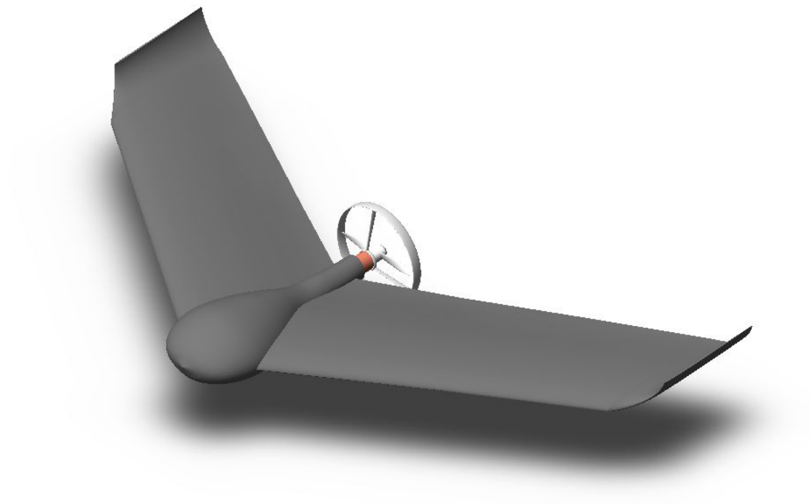
# The Galaide



**Submitted in Response to the Real World Design Challenge National Unmanned Aerial System Challenge**

Submitted by
**Young Engineering Team of Islanders (YETI)**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# ABSTRACT

As of 2019, 4.2 million deaths occur annually as a result of exposure to outdoor air pollution, and 91% of the world's population live in places where air quality does not meet World Health Organization guideline limits (World Health Organization [WHO], n.d.). To address this problem, cities have begun incorporating more plants in the environment to curb pollution (Whiting, 2018). Unmanned Aircraft Systems (UAS) have demonstrated potential in many civil and commercial applications such as precision agriculture. In response to the Real World Design Challenge, the Young Engineering Team of Islanders (YETI) have developed a UAS to survey plant health in an urban environment as part of the city's initiative to curb pollution.

The design solution must meet the safety, spatial, and budget requirements established by the city. Due to the nature of urban unmanned aerial vehicle (UAV) operation, the solution is designed with safety as the primary focus. The UAV must be launched and recovered within a 3 m by 3 m space, navigate without the Global Positioning System (GPS), avoid obstacles, operate beyond-line-of-sight (BLOS), and emergency land while minimizing the risk of damage to property and injury to people.

The team researched different agricultural UAVs and UAV technologies and explored the effectiveness of each system. The team learned to identify the level of implementation of different experimental technology such as simultaneous localization and mapping (SLAM) and visual navigation to determine whether it would be realistic to incorporate the system into the design solution. The final design, for all hardware in the payload, air vehicle element, C3, and support equipment, costs $14,357.60, making the design solution a relatively low-cost UAS.

The design solution, the Galaide, is an autonomous flying wing UAV equipped with high-resolution multispectral cameras, multiple air quality sensors, and multiple proximity sensors capable of sensing up to 60 m away. The Galaide uses near-infrared (NIR) cameras and normalized difference vegetation index (NDVI) to detect plant health at 35 mm/px or better. The height of the plants is predicted through the structure-from-motion (SfM) software and are used to estimate growth over time. To counteract the urban canyon, the Galaide can navigate without GPS in an urban space using network triangulation, onboard Light Imaging and Detection Radar (LiDAR) sensors, and visual navigation. In addition, the Galaide can be controlled through a 4G LTE network if radio signal interference occurs. To operate safely in an urban environment, the Galaide autonomously determines safe areas for emergency landing through the Safe2Ditch software and deploys its parachute at an appropriate altitude. To fit the spatial requirements, the launch and recovery of the Galaide are completed through a catapult and net. The Galaide is capable of high bank angle turns with thrust vectoring, allowing 180° turns within 20 m wide roads. Furthermore, the Galaide is designed specifically to maximize its value to the city with its air pollutant sensor suite and data analysis package, allowing the city to empirically determine the success of the city's initiative to curb pollution over time.

The Galaide is a time- and cost-effective method to survey plants in the city, capable of surveying all areas in about 26 minutes over two separate trips. To make the bid competitive in meeting the city's Request for Proposal (RFP), Team YETI offers a versatile and comprehensive service package that is able to provide raw image and pollution data, as well as survey summaries, a digital elevation model, and orthomosaic maps generated through the Pix4D software. The use of the Galaide provides benefits beyond plant health surveys, as it is able to fly for more than an hour while capturing high-quality image and air quality measurements and contains hardware capable of long-distance obstacle detection and emergency landing.


*Keywords*: UAS, UAV, plant health, pollution, obstacle avoidance, safety, flying wing, navigation

## Specification Sheet

**Table 1. The Galaide's Specification Sheet.**

| Criteria | Value | Survey Area | Checklist |
|---|---|---|---|
| Takeoff Weight | 4.48 kg | Walled Road | ✓ |
| Wingspan (fixed-wing) | 2.43 m | Road with Median | ✓ |
| Maximum Airspeed during Mission | 11 m/s | Vacant Lot/Park | ✓ |
| Maximum Altitude during Mission | 190 m | Rooftop Garden | ✓ |
| Time in Flight | 26 min 28 s | Road with Building Vegetation | ✓ |
| Distance Traveled | 17,462 m | | |

# 1. Team Engagement

## 1.1 Team Formation and Project Operation

The team members of YETI are all seniors enrolled in John F. Kennedy High School's Pre-Engineering Honors class. Since most of the students within the class had not previously participated in the Real World Design Challenge (RWDC), the members of the team were chosen based on their work ethic and their diverse interests. Members were then placed into departments according to the competition deliverables: the business department would analyze the Galaide's commercial benefit, the simulation department would perform all computer-aided design (CAD), and the research department would perform scientific and mathematical analyses. The Project Manager worked alongside the departments, and ensured the productivity of team members by setting and documenting the progress being made. The team planned to complete the notebook by March 5, 20 days before the March 25th due date, leaving the team with ample time for revisions (See Section 2.1.6). Below are the details of the members' backgrounds, skills, and specific roles in the team:

__**Yvan Chu (*Project Manager)***__

Yvan Chu has been an active student in numerous competitions and clubs, many of which pertain to Science, Technology, Engineering, and Math (STEM). Throughout his high school career, Yvan has acted as the Project Manager in engineering competitions such as the Green Dream School Competition, Toshiba ExploraVision, and the Marine Advanced Technology

Education (MATE) Regional Competition. Additionally, Yvan participated in last year's RWDC. Yvan took two years of Air Force Junior Reserve Officers' Training Corps (AFJROTC), which helped him build a foundation of Aerospace Science and leadership. Yvan is also enrolled in multiple Advanced Placement (AP) and Honors courses. Because of his ability to balance schoolwork and extra-curricular activities with management experiences in multiple leadership positions, Yvan was selected to lead the team as Project Manager in this year's RWDC.

**Jean Clemente *(Project Scientist)***

Jean Clemente has maintained a stellar academic record across a wide range of subject areas. He has completed all available math courses offered at the school and Calculus II at the University of Guam. Jean aspires to be a biologist. He was part of the winning team in the 2017 Green Dream School Competition, a regional competition on the topic of sustainability and green energy. His interest in biology and sustainability and his ability to learn complex concepts made him an ideal fit for the role of Project Scientist on the team. In addition to his academic endeavors, he is also the president of the school dance team, Uprising. His outgoing personality combined with his position as Project Scientist allows him to lead team discussions.

**Owen Kamtinay *(Lead Editor/Co-Project Manager)***

Since elementary school, Owen Kamtinay has striven for academic excellence, joining clubs like Math Meets and Squires of Columbus to enhance both his learning ability and sense of community. His diligence for academic excellence led Owen to enroll in many AP and Honors courses. Owen also comes from a long line of mechanical engineers which contributes to his experiential learning in STEM. In addition to his family history in STEM, during middle school, Owen participated in an island-wide robotics competition where he and his team constructed a robot capable of completing a series of tasks in an obstacle course. It is from these experiences that Owen seeks an engineering career. Owen was assigned as both the Co-Project Manager and Lead Editor because of his great work ethic and ability to accomplish many tasks in a timely manner.

**Vincent Fanathin *(Systems Engineer)***

Vincent Fanathin aspires to be a mechanical engineer primarily from the stories his uncle, an aircraft mechanic with United Airlines, told him as a child. These stories inspired Vincent to learn how everyday objects worked, often through taking apart and reassembling old electronics like televisions, VCRs, and computers. Vincent continued to build his STEM background by taking Robotics classes in both middle and high school, where he learned to program. Vincent was chosen as a systems engineer to analyze and select different components necessary for the unmanned aerial vehicle (UAV) because of his experience in reverse engineering and his ability to understand complex systems, such as those used in programming.

**Nyah-Kimani Chamberlain *(Co-Editor/Researcher)***

Nyah-Kimani Chamberlain is currently enrolled in the AFJROTC unit in the school. She displays academic strength and attention to detail as well as work discipline developed through her contribution to AFJROTC and her participation in the college-preparatory program Upward Bound. She has participated in the AFJROTC Leadership and Academic Bowl, demonstrating knowledge in multiple academic areas. Her background in playing softball and baseball also makes her adaptable in a team-based environment. Her experience with leading and inspecting cadets while taking on challenging courses to aid her in preparation for college makes her a valuable team member. Because of her great depth of knowledge in many areas and ability to work with the team, she was chosen as an editor and a researcher.

**Kai Ortega *(CAD Specialist)***

Kai Ortega is a well-rounded individual whose diversity of interests in and out of STEM has aided the team's creative processes and made him a capable Computer Assisted Design (CAD) Specialist. Additionally, Kai is capable of using Adobe's Creative Cloud. In school, he is the current editor-in-chief of the Yearbook Club, historian of the school's dance team, and public relations officer of the Spanish Club. Kai's diverse interests and outgoing personality contributes to the team's creative processes by encouraging the team to look beyond the scientific aspect of the challenge and keeping the team members open-minded about different ideas.

**Chris Morikami *(Business Analyst)***

As captain of the school's varsity basketball team, Chris Morikami is familiar with the qualities needed to be a part of a competitive team. Throughout high school, Chris has taken on multiple leadership positions such as being the historian for the National Honor Society. As both a member and leader of different organizations, he is able to work well with others and keep an open mind. Chris has the self-motivation and discipline to take on new tasks which feed his knowledge of a diverse number of topics, like computer science and business. Chris's interest in computer programming led him to learn basic web development through the online FreeCodeCamp curriculum. Chris was chosen as the Business Analyst as he is also knowledgeable in basic economics and business through his interest in stock and cryptocurrency investments.

## 1.2 Acquiring and Engaging Mentors

Before contacting possible mentors, the team determined that they needed the most mentorship in aerospace engineering. In October, all mentors in the RWDC Mentor List who had a background in aerospace engineering were contacted, as there were no local aerospace engineers on Guam who could be approached. Of the three aerospace engineering mentors that were contacted, only Dr. Geoffrey Bland, NASA engineer, responded. Due to his frequent traveling and the significant time difference between the team and Dr. Bland, the team primarily communicated with him through email. Dr. Bland helped the team understand basic aerospace and maneuvering concepts and suggested several ideas for the team to include, such as thrust vectoring and having counter-rotating propellers.

Leo Chang, a John F. Kennedy High School alumnus from the Jet Propulsion Laboratory, directed the team to Dr. Terrisa Duenas, the former program director of NextGen Aeronautics, a UAV company in Torrance, California. Dr. Duenas's guidance proved to be an indispensable asset, as she provided valuable advice about project management and guided the team toward possible technologies to implement. At least once every two weeks, the team communicated with Dr. Duenas via email, where Dr. Duenas answered questions on multiple areas of the competition, ranging from constructing an engineering timeline and framework to determining which components the team should invest the most money in, as well as other issues that the members needed guidance with. The team also sought her feedback on their engineering notebook and presentation.

The Project Scientist visited Dr. Hyunju Oh, a mathematics professor at the University of Guam, for mentorship. The Project Scientist worked with Dr. Oh to understand certain mathematical concepts behind the UAV design, such as determining the UAV's angle of climb. She also assisted the Project Scientist in his research on UAV performance and certain sensors and reviewed the notebook to verify their calculations.

Another RWDC team referred the team to their mentor, Maria Kottermair, a certified Geographic Information System Professional from the University of Guam, because of her knowledge and experience with UAV mapping and data processing. With Ms. Kottermair's expertise, the team sought her assistance with determining the number of trips, selection of data analysis software, and the presentation of overlooked conditions (e.g., shadows from buildings, glare caused by rain and sun, and low shutter speeds). The team scheduled meetings with Ms. Kottermair, who discussed her experiences with mapping and advised them on mission planning, such as having a 75% front and side overlap for survey and flying at a constant altitude, structure-from-motion (SfM) processing to create point clouds, digital elevation models, and orthomosaics.

Overall, it was difficult for the team to acquire mentors because of the limited amount of engineers and lack of aerospace expertise on the island. The team was forced to reach out to engineers in the continental United States for mentorship; however, this posed issues in time zone differences, and as a result, it was difficult to schedule calls that were convenient for both parties. Regardless, the team worked to reach out to as many mentors as possible from the RWDC mentor list and others' recommendations. Though many did not respond, the team maintained communication throughout the process with mentors who agreed to help to ensure that the notebook incorporated the suggestions of professionals and that the team's problems or questions were resolved.

### 1.3 State the Project Goal

This year's National challenge requires the development of an unmanned aircraft system (UAS) for surveying plants in an urban environment for under $200,000 in response to a Request for Proposal (RFP) contract by a city in the United States of America. The UAS must survey plants located in the five surveying locations in a test of concept environment: vacant lots/parks, rooftop gardens on 120 m buildings, roads with building vegetation, walled roads, and roads with medians. Given that the survey is in a city, the UAV must be launched and recovered within a 3 m by 3 m area, navigate without the Global Positioning System (GPS), avoid obstacles, fly beyond-line-of-sight (BLOS), and emergency land. There are also multiple no-fly zones and temporary no-fly zones for emergency scenarios in the urban environment. The city has requested a breakdown of all missions that are to occur as a Concept of Operations (CONOPS).

Furthermore, because the survey must be conducted eight times per year, the team must consider how the plants in each area respond to the changing seasons. The UAV must also be able to identify other aircraft through a transponder and include redundant safety systems. The team must also determine whether the application of Federal Aviation Administration (FAA) regulations limits the measurement of city plant life. Although the UAS is not required to meet any specific regulation, the team must be familiar with and explain how their UAS generally complies with FAA regulations. These regulations serve as a reference for understanding how safety limits the operation of the UAS. Regardless, safety must remain the primary factor in design; thus, the design solution must incorporate redundant system elements for propulsion, navigation, obstacle avoidance, and communication, command, and control (C3).

The team must also document the challenge's three main components in the engineering notebook: Task Analysis, Strategy and Design, and Costs. The team must analyze the mission and understand the tasks to be performed. In the Strategy and Design section, the team details their design process and the descriptions of the mission execution, including details and rationale regarding each component design or selection, the concept of operations, and personnel involved in the mission. The team must also determine the cost and capabilities of their UAS, including costs associated with their design and operation, as well as strategies used to create a competitive and viable business contract. To document their business case, the team will detail how their UAS meets the requirements of the RFP to the contracting city while identifying the feasibility and risk of the design; therefore, the cost of the UAS must be proportional to its capabilities and include a reasonable profit margin. The team must minimize the contract bid while maximizing the profit for their company.

## 1.4 Tool Set-up/Learning/Validation

**SOLIDWORKS**

The team used the SOLIDWORKS software for 3D design. The Project Manager acquired multiple license keys through the SOLIDWORKS's Student Sponsorship for Design Competitions. This sponsorship gave the CAD Specialist full access to the software required for RWDC, including fluid analysis. However, when the CAD Specialist began using SOLIDWORKS, he had encountered numerous errors while testing a sample UAV through Flow Simulation because he did not have sufficient knowledge of the program. This led to the CAD Specialist's use of more sources for help.

The CAD Specialist began learning SOLIDWORKS through related videos from YouTube and posts on forums. His first issue was not being able to create an airfoil using the 3D spline tool. Ms. Beausoliel, the team's coach, helped him by providing a link to the National Advisory Committee for Aeronautics (NACA) file database that had preset airfoils that can be transferred to SOLIDWORKS. There was an issue with Flow Simulation where the air flowed throughout the object  in many directions. The CAD Specialist was able to solve the problem by inserting global goals (a parameter calculated in the computational domain) and setting it to a velocity and a force in the *x* and normal force. Due to the addition of the global goals, the airflow simulated through the computational calculation was shown to flow through the z-axis.

**XFLR5**

XFLR5, introduced in the RWDC webinars, is an XFoil airfoil analysis program. JavaFoil analysis programs were also considered as an alternative airfoil analysis method. Although both methods are relatively accurate compared to actual wind tunnel analysis (Stengel, 2016), XFLR5 was more user-friendly and compatible with the Mac operating systems used by team members and was thus used by the research department. Initially, the team had difficulty with the interface of the program, but the team soon learned to adapt to the interface and used XFLR5 to perform lift, drag, and washout analyses.

**Google Suite**

Google Suite is a series of free cloud-based services. In particular, Google Drive, Google Docs, and Google Sheets were most frequently used by the members to collaborate and organize files. Since Google Suite is cloud-based, it allowed the team to work in real-time regardless of location. The team's shared folder consists of subfolders pertaining to research, schedules, and other components of the notebook, which were created and edited through Google Docs and Google Sheets.

## 1.5 Impact on STEM

All team members held deep interest in STEM prior to RWDC, with six members hoping to pursue an engineering career and one member focusing on environmental science or biology. The team expected the challenge to be straightforward: design a UAV capable of surveying plant health within given constraints. Because the challenge seemed simple, the team believed that the time spent in the Pre-Engineering class would be ample time to complete it. However, the team soon found the challenge to be increasingly difficult when additional details were introduced (e.g., field of view calculations, C3 components, battery selection, etc.) that led to meetings outside of class. The team also had to learn flight and engineering principles from little to no prior knowledge, which made the early months of the challenge more difficult.

By the completion of the project, however, RWDC exposed the team to the amount of effort and difficulty real STEM projects required. This had different effects on each member based on their positions and interests: some members were intrigued by the topics they studied and enjoyed their work strengthening their interests in a STEM career. Others did not feel as passionate for their research topics, which made their workload difficult and possibly led them to question pursuing a STEM career. Regardless of RWDC's impact on the team's perspective on STEM, the members were introduced to many new career opportunities that could lead to further interests in STEM fields or new interests in entirely different ones. The challenge helped the team develop an engineering mindset that applies to many different aspects of their lives—approaching problems systematically and persistently working to solve them.

The creation of a Pre-Engineering class and participation in RWDC have also sparked interest in STEM throughout the school. Current underclassmen have expressed their excitement to the team's coach to take the class. Teachers and the administration have eagerly awaited the completion of the challenge as well; different departments have enjoyed seeing the team apply the skills they learned in class, from writing to mathematics, to the challenge. Since the team's completion of the State challenge, the Principal and coach have worked tirelessly to assist the team in traveling to the National competition. This challenge, however, marks only the beginning of the school's push toward offering more STEM opportunities for students of all grades.

# 2. Document the System Design

## 2.1 Conceptual, Preliminary, and Detailed Design

### *2.1.1 Engineering Design Process*

In conceptual design, the team sought to thoroughly understand the challenge. Members studied both the Detailed Background Document and Scoring Rubric to determine the new National challenge requirements, and others analyzed the notebooks of previous winners to understand *how* they approached these requirements. Then, the team began research into the various subsystems of the UAV, exploring general types of UAVs and sensors that could be used to meet challenge requirements. During this phase, the team held open discussions to decide the general direction of the UAV's design, and from these discussions, members presented questions to research in the preliminary phase.

In preliminary design, the team explored deeper into the different technologies available for guidance without GPS, obstacle avoidance, emergency landings, and flight BLOS. The team researched and compared several sensor components for these requirements and chose specific methods to approach each requirement; similarly, the team compared different commercial UAVs and chose one as the basis for the final design. At this stage, the team also developed the theory of operations for the mission after discussing the advantages and drawbacks of each survey area and path, and how each season affected the mission.

Lastly, in detailed design, the team selected all necessary components for the mission and drafted the CAD model for the UAV. Once variables like wingspan, washout, and weight were confirmed, the team began analyses on the design to ensure structural and flight stability. Neither, however, proved easy: this phase was the most iterative, as the finalized UAV's center of pressure and lift, moment coefficient, lift, and drag (among others) often conflicted and made theoretical flight difficult or impossible.

