be adjusted and added depending on the goals of the CNN. They have demonstrated great accuracy and handling with large amounts of data, and like SIFT, they can be immune to translation, rotation, and scale variance [42]. Unfortunately, CNNs also need large amounts of labeled data and can be computationally expensive as well. Most importantly, interpretability can be hard, and it may be difficult to understand what the network learned. This can lead to flaws in image detection and analysis.

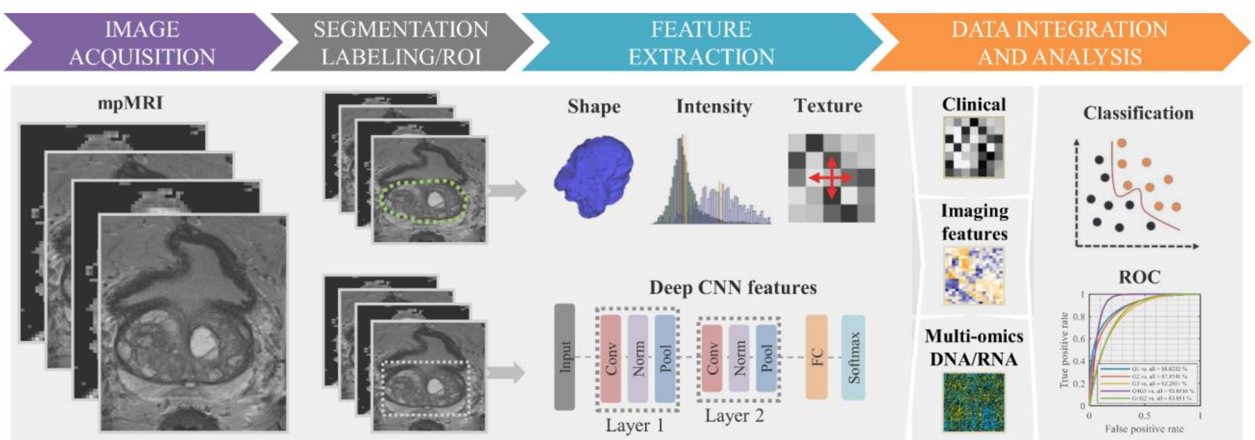

Figure [I]: Flowchart of each step in a CNN model. Shows the process to acquire, label, extract, and analyze images and their details [43].

Finally, YOLO, or You Only Look Once, is best known for its name [44]. To the layman, one may recognize seeing the bounding boxes that follow objects in front of it with a label indicating what type of object it is. Suitable for real-time detection, many see it as a good fit for autonomous cars. Despite being a single-shot object detector, YOLO is unique in that it is quick and accurate, which is possible due to the CNN network used under it. YOLO divides the input image into a grid of cells, each responsible for predicting objects that fall within the boundaries. By predicting bounding boxes that enclose objects in a cell, YOLO predicts the coordinates, dimensions, and a confidence score that it has accurately predicted the object. YOLO's real-time analysis and precision are greatly valued, however, to detect small objects, YOLO may lose its precision and hinder the analysis.

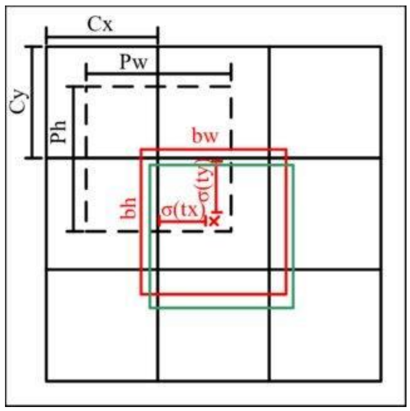

Figure [J]: The above image shows how the YOLO algorithm tracks and forms the bounding box around the object/area of interest [45].

Considering all of the models available, it was decided that CNNs would be best suited for the purposes. While the network does need to be trained on a lot of data, the model can be trained on specific data to be able to detect small details from thermal images. SIFT could be useful as well, however, it is better suited for RGB images, and its heavy computational cost for a large space like a farm may prove to be burdensome. On the other hand, YOLO may not be able to notice the small details reliably enough for consideration.

Model and Methodology

Before implementing the model, the logistics of its application need to be considered. As the CNN model would have to work in a field and analyze details like moisture, pests, disease, and ripeness, the training data set must contain similar images.

Figure [I] provides a visual representation of how CNNs work in detail. First, the model receives the image input and breaks it up into segments. In this case, the image would be the thermal image output. This step is vital to the image analysis process, as it allows the algorithm to break the image into labeled features. The differences in heat signatures will be compared to other images and heat signatures to ensure that it is matching the correct label to the correct feature. This is called feature extraction, and it is where the "layers" of the model break down, label, and compare the images. Finally, the model will classify the data and perform confidence tests to confirm the model's accuracy.

