

Dream with Us High School Engineering Design Challenge

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Hybrid VTOL Quadplane UAS for Mediterranean Fruit Fly Detection and Sampling

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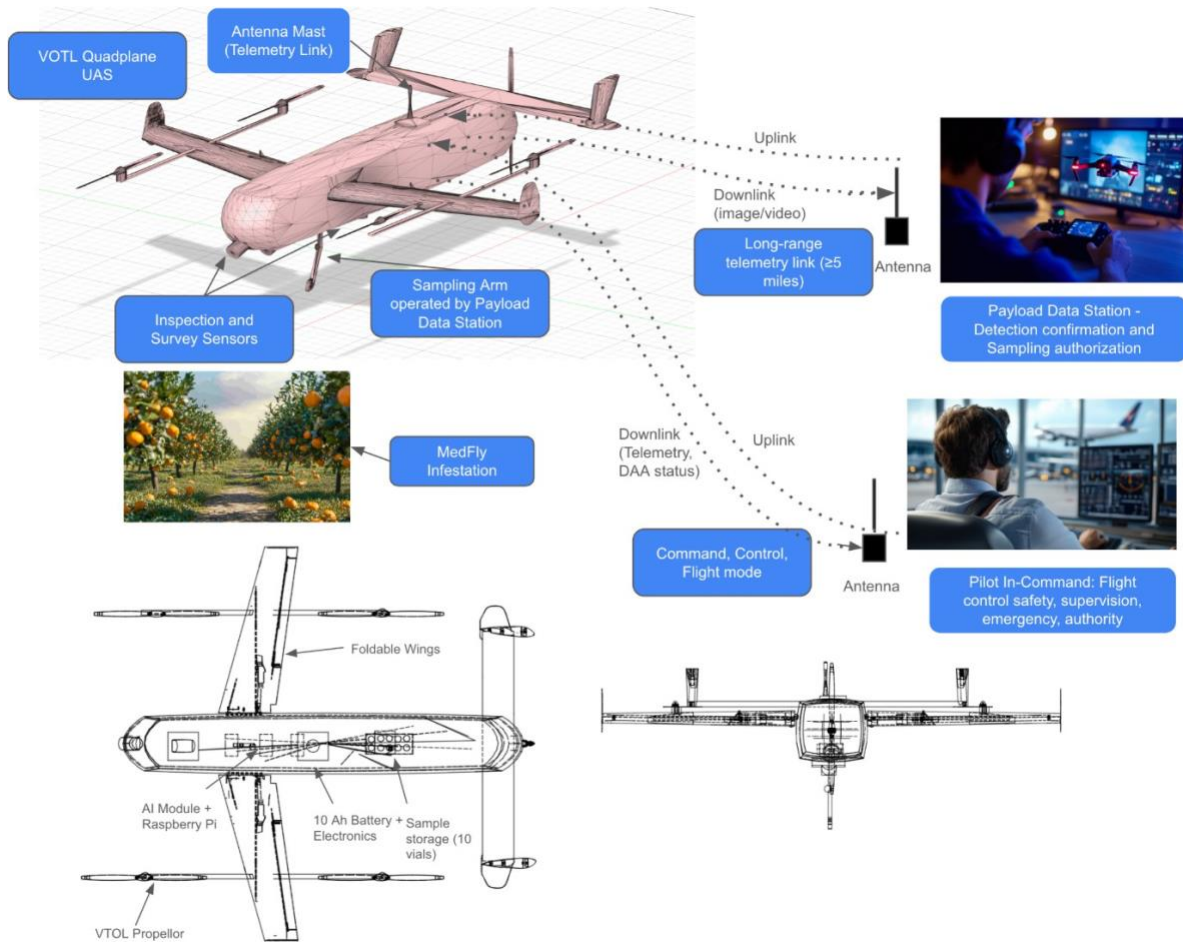
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Executive Summary

Agricultural pests pose a significant and growing threat to food security, economic stability, and environmental sustainability. In Santa Clara County, recent detections of the Mediterranean fruit fly (Medfly) have triggered quarantine zones and emergency response measures due to the pest's ability to infest over two hundred and fifty fruit and vegetable species and cause widespread crop loss. Traditional monitoring approaches rely heavily on labor-intensive ground inspection and delayed visual confirmation, often identifying infestations only after irreversible damage has occurred. This project presents a novel uncrewed aerial system (UAS) designed to enable early, targeted detection and precision sampling, providing actionable intelligence before infestations escalate.

The proposed solution is a hybrid VTOL (Vertical Takeoff and Landing) quadplane specifically engineered to combine the strengths of fixed-wing aircraft and multirotor drones. Unlike conventional agricultural drones that must choose between endurance or precision, this design seamlessly integrates both. In fixed-wing mode, the aircraft efficiently surveys large agricultural areas, covering a 0.5 mile by 0.5 mile field in a single autonomous flight. In VTOL multirotor mode, the aircraft transitions into a stable hover, allowing it to safely operate near trees and fruit canopies for close-range inspection and physical sample collection. This dual-mode capability is central to the system's novelty and enables mission profiles that neither fixed-wing nor multirotor platforms can safely accomplish alone.

At the core of the detection system is an AI-enabled, two-stage sensing architecture. A wide-area survey sensor identifies fruit-bearing regions and plant stress patterns across the field. When anomalies are detected, the aircraft transitions to a controlled hover and uses a close-range RGB inspection camera to visually confirm fruit-level damage. A lightweight onboard computer runs a convolutional neural network–based algorithm that localizes fruit and evaluates surface anomalies consistent with Medfly oviposition damage, discoloration, and early rot. This layered detection approach dramatically reduces false positives and ensures that physical sampling is performed only when evidence warrants it, conserving flight time and minimizing unnecessary disturbance to crops.

A key differentiator of this design is its human-in-the-loop autonomy model, implemented through a dual-operator ground control station. One operator serves as the pilot-in-command, overseeing aircraft safety, navigation, and flight modes, while a second payload/data operator focuses exclusively on sensor interpretation, AI detection outputs, and sampling authorization. This division of responsibility reduces cognitive load during high-risk operations near vegetation and mirrors best practices used in professional aviation and robotic inspection systems. Autonomous survey and stabilization functions further reduce operator workload while preserving human judgment for critical decisions.

The system also introduces a deployable, center-of-gravity-balanced sampling mechanism capable of collecting up to ten physically isolated fruit tissue samples during a single mission. The servo-actuated sampling arm extends laterally from a protected fuselage bay, extracts a small, biologically relevant fruit sample, and deposits it into a sealed internal container. By locating both the sampling mechanism and storage rack near the aircraft's center of gravity, the

design maintains stability in both hover and cruise flight as samples accumulate. This capability enables laboratory-verifiable evidence collection without requiring repeated landings or multiple aircraft.

Safety is integrated throughout the design. An onboard Detect-and-Avoid system allows the aircraft to sense, detect, and avoid obstacles such as branches, trunks, and nearby people during close-proximity operations. All time-critical safety decisions are made onboard to eliminate latency risks, while status and alerts are continuously communicated to the ground station. Conservative lost-link protocols, geofencing, battery safety thresholds, and mechanical interlocks ensure predictable and safe behavior even during abnormal conditions.

From an operational and economic perspective, the system delivers significant impact. A single forty-five-minute mission can survey approximately one hundred sixty acres, a task that would otherwise require several days of manual inspection. Early detection enables targeted intervention, reducing unnecessary pesticide use and preventing large-scale crop loss. The system's low operating cost, rapid deployment time, and scalable architecture make it suitable not only for emergency response but also for routine agricultural monitoring.

1. Introduction

1.1 Local Agricultural Pest

For this challenge, our team selected the Mediterranean Fruit Fly, a species of fruit fly from Africa which currently exists in our local Santa Clara County as an invasive agricultural pest. Commonly known as the Medfly, this fly is noted by the Animal and Plant Health Inspection Service of the USDA to be one of the world's most damaging pests. It has the capacity for mass damage across many different types of crop because of its broad host range, having the ability to infect over 250 different species of fruit and vegetable, without a preference for any type in particular.



Figure 1: Image of the Mediterranean Fruit Fly from the National Invasive Species Information Center

The Mediterranean Fruit Fly can be identified with its tan colored body and black spots across its thorax. It is an individually small pest, only about $\frac{1}{4}$ of an inch long, that causes large damage to crops due to its method of reproduction. Female Medflies lay eggs inside developing host fruit, which can hatch in either under 4 days in warm temperatures or up to 18 days in cooler temperatures, and then develop into larvae, tiny white worm-like creatures, that feed on the growing pulp of the fruit from the inside. The larvae feed on the interior of the fruit and develop into adult Medflies and leave the crop only after 6-11 days after hatching, but the feeding during the short growing phase continuously decays the fruit to the point where it falls off its branch, resulting in damage that renders the fruit unrecoverable and inedible. The grown

meter radius of any female Medfly sighting. Preventive measures such as limiting agricultural shipments from within the quarantine zone and encouraging residents who grow their own crop to not share their homegrown produce outside of their homes. Such immediate action taken against the Medfly is in valid response to its high destructive potential.

The primary resources we used in learning about this pest and its current-day impact in our local industry include the Santa Clara County Website and data from their agricultural reports, the California Department of Food and Agriculture website with their projected economic impacts, and the United States Department of Agriculture's webpage about the Mediterranean Fruit Fly. Coupled with recent articles from local news stations such as ABC 7 current development of the Mediterranean fruit fly sightings and actions taken from the County, we were able to learn about the pest, understand its effects, analyze its agricultural impact, and altogether gauge its economic influence while feeling a growing sense of responsibility to contribute to providing a tangible solution to this problem that directly impacts our own community.

1.2 Team Organization

Our team consisted of three members: Dhruv Yadati, Pranav Rajkumar, and Arnav Sharma. On top of sharing a passion for interdisciplinary engineering, each member had distinct roles throughout the process of creating this project in which they leveraged their own specific interests and skills to optimize our end result.

Dhruv Yadati served in a leadership position while being the driving force behind the design of the product itself, essentially managing the team's workflow while handling the bulk of the design process. He applied his strong interest in STEM and engineering to drive the development and refinement of the technical aspect of the solution, making sure the end product is a realistic and working solution to the problem.

Pranav focused on the biological and ecological aspects of the project. From his interest in biology and bioengineering, he helped to analyze and understand the pest's implications at a micro and macro level in a habitat. Understanding the issue from a biological and scientific standpoint assisted the team in nailing down what the problem was and then allowing the team to work toward a scientifically applicable solution.

Arnav Sharma zoned in on the business and communications side of the project. He took the lead on business analytics and communications. He evaluated the business costs and logistical implications of the product, and also took various factors into account to address the economic impact. He made sure that the end result was economically justifiable, an important step beyond the product being technically sound.

1.3 Acquiring and Engaging Mentors

Early on in the design process, we actively sought external mentorship to help strengthen the technical design aspect of our solution. After looking for professionals with experience in working with unmanned aerial systems (UAS) and object detection, we identified and cold-reached out to Esteban Figuera. Esteban Figuera is a Yale College graduate with a Bachelor of Science in Electrical Engineering with experience in robotics and aerospace systems.

Esteban's background, particularly in UAS systems, robotics research, and avionics, made him a strong fit as a mentor for our project, particularly in the product design and its feasibility. He became involved with our group early on in the ideation and the design phases, helping us evaluate our concepts and how they could transition to be an actual deployable system. He provided feedback targeted on system architecture, design constraints, and sensing strategies, greatly helping our group make refinements to our approach at a conceptual level.

Throughout the project, Esteban provided us with iterative design feedback by questioning us with targeted questions that made us properly justify assumptions, consider the operational conditions of the real world, and overall led to us improving design efficiency. His experience working in aerospace and robotics systems helped to guide our project with professional engineering standards, all while we worked independently on our design. Although he served as a mentor, all research, design development and implementation, and refinements were done by our team. His mentorship enhanced what we learned while working toward our solution by exposing us to the real industry level thinking that happens in advanced engineering projects.

1.4 Impact on STEM

Participating in this challenge influenced our perspectives on STEM by showing us how crucial collaboration between different fields is when solving a real-world issue. We learned that actual impactful solutions are very interdisciplinary and require input from various different niches to become feasible.

For Dhruv, participating in this challenge reinforced his interest in electrical engineering. Taking on design responsibilities gave Dhruv the opportunity to apply principles of engineering in a practical way, allowing him to first-handedly experience the transition from theory into application. Designing as well as refining the solution further strengthened Dhruv's interest in studying electrical engineering and influenced him to pursue a career built on applied technology and innovation.

For Pranav, this project exemplified his interest in studying bioengineering. Analyzing biological interactions and environmental implications of an issue and seeing how engineering principles are used to tackle an issue in living systems emphasized the importance and necessity of this field. This project allowed him to clarify how biology and engineering are both integrated to solve an issue, and further motivated him to pursue a career focused on solving issues in biological systems.

For Arnav, this experience allowed him to express his interest in business and computer science. Analyzing data, evaluating economic implications, and effectively communicating ideas allowed him to exercise his interest while also teaching him how computational and business thinking intersect to give him the ability to implement real-world ideas. This project strengthened his interest in pursuing a career that merges entrepreneurship with his interest in computer science and business.

Past individual impacts, taking part in this challenge to engage with STEM in our respective school communities. Briefly conversing about this challenge to peers both excited us while interested them, and allowed us to share our passion for engineering together with people from our schools' communities. It demonstrated to peers as well as us how knowledge from the classroom can genuinely be taken further into the real world, solidifying our interests as well as encouraging peers to explore STEM.

2. Design

2.1 Engineering Design Process

The team approached this challenge using a structured engineering process similar to that used by a startup engineering team. Initially, we discussed and finalized the requirements on what the aircraft must do. Once we aligned on the requirements, we designed some ideas quickly using sketches and rough CAD and tested them. After that, we finalized the parts, materials and captured what effort it would take for the whole integration. One key lesson we learned during early brainstorming for the design was that every subsystem decision changed other subsystems. For example, choosing a heavier pest-detection camera would force us to choose a larger battery. That in turn shifted the center of gravity (CG) of the UAS. Moving the battery would again change the wiring routes and the wiring routes changed how wings folded. Wing folding determined whether the aircraft fits the transport container. Because of that, we split our design into three phases and used regular check-ins to prevent one subsystem from breaking the full system.

Conceptual design phase (mission understanding and big configuration choice)

We started by reading the benchmark mission and turning it into a short list of requirements: (1) cover a 0.5 mi × 0.5 mi field efficiently, (2) maintain safe hover near trees to take samples, (3) carry ten separate samples without cross contamination, (4) keep a reliable ≥ 5 mile communications link back to the ground station, and (5) fit fully assembled or folded within the project's transport constraint of a 34 × 24 × 12.5 in container, while allowing rapid field deployment without tools. We brainstormed on three ideas for the UAS to fit these mission challenge requirements, including helicopter drone (multirotor), airplane, and hybrid. We also realized that sampling is a precision positioning task where the aircraft has to hold a steady hover next to fruit and deploy a tool without forward motion, which is why we needed drone-like multirotor control during sampling.

The multirotor-only idea was initially attractive to us, but it failed our “area coverage” requirement because we learned that multirotors burn energy constantly to stay up and they usually have shorter endurance than a wing. The fixed-wing idea also seemed attractive to us because wings are efficient over distance, but it failed our “sampling near plants” requirement because a plane cannot stop and hover in front of a fruit tree without unsafe maneuvers. So, we landed with a hybrid approach where we selected a VTOL quadplane layout (a fixed wing for

efficient cruise plus four vertical lift rotors for hovering). The hybrid approach seemed to solve for range as well as for stability to collect samples.

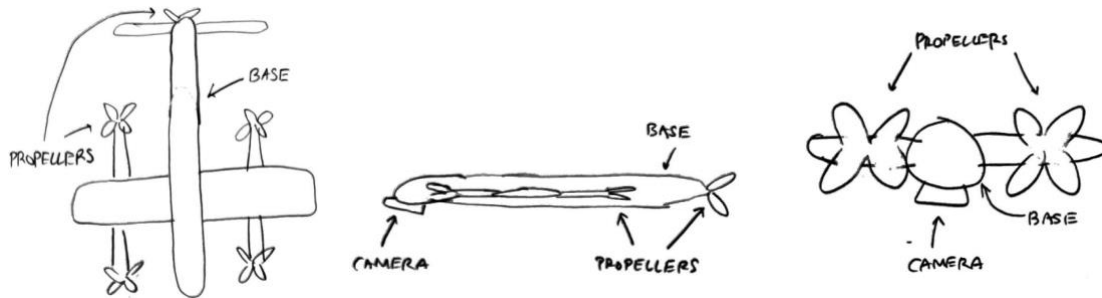


Figure 3: Conceptual phase designs for UAS

Preliminary design phase

Once we finalized the configuration of the UAS with the hybrid quadplane layout, we started working on the details of the design. We rebuilt the aircraft as a simplified model in Onshape to tackle some questions, such as where does the battery physically fit, where can a sampling mechanism extend without hitting the propellers, where do antennas go so the wing does not block them.