Throughout the challenge, the team faced each issue by first understanding a given problem and defining what components or decisions had to be made. Then, after thorough research, discussion, and consultation with mentors, the team chose a solution to the problem and analyzed how the solution would work within the UAV subsystem. If required, changes were made to the CAD model and system design. This process, shown in Figure 1, was repeated for each problem the team encountered.

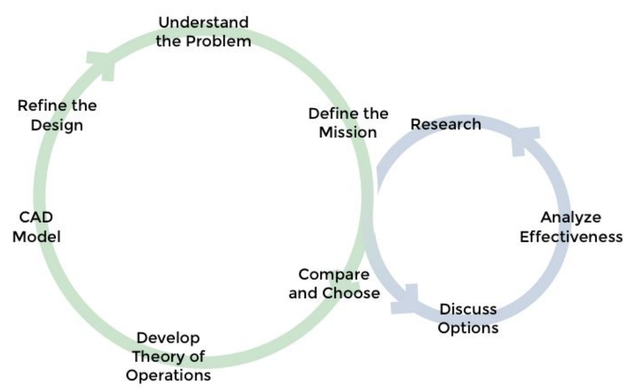


**Figure 1. Engineering Design Process**

### 2.1.2 Conceptual Design

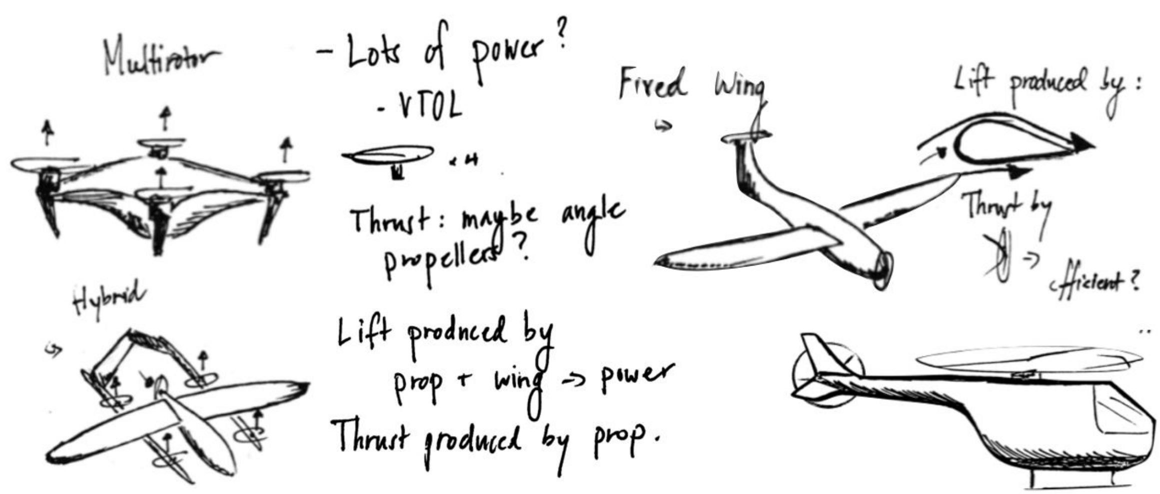


**Figure 2. A sketch of the UAV's possible airframe types.**

## Airframe

The main focus of the challenge is to design a vehicle that is not a potential risk to the urban environment and executes the mission while minimizing cost and time. Different airframes and their capabilities of carrying out the mission were researched to meet that focus. The four most common types of UAV airframes, rotary wing, multirotor, fixed-wing, and hybrids, were identified throughout this research, and the team compared their capabilities.

**Rotary Wing:** Rotary wing UAVs consist of a single large rotor to generate lift and a smaller rotor on its tail for stabilization and steering (Herrick, 2017). Because rotary wings are capable of hovering, the UAV is able to survey plants more accurately than a fixed-wing. They are also capable of vertical takeoff and landing (VTOL), guaranteeing the ability to take off and land within the 3 m by 3 m launch and recovery area. Because of their large, slow-rotating rotor blades, rotary wing UAVs are more energy efficient than a multirotor (Chapman, n.d.).

**Multirotor:** Multirotor UAVs use more than one rotor to generate lift and allow maneuverability (Kadamatt, 2017). Additional motors on a UAV increase stability at the cost of higher energy consumption. Multirotors are capable of VTOL and hovering, and the UAV's camera can capture higher quality images and make point turns ("Single," 2018). However a multirotor is slow, consumes a high amount of energy for the distance it must cover, and would require to be refueled/recharged multiple times during the mission (Chapman, n.d.).

**Fixed-Wing**: Fixed-wing UAVs have a rigid structure, and its lift is generated under the wing as a result of airspeed (Coptrz, n.d.). As seen in Table 2, fixed-wing UAVs are the fastest of the UAV types. Fixed-wing UAVs also have the best power economy (Chapman, n.d.). Because they are able to fly faster while achieving longer distances compared to other airframes, the time needed to complete the mission would be reduced. Additionally, fixed-wing vehicles have both a turning radius and an ascending/descending angle that could make maneuvering through a dense city difficult. As fixed-wings are unable to hover, the UAV would require a camera capable of recording data at high speeds to capture the data needed for the mission.

**Hybrid:** The hybrid UAV combines the capabilities and components of a fixed-wing UAV and a multirotor UAV ("The Different," n.d.). Therefore, a hybrid UAV is capable of VTOL and high-speed surveying. Unfortunately, the design and maneuver analysis involved with the hybrid's design is more difficult than the fixed-wing and multirotor. Additionally, because not many hybrid UAVs are commercially available, there is a relatively small amount of background information regarding their design as compared to fixed-wing and multirotor UAVs ("Types," 2017). Although the hybrid is a fixed-wing with VTOL motors, its performance does not exceed the fixed-wing's high speeds or the multirotor's hovering capabilities (Chapman, n.d.).

**Table 2. A comparison of the different UAV airframes.**

| UAV Options | Weight (kg) | Speed (m/s) | Endurance (min) | Cost ($) |
|---|---|---|---|---|
| Multirotor | 7.00 | 10.0 | 16 | 6,000 |
| Rotary Wing | 9.07 | 11.1 | 30 | 8,000 |
| Fixed-Wing (Tractor) | 1.26 | 16.7 | 55 | 5,000 |
| Fixed-Wing (Pusher) | 14.9 | 22.0 | 110 | 15,000 |
| Hybrid | 11.34 | 18.0 | 60 | 25,000 |

### Obstacle Avoidance

The mission requires the UAV to avoid all known and unknown obstacles through geofencing and other methods while maintaining a distance of at least one meter from all obstacles. Thus, the team discussed several methods of obstacle avoidance. Because of research done prior to the challenge, the Project Manager suggested Light Imaging Detection and Ranging (LiDAR) as a possibility. Other members suggested the use of infrared and sonar, prompting further research. Furthermore, although the mission only requires that the UAV stay *at least* one meter away from any object, both the UAV's cruising velocity and the possibility of a quickly approaching obstacle, such as a bird, were taken into consideration. For that reason, it was decided that the UAV's sensor must sense *beyond* one meter, and preferably beyond five meters, to allow adequate distance and time for the UAV to sense the obstacle and react accordingly (e.g., turn or dip).

The team had difficulties determining whether the sensor should be only forward-facing or sense around the UAV. While some members argued that because the UAV could be continuously moving, its front should only be focused on where the UAV *will be*, others argued that a moving obstacle, like a bird, could possibly damage the UAV if it hovers. Ultimately, a far-ranging, forward-facing sensor would be most beneficial in regard to safety, as focusing the sensor's abilities on the front would reduce the risk of any possible damage to the UAV, buildings, and, most importantly, pedestrians. The possibility of a 360° sensor was not taken out of consideration, so long as it did not compromise weight, budget, power, or the UAV's aerodynamics.

## Plant Health Survey

Several problems guided the team's selection of the method of plant health surveillance. Due to the lack of prior research, discussions prompted the team's deeper exploration into the topic. During these discussions, the team primarily examined the array of leaf colors needed to determine a plant's health, as measuring the amount of chlorophyll (and hence, the color) in leaves seemed simple and viable for a moving UAV. The Project Scientist also suggested that plant health could possibly be determined by leaf shape, the hydration and nutrient content of the soil surrounding the vegetation, the rate at which oxygen is released, weed growth, and the presence of pests. Canopy growth and plant height over time could also determine health (Staley, n.d.). A passing UAV can measure the color and shape of leaves to determine health. It can also view pests and weed growth with a camera of sufficient resolution, but nutrient information may require soil sampling. Data can also be collected by sampling leaves from the plants.

## GPS Alternative

The Galaide will use GPS as its primary method of positioning. Certain sensors allow for preset geofencing, which, with periodic checks, could monitor whether the Galaide deviates from its flight path. However, these methods require accurate data from alternative positioning methods that would not rely on GPS in the case of poor signal reception due to the urban canyon phenomenon ("GPS," 2011). In evaluating these alternatives, different methods were considered that could avail of the unique circumstances of the environment.

If the mission environment is typical of cities in the United States, it was considered safe to assume that Wi-Fi signals would be frequent throughout the mission. Thus, the Galaide could use these signals to approximate its location, but the Galaide would need a secondary and/or auxiliary system for accuracy. Surveying in an urban environment presents the risk of damage to people, buildings, and the UAV, so accuracy is imperative. Cell towers could also be used to approximate location (Trahn, 2015). Though the urban canyon phenomenon also limits the range and accuracy of these towers (Romero, 2007), the UAV can still use them to triangulate its position relative to the towers. The Galaide would still need a secondary and/or auxiliary system for further accuracy.

Furthermore, though the Galaide's primary mission is to survey plants in the specified urban environment, the UAV will not only be above vegetation throughout its entire flight; it will also be above pedestrians, sidewalks, and roads. Though a true positioning system cannot determine what is below the Galaide, a proximity sensor could be used to find the “texture”—the slight differences in distance to the UAV—to determine what is below it. This method allows the Galaide to deduce when it is above a survey area.

### Emergency Landing

One of the mission requirements was to have a safe emergency landing procedure for the UAV. The landing process and the potential causes for the emergency were taken into consideration. The first aspect of the emergency landing discussed was the landing method.

Since the airframe was not selected at the time of discussion, the gliding capability of the UAV was not guaranteed. The mission requires the propeller to not be spinning when landing. Therefore, it was determined that the emergency landing system must be able to land passively and safely without thrust from the propellers. Some ideas considered include using an airbag similar to NASA’s Mars Exploration Rover (National Aeronautics and Space Administration [NASA], 2004), using a parachute, or covering the vehicle with a soft foam-like material to make landing less damaging.

Ideas were suggested on the method for notifying pedestrians in the event of an emergency landing. Different audio and visual warning systems will instruct people to evacuate. Common languages such as English and Spanish could be used to help notify people in the surrounding area. For the audio warning, a speaker with recorded warning messages in various languages could be used to inform nearby pedestrians. For the visual warning, a component could be easily incorporated into the UAV and would be safe when activation was desired. A warning light, expanding airbag or flag, and shooting a flare were the options for a visual warning. The flare was immediately eliminated as it could cause a fire or injure people or property, so it was decided to only consider warning lights or expanding visual signals.

The mission also required safety features for the propeller. If a rotor lift vehicle were to be used, the propellers would be contained in an enclosed structure. For a pusher fixed-wing aircraft, the team considered using a light sensor and a light emitting diode (LED) to sense when the propeller blade stopped parallel to the ground. In emergency descent, the propellers would move slowly until the blades are covered by the wings and fuselage of the aircraft. Safe2Ditch, a program used for autonomously determining a clear landing site and monitoring system health, could also be used to land safely without operator control (NASA, n.d.).

### 2.1.3 Preliminary Design

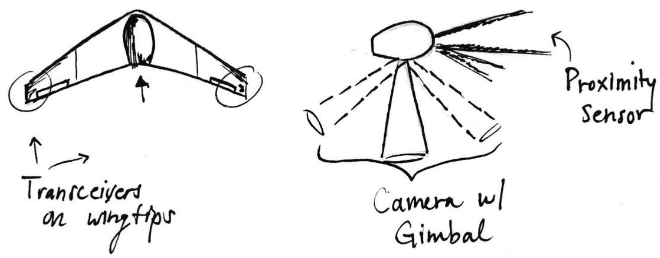


**Figure 3. A draft of the Galaide's early design and possible sensor positions.**

Airframe: Tractor or Pusher

Fixed wings were chosen to be the Galaide's airframe because they are the fastest and have the longest endurance, as shown previously in Table 2. Therefore, two fixed-wing body types were considered: the pusher configuration and the tractor configuration. It was decided to research only pusher fixed-wing designs because tractor fixed-wings had several design disadvantages. The tractor fixed-wing's propellers may strike civilians or property when landing. The propellers of a tractor fixed-wing would also need a cover or shroud for the propeller, or a folded propeller. In contrast, pushers often include structures near the propeller area where the enclosure can be installed; adding a safety structure in front of the aircraft could disrupt airflow and create more drag ("Pusher," n.d.).

Launch & Recovery

Through discussion, problems were found regarding the methods for launching and recovering the UAV. Each method was proposed strictly for fixed-wing airframes. Tables 3 and 4 below were used to compare the different methods of launch and recovery.

**Table 3. A comparison of the cost and weight of different launch methods.**

| Methods | Cost | Weight (kg) |
|---|---|---|
| Hand Launch | ~$35 (personnel wages) | N/A |
| Catapult Launcher | >$1,000 | >50 |
| Bungee Launch | ~$500 (for all pieces) | ~30 |

**Table 4. A comparison of the cost and weight of different recovery methods.**

| Method | Cost | Weight (kg) |
|---|---|---|
| Belly Landing Recovery | N/A | N/A |
| Net Recovery | ~$150 | 20 |
| Parachute Landing | ~$300 | ~3 |

Of the multiple launch methods examined, the hand launching method was rejected because of the uncertainty of the personnel's ability to launch the UAV. The personnel could misjudge the launch and damage the UAV or injure themselves. Though the bungee and catapult methods are similar, the catapult method would be more accurate and effective in its initial launch speed and angle. After contemplating the pros and cons of each method, the catapult launch method was chosen.

After selecting the launch method, the recovery method was needed. The team had previously researched the belly landing, parachute, and net recovery methods. With additional research, the team rejected the belly landing method because of the risk of extensive damage to the UAV, property, and/or pedestrians if the landing was miscalculated. The parachute method was also rejected as the primary landing method because of the logistical requirement of resetting the parachute prior to each launch. Also, the UAV could be blown off course by wind if it relied on the parachute for a safe descent. For the UAV recovery, the net method was selected as it provided the ability to modify the height and angle of capture which would minimize possible damage to the UAV.

### Obstacle Avoidance

After reviewing current methods of obstacle avoidance five possible methods of obstacle avoidance were discussed: sonar, infrared, LiDAR, time-of-flight (ToF), and stereo vision. Upon further discussion, the specifications of each method, including the weight, cost, update rate, and range of sensors that use them were analyzed and evaluated. These methods are described below.

**Sonar and infrared:** Sensors that use sonar or infrared to sense obstacles generally have two adjacent openings to emit a high-frequency sound pulse or infrared pulse, respectively, and to receive any waves that bounce off an object ("Ultrasonic," n.d.; Burnett, 2007). These sensors measure the time between transmitting a pulse and its return, and using this information, can determine the distance between an object and the sensor ("Ultrasonic," n.d.; Burnett, 2007). The team's research showed that sonar sensors are generally cheap, common in the market, lightweight, and insensitive to external factors like light, dust, and smoke. However, many current sonar sensors either do not have the range necessary to meet mission requirements or trade off a practical range for an impractical field of view. For instance, while the XL-MaxSonar in Table 5 is capable of sensing an obstacle up to 7.5 m away, the field of view is only 60 cm at the maximum distance ("MaxSonar," n.d.). Some infrared sensors, such as the Sharp Long Range

Infrared Proximity Sensor in Table 5, are capable of sensing beyond 5 m, but such long range sensing requires a tradeoff in field of view and accuracy.

**LiDAR and ToF:** LiDAR and ToF sensors function similarly to sonar but emit light in lieu of sound. LiDAR sensors use small LEDs or lasers to transmit light ("How does," n.d.); thus, field of view is dependent on the aperture of the laser and faces limitations even at distances beyond 10 m. Research found, however, that these sensors are often cheap, lightweight, capable of measuring farther distances than other methods of avoidance, and can sometimes rotate, allowing for a full 360° field of view. ToF sensors work under the same mechanics but rely on a flash of light; therefore, they produce a depth map of a single shot at a time (Li, 2014). Like LiDAR, they are capable of measuring larger distances, but the maximum range of LiDAR and ToF sensors are limited by direct sunlight and the color of objects (Sun, Hu, MacDonnell, Weimer, & Baize, 2016; "Technology," n.d.). These drawbacks can be remedied by using sensors with larger range capabilities.

Stereo vision cameras work similarly to human vision: two or more cameras in different positions take several two-dimensional images and stitch these to identify pixels across the images that correspond to a single point in the physical scene (Bebis, n.d.). Thousands of these points are determined to create a 3D image (Bebis, n.d.). While this method could have a large field of view, the research team found that stereo vision cameras are not common in the market and have low range capabilities. The Tara Stereo Vision Camera, for example, has a maximum depth of 300 cm. ("USB," n.d.)

Thus, sonar and LiDAR/ToF obstacle avoidance sensors were primarily explored because of their range capabilities, relatively high update rates, and generally low cost, but the team ultimately focused on LiDAR/ToF sensors for their range, accuracy, and field of view. Sonar sensors' lower specifications, as well as the possibility of sonar interference from electrical components and the urban environment ("Ultrasonic," 2017), made sonar a nonviable method of obstacle avoidance. Table 5 compares the field of view and range of sensors reviewed for detecting obstacles.

**Table 5. A comparison of sample sensors from each method of obstacle avoidance.**

| | XL-MaxSonar-W RM1 | SlamTec RPLIDAR A3 | TeraRanger Evo 600Hz | Sharp Infrared Long Range | Tara Stereo Vision |
|---|---|---|---|---|---|
| Field of View | 0.6 m @ 7.65 m | 360° * | 2° | ** | 60° |
| Range | <7.65 m | 25 m | <8 m | 1-5.5 m | 3 m |

*Uses a laser, but spins to create 360° field ("RPLIDAR," n.d.)
**Beam divergence is minimal at 5.5 m, so field of view is assumed to be a point.

## Plant Health Survey

Before deciding which sensor(s) to use to monitor plants in the city, further research was needed on factors that determine plant health, and current methods of measuring these factors. Of these, plant color and leaf shape proved to be the most measurable, as these factors required only a camera with sufficient quality and could be analyzed with the normalized difference vegetation index (NDVI) algorithm or other color-sensing capabilities, like near-infrared radiation (NASA, 2000). Analyzing plant color with an NDVI algorithm determines the density of green, and thus chlorophyll in a given area, by measuring the reflectance of near-infrared light and absorbance of red (NASA, 2000). In healthy vegetation, leaves reflect high levels of NIR and absorb high levels of red light (NASA, 2000). Conversely, unhealthy leaves reflect lower levels of NIR and reflect higher levels of red light as there is less chlorophyll to absorb it (NASA, 2000). This information is presented as a value between -1 to 1, and when combined with a camera, is assigned a color value for each pixel to create a map highlighting zones of low NDVI values (NASA, 2000). Should the camera have sufficient quality to record at least five centimeters per pixel, leaf shape (whether they curl or exhibit holes and irregular edges from bites) can also be measured and used to check the health and the presence of pests. Cameras with these capabilities are common in the market and generally lightweight.

Other factors to determine plant health were considered in the conceptual phase but proved difficult or impractical to measure with the UAV. Calculating the rate of photosynthesis, whether through the production of oxygen or uptake of carbon dioxide, would require methods that involve prolonged monitoring of the plant which cannot be done by a UAS with limited flight time and power, or uses large, heavy equipment like an infrared gas analyzer (Science and Plants for Schools, n.d.), that cannot be implemented on a UAS. Soil moisture can be measured with a microwave radiometer, but these sensors are large and difficult to find (Calla et al., 2009).

Upon closer inspection of the Detailed Background Document, the Project Manager pointed out that the city's main purpose in increasing the vegetation was to curb the effects of pollution, so the team researched and identified the following key pollutants in an urban environment: carbon monoxide (CO), nitrogen dioxide ($NO_2$), ozone ($O_3$), sulfur dioxide ($SO_2$), particulate matter ($PM_{2.5}$), and other volatile organic compounds (VOC) (Bolla et al., 2018). The details of selecting the specific sensors can be found in Section 2.2.1.