For this report, a Python implementation of a CNN model was written here: https://github.com/aryaarawat/NASAAF-ThermalScannerswUAS [46].

```
model = Sequential()
model.add(Dense(128, activation='relu', input_shape=(2,)))
model.add(Dense(num_classes, activation='softmax'))
```

```
model.compile(loss='categorical_crossentropy', optimizer='adam', metrics=['accuracy'])
```

```
history = model.fit(X_train, y_train, validation_data=(X_test, y_test), epochs=70, batch_size=32)
```

Figure [K]: The labels used in processing the image. Depending on the task, one can add fewer or more layers.

Figure [K] shows the main part of the CNN model with thermal images. One can see the layers added for convolution, as well as the sequential. The softmax function calculates the probabilities for each class, while the real function solves the vanishing gradient problem. The vanishing gradient problem becomes prominent in especially large datasets and describes how network parameters can be degraded to the point of significantly slowing down the algorithm. Relu fixes this problem by introducing nonlinearity which allows the gradients to adapt to the growing network.

While plant images were not tested, the model is a good estimator of how the model may work with thermal images as a whole. In a real-life implementation, the CNN model would have to be able to analyze small objects, pests, and details, so a future implementation may train on a data set that fits those requirements. With proper training data, this algorithm could be very successful.

Readable Output

Basic Requirements

The final step in the software design is the actual output of the data. For the scanners to have the desired impact, they must be output in a readable format. This output should include the image of interest, a bounding box around the specified area, and details about the image, as well as the image's metadata. For convenience, this should be accessible from a computer, be printable, and be communicated in language that is easily understood.

UI Design

Figure [L] depicts the user interface for the application connected to the scanner. The figure focuses on the "Image" tab, which contains an image of an area of interest. As shown, there are two bounding boxes around the specific area of concern to help the user focus on what is happening in the picture. To the left of the screen, there will be a column describing data about the drone, the drone's location at the time of this picture, latitude and longitude, and the exact time, date, and day. In addition to this metadata, below the image are listed the suspected afflictions that may be of interest, as well as a percentage of confidence. All of these details are meant to help the user gain a better understanding of what could be impacting their field.