Our early sketches placed the sampling system directly under the nose. But we realized that this would obstruct the front VTOL rotors and would limit how close the aircraft could safely approach a tree. That led us to move the sampling concept towards a two-segment, articulated arm that extends downward and laterally away from the fuselage and is mounted near the center of gravity instead of a fixed downward tool.

At this stage, we also discussed how pest detection would work at a system level. We defined an early requirement that some form of onboard data processing or AI filtering would be needed to highlight “likely infestation” areas before a human operator makes the final decision to instruct the remote pilot to collect samples. We did not select specific hardware or algorithms yet, but we reserved space and power in the electronics bay for a small onboard computer that could later support image processing and basic machine learning.

For sampling, we considered three key constraints that later helped with the detailed design:

1. The sampling tool must be controlled with stability and must not dangle or hang freely.

2. The sampling tool must deploy laterally or diagonally, not straight down into the rotor wash.
3. The sampling system must be located near the center of gravity so that collecting multiple samples would not destabilize flight.

To satisfy the transportation requirement of fitting the aircraft into a single 34 × 24 × 12.5 in container, we looked at two types of design. If wings are not removable or foldable, a quadplane becomes too large to pack. We had two options to choose from that included a detachable wings design and a foldable wings design. One advantage we realized was that the foldable design helps with reducing the field assembly time and also helps to reduce risk of losing hardware during packing. So, we picked a foldable design where each wing panel folds inward along the fuselage using a pinned hinge at the wing root, allowing the aircraft to collapse into the transport container without removing components or disconnecting wiring.

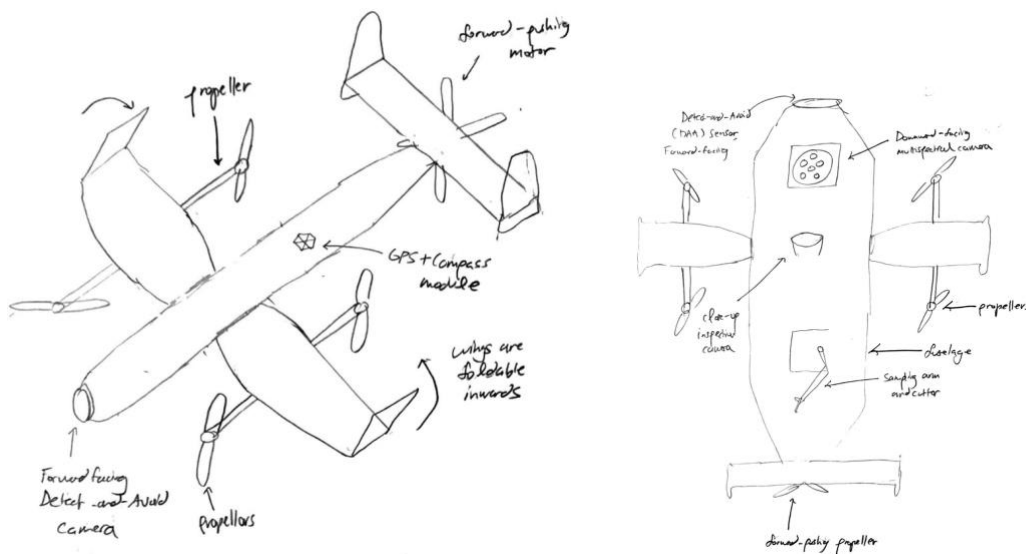


Figure 4: Preliminary designs with Quadplane and Sampling arm cutter

Detailed Design Phase: Final Parts, Materials, and Payload integration

After doing the preliminary design, we used Fusion CAD design software to draw up the detailed design. In Fusion we assigned materials, added mounting features (rails, standoffs, hatches), and calculated mass properties using the model. The battery, autopilot, onboard computer, cameras, and sample storage were all clustered around the wing aerodynamic center to maintain stability in both hover and cruise.

Two cameras are used: a downward-facing survey camera for wide-area detection and a forward-angled inspection camera for close-up confirmation during hover. Both feed data to a Raspberry Pi running a lightweight pest detection model. The AI produces a simple classification output that is transmitted to the ground station, where the payload operator confirms whether sampling is required.

The sampling mechanism consists of a servo-driven deployable arm with a cutter and scoop at the tip. The arm extends laterally during hover, removes a small plant sample, then retracts and deposits the sample into one of ten sealed internal containers. These containers are located near the CG to prevent balance shifts and to avoid cross-contamination.

Flight control is handled by a Pixhawk-class autopilot capable of quadplane operation. Long-range telemetry provides command and control over distances exceeding 5 miles. The ground station includes two operators: one piloting the aircraft and one monitoring sensor data and AI results.

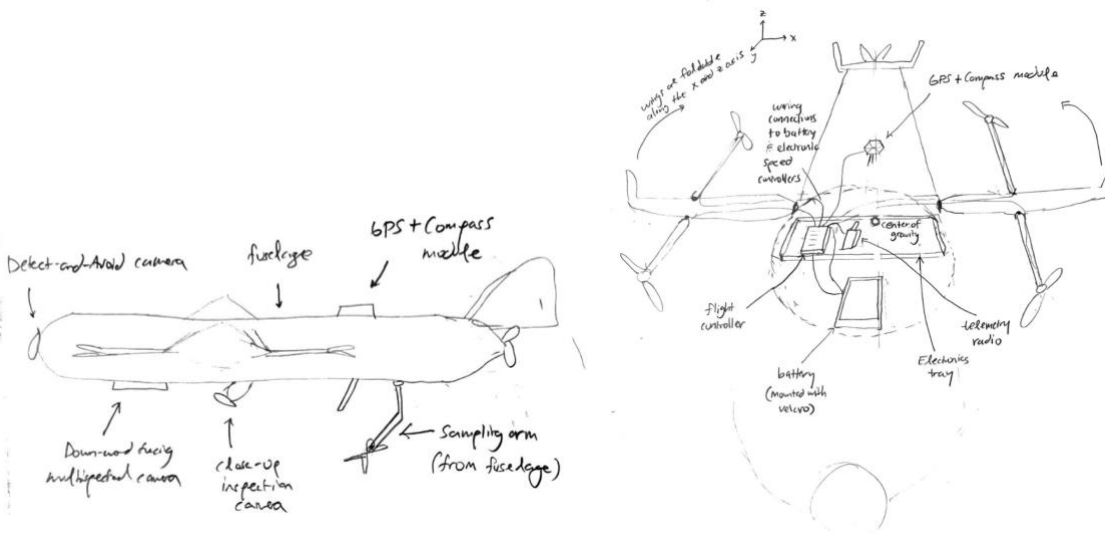


Figure 5: Side-view and cross-section showing integrated flight and sampling

2.2 Project Plan

We built our project plan by working backward from the January 23 target date and then scheduled the high-risk tasks early in the timeline. We created milestones and artifacts that needed to be produced (sketches, CAD model, parts shortlist, business and comms plans etc).

Milestones:

Milestone ID	Milestone Name	Description	Owner	Completion Date
1	Mission Analysis and Problem Definition	Research local agricultural pest and analyze benchmark mission requirements and scoring rubric	All	2025-10-10
2	Biological Research	Research and selection finalization of agricultural pest and alignment with technical design	Pranav	2025-10-15
3	Engineering Operations	Defining engineering process and planning milestones	Pranav and Arnav	2025-11-01
4	Airframe Trade Studies and Concept Selection	Evaluate multirotor fixed-wing and hybrid concepts and select VTOL quadplane configuration	Dhruv	2025-11-18
5	Detailed CAD Design and Subsystem Integration	Finalize C3 DAA avionics sensor and sampling system integration and design in Fusion CAD	Dhruv	2025-12-23
6	Benchmark Mission and Performance Analysis	Analyze mission timeline energy endurance and communication range	Dhruv	2026-01-05
7	Safety Analysis and Validation	Complete DAA lost-link and operational safety analysis and revise design	Pranav and Dhruv	2026-01-12
8	Business Case and Cost Analysis	Finalize operating costs fixed costs logistics and economic impact analysis	Arnav	2026-01-16
9	Public affairs and communications plan	Stakeholder identification and communication and legal-regulatory adherence	Arnav	2026-01-19
10	Documentation Review and Final Submission	Complete engineering notebook figures captions formatting and final PDF submission	All	2026-01-23

Table 1: Milestones for the Project Plan

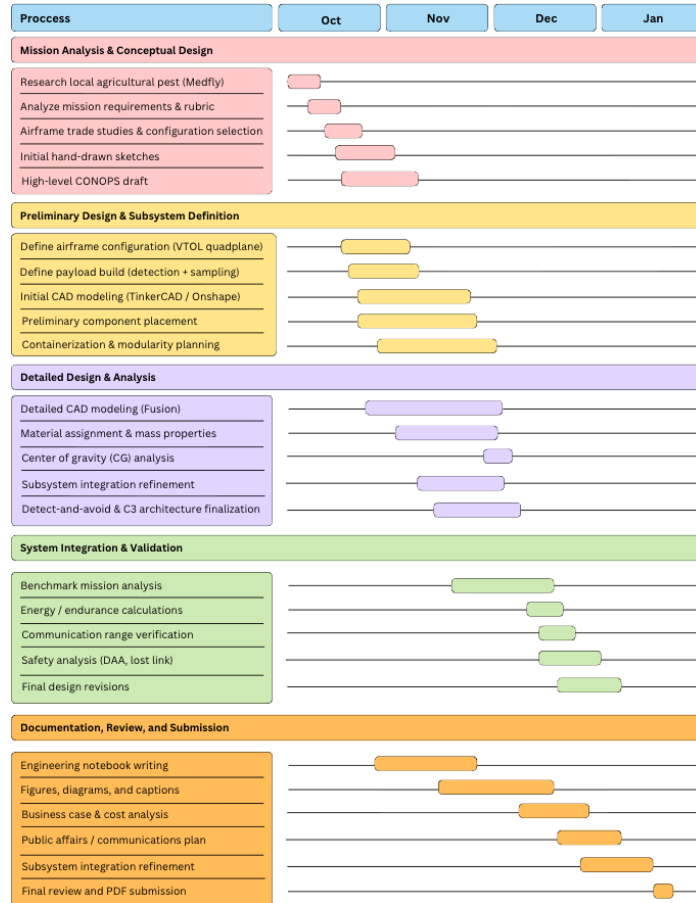


Figure 6: Gantt Chart for Detailed Task Breakdown

2.3 Subsystems

2.3.1 Air Vehicle

We designed the air vehicle to support three core mission functions: wide-area pest detection, close-range inspection, and physical sample collection. We drove our design primarily by operational needs such as safe hover near plants, controlled deployment of a sampling tool, stable sensor imaging, and reliable long-range communication.

Conceptual Phase: Selecting the Quadplane Layout

Once we realized we needed both efficient survey and stability for hovering, we committed to the quadplane. We sketched multiple quadplane shapes: (1) long fuselage with wing-mounted VTOL arms, (2) shorter fuselage with VTOL arms closer to the CG, and (3) twin-boom style. We eliminated the twin-boom idea because our sampling bay would be more complicated to place

and protect. We kept a central fuselage because it gave one clean internal volume to mount the battery, avionics, and sample rack.

We designed the system to operate like a drone during sampling because physical interaction with plants requires precise hovering, zero forward speed, and the ability to hold position next to a canopy while a tool extends. A fixed-wing aircraft cannot safely stop and “park” in front of fruit, so VTOL multirotor mode is required for stable sampling. We then use fixed-wing cruise only for efficient wide-area surveys.

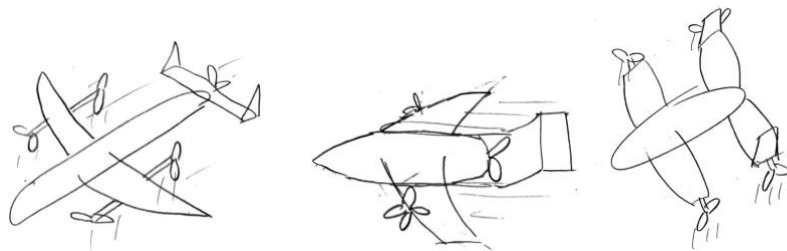
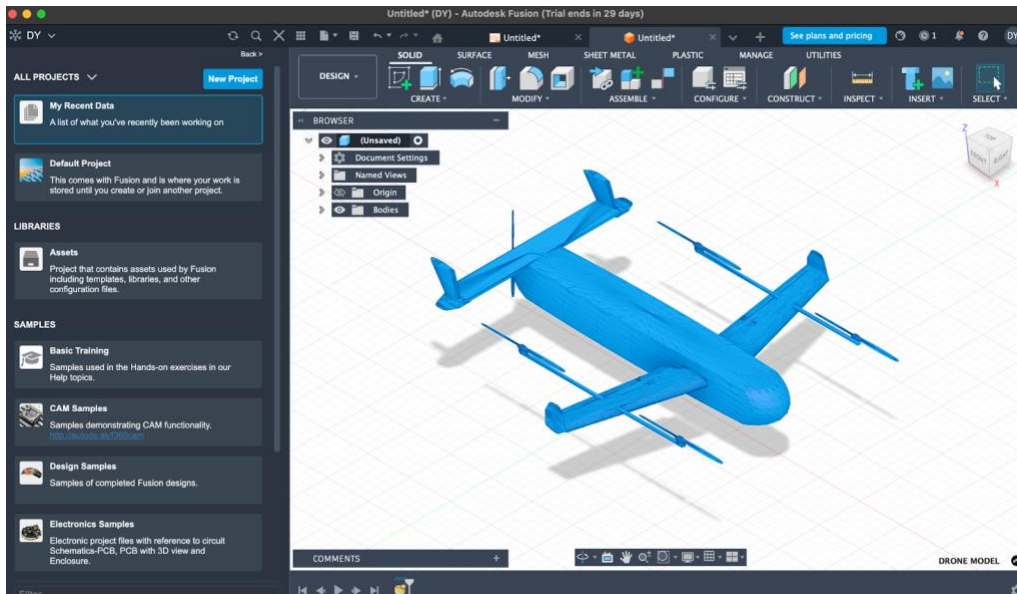


Figure 7: Conceptual Sketches of Preliminary UAS Design

Preliminary Phase: Geometry and Packaging

In preliminary CAD, we locked the following physical decisions because these criteria decided everything else: battery at CG, electronics tray above battery, cameras on the belly, sample bay near CG, GPS on top of fuselage away from power wires, and a rear pusher motor for cruise.



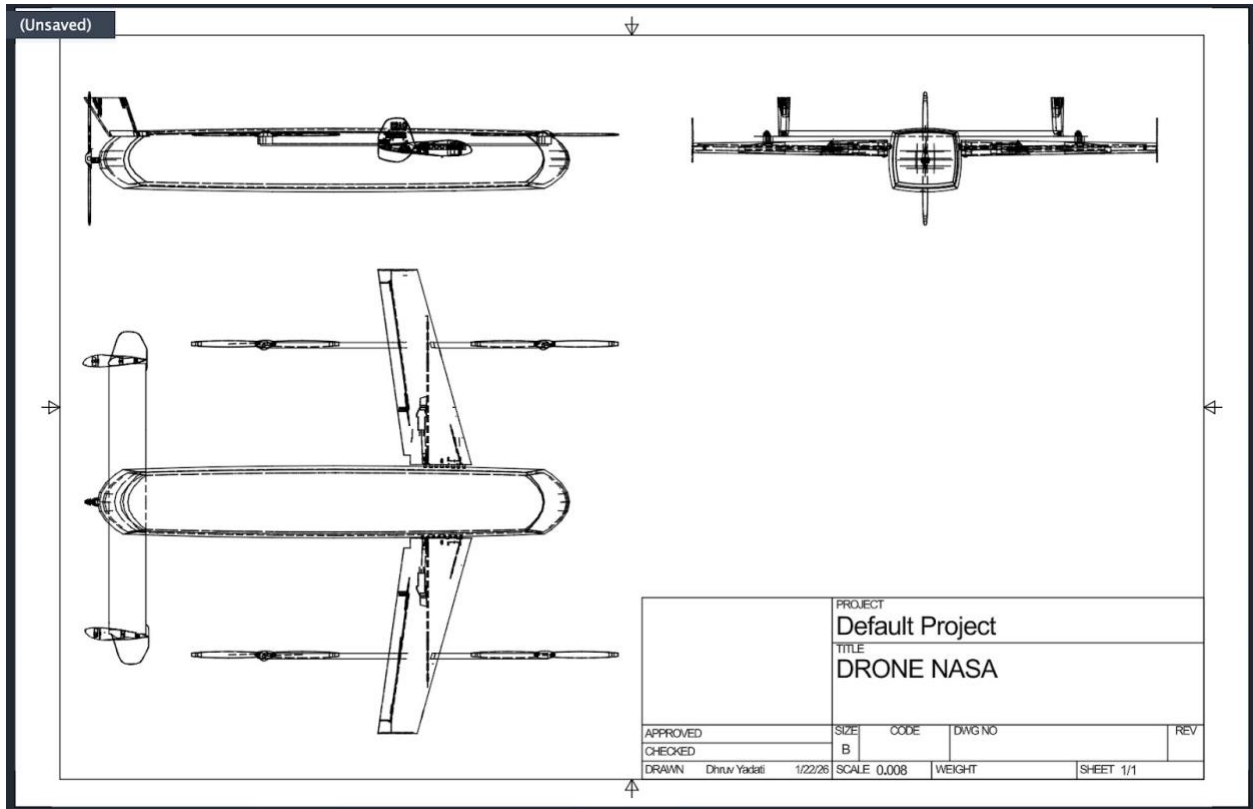
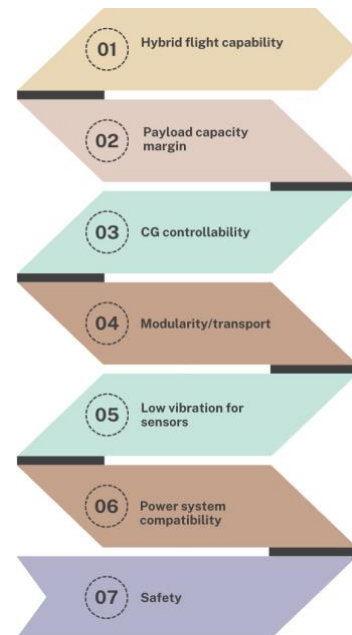


Figure 8. Three-view of preliminary uncrewed system design.