## GPS Alternative

Sensors that position by Wi-Fi and cell towers were explored, in addition to simultaneous localization and mapping (SLAM) and real-time kinematic (RTK) positioning, which were not discussed in the conceptual design stage. The team members weighed the viability of each method. In their research, the functions and accuracy of these methods were discussed.

Wi-Fi positioning systems determine location by measuring the strength of nearby Wi-Fi signals (the received signal strength indication, "RSSI"). Access points, especially Wi-Fi hotspots, have correlating GPS data that Wi-Fi positioning systems can access (Zahradnik, 2018). These systems infer a location relative to the access point through the strength of the received signal (Zahradnik, 2018). Consequently, more access points yield higher position accuracy, and in an urban environment, it is realistic to assume that the Galaide will receive signals from at least one access point throughout its flight.

Cell tower triangulation works in a similar manner: a cell tower's range is divided into three sectors (each 120°), and when it receives a signal, it measures the strength of that signal to create a "band" in the sector where the source could lie (Locke, 2012). When two or more towers receive the signal, the possible location of the source is limited to the overlap of the bands of each tower; as a result, location is more accurate when more towers receive the signal (Locke, 2012). Because cell tower density correlates with the presence of a metropolitan area (Dodge, n.d.), the team concluded that cell tower triangulation is a viable solution for the Galaide.

Incorporating SLAM navigation on the Galaide was also researched. This method uses proximity sensing to construct and continuously update a virtual model of the environment that the UAV uses to approximate its location relative to boundaries on the map (Maxwell, 2013). The Galaide could use this method to determine when it passes buildings, and from that information deduce its approximate position. In the Project Scientist's research, most sensors capable of SLAM navigation use LiDAR to construct a map of the UAV's surroundings from several measured points.

The team also considered using RTK positioning for more accurate positioning. This method is capable of relaying centimeter-accurate positions through a "base" receiver with a fixed, known location that measures the relative location of another moving "rover" receiver ("How RTK," n.d.). Although this method provides accurate data, it still relies on GPS and is thus limited in range and accuracy by the urban canyon phenomenon. Furthermore, this method is costly, as full setups of current RTK sensors that the team researched cost upwards of $1500.

## Material

Since it was determined that a lightweight fixed-wing would be optimal for efficiency and landing safety, there were three materials that met the team's standard for a density of 2 kg: foam, plastic, and carbon fiber. Of the three materials for the possible design, expanded polypropylene (EPP) foam for the airframe with carbon fiber spars built within the foam was chosen for the UAV. While a UAV made of carbon fiber would be more ideal because it is stronger than the other choices ("Aluminum," 2015), the safety issues that surround emergency landing with a hard wing made it undesirable as the UAV's main material. While a carbon fiber frame is lightweight, sturdy, and flexible, its strength and density will not cause damage to buildings, objects, and people if complications were to arise mid-flight. Therefore, foam was evaluated. EPP foam is sturdy, flexible, and lightweight (G., 2013). However, the UAV may be blown off course by the wind because it is too lightweight and flexible. Therefore, to counter this issue, the airframe uses built-in carbon fiber spars, which would provide stability to the airframe.

## Emergency Landing

Given that the UAV would be a fixed-wing vehicle, the option of expanding airbags was eliminated for different reasons. First, carrying multiple airbags around the wing would significantly increase the wing thickness, surface area, and weight, creating more skin friction drag. Second, the lack of control over deployed airbags may be problematic for precise landing in the city. Therefore, the team researched parachutes for emergency landing. One problem noticed was the systems equipped with parachute landing. The landing accuracy significantly decreases as the height of parachute deployment increases (Wyllie, 2001). Thus, a gliding maneuver may be executed before the parachute deploys at a reasonable altitude.

The concept of using a foam frame was kept. UAV reviewer Ilgenfritz (2016) described a collision with the EBee, a UAV built with EPP foam and carbon fiber spars, as being hit by a toy ball rather than an actual vehicle (because a foam frame is less likely to cause any serious injuries compared to harder materials). Using EPP foam would minimize damage or injury, in case the vehicle landed on property or people.

For the audio warning system, a speaker with recorded messages loud enough to warn people were as costly as $1,300 and as heavy as 4.81 kg ("Sky," n.d.). A buzzer with a loud sound could gain the attention of the pedestrians. The sound level of the buzzer would need to be comparable to ambulance sirens at about 120 dB (NIH MedlinePlus, 2015). A personal alarm system was an option considered for its lightweight at around 20 g and the five years of battery storage time, but further research revealed the sound buzzer itself was much cheaper and would allow more flexibility with the electrical wiring ("Sound Grenade," n.d.). To complement the audio warning system, it was decided to research LED signal lights because LEDs would not be bright enough to disrupt city function by blinding drivers and causing crashes, but it would still capture the attention of pedestrians when combined with a loud alarm.

After consulting with Dr. Bland, the LED/light sensor propeller-locking idea was rejected for its various limitations. One limitation with the blade-lock idea is that it restricts using two blade propellers. The propeller blade width must also be shorter than the camber height of the wing near the propeller to avoid striking objects when landing. Another key limitation, later realized through calculating the Galaide's thrust data, was that the blades could be spinning at up to 10,000 rotations per minute (RPM), and detecting and stopping a propeller at that speed did not seem as plausible as was hoped. Additionally, although blade-locking prevents the blade from striking any object as the UAV flies forward, this feature technically does not fit into the mission requirement of an enclosed propeller. Thus, the team decided to create an enclosure for the propeller.

Lastly, software programs with algorithms that determine emergency/forced landing sites were found, but not many commercial software programs with those algorithms could be purchased. Though the programs that could be purchased proposed a complete service set including the actual flight mission, the programs were offered at a high price. Thus, the plan to use Safe2Ditch was kept.

### 2.1.4 Detailed Design

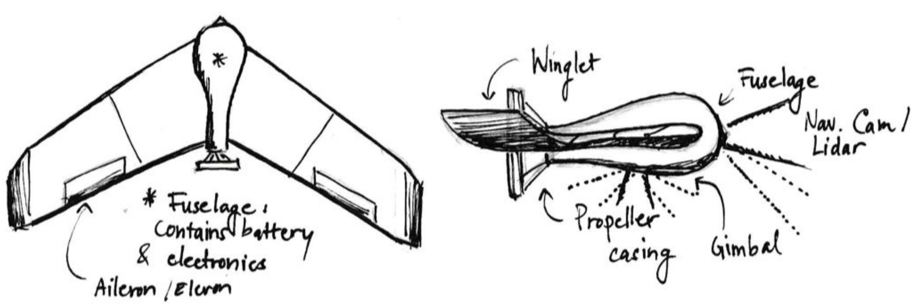


**Figure 4. A sketch of the Galaide's finalized design.**

To determine the basic structure of the Galaide, research was conducted on available fixed-wing UAVs specialized for reconnaissance and agriculture as recommended by the team's mentor, Dr. Duenas. The UAV's components and their advantages and drawbacks were analyzed. Table 6 lists the commercial UAVs that were favored in the research.

**Table 6. A comparison of different commercial UAVs.**

| UAV | Mass (g) | Speed (m/s) | Endurance (min) | Launch Method | Recovery Method | Cost |
|---|---|---|---|---|---|---|
| Bramor C4EYE | 4500 | 16-22 | 240 | catapult/hand | net/parachute | $45,000 |
| EBee SQ | 1100 | 11-30 | 55 | hand | belly landing | $25,000 |
| Blade Theory Type W | 480 | 40 | 5 | hand | belly landing | $449.99 |
| Avian-RTK | 5200 | 19 | 70-90 | catapult/ bungee | parachute | N/A |

One of the UAVs analyzed was the Bramor C4EYE which specializes in agricultural surveying. The Bramor C4EYE has a flying wing design which was adopted into the Galaide. The idea of using a net as a recovery method and using a parachute for emergency landings was also adopted from the Bramor C4EYE ("Bramor," n.d.).

Ebee SQ was another UAV that was researched. It had the agricultural components that were desired for the challenge ("Ebee," n.d.). However, the starting price of $25,000 made it too costly, and it would be more cost-effective to reverse engineer a similar vehicle and additional components to meet the requirements of an urban operation (Ilgenfritz, 2016).

The team next analyzed the Blade Theory Type W. This UAV had all the specifications the team was looking for in terms of dimension, weight, and price; however, the endurance did not meet the team's criteria. It is primarily used for racing, so the flight time was incredibly short at approximately five minutes (Spektrumrc, n.d.)

Another UAV that was analyzed was the Avian-RTK(PPK) (Avian-RTK, n.d.). The Avian-RTK is a fixed-wing tractor UAV that has multiple uses such as agriculture surveying, aerial mapping and forest monitoring (Avian-RTK, n.d.). However, the Avian was rejected for its cruise speed of 19 m/s as it is too fast for data collection which would not work well with the challenge to survey plant health in an urban environment and could make obstacle avoidance difficult. The safety would be compromised because it is unlikely that a vehicle at this speed can react to avoid obstacles.

After looking over the models shown previously in Table 6, a flying-wing design was selected for its high lift-to-drag ratio and low fuel consumption as compared to a traditional aircraft (Barr, 2006; Williams, 2010). From there, the CAD Specialist created the body of the UAV, using NACA MH-60 airfoil (See Section 2.1.4 Airfoil Selection) and the EBee frame shape.

The flying wing requires a swept wing and washout (See Section 2.1.4 Stability) to stabilize the UAV during sudden gusts using elevons (Hallion, 2011; “Why,” n.d.). A winglet structure was also included to reduce wingtip vortices and potentially double the lift to drag ratio (Larson, 2001). This finalized airframe is shown in Section 2.5, including the eBee frame shape, winglets, and pusher propeller with enclosure, after structural and flow analysis.

### Airfoil Selection

Because the payload only consists of lightweight sensors, it was decided that the Galaide’s airfoil will prioritize low drag/high speed rather than high lift. Some options considered were NACA M3, Wortmann FX 76-120, NACA 2414, NACA 2415, and NACA 1412. Two other options were suggested from the research department based on airfoils published and used in F3B tailless model airplanes: MH 60 and MH 61 (Hepperle, 2018). Basic analyses of these airfoils are found in an online airfoil database; however, the data had a very limited range of Reynold’s numbers for each airfoil, and there was no function to overlay graphs to allow performance comparisons (“Airfoil,” n.d.). Thus, XFLR5 was used to further analyze the selected airfoils’ coefficients of lift (*Cl*) and drag (*Cd*), the relative thickness in percentage, the stall angle, and the efficiency(*Cl*/*Cd*). The Reynold’s number was assumed at 520,000 based on the initially estimated speed of 20 m/s.

To find the right airfoil, a comparison was made about the different aerodynamic coefficients of each airfoil. The performance of each is summarized in Table 7 below. A higher stall angle was preferred to allow the UAV to perform high angle of attack (AOA) maneuvers in the city. The green sections in Table 7 show the preferable traits of the airfoil and the red shows undesirable.

**Table 7. A comparison of different airfoils.**

| Airfoil | *Cl* | Stall Angle | Thickness *(%)* | Note |
|---|---|---|---|---|
| MH 60 | 0.10~1.17 | 13.02 | 10.08% | Comparable efficiency |
| MH 61 | 0.05~1.01 | 10.99 | 10.23% | Efficiency drop >5° AOA |
| NACA 1412 | 0.12~1.14 | 14.03 | 12% | Lower eff. at 5°<AOA<10° |
| NACA 2414 | 0.23~1.23 | 15.99 | 14% | Most efficient |
| NACA 2415 | 0.23~1.23 | 14.99 | 15% | Most efficient |
| NACA M3 | 0.00~1.02 | 11.93 | 11.90% | Least efficient |
| Wortmann FX 76-120 | 0.00~1.05 | 14.95 | 12.08% | Second least efficient |

The NACA 2414, 2415, and the MH60 were the most suitable airfoils for the Galaide, so the Project Mathematician went on to further compare the two airfoils. Graphs analyzing the NACA 24 airfoils with different thickness and MH 60 were generated to prioritize efficiency and minimize weight. The NACA 24 family is able to produce around 0.04 more lift than MH 60 at 10° AOA, but the extra lift is proportional to the drag of the NACA 24(12-15), resulting in similar efficiency curves. NACA 2410 and 2411 showed significant lower efficiency, being 54 and 60 respectively (compared to 65 to 74 for the other airfoils). After careful discussion, it was decided to select MH 60 for its smaller pitching, thinner airfoil, comparable efficiency to NACA 2413, and proven flight results for tailless UAVs.

## Obstacle Avoidance

Multiple commercial sonar and LiDAR sensors were researched, but the team later eliminated sonar as a viable option. Initially, the sonar choices were limited to certain sensors of the XL-MaxSonar-WR series (specifically, XL-MaxSonar-WRM1, -WR1, -WR, -WRA, and -WRMA1) as each could measure up to 7.5 m, were waterproof, and were lightweight at an average of about 50 g. At a cost of $99.95 each, the sensors' capabilities proved appropriate for their cost. The team, however, was concerned about sonar interference, and because their limited fields of view (0.6 m wide FOV at 7.5 m distance) could present a threat to obstacles that the sensors may miss ("MaxSonar," n.d.). As a result, sonar altogether was jettisoned, and the team focused on LiDAR sensors, listed in Table 8 below.

**Table 8. A comparison of the specifications of different LiDAR and ToF sensors.**

| | TeraRanger Evo | TeraRanger Tower | Puck LITE | LeddarVu 8 | Slamtec RPLIDAR A3 |
|---|---|---|---|---|---|
| Cost ($) | 112 | 689 | 4,000 | 650 & 690 | 50 |
| Weight (g) | 9 | 92 | 590 | 80, 75, 97 | 190 |
| Power (W) | 0.475-0.95 | 13.2 | 8 | 2 | 2.25-3.3 |
| HFOV (°) | 2 | 4 or 8 | 360 | 20, 48, 100 | 360 |
| Update Rate (Hz) | 600,240 | 600 or 320 | 5-20 | 100 | 5-20 |
| Range (m) | 8, 60 | 8 | 100 | | 25 |

Ultimately, one TeraRanger Evo 60m and two TeraRanger 600Hz sensors were chosen, because their high update rates would assist in maintaining altitude and act as an auxiliary sensor for the TeraRanger Evo 60m. These sensors proved to work best in the direct sunlight ("Test," n.d.) and were found to function best for price. Furthermore, the use of LiDAR on the

Galaide allowed for the measuring of tree height, which is one method for determining plant health.

### GPS Alternative

The team researched trackers and position sensors that used GPS, Wi-Fi, and/or cell signals to ascertain location. The final choices were the Trackimo Tracker and the GPS sensor listed in the challenge catalog; the GPS sensor could measure altitude and at $50.00 served as a cheap yet functional primary system. The Trackimo is capable of positioning by GPS, Wi-Fi, and cell signals (“Trackimo,” n.d.). Although it was one of the more expensive sensors considered, its $5.00 annual subscription charge was the lowest among the sensors, and it was aerodynamic in shape. However, the Trackimo had a low update rate at one update per minute (“Trackimo,” n.d.), so it was decided that it would be used to support the Galaide’s LiDAR SLAM navigation and visual navigation (explained in Section 3.2.2). Table 9 presents the five possible sensors researched.

**Table 9. A comparison of the specifications and methods of different positioning sensors.**

| | iTraq Nano | Trackimo | FlyTrex | tBeacon | GPS Sensor (Catalog) |
|---|---|---|---|---|---|
| GPS | X | X | X | X | X |
| WiFi | X | X | | | |
| Cell | X | X | | | |
| Weight (g) | 40 | 42 | 31 | 6 | Negligible |
| Cost ($) | 119 | 140 | 190 | 60 | 50 |

### 4G LTE Network

To take advantage of the urban environment and combat the possible interference in radio telemetry, implementation of 4G connection as an alternative communication mode was considered because of the strong cellular network connection in an urban environment (Radišić, Vidović, Ivošević & Wang, 2018). A 4G connection could provide a stable mode of communication between the operator and the UAV when radio connection is unavailable (Radišić et al., 2018). In terms of hardware, a 4G enabled system would require a companion computer onboard the Galaide and a USB dongle or router for stable 4G/wifi connection for both the ground station and onboard (Li, 2016).

The cost and size of potential companion computers have decreased in the recent years, with relatively cheap options such as the Raspberry Pi Zero, which is smaller than a credit card and costs around $5 (Upton, 2015). Upon further research, the Odroid XU4 was selected as the companion computer for the Galaide because of its computing power-- seven times faster compared to the Raspberry Pi 3 (“Odroid,” n.d.). Although at $60.00 it costs slightly higher than other options, the computing power will be important for updating commands as fast as possible and minimizing delays from servers (“Odroid,” n.d.). The companion computer will also be performing the obstacle avoidance and visual navigation data processing and calculation, which are integral to establishing a safe flying condition for the Galaide.

The increased safety of the Galaide’s operation from the 4G network make this selection a worthy investment despite the recurring variable cost for connection. The 4G cellular plan would also be used for the ground station, allowing another mode of communication with the stakeholders and the city before, during, or after an operation. The benefits of a plan become increasingly important in the case of interference in the urban environment.

### Emergency Landing

An integrated parachute was chosen for only emergency landings because it would need to be restocked before each mission if the parachute were used as the primary recovery method. A parachute landing would be less destructive than a belly landing (Abinaya & Arravind, 2017). The UAV may also be unable to perform a parachute landing safely if the emergency system is activated by the motor malfunctioning. The Iris 60" Ultra Light Parachute was ultimately chosen for its weight of 115 g and appropriate rating for 4.99 kg.

By restricting the search to piezoelectric buzzers capable of producing 120 dB sounds, various models were found and compared for their prices, weight, and product reviews. It was reasoned that the buzzer would be used as the primary warning system as it is more effective in getting the attention of people. Thus, two 120 dB buzzers would be placed symmetrically on the bottom of the wings for added safety. The UAV would also have LED lights as a visual warning for pedestrians. The UAV would be colored vibrantly on the bottom of the vehicle to increase visibility during flight.

A two-blade propeller would be used for the propulsion system, and the propeller safety requirement will be addressed by a cylindrical housing around the propeller. Further research into the capabilities of Safe2Ditch supported its inclusion in the Galaide safety system based on its health monitor interface, landing site selection algorithm, navigation/route optimizer, landing site verifier with secondary sensors, and adaptive control maneuver through an intelligent hub (NASA, n.d.).

### Appropriate Cruising Speed

The team aimed to maximize the speed to decrease operation time without risking pedestrian safety. Finding out the cruising speed of the vehicle would determine lift and thus the pitch of the aircraft. In order to determine an appropriate speed that is safe for urban operation, various factors were considered. As stated in FAA regulations Part 107, the maximum speed for a UAV is 44.7 m/s, a speed far higher than most survey UAVs. Thus, Dr. Bland, the team's mentor, recommended a safe speed was based on having the same kinetic energy (KE) of a bike rider at 10 mph, which was calculated to be 21 m/s. This speed exceeds the speed limit for cars, which may cause citizens concerns with its safety. Thus the UAV's cruising speed was capped at 11 m/s, just below the lowest speed limit of the city. The Mapir Survey3 camera can capture images with 95% frontal overlay for walled areas at 11 m/s. (See Section 2.4, Footprint)

$$KE\ of\ Bike\ Rider:\ 0.5(88.21\ kg)(4.47\ m/s)^2 = 881.26\ J \tag{1}$$

$$KE\ of\ Finalized\ UAV\ Speed:\ 0.5(4\ kg)(11\ m/s)^2 = 242\ J \tag{2}$$

The team also found a demonstration on an obstacle avoidance program for a flying wing performing at 13.4 m/s (Massachusetts Institute of Technology's Computer Science and Artificial Intelligence Laboratory, 2015). Thus, obstacle avoidance was possible at 11 m/s. Using the same kinetic energy calculation, the Galaide would have the kinetic energy of only 27% of the bike rider at 10 mph. This operational speed would allow the Galaide to collect high-quality data while safely avoiding obstacles while flying through the city.