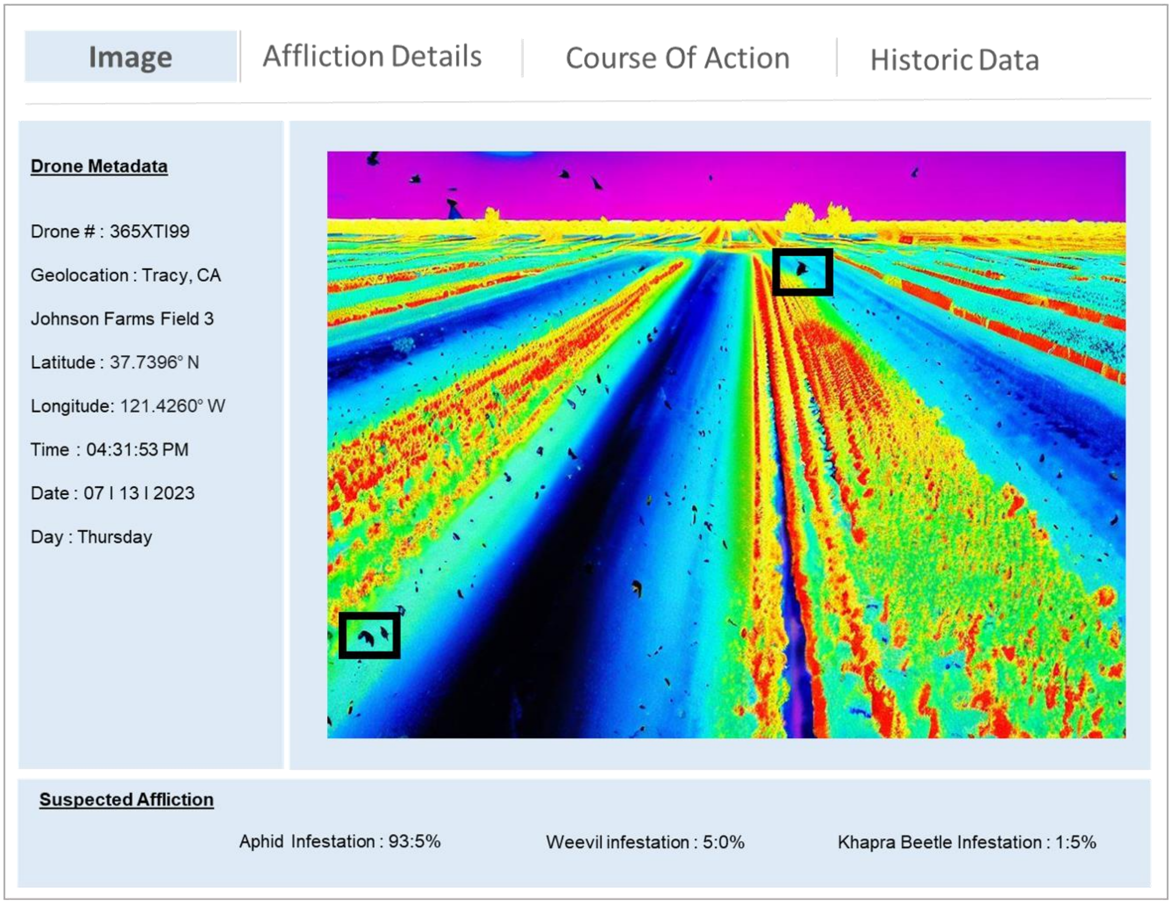

Figure [L]: Sample of what the UI design would look like—thermal image generated by Bing AI image generator.

There are three other tabs in the image shown. The second tab, “Affliction Details”, lists common facts and features of what the problem could be in the image. The tab may also include degrees of severity and whether action should be taken. The third tab, “Course of Action”, will list suggestions for the farmer to take to fix the problem. This could include pesticides, a new watering system, replanting, and more, depending on the affliction itself. Finally, the fourth tab will detail historic data about this field and whether this has been a common occurrence in the past, as well as region-specific data. As the thermal scanner is used for many years, it will add to the data, but even with no prior usage, the tab will display common pest habits of the area, trends regarding temperature and ripeness, and more.

Economic Feasibility

Introduction

The implementation of thermal scanners on drones at a large scale is a substantial method to survey agricultural farms and reduce food waste. For an industry creating approximately 51.1 billion dollars in California alone in 2021, implementation on a smaller scale won’t provide the reduction of food waste desired [47]. For farmers to implement and purchase new technology, economic feasibility and profitability are a must. Without an incentive to implement for farmers, it would be very difficult to execute a food waste reduction program on a wide scale. The main focus of the project's economic feasibility is ensuring that thermal scanners and drones on farms will reduce food waste and increase profits for agricultural farms. To ensure profit, factoring in the estimated prices of drones, scanners, and maintenance are essential. Establishing that drones create profit, their usage can be incentivized and increase the chances of large-scale implementation. Maintaining economic feasibility will increase overall usage, and therefore decrease total food waste.

On individual prices, drone and thermal scanner purchases will be the most expensive costs for farmers and farms. One possible drone and thermal scanner combination that has been selected for these economic calculations is the DJI Mavic 3 Thermal, which comes in at $5,500. This drone combined with its thermal camera can reduce food waste by early detection of plant disease, maximizing yield by identifying maturity within crops and areas, and minimizing losses in overripe crops and produce. Food waste on the farming level is high, with an estimated 15.3% of food produced being wasted [48]. Putting this into perspective just in California in 2022, this would be an approximate 9.23 billion dollars in gross revenue lost at the farm level alone. While 9.23 billion dollars seems massive compared to a $5,500 drone, the team had to take into account the percentage of food waste being mitigated by drone usage and compare the cost to profit.

Implementation

To analyze the percentage of mitigation needed, this section looks at two different types of produce farms in California and calculates the estimated revenue lost at the farm level for the average farm. After finding the estimated revenue, and estimated revenue lost, one can evaluate the percentage of waste reduction needed to make the thermal scanners and drones realistically and economically viable.

Grape Analysis

First is the analysis of grapes in California, which is a good indicator for the whole United States, as 98% of table grapes in the US are produced in California [49]. The median size of a grape farm in California is approximately 15 acres, with 29% of grape farms in California being between 5.0 and 24.9 acres [50]. With an estimated yield level of 8-10 tons per acre for table grapes, and an approximate $30,000 gross per acre, one can create an approximation of the economic feasibility of the usage of thermal scanners in tandem with drones [51][52].

Using these statistics, one can calculate the approximate revenue per acre wasted, being $5,419.12 per acre of land. Extrapolating that to the farm level for an average farm of 15 acres provides an approximate wasted revenue per farm of $81,286.89. The upfront cost per farm would be approximately $5,500, with an additional cost of $339 in maintenance. This totals a cost of $5,839. To cover this $5,839 cost of the drone, camera, and maintenance, the drone would have to provide at least a 7.18% decrease from current waste during the farm stage or 1.10% of the estimated 15.3% of food that is wasted during the farm stage. This could come from multiple factors, including drones leading to higher yield by maturity identification, lowering disease by early thermal detection in crops, or identifying pests before they create food waste.