We created a set of criteria for the aircraft based on the mission requirements:

3. Must hover precisely for sampling and still cruise efficiently for survey.
4. Must carry sensors + sampling tool + ten samples with stability margin.
5. Heavy items must sit near CG so both hover and forward flight are stable.
6. Wings/arms must remove/fold to fit the container plan.
7. Autopilot and cameras need vibration isolation and rigid mounts.
8. Battery voltage must match motors/ESCs and provide endurance.
9. Geometry must protect payloads (prop clearance, belly clearance, guarded edges).



We also verified prop clearance where VTOL propellers face upward (vertical thrust) for hover, while the cruise propellers face forward (pusher) to drive the aircraft ahead in airplane mode.

Geometry, Packaging, and Container Constraints

Transportation constraint requirements influenced the physical design of our quadplane design. The aircraft is required to fit inside a container with internal dimensions of 34 × 24 × 12.5 inches. To satisfy this, the wings were designed with a fold-in hinge mechanism at the wing root, allowing each wing to fold downward and inward along the fuselage. We chose the foldable design as it eliminates the need to remove components or disconnect wiring during packing.

We used Fusion CAD to assign materials, mounting features such as rails, standoffs, and access hatches, and calculate mass properties. The final configuration had a total mass of approximately 4.1 kg and fit within a folded envelope of approximately 82 × 58 × 30 cm. These dimensions confirmed that the aircraft could be stored inside the required transport container.

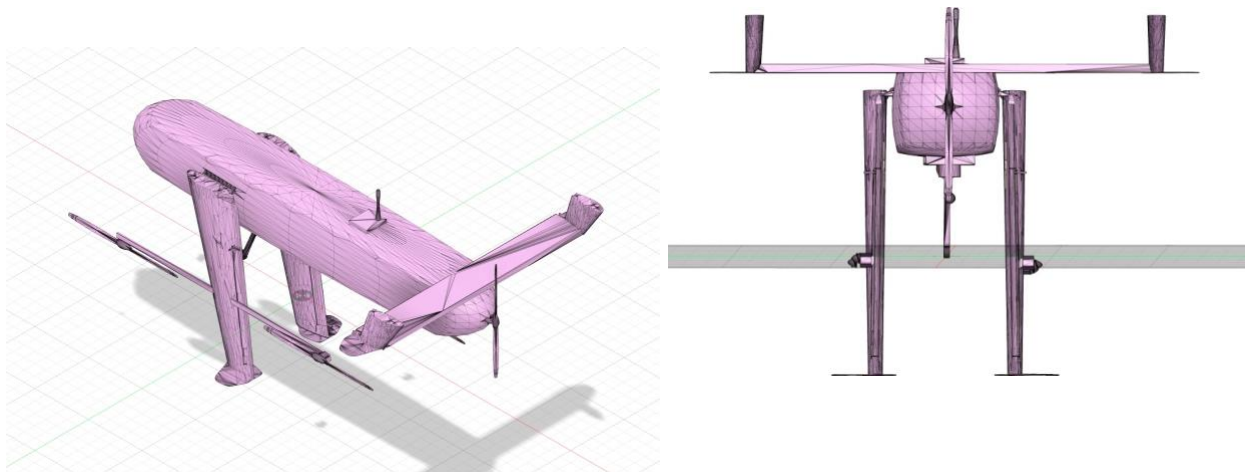


Figure 9: Preliminary CAD view showing folded wing/arm arrangement

Detailed Phase: Final Component Selection and Materials Manufacturing Approach

In detailed design, we finalized specific models for the motors/props and created an integration plan (mounting, wiring, vibration isolation, fasteners). We picked parts that are commonly used in hobby VTOL builds. We also finalized materials and mass that made up the aircraft including the battery and calculated the center of gravity.

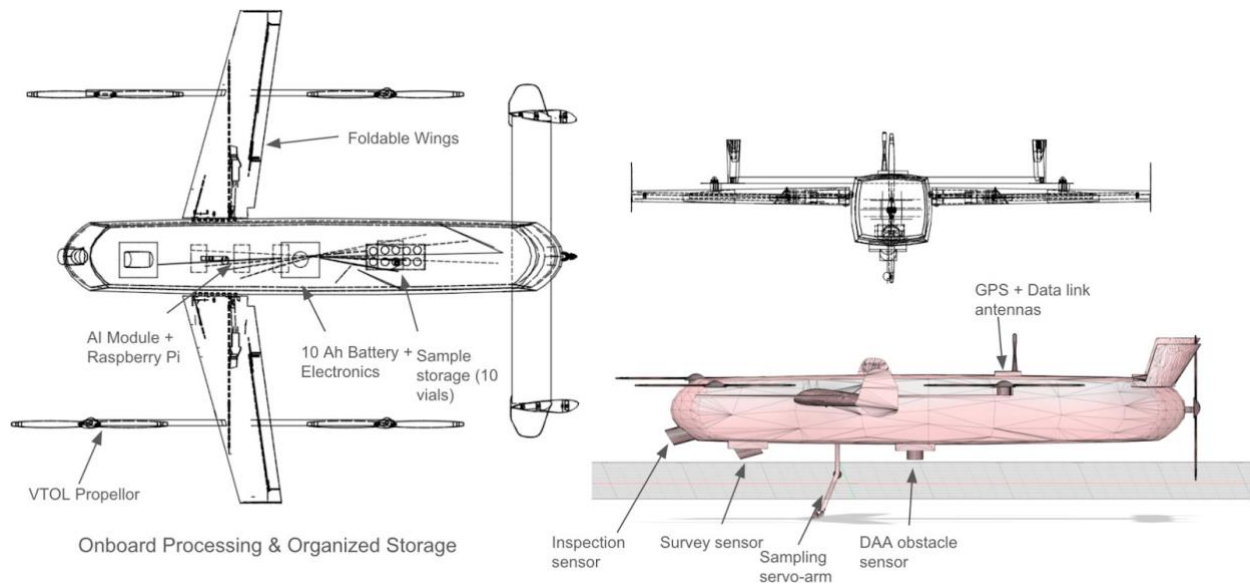


Figure 10: Detailed design sketch of final VTOL quadplane configuration showing sensor placement and sampling arm integration

Airframe Configuration and Overall Layout

Based on the mission requirement to both cover large areas and hold a stable hover next to plants for sampling, we selected a VTOL quadplane configuration. This layout combines four vertical lift rotors for takeoff, landing, and drone-like hovering during inspection and sampling with a fixed wing and a forward cruise motor for efficient survey flight. This configuration allows the aircraft to handle two requirements, which are efficient fixed-wing cruise for detection and multirotor-style hover for inspection and sampling near fruit and branches. A central fuselage layout was selected instead of a twin-boom or distributed layout because it provided a single protected internal volume for the battery, electronics, onboard computing hardware, and sample storage.

Flight Controls and Communications (C3 Integration)

We selected a Pixhawk-class autopilot because a VTOL quadplane requires a flight controller capable of managing multiple flight regimes, including vertical takeoff and landing, transition flight, and fixed-wing cruise. This controller was compatible with the quadplane control logic, sensor fusion from multiple IMUs for improved stability, and autonomous waypoint navigation.

We found that these capabilities help with safely hovering near plants and maintaining reliable autonomous operation during long survey flights.

The autopilot is mounted on a rigid electronics tray directly above the main battery and near the aircraft's center of gravity. We placed it here to reduce vibration and rotation effects on the sensors, which helps keep the aircraft stable during hover, transitions, and other maneuvers.

For communication, we used a dedicated long-range telemetry radio instead of Wi-Fi. We chose this because Wi-Fi is not reliable over long distances in outdoor farm environments. The telemetry link provides command and control over distances of at least 5 miles and continuously sends important information such as GPS position, battery level, flight mode, and system health back to the ground station in real time.

Sensor Placement and Detection Architecture

Sensor placement was designed to support two stages of detection. First, a downward-looking survey sensor is mounted under the fuselage near the center of gravity so it can scan while the aircraft flies a lawnmower pattern across the 0.5 mi × 0.5 mi field. Second, a close-up inspection camera is mounted on the lower front of the fuselage with a slight forward angle so that during hover it can look into the canopy and confirm suspected pest signs before sampling. Both sensors are mounted on a rigid plate with vibration isolation to ensure high image quality of the plants.

Onboard AI and Data Flow

We designed the detection workflow so that an AI algorithm can run onboard for fast filtering, while the final sampling decision stays human-supervised. A small onboard computer such as a Raspberry Pi is mounted inside the central electronics bay next to the autopilot. The Pi receives images from the inspection camera and runs a lightweight pest detection model that produces a simple output like “suspected infestation yes or no” and a confidence score. That result and the live video feed are transmitted to the ground station for the payload operator to review. The payload operator confirms whether a sample is needed, then the remote pilot-in-command positions the aircraft in stabilized hover and triggers the sampling sequence.

Sample Gathering Mechanism and Storage

We designed a sample gathering mechanism that is placed on the belly of the fuselage near the center of gravity so collecting up to ten samples does not shift balance enough to affect flight. The mechanism consists of a servo-driven deployable arm with a simple cutting and scooping end effector. The arm extends laterally and slightly downward during hover so it can reach fruit or leaves without bringing the fuselage or propellers into the canopy. At the tip of the arm is a small cylindrical cutter combined with a shallow scoop. When aligned with a target plant, the cutter removes a small plug of tissue (for example, fruit peel and near-surface flesh or a section of leaf). The scoop holds the sample using light mechanical pressure or gravity and prevents it from falling during retraction. Once the sample is collected, the arm retracts back into the fuselage bay. As it retracts, the end effector passes over an internal storage rack and releases the sample into a sealed vial. The rack then indexes to the next empty position. This system allows up to ten samples to be collected in a single mission without cross-contamination. The entire arm is stowed inside a protected bay during cruise flight to reduce drag and prevent accidental contact with obstacles. Inside the fuselage, samples are stored in ten separate sealed compartments or vials arranged in a small rack located near the CG. This prevents cross-contamination and also avoids major center-of-gravity changes as samples accumulate.

Sampling and Storage Sequence

- The aircraft enters a stabilized hover near the target canopy.
- The sampling arm deploys laterally and slightly downward to reach the fruit while staying clear of propellers.
- The end-effector presses a small circular cutter into the fruit surface to remove a small tissue plug (peel + near-surface flesh).
- As the arm retracts, the plug is retained in a shallow scoop on the end-effector.
- The arm retracts fully into a protected belly bay and passes through a “drop-off port” located directly above the internal sample rack.
- At full retraction, the arm pauses at a fixed “deposit position.” A small servo motion (tilt/backshake) releases the plug into a funnel/chute that guides it into the next empty sealed container.
- The sample rack indexes to the next vial position (or the aircraft uses a fixed row of vials and deposits sequentially).

- The bay door closes and the aircraft returns to inspection or resumes the survey mission.

Power System, Electrical System and Center of Gravity

We selected a 6S 10,000 mAh LiPo battery as the main power source for the aircraft. This type of battery is commonly used in hobby and student-built drones because it provides high energy density, high current output, and is easy to source. The battery weighs about 1.4 kg, making it one of the heaviest single components on the aircraft.

Because of this, the battery position strongly affects the center of gravity (CG). We mounted the battery on a quick-swap tray directly under the electronics bay and near the aircraft CG. This allows fast battery changes between flights and keeps the aircraft stable in both hover and forward flight. In Fusion, we found that moving the battery by even 2 cm noticeably changed the balance, so we treated the battery location as fixed and arranged the autopilot, onboard computer, cameras, and sample storage around it.

Electrical power is distributed using a central power distribution board (PDB). The PDB sends:

- High-current power directly to the five ESCs (four VTOL motors and one cruise motor)
- Regulated 5 V and 12 V power to avionics, sensors, and payloads using DC-DC converters
- Redundant power inputs to the Pixhawk autopilot for reliability

The battery is secured using a Velcro strap and mechanical stop so it cannot shift during aggressive VTOL maneuvers or transitions.

To verify that the power system is sufficient, we performed a basic electrical load estimate. The main loads are:

- VTOL motors (4×): high current during takeoff and hover
- Cruise motor (1×): moderate current during forward flight
- Autopilot and avionics: low but continuous
- Sensors and cameras: moderate
- Sampling arm servos: short-duration peaks

During VTOL hover, the four lift motors dominate power usage. Assuming conservative hover currents of 15-20 A per motor, total VTOL hover current is approximately 60-80 A. During fixed-wing cruise, the cruise motor typically draws 10-20 A, while the VTOL motors are inactive. Avionics and sensors together draw approximately 2-5 A.

This creates a dual-mode power profile: high power for short periods during VTOL, and much lower power during cruise. This matches the mission well, since most of the flight time is spent in efficient fixed-wing survey. Based on these estimates and the selected battery capacity, the aircraft is expected to have enough endurance to complete the benchmark mission with margin for loitering, sampling, and safe return.

Power and Endurance Calculations

Battery type: 6S LiPo

Nominal voltage: 22.2 V

Capacity: 10,000 mAh = 10 Ah

Battery Energy = Voltage × Capacity = 22.2V × 10Ah = 222Wh

Hover Power (VTOL Mode)

Assumption: Each VTOL motor draws about 17.5 A in hover.

Total Current: 4 × 17.5A = 70A

Hover Power = Voltage × Current = 22.2V × 70A = 1,554W

Hover Endurance

Time = Energy / Power = 222Wh / 1,554W = 0.143 hours

Hover endurance ≈ 8 minutes

Cruise Power

Assumption: cruise motor draws 15 A.

Power = 22.2V × 15A = 333W

Cruise Endurance

Time = 222Wh / 333W = 0.667 hours

Cruise endurance ≈ 40 minutes

Avionics and Payload Power

Assumption: avionics and sensors draw 3 A.

$$\text{Power} = 22.2\text{V} \times 3\text{A} = 67\text{W}$$

These calculations show that the selected 6S 10,000 mAh battery provides sufficient energy for short high-power VTOL operations and long efficient fixed-wing cruise, enabling the aircraft to complete the benchmark mission with adequate safety margin.

Mass Properties and Stability

The final aircraft mass is approximately 4.1 kg after all the components were integrated (see sample table below). We designed how the internal electronics are stored in a central electronics bay and with an electronics tray and clean harnessing to each wing/arm. We had to ensure that the center of gravity did not cause problems to tilt the quadplane, so we designed it so that heavy items (battery, autopilot, payload camera, sample rack) were all kept near the wing's aerodynamic center. This way, we also would not end up with an aircraft that is stable in one flight mode but unstable in another. Because all major masses are clustered near the wing aerodynamic center, the aircraft remains stable in both VTOL and fixed-wing modes, and trim does not change significantly as samples are collected.