### Propulsion/Power Plant System

The general trend for selecting propulsion systems involves first selecting the propeller dimension, based on space available for the diameter, and the pitch, based on the thrust required ("All about," 2018). Next, the motor is selected based on the RPM necessary to generate sufficient thrust to obtain lift. Lastly, a battery with sufficient energy to power the propulsion and all other elements of the vehicle for the duration of a survey flight is selected. Based on the initial model of the UAV, the maximum size of the propeller would be 16 in, and the weight of the vehicle would be estimated at 3.5 kg. The team researched different sources on the proper thrust to weight ratio, and after discussion with Dr. Bland, concluded that a 1:1 weight to thrust ratio or better will make hand launch possible, but 4:3 or 2:1 is also likely to support the aircraft in flight. The research team used the Godollo Airport Thrust Calculator to determine the propeller pitch and motor RPM combination to generate the speed and static thrust the UAV requires. According to the calculator, a 16 in by 6 in pitch propeller would generate 6.49 kg of thrust at 8800 RPM and estimated cruising speed of 11 m/s at 4400 RPM. A flight endurance of over one hour was chosen to ensure ample battery life for one mission.

$$Motor\ power\ consumption\ at\ cruising\ speed:\ 116\ W$$

$$Current\ required:\ \frac{116\ W}{22.8\ V} = 5.08\ A\ ,\ Desired\ battery\ capacity\ >\ 5080\ mAh \qquad (3)$$

Since RPM is highly dependent on the payload attached to the motor, and the team is unable to purchase the actual motor and propeller to test the RPM, the team based the RPM used in the calculator as the KV rating of the motor multiplied by the voltage of the battery multiplied by 85% for assumed efficiency. A motor providing 11,000 theoretical RPMs (KV*V) would be ideal to provide the same maximum estimated realistic RPMs of 8800 (8800 = Kv*V*.8). Consequently, a motor rated for a 4 kg RC Plane was selected along with a 6S Li-Po battery.

There were few suitable motors found for the final setup, but the team discovered that using a 470Kv motor with a 6S 5400mAh battery would meet the team's condition of at least one hour of battery life and sufficient thrust. Although the voltage of a 6S Li-Po battery can be stepped down to 12V using a voltage regulator to power the electronics, a second three-cell battery to power the electronics was selected as a redundant measure for the C3 system.

Due to the two no-fly zones and the situational temporary no-fly zone, the Galaide needed more maneuverability to perform higher ascents and possibly the Immelman turn maneuver used in UAV aerobatics. To meet the flight capabilities the team desired, the team added two linear actuators to create a 2D thrust vectoring control (TVC). Thrust vectoring is a technology that allows additional control over aircraft from the thrust generated by the engine of the aircraft (Wollenhaupt, n.d.). Thrust vectoring would be built into the flight control system, so it works automatically in response to commands from the pilot. When the pilot turns the aircraft, the nozzle moves in the desired direction along with the Galaide elevon control surfaces. The linear actuators would control the orientation of the propeller and allow it +/- 10.48 degrees of movement, as shown in Figure 5. Using TVC, combined with the Galaide's high thrust to weight ratio, would increase maneuverability through pitch angle control which would allow better longitudinal stability and pitch control to maintain high AOA at low speeds.

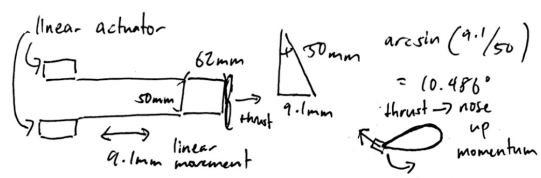


**Figure 5. Calculations for the degree of movement with the 9.1mm linear actuator.**

## Stability

The position of the center of gravity (CG) was determined through a longitudinal stability analysis. A rough sketch of the Galaide was drafted in XFLR5 to observe the general aerodynamic performance. Three key variables identified for stability were the cruising speed of the Galaide (See Section 2.1.4, Speed), angle of twist required for the washout, and CG position.

The initial sketch of the Galaide was tested for the zero-moment lift, the lift coefficient when the moment coefficient is 0, and the results were a lift coefficient of -0.003 (See Figure 6), meaning that the wing would not generate positive lift at its stable position. Since flying wings do not have elevators, the main wing must achieve its own stability (Deperrois, 2010). To create a stable wing, a negative washout at the tip of the wing was implemented. The positive moment at the tip would balance with the negative moment at the root (Deperrois, 2010). As the degree of the washout increases, the overall lift decreases (Deperrois, 2010). Therefore, a more systematic approach was used in calculating the twist required. The twist/washout angle was calculated using the Panknin Twist Formula (Panknin, 1989), and by inputting the cruising speed, the twist angle of -5.0° was reached. With the -5.0° washout included, the zero-moment lift became 0.02.

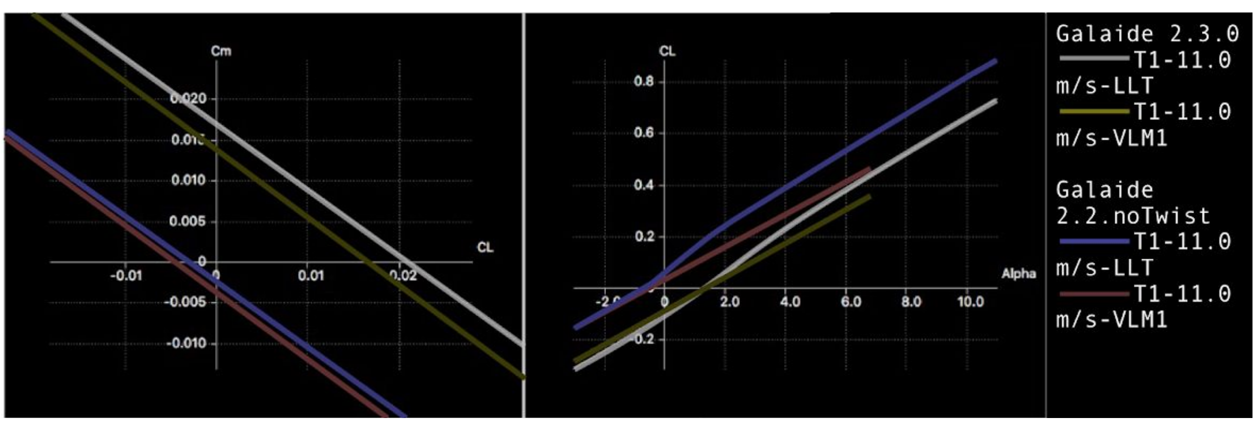


**Figure 6. The higher zero-moment lift and lower general lift caused by a -5.0° washout.**

Thus, the stability of the wing was confirmed, but the degree of stability needed confirmation. The stability of an aircraft can be measured by its static margin (SM), with 10% SM acceptable for most aircraft (RC AeroBase, n.d.). To quantify and optimize stability, calculations using the formula for calculating SM to determine the position of CG were performed. Since the positions of the neutral point (NP) and the mean aerodynamic chord (MAC) only depend on the geometry of the plane, the CG can be calculated with an SM estimate of 5% to 15%. The CG was determined to be between 0.3963 m to 0.4541 m behind the nose.

$$SM = \frac{(X_{NP} - X_{CG})}{MAC_{wing}} \tag{4}$$

$$X_{CG} = X_{NP} - (SM \times MAC_{wing})$$

$$0.4541\ m = 0.483m - (0.05 \times 0.578m) \tag{5}$$

$$0.3963\ m = 0.483m - (0.15 \times 0.578m) \tag{6}$$

## Structural Safety

An airframe made almost entirely EPP foam provided benefits to the Galaide; primarily, it kept the UAV’s cost and weight relatively low as compared to other airframes, especially after shelling the frame of the wings. That low weight, however, brought a possible danger to the team’s attention: the Galaide’s airframe may not have been able to handle the load from strenuous maneuvers like banking turns. After several iterations in the frame to account for variables such as the neutral point, CG, and pressure, the CAD Specialist performed structural testing on the wings and fuselage to simulate the G-forces from a banking turn with a turning radius of 7 m (which would allow the Galaide to perform necessary U-turns in the city). Each part of the wing was subjected to the load, and G-forces were calculated from the equation

$$G = 1/cos(\theta) \tag{7}$$

where the bank angle was determined from the turn radius equation.

$$R = \frac{V^2}{9.8 tan\theta} \tag{8}$$

As shown in Figure 7, both the wings and Galaide are capable of carrying the loads from a 60.4° banking turn (approximately 89 N of force). Both yielded a minimum safety factor of at least five times the necessary strength which proves its ability to withstand maneuvers. Because stable flight and structural stability had been proven, the neutral point and CG were in accord, longitudinal stability was established, the team chose to finalize the design.

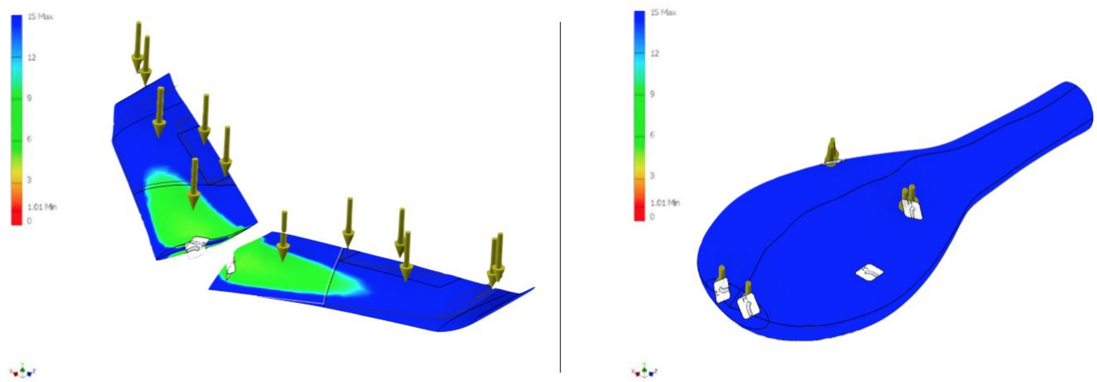

**Figure 7. Fuselage and Wing Stress Analysis.**

### *2.1.5 Lessons Learned*

During the initial research for the conceptual design phase, members learned to analyze their ideas and classify the hardware and software requirements to turn each concept into reality. The members also developed their specific working team dynamic with each other that allowed the Project Manager to organize them into departments to maximize productivity. Team members each led discussions and learned to clarify arguments based on quantitative data rather than qualitative words.

In the preliminary design phase, team members learned the importance of documentation and citations after backtracking several times to find the original research paper or product page for data. Once the members became familiar with navigating through websites and extracting crucial information quickly, research speed picked up, and they were able to make decisions more quickly. Past winners' notebooks, as well as the official challenge document, were read and re-read several times to fully understand the level of detail the engineering notebook required, and each member learned to write concisely. Toward the last two months of the State challenge, the detailed design phase began, where final decisions were made. The team learned to detach the design solution from personal preferences to optimize the UAV for the mission. Since time was limited during this design stage, team members learned to manage work time carefully and not hesitate to ask for help from the coach and mentors. The team also learned to cross verify calculations with online calculators and research sources for components to make sure no inaccuracies or discrepancies existed.

Throughout the challenge, the team learned to coordinate multiple schedules and work together. Work always continued after their Pre-Engineering class, so the team quickly adapted to each other's schedules for out-of-class meetings. Team members partnered up to learn difficult concepts, such as aerodynamics, CAD software, and various UAV subsystems, and communicated their problems effectively to the coach and mentors when seeking help. Prior to the challenge, most of the members had neither researched nor written any scientific paper at the scale of RWDC, so all members learned to write scientifically and plan effectively in order to finish the notebook on time.

### *2.1.6 Project Plan Updates and Modifications*

During the initial team formation phase, the Project Manager created a Gantt chart and an objective list, both color-coded to indicate progress and specific milestones. The chart was generated with the members' suggestions from looking at the past winners of the RWDC and Project Manager's experience leading other projects. The chart in Figure 8 displays different milestones that the team sought to meet every month for the National challenge.

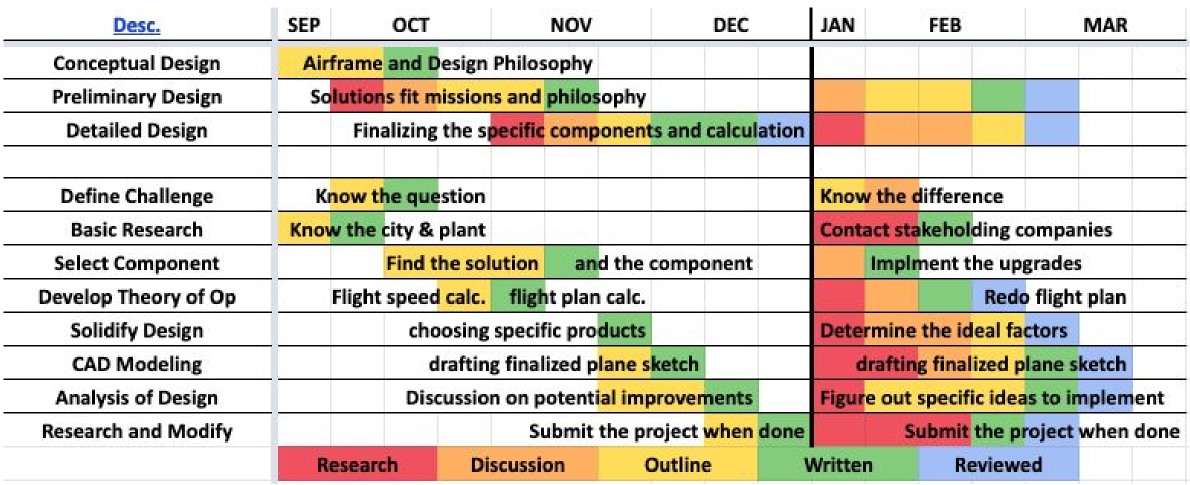


**Figure 8. Detailed Gantt Chart and Milestones.**

Eight weeks before the state challenge deadline, the Project Manager reviewed the objective list, rearranged the timeline to add finer details, and began organizing additional meetings to extend the hours worked per week. A sticky note wall was used at the end of November to give a visual representation of tasks to be completed. The wall was divided into "to-do's" by department and status (discussion, review, or completion). The new systems were implemented to be more organized, easily accessible, and rearrangeable than shifting between tabs on a laptop. Using sticky notes allowed the order of systems component selection and their calculations to be easily re-evaluated, changed, and rearranged.

The sticky note wall system shifted when the team obtained a dedicated whiteboard for the National challenge. The whiteboard generated no paper waste and allowed for quick legible writing. The whiteboard eventually took over the sticky note wall system, as shown in Figure 9. A due date countdown for March 5th, when the team had planned to finish the notebook draft, was also drawn on the board to remind the members of the time constraint.

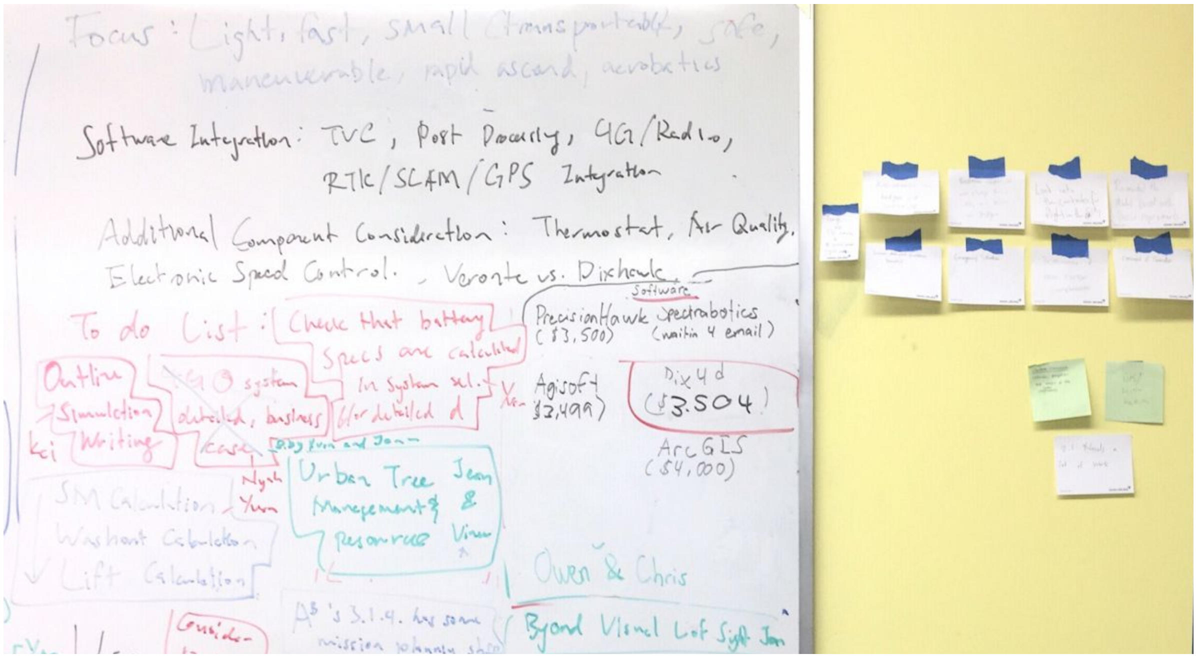


**Figure 9. The transition from the sticky note wall system to the whiteboard.**

## 2.2 Selection of System Components

### *2.2.1 Payload Selection*

The Galaide's payload is composed of one navigational camera, two cameras (one fixed; one on an EMAX servo-controlled gimbal) to measure and record plant health, and air pollution sensors. For navigation, the Galaide uses a forward-facing GoPro HERO7 White Camera. As the mission mandates flight BLOS, the UAV requires a navigational camera for ground personnel who monitor it mid-flight. The HERO7 was primarily chosen for its low cost and high resolution (1440p at 60fps); it also boasts video stabilization that is necessary for the UAV's continuous movement as well as a waterproof casing for the Galaide's operation in all seasons ("GoPro," n.d.). Table 11 summarizes the payload selections, as well as their total weight and price.

For determining and recording plant health, the Galaide uses two Mapir Survey3W cameras positioned to record images of vegetation either beside or directly beneath the Galaide. This camera provides NIR data which can be processed as NDVI index to approximate the health of the city's vegetation (as described in Section 2.1.3). From the NIR/NDVI cameras explored, the Mapir Survey3W proved to be the most cost effective at $400.00, as it has an 87° field of view and geo-tagging function, compared to an average cost of almost $3,500 for other cameras with similar capabilities ("Survey3W," n.d.). Furthermore, the Survey3W is relatively lightweight and has a sufficiently robust resolution (3840 x 2160 px at 24 fps) to measure plant health as the Galaide flies above it ("Survey3W," n.d.); at 70 m above vegetation, the Survey3W records 33 mm/px (calculated in Section 2.4 Footprint). When the UAV is flying above vegetation that is not directly beneath it, such as with a walled road, the gimbals are able to angle the cameras toward the vegetation.

Given that the city's ultimate goal is to curb the effects of air pollution, it would be beneficial to measure the concentration of various types of atmospheric pollutants present in the urban environment over time while simultaneously surveying plant health. Data on pollutants like $CO_2$ and particulate matter would also allow the city to identify areas with a high concentration of dangerous pollutants and quantify its efforts to curb pollution. However, many current sensors like the TZOA PM Research Sensor ($600.00) and Dylos DC-1100 Pro ($260.00) are relatively expensive for the Galaide (Feinberg, 2016). Thus, the team researched on companies such as TE Connectivity, Sensirion, and Alphasense and selected the AmbiMate 2314291-1, the Alphasense OPC-N2, NO2-A43F, CO-A4, and OX-B431 sensors, and the Alphasense 3-Sensor

AFE, which connects the Alphasense sensors. These amount to $111.00 and measure several pollutants. Table 10 lists each sensor's cost, weight, and measured pollutant. These sensors are small in size and can be mounted on the UAV with ease.

**Table 10. The pollution sensor components.***

| | AmbiMate 2314291-1 | OPC-N2 | NO2-A43F | CO-A4 | OX-B431 | Alphasense AFE |
|---|---|---|---|---|---|---|
| Cost | $26.00 | $2.00 | $1.00 | $1.00 | $1.00 | $80.00 |
| Weight (g) | -- | 105 | 6 | 6 | 6 | -- |
| Pollutant | VOC, $CO_2$ | Particulate Matter | $NO_2$ | CO | $O_3$, $NO_2$ | -- |

* All Alphasense sensors from (Bolla, et al., 2018)

**Table 11. The total weight and price of the Galaide's payload.**

| Component | Quantity | Price | Weight (g) |
|---|---|---|---|
| GoPro HERO7 White | 1 | $179.99 | 92.4 |
| Survey3W Camera | 2 | $800.00 | 152 |
| EMAX ES08MA Servo | 1 | $7.99 | 12 |
| Pollution Sensor Components | 1 | $111.00 | 123 |
| | Total: | $1,098.98 | 379.4 |

### *2.2.2 Air Vehicle Element Selection*

#### Airframe

It was decided to use a power source that is environmentally friendly while also providing the energy required for the UAV to operate. With the previous requirements in mind, the primary power source would come from a battery. Research was done on Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium Polymer (LiPo), and Lithium-ion (Li-ion). Using a Li-ion battery was preferred, given its high energy density, operability at wider temperature ranges, and a higher cycle life; factors that would fit into the UAV's year-round operation plan ("What's," 2017). However, the price and specification estimations online for the 6S Li-ion batteries that matched the current draw were not  found and the Li-ion batteries that were found had discharge rates that were too small for the Galaide. Thus, LiPo batteries were used.