Strawberry Analysis

Next, the team analyzed strawberries and strawberry farms in California. Grossing 3.02 billion dollars in 2021, strawberries in California contribute to approximately 91% of US-grown strawberries [53]. In California, the average yield of strawberries per acre is 68,000 pounds, with an average price of $1.43 per pound [53].

Using these statistics, it is possible to calculate the approximate revenue per acre wasted, being $17,565.19 per acre of strawberry farm. Based on the USDA's 2017 Agriculture Census, the average strawberry farm in California has a size of 55.9 acres [54]. Using per-acre values, it is possible to approximate the average strawberry farm losing $981,894.12 in gross revenue. To cover this $5,839 cost, the drone would have to provide at least a 0.59% decrease from current waste during the farm stage or 0.09% of the estimated 15.3% of food that is wasted during the farm stage.

Summary

This 0.59% waste reduction seems much more attainable than the 7.18% needed to break even for grape farms. The two factors that are evident in these two scenarios for the difference in waste reduction needed are in gross revenue per acre, and average farm acreage. Since the drone and scanner as well as maintenance are a one-time cost and singular, it will be more economically feasible and profitable for farms that are bigger and have more area to work with. This lowers the percentage of waste needed to be mitigated for profitability. The more area the drone can cover increases profitability since the cost doesn't scale with the area.

The use of thermal scanners and drones shows the potential for economic feasibility and profitability in farms. Profitability and economic feasibility increase with farm size, lowering the percentage of waste reduction required to profit, which can work towards moving this technology into larger farms, and increase overall usage.

Future Advancement

In the future, these drones and the methods of surveying the fields can be further enhanced. However, presently, there are many limitations to improving drone surveillance due to having to abide by the current FAA regulations. One of the main focal selling points of drones to farmers is that they are straightforward and beneficial to the farm. Though, many of these FAA regulations hinder that effectiveness for farmers. Eliminating a few of these FAA regulations is just one step in doing that.

One hindrance to improving drone surveillance is that, as stated, only one aircraft can be controlled per operator [12]. For large fields, if multiple drones are required to survey the field for time efficiency, multiple operators are required as well. However, without this FAA regulation in place, surveying the fields can become a much simpler task. As time progresses, the airspace becomes more advanced, and thus, more complex. And, as airspace technology changes, in time, so will the FAA regulations. Provided that FAA regulations have changed, instead of many operators, the drones can fly synchronously in a swarm controlled by fewer operators, each drone having a designated role and part of the field to survey. In another scenario, if there was no restriction on what operates drones, artificial intelligence could become a viable solution to operate them. As of now, the current drone design uses artificial intelligence to detect obstacles and analyze images. Despite that, in the future, with a larger role of artificial intelligence, it could become fully autonomous. If artificial intelligence is allowed to do the heavy lifting of autonomous flying, the role of an aircraft operator could be eliminated, making operations far more efficient. In one instance, from a company called VOTIX, drones are already being simulated with control by artificial intelligence [55]. This is just one step into enhancing drone survey capabilities.

An additional FAA regulation that impedes drone surveillance is the regulation that states the drones must stay within visual line of sight [12]. In the future, with improved technologies and adjusted FAA regulations, given this regulation wasn't in place anymore, farm surveys could be much more efficient. Instead of being within visual line of sight, on large farms that have many acres of land, the drones can survey the entirety of the agriculture without staying within view. With artificial intelligence taking the wheel as well, the drones could be out of sight, out of mind.

Furthermore, as technology continues to proceed, new generations of drones will come to fruition. With more time and money, more advanced drones may be a viable option for surveying fields.

A large issue that shows up when using thermal cameras is noise. Noise is essentially grain that clouds images captured on a thermal sensor. Noise is caused by background heat in the area that is being sensed, or more commonly heat that is produced by the thermal camera itself [56]. Thus, the necessity for cooling in thermal cameras arises. Cooled thermal cameras produce images without noise, and therefore clearer images [56]. While this is greatly beneficial for the purpose intended with the thermal cameras, it increases the cost significantly. With future advancements, having more time and money, this addition to the drone may be more applicable. With cooling systems, the increase in clarity is necessary as it allows for greater magnification, which is vital in an agricultural environment [57]. Another large issue that could be solved through cooling is the stitching of multiple thermal images together [56]. Thermal grain is especially problematic near the edge of the images, where it can create large clouds which makes it hard to use multiple aerial thermal images together. Cooling would reduce the noise and solve this problem, and an alternate solution that could be used alongside cooling is the implementation of identifiable thermal plates. If there were plates with identifying markings placed around the desired location before the images were taken, the images will have clear points near the edges that can help stitch them together. These plates would be packaged with the drone and have clear instructions to help the farmers understand their necessity.