Component	Qty	Mass (g)	Subtotal (g)
6S 10Ah battery	1	1400	1400
VTOL motors (22xx)	4	55	220
Cruise motor	1	55	55
ESCs	5	25	125
Propellers	5	15	75
Pixhawk autopilot	1	40	40
Raspberry Pi	1	45	45
Cameras & sensors	2	80	160
Sampling mechanism	1	300	300
Sample rack + vials	1	200	200
Airframe (fuselage, wings, arms)		1200	1200
Wiring, mounts, fasteners		300	300
Total			4,120 g \approx 4.1 kg

Table 2: Aircraft Mass Breakdown (Derived from Bill of Materials)

Center of Gravity (CG) Analysis

To verify that the aircraft remains stable in both VTOL and fixed-wing flight, a first-order center of gravity (CG) analysis was performed using a component mass-moment method. A longitudinal

data point was defined at the nose of the fuselage, and all component distances were measured aft of this point along the fuselage centerline. We learned that this approach is commonly used during early aircraft design to validate CG placement before final hardware integration.

Table below shows the component masses, assumed longitudinal locations, and resulting moments used to calculate the CG location.

Component	Mass (g)	Distance from Datum (cm)	Moment (g·cm)
Battery (6S 10 Ah)	1400	40	56,000
Pixhawk autopilot	40	42	1,680
Raspberry Pi	45	42	1,890
Cameras & sensors	160	30	4,800
Sampling mechanism	300	45	13,500
Sample rack + vials	200	45	9,000
VTOL motors (×4)	220	50	11,000
Cruise motor	55	70	3,850
ESCs	125	45	5,625
Propellers	75	50	3,750
Airframe structure	1200	45	54,000
Wiring & mounts	300	45	13,500
Total	4,120 g		178,595 g·cm

Table 3: Resulting component moments to calculate Center of Gravity

$$\text{CG} = \text{total moment} \div \text{total mass}$$

The calculated CG location of approximately 43 cm aft of the nose places the center of gravity near the aircraft’s wing aerodynamic center and close to the geometric center of the fuselage. This location was driven primarily by the placement of the battery, avionics, and sample storage system.

Positioning the CG near the wing aerodynamic center provides two key benefits:

- Stable fixed-wing cruise, reducing trim drag and control surface deflection.
- Balanced VTOL hover, minimizing control effort and asymmetry between lift rotors.

The sampling mechanism and sample storage rack are located near the CG. It collects up to ten samples and does not significantly shift the aircraft balance. The aircraft remains stable throughout the mission as samples are accumulated.

Folded Size and Transport Container Verification

The aircraft was also evaluated against the required transport container constraint of 34 × 24 × 12.5 inches. Converting to metric, the container internal dimensions are approximately 86 × 61 × 31.8 cm. Using Fusion CAD, the aircraft was modeled in its fully folded configuration with wings hinged inward, VTOL arms aligned along the fuselage, and the sampling arm fully stowed.

The resulting folded envelope of the aircraft is approximately 82 × 58 × 30 cm, which fits within the container limits in all three axes with margin. Table Y summarizes the comparison.

Dimension	Aircraft (folded)	Container limit	Margin
Length	82 cm	86.4 cm	+4.4 cm
Width	58 cm	61.0 cm	+3.0 cm
Height	30 cm	31.8 cm	+1.8 cm

Table 4: Folded envelope dimensions calculation

Fuselage

The fuselage is modeled as a lightweight structural spine using a carbon-fiber or fiberglass tube. Carbon fiber was selected for its high stiffness-to-weight ratio, while fiberglass is considered as a lower-cost alternative. Internally, the fuselage houses the battery, electronics tray, payload bay, and wiring harness.

Manufacturing approach:

- Tube cut to length
- Internal trays bonded or bolted
- Access hatches cut for battery and payload servicing

Wings

The wings use foam cores (XPS or EPP) reinforced with a carbon-fiber spar. This is a common hobby aircraft construction method that is lightweight, inexpensive, and easy to repair.

Manufacturing approach:

- Foam cores cut using hot-wire or hand tools
- Carbon spar bonded with epoxy

- Outer surface covered with laminate film or reinforced tape

VTOL Arms

VTOL arms use carbon or aluminum tubes with 3D-printed motor mounts and clamps.

Manufacturing approach:

- Tubes cut to length
- Motor mounts 3D printed
- Assemblies bolted using machine screws

Electronics Tray

The electronics tray is a flat carbon or fiberglass plate used to mount the Pixhawk, PDB, and companion computer.

Manufacturing approach:

- Laser-cut or hand-cut plate
- Components mounted using standoffs and vibration isolators

2.3.2 Command, Control, and Communications (C3)

Conceptual Design Phase: Defining C3 Requirements, Autonomy, and Human Roles

During the conceptual design phase, we translated the benchmark mission requirements into a set of functional Command, Control, and Communications (C3) needs. At a minimum, the system had to (1) support autonomous waypoint navigation and VTOL flight mode transitions, (2) transmit aircraft state, health, and position data continuously to the ground station, (3) relay sensor data needed for pest detection and sampling decisions, and (4) maintain a reliable communication link of at least five miles under real-world operating conditions. In addition, the benchmark mission specifies two human operators, which required the C3 system to support a pilot-in-command and a payload/data monitor working simultaneously without overloading either individual.

We defined the responsibilities of the two operators. One pilot operator would supervise the mission, authorize takeoff and landing, and intervene for safety, while the second payload operator would focus on sensor interpretation, detection confirmation, and sampling decisions.

Preliminary Design Phase: C3 Architecture, Trade Studies, and Autonomy Strategy

In the preliminary phase, a high-level C3 architecture was developed that separated onboard autonomous navigation from ground-based supervision and decision-making. Several communication approaches were evaluated, including Wi-Fi-based links, consumer RC radios, and long-range telemetry systems. We eliminated the Wi-Fi and consumer radios options as they did not provide sufficient range, and were susceptible to interference and telemetry reliability.

Further research and comparisons on pilot software and telemetry range led us to center our architecture on a Pixhawk-class autopilot paired with a dedicated telemetry radio operating in the 900 MHz or 433 MHz band. These lower-frequency links were selected because of their superior propagation through foliage and terrain, which was critical for this mission that needed to be conducted under complex plant canopies. During this phase, we also decided on the antenna placement as wing position and folding geometry could easily shadow antennas if not considered early.

At the same time, we defined the aircraft's autonomous navigation behavior. For large-area surveying, the aircraft operates autonomously using a predefined coverage path uploaded from the ground station. This allows efficient, repeatable inspection of the entire 0.5 mi × 0.5 mi field while minimizing pilot workload. When a suspected pest signature is detected, the aircraft transitions from survey flight to a stabilized loiter or hover mode, enabling a controlled handoff to the payload operator for confirmation and sampling authorization.

To support this behavior, we considered multiple path-planning approaches. The final strategy uses a boustrophedon (“lawnmower”) coverage pattern for systematic area survey, combined with localized A* path planning for short-range repositioning near obstacles or sampling targets. We used this layered approach as it balances computational simplicity with operational flexibility. The comparison and final decision between path-finding candidates is shown in the table below.

Algorithm	Advantages	Limitations	Assessment
Boustrophedon (Lawnmower)	Simple, efficient, predictable, ideal for full-field coverage	Not reactive by itself	Selected for survey phase
A*	Fast, optimal, low computational cost	Requires defined local grid	Selected for local replanning
RRT / RRT*	Handles complex spaces	High computational cost, unpredictable paths	Rejected
Potential Fields	Simple implementation	Local minima, unstable near trees	Rejected
Dijkstra	Guaranteed shortest path	Computationally inefficient for this mission	Rejected

Table 5: Comparison between path-finding methodologies

In parallel, we sketched and evaluated ground control station workflows. The pilot requires continuous access to flight mode, position, battery state, and failsafe alerts, while the payload operator requires live sensor imagery. This analysis led to the early adoption of a two-screen, two-operator ground station concept.

Detailed Design Phase: Final C3 System and Integration

In the detailed design phase, the C3 architecture was finalized and integrated with the air vehicle. The system is centered on a Pixhawk 6C-class autopilot. The autopilot performs onboard sensor fusion, flight stabilization, autonomous waypoint navigation, and VTOL transition management, allowing safe operation even if ground commands are delayed or temporarily interrupted.

In the design, we mounted a GPS module with a built-in compass on a small mast above the fuselage so it is not affected by electrical noise from the motors and wires. This gives the aircraft accurate position and direction information, which the autopilot uses for navigation. The GPS data is also sent to the ground station so the operators always know where the aircraft is and so the system can return safely if communication is lost.

For communication, we used a long-range telemetry radio instead of Wi-Fi because it works much better over long distances in outdoor environments. This radio link sends control commands from the ground station to the aircraft and sends back important data like position, battery level, and flight mode. The antennas are placed on the fuselage away from the wings so the signal is not blocked when the wings are folded or during flight.

Ground Control Station Design and Human Resources

The ground control station is designed around two human operators. The pilot-in-command operates mission planning and flight monitoring software, supervising autonomous flight, authorizing transitions, and intervening during abnormal or emergency conditions. The payload/data monitor views live imagery from the pest-detection and close-up inspection cameras, logs detections, and authorizes sample collection.

By separating these roles, the system significantly reduces cognitive load during critical operations such as hover sampling near trees. The human resource requirements for the final design are:

- Pilot-in-command: aircraft safety, mission supervision, emergency intervention
- Payload/data monitor: sensor interpretation, detection confirmation, sampling authorization

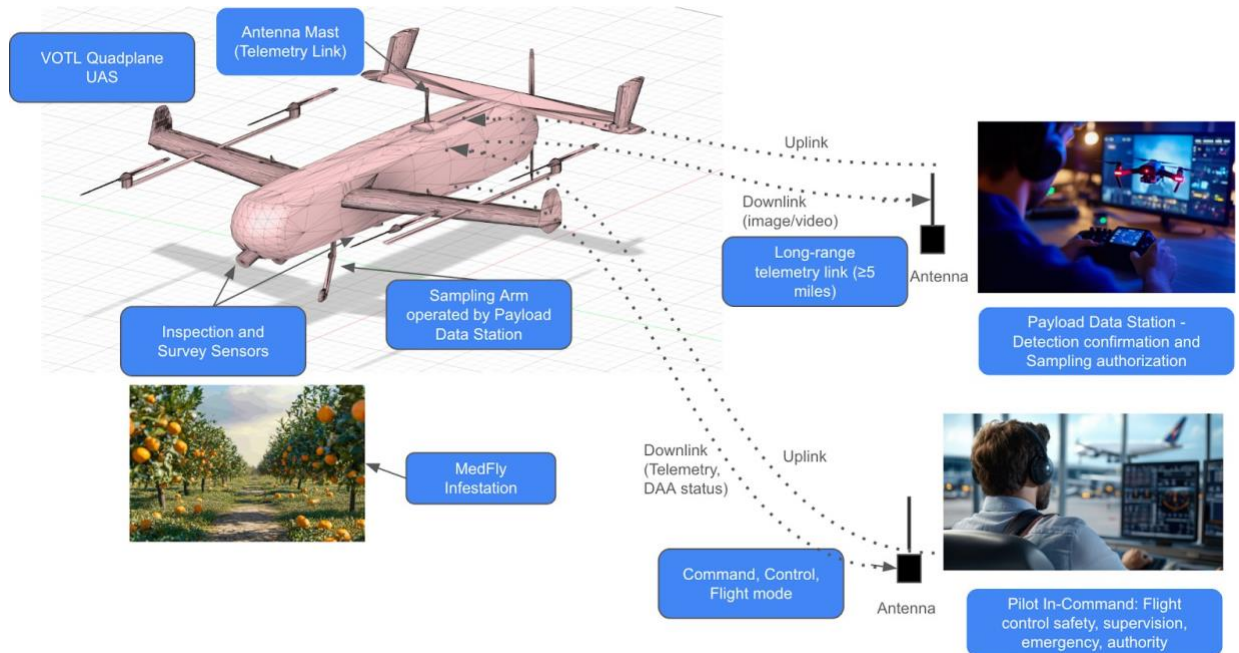


Figure 11: C3 configuration and associated interfaces

Integration of Detect-and-Avoid and Real-Time Location

The C3 system is also used for safety features such as Detect and Avoid (DAA) and real-time location tracking. Forward-facing sensors are connected to the autopilot so the aircraft can detect obstacles like trees, birds, or other aircraft. This information is processed onboard and sent to the ground station so both the system and the operators are aware of possible dangers during flight.

The aircraft's GPS system continuously sends its location to the ground station. This allows the operators to always know where the aircraft is, helps the aircraft return safely if communication is lost, and supports safe operation around other aircraft.

2.3.3 Payload – Pest Detection

Conceptual Design Phase: Defining What Must Be Detected

The pest selected for this project is the Mediterranean fruit fly (Medfly), which is a major agricultural pest in our region. Medflies mainly affect the fruit itself, not the leaves. Female flies lay their eggs just under the fruit skin, and the larvae grow inside the fruit. Because of this, early signs of infestation are usually seen on the fruit, such as small puncture marks, soft or bruised

spots, changes in color, and early fruit drop. Leaf damage may appear later, but it is not a reliable way to detect Medfly infestation.

We concluded that no single sensor could efficiently meet all detection needs. Instead, the payload would require two complementary sensing functions:

1. A wide-area survey sensor capable of scanning large portions of the field efficiently to identify trees or regions exhibiting abnormal stress patterns.
2. A close-up inspection sensor capable of resolving fruit-level visual evidence before committing time and energy to physical sampling.

This two-layer approach ensured that the aircraft could cover the entire benchmark area efficiently while still providing the resolution necessary to make confident sampling decisions.

Preliminary Design Phase: Sensor Requirements and Trade Studies

With the detection objectives defined, we translated them into sensor selection criteria. The pest detection payload needed to:

- Provide sufficient spatial resolution from a safe standoff altitude
- Detect indicators relevant to Medfly infestation (stress patterns and visible fruit damage)
- Be compatible with the air vehicle's mass and center-of-gravity constraints
- Produce data that could be processed onboard and reviewed by a payload operator in real time
- Integrate cleanly with the C3 system and ground station workflow

At this stage, we evaluated whether a single sensor could meet all needs. RGB-only solutions were attractive for simplicity, but lacked sensitivity to subtle physiological stress. High-end multispectral systems offered excellent stress detection but were heavier, more expensive, and not optimized for fruit-level visual confirmation. As a result, we committed to a dual-sensor architecture: multispectral sensing for detection and RGB imaging for confirmation.

Multispectral Sensor Trade Study

Multispectral imaging was evaluated specifically for its ability to detect plant stress patterns that may correlate with early infestation. Several representative multispectral options were compared before narrowing the selection.

Candidate Class	Why Considered	Advantages	Limitations	Decision
Compact UAS multispectral (e.g., Sequoia-class)	Commonly used in agricultural surveys	Lightweight, proven NDVI/NDRE capability	Added mass, integration complexity	Selected as primary survey sensor
High-end multispectral (e.g., RedEdge-class)	Advanced spectral resolution	Excellent data quality	Heavy, costly, higher power draw	Rejected (overkill)
RGB-only mapping	Simplest approach	Low cost, easy workflow	Cannot detect subtle physiological stress	Supplement only

Table 6: Comparison between multispectral sensors

The selected multispectral class provides sufficient spectral bands to flag anomalous trees or regions without imposing excessive mass or power penalties. Importantly, it is used as a screening tool, not a final diagnostic instrument.

Detailed Design Phase: Close-Up Detection and Final Payload Architecture

Once wide-area detection candidates are flagged, the mission transitions to close-up visual confirmation. This phase relies on a dedicated RGB inspection camera mounted on the lower fuselage, angled downward and aft to observe fruit directly during stabilized hover. This camera is optimized for high spatial resolution, allowing the payload operator to identify visible oviposition marks, discoloration, deformation, or localized decay on individual fruits.

Several close-up camera options were evaluated based on resolution, mass, integration complexity, and data handling requirements. A camera trade study illustrating the different candidates for selection initially are shown in table below.

Candidate	Advantages	Limitations	Decision
Compact embedded RGB camera (e.g., Pi-class)	Small, lightweight, flexible integration	Requires companion compute	Selected
Self-contained micro action camera	High-quality video, low mass	Data integration complexity	Alternate
Stereo/depth camera	Range and depth data	High power and compute cost	Rejected for detection

Table 7: Illustration of inspection camera candidates

The selected RGB camera provides sufficient image quality for fruit-level inspection while remaining lightweight and easy to integrate into the avionics stack. It is rigidly mounted near the aircraft CG to minimize blur and is isolated from vibration to maintain image clarity during hover.

How Pest Detection Works in Flight

During a mission, the aircraft first flies an autonomous survey pattern using the multispectral sensor to scan the field. Onboard processing or ground-station review identifies trees or regions exhibiting abnormal stress signatures. These candidates are flagged for closer inspection.

The aircraft then transitions to a stabilized hover near the target canopy. The close-up RGB camera provides live imagery to the payload operator, who inspects individual fruits for visible Medfly indicators. Only when both sensor layers suggest a credible infestation does the operator authorize physical sampling. This workflow reduces unnecessary sampling attempts and ensures that flight time and payload capacity are used efficiently.