**Airframe:** The airframe consists of both wings providing the lift and the fuselage shell storing onboard electronics, with the carbon fiber spars supporting the overall structure. The fuselage shell is made of carbon fiber to protect the inner components. The wing is made of EPP foam supported by carbon fiber rods as spars (see Section 2.1.3 for material selection justification). As this material is lightweight, it poses less danger to people and property. The price is calculated as the net price of the material as the manufacturing costs would be difficult to calculate.

**Turnigy Bolt 5400mAh 6S High Voltage Lipoly Pack**: Due to the motor's high voltage requirement, a separate battery was chosen solely to power the motor. At 5400 mAh, the battery was calculated to last approximately 1.06 hours of flight. Batteries with higher mAh values would allow for longer flight times but would add more weight to the UAV, and the research team concluded that 5400 mAh provided enough power, accounting for that battery's degradation over its lifetime, for the UAV's 26-minute flight time and to power the flight components through the voltage regulator, should any malfunction occur with the 2200mAh battery.

**Turnigy 2200mAh 3S 25C Lipo Pack**: The Turnigy 2200mAh three-cell battery provides power to all other equipment onboard. It was calculated to last roughly an hour. This battery was chosen as it lasted longer than the UAV's flight and was the cheapest and lightest for its capabilities.

**EMAX ES08MAII Mini Metal Gear Analog Servos**: Two analog servos will be used to move the Galaide's ailerons. At only 12 g ("Emax," n.d.), the EMAX ES08II is both lightweight and small. These servos are necessary to allow the Galaide to maneuver turns and to ascend or descend as it approaches a survey area.

**Propeller/Motor Combination**: As explained in 2.1.4, a 16 inch x 6 inch Master Airscrew S2 propeller will be used to generate sufficient thrust for the Galaide to maneuver and lift. The propeller must be matched with a compatible motor, and the Eflite Power 60 470 Kv motor, rated for 5kg airplanes ("Power," n.d.), would fit the operating parameters.

**Spektrum 1.9-Gram Linear Long Throw BB Servo**: Two linear servos will be used to move the motor to allow 2D thrust vectoring control. The Spektrum 1.9-Gram Linear Long Throw BB Servo is both light and small. These linear servos will allow control over thrust and pitching moment distribution through the motor orientation.

**Micro BEC Voltage Regulator**: If the circuit battery is damaged or malfunctions and fails to provide power to the onboard sensors and flight controls, then the BEC voltage regulator down steps the voltage of the propulsion battery and allows for its use on the Galaide's flight controls to perform a controlled emergency landing. Because the Micro BEC is only 4 g and 22 mm across, it is small and ideal for the Galaide's limited fuselage space ("Micro," n.d.). Additionally, because the onboard C3 system takes 12V of input, a voltage regulator that can either step up the 11.1V battery or step down the 22.2V battery is required. Although it supplies 3A of electricity, it is sufficient for the C3 system and the emergency landing procedure.

**Universal Battery-Elimination Circuitry (U-BEC):** The U-BEC serves as an alternative power regulation module. If the UAV's power falls below the levels necessary for normal flight, then the U-BEC will divert all of the power to the aileron servos to allow for a controlled descent. The U-BEC is a necessary component for the Galaide, for the mission's setting in an urban environment poses the risk of civilian harm.

**Hobbywing Skywalker ESC:** The Hobbywing Skywalker Electronic Speed Controller allows the motor to connect with the battery. It will work in conjunction with the motor to control the speed of the propeller's rotation. It is rated for 80 A, the recommended rating for the Eflite 470Kv motor. Table 12 lists the airframe components of the Galaide.

**Table 12. The total weight and cost of the Galaide's airframe elements.**

| Component | Quantity | Price | Weight (g) |
|---|---|---|---|
| Airframe (Wings, Fuselage, and Carbon Fiber Spars) | 1 | $49.64 | 1576.5 |
| Turnigy Bolt 5400mAh | 1 | $115.18 | 841 |
| Turnigy 2200mAh | 1 | $10.99 | 188 |
| EMAX ES08MA Servo | 2 | $15.98 | 24 |
| Master Airscrew S-2 | 1 | $6.82 | 92 |
| UAV Brushless Motor | 1 | $109.99 | 380 |
| Spektrum Linear BB Servo | 2 | $27.98 | 3.80 |
| Micro BEC Voltage Regulator | 1 | $5.99 | 4 |
| U-BEC | 1 | $20.00 | 7.37 |
| Hobbywing Skywalker ESC | 1 | $24.99 | 82 |
| | Total: | $387.56 | 3198.67 |

## Sensors

**Digital Compass:** The digital compass sensor measures the Galaide's magnetic heading within 3° to 4° of accuracy and allows the UAV to determine direction. While the UAV is capable of sensing heading through the Trackimo and Pixhawk's accelerometers, as well as direction and orientation through the Pixhawk's magnetometer and gyroscope, the digital compass acts as a tertiary auxiliary system. The compass's support will provide additional safety to the UAV and its surroundings.

**Global Positioning System (GPS) Sensor:** The GPS sensor gives the UAV its position (latitude, longitude, and altitude) for autopilot flight. Although the UAV must be able to fly without GPS, the sensor provides a cheap system to reference the Trackimo's measurements and SLAM navigation when a GPS signal is available. The PixHawk's internal GPS will support this sensor.

**9-Degree of Freedom (DOF) Inertial Measurement Unit (IMU):** This device is supported by the Trackimo and digital compass sensor. It measures the UAV's velocity and orientation to assist the autopilot in maintaining direction and speed. Because the UAV will fly BLOS, this component is essential to the UAV's safety and completion of the mission.

**TeraRanger Hub Evo, TeraRanger Evo 60m, (2) TeraRanger Evo 600 Hz:** The TeraRanger Evo 60m and one TeraRanger Evo 600Hz are used primarily for proximity sensing and obstacle avoidance, but they will also be used for SLAM navigation. The other TeraRanger 600Hz will mainly be used to assist in maintaining altitude should the GPS sensor fail; however, it will also be used to determine when the Galaide is directly above vegetation (further explanation are provided in Sections 2.1.3 Obstacle Avoidance, GPS Alternative, and 3.2.2, respectively) and to measure tree height. The TeraRanger Hub Evo allows for the integration of different sensor data.

**Trackimo 3G Drone Tracker:** The Trackimo will be used in conjunction with the GPS sensor and TeraRanger sensors to maintain accurate positioning for optimal safety to the civilians, buildings, and the UAV. As it determines position through Bluetooth, cell signal, Wi-Fi, and GPS ("Trackimo," n.d.), its variegated methods are most optimized for an urban environment. Table 13 lists the Galaide's sensor components.

**Table 13. The total weight and cost of the Galaide's sensor elements.**

| Component | Quantity | Price | Weight(g) |
|---|---|---|---|
| Digital Compass | 1 | $45.00 | 0.85 |
| GPS sensor | 1 | $50.00 | negligible |
| 9D Inertial Measurement Unit | 1 | $40.00 | 0.6 |
| TeraRanger Hub Evo | 1 | $134.36 | 13.0 |
| TeraRanger Evo 60m | 1 | $134.36 | 9.0 |
| TeraRanger Evo 600 Hz | 2 | $268.72 | 18.0 |
| Trackimo 3G UAV GPS-GSM | 1 | $199.98 (+$5 yearly cost) | 39.69 |
| | Total: | $872.42 | 81.14 |

### Emergency Landing

**Emergency Light and Buzzer**: If the Galaide must execute an emergency landing, an alarm will go off and an LED buzzer will alert pedestrians with lights as the UAV descends. At 120 dB ("Sound and," n.d.), the alarm is louder than the average car stereo (Syal, 2004), providing ample notice in the urban environment. Two buzzers will be used to ensure that it attracts attention.

**Parachute**: Because the Galaide is a flying wing, it is incapable of vertical emergency landing. On its own, the UAV can only belly land. The Iris 60" parachute allows the Galaide to land slowly and safely regardless of altitude drop ("Iris," n.d.) on a surface that Safe2Ditch senses is free of people and property.

**Parachute Servo:** An additional servo is necessary to keep the parachute mechanism closed, and to open it when the Galaide is executing an emergency landing. During most surveys, this servo will not be in use. Table 14 lists the Galaide's components that assist in emergency landing, and Table 15 lists the total cost and weight of the air vehicle elements.

**Table 14. The total weight and cost of the Galaide's emergency landing elements.**

| Component | Quantity | Price | Weight (g) |
|---|---|---|---|
| Sound and Light Alarm | 1 lot (2 pcs) | $8.80 | 250 |
| Iris 60" Ultra Light Parachute | 1 | $275.00 | 115 |
| EMAX ES08MA Servo | 1 | $7.99 | 12 |
| | Total: | $291.79 | 377 |

**Table 15. The total weight and cost of the Galaide's air vehicle elements.**

| Component Category | Price | Weight (g) |
|---|---|---|
| Air Frame | $387.56 | 3198.67 |
| Sensors | $872.42 | 81.14 |
| Emergency Landing | $291.79 | 377 |
| Total | $1,551.77 | 3656.81 |

## *2.2.3 Command, Control, and Communications (C3) Selection*

### Ground Control

**Antenna Set:** This set consists of two 900 MHz Data Transceiver Sets, one 900 MHz Video System, and one 5.8 GHz Video System. The video systems are used to stream the navigational camera feed to the ground station (one acts as a backup). This is necessary for the pilot to continually monitor the Galaide's flight. Thus, the Galaide effectively limits the risk of interference with the cheaper low power system. The data transceiver sets allow wireless communication of control commands and telemetry data between the Galaide and ground control. Two transceiver sets are positioned on the wingtips of the UAV to account for interference, and further limit the risk of interference by employing the frequency-hopping spread spectrum (FHSS) method. All four onboard antennas will be attached at the trailing edge of the UAV, separated by at least 0.5 m to minimize interference. The video system and transceiver sets' ranges will be boosted by a Patch Antenna and YAGI Antenna to allow for communication throughout the entire city.

**YAGI-Directional Antenna (900 MHz):** The YAGI Directional Antenna is used to increase the communication range between the Galaide and ground control. The transceiver set and video system cannot communicate beyond 800 m to the Galaide, but communication beyond that range is necessary to both civilian and UAV safety. Therefore, the YAGI-Directional Antenna is used to increase the communication range by approximately 300%.

**PixHawk 4 Autopilot:** The PixHawk is used alongside the Antenna Pan/Tilt to move the YAGI-Directional Antenna. As the YAGI-Directional Antenna cannot function unless it is pointed directly to the UAV, the PixHawk uses the free ArduPilot Antenna Tracker software to record the Galaide's position. The PixHawk then allows the Antenna Pan/Tilt to track and follow the UAV.

**Antenna Pan/Tilt:** The Antenna Pan/Tilt is used alongside the YAGI-Directional Antenna and PixHawk. Through research, it proved to be the cheapest long-term method of UAV tracking beyond manual control, whose labor costs over three years would exceed the cost of the Antenna Pan/Tilt. The Antenna Pan/Tilt was also the cheapest of the servo-controlled antenna mounts that were explored.

**Patch Antenna (5.8 GHz):** The Patch Antenna is used to increase the secondary system's communication range. Unlike the YAGI-Directional Antenna, it is not required to be aligned with the Galaide, and must only point in its general direction. Alongside the secondary system's range, the antenna's boost and signal field reduces the risk of signal loss to the Galaide.

**Panasonic Toughbook:** The Panasonic Toughbook will be the ground station laptop that is responsible for the operation and communication between the operators and the UAV. It has an Intel Core i5 2.8GHz Processor, 16GB RAM, 512GB solid state drive, and it runs on a Windows 10 64-bit operating system ("Refurbished," n.d). This selection was made over the catalog option for the superior operating system, processing power, storage, and lower cost.

**Thrustmaster HOTAS Warthog Joystick:** The Thrustmaster HOTAS Warthog Joystick is around 3 kg, providing sturdiness to the controls. It has precise control with 16-bit accuracy with

65,535 discrete values which decrease dead zones in the joystick and increases accuracy (Hutchinson, 2014). It has a configurable software suitable for programming the UAV.

### Flight Controls

**Microcontroller and Serial Servo Connector**: Two of the 12 analog inputs will be configured to control the two aileron servos. Nine others will be connected to the nine constituent sensors of the 9-DOF IMU. With a transceiver, the microcontroller allows for ground control of the servos, should the onboard sensors fail or some other emergencies require direct control of the Galaide. The serial servo connector will be used in addition with the microcontroller to control the camera gimbal and parachute servo, as the microcontroller is limited to 12 analog inputs.

**Pixhawk 4 Autopilot:** As the UAV will fly BLOS for most of its survey, the Pixhawk 4 autopilot is a vital component to the Galaide. Its onboard accelerometers and GPS sensor, coupled with the Galaide's secondary sensors, ensure exact positioning within the city. Furthermore, the Pixhawk allows for autonomous flight by controlling servos and can automatically correct the UAV's flight. Therefore, the Galaide will perform the surveys accurately, leveled, and on path. Furthermore, the Pixhawk includes an internal accelerometer, gyroscope, compass, and barometer to provide support to the Galaide's other flight sensors.

**4G Communication Kit:** The 4G communication kit enables the UAV to be controlled at a further distance than a radio transmitter would allow (Li, 2016). The kit consists of an Odroid-XU4 and two Huawei E3276s-505s. The Odroid-XU4 acts as the companion computer onboard the UAV and communicates between the ground station and the Pixhawk 4 autopilot (Hardkernel, n.d.). The Odroid is powered by the UAV's battery using an EXUAV Converter ("EXUAV," n.d.) The Huawei E3276s-505s is a 4G LTE dongle that would provide the internet connection through a monthly $120.00 cellular data plan ("New," n.d.; "Cell," n.d.).

**Multiplexer:** The multiplexer provides an interface to switch between autonomous and manual control. It is necessary in times of emergency landings or situations which require the Safety Pilot to land manually. These commands will be received by the onboard transceivers and parsed by the multiplexer.

**ping20S Mode S Transponder:** The transponder allows the UAV to identify itself to nearby flying vehicles with transponders and assists with detection and avoidance by identifying other transponders. Although it is $1999.99 ("Ping20S," n.d.), it was relatively cheap compared to other transponders. Table 16 lists the C3 components of the Galaide.

**Table 16. The total weight and cost of the Galaide's C3 components.**

| Component | Quantity | Price | Weight (g) |
|---|---|---|---|
| YAGI-Directional Antenna (900 MHz) | 1 | $60.00 | -- |
| Antenna Pan/Tilt | 1 | $59.99 | -- |
| Patch Antenna (5.8 GHz) | 1 | $55.00 | -- |
| Panasonic Toughbook | 1 | $1,269.00 | -- |
| Thrustmaster HOTAS Warthog Joystick | 1 | $468.99 | -- |
| Antenna Set | 1 | $365.00 | 111.34 |
| Multiplexer | 1 | $25.00 | 15.02 |
| ping20S Mode S Transponder | 1 | $1,999.99 | 15 |
| Microcontroller | 1 | $100.00 | 9.92 |
| Serial Servo Connector | 1 | $25.00 | 9.90 |
| Pixhawk 4 Autopilot | 2 | $359.98 | 15.8 |
| 4G Communication Kit | 1 | $111.40 (total) | 375.38 |
| | Total: | $4,899.35 | 552.36 |

### *2.2.4 Support Equipment Selection*

**Feiyu UAV Catapult Launcher:** The challenge requires the launch procedure to operate within the 3 m by 3 m launch area. The Feiyu catapult launcher was selected as it is the only catapult found to fit within that area that provided a price. It is also able to give the UAV a sufficient initial velocity at ~12 m/s for the initial ascent.

**Recovery Net:** The recovery system will be made of four poles and a net, similar to a baseball training net. Since a net was selected for the recovery method, the team decided on using a net made of nylon for the recovery. The nylon should be able to withstand the impact of the landing UAV while being resistant to rips or tears for future surveys.

**Battery warmer:** Since the mission requires that the Galaide complete a survey twice during winter, the Galaide may be exposed to temperatures below 5°C. These temperatures may diminish the capacity of the battery ("What's," 2017). Thus, a battery warmer will be used to prepare the battery for use in cold temperatures.

**MAPIR Camera Reflectance Calibration Ground Target:** As the Galaide will operate throughout the year under different light and weather conditions, use of the MAPIR Calibration Ground Target normalizes light conditions in survey images and allows for normalization across surveys in different times (“Calibrating,” n.d.). Plant data will be more consistent, and analysis of such data will be more accurate.

**Streamline Shelter:** The streamline shelter will be used to house and transport the UAV and support equipment. It will also be used during the mission as a workstation for personnel. Though it is the cheapest of the trailers, it provides ample space for work and storage with one UAV rack.

**Pix4D:** Data analysis is a prime component in the YETI urban survey package. This software allows the use of photogrammetry and multispectral imagery processing to map out the plants in the city and to determine their overall health. The MAPIR camera being used for the Galaide had two recommended software programs to be used for surveying plant health: Pix4D and Agisoft (“MAPIR,” n.d.). Pix4D was selected out of the two because Agisoft only comes with one node-locked license whereas Pix4D comes with two floating licenses (“Pix4DMapper,” n.d.; “Agisoft,” n.d.). Additionally, both software are near the same price, and according to user forums, the main difference between the two would be the user interface. Pix4D is listed as a yearly subscription cost in Table 20, the mission’s budget summary table. Thus, it is not listed in Table 17 below.

**Table 17. The total cost of the Galaide’s support components.**

| Component | Quantity | Cost |
|---|---|---|
| Feiyu Catapult | 1 | $1,508.00 |
| Nylon Net | 1 | $19.99 |
| Aluminum Outdoor Pole (Set of 3) | 2 | $62.00 |
| Turnigy Programmable Lipo Battery Warmer Bag | 1 | $16.97 |
| MAPIR Camera Reflectance Ground Target | 1 | $200.00 |
| Streamline Shelter | 1 | $5,000.00 |
| | Total Cost | $6806.96 |

### 2.2.5 Human Resource Selection

**Safety Pilot**

Cost: $35.00 per hour

Amount Required: 1

Justification: The Safety Pilot ensures the UAV lands and recovers properly. The pilot will operate the UAV within line-of-sight (LOS) and will have the UAV land accordingly, and when BLOS, the pilot will observe the visual feed from the navigation camera. This role is also responsible for taking command over the UAV if any unexpected flight paths occur and will land the UAV in times of emergency. This role gives the Operational Pilot less strain on flying the UAV and ensures the UAV is undamaged and safe.

**Operational Pilot**

| Cost: $35.00 per hour |
| --- |

Amount Required: 1

Justification: The Operational Pilot monitors the operation of the UAV during autonomous or semi-autonomous flight. This role will keep track of aircraft state (altitude, attitude, location) to ensure completion of the survey task. This role will communicate with other personnel to ensure flight is smooth and effective.

**Range Safety/Aircraft Launch & Recovery/Maintenance Officer**

| Cost: $35.00 per hour |
| --- |

Amount Required: 1

Justification: The Maintenance Officer oversees the communication between the UAV and other flight operations in the airspace. This role will oversee the launch of the UAV. The role also is responsible for maintaining correspondence between air traffic personnel to ensure airspace restrictions are met accordingly. The role will be responsible for the maintenance of the UAV and its equipment, as well as the recharging of the UAV batteries and ground station.

**Data Analyst**

| Cost: $50.00 per hour |
| --- |

Amount Required: 1

Justification: The Data Analyst provides the ability to process data that may have not been processed in real-time. The primary duty involves ensuring sensor data is complete upon UAV recovery. This role will be responsible for reviewing and sending the finalized data to the city for future assessments on plants.

## 2.3 Component and Complete Flight Vehicle Weight and Balance

The SOLIDWORKS Mass Properties tool was utilized to find the CG of the UAV, whose total weight is 4.48 kg including the airframe and the payload block. The payload block was created to simulate the weight of the smaller components of the Galaide. SOLIDWORKS was used to view the center of mass of all the Galaide’s components, in order for the CAD Specialist to accurately obtain the CG of the Galaide. Since the gravitational field of the area surrounding the Galaide is uniform, the position of the center of mass is equal to the CG.

After inputting the other components, such as the propeller and emergency lights, into the assembly, SOLIDWORKS was able to simulate the CG at 0.41 m from the nose, as seen in Figure 11. The CG is 0.03 m in front of the neutral point and the mean aerodynamic chord length is 0.58 m, thus giving the Galaide a static margin of 5.62%. The CG is in its ideal location since it is located in front of the center of lift, which means that the Galaide will self-stabilize during flight.