If the drone has a cooling system, the payload must accommodate it. By carrying a larger payload of equipment, the drone itself must be more powerful and, thus, heavier. While the current drone does not exceed FAA regulations that state drones must be under 55 pounds, with a cooling system and the appropriate accommodations, it may [12]. Under the assumption that the drone does end up being over 55 pounds, provided that this regulation also changes in the future to a higher weight, then it likely wouldn't be a problem.

Moreover, with more advancements in components such as battery life and resolution, the drone would be further improved. With increased battery life, the drone flight time would increase as a result, allowing for the drones to survey the fields for longer durations of time. A higher resolution provided that the imaging quality was better with this aspect, the drone could theoretically also operate at a higher altitude when needed. However, one barrier to this is the FAA regulation that restricts drone altitude to 400 feet [12]. Given this barrier was changed in the future, the drones could theoretically operate at a higher altitude if needed, enabling them to have an oversight of a larger portion of agriculture.

To add on, with more funding, instead of using solely mid-wavelength thermal cameras, as stated before, short-wavelength and long-wavelength cameras become options depending on climate conditions. Additionally, at short wavelengths, thermal cameras tend to have less motion blur while moving. So, when using the short-wavelength camera, the drone may be capable of operating at faster speeds without creating motion blur. Given this was possible, a new type of drone flight may be more effective. Currently, it is intended to use multirotor drones to accommodate the motion blur, avoiding high speeds. Without this variable though, when trying to survey the fields at a faster pace, a hybrid drone may be effective. A hybrid drone has all the vertical hovering capabilities that multirotor drones have but has additional fixed wings that allow high speeds to be energy efficient.

In short, given more time, money, and relaxed FAA regulations, this drone's applications and efficiency can be made more advanced. These changes would allow agriculture surveillance to be achieved faster, in an improved manner.

Conclusion

Unmanned drones aided by artificial intelligence, in the future, can utilize thermal signaling cameras to survey fields to detect levels of pests, moisture, fertilization, etc. Employing these drones can allow the farmers to create the best quantity and quality of yield with the resources provided and ultimately dampen the problem of food waste.

This solution is especially helpful due to its unique blend of thermal imaging, image analysis, and a broad brush approach. Rather than focusing on certain types of problems, the drone aims to help farmers solve any problem they face, whether that be irrigation issues, plant disease, pest infestations, and more. This holistic approach means that farmers can target the biggest threats to their yield weeks in advance in order to preserve their crop.

The use of drones accompanied by thermal scanners shows the potential for economic feasibility and profitability in farms. Profitability and economic feasibility increase with farm size, lowering the percentage of waste reduction required to profit, which can work towards moving this technology into larger farms, and increase overall usage.

Drones have already shown their potential in advancing agriculture. It can be concluded, with the help of thermal cameras, as they continue to provide detailed views and crop analysis, these drones are a step to thriving farms and a prosperous economy and environment, building a future where food waste is minimal.

Works Cited

[1] Hitaj, C. Food Loss at the Farm Level. *www.usda.gov*. https://www.usda.gov/media/blog/2019/04/16/food-loss-farm-level.

[2] Buss, D. Solving Food Loss from Seed to Market. *info@ift.org*. https://www.ift.org/news-and-publications/food-technology-magazine/issues/2022/march/features/solving-food-loss#anchor-5a02f91d-2bc5-4092-9d1a-2cf24e3eb99a. Accessed Jul. 1, 2023.

[3] US EPA. From Farm to Kitchen: The Environmental Impacts of U.S. Food Waste. *www.epa.gov*. https://www.epa.gov/land-research/farm-kitchen-environmental-impacts-us-food-waste. Accessed Jun. 29, 2023.

[4] Food Waste Problem | ReFED. *refed.org*. https://refed.org/food-waste/the-problem/. Accessed Jun. 30, 2023.

[5] United Nations. Goal 12 | Ensure Sustainable Consumption and Production Patterns. *sdgs.un.org*. https://sdgs.un.org/goals/goal12. Accessed Aug. 2, 2023.

[6] Optimize the Harvest - ReFED, Inc. - Food Waste Organization. *refed.org*. https://refed.org/action-areas/optimize-the-harvest/. Accessed Aug. 3, 2023.

[7] The Environmental Impact of Food Waste | Move for Hunger. *moveforhunger.org*. https://moveforhunger.org/the-environmental-impact-of-food-waste?gclid=CjwKCAjw-b-kBhB-EiwA4fvKrAve5ATMP-F1YiHgRnCcD7pt1XFRgKSqwTSlqJ_YVdEKEozCjvxfuxoC1vQQAvD_BwE. Accessed Aug. 3, 2023.