Final Pest Detection Payload Configuration

The final pest detection payload consists of:

2. One multispectral survey sensor for wide-area stress detection
3. One close-up RGB inspection camera for fruit-level visual confirmation
4. Rigid mounting hardware with vibration isolation
5. Electrical and data interfaces integrated into the C3 system

2.3.4 Payload – Sample Gathering

Conceptual Design Phase: Determining What to Sample

The sample-gathering payload was designed only after we fully understood the biological behavior of the Mediterranean fruit fly. Unlike pests that directly damage leaves or sap flow, Medflies lay eggs inside fruit, and larval development occurs entirely within the fruit flesh. As a result, leaf-only sampling was determined to be insufficient and potentially misleading. A healthy-looking canopy can still harbor infested fruit, especially during early stages of an outbreak.

Based on this understanding, we concluded that fruit tissue, specifically the outer peel and near-surface flesh, was the most meaningful physical evidence to collect. This approach allows laboratory analysis to identify oviposition damage, larval presence, or early tissue breakdown without requiring removal of entire fruits, which vary widely in size and mass. Sampling a small, consistent fruit plug also minimizes damage to the tree and reduces the mechanical complexity required onboard the aircraft.

From this conceptual analysis, the following sampling requirements were defined:

2. The system must safely interact with fruit without contacting propellers or damaging branches.
3. The system must extract a small, repeatable fruit tissue sample.
4. The system must store ten physically separated samples to prevent cross-contamination.
5. The system must keep mass close to the aircraft center of gravity to avoid destabilizing flight.

Preliminary Design Phase: Mechanism Concepts and Layout

During the preliminary design phase, we explored several mechanical approaches for collecting fruit tissue, including fixed downward cutters, suction-based probes, and articulated arms. We did not incorporate fixed cutters because they required the aircraft to maneuver precisely underneath fruit, increasing collision risk. Suction-based systems were also rejected due to inconsistent performance across fruit types and difficulty sealing against curved surfaces.

We ultimately converged on a deployable sampling arm stored within the fuselage. This approach allows the aircraft to remain at a safe standoff distance from the canopy while

extending the tool only when needed. Early sketches explored both downward and sideward deployment; sideward deployment was selected because it improves visibility for the inspection camera and provides better access to fruit growing on the outer canopy.

The preliminary mechanism consists of:

8. A sampling arm stored inside a protected fuselage bay.
9. A hinged or servo-driven joint allowing the arm to extend laterally and slightly downward during hover.
10. An end effector combining a small cutter and scoop/gripper to extract fruit tissue.
11. An internal sample storage rack positioned at the aircraft CG.

At this stage, we also defined the internal storage strategy. A central sample rack or carousel holding ten capped vials was selected to ensure samples remain isolated and to prevent shifts in mass as samples accumulate. Keeping the rack near the CG minimizes changes in aircraft trim over the course of a mission.

Detailed Design Phase: Final Sampling Mechanism and Operation

In the detailed design phase, the sampling system was fully modeled and integrated into the aircraft. The final design uses a servo-actuated sampling arm that deploys from a belly-mounted bay during stabilized hover. The arm provides sufficient reach to access fruit while maintaining safe separation from propellers and structural components.

The end effector consists of a small cylindrical cutter combined with a shallow scoop or gripper. When aligned with a target fruit, the cutter removes a small plug of peel and underlying flesh. The sample is retained by the scoop and transferred back into the fuselage as the arm retracts. This method produces a consistent sample size suitable for laboratory inspection while minimizing force on the fruit. Once retracted, the arm positions the sample above the internal storage rack. The sample is released into a sealed vial, and the rack indexes to the next empty position. This process allows up to ten samples to be collected in a single flight without cross-contamination. The sampling bay remains closed during cruise flight to protect the mechanism and reduce aerodynamic drag.

The full sampling sequence is:

1. Aircraft enters a stabilized hover near the target tree.

2. Sampling arm deploys from the fuselage bay.
3. The end effector extracts fruit tissue samples.
4. Arm retracts into the fuselage.
5. Sample is deposited into a sealed vial.
6. Rack indexes and prepares for the next sample.

This sequence was designed to be repeatable, slow, and deliberate, prioritizing safety and reliability over speed.

Final Sample Gathering Payload Configuration

The final sample-gathering payload includes:

5. One deployable sampling arm
6. One cutter/scoop end effector
7. One internal sample rack or carousel
8. Ten sealed sample containers

2.3.5 Ground/Support Equipment

Conceptual Design Phase: Defining Ground Support Requirements

Ground and support equipment were designed using the same systems-engineering mindset applied to the air vehicle. Early in the project, we recognized that the benchmark mission would require multiple sorties, safe handling of biological samples, and continuous situational awareness for operators over long distances. As a result, the ground system was treated as an operational subsystem rather than an afterthought.

From the benchmark mission and safety requirements, the following ground support needs were identified:

1. Continuous command, control, and monitoring for a VTOL aircraft operating beyond visual line of sight of the operators
2. A workflow that supports two distinct human roles without task overload
3. Safe handling, charging, and transport of high-energy LiPo batteries
4. Secure collection, labeling, and transport of up to ten biological samples per flight
5. Rapid turnaround between flights to complete the benchmark mission efficiently

Preliminary Design Phase: Ground Workflow and Human-Centered Layout

During the preliminary design phase, we mapped the entire field operation from arrival at the mission site through post-flight shutdown. This exercise revealed that poor ground organization could easily negate the benefits of a well-designed aircraft. As a result, the ground station was designed around task separation and workflow efficiency, not just hardware availability.

The ground control station was divided into two functional zones:

1. A pilot station, responsible for mission planning, aircraft state monitoring, safety oversight, and emergency intervention
2. A payload/data station, responsible for live sensor monitoring, detection confirmation, sampling authorization, and data logging

This separation was driven directly by human factors considerations. During hover sampling near trees, cognitive load is high; forcing a single operator to both fly and interpret sensor data would increase the risk of error. By splitting responsibilities, each operator can maintain situational awareness within their domain.

Preliminary planning also addressed antenna placement, battery logistics, and sample handling. Antennas needed to be deployable quickly and positioned to maintain clear line-of-sight to the aircraft. Battery handling procedures had to minimize turnaround time while meeting safety requirements. Sample handling procedures needed to preserve chain-of-custody and prevent cross-contamination.

Detailed Design Phase: Final Ground/Support Configuration

The final ground/support system consists of the following major components: Ground Control Station Hardware, Power and Battery Support Equipment, Sample Handling and Transport Equipment, and Human Resources.

Ground Control Station Hardware

6. Two computing devices (laptop or tablet class): one dedicated to piloting and mission supervision, one dedicated to payload monitoring
7. Long-range telemetry radio interface connected to the pilot station
8. Directional or high-gain antennas mounted on portable tripods to extend communication range
9. Sun shades, folding tables, and weather protection to ensure reliable outdoor operation

The pilot station runs mission planning and flight monitoring software, displaying aircraft position, battery status, flight mode, and failsafe alerts. The payload station displays live imagery from the pest detection and close-up cameras and provides tools for logging detections and sample metadata.

Power and Battery Support Equipment

- LiPo balance chargers capable of charging 6S batteries safely
- Fire-resistant LiPo storage and charging bags
- Spare batteries staged for rapid swap between flights

Battery management procedures were designed to minimize downtime while maintaining safety. After each flight, batteries are swapped, inspected, and placed on charge or into safe storage as appropriate.

Sample Handling and Transport Equipment

7. Sealed secondary containment box for collected samples
8. Pre-labeled sample containers matched to onboard sample rack positions
9. Log sheets or digital logs linking each sample to GPS location, time, and flight number

Immediately after landing, samples are removed from the aircraft and transferred into secondary containment to preserve integrity and traceability.

Human Resources and Cost Analysis

The final ground operation requires two trained human operators:

1. Pilot-in-command (1)
Responsible for aircraft safety, mission execution, emergency intervention, and regulatory compliance.
2. Payload/Data Monitor (1)
Responsible for interpreting sensor data, confirming detections, authorizing sampling, and maintaining data records.

Role	Quantity	Estimated Hourly Rate	Estimated Mission Hours	Estimated Cost
Pilot-in-command	1	\$50/hr	6 hrs	\$300
Payload/Data Monitor	1	\$40/hr	6 hrs	\$240
Total Personnel Cost				\$540

Table 8: Estimated Personnel Costs

Component	Quantity	Estimated Unit Cost	Subtotal
Ground control computers	2	\$800	\$1,600
Telemetry radio + antenna system	1	\$500	\$500
Battery chargers	2	\$100	\$200
Fire-safe battery storage	2	\$50	\$100
Sample containment & labeling kit	1	\$150	\$150
Misc. field equipment (tables, mounts, cables)	-	\$150	\$150
Total Ground Equipment Cost			\$2,800

Table 9: Estimated Ground Equipment Costs

2.4 Lessons Learned

Throughout the project, we learned that engineering is not the act of selecting parts in isolation, but the process of managing tradeoffs across a tightly coupled system. Several key technical

lessons emerged that fundamentally shaped the final design and improved our understanding of real-world aerospace systems.

One of the earliest lessons was the importance of requirements-driven design. Initial ideas often seemed reasonable until they were tested against hard constraints such as communication range, transport size limits, and biological relevance of pest indicators. For example, early consideration of leaf sampling was quickly eliminated once the biological behavior of the Mediterranean fruit fly was fully understood. This reinforced that effective engineering decisions must be grounded in domain-specific knowledge and not just mechanical feasibility.

We also learned that subsystem decisions are rarely independent. Choices made for one subsystem frequently propagated unexpected consequences elsewhere. Selecting heavier sensors increased power demand, which required a larger battery, which shifted the center of gravity and affected wing folding geometry. This cascade effect highlighted the need to evaluate designs holistically rather than optimizing subsystems in isolation. Maintaining a central electronics tray near the center of gravity proved critical in preventing instability across multiple flight modes.

Another significant lesson involved autonomy and human-in-the-loop control given the requirement to have two operators. Initially, it was tempting to either significantly automate the mission or rely heavily on manual control. Through iteration, we learned that semi-autonomous operation, autonomous survey combined with human-supervised sampling, provided the best balance between efficiency and safety. This approach reduced operator workload while still preserving human judgment during high-risk, close-proximity operations near trees.

From a mechanical design perspective, we learned that simplicity improves reliability. Early sampling mechanism concepts were overly complex and difficult to integrate within mass and space constraints. By narrowing the design to a single deployable arm with a repeatable cutting motion and centralized sample storage, the final system became easier to analyze, model, and explain. Designing the sampling mechanism to operate slowly and deliberately improved safety and reduced the risk of destabilizing the aircraft during hover.

The project also reinforced the importance of designing for logistics and operations, not just flight. Transport container size restrictions directly influenced wing folding decisions, which in

turn affected structural design, wiring routes, and antenna placement. Similarly, ground support procedures and sample handling workflows were just as critical to mission success as airborne performance. This highlighted that a technically capable aircraft can still fail operationally if support systems are not carefully planned.

Finally, we learned the value of early modeling and iterative refinement. Starting with hand sketches, then progressing through rough CAD and finally detailed mass-property models, allowed major issues to be discovered early when changes were inexpensive. Using CAD tools such as Fusion CAD to calculate center of gravity and verify folding clearances prevented late-stage design conflicts and increased confidence that the final configuration was feasible.

2.5 Final Design Drawings

Figure 12 depicts the three-view of the final unmanned system design.

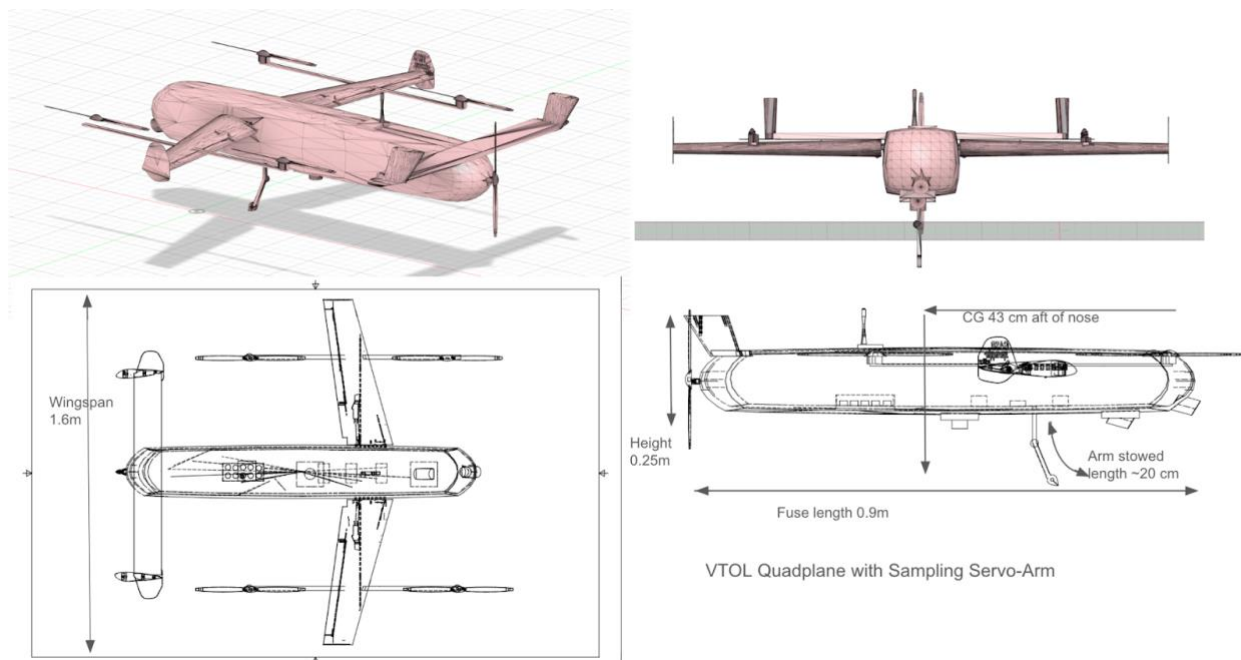


Figure 12. Three-view of final uncrewed system design showing components and center of gravity.

Figure 13 depicts the sensors, AI-module and sample gathering system.

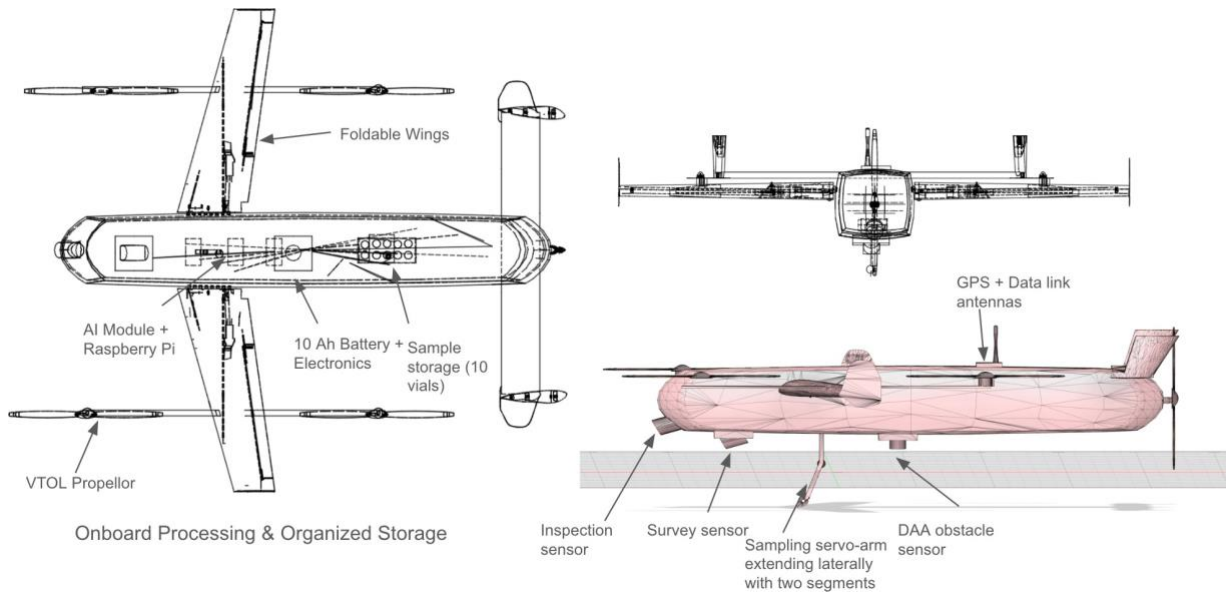


Figure 13. Sensors, AI-Module and Sampling System

Figure 14 depicts the Folded Quadplan model.