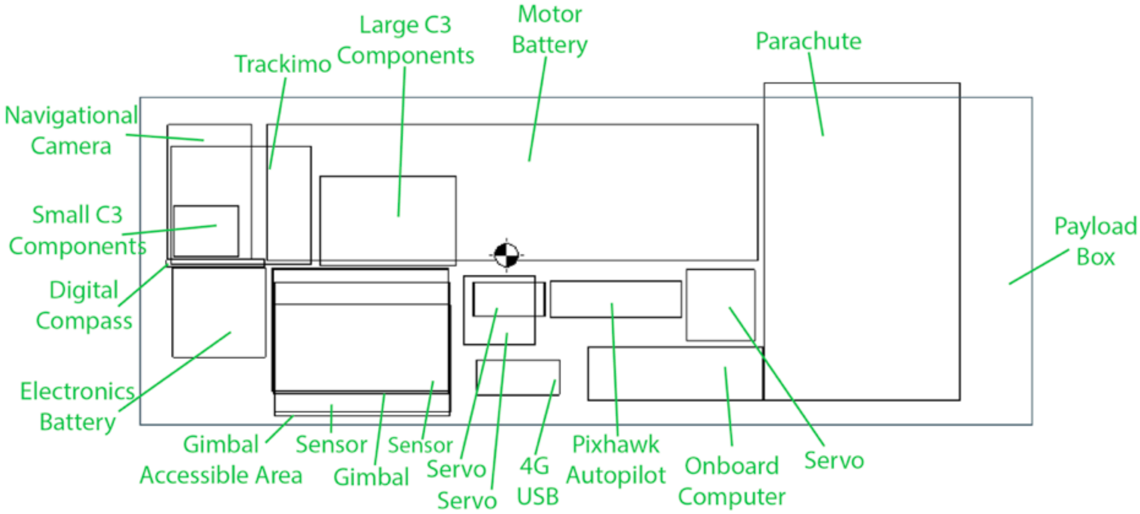


**Figure 10. A side view of the payload.**

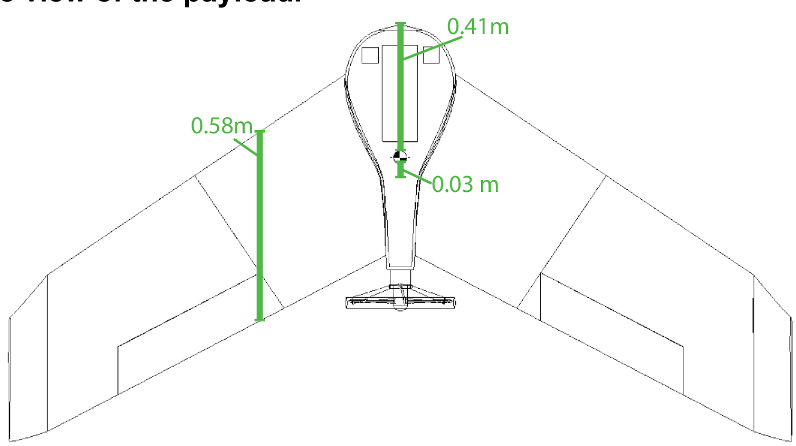


**Figure 11. A top view of the Galaide and its center of gravity.**

## 2.4 Operational Maneuver Analysis

Footprint

The mission of the Galaide is to provide plant health data to the city; thus, the operation limitations were based on the quality of survey data. The quality of the survey data is dependent upon the location of the plant surveyed. The survey areas were categorized into either ground or wall areas. Through initial calculations, the camera was found to be able to support speeds of 11 m/s at the wall area with over 75% frontal overlay-- an overlay amount suggested by the team's mentor, Ms. Kottermair. The flying altitude for ground areas was determined to be 70 m based on the data quality of 35 mm/px. The Galaide flies above the center of the road between walled areas. To ensure that no data holidays exist in the survey plan, the calculations for the footprint overlay were made. The following calculation in Figure 12 and Table 18 demonstrates the data quality insurance based on the survey camera specification.

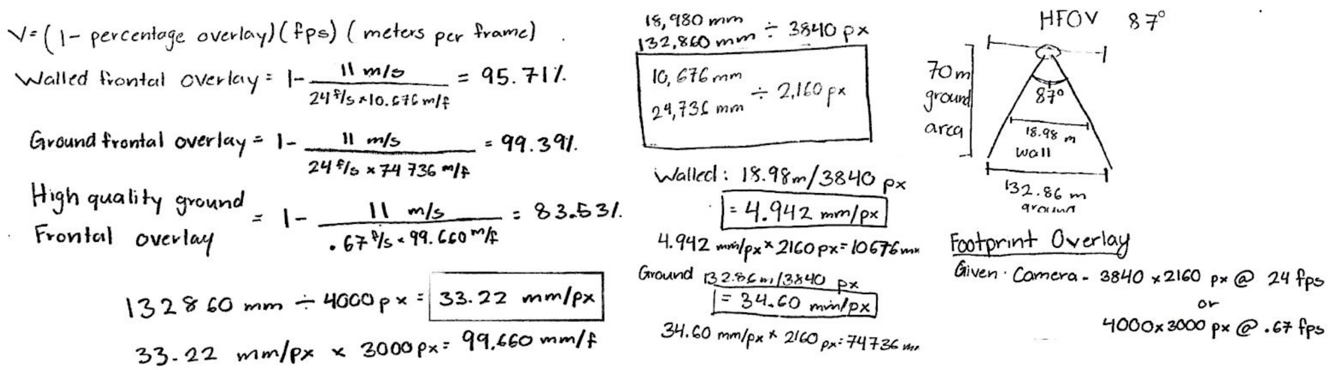


**Figure 12. Survey footprint calculations.**

**Table 18. Survey area calculations.**

| Area\Data Quality | Pixel Size (mm/px) | Frontal Overlay (%) | Side Overlay (%) |
|---|---:|---:|---:|
| Road | 33.2 | 83.53 | 232 |
| Field | 33.2 | 83.53 | 75 |
| Wall | 4.94 | 95.71 | 532 |

As demonstrated in the calculation, the frontal overlay ensures the accuracy of data captured. The side tolerance/overlay percentage counters any offset caused by gust or obstacle avoidance. The Pix4D software could also identify any noticeable features, such as signs, trees, and bushes, to aid in combining image data.

## Straight Flight During Cruise

To achieve straight flight during surveys, the Galaide's net vertical force must be at equilibrium; i.e., the vertical components of its thrust $T$ and lift $L$ must equal the weight $W$. If the Galaide flies completely horizontal (i.e., an attack angle $\alpha$ of 0°), its airfoil produces a negative (-19N) lift, the Galaide will have a net force downward, and it will descend. These forces are illustrated in Figure 13.

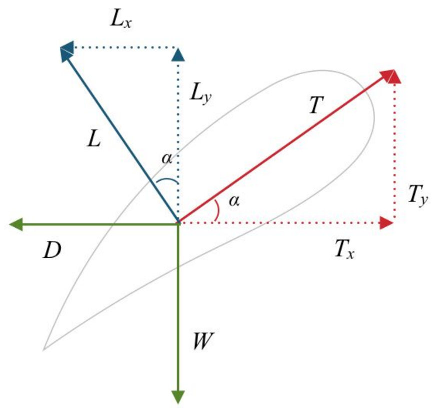


**Figure 13. A representation of the four force vectors on the airfoil.**

Thus, the research team sought to find an AOA *α* such that

$$W = T_y + L_y = T sin\alpha + L cos\alpha , \quad (9)$$

where $T = 15.88\ N$ & $W = 42.054\ N$. The known variables, the density of air ($\rho$), area (*A*), and velocity (*V*) were then plugged into the lift equation to solve for lift (*L*) as a function of the *Cl*:

$$L = \frac{1}{2}(\rho * V^2)A * Cl = \frac{1}{2}[(1.2045\frac{kg}{m^2})(11\frac{m}{s})^2](2.650m^2)Cl = 193.11Cl \quad (10)$$

Through analysis of the MH60 airfoil, the research team produced Figure 14, the Cl versus AOA graph, and its trendline equation *Cl(α)*. Combining Equations 10 and 11 yields

$$42.054 = 15.88 sin\alpha + 193.11 * Cl(\alpha) * cos\alpha \quad (11)$$

and, upon solving, produces *α* = 3.769°. However, the inclusion of thrust vectoring allows for a higher degree of freedom with the direction of thrust; 3.769° represents the required AOA with the thrust force parallel to the plane to keep level flight.

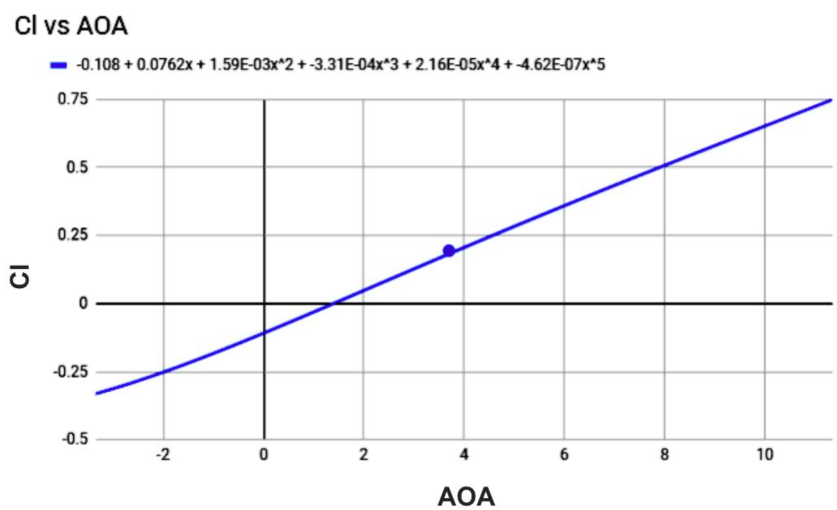


**Figure 14. The Cl versus AOA graph.**

## Climb Angle

At launch, the UAV starts off from a takeoff space of 3 m by 3 m and is launched with an initial release velocity of around 20 m/s with positive acceleration (Novaković & Medar, 2013). Assuming 15 m/s as the airspeed from launch, the rate of climb (ROC) can be deduced from its formula where $P_r$ is the power required for forward flight (equal to drag, $D$), $P_a$ is the forward thrust available, and $W$ is the weight of the Galaide. Since forward thrust is $T_x$, and the total opposing thrust is $D + L_x$, then the equation is written as

$$\frac{P_a - P_r}{W} = \frac{V(T_x - (D + L_x))}{W} = \frac{15\frac{m}{s}(15.88cos(0.866°)\,N - (1.3932 + 47.123sin(0.866°))\,N)}{42.05\,N} \quad (12)$$

which yields a ROC of 4.91 m/s. The Galaide is able to ascend 110 m from the second launch to survey rooftop gardens in 317 m of travel.

## Banking Turns within the Urban Environment

The flight plan included many turns with turning radii ($R$) as low as 7 m. The turn radius equation, Formula 9, was used to determine that the bank angle ($\theta$) required for the smallest turn would be 60.45° at normal cruising velocity. In order to prove that the Galaide is capable of turning at 60.45° bank angle, the research team calculated the maximum possible bank angle by distributing the maximum lift force ($L$) at stall angle generated at cruising velocity into vertical ($L_y$) and horizontal ($L_x$) lift force and matching the vertical lift force with the weight (W) of the vehicle.

$$L_x = \sqrt{L^2 - W^2} \Rightarrow 134.3\,N\ \sqrt{140.76\,N^2 - 42.05\,N^2} \quad (13)$$

Plugging in the maximum stable lift at 11° AOA (140.76 N), yields 134.3 N of horizontal lift force, the centripetal force of the turning vehicle. With that information, it is possible to calculate the bank angle formed by the UAV with the following equation:

$$\theta = tan^{-1}(L_x/L_y) \Rightarrow 73.65° = tan^{-1}(134.3\,N/42.05\,N) \quad (14)$$

The maximum bank angle based on lift was determined to be 73.65°. The theory of operation was designed with multiple 7 m and 11.4 m radius turns for the duration of the survey, for which the bank angle and G force calculations are listed in Table 19 below. Furthermore, because more lift is required to remain level in turns, the table also lists the AOA required to remain level at each turn radius from the equation

$$43.93 = Lsin(\theta) \text{ where } L = 193.1Cl(\alpha) \quad (15)$$

For G force stress analysis on the airframe material, see Section 2.1.4 for Stress Analysis.

**Table 19. Bank angle, G force, and rate of turn for different turn radii.**

| Turn Radius (m) | Bank Angle $\theta$ (°) | G Load (G) | Rate of Turn (°/s) | AOA (°) |
|---|---|---|---|---|
| 7 | 60.45 | 2.02 | 90°/s | 7.2 |
| 11.4 | 47.28 | 1.47 | 55.3°/s | 5.0 |

## 2.5 Three View of Final Design

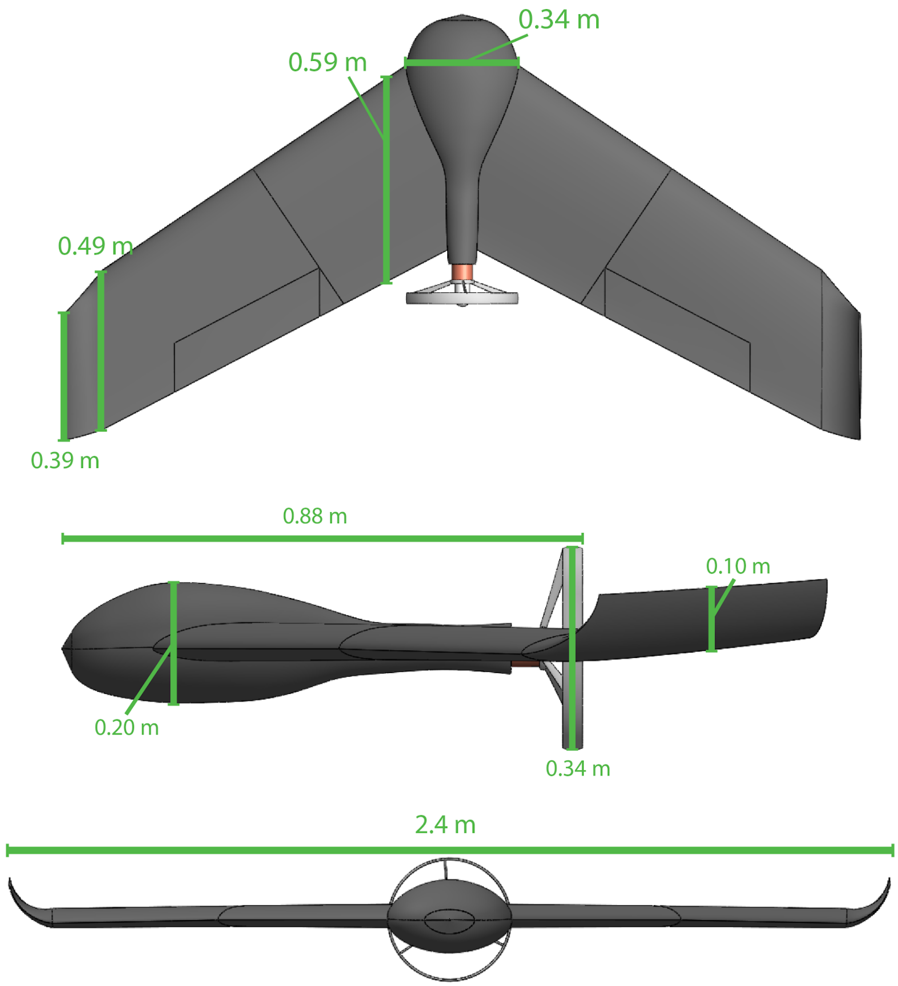


**Figure 15. Three views of the Galaide.**

**Dimensions of the Galaide**

UAV Wingspan: 2.43 m

UAV Length: 0.88 m

UAV Height: 0.34 m

# 3. Document the Missions

## 3.1 Concept of Operations

### *3.1.1 Pre-Mission*

The success of each survey relies on thorough preparation before every flight. As such, to ensure that data is complete and accurate and that the UAV poses no danger to people or property, the company must aim to prevent any avoidable issues before, during, and after the mission. Thus, the team must consider several factors when deciding to begin a survey:

***City preference.*** Although the availability of a survey is dependent on many factors, the decision to fly should rely on when the contracting city wants the survey completed. Before each survey year, the company must ask the city for *at least* eight preferred two-week timeframes for the upcoming year and must strive to perform the eight missions within those dates.

***Atmospheric Conditions.*** The weather and temperature of the flight day are critical to the safety of the UAV. The team must check this information through an automated terminal information service (ATIS) and determine whether conditions hinder flight. Flights will be canceled if wind speeds exceed 4.5 m/s (“Flying”, 2011), which may force the UAV to use more power to correct its path, if temperatures are below 10°C and above 40°C, which can hamper the endurance of the battery (“BU-502,” 2018), if there is precipitation, or if there is fog, which the team’s mentor Ms. Kottermair suggests may affect data accuracy. Even direct daylight may limit the range of the LiDAR sensors and curb the accuracy of obstacle avoidance (“Test,” n.d.). The company must check one week before each given timeframe for ideal and safe conditions like clear skies. During harsh weather, the company must work with the city to schedule another survey date.

***Permission to fly.*** One week prior to the proposed flight date, the Maintenance Officer (MO) must receive permission from the proper city authority (e.g. the City Manager, Mayor, etc.) to begin flight, and the company, city, and FAA must have copies of all signed waivers and permits to continue. Although the city has all the necessary waivers from the FAA to operate in the urban airspace, the MO must still contact nearby air traffic control (ATC) and ATIS to confirm any temporary no-fly zones. The MO must also contact city officials in charge of the pilot program, as well as the owners of each designated takeoff and landing (DTL) building (if it is privately-owned) for written permission to fly.

***Public Privacy and Safety.*** While the UAV's flight poses a potential risk to public safety, the public may also perceive the Galaide's survey cameras as a risk to their privacy, especially if the UAV flies over a public event or gathering, because the cameras may be panning as the Galaide flies above citizens. While the data gathered from surveys could be processed to obfuscate faces (Li, Vishwamitra, Knijnenburg, Hu, & Caine, 2017), privacy may still be of concern to the public, given that civilians will find being documented to be undesirable. Thus, the company must schedule and publicize flight days with the city prior to conducting a survey. Surveys should ideally be completed on weekends without scheduled community events to limit public exposure; however, weather or other emergencies may require weekday missions. If city officials prefer weekday missions, the MO will coordinate operations to satisfy this preference.

#### Preparing for Launch

One week prior to the selected launch date, the team must begin preparations for launching the UAV. The MO must inspect all Galaide components, ground station equipment, and support equipment to ensure that they were not damaged during previous surveys, storage, or transport.The MO must also check that all batteries and components are fully charged before launch. In winter, the battery warmer must also be used to prepare batteries for flight. Lastly, once all operators confirm the flight date, the recovery net's poles and net must be accounted for and the catapult must be properly folded for transport to the specified DTL area.

### 3.1.2 Mission

One day prior to the launch, the MO must initiate communication with city officials and ATC to confirm permission for launch and for any temporary no-fly zones during the launch day. The MO must also notify the police and fire department of the launch and maintain communication with them should an unexpected emergency, such as a fire, arise that may block the expected flight path. The MO must also check if the YAGI or patch antenna is receiving signal interference. Once all communication with all proper authority is established and launch is cleared by ATC, the City Manager, fire department, and police department.

On the survey day, the team must account for all personnel and check all specified criteria from Section 3.1.1 on a checklist before proceeding with the first launch. If all personnel have been accounted for and weather conditions meet the criteria, the Galaide can be transported to the DTL zone. The team may begin setting up the catapult within the launch space. Once there, the MO must conduct a final safety inspection of the Galaide and ensure that all supporting equipment is in working order before launching.

## Launch

The safety of the Galaide and urban population relies on constant communication between operators, the city, and the UAV. Once the UAV flies BLOS, the Operational Pilot must continually watch incoming telemetry data to check for any errors or shifts; similarly, the Safety Pilot must continually monitor the incoming feed from the navigational camera to check for obstacles or deviation from the flight path. Communication is critical between the Operational and Safety Pilots in case telemetry data and the visual feed differ, or the telemetry data suggests a malfunction, shift in heading, or change in speed that the Safety Pilot must correct. The MO must also maintain continual communication with nearby ATC and city officials in the case of a sudden temporary flight restriction or emergency (i.e., circumstances that require rerouting or emergency landing) so that the Safety Pilot can be notified. Lastly, as soon as the Galaide is launched, the recovery team will begin setting up the recovery net.