[8] Igini, M. 10 Food Waste Statistics in America. *Earth.org*. https://earth.org/food-waste-in-america/#:~:text=In%20the%20US%2C%20agriculture%20alon. Accessed Aug. 3, 2023.

[9] Food Waste Problem | ReFED. *refed.org*. https://refed.org/food-waste/the-problem/.

[10] About Food Waste | Move For Hunger. About Food Waste | Move for Hunger. *Moveforhunger.org*. https://moveforhunger.org/food-waste. Accessed Aug. 2, 2023.

[11] Just, D. 3 Ways Nutrition Influences Student Learning Potential and School Performance – Healthy Food Choices in Schools. *Extension.org*. https://healthy-food-choices-in-schools.extension.org/3-ways-nutrition-influences-student-learning-potential-and-school-performance/. Accessed Aug. 2, 2023.

[12] Certificated Remote Pilots Including Commercial Operators | Federal Aviation Administration. *Faa.gov*. https://www.faa.gov/uas/commercial_operators. Accessed Aug. 2, 2023.

[13] Arora, Y. Agriculture Drone Swarm | Mechanizing and Automating ... *www.leadingedgeonly.com*.https://www.leadingedgeonly.com/innovation/view/agriculture-drone-swarm. Accessed Aug. 3, 2023.

[14] Inc, C. I. Thermal Imagery for Agriculture. *www.ceresimaging.net* https://www.ceresimaging.net/thermal. Accessed Aug. 2, 2023.

[15] Thermal Drones (Infrared) – Dronefly. *Dronefly.com*. https://www.dronefly.com/thermal-drones.html. Accessed Aug. 3, 2023.

[16] Thermal Drone-Based Sensing | PrecisionHawk. *www.precisionhawk.com*. https://www.precisionhawk.com/sensors/advanced-sensors-and-data-collection/thermal. Accessed Aug. 4, 2023.

[17] Liang, M., and Delahaye, D. "Drone Fleet Deployment Strategy for Large Scale Agriculture and Forestry Surveying." *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, 2019. https://doi.org/10.1109/itsc.2019.8917235.

[18] DJI Thermal Analysis Tool 2.1 - Download Center - DJI. *DJI Official*. https://www.dji.com/downloads/softwares/dji-dtat2. Accessed Aug. 3, 2023.

[19] Juniper, A. DJI Mavic 3T Enterprise Thermal Review. *digitalcameraworld*. https://www.digitalcameraworld.com/reviews/dji-mavic-3t-enterprise-thermal-review. Accessed Aug. 3, 2023.

[20] DJI M30T Drone Review: Best Enterprise Drone of DJI Matrice Series. *Drone U™*. https://www.thedroneu.com/blog/dji-m30t-review/. Accessed Aug. 3, 2023.

[21] DJI Agras T30-A New Digital Flagship for Agriculture. *DJI*. https://www.dji.com/t30. Accessed Aug. 2, 2023.

[22] simoniot. Agricultural Drones: Capabilities of Today. *SIMON IoT*. https://www.simoniot.com/agricultural-drones-capabilities-of-today/#:~:text=By%20flying%20over%20fields%20and. Accessed Aug. 3, 2023.

[23] seferyan. Everything You Should Know about Thermal Imaging Cameras. *FindLight Blog*. https://www.findlight.net/blog/everything-you-should-know-about-thermal-imaging-cameras/#:~:text=Types%20of%20Thermal%20Imaging%20Cameras. Accessed Mar. 6, 2023.

[24] Hayk, M. Benefits of Using Medium-Wavelength (MWIR) Thermal Imagers instead of Widely Used Long-Wavelength (LWIR) Cameras. *ametek-land*. https://www.ametek-land.com/pressreleases/blog/2023/february/benefits-of-using-mwir-thermal-imagers#:~:text=%22Longer%20wavelength%22%20instruments%20are%20primarily,longer%20wavelengths%20have%20larger%20waves. Accessed Aug. 2, 2023.

[25] Group, S. M. Shortwave Infrared Cameras for High-Temperature Manufacturing and R&D Processes. *www.techbriefs.com*. https://www.techbriefs.com/component/content/article/tb/supplements/pit/features/articles/36146#:~:text=The%20Science%20Behind%20SWIR&text=Thermal%20cameras%20detect%20the%20amount. Accessed Aug. 3, 2023.

[26] Drone Thermal Cameras: Everything You Need to Know | the Drone Life. https://thedronelifenj.com/drone-thermal-cameras-everything-you-need-to-know/. Accessed Aug. 2, 2023.