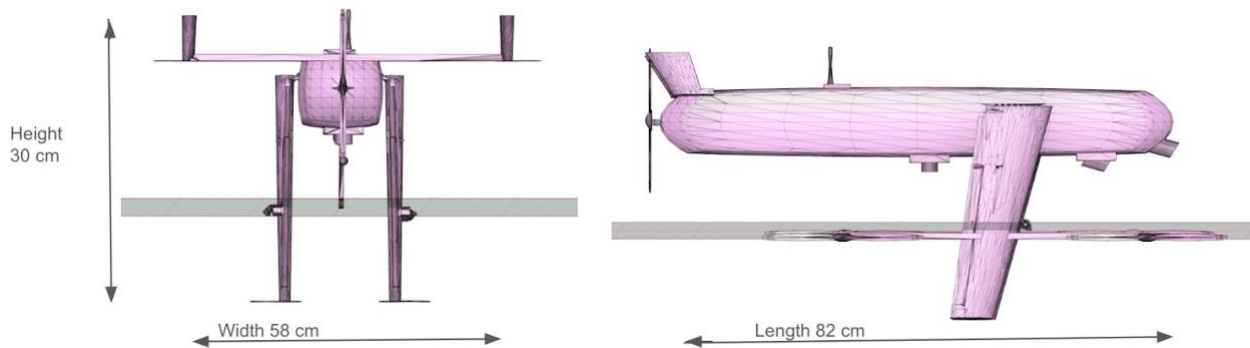


Figure 14. Front and Side-Views of Folded Quadplane

3. Mission Discussion

3.1 Concept of Operations

3.1.1 Preparation

Preparation is divided into ground control station setup, aircraft preparation, and final safety and readiness checks, with tasks clearly assigned to each operator to minimize errors and workload

overlap. A clearly marked staging area near the ground control station is used for aircraft unpacking, inspection, battery installation, and pre-flight preparation before takeoff.

Ground Control Station Setup

Preparation begins with the setup of the ground control station. The pilot-in-command is responsible for establishing command and control capability, while the payload/data monitor prepares sensor and data systems.

The pilot-in-command deploys the ground station table, computing device, and telemetry radio interface. High-gain telemetry antennas are mounted on portable tripods and oriented toward the mission area to ensure a clear line of sight. The pilot verifies power to the telemetry radio and confirms a stable communication link with the aircraft once it is powered on.

In parallel, the payload/data monitor sets up the payload monitoring station, including the secondary display used for sensor feeds and detection review. Data storage devices are verified to have sufficient capacity, and logging software is initialized to record mission metadata, detections, and sampling events.

Once both stations are active, the pilot and payload operator confirm inter-operator communication and review the planned mission objectives, expected flight duration, and contingency procedures.

Aircraft Preparation and Inspection

While the ground station is being established, the aircraft is prepared in the staging area. The pilot-in-command performs the primary aircraft inspection, assisted by the payload/data monitor as needed.

The aircraft is removed from its transport container and placed on a level surface. Foldable wings are deployed and locked into their flight configuration. All structural connections, hinges, and locking mechanisms are visually inspected to confirm full engagement. VTOL motor arms and propellers are inspected for damage, secure mounting, and free rotation.

The battery is installed and secured using the designated retention system. Battery voltage is checked to confirm sufficient charge for the planned flight, and connectors are inspected for

wear or looseness. The payload/data monitor confirms that the internal sample rack is empty and that sealed sample containers are correctly installed and indexed.

Sensors are inspected next. The multispectral sensor and close-up inspection camera lenses are checked for cleanliness and secure mounting. The sampling arm bay is inspected to confirm that the mechanism is fully retracted and unobstructed. The GPS antenna mast is checked for proper orientation and clearance from other components.

System Power-Up and Sensor Checks

Once physical inspection is complete, the pilot-in-command powers on the aircraft. The autopilot completes its initialization sequence, and telemetry connection with the ground station is confirmed. The pilot verifies correct flight controller status, GPS lock, compass health, and battery telemetry.

The payload/data monitor confirms live video and data feeds from the pest detection sensors. Camera orientation, exposure, and focus are verified using the ground station display. Any abnormal sensor readings or data dropouts are resolved before proceeding.

The pilot verifies that flight modes, failsafe settings, geofence boundaries, and lost-link behaviors are correctly configured. Control surfaces and VTOL motors are tested at low power to confirm correct response and direction.

Mission Programming and Final Safety Check

With systems verified, the pilot-in-command uploads the preplanned mission to the aircraft. This includes the autonomous survey pattern, altitude limits, loiter parameters, and return-to-launch instructions. The payload/data monitor reviews the mission plan to ensure sensor coverage and overlap meet detection requirements.

Before arming the aircraft, a final safety check is conducted. The pilot visually scans the flight area for people, animals, vehicles, or unexpected obstacles. Wind conditions are assessed to confirm they are within operational limits. The payload operator confirms readiness for detection and sampling operations.

Once all checks are complete and both operators verbally confirm readiness, the aircraft is moved from the staging area to the designated takeoff location. Personnel maintain a safe distance, and the pilot announces arming status prior to initiating takeoff.

3.1.2 Pest Detection

Overview: What the system detects and why

During flight, the uncrewed aircraft system does not attempt to visually identify the Mediterranean fruit fly insect itself. Instead, the system detects evidence of infestation on fruit, which is the same approach used in real-world agricultural inspection and biosecurity operations. Mediterranean fruit fly infestation manifests through observable physical changes in fruit, including oviposition puncture marks (“stings”), localized discoloration, early tissue breakdown, soft spots, and fermentation-related rot. These features are visible on the fruit surface before larvae are externally visible and often before fruit drop occurs.

Detecting harm indicators on fruit rather than the insect itself was selected for three reasons. First, the adult Medfly is small, fast-moving, and visually indistinguishable from other insects at operational flight distances. Second, infestation symptoms persist on fruit long after the insect departs, making them more reliable detection targets. Third, these symptoms are directly relevant to agricultural decision-making, since mitigation actions are triggered by evidence of damaged fruit rather than confirmed insect sightings. This detection philosophy guided all sensor, algorithm, and data-selection decisions described below.

Conceptual Design Phase: Defining detection objectives and constraints

In the conceptual phase, the team translated the biological behavior of the Mediterranean fruit fly into visual detection objectives. Based on agricultural literature and county quarantine practices, the team identified three primary visual indicators of concern:

- Oviposition puncture marks (small dark spots with surrounding discoloration)
- Localized necrotic or bruised tissue
- Early-stage rot or fermentation patterns

From an aerial systems perspective, these indicators created two distinct detection challenges. First, the aircraft must rapidly identify where fruit is located within a complex tree canopy. Second, it must examine the fruit surface closely enough to identify small, localized anomalies. This led to a two-stage detection concept: wide-area fruit localization followed by close-range anomaly detection.

At this stage, the team also decided that detection would be performed using machine learning-based computer vision, rather than simple thresholding or manual inspection. The variability of lighting, fruit orientation, background foliage, and symptom appearance made rule-based image processing unreliable for the mission environment.

Preliminary Design Phase: CNN architecture trade study

Once the decision to use a convolutional neural network (CNN) was made, the team evaluated several commonly used object detection and classification architectures that are suitable for deployment on embedded or semi-embedded platforms. The goal was to select a model that balanced detection accuracy, inference speed, training complexity, and suitability for small, localized defect detection.

The candidate architectures considered were:

- YOLO (You Only Look Once, v5/v8 class)
- RetinaNet
- ResNet-50-based classifiers

To make this decision systematic, the team used a Pugh decision matrix, scoring each architecture against mission-relevant criteria on a scale from 1 (poor) to 5 (excellent). YOLO was used as the reference baseline.

Criteria	YOLO (v5/v8)	RetinaNet	ResNet-50
Small object detection capability	4	5	3
Real-time inference speed	5	3	2
Ease of deployment on UAS hardware	5	3	4
Dataset labeling compatibility	5	4	2
Ability to combine detection + class	5	4	2
Training complexity	4	3	3
Total Score	28	22	16

Table 10: CNN Architecture Selection (Pugh Matrix)

Based on this comparison, a YOLO-based architecture was selected as the primary detection model. Although RetinaNet performs well for small-object detection, its slower inference speed and higher computational cost made it less suitable for onboard or near-real-time processing. ResNet-50, while powerful as a feature extractor, lacks native object detection capability and would require a separate region proposal stage, increasing system complexity.

YOLO's ability to simultaneously locate fruit and classify surface anomalies within a single model made it the most practical and robust choice for the mission.

Detailed Design Phase: Training strategy and datasets

A key challenge identified during detailed design was the lack of a single, comprehensive dataset containing labeled images of Medfly-damaged fruit specific to the Cupertino region. Rather than treating this as a limitation, the team adopted a multi-stage training strategy, reflecting how real-world agricultural AI systems are developed when data is scarce.

Stage 1: Fruit localization (object detection backbone)

The first training stage teaches the CNN to recognize fruit shapes and ignore background clutter such as leaves, branches, and sky.

Dataset used: Fruits-360 Dataset (Kaggle): <https://www.kaggle.com/datasets/moltean/fruits>

This dataset contains thousands of images of fruits such as apricots, lemons, plums, and similar produce captured under varied lighting and orientations. Training on this dataset allows the CNN to reliably identify fruit regions within complex scenes.



Figure 15: Fruits-360 sample images

Stage 2: Surface anomaly detection (harm indicators)

The second training stage focuses on identifying surface anomalies that resemble Medfly oviposition stings or early rot.

Dataset used: Citrus Disease Dataset (Mendeley Data):

<https://data.mendeley.com/datasets/3f83gxm57/2>

Although this dataset is labeled for citrus diseases such as canker and black spot, the visual features, dark necrotic centers, circular discoloration, and textured surface breakdown, closely resemble Medfly damage patterns from a computer vision perspective. The model is therefore trained to recognize generic “skin anomalies”, which are then interpreted operationally as potential infestation indicators.



Figure 16: Citrus disease / skin anomaly images

This transfer-learning approach allows the system to generalize across fruit types (e.g., apricots in summer, lemons in winter) while remaining sensitive to the physical manifestations of infestation.

In-flight detection workflow

During flight, pest detection occurs in a structured sequence:

1. The aircraft follows a preplanned autonomous survey path at a safe altitude.
2. The wide-area camera captures imagery used to identify fruit-bearing regions.
3. The CNN detects individual fruits within the image frame.
4. The same model evaluates fruit surfaces for anomaly patterns.
5. Detection confidence scores are generated for each fruit.
6. High-confidence detections are flagged and transmitted to the ground station.

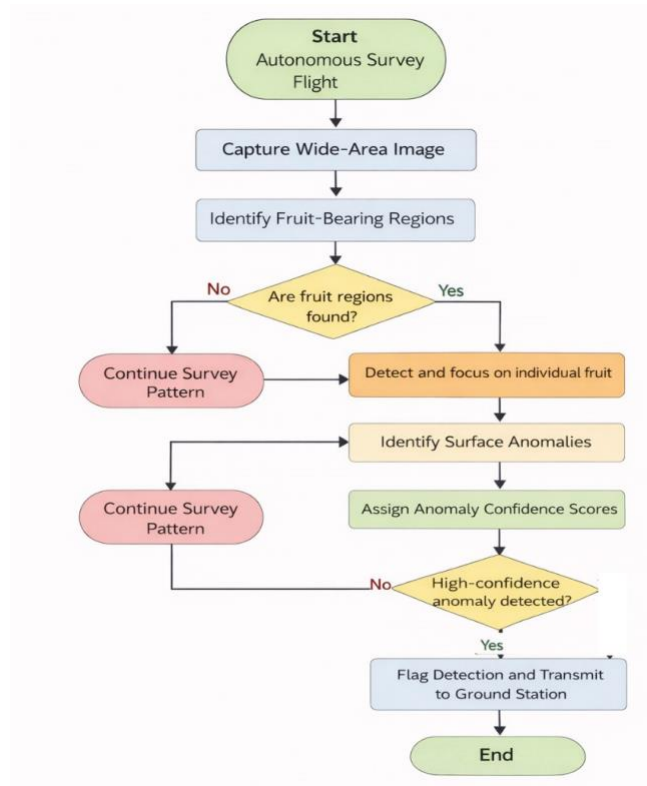


Figure 17: In-flight pest detection sequence from image capture to detection flag

Communication during pest detection

During detection, communication between the aircraft and ground station occurs continuously but efficiently to manage bandwidth.

- Telemetry data (position, altitude, battery state, flight mode) is streamed continuously to the pilot station.
- Detection metadata (fruit location, anomaly confidence score, image thumbnail reference) is transmitted to the payload/data monitor.
- Full-resolution imagery is either stored onboard for post-flight analysis or selectively transmitted when a high-confidence detection occurs.

This architecture ensures that the payload operator can make informed decisions without overwhelming the communications link. When a detection exceeds a predefined confidence threshold, the payload operator is alerted and can decide whether to initiate a closer inspection or authorize sampling.

Operator interaction during detection

The pest detection system is designed to support human-in-the-loop autonomy. Autonomous flight and detection reduce pilot workload during surveys, but final decisions remain with the human operators. The pilot maintains authority over aircraft motion and safety, while the payload operator interprets detection outputs and determines whether sampling is warranted.

3.1.3 Sample Gathering

Overview: When and why a sample is gathered

Sample gathering is initiated only after the pest detection system identifies high-confidence evidence of Mediterranean fruit fly infestation on fruit and a human operator confirms that sampling is warranted. This ensures that samples are collected selectively, minimizing flight time, mechanical wear, and unnecessary disturbance to plants.

The system follows a human-in-the-loop decision model: autonomous detection proposes a sample location, but the payload/data monitor makes the final decision to collect a sample. This approach aligns with real agricultural inspection workflows, where automated tools flag areas of concern and trained personnel authorize physical sampling.

Determining when a sample should be gathered

During the detection phase, each fruit analyzed by the onboard CNN is assigned a confidence score between 0 and 1 representing the likelihood that the observed surface anomaly corresponds to Mediterranean fruit fly-related damage (e.g., oviposition puncture marks, localized necrosis, or early rot). These confidence scores are transmitted to the ground station along with image references and geographic location.

A sample is recommended when all of the following conditions are met:

- The detection confidence score is ≥ 0.80 , indicating a high likelihood of infestation-related damage
- The anomaly is visually confirmed by the payload/data monitor using live or stored imagery
- The aircraft is positioned in a stable hover, with sufficient clearance for safe tool deployment and no detect-and-avoid conflicts

Once these conditions are satisfied, the payload/data monitor authorizes sample collection through the ground control interface. The pilot-in-command confirms aircraft stability and environmental clearance before enabling the automated sampling sequence.

Aircraft positioning for sampling

Before sample collection, the aircraft transitions from survey flight to a stabilized hover mode. Autonomous position-hold functionality maintains the aircraft's location relative to the target fruit, compensating for wind and minor disturbances. This stabilization is critical to ensure accurate tool placement and to prevent unintended contact between propellers and vegetation.

The pilot-in-command monitors aircraft attitude, altitude, and obstacle proximity, while the payload operator focuses on aligning the sampling mechanism with the target fruit using the camera feed.

Sample collection mechanism and process

The sampling system consists of a deployable sampling arm housed within the fuselage. When commanded, the arm extends outward and downward from the aircraft, reaching into the fruit zone without passing through the propeller plane. The arm provides controlled motion in multiple degrees of freedom, allowing precise positioning relative to the fruit surface.

At the end of the arm is a compact end-effector designed to remove a small fruit plug or peel/flesh sample. This approach captures biologically relevant material that may contain eggs, larvae, or tissue degradation while avoiding the need to harvest the entire fruit. The cutting and collection action is designed to be quick and localized, minimizing damage to the tree.

Once the sample is extracted, it is transferred directly into a sealed container located within the aircraft's internal sample storage system.

Sample storage and contamination control

Samples are stored in an internal multi-sample storage rack capable of holding up to ten individual samples during a single mission, in accordance with benchmark mission requirements. Each sample is placed into a separate sealed pod or vial, preventing cross-contamination between samples collected from different trees or locations.

The storage system is indexed so that each container corresponds to a specific sampling event. Metadata including time, location, detection confidence, and operator notes are logged at the ground station and associated with the correct sample container. This ensures traceability from in-flight detection through post-mission laboratory analysis.

The system is designed to support multiple samples per flight. If the sample rack reaches capacity, the aircraft returns to the ground station for unloading before continuing the mission.

Communication during sample gathering

Communication between the aircraft and ground station during sampling is more intensive than during survey flight but remains structured to maintain safety and reliability.

During sampling:

- The aircraft transmits real-time telemetry (position, attitude, battery state) to the pilot.
- The payload camera feed is prioritized to provide the payload/data monitor with a clear view of the sampling area.
- Status signals indicate arm deployment, tool engagement, sample secured, and arm retraction.

Command inputs from the ground station include:

- Authorization to deploy the sampling arm
- Commands to pause or abort the sampling sequence if conditions change
- Confirmation to stow the mechanism and resume flight

All sampling actions can be interrupted immediately by the pilot if a safety concern arises.