The Galaide's flight operations will differ depending upon the survey area. In ground-type areas where the Galaide will simply fly above to survey (road with median, vacant lots, parks, and rooftop gardens), the Galaide performs a serpentine flight path 70 m above ground to ensure sufficient overlap (see Section 2.4 for footprint calculations). In these surveys, the Galaide's survey cameras are pointed directly downward. In the wall-type areas (roads with building vegetation and walled road), the Galaide flies above the middle of the road at an altitude of 3 m. The gimbals of the two survey cameras move to point them directly left and right, respectively, of the UAV; thus, the Galaide will survey both walls in these areas during a single fly-through.

The Galaide's flight operations will also differ in each season. Surveys conducted in early spring cannot rely on crown shape or color as most perennials may still be waking from dormancy and most annuals may be dead ("Deciding," n.d.). The Galaide's survey cameras can, therefore, search for leaf buds in perennial trees with no leaves. Camera data may also be used to identify pests. In summer and late spring, survey operations continue normally.

Similarly, in later fall and winter, the Galaide cannot rely on color or leaf shape, as perennials enter dormancy and shed their leaves, and annuals begin producing seeds and dying ("Deciding," n.d.). Differentiation between dormancy and death is also difficult to ascertain without physical sampling (Wong, 2017), and grasses cannot reasonably be measured because of snow cover in the later months. As a result, although surveys in these periods can only record the bare branches of trees (excluding pines and other evergreens), this data can still be used to identify signs of damage, fungi, or disease, such as powdery mildew or cankering on branches (Moorman, 2014).

In ideal surveys, the mission begins at the 50 m DTL in Quadrant IV (Q IV) of the city and surveys the road with median, walled road, road with building vegetation in Quadrant III (Q III), and all vacant lots and parks except the vacant lot in Quadrant I (Q I). It then returns to the original DTL, where, upon recovery, the team launches the Galaide again to survey all rooftop gardens and the remaining road with building vegetation and vacant lot. The team travels two blocks to the vacant lot and prepares for recovery. For the survey plan, the six distinct survey areas are categorized as either a walled area or a ground area. The wall type areas include the walled roads and roads with building vegetation areas, which would be surveyed through two survey cameras angled toward each side of the Galaide at 3 m altitude and center of the road. The ground type areas include the road with median, parks, rooftop gardens, and vacant lots, which would be surveyed through serpentine-like patterns, at 70 m above vegetation patch altitude, centered on the survey path. The team developed two flight plans to reflect these conditions: the Galaide will survey the city in two flights; the first flight will be completed at 70 m and 3 m altitudes, then the second will begin at 160 m to survey the rooftop gardens, then will descend to survey at 3 m and 70 m and land. Furthermore, survey patterns were made to allow for 70% overlay.

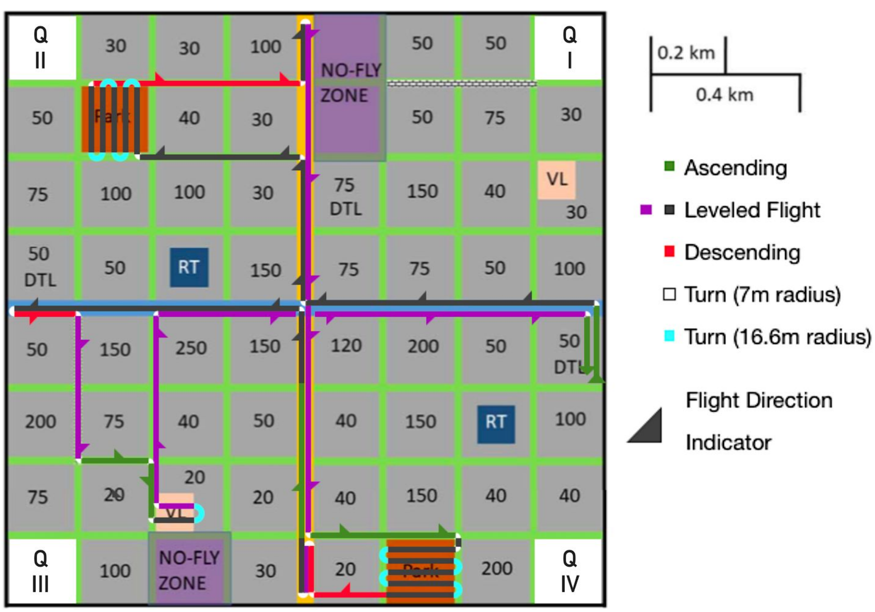


**Figure 16. Flight Path 1.**

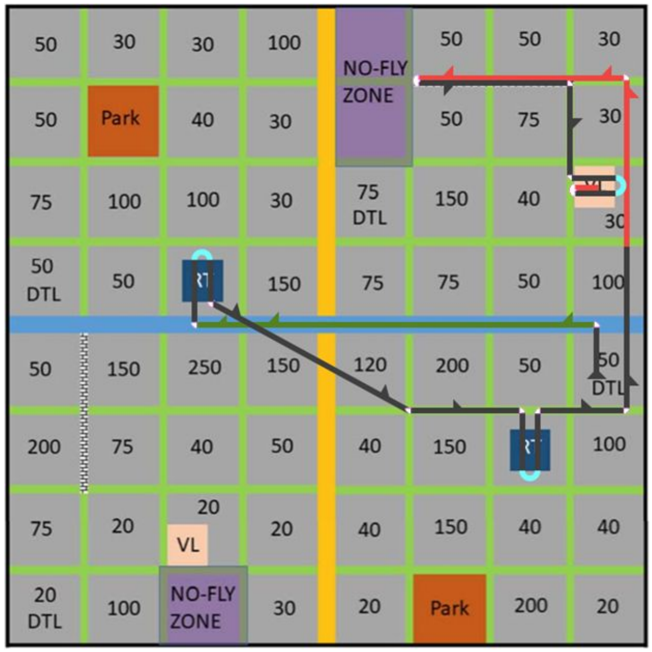


**Figure 17. Flight Path 2.**

## Recovery

Preparation for recovery begins once the UAV is launched. The recovery net is erected using four poles, similar to the net shown in Figure 18 (during the second flight, the recovery team must disassemble the net and move to the vacant lot in Q III before re-erecting the net). After the UAV is recovered, the MO conducts an inspection for any damage incurred during flight. Lastly, if the Galaide's second survey is complete, the MO will inspect the integrity of the data. Any lapses in data from a malfunction or human error can be addressed by a third survey.

**Figure 18. The recovery net. Reprinted from Baseball Training Nets by PowerNet (n.d.).**

### 3.1.3 Post-Mission

Once the UAV is recovered and the data analyst approves of the data, the MO will be in charge of storing the Galaide in the UAV rack and securing support equipment in the trailer. The personnel will debrief to summarize the flight and analyze errors to determine the root causes. They will also inform the appropriate authority (i.e. ATC, mayor, public) of the completion of the mission. The personnel will transport the equipment back to the company. The data gathered from the mission will be analyzed by the Data Analyst through Pix4D, a data analyzing software. The photogrammetry and multispectral imagery processing features will be used to render plant data. In this software, several models are created to display topography and heights. The Digital Surface Model and orthomosaic model will derive a map of the city and display the plants in different colors. Geotiff will be used for georeferencing, which allows ground distances and areas to be measured. The final map of the surveyed areas will be in the orthomosaic model where the city and plants will be viewed aerially and can be seen in detail. The data will then go through several procedures prior to sending it off to the city: First, it will be screened to check for any issues or inconsistencies; then, data will be compared with previous data to ascertain any differences and to possibly discover new developments or illnesses in plants. This can be done by using the i-Tree database that stores old or updated data on plants in urban cities. Visual obfuscation techniques will be conducted in order to protect the privacy of others and avoid any potential lawsuits. The data will be summarized by the Data Analyst in order to accommodate the city and for data to be easily readable. The finalized data, which includes the orthomosaics, data summaries, and the censored raw data, will be sent to the city for officials to assess plants that are in need of treatment.

### 3.1.4 Emergency Situation

During surveys, the MO must maintain constant communication with ATC, city officials, and the police, should the city call for an emergency situation for immediate grounding of all UAVs. The city requires that the company lands the UAV within 15 minutes after they are notified; thus, the MO must immediately inform the Safety Pilot to prepare for an emergency landing. During emergencies, the ground station decides whether the Galaide will land automatically or manually. Predetermined recovery zones were decided based on the Galaide's altitude and proximity to DTLs, vacant lots, and parks in different locations. Figure 19 illustrates which vacant lot, DTL, or park the UAV will be programmed to automatically land in during emergencies—there are 8 landing zones in the city, with 2 per quadrant, and each landing zone is designated a specific colored section in the quadrant. The colors in Figure 19 correspond to these landing zones; e.g., if the Galaide is in the blue zone, it will land in the DTL in Q I. If the situation prevents the Galaide from reaching the predetermined recovery zone or the city requires manual landing, then the safety pilot must take manual control of the UAV and land in the nearest accessible park, vacant lot, or DTL. Otherwise, ground station must notify the Pixhawk autopilot of the emergency situation for the Galaide to find the closest landing zone. Normal emergency landing procedures take place when the UAV finds and reaches a landing zone. The emergency light and buzzer system alerts any civilians beneath the Galaide with an alarm and flashing lights on both wings (See Section 3.2.5).

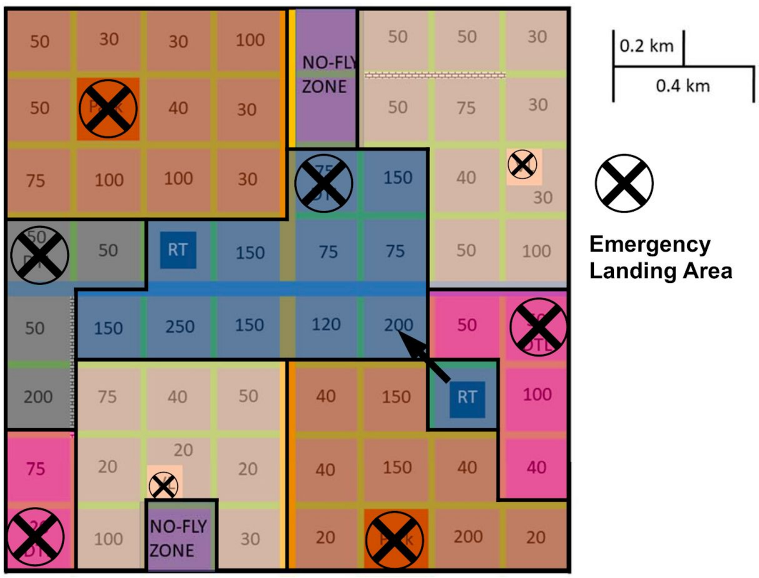


**Figure 19. The Galaide's landing zones during emergency situations.**

### *3.1.5 Temporary No-Fly Zone*

Although the company's survey dates will be based primarily on the city's preference, the MO will still keep communication with ATC and city officials before and during the flight, should the city call for a temporary no-fly zone at any point within the mission. The MO relays this information to the Safety Pilot, who then takes over manual control to complete the mission (see Section 3.2.4 for BLOS control).

The temporary no-fly zones that the city provides will prevent the UAV from completing its normal survey path. The no-fly zones block off access to the road with building vegetation and the northeastern vacant lot from any flight path, and because of this, the UAV *must* fly above the 100 m building to access the road with building vegetation without flying beyond the city's test area. Because the imposition of temporary no-fly zones may occur at any time during the mission, the flight plans were created to avoid these areas, regardless of whether the city called for a temporary no-fly zone. The Galaide will never cross any permanent or temporary flight zones. Although accounting for the temporary no-fly zone in all flights forces the Galaide to fly over the 100 m building in Quadrant 1 to access certain survey areas, a two-flight survey limits altitude changes that may increase power consumption.

In real emergencies, however, the team cannot predict where a temporary no-fly zone will occur and thus cannot prepare a modified flight plan in advance. During missions, the MO's communication with ATC, the police, and city officials overseeing the pilot program is crucial because of the risk of such cases. The MO must tell the Safety Pilot to take over manual control to complete the mission without flying over any no-fly zones or emergency land if the Galaide *is* in the no-fly zone.

## 3.2 Mission Requirements

### *3.2.1 Launch and Recovery*

Since the team chose to utilize a catapult for the launch method, the team will have its purchased catapult system on standby. The MO will conduct an inspection of the functionality of the UAS. Once the inspection is completed and launch is authorized, the catapult will be set up. The catapult's length at 2.5 m follows the guidelines of launching from a 3 m by 3 m area. The MO will retract the bungee within the catapult and set it in place. Then, the UAV will be placed onto the catapult and have its systems (such as cameras, sensors, lights, etc.) initiated. Once the systems are confirmed to be operational, the MO will launch the UAV according to the Feiyu Catapult manual.

The team decided to utilize the net method for the UAV's recovery. During the mission, a pre-made net apparatus made using aluminum poles and a nylon net will be secured in place prior to the final area survey. As the UAV finishes its last survey, it will head towards the landing area. Once the UAV descends to 1.5 m, its propeller will stop and allow the UAV to glide into the two meter wide and three meter tall net to complete the recovery process (for further explanation on the preparation for launch and recovery, see Section 3.1.1).

### *3.2.2 Guidance without GPS*

Throughout the survey, the Trackimo Tracker can determine whether the UAV has traveled beyond the geofencing boundary, and adjust its position accordingly. The UAV's primary positioning system uses the GPS sensor offered in the Detailed Background Document, supported by GPS tracking with the Trackimo Tracker and Pixhawk 4 autopilot, to accurately determine its position within the city. As the GPS sensor and Pixhawk update at a rate of 10Hz (“Pixhawk”, n.d.), they are faster than the Trackimo’s 0.017Hz update rate (“Trackimo,” n.d.) and will consequently act as the Galaide’s primary positioning system. Each minute, the Trackimo will run an auxiliary “check” on the two sensors: if the Operational Pilot notices the sensors produce different position data from interference by the urban canyon phenomenon or if GPS sensing fails altogether, then the UAS will rely on the Trackimo's positioning by cell and RSSI to approximate location from cell tower and Wi-Fi signal triangulation. Thus, if GPS and one other method of positioning fail or suffer from interference, the Trackimo falls back on its final method of positioning, supported by SLAM navigation, which, using the gimbal and TeraRanger Evo 600Hz attached to the survey camera, measures several data points that can then be used to determine when the UAV has passed a block (e.g., LiDAR senses a building wall along its path then abruptly senses nothing). Finally, if all three of the positioning methods fail, then the Galaide will execute an emergency landing.

It is also possible to use visual navigation to navigate without GPS. The visual odometry and image registration would be used to predict navigation data similar to a GPS (Krajník, Nitsche, Pedre, Reucil, & Mejail, 2012). This would be an ideal option because it does not require any major additional payload to the Galaide (Krajník et al., 2012). Visual navigation is even easier to execute in urban environments because of the abundance of structured and recognizable patterns as compared to rural areas (Krajník et al., 2012). This works with the assumption that geofencing data is provided by the city for reference. To speed up the processing time to determine position, multiple filter algorithms may be applied to quickly distinguish salient features from the visual data (Krajn et al., 2012). Multiple algorithms exist (Conte & Doherty, 2008; Krajn et al., 2012); thus the company could decide the most appropriate one to use based on future experimentation results.

The Galaide’s position is transmitted to the Operational Pilot through two data transceivers on its wingtips. These transceivers operate on a limited range along the 900 mHz frequency band to limit signal interference and employ the FHSS method to further prevent signal interference of telemetry data. However, while the primary transceiver operates up to 1.6 km when the UAV is within LOS, the urban environment limits the range over which signals can be sent at 0.6 km. Thus, ground control will use a 900 MHz YAGI-Directional Antenna to boost the communication range by approximately 300% to 2.4 km, and using the AntennaTracker firmware from ArduPilot, a separate PixHawk 4 will control the antenna pan/tilt to track and follow the UAV's position to further increase range.

### *3.2.3 Obstacle Avoidance*

Several sensors work in tandem on the Galaide to sense and avoid unknown stationary or moving obstacles and noncooperative UAVs. The UAS first ensures that it does not travel beyond its flight path (and thus into any buildings, people, or vegetation) with the Trackimo Tracker, which allows geofencing to be set along the predetermined flight path and periodically checks if the UAV crosses the set boundaries. However, because the Trackimo has a less-than-ideal update rate at one check per minute, the UAV is continuously moving, and many unknown moving variables exist within the urban environment, the UAS requires further methods of detecting obstacles. Consequently, two LiDAR sensors were included on top of the UAV to sense for both stationary and moving obstacles to support the Trackimo's geofencing (See Figure 4). Primary obstacle avoidance uses the TeraRanger Evo 60m; although its horizontal field of view is limited to a 2° range, its sensing capabilities of up to 60 m ("TeraRanger Evo Long Range," n.d.) compensate for moving obstacles and its restricted field of view. The sensor provides a scan of a 2 m by 2 m square at 60 m ahead of the UAV, and its range beyond the 1 m requirement accounts for any limitations caused by interference from direct sunlight ("Test," n.d.). This TeraRanger is positioned to face directly ahead  of the UAV, but if it fails to detect an obstacle or should a new obstacle not be scanned at 60 m appear, a TeraRanger 600Hz, positioned directly below the first, is used as a secondary system. Though it is only capable of sensing up to 8 m, the TeraRanger has a 600Hz update rate to more quickly sense a missed obstacle (Object Detection," n.d.). Thus, the Galaide will always remain at least 1 m away from any stationary or moving object as the sensors detect at least 8 m ahead, and the PixHawk will allow it to automatically turn, ascend, or descend as necessary. In the event both TeraRanger sensors fail to sense an obstacle, the Safety Pilot continuously monitors the Galaide's flight through its navigational camera and can take control through an onboard transceiver set to manually avoid obstacles. The Galaide's third LiDAR sensor, attached to the surveying camera, will rotate to record data on the obstacle to be incorporated into the geofencing data set. Lastly, the Galaide senses and communicates with other cooperative UAVs through the onboard uAvionix ping20S transponder. Through the transponder, the UAV receives and sends signals to other Mode S transponders on cooperative UAVs, as well as to interrogations by Air Traffic Control (ATC).

### 3.2.4 Beyond Line of Sight

Although the Galaide must operate BLOS for most of the mission, the Safety Pilot continuously monitors the Galaide's flight through the navigational camera. The camera feed is streamed back to the pilot's laptop through the onboard 900 MHz Video System antenna to the ground-based RX antenna and, should that system fail, the feed is streamed through a secondary 5.8 GHz video system. Neither radio is capable of communicating at the maximum possible distance to the UAV (2.26 km in opposite corners of the city), so the systems are supported by a YAGI-directional antenna and patch antenna, respectively, that track the UAV and boost the radio signal ranges. A PixHawk at ground station allows the Antenna Pan/Tilt to follow the Galaide as well, "significantly improving the range" of signals ("AntennaTracker," n.d.). Thus, the Safety Pilot is allowed a first-person view of the Galaide's flight and can see when it encounters an emergency (e.g., damage to the UAV or system malfunction) and can manually control it at any point of the mission. Through the onboard multiplexer, the Safety Pilot can switch between autonomous and manual flight and control the UAV with the Warthog joystick. The pilot will also be notified by the Safe2Ditch software when the emergency system is triggered. Should the Galaide require manual control (for instance, due to a failed autopilot), the UAV is equipped with two control transceivers on the wingtips to receive commands from the Safety Pilot through the HOTAS joystick and Toughbook. The antenna setup of this communication system is explained in Section 3.2.2. Finally, 4G communication will also act as another redundant system.

When the Galaide is under normal cruising or surveying conditions, it is controlled autonomously by the onboard PixHawk autopilot and the ArduPilot software. Using data from the UAV's sensor components, alongside the PixHawk's internal sensors, ArduPilot maintains the Galaide's directional heading, altitude, and speed through the elevons and motor, and performs turns, ascents, and descents when necessary. Furthermore, the software allows the Galaide to avoid known and unknown obstacles using data from the Trackimo and proximity sensors.