[27] Dual Sensor Video Analytics in Thermal Cameras for Intrusion Detection. *SIGHTLOGIX DUAL SENSOR VIDEO ANALYTICS*. https://www.sightlogix.com/dual-sensor-video-analytics-in-thermal-cameras/. Accessed Aug. 3, 2023.

[28] THE MAIN PARAMETERS of THERMAL IMAGING DEVICES | Pulsar. *THE MAIN PARAMETERS OF THERMAL IMAGING DEVICES | Pulsar*. https://www.pulsar-nv.com/glo/support/thermal-imaging-technologies/the-main-parameters-of-thermal-imaging-devices/2375/. Accessed Aug. 3, 2023.

[29] itsadityash. What Is Dijkstra's Algorithm? | Introduction to Dijkstra's Shortest Path Algorithm. *GeeksforGeeks*. https://www.geeksforgeeks.org/introduction-to-dijkstras-shortest-path-algorithm/

[30] Sanoj68. English: Example Graph for the Illustration of the Parallel Dijkstra Algorithm for the All-Pair-Shortests-Paths Problem. *Wikimedia Commons*. https://commons.wikimedia.org/wiki/File:Apsp_dijkstra_graph.png. Accessed Aug. 3, 2023.

[31] Belwariar, R. A* Search Algorithm - GeeksforGeeks. *GeeksforGeeks*. https://www.geeksforgeeks.org/a-search-algorithm. Accessed Aug. 2, 2023.

[32] A* Algorithm in Artificial Intelligence You Must Know in 2022. *Simplilearn.com*. https://www.simplilearn.com/tutorials/artificial-intelligence-tutorial/a-star-algorithm. Accessed Aug. 2, 2023.

[33] dbenzhuser. English: Example of the A* Search Algorithm. *Wikimedia Commons*. https://commons.wikimedia.org/wiki/File:Pathfinding_A_Star.svg. Accessed Aug. 3, 2023.

[34] Tian, L., Zhang, Z., Zheng, C., Tian, Y., Zhao, Y., Wang, Z., and Qin, Y. "An Improved Rapidly-Exploring Random Trees Algorithm Combining Parent Point Priority Determination Strategy and Real-Time Optimization Strategy for Path Planning." *Sensors*, Vol. 21, No. 20, 2021, p. 6907.https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8537961/.

[35] Jermyn, J. A Comparison of the Effectiveness of the RRT, PRM, and Novel Hybrid RRT-PRM Path Planners. *www.ijraset.com*. https://www.ijraset.com/research-paper/effectiveness-of-the-rrt-prm-and-novel-hybrid-rrt-prm-path-planners. Accessed Aug. 3, 2023.

[36] Hsu, D., Latombe, J.-C., and Kurniawati, H. “On the Probabilistic Foundations of Probabilistic Roadmap Planning.” *The International Journal of Robotics Research*, Vol. 25, No. 7, 2006, pp. 627–643.http://ai.stanford.edu/~latombe/papers/foundation-prm-05/paper.pdf.

[37] Kavraki, L., Svestka, P., Latombe, J.-C., and Overmars, M. Probabilistic Roadmaps for Path Planning in High- Dimensional Configuration Spaces. *https://www.cs.cmu.edu/*. https://www.cs.cmu.edu/~motionplanning/papers/sbp_papers/PRM/prmbasic_01.pdf. Accessed Aug. 2, 2023.

[38] Rawat, A. NASA AF-ThermalScanners with UAS. *GitHub*. https://github.com/aryaarawat/NASAAF-ThermalScannerswUAS. Accessed Aug. 3, 2023.

[39] Ning, M. SIFT(Scale-Invariant Feature Transform). *Medium*. https://towardsdatascience.com/sift-scale-invariant-feature-transform-c7233dc60f37. Accessed Aug. 2, 2023.

[40] Wikipedia, L. M. at E. English: These Images Are from My Presentation of the SIFT Algorithm, Which Can Be Found At: *Wikimedia Commons*. https://commons.wikimedia.org/wiki/File:Sift_keypoints_filtering.jpg. Accessed Aug. 3, 2023.

[41] Convolutional Neural Network (CNN) in Machine Learning. *GeeksforGeeks*. https://www.geeksforgeeks.org/convolutional-neural-network-cnn-in-machine-learning/. Accessed Aug. 2, 2023.

[42] Introduction to Convolution Neural Network. *GeeksforGeeks*. https://www.geeksforgeeks.org/introduction-convolution-neural-network/. Accessed Aug. 2, 2023.