Operator roles during sampling

The sampling operation relies on clear division of responsibilities:

- **Pilot-in-command:**
Maintains aircraft stability, monitors obstacle clearance, manages flight mode transitions, and retains override authority throughout the sampling process.
- **Payload/data monitor:**
Confirms detection validity, authorizes sample collection, monitors the sampling camera feed, and verifies successful sample capture and storage.

This coordination ensures that the aircraft remains safely controlled while the sampling task is performed accurately and deliberately.

Post-sampling transition

After the sampling arm retracts and the system confirms that the sample is secured, the aircraft either:

- Proceeds to the next detection location, or
- Returns to the ground station if sampling capacity or battery limits are reached.

In both cases, the system logs the completion of the sampling event and resumes standard flight operations.

3.1.4 Post-Mission

Aircraft shutdown and recovery

After the final flight, the aircraft is commanded to return to the designated landing area and is brought to a full stop by the pilot-in-command. Once the motors are disarmed, the pilot verifies that all propulsion systems are powered down and that the aircraft is safe to approach.

The aircraft is then moved from the landing area back to the staging area. The sampling mechanism is visually inspected to confirm that it is fully stowed and undamaged. Any external debris (dust, leaves, moisture) is removed from the airframe, sensors, and propellers to prevent contamination or mechanical wear.

The battery is disconnected and removed from the aircraft. Battery voltage and temperature are checked, and the battery is placed into a fire-safe storage or charging container, depending on its state of charge and reuse plans.

Sample removal and handling

Collected samples are removed from the aircraft's internal sample storage system by the payload/data monitor. Each sealed sample pod is verified against mission logs to ensure that sample identifiers match recorded detection locations and timestamps.

Samples are then placed into a labeled secondary containment box designed for biological material transport. If required, samples are transferred to a cooled storage container to maintain sample integrity prior to laboratory analysis.

Data offload and review

After physical recovery of the aircraft, flight logs, detection data, and imagery are offloaded from the onboard systems to the ground control station. The payload/data monitor performs a preliminary review to confirm that all detections and sampling events were properly recorded.

This data is archived and backed up for later analysis, reporting, and comparison with laboratory results. Any anomalies observed during flight, such as communication dropouts, unexpected detections, or mechanical issues are noted for future system improvement.

Ground control station shutdown

Once data offload and review are complete, the ground control station is shut down in a controlled sequence. Telemetry links are powered off, antennas are disconnected, and computing devices are properly shut down to prevent data corruption.

Antennas, radios, and cables are coiled and packed to prevent damage. Displays, tablets, and laptops are stored in protective cases. All ground station equipment is inventoried to ensure nothing is left in the field.

Aircraft storage and transport

The aircraft is prepared for transport by folding the wings into their stowed configuration and securing all movable components. Protective covers are placed over sensitive sensors and camera lenses.

The aircraft is then placed into its designated transport container, which complies with project size and safety requirements. Batteries, sample containers, and ground equipment are stored separately according to safety guidelines.

Human roles during post-mission

- **Pilot-in-command:**
Responsible for aircraft disarming, propulsion safety checks, battery removal, and airframe inspection.
- **Payload/data monitor:**
Responsible for sample handling, data offload, data verification, and equipment inventory.

3.2 Benchmark Mission

To evaluate the effectiveness, efficiency, and safety of our design, the uncrewed aircraft system must complete the benchmark detection and sampling mission defined by the challenge. The benchmark mission requires the aircraft to depart from a ground station, survey a designated agricultural test field, collect ten physical samples, and return all samples safely to the ground

station. Mission time, energy usage, communication range, and operational safety are key performance factors.

Mission Geometry and Assumptions

The benchmark mission geometry is defined as follows (based on the provided diagram):

- Ground station to test field distance: 3 miles (one way)
- Test field size: 0.5 mi × 0.5 mi
- Total field area: $0.5 \times 0.5 = 0.25$ square miles
- Sample locations: 10 total, each located at the center of its respective square
- Elevation change: Assumed to be negligible between ground station and test field

Mission Flight Profile Overview

The aircraft completes the benchmark mission using a hybrid VTOL quadplane flight profile:

- VTOL takeoff from the ground station
- Fixed-wing cruise to the test field
- Fixed-wing survey of the entire field
- VTOL hover for inspection and sampling at ten locations
- Fixed-wing return flight to the ground station
- VTOL landing

The aircraft is designed to complete the benchmark mission in a single flight under nominal conditions, but the mission can be split into multiple flights if required.

Outbound and Return Transit Calculations

Distance from ground station to test field:

- Outbound: 3 miles
- Return: 3 miles
- Total transit distance: $3+3 = 6$ miles

Assumed fixed-wing cruise speed: 12 m/s (≈ 27 mph), typical for small VTOL aircraft

Transit time (one way): $3 \text{ miles} / 27 \text{ mph} \approx 0.11 \text{ hr} \approx 6.7 \text{ minutes}$

Total transit time (round trip): $2 \times 6.7 \approx 13.5 \text{ minutes}$

Field Survey Distance and Time

The aircraft surveys the 0.5 mi × 0.5 mi field using a lawnmower (back-and-forth) pattern.

Assumptions:

- Track spacing: 30 m (≈ 100 ft), appropriate for visual survey sensors
- Field width: 0.5 miles ≈ 805 m

Number of survey passes: $805/30 \approx 27$ passes

Length of each pass: 0.5 miles ≈ 805 m

Total survey distance: $27 \times 805 \approx 21,735$ m ≈ 21.7 km

Survey speed: 12 m/s

Survey time: $21,735/12 \approx 1,811$ s ≈ 30 minutes

Inspection and Sampling Time

The mission requires ten samples, each collected during stabilized hover.

Per-sample time estimate:

- Transition to hover and alignment: ~ 30 s
- Inspection and confirmation: ~ 30 s
- Sampling arm deployment, cut, retract: ~ 30 s

Total per sample: ~ 90 s

Total sampling time: 10×90 s = 900 s = 15 minutes

Mission Segment	Time
Outbound cruise	~ 7 min
Field survey	~ 30 min
Hover inspection + sampling	~ 15 min
Return cruise	~ 7 min
VTOL takeoff/landing & transitions	~ 3 min
Total flight time	~ 62 minutes

Table 11: Total Flight Time Estimate

The mission could also be split into two flights of ~ 30 – 35 minutes each, with samples removed and battery swapped between flights.

Energy Sufficiency Verification

Battery energy (from Section 2.3.1): $E = 22.2$ V $\times 10$ Ah = 222 Wh

Power usage:

- Fixed-wing cruise: ~ 333 W
- VTOL hover: $\sim 1,550$ W (short duration)

Hover energy (15 minutes): $1,550 \times 0.25 = 388$ Wh

Based on cruise endurance (~40 minutes) and hover endurance (~8 minutes continuous equivalent), the aircraft has sufficient energy margin to complete the mission when hover is distributed across the flight.

Communication Range Verification

The maximum mission distance from the ground station is 3 miles, while the telemetry system is capable of maintaining a reliable link at distances of at least 5 miles, providing sufficient margin for command and control, real-time telemetry, Detect-and-Avoid alerts, and payload video and sampling status transmission.

Ground Station Actions Between Flights

If the mission is split into two flights:

- Battery swap: ~3 minutes
- Sample removal and sealing: ~5 minutes
- System checks: ~2 minutes

Total turnaround time: ~10 minutes

Post-mission procedures

After completion of the benchmark mission, aircraft shutdown and inspection, sample removal and labeling, data download and storage, and folding and packing of the aircraft are completed, with the total post-mission process requiring approximately 15 minutes.

Benchmark Mission Summary

- Ground station distance: 3 miles
- Survey area: 0.25 sq mi
- Samples collected: 10
- Flights required: 1 (2 if conditions require)
- Total flight time: ~60 minutes
- Total mission time (including setup/teardown): ~90 minutes
- Energy margin: Adequate
- Communication margin: Adequate

This analysis demonstrates that the aircraft can safely and reliably complete the benchmark mission while meeting endurance, communication, and sampling requirements.

3.3 Safety Requirements

3.3.1 Detect and Avoid

We implemented a layered Detect and Avoid (DAA) system to allow the aircraft to safely operate near trees during inspection and sampling. We placed a near-field obstacle sensor on the lower front of the fuselage so it directly monitors the direction of motion during slow hover and sampling alignment. This sensor detects branches, trunks, and other obstacles within approximately 0.2-5 m. When an obstacle is detected within 3.0 m, the autopilot limits horizontal motion. If the distance decreases below 1.5 m, forward motion is blocked, and below 0.8 m the aircraft automatically stops and retreats to a safe standoff.

For faster survey and repositioning flight, we rely on mid-range forward detection using onboard velocity estimates and distance sensing to provide 5–30 m of look-ahead. This allows the aircraft to slow down, climb, or laterally offset before entering the close-proximity envelope. DAA decisions are made onboard by the autopilot to avoid delays caused by telemetry latency. DAA status and avoidance actions are continuously sent to the ground station so the pilot and payload operator can monitor safety and intervene if needed. This design allows the aircraft to hover and sample safely among plants while maintaining autonomous protection against collisions.

3.3.2 Lost Link Protocol

We designed the lost-link behavior as a safety feature. We defined two communication loss states: partial loss and total loss. During a partial loss of communication, the aircraft automatically reduces speed, disables sampling deployment, and prioritizes stabilized flight modes. The pilot pauses mission progression and attempts to restore the link. If communication quality does not recover within a short time window, the pilot commands a return-to-home.

For a total loss of communication, the aircraft executes an onboard failsafe sequence without waiting for operator input. The sampling arm is immediately aborted and retracted, the aircraft transitions to a safe stabilized mode, and a Return-to-Launch command is executed using GPS. If communication is not restored upon arrival, the aircraft performs a controlled landing. These

procedures ensure the aircraft behaves predictably and safely even when operator control is unavailable.

3.3.3 Integration with Manned Aircraft and Other Aircraft

Procedures to safely operate alongside crewed aircraft and other UAS in low-altitude agricultural airspace should be defined and followed. Before flight, a visual airspace check is to be performed and altitude limits and geofencing are configured in the autopilot. During flight, the aircraft should remain within the defined mission boundary and use separate altitude bands for survey flight and hover sampling.

If any crewed aircraft or unexpected air traffic are observed, the mission should immediately abort sampling, stow all mechanisms, and command the aircraft to descend to a safe altitude or land as appropriate. This approach ensures safe integration with other aircraft. The system does not rely on perfect detection of other aircraft and always prioritizes conservative behavior.

3.3.4 Additional Safety

The system should configure conservative battery safety thresholds, including early warnings, automatic return-to-home triggers, and forced landing limits to prevent power-loss accidents. To replace the sensory awareness of an onboard pilot, structured pre-flight and post-flight checklists should be performed. These include propeller inspections, sensor and camera checks, vibration health verification, and dry-cycle testing of the sampling mechanism.

4. Business Case

4.1 Cost Analysis

4.1.1 Operating Costs

Operating costs are the costs that change depending on how many times a benchmark mission is carried out. These costs are based on how much energy is used, how much consumables lose value, and how much professional labor costs.

(a) Energy and Consumables

As stated in Section 2.3.1, the plane uses a 6S (22.2 V nominal) LiPo battery with a capacity of 10,000 to 16,000 mAh. A complete mission cycle consumes approximately 0.40 kWh of electrical energy.

Energy Cost: At \$0.20/kWh, the direct energy cost per flight is **\$0.08**.

Battery Lifecycle Depreciation: With a replacement cost of \$280.00 and a 250-cycle lifespan, the depreciation cost per mission is **\$1.12**.

Propeller and Motor Wear: The T-Motor MN2212 motors and APC propellers (Section 2.3.1) require replacement every 150 flight hours. With a \$250.00 replacement kit cost, the per-mission depreciation is **\$1.66**.

Total Energy and Consumables per Mission: **\$2.86**

(b) Personnel Costs

The mission requires a two-person crew operating for 1.5 hours (30 minutes setup with foldable wing deployment, 45 minutes flight, 15 minutes data offload and sample retrieval).

Pilot-in-Command: $\$45.00/\text{hr} \times 1.5 \text{ hrs} = \67.50 Payload/Data Monitor: $\$40.00/\text{hr} \times 1.5 \text{ hrs} =$
\$60.00

Total Labor per Mission: **\$127.50**

Total Operating Cost per Benchmark Mission: **\$130.36**

4.1.1 Fixed Costs

The initial capital investment needed to acquire and assemble the entire system is represented by fixed costs. High-reliability commercial off-the-shelf components were given priority during the component selection process, which adhered to the startup engineering approach described in Section 2.1 while keeping the overall system cost under \$10,000.

Category	Item/Subsystem	Technical Justification	Estimated Cost
Airframe & Propulsion	Carbon/EPP frame, 5x T-Motor MN2212 V2 920KV, ESCs, APC props	Selected from trade study Section 2.3.1 for torque/efficiency balance; field-repairable	\$1,800.00
Avionics & C3	Pixhawk 6C, GNSS/GPS, 900MHz telemetry, 2.4GHz video	Triple-redundant IMUs; open-source ArduPilot; 5+ mile range	\$550.00
Detection Payload	Compact multispectral (Sequoia-class), 4K RGB camera	Red Edge detection for pre-visual stress (Section 2.3.3)	\$3,200.00
Sampling Payload	Deployable arm, cutter/scoop, 10-slot carousel	Zero cross-contamination; CG stability (Section 2.3.4)	\$850.00
Safety & DAA	2x LiDAR, optical flow sensor	40m obstacle detection; automatic safety buffer	\$600.00
Ground Support	2x laptops, antenna mast, containers, chargers	Meets 34x24x12.5 in constraint (Section 2.3.5)	\$2,800.00
TOTAL CAPEX	Complete ready-to-fly system		\$9,800.00

Table 12: Estimated Total Cost for the System

The compact spectral sensor provides essential Red Edge (700-800nm) capability to detect bacterial stress weeks before visible rot (Section 2.3.3). The Pixhawk 6C (Sections 2.3.1, 2.3.2) supports native VTOL quadplane operations via open-source ArduPilot, eliminating licensing fees. The foldable wing hinge (Section 2.3.1) keeps wiring inside during transport, eliminating connector wear and extending operational life to over 300 missions. The deployable specimen arm with 10-slot rotary carousel (Section 2.3.4) maintains sample mass at the aircraft center of gravity, preventing trim changes as samples accumulate while ensuring zero cross-contamination through individual sealed vials.

4.2 Logistics Details

The logistics strategy is based on the goal of deploying in 10 minutes, which was set in Section 2.1. This makes it possible to have multiple sorties every day.

Pilot-in-Command

Pilot-in-Command (PIC) is in charge of putting together planes, checking their safety, and supervising flights. When the PIC arrives, they use the pinned-hinge mechanism (Section 2.3.1) to deploy the foldable wings and do pre-flight checks. These checks include checking the battery voltage, inspecting the motor and propeller, calibrating the Pixhawk autopilot, confirming the GPS fix, and testing the communication link range. During autonomous flight operations, the PIC monitors aircraft telemetry and maintains authority over the Return to Land protocol. The PIC supervises autonomous waypoint navigation and VTOL transitions (Section 2.3.2) rather than manually flying the aircraft.

Payload/Data Monitor

Payload/Data Monitor manages the ground control station and analyzes live sensor data from both detection cameras (Section 2.3.3). This operator monitors the multispectral feed to identify trees exhibiting abnormal stress signatures using NDVI and NDRE indices. When a suspect tree is flagged, the Payload Monitor reviews the RGB camera feed during stabilized hover to confirm visual evidence of infestation. During sampling, the Payload Tracker operates the servo-actuated deployable arm (Section 2.3.4), ensuring proper alignment before extraction. Each sample is logged with GPS coordinates, timestamp, and field observations as the rotary carousel indexes to the next tightly sealed vial.

Mission Turnaround Protocol (total 10 minutes):

1. Battery Swap (3 minutes): PIC removes depleted 6S LiPo using Velcro strap retention (Section 2.3.1), installs charged replacement, verifies voltage
2. Sample Retrieval (5 minutes): Payload Monitor removes 10-slot carousel from belly-mounted bay, transfers sealed vials to secondary containment with chain-of-custody documentation
3. Abbreviated Pre-flight (2 minutes): PIC performs visual inspection, confirms autopilot ready state

This protocol enables up to six sorties per day, covering approximately 960 acres. Both transport containers (34×24×12.5 inches per Sections 2.3.1, 2.3.5) fit in a standard pickup truck. The foldable wing design maintains electrical integration during transport via the pinned-hinge

mechanism, eliminating field reassembly of connections and preventing Foreign Object Debris contamination.

4.3 Economic Impact

California's \$17.9 billion agricultural economy is at risk from the Mediterranean Fruit Fly. When more than 82 adult Medflies were found in Santa Clara County in late 2025, emergency quarantines covering more than 200 square miles were imposed.