### 3.2.5 Emergency Landings

When the Galaide's Safe2Ditch system detects an anomalous condition, such as low battery levels or loss of control, it will activate its emergency system. The emergency system will alert the surrounding environment through an alarm buzzer which produces sounds at 120 dB, comparable to the volume of ambulance sirens (NIHMedlinePlus, 2015), and flashing red lights below its vibrant-colored wings to increase visibility. Internally, the Safe2Ditch crash management system will determine whether to ascend or descend depending on current battery levels and the distance from the closest vacant lot. The Galaide will prioritize emergency landing in the established landing areas on top of buildings and vacant lots, but in the case neither is in close proximity or the vehicle cannot physically reach it, the Safe2Ditch system will analyze the LiDAR and camera data to select a place that is clear of people and property to land. As explained in the design process, parachute deployments require no landing gear on the ground, making them ideal for emergency landing. However, because parachutes lack accuracy when deployed at a high altitude (Abinaya et al., 2017), the UAV will glide towards the landing area before it deploys the parachute. Once the parachute activates, the rate of descent will decrease, giving nearby pedestrians time react to the visual and audio warning from the lights and buzzers and move away from danger. Both the lights and buzzers will flash intermittently once the parachute is deployed, and they will continue to do so until the UAV is retrieved. In the case that the Galaide is surveying a wall area, it would ascend to cope with the altitude requirement of the parachute and attempt to land on a rooftop. Given the size of the parachute, pedestrians will be able to see the UAV as it descends, making the parachute and UAV themselves another visual cue in an emergency landing. According to Fruity Chutes Parachute Descent Rate Calculator, the UAV would be landing at 4.23 m/s, only 15% of the kinetic energy at cruising speed ("Iris," n.d.). The propeller would not be powered during the glide, and since the rotor on the vehicle is enclosed, the propeller blade would not be able to strike any objects. All parts of the landing will be autonomous, and when the emergency system activates, the UAV will send a notification of its location for retrieval.

## 3.3 Survey Considerations

### Design/Mission Strategy

As the cameras are able to support a 75% overlay, it was determined that the Galaide will fly at speeds of 11 m/s throughout the mission. While surveying the walled areas, the Galaide's survey cameras will face outwards and the UAV will keep a height of three meters above the middle of the roads allowing both sides of the road to be surveyed at the same time. During ground surveying, one survey camera will face downward while the Galaide surveys the areas in a serpentine path at 70 m above the ground. One mission involves two flights (further explained in Sections 2.4 and 3.1.2); the first flight surveys low-altitude areas and the second surveys higher-altitude areas. Separating the mission into two flights limits the number of ascents and descents performed by the UAV and, consequently, reduces battery consumption needed for those maneuvers. Furthermore, these flight plans were designed to account for both the permanent and the given temporary no-fly zones for all flights, eliminating the possible risk of logistical errors from sudden flight changes if the temporary no-fly zone is called during flight.

Two Survey3W cameras allow the UAV to examine walled roads and roads with building vegetation in one flythrough per mission, eliminating the need to fly above the walled road, the longest survey area (1600 m), a second time to record the other side. Furthermore, the use of LiDAR proximity sensors, the GPS sensor, and preset geofencing allows the Galaide to safely fly above roads to limit ascents and above buildings to reduce flight time, minimizing battery consumption during missions. Additionally, redundant systems in proximity sensors, positioning sensors, batteries, C3 components, and visual/auditory warnings also make flying-wings a safe and viable airframe for the city, despite its inability to hover or perform VTOL. Lastly, the inclusion of three TeraRangers allows the UAV to stay within road boundaries, and the inclusion of secondary transceivers and directional antennas makes flight in any part of the city possible by increasing signal range.

### Benefits of the Galaide

The Galaide provides the city with a surveying system that is safe, cost-efficient, and versatile, creating a competitive bid while increasing profit to the company. The company offers data-processing services and air quality sensors in addition to plant health surveys; thus, the company provides a comprehensive data package for the city that is useful in evaluating not only the plant health, but also the effectiveness of using plants to curb urban pollution. As detailed in Section 4.1.1, the total cost, including profit, needed to operate the Galaide is $32,217.69, which is approximately 16% of the total budget of $200,000 given for the bid. This low cost, paired with Galaide's exceptional safety features, high-quality data package that reduces end user costs in analysis, and additional environmental monitoring data, make the company a clear choice for urban plant health surveys. Because of this, the additional services make the Galaide an increasingly competitive bid, raising the possibility that the company’s bid is chosen, and, more importantly, that the company receives the 15% profit.

### Compare and Contrast

There are two common types of ground surveying methods used to assess the health of urban trees: windshield surveys and foot surveys (Swiecki & Bernhardt, n.d.). Both surveys evaluate tree health based on visual observations, but differ in that windshield surveys are done by an arborist who is driven around during the survey while walking surveys are done on foot.

Although both methods are well established in arboriculture, they are time-consuming, expensive, and prone to error (Rooney, Ryan, Bloniarz, & Kane, 2005).

Few cities also survey their forests by examining the tree canopy of infected trees. This method, however, is able to survey only 12 trees per hour at a price of $125.00 per tree using a bucket truck (Staley, n.d). The cost per hour amounts to $1500.00. On top of costing more, this type of survey in a city is ineffective due to the amount of time needed and the use of heavy equipment which can affect city traffic, thus costing the city more money through productive time.

The Galaide will be able to provide a faster, less expensive, and more reliable surveying service to the city compared to the two current methods. A study done in 2005 tested whether windshield surveys can be a reliable replacement for walking surveys because it would allow for a faster observational period (Rooney, et al., 2005). The survey was conducted on 217 km of town-maintained roads and took 72.5 hours over 20 nonconsecutive days to complete, which averages to a survey rate of about 0.83 m/s. This is inferior to the Galaide's ability to theoretically survey at speeds two orders of magnitude greater at 11 m/s without any discrepancies.

The Galaide is also a more cost-efficient alternative to surveying missions. Walking surveys tend to be the most costly surveying method, with the New England contractors charging approximately $5.00 per tree surveyed in a study (Rooney et al., 2005). The windshield survey in the study surveyed around 17,500 trees, which would cost approximately $87,500.00 if done through walking survey (Rooney et al., 2005). To meet the mission requirements of eight surveying trips, the walking survey would cost the city about $700,000.00 per year. In comparison, if the Galaide surveyed the same 217 km of road eight times using batteries with sufficient amp hours, the operating costs would sum to roughly $13,200.00; this cost is only 2% of the walking survey and includes the data analysis service that the study did not provide. The study done to compare the other two methods found that the windshield surveyors were only able to locate 58% of the 94 trees rated 7-12 on the hazardous rating found during the walking survey (Rooney et al., 2005). Both windshield and walking surveys are conducted over a long period of time, during which the plant health could change dramatically, whereas the Galaide captures the conditions of all plants within one day.

## 3.4 Regulations and Additional Safety

The UAV will operate outside of the FAA Regulations §107.31, §107.33, and §107.39 in order to meet the requirements of the mission. Regulation §107.31 states that the UAV must always operate within visual-line-of-sight (VLOS); however, the challenge requires the Galaide to operate beyond-visual-line-of-sight (BVLOS). In order to account for operating BVLOS, the UAV will have redundant safety features such as multiple cameras and obstacle avoidance, as well as a 4G system should the Safety Pilot need to take control. FAA Regulation §107.33 states that the UAV must remain close enough to the person controlling the sUAS so that it can be seen unaided by any device other than corrective lenses. Due to the route of the mission, however, buildings that are taller than the survey altitude will block the pilot's view of the UAV. At any moment during the mission, should the UAV operate BVLOS, the camera will be streaming live footage of the UAV's point of view directly to the ground station for the Safety Pilot to monitor. The route also requires the UAV to survey over populated areas causing the UAV to have to fly over people which is outside of FAA Regulation §107.39. Because this regulation is not met in urban operation, the UAV's speed is reduced to 11 m/s, lowering dangers of direct impact. The UAV is also equipped with an emergency landing procedure and made of EPP foam, minimizing the risk of injury should any complication occur.

Personnel will complete a preflight inspection, in compliance with Regulation §107.49. Although the UAV will operate at altitudes above 400 feet, which is outside Class G Airspace, the UAV will fly within 400 ft of a structure which satisfies Regulation §107.51. The UAV will also be able to land using a parachute, which would lower the terminal velocity of UAV in free fall. The UAV will also operate within the maximum speed of 100 mph, making it fully compliant with Regulation §107.51.

The UAV will incorporate redundant safety features and procedures for emergency scenarios. The UAV will have two batteries: one main battery to power the propeller motor and a secondary battery to power the visual and audio warning systems, emergency landing procedures, and sensors. The UAV will contain three LiDAR sensors: two sensors primarily for obstacle avoidance and navigation, while the third sensor will be used to assist in maintaining altitude should the GPS sensor fail. The UAV will also contain a parachute that will deploy in the event that the UAV stalls mid-flight, which will decrease falling speed. Section 3.1.5 outlines the emergency landing procedure that will be programmed to guide the UAV to safety.

# 4. Document the Business Case

## 4.1 Budget Requirements

### 4.1.1 Budget Summary

**Table 20. The Galaide's total cost.**

| Line Item | | Cost |
|---|---|---|
| **Fixed Costs** | | |
| | Airframe | **$387.56** |
| | Sensor | **$2,263.19** |
| | Command, Control, Communication | **$4,899.35** |
| | Support Equipment | **$6,806.96** |
| **Total Fixed Costs** | | **$14,357.06** |
| Operating Cost (Variable costs, annual) | | |
| | Total Personnel Costs | **$4,040.00** |
| | Total Electricity Costs | **$0.09** |
| | Total Subscription Costs | **$4,949.00** |
| **Total Yearly Operating Costs (Variable cost)** | | **$8,989.09** |
| **Contingency (20%)** | | **$4,669.23** |
| **Project Budget (Before Profit)** | | **$28,015.38** |
| **Profit (15%)** | | **$4,202.31** |
| **Total Budget** | | **$32,217.69** |

### 4.1.2 Operating Costs

The $8,989.09 yearly operating costs for eight survey missions consist of labor, electricity, and annual subscription fees. The labor roles are comprised of the Operational Pilot, Maintenance Officer, Safety Pilot, and Data Analyst (see Section 2.2.5). The Data Analyst will be paid for a full day (8 hours) when the surveys are conducted because the data must be semi-manually processed. All other personnel are paid according to the hours actually worked. Assuming the survey, including equipment transportation, set-up, and breakdown, takes one hour to complete and includes the eight hours it would take for the data to be processed, the final personnel cost amounts to a total of $505.00 per mission.

The Galaide does not rely on liquid fuel for its survey tasks, so energy costs will be based on the amount of electricity, in kilowatt hours (kWh), needed to fully charge the batteries. The average cost of electricity in the United States is $0.12/kWh ("Electricity", 2018), and one survey mission (two trips) will take approximately 26 minutes and 28 seconds to complete, so the cost of electricity for the UAV per mission is approximately $0.0037. The cost for recharging the ground station was calculated as well. The ground station is a Panasonic Toughbook that will consume approximately .0603 kWh for 8 hours of usage, costing $0.0072 per mission. It will power the USB modem, transceivers, antennas, through wired connection and operate the command and data analysis software. Both the component battery and motor battery will retain approximately 43% of their power supply after a complete survey mission, so recharges will be done before each mission. Electricity therefore costs only $0.01 per mission to power and charge the UAS.

The subscription cost includes the subscriptions for the Trackimo Drone Tracker, 4G data plan, and Pix4D's data analysis software. The Trackimo Drone Tracker has a $5.00 yearly fee as a service cost. The data plan includes two lines connected to 4G LTE for a total monthly cost of $120.00. Since the survey missions occur year-round, the annual cost of the data plan amounts to $1440.00. The majority of the annual subscription costs comes from Pix4D, which has an annual subscription cost of $3,504.00. This includes uploading data to a cloud, support/updates, and floating licenses for the Data Analyst. Thus, subscriptions would cost $4,949.00 annually.

In total, the cost of a single mission sums to $505.01, including the personnel costs for one day and fuel costs for one recharge (subscription costs are not included because they are annual expenses). Missions will be conducted twice each season, for a total of eight missions annually. In one year, all personnel will work for eight hours, except the data analyst, who will work for 64 hours. The cost of labor amounts to $4,040.00 given that all procedures run smoothly during each mission. The electricity cost for ground control and batteries is $0.011 per mission, thus amounting to an annual cost of electricity of $0.09. In total, operations within a year will cost $8,989.09, including the annual personnel, fuel, and subscription costs.

The selection of the flying wing airframe was based on the need to survey all five survey areas. The team chose to survey all five areas in the State challenge; however, the inclusion of no-fly zones prompted modifications to the original flight path: in the initial plan, the UAV flew above the walled roads twice to survey each side individually. The addition of the no-fly zones forced the team to lengthen the flight plan, but because the walled road is one of the longest survey areas, flying above it twice would be costly. The team chose to include another camera that allows the walled road and buildings with vegetation to be surveyed at once instead. Furthermore, because the no-fly zones may require increased maneuverability to reach survey areas in the city, the team added thrust vectoring capabilities to the propeller to limit the length, and ultimately cost, of the flight path. The Galaide's reliance on batteries to power the propulsion and other elements ensures that any additional time needed to complete the mission will not hinder electricity costs because of its insignificant rate. Electricity costs are further reduced because the Galaide features EPP foam, making it lightweight. By considering factors such as airframe, electricity, and material, the Galaide exhibits strong endurance and faster speeds reducing the time of the mission and the cost of electricity and personnel.

### *4.1.3 Profit Analysis*

The team designed the Galaide and its services as a competitive bid for the city's RFP. In selecting components, the team sought to find three to five options for each design element, ultimately choosing that which was optimal for the urban environment in terms of safety, weight, or cost. In some cases, the cheapest option did not necessarily mean the best. For example, the 4G kit required both an onboard companion computer and incurred a monthly cost for the 4G data plan, but 4G communication would be the safest method for communication in radio interference caused by an urban canyon. The team focused on maximizing profit while ensuring the bid was proportional to the UAV's capabilities.

The company also ensures profit by offering a practical bid and surveying method to the city with additional services. First, the Galaide's fixed-wing design reduces operation time, which decreases personnel and recharging costs. Second, it has multiple safety components that are ideal for urban environments. Ultimately, the company's bid lay on a design that maximized safety while remaining a low-cost, high-performance UAV. However, the major factor in maximizing profit was the inclusion of additional services. This creates more opportunities in the expansion of urban surveying: the addition of pollution sensors and a data analysis software increases fixed and variable costs, respectively, and though these services increase budget costs, they yield higher profits for the company and offer a quality package to the city that ultimately saves them time and money.

That profit will not be affected if the UAV cannot fly on a given day. As per the suggestion by the team's mentor, Dr. Duenas, the total budget includes a 20% contingency cost that acts as insurance for any unexpected expenses, such as a manufacturing error that requires additional purchases or data corruption that will require one more survey flight. Before profit, that 20% sums to $4,669.23, which can theoretically cover the cost of nine canceled flights.

Regardless, the company has several measures in place to prevent a canceled flight from occurring. As detailed in Section 3.1.1 and 3.1.2, the company and city must communicate to schedule the eight two-week periods before the first survey of each year, and the company is given flexibility in surveying within each two-week period. Then, one week before the flight, the company must check for conditions like weather that may hinder flight, and the day prior to the flight, the MO must check for weather conditions and emergencies before beginning preparations for flight.

### 4.2 Cost/Benefits Analysis and Justification

The company's proposal offers a competitive bid to the the city's RFP by providing an efficient, profitable, and, most importantly, safe system to measure and analyze plant health in the urban environment. The company's proposal, the Galaide, serves as both a product and service— the data provided from each mission addresses not only the city's goal to measure plant health, but their ultimate goal to curb pollution and its effects.

The Galaide's design and components make it a cost-effective solution to the city's RFP, coming in at less than 20% of the maximum project budget of $200,000. The airframe primarily uses low-density EPP foam to reduce weight. As a lightweight fixed-wing UAV, the Galaide can perform with a lower thrust-to-weight ratio and, as a result, a cheaper propulsion system: for instance, the Galaide's $7 Master Airscrew Scimitar Propeller provides sufficient thrust for forward movement and stable flight, whereas multirotors would require four or more propeller, each with their own motor. The low weight also allows the Galaide to operate with batteries— motors are significantly lighter and cost significantly less than engines but provide ample thrust nonetheless. Although batteries are not as energy-dense as gasoline, flying-wings consume less energy with a higher efficiency than other airframe types.

The UAV's system elements were also chosen in consideration of cost-effectiveness. While not all of the UAS's components were the cheapest offered, the team sought to ensure that each component added value to the system as a whole. For example, while the SlamTec RPLIDAR A1 is capable of 360° obstacle avoidance and is $115, the team's ultimate sensor choice for obstacle avoidance, two TeraRanger Evos at $537.44, boasted lower weights, higher ranges and update rates, and were optimized for outdoor use. The Fruity Chute parachute was lightweight, and the 4G communication, although costing $1,440 annually, provides a reliable auxiliary system for C3.

The practicality and importance of its design lies in the company's primary focus on safety. Each of the Galaide's subsystems incorporate several redundant systems for improved safety. If the UAV cannot determine its position by GPS, it can do so by triangulating cell tower and Wi-Fi signals, SLAM navigation, or by visual navigation; the navigational camera sends the feed on a 900 MHz video system, but has a secondary 5.8 GHz video system and 4G; the payload battery can last for two missions without charge, but if it malfunctions, the output of the motor battery can be stepped down, among others. Despite the increase in cost, redundancy allows the Galaide to complete the mission with minimal risk to people, the city, and the UAV.

The major differentiator with the Galaide's competitive bid, however, is the additional services it will provide to the city. After each mission, the Data Analyst will process the data into a package consisting of a summary of the survey, an orthomosaic map, digital elevation map, and a multispectral map. This provides the city with easily understandable and ample information to determine the health of its plants through tree height, IR reflectance (NDVI), and leaf shape. This benefit poses considerable savings in personnel costs for the city, as the technical expertise required to use Galaide's data is within the capability of technicians without the need for highly paid data analysts. If geotagging fails due to the urban canyon phenomenon, then the point cloud feature in the Pix4D software is able to stitch images together to make a map using noticeable patterns (e.g. signs, trees, etc.), ensuring that data is processed properly regardless of GPS signals.

Furthermore, as the city's ultimate goal is to curb the effects of pollution, the use of pollutant sensors (VOC, $NO_2$, $PM_{2.5}$) on the Galaide provides the city empirical evidence to measure and document the success of its efforts. A partial map showing the distribution of pollutants in the city could be made from the data collected through the air quality sensors. The sensors offer high value data to the city, but are inexpensive and lightweight components.

Lastly, the Galaide's flexibility allows for other applications besides surveying plant health. Other city surveys for construction or topography can be easily completed by the UAV's two survey cameras. That flexibility, alongside the services offered by the Galaide, present an incomparable solution to the city's RFP. By focusing on safety and efficiency, saving the city money and time from hiring a data analyst themselves, allowing the city to quantify their efforts to curb pollution, and opening the potential for use beyond vegetation surveys, the Galaide acts as a indispensable benefit to the city.

# 5. Conclusion

The design solution, the Galaide, is a time-saving and cost-effective autonomous flying wing vehicle designed for safety and versatility. It is also able to provide comprehensive data on the plant health of the city and its impact on air pollution within the urban environment. The Galaide uses a catapult launch to achieve the required initial velocity for takeoff and maintains a cruising speed of 11 m/s, allowing the Galaide to survey the required areas in under 30 minutes. The Galaide can navigate using LiDAR and a GPS/GSM/Wi-Fi/BT tracker in addition to two GPS sensors onboard, making it robust enough to operate in an urban environment. It is capable of operating autonomously in any situation, including emergency landings with a built-in parachute; it could also be manually overridden for control BLOS and contains a redundant transceiver set as well as Wi-Fi/4G capabilities to combat possible interferences for urban surveys.

The Galaide collects quality plant health data using both a LiDAR sensor and a multispectral camera to collect images at a resolution of 4.94-33.2 mm/px, capable of detecting leaf shapes and its abnormalities. The battery life of over one hour allows the Galaide to complete up to two missions on one charge cycle. The Galaide's motor battery can be stepped down to power the electronics in case of emergencies, and the Safe2Ditch software would manage the overall condition of the UAV as well as determine appropriate landing areas. The Galaide incorporates three LiDAR sensors to anticipate and avoid obstacles from as far as 60 m. The data package provided through YETI includes survey summaries, digital elevation models, and orthomosaic maps that are easily understandable and comparable for change in plant height and color over time.

The UAS opens the possibility for more benefits to both the city and company. Through redundancy in the Galaide's battery, C3, positioning, avoidance, and navigation systems, safety remains the ultimate priority of the UAV's design. The significance of redundancy becomes much more undeniable in the circumstances of the city: flying above people and near buildings BLOS could pose a major risk to the UAV and, more importantly, citizens. Alongside the design's ability to measure pollutants in the air, that safety also creates the potential for further expansion within the city and other projects beyond it. By providing a service that allows the city to quantify the effects of its efforts to curb pollution, the Galaide is vital to the wellbeing of the city's residents: the Galaide helps control a problem whose implications only continue to plague the health of people, wildlife, and the world.

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