[43] T, C., A. ; Kucharczyk, M. J. ; Cheddad, A. ; Clarke, S. E. ; Hassan, L. ; Ding, S. ; Rathore, S. ; Zhang, M. ; Katib, Y. ; Bahoric, B. ; Abikhzer, G. ; Probst, S. ; Niazi. English: Flowchart of the Standard Radiomics Model. (1) Multiparametric MRI (MpMRI) Image Acquisition. (2) Segmentation: Tumor Labeling-Green/White Contour. (3) Imaging Features Extraction Using Shape, Texture, And/or Deep Features Derived from Convolution Neural Network Layers. (4) Clinical, Radiomic Features, Molecular Data for Statistical Analyses, Based Significance Test and Classifier Models, to Identify Relevant Features for Predicting the Clinical Outcome (E.g., Gleason Score). *Wikimedia Commons*. https://commons.wikimedia.org/wiki/File:Flowchart_of_the_standard_radiomics_model.png. Accessed Aug. 3, 2023.

[44] Kundu, R. YOLO: Real-Time Object Detection Explained. *www.v7labs.com*. https://www.v7labs.com/blog/yolo-object-detection. Accessed Aug. 2, 2023.

[45] Zhang, Y.-J., Lu, Z.-M., and Xiao, F.-S. Helmet Wearing State Detection Based on Improved Yolov5s. *ResearchGate*. https://www.researchgate.net/publication/366344091_Helmet_Wearing_State_Detection_Based_on_Improved_Yolov5s. Accessed Aug. 2, 2023.

[46] Rawat, A. NASA AF-ThermalScanners with UAV. *GitHub*. https://github.com/aryaarawat/NASAAF-ThermalScannerswUAV. Accessed Aug. 3, 2023.

[47] CDFA - Statistics. *www.cdfa.ca.gov*. https://www.cdfa.ca.gov/Statistics/#:~:text=In%202021%20California. Accessed Aug. 2, 2023.

[48] Gama, L., Prezkop, L., Walsh, L., Weir, C., Gupta, M., and Trewern, J. *THE GLOBAL IMPACT of FOOD LOSS and WASTE on FARMS EXECUTIVE SUMMARY* . WWF, 2021.

[49] Geisseler, D., and Horwath, W. *Grapevine Production in California*.

[50] Alston, J., Lapsley, J., and Sambucci, O. *Grape and Wine Production in California Chapter 8. Grape and Wine ProduCtion in California*.

[51] How Many Grapes Can I Produce per Acre? How Much Yield Can I Expect When They Are in Full Production? – Grapes. *grapes.extension.org*. https://grapes.extension.org/how-many-grapes-can-i-produce-per-acre-how-much-yield-can-i-expect-when-they-are-in-full-production/#:~:text=Winegrape%20vines%20can%20produce%20from. Accessed Aug. 3, 2023.

[52] Alternatives to Hand Labor in Table Grapes - Rural Migration News Blog | Migration Dialogue. *migration.ucdavis.edu*. https://migration.ucdavis.edu/rmn/blog/post/?id=2740#:~:text=The%201.1%20million%20tons%20of. Accessed Aug. 3, 2023.

[53] Strawberries | Agricultural Marketing Resource Center. *Agmrc.org*. https://www.agmrc.org/commodities-products/fruits/strawberries. Accessed Aug. 2, 2023.

[54] Maxiner, E. California Strawberries: A Crop of Opportunity for Mexican-Americans | 2019-05-31 | Agri-Pulse | Agri-Pulse Communications, Inc. *www.agri-pulse.com*. https://www.agri-pulse.com/articles/12262-california-strawberries-a-crop-of-opportunity-for-mexican-americans#:~:text=The%20result%20is%20a%20few. Accessed Aug. 3, 2023.

[55] Cloud-Based AI Software (SaaS) & Connectivity for Drone Automation, Remote Operation & Fleet Management. *Unmanned Systems Technology*. https://www.unmannedsystemstechnology.com/company/votix/. Accessed Aug. 2, 2023.

[56] Studio, A. W. Cooled vs. Uncooled LWIR Thermal Cameras. *Axiom Optics*. https://www.axiomoptics.com/blog/cooled-vs-uncooled-lwir-thermal-cameras/?gclid=CjwKCAjwh8mlBhB_EiwAsztdBEu04WJXnwWskgG1MyMZqhpGtvYXGGINYRVeATq6w0ennpcsjOrH9hoCeU4QAvD_BwE. Accessed Aug. 3, 2023.

[57] Cooled or Uncooled? *www.flir.com*. https://www.flir.com/discover/rd-science/cooled-or-uncooled/#:~:text=Cooled%20cameras%20typically%20have%20greater. Accessed Aug. 3, 2023.

[58] Agriculture Drone | Drone for Farming | Agriculture Software | DroneDeploy. *www.dronedeploy.com*. https://www.dronedeploy.com/solutions/agriculture-test-drift. Accessed Aug. 5, 2023.