Direct Crop Loss Prevention:

More than 250 types of fruits, nuts, and vegetables are infested by medflies. In order to lay their eggs, female flies pierce the fruit's skin; the larvae feed internally, causing total rot and early drop. Rot is only discovered by traditional ground inspection once the larvae have grown and dispersed. Weeks before visual symptoms manifest, the compact multispectral sensor (Section 2.3.3) detects fermentation stress using the Red Edge spectral band. Instead of demolishing entire blocks, this allows for surgical treatment of individual infested trees. An orchard block worth more than \$50,000 in food bank donations can be saved in a single 45-minute mission that covers 160 acres.

Export Market Protection:

Pest-free certification is a prerequisite for agricultural exports from California. Losses from the 2006–2007 Medfly outbreak exceeded \$100 million. The County can demonstrate that infestations are spatially localized rather than endemic thanks to the system's precision GPS-tagged sampling (Sections 2.3.2, 2.3.4). Instead of county-wide trade restrictions endangering billions of dollars' worth of yearly exports, this allows for micro-quarantine zones that impact individual properties. Samples are guaranteed to retain their full evidentiary value thanks to the contamination-free rotary carousel.

Labor Efficiency and Chemical Reduction:

160 acres of traps can be inspected in five to seven working days using traditional monitoring. Using the autonomous boustrophedon pattern (Section 2.3.2), the system completes the same coverage in 45 minutes, saving 98% of the inspection time. Applications of broad-spectrum pesticides are the foundation of traditional eradication. An estimated 80% less chemical is used thanks to the system's early detection, which allows for targeted spot treatment.

Performance Metric	Traditional Ground-Based Methods	UAS-Based Detection System
Survey Time (160 acres)	5 to 7 Working Days	45 Minutes
Detection Window	Post-Infestation (Visible Fruit Rot)	Pre-Infestation (Spectral Stress Signature)
Labor Requirement	1 crew per 5-10 acres/day	1 crew per 160+ acres/mission
Pesticide Application Strategy	Broad-scale neighborhood application	Surgical spot treatment (80% reduction)
International Trade Impact	High risk of regional quarantine	Data-driven micro-quarantine zones

Table 13: Comparison of Traditional and UAS-Based Detection Systems

Return on Investment:

Significant returns are produced by the \$9,800 capital investment and the \$130.36 operating cost per mission. In the first season, saving a single 20-acre orchard worth more than \$200,000 yields a return on investment of more than 20:1. There is incalculable value in preventing a county-wide trade ban (estimated losses of over \$500 million annually). Vulnerable populations will always have access to fresh produce if food bank orchards are protected.

5. Public Affairs/Communications Plan

5.1 Public Relations Strategy Template

5.1.1 Background and Purpose

The detection of Mediterranean fruit flies in San Jose in 2025-2026 resulted in an urgent agricultural crisis that necessitated surveillance over more than 200 square miles of quarantine zones. Nonetheless, significant areas include crowded residential areas where homeowners keep fruit trees in their backyards that act as the main carriers of infestations. Concerns about safety, noise, and privacy are raised by operating unmanned aircraft systems over residential property.

By being transparent and actively involved, this approach obtains social license to operate. In contrast to conventional farming operations in isolated rural regions, this mission necessitates ongoing communication with urban dwellers who might not be familiar with UAS technology or

pest control. Even technically superior systems may become ineffective in the absence of public support due to formal complaints, community opposition, or restrictive ordinances.

Three goals must be achieved by a successful strategy: inform the public about actual agricultural and economic risks; show through clear technical explanations that the system is essentially privacy-preserving and safety-focused by design; and involve the community as active partners in safeguarding their trees and the larger food supply.

5.1.2 Audience and Messaging

Primary Audience: San Jose Residents (Homeowners in Quarantine Zones)

Desired Outcome: Understanding that early detection protects their trees and avoids county-mandated neighborhood-wide fruit destruction, residents actively accept and support operations close to their homes.

Our Messages:

- By identifying particular infected trees before the County is required by quarantine regulations to require neighborhood-wide fruit stripping, the system safeguards residential harvests.
- Sensor design provides privacy protection. It is physically impossible for the small multispectral camera (Section 2.3.3) to record identifiable human activity, license plates, or facial features. The sensor produces abstract maps of vegetation health by only detecting plant chlorophyll stress in the Red Edge spectral band.
- Hardware ensures safety. Even in the event of a pilot error or communication breakdown, the LiDAR Detect and Avoid system (Section 2.3.2) automatically maintains a 15-foot digital buffer from all structures and people, preventing contact.
- Advance notification is used to provide operational transparency. 48 hours beforehand, flight paths utilizing the autonomous boustrophedon pattern (Section 2.3.2) are released. A web interface allows for real-time mission tracking.

Secondary Audience: Agricultural Stakeholders

Desired Outcome: Stakeholders support the system's operations and actively promote it.

Our Messages:

- The tiny percentage of infested trees is identified by precision protection using NDVI/NDRE analysis (Section 2.3.3).
- Red Edge detection early warning gives weeks' notice before visual symptoms appear.
- Laboratory-confirable evidence is provided by export protection using GPS-tagged sampling with a contamination-free carousel (Section 2.3.4).
- deployment that is more affordable at \$130 per 160-acre survey compared to thousands of crop losses

Tertiary Audience: Government and Regulatory Authorities

Desired Outcome: Authorities offer regulatory flexibility and see the system as an emergency response model.

Our Messages:

- NASA-approved design under federal supervision
- Complete adherence to FAA Part 107 regulations; autonomous operations (Section 2.3.2) reduce human overflight
- Coordination between agencies and real-time data sharing from the California Department of Food and Agriculture
- Rapid deployment is made possible by scalable architecture at a \$9,800 system cost (Section 4.1.2).

Legal and Regulatory Framework

The system handles residential overflight and biological sample collection under extensive legal authorization. All uncrewed aircraft operations are governed by Federal Aviation Administration Part 107 regulations. The pilot-in-command has a small UAS rating and is currently certified as a remote pilot. Part 107.39, which forbids flying over people who are not directly involved in operations, is followed during operations. The purpose of the autonomous flight patterns outlined in Section 2.3.2 is to reduce direct overflight of buildings that are occupied.

California Food and Agriculture Code Section 5322, which gives County Agricultural Commissioners permission to enter private property for pest detection and eradication operations during declared agricultural emergencies, is the source of sample collection

authorization. According to California Code of Regulations Title 3, Section 3591.17, the current Mediterranean Fruit Fly quarantine offers a legal foundation for the collection of fruit tissue samples from private residential property without the need for individual property owner consent.

Sensor design, not policy compliance, ensures privacy protection. Electromagnetic radiation in the 700-800 nanometer Red Edge spectral band is captured by the multispectral camera discussed in Section 2.3.3. Human faces, car license plates, and activities inside buildings cannot be physically resolved within this wavelength range. Vegetation health indices are the only output from the sensor. This technical restriction offers complete privacy protection that cannot be evaded by altering operating procedures or software.

The California Department of Food and Agriculture's guidelines for quarantine pest evidence are followed in the chain-of-custody procedures for samples that are collected. GPS coordinates, a UTC timestamp, and operator identification are recorded for every sample obtained through the carousel system (Section 2.3.4). Within thirty minutes of collection, samples are turned over to the County Agricultural Commissioner for laboratory examination by qualified entomologists from the California Department of Food and Agriculture. In proceedings to enforce quarantine, laboratory results are admissible as evidence.

Comprehensive general liability insurance from the county government and a special aviation liability policy that covers uncrewed aircraft operations are used to maintain liability coverage. The redundant safety layers provided by the system's LiDAR-based Detect and Avoid architecture (Section 2.3.2) surpass Federal Aviation Administration guidelines for operations close to structures.

5.1.2 Audience and Messaging

Primary: San Jose Residents

Desired Outcome: Accept operations close to residences while keeping in mind that flights safeguard trees and avoid their necessary destruction.

Key Messages:

- Protect your harvest - Prior to the county requiring neighborhood stripping, identify specific infested trees.

- Privacy by design - The multispectral sensor (Section 2.3.3) only detects plant health and is unable to physically capture faces.
- Safety first - A 15-foot buffer is automatically maintained by LiDAR (Section 2.3.2).
- Transparent operations - Flight routes are released 48 hours in advance, and real-time tracking is accessible.
- Legal authorization - Activities carried out under the state's agricultural emergency authority

Secondary: Agricultural Stakeholders

Key Messages:

- Precision protection - NDVI/NDRE identifies 1-2% infested trees
- Early warning - Red Edge detection provides weeks of advance notice
- Export protection - GPS-tagged sampling prevents county-wide trade bans
- Cost-effective - \$130 per 160-acre survey

Tertiary: Government/Regulatory

Key Messages:

- NASA-validated design
- Full FAA Part 107 compliance
- Real-time CDFA data sharing
- Scalable \$9,800 system cost

5.2 Products to be Created

Public Affairs Deliverables and Strategic Objectives			
Product Name	Distribution Format	Target Audience	Strategic Communication Objective
Safe Skies Technical Brief	Digital PDF and printed flyer	Residential homeowners	Visually demonstrate LiDAR-based digital safety buffer (Section 2.3.2) preventing aircraft contact with property
What We See Comparison Video	30-second social media video	General public	Provide side-by-side comparison of standard RGB vs actual multispectral output to prove privacy protection
Protect Our Harvest Community Guide	Bilingual brochure (English/Spanish)	Farmers Market attendees	Explain Medfly lifecycle, \$17.9B threat, system operation protecting food banks
Live Flight Path Tracking Application	Interactive web application	All stakeholders	Provide real-time transparency showing autonomous survey pattern and aircraft position

Table 14: Table summarizing Products and Communication Objectives

Product Specifications:

Safe Skies Technical Brief: One-page visual document that shows how the LiDAR Detect and Avoid system works (Section 2.3.2). Explains how dual LiDAR sensors can detect things up to 40 meters away and how the Pixhawk 6C autopilot always keeps the plane from going into a 15-foot safety buffer, no matter what the pilot does. Diagrams that are easier to understand show the shape of the detection cone. Addresses primary concern: Will the aircraft strike my house, trees, or power lines?

What We See Comparison Video: 30-second video showing standard drone footage (high-resolution, identifiable details) labeled "NOT what we use," then transitions to actual Sequoia-class multispectral output showing neon NDVI heat maps with no ground detail. Emphasizes: Our sensors detect plant stress using Red Edge at 700-800nm. This invisible light cannot capture people, homes, or private activities. We measure only chlorophyll levels.

Protect Our Harvest Community Guide: Tri-fold brochure with Mediterranean Fruit Fly biology, economic threat (Section 4.3), and system operation without technical jargon. Includes food bank director testimonials and photos of oviposition damage to help residents identify potential infestation. Printed in English and Spanish.

Live Flight Path Tracking Application: Web application displaying aircraft GPS position overlaid on a map showing an autonomous boustrophedon pattern (Section 2.3.2). Updates every 5 seconds via 900MHz telemetry. Shows altitude, battery remaining, and mission phase. Provides unprecedented transparency, allowing residents to verify the aircraft follows its pre-published path.

5.3 Distribution Plan

Phase 1: Pre-Announcement (7 Days Prior)

Santa Clara County Division of Agriculture issues press releases to San Jose Mercury News, local TV (ABC7, KTVU), Board of Supervisors, California Department of Food and Agriculture, and agricultural extension offices.

Phase 2: Targeted Notification (48 Hours Prior)

Geofenced digital ads on Nextdoor and Facebook, targeting a 2-mile radius include: map underneath showing survey boundaries, link to live tracker, downloadable scientific brief, and contact information. Physical brochures distributed at Farmers Market (Saturday 8 am-12 pm), community centers, libraries, and post offices in isolation zones.

Phase 3: Day-of-Operation Engagement

Payload/Data Monitor (Sections 2.3.5, 4.2) serves as Ground Ambassador: wears a high-visibility vest labeled "Agricultural Survey Team," positions near the ground control station, carries a tablet with live multispectral imagery and telemetry, approaches bystanders proactively, and distributes materials. The portable banner displays project identification, NASA affiliation, real-time flight path on a visible laptop, QR code to tracker, and partner logos.

Phase 4: Post-Operation Follow-Up

Within one day: an invitation to a community presentation at the library, a thank-you note on Nextdoor, and a mission summary to the county (format: "Surveyed 160 acres, identified 3 suspect trees, zero incidents").

Distribution Roles:

Pilot-in-Command: Ensures a professional, well-organized ground station that is open to public inquiries while maintaining safety.

Payload/Data Monitor: Primary public relations with non-technical communication training. furnished with contact cards, brochures, and a tablet.

Public Relations Budget

Item	Estimated Cost	Justification
Digital advertising (Nextdoor/Facebook)	\$800.00	Precision geographic targeting ensures ads reach only affected residents
Professional printing (500 brochures, 200 briefs)	\$400.00	Bilingual high-quality color printing for credibility
Web hosting and tracker development	\$150.00	WordPress site with open-source mapping libraries
Community presentation materials	\$150.00	Projector rental and printed handouts
TOTAL PR BUDGET	\$1,500.00	Fully within \$2,800 Ground Support allocation (Section 4.1.2)

Table 15: Budget Justification Summary

Crisis Communication Protocol:

1. Immediate Acknowledgment (within 2 hours): A spokesperson provides a factual response regarding the incident, safety precautions, and a schedule for comprehensive follow-up.
2. Safety-First Suspension: Operations are immediately halted while an investigation is conducted if there is a valid safety concern (the aircraft flew closer than the buffer parameters).
3. Transparent Incident Report (within 24 hours): A technical report would be published describing the preventive measures (autopilot parameter adjustment in accordance with Section 2.3.2, additional checklist items) and the root cause (GPS drift, transmission delay, pilot error).
4. Community Meeting (within 48 hours if needed): If persistent concerns arise, hold a meeting in the library in the evening to have direct conversations, show off the updated systems, and take direct questions.

Success Metrics:

Awareness: Website traffic, engagement, and social media reach. Sentiment: Tone analysis of comments to determine whether they are positive, neutral, or negative. Acceptance: Formal complaints as a percentage of overall operations (<3 complaints per 100 flights is the target). Partnership: Survey requests from property owners.

Target: >70% positive/neutral sentiment, <3% complaint rate, and at least 10 voluntary survey requests that show the value of the system is acknowledged by the community.

6. Conclusion

This work presents a complete, requirements-driven design for an uncrewed aircraft system capable of detecting Mediterranean fruit fly infestation and collecting physical plant samples in support of agricultural protection efforts. The final solution integrates a VTOL quadplane air vehicle, a layered pest detection payload, a precision sample-gathering mechanism, and a robust command, control, and communications architecture to meet all benchmark mission, safety, and logistics constraints defined in the requirements.

The selected VTOL quadplane configuration directly addresses the competing mission needs of efficient wide-area coverage and precise, stationary hover near vegetation. Fixed-wing cruise enables long-endurance survey of the 0.5 mi × 0.5 mi test field, while multirotor hover allows safe inspection and controlled sampling near fruit-bearing canopies. Mass properties and center-of-gravity placement were managed by clustering heavy components near the wing aerodynamic center, ensuring stable operation in both flight modes and throughout the sample collection process.

The pest detection system was designed around biological reality. By detecting evidence of infestation on fruit rather than attempting to identify the insect itself, the system aligns with real-world agricultural inspection practices. A two-stage sensing approach including multispectral wide-area screening followed by close-up RGB inspection, efficiently balances coverage, resolution, and onboard processing limits. Human-in-the-loop decision-making preserves safety and accountability while leveraging onboard autonomy to reduce operator workload.

The sample-gathering payload provides a controlled, repeatable method for extracting biologically relevant fruit tissue while preventing cross-contamination and minimizing aircraft disturbance. The deployable sampling arm, internal storage rack, and indexed sealed containers allow up to ten samples per mission without destabilizing the aircraft. This design choice was justified through center-of-gravity analysis, operational safety considerations, and benchmark mission requirements.

Safety was treated as a core design driver throughout the process. Detect-and-avoid capabilities, conservative lost-link protocols, geofencing, and software interlocks ensure safe operation near plants, structures, and people. Command and control decisions are handled onboard to eliminate latency during time-critical avoidance maneuvers, while continuous telemetry keeps operators informed and able to intervene when necessary.

Finally, the system was designed with real-world deployment in mind. Foldable wings satisfy strict transport constraints, ground operations are streamlined to enable rapid turnaround, and cost analysis demonstrates that the system is economically viable relative to the agricultural losses it helps prevent. The integration of technical performance, biological relevance, safety, and operational practicality makes this design well-suited to a real-world deployment. By basing engineering decisions on mission needs, biological understanding, and operational constraints, the proposed system offers a credible and effective approach to early pest detection and targeted agricultural response.

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