

Unmanned Aerial Vehicle Competition

by

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Abstract—The UAV Competition capstone represents the very first attempt to design a system for entry into the Association for Unmanned Vehicle Systems International (AUVSI) Student Unmanned Aerial System (SUAS) Competition by Naval Academy Midshipmen. The four main design tasks of the SUAS competition are: (1) Autonomous take-off and landing, (2) Autonomous waypoint navigation, (3) Acquisition, identification, and localization of ground-based targets, and (4) Accurate ballistic payload deployment. These design tasks led to a logical division of work among team members, where separate subsystems were developed and tested both independently and concurrently to ensure interoperability. These subsystems together form the final result of the first Midshipmen-designed UAS for entry into the SUAS competition.

INTRODUCTION

Mission Requirements Analysis

The 2016 AUVSI Student Unmanned Aerial Systems (SUAS) competition consists of two primary and eight secondary tasks stated by parameters under the SUAS rules. Additionally, all primary tasks need to be fulfilled first before doing any of the secondary tasks. In line with this, our team has concentrated our efforts to strategies that will meet the primary mission requirements first. The primary tasks such as autonomous takeoff, flight, landing and waypoint navigation were identified as our mainly goals. After achieving threshold parameters of the primary tasks, the team then started to work on some of the secondary tasks which include automatic detection, localization, and detection of targets and airdrop. These systems, as well as primary tasks have been tested regularly during flight tests using simulations from Mission Planner and XPlane 10. The mission tasks were analyzed as shown in Table 1 and Table 2

Primary Tasks

Task	Parameter	Threshold	Objective
1	Autonomous Takeoff	100%	100%
	Autonomous Flight	100%	100%
	Waypoint Navigation	100%	100%

	GCS Display Items	100%	75%
	Autonomous Landing	100%	100%
2	Localization (each standard and QRC target)	100%	100%
	Classification (each standard target)	100%	100%
	Classification (QRC target)	100%	N/A
	Imagery (each target)		100%

Secondary Tasks

Task	Parameter	Threshold	Objective
	Automatic Localization (each target, standard and QRC)		100%
	Automatic Classification (each standard target)		100%
	Automatic Classification (each QRC target)		N/A
	False Alarm Rate (FAR) on Classification.		N/A
	Actionable Intelligence (any target)	100%	100%
	Imagery		100%
	Classification	100%	100%
	Payload Autonomy		100%

	In-flight re-tasking		N/A
	Autonomous Search		N/A
	Target Identification	100%	100%
	Release	100%	100%
	Drop Accuracy	100%	80%
	Bull's Eye Delivery		80%
	SRIC Download task		N/A
	SRIC Upload task		N/A
	Autonomous SRIC task		N/A
	Download & Display Server Info and Time	100%	N/A
	Download & Display Obstacles	100%	N/A
	Upload Target Details		N/A
	Stationary Obstacle Avoidance	100%	N/A
	Moving Obstacle Avoidance	100%	N/A
	Autonomous Search		N/A
	Secret message		N/A

*The table cells painted with green indicates that the team successfully performed the assigned task. The percentage inside each cell indicates the rate of success of accomplishing those mission tasks. The cells painted in red means that no threshold is available for that task.

Expected Performance

We expected to complete the primary competition tasks of autonomous takeoff, landing, flight, waypoint navigation, and search. We also expected to perform the secondary tasks of image processing, localization and classification, airdrop delivery, and network interoperability. In simulation we completed all the primary flight tasks. All the secondary tasks were completed during benchtop testing.

The extent of the completion of each task is addressed in the separate subsections relevant to those tasks.

Expected Risk and Mitigation

For any a project of this magnitude there are several inherent risks that needed to be addressed as soon as possible in order to avoid a catastrophic failure. The greatest risks associated with this project were blunt force trauma occurring from the plane hitting somebody during flight, losing an appendage due to the propeller spinning, and losing communication with the aircraft mid-flight from the ground control station. In order to mitigate these risks several steps were taken to ensure safety for all those involved. To avoid the blunt force trauma caused by the plane hitting somebody, our team will ensure everybody who is standing near the UAV's airspace will be wearing a hard hat as well as other PPE. Additionally, the ground control station will maintain positive flight control the whole time and will practice dropping the water bottle on practice targets in an attempt to minimize their chance for an errant drop. To avoid having somebody's finger or other body part cut off due to the propeller spinning the team will ensure anyone holding the UAV will be wearing gloves and nobody will put their hands near the propeller if it is spinning. In order to avoid losing communication with the aircraft during flight the team will program a warning to appear on the ground station if the aircraft is approaching the edge of its controllable range and then steer the plane back into a more controllable range.

Other minor or less-likely risks were associated with this project and the team took steps to mitigate these as well. These risks were a lack of time to complete the overall project, a software failure in the ground control station, exposure due to heat and the sun, and electrical fires and meltdowns. In order to lessen the likelihood of these risks the team ensured a proper work breakdown structure was created to keep all team members on track as well as everything was uploaded to Google Drive to prevent loss of code. Additionally, the team will wear bug spray, sunscreen, and hats all while remaining under the large tent that was purchased in order to minimize time spent in the sun during the hot month of June. In order to prevent electrical fires and meltdowns, the team bought battery bags to store batteries in, a fire extinguisher to eliminate any fires and a first aid kit to handle any small injuries that may occur during the competition.

OVERALL DESIGN

Objectives

Since the goals of this project are connected to those of the competition, it is necessary to go over its objectives. The Student Unmanned Aerial System (SUAS) Competition is aimed at stimulating and fostering interest in unmanned system technologies. The focus is on engaging students in systems engineering and creating feasible solutions to complex problems. There are primary and secondary tasks. Our team has focused on all primary tasks and almost all but the last of the secondary tasks.

The primary goals are the following:

- Autonomous takeoff/landing and flight
- Autonomous waypoint navigation
- Autonomous search

The secondary tasks are the following:

- Image processing
- Localization and classification (ADLC)
- Airdrop delivery
- Network interoperability
- Sense, Detect and Avoid (SDA) tasks for introduction to the National Airspace (NAS) integration challenge

The team also considered the following objectives regarding operations and management:

- Safe - A safe system is defined as one that poses minimal risk to the user and anyone nearby
- Reliable- A reliable system will consistently successfully complete its assigned task.
- Easy to Operate- Ensure the system is easy to train somebody completely removed from our project to operate the UAV at full capacity.
- Upgradeable - Ensure the system is always capable of having more features added and upgraded hardware.

Component Selection

The airframe subgroup had to select the airframe, servo and hinges for the drop box, and the RC transmitter and receiver. For the airframe we considered fixed wing, flying wing, and rotary wing aircraft. Rotary wing was eliminated because it did not have the range and flight time required to meet all the competition requirements, while both fixed and flying wing aircraft could. The flying wing was attractive because it had less moving parts, but fixed wing was ultimately chosen because it was inherently more stable. We chose the Senior Telemaster, a fixed wing RC aircraft, because of its proven reputation as a stable, easy to fly aircraft. Its ability to carry heavy loads without greatly degrading its unloaded flight characteristics makes it perfect for carrying all the systems associated with target acquisition part of the competition.

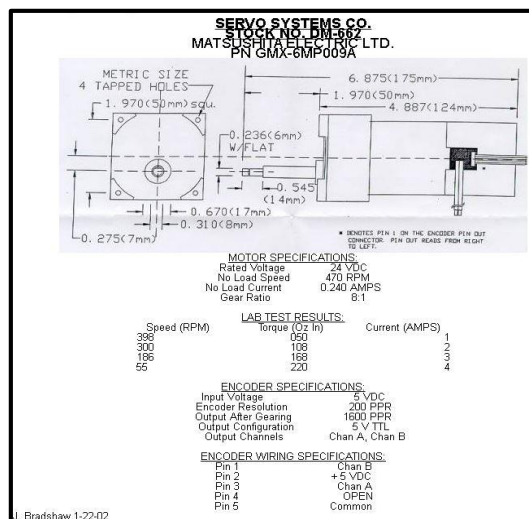
We selected the same servo and hinges that are used to control the rudder and ailerons of the Telemaster for the drop box. This simplifies the ordering process as well as maintenance. The aircraft servos have enough torque to hold the bomb bay doors closed while under load from the eight-ounce water bottle, and the aileron hinges and control wire make opening and closing the doors smooth. A DC motor would not have been appropriate for this task because it is not as easily controllable as a servo and has more of a range of motion than is necessary. We decided against using a solenoid to push the water bottle out of a retaining device because we did not want to leave the bomb bay open to the air. Adding a solenoid to the servo controlled bomb bay would unnecessarily complicate and weigh down the aircraft. For the RC transmitter/receiver pair we selected the Spektrum DX9, because it was the best money could buy. The nine channels cover all the required signal inputs for the systems on the aircraft. The receiver has “a built-in telemetry feature that gives you real-time information on things like your

model's battery voltage, signal quality, engine or motor temperature, airspeed, and altitude.” It also has a voice alert system that calls out “specific telemetry values that reach or exceed limits you define.”

The Autopilot subsystem had very few parts that needed to be selected in order to achieve autonomous flight. Modern day autopilots are all capable of following a flight plan designed on a Ground Control Station such as Mission Planner or QGroundControl. The 3DR Pixhawk was chosen as the autopilot for our project due to its small size, weight, and low cost. Compared to the HKPilot 2.7 autopilot which was one of the competitors for selection, the Pixhawk is a more powerful autopilot and the more user friendly. When compared against the Piccolo SL autopilot, another option that was considered, the Pixhawk is a less powerful autopilot, however it is significantly smaller in dimension and weight. The weight and size were the primary reasons for selecting this autopilot because no decisions were made without examining how the weight of the aircraft would be affected by adding a part to the airframe and this was the determining factor for any purchase made. Other purchases made by the autopilot team were the telemetry radios in order to maintain communication between the ground station and aircraft during flight.

The Image Processing Subsystem had to select a camera that can take a photo from high altitude of the aircraft and compatible with the selected gimbal but does not interrupt safety of the flight due to the weight and movement of the camera while mounted on the gimbal. The subsystem selected Flea3 5.0 MP due to the best resolution, size and weight of the available camera. Flea3 2.0MP has a worse resolution. Computar ½” 12-120mm f1.8 is too big to fit on the aircraft.

The Antenna Pointing subsystem necessitated several important design decisions, primarily concerning the motor choice to move the physical antenna and associated components. To accomplish this, specifications of antenna weight and maximum expected component weight/moment arm were used to calculate needed torque (in oz-in) from the motors. Additionally, performance considerations were taken into account to determine the maximum speed (in RPM) the motors would need to turn. Using these calculations, it was determined that the altitudinal control motor would need to have at least a maximum torque output of 69 oz-in, and both horizontal and altitudinal control motors would need to be able to turn at 4.3 RPM. From the selection of in-house motors at TSD, the base/motor pair used in the ES309 course with the Matsushita GMX-6MP009A 24VDC motor. For the altitudinal motor, we decided to use the in-house Brevet S58-260 12VDC geared motor. Below are the specification sheets found on the TSD website.





SMALL GEARED 12 VDC MOTOR

COMPANY: BREVEL

MODEL #: S58-260

VOLTS: 12 V

RUNNING CURRENT: .4 A

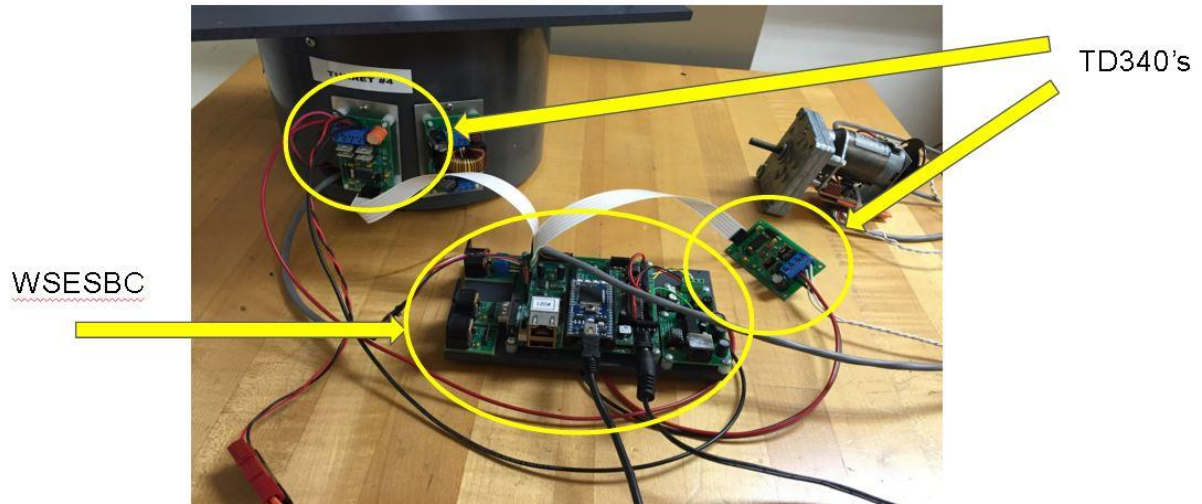
STARTING CURRENT: 1.0 A

RPM: 20

TORQUE: LIGHT

In addition to motor selection, a design decision for pointing the aircraft using MATLAB functions needed to be made. Considering the experience of some team members using East-North-Up coordinate conversion from GPS, the decision was made to use MATLAB's native 'geo2enu' function for angle calculations.

Finally, the powering and control of the motors requires additional components. Due to previous experience with the TD340 motor driver and Weapons and Systems Engineering Single-Board Computer (employing the mbed LPC1768 microcontroller), these components were selected and are shown below.



The Morph Chart below shows the part selection process for large-scale items such as the airframe, autopilot, and camera.

Function	Function Concepts		
Fly	Fixed Wing	Flying Wing	Rotary Wing
Communicate	Rotating Antenna	Stationary Antenna	IR
Locate Target	GPS	Radar	Visual
Remote Control	Competition Specified		
Identify Target	Flea3 5.0 MP (Sony ICX655/Matlab)	Flea3 2.0 MP (Sony ICX273/Matlab)	Computar ½" 12-120mm f1.8 10x Motorized Zoom
Drop Water Bottle	Servo Motor	Solenoid	DC Motor
Autonomously Land	3DR Pixhawk	Piccolo SL	HKPilot 2.7

Functional Block Diagram

Due to the magnitude of this project, a very extensive functional block diagram was developed to show how the systems interconnect. This diagram is located in the appendix and is color coded to show what components were on the airframe, the ground, and the antenna pointing station.

Airframe Subsystem (final design and results/testing for each)

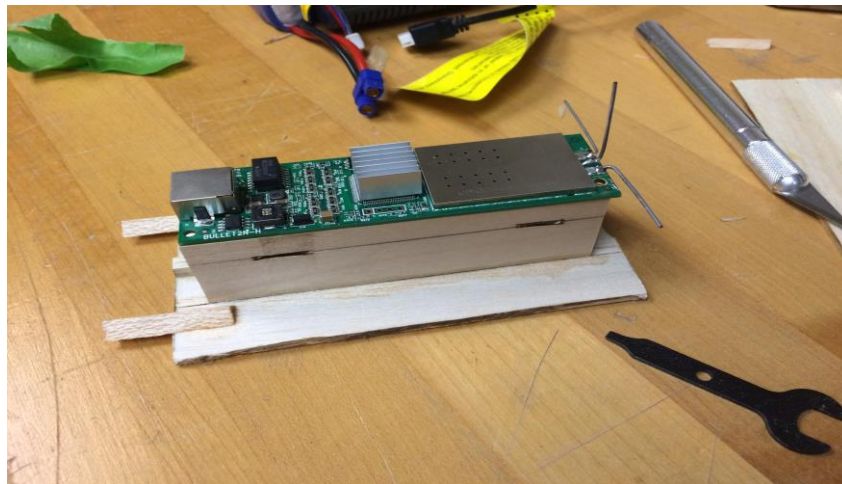
The off the shelf Senior Telemaster required many modifications to fully integrate the individual subsystems into the airframe. To house the gimbal, we cut a 6.5cm by 8.5 cm hole beneath the battery tray, reinforced the battery tray with a laser cut piece of one eighth inch plywood, and screwed the shock absorbing gimbal base onto the reinforced tray.



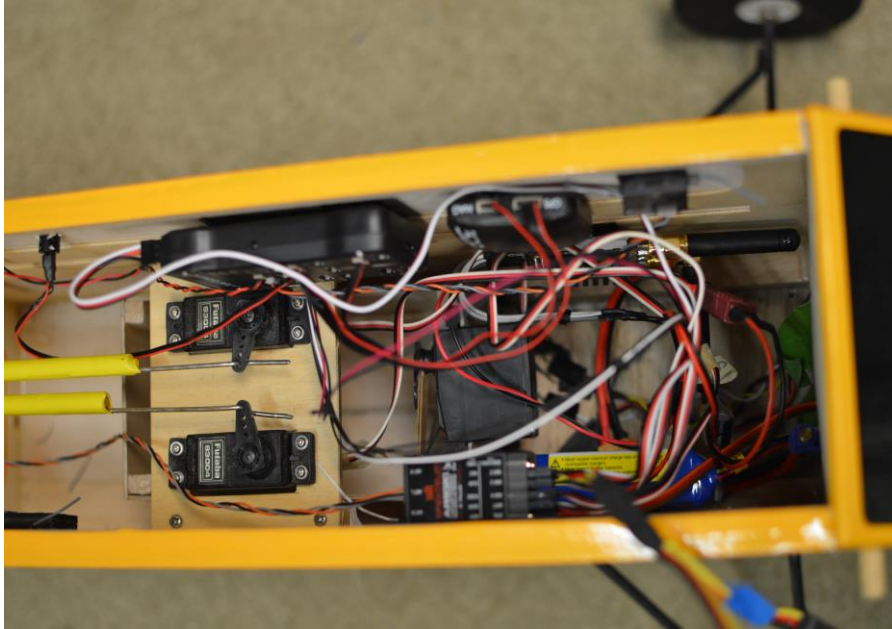
To mount the airspeed sensor, we glued a foam base onto the airframe skin to provide a stable surface to mount the sensor. This base was mounted on the bottom of the left wing, one half inch off the trailing edge and twelve inches away from the fuselage to ensure minimal interference from the prop. We then epoxied the sensor onto the foam and cut a hole in the wing through which we ran the hose and wiring. We cut a section of skin out of the wing along the edges of the internal frame to create a compartment to house the airspeed sensor's hardware. We were able to run the hose and wiring through the hollow center of the wing. We made a removeable panel out of the cut out section of the wing to restore the wing's aerodynamic properties while allowing us to access the internal hardware when the needs arises.



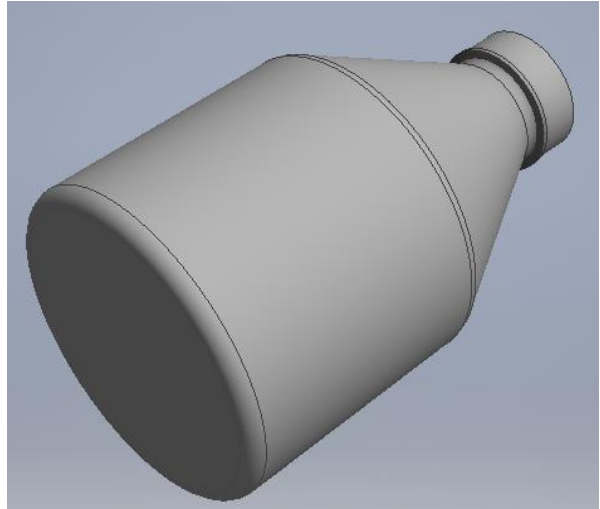
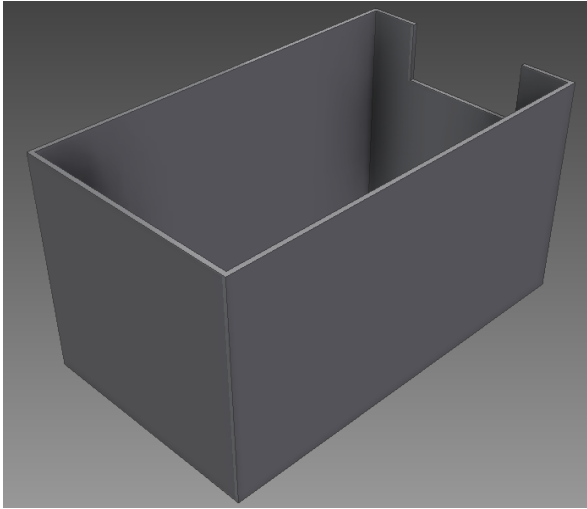
To install the Ubiquiti we cut a panel out of the bottom of the airframe as far back as possible. The Ubiquiti needed to be as far away from the Pixhawk and RC receiver as possible, but we did not want to make the plane too tail heavy. We also had to avoid the rudder and aileron control rods while installing the Ubiquiti because they run the length of the tail. We mounted the Ubiquiti to the removable access panel instead of installing it within the plane itself so that we could more easily access it.



The Pixhawk, GPS, RC receiver, and secondary battery were attached to the side walls of the main airframe compartment with model aircraft Velcro. The GPS, Pixhawk, and 900 MHz radios were all mounted on the same wall because they were required to be in the same orientation. The receiver and battery were mounted on the opposing wall to balance the weight.



This Velcro was also used to create the access panels for the Ubiquiti and airspeed sensor. The drop box was made out of one eighth inch plywood with quarter inch balsa blocks for reinforcement and installed in the center of the airframe to minimize the shifting of the center of gravity when the water bottle was dropped. The cut to install the box measured 7.5 cm by 12 cm. The bomb bay doors were made out of the panel we cut in the bottom of the plane to install the drop box. The drop box worked consistently during testing - the water bottle never snagged on the doors and the doors fully opened and closed every time. The transmitter and receiver worked as expected during testing too - the flaps, ailerons, rudder, drop box, and motor all responded appropriately to the user inputs.



We bought a Sport Cub model airplane, aerodynamically very similar to the Senior Telemaster, to test our various onboard systems in the air without having to risk flying the completed Telemaster. To quantify the aerodynamic similarity, we compared the three dimensional wing loading between the off the shelf Sport Cub and modified Telemaster in the table below. We found that subtracting one ounce from the Sport Cub gave it the same k value as the modified Telemaster. This value accounts for the differences in wing length and wing area compared to the two planes' weight.

Model	Wingspan Inches	Wing Area in ²	Weight oz.	Wing Load oz./100 in. ²	k oz./in. ³
Sr. Telemaster	94	1330	168	12.6	.0013
Custom Tele	94	1330	190	14.3	.0015

Sport Cub	51	417	33	7.9	.0016
Custom Cub	51	417	32	7.8	.0015

$$Velocity = k_2 * Wingspan \quad [1]$$

$$Turning Radius = k_3 * Wingspan \quad [2]$$

$$Acceleration = \frac{Velocity^2}{Turning Radius} \quad [3]$$

$$Acceleration = k_4 * Wingspan \quad [4]$$

$$Lift = \frac{1}{2} * Density * Velocity^2 * Coefficient of Lift * Wing Area \quad [5]$$

$$Lift = Weight * Acceleration = Weight * k_4 * Wingspan \quad [6]$$

$$Weight = k_5 * Wing Area * Wingspan \quad [7]$$

Autopilot Subsystem

In order to have an autonomous aircraft, an autopilot system had to be designed which could control the aircraft to autonomously take off and land as well as steer to GPS designated waypoints. This was accomplished by purchasing and installing an off the shelf 3DR Pixhawk Autopilot. This autopilot communicated with the Ground Control Station via off the shelf telemetry radios which could send GPS data to the laptops on the ground in order to track the UAV with the antenna pointing system. In order to autonomously steer the aircraft, the software Mission Planner was used to designate GPS waypoints that were uploaded to the aircraft prior to flight. Following the uploading of these waypoints, the plane could autonomously take off, fly, and land at all the desired waypoints. In case of an emergency an RC transmitter and receiver package had to be installed on the aircraft to override the commands uploaded on the Pixhawk prior to flight. To accomplish this task the Spektrum DX9 Transmitter and AR9020 Receiver package was purchased; the receiver was installed on the aircraft after being connected to the Pixhawk and if the transmitter was turned on while the aircraft was in the air, and commands given by the transmitter would override Pixhawk commands and a pilot on the ground could have complete control over the aircraft.

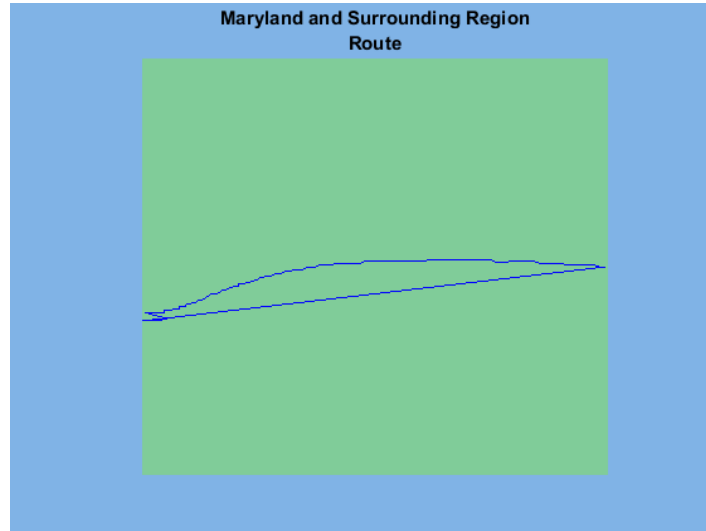
The images below show the wiring diagrams for the 3DR Pixhawk autopilot. In the final setup for our aircraft the Pixhawk was connected to the external GPS all facing the same way inside the Telemaster in order to maintain proper GPS fixes during flight. Several motors were connected to the Pixhawk which included motors for the ailerons, rudder, elevators, camera gimbal, and the electric speed controller.



The flight plans were designed for the aircraft using the Ground Control software, Mission Planner. This software enables the user to design custom flight plans from a laptop which are then uploaded to the autopilot prior to flight. These flight plans are made by specifying GPS data points on a world map at varying altitudes in the proper flight order. Additionally, varying altitudes can be specified in order to create a smooth flight and avoid unnecessary dives and climbs while in flight. Finally, the user can specify whether the GPS waypoints selected are simply waypoints the aircraft must pass through or whether they are landing or takeoff points at which the aircraft will leave the ground or touch-down during its final descent.



The plot below shows a flight plan plotted in MATLAB. This path was created in Mission Planner and then flown in a simulation using XPlane 10. Following the completion of the flight, the GPS data stored within Mission Planner about the actual path flown by the aircraft was exported to MATLAB and then plotted onto a geographic map of Maryland since this simulation was flown over BWI airport. This data transport and plotting in MATLAB was all done post flight.



The image below is the flight simulator XPlane 10 which was purchased in order to conduct realistic flight simulations with the flight plans designed in Mission Planner. The simulation was run by using the PT-60 RC plane found in XPlane 10 in order to replicate the flight controls of the Telemaster as closely as possible. Testing was done by first manually flying the aircraft in the flight simulator to verify that the plane actually flew. Following the mastery of manual flight simulations were then conducted user flight plans which were designed in Mission Planner and then transferred to XPlane 10. The final product of these simulations were able to autonomously take-off, fly to GPS waypoints specified in the flight plan to within an altitude of 3 meters, and finally land back on the ground autonomously as well. Additionally, the simulation could be switched out of autoflight mode and into manual mode in which the user had complete control over the flight of the aircraft so as to simulate the pilot taking control in an emergency.



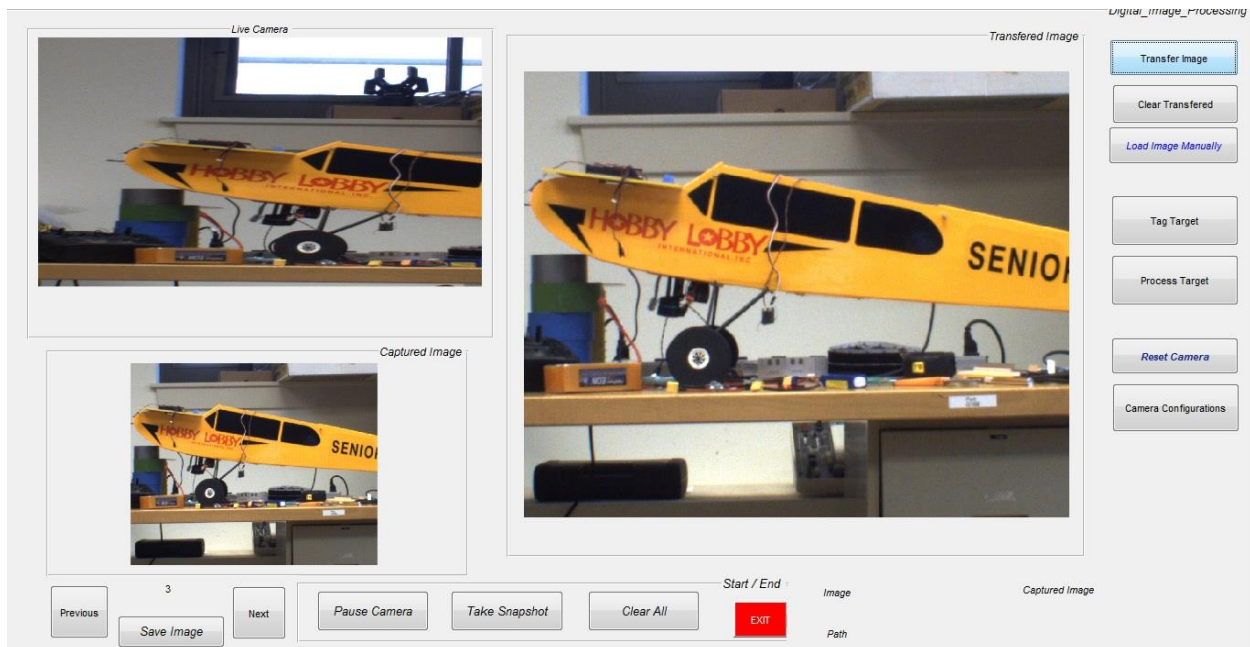
Imaging Subsystem

The image processing system integrates software and hardware via interface created by MATLAB to accomplish the following tasks according to the SUAS competition rules:

- Sends live video stream to the ground station through a Digital Image Interface created by MATLAB. The interface allows the user to store snapshots in a library.
- Automatically locates at least five unique targets while the aircraft is in autopilot mode given determined waypoints.
- Visually identifies characteristics of a target such as shape, background color, alphanumeric color, alphanumeric symbol and orientation.
- Automatically locates the target by using GPS and telemetry information and an image on the interface.

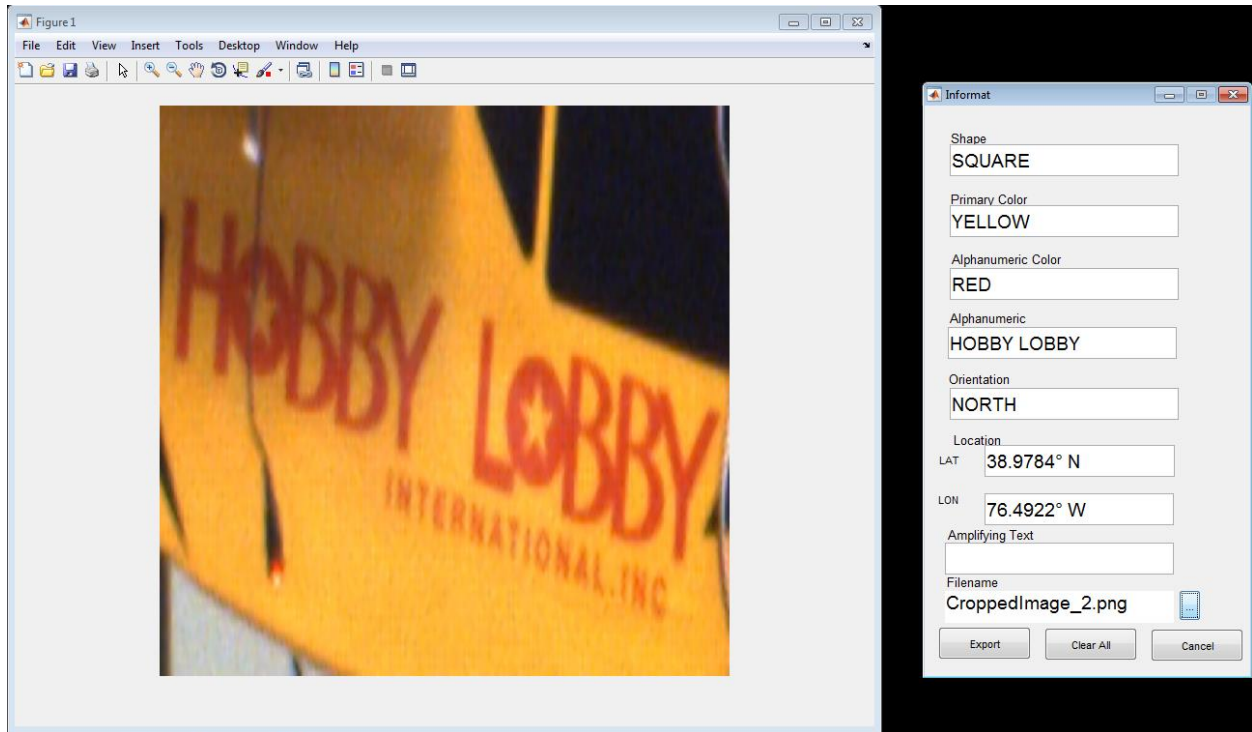
Interface

This interface was created using MATLAB GUIs feature. Mainly, the user can take snapshots with it by just clicking a button. It allows also the user to easily identify and process pictures obtained. This interface contains several axes that: shows live stream from the camera, keeps a library of pictures for easy processing, displays the picture to be processed that allows the user to crop selected area. It also calls another GUI that permits the user to enter all data pertaining the identified target: shape, primary color, alphanumeric color, alphanumeric sign, orientation and location. The obtained data will automatically be appended to a MS Excel spreadsheet which will be shown to the judges in a .txt file. The design is the following:



There are many other additional functionalities on the interface. The button “Camera Configuration” enables the user to select a predetermined configuration such as RAW, Mono, RGB, YUV

before starting the camera. Since the configuration is stored in the camera's memory, the interface has a reset button that will actually reset the configurations stored. Finally, it permits the user to manually load pictures that are stored in the library to process as if it were a transferred image.



Gimbal

The gimbal is gyro stabilized and has three modes to control. Heading and Pitch Follow Mode stabilizes and allows the camera to point straight down to the ground. Heading Follow Mode stabilizes and allows users to control pitch of the camera. Heading Lock Mode stabilizes and allows users to control pitch and yaw of the camera. The gimbal is originally made for GoPro camera but we modified it to be compatible with the Flea3 camera.

Target Localization

Users can locate targets on the ground via the interface. Location of targets on the ground can be calculated by the following equation.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = (R_0^c)^{-1} (A_c^m)^{-1} \left(s \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} - A_c^m t_0^c \right)$$

R_0^c = 3x3 rotation matrix relating points in the global frame (Frame 0) to points in the camera frame (Frame c).

A_c^m = 3x3 affine transformation representing the camera's intrinsic matrix relating points in the camera frame (Frame c) to points in the image.

t_0^c = 3x1 vector describing the position of the global frame (Frame 0) relative to the camera frame (Frame c).

s = distance from the aircraft to targets

u,v = position of a point of interest in column and row of in the camera frame relatively.

x, y, z = latitude, longitude, altitude of the target selected in the camera frame in Cartesian.

Assumptions to this equation is that the users know roll, pitch, yaw of the aircraft and camera; latitude, longitude, and altitude of the aircraft. Location of the target selected in the camera frame is obtained in Cartesian and is converted into degrees as an output for the interface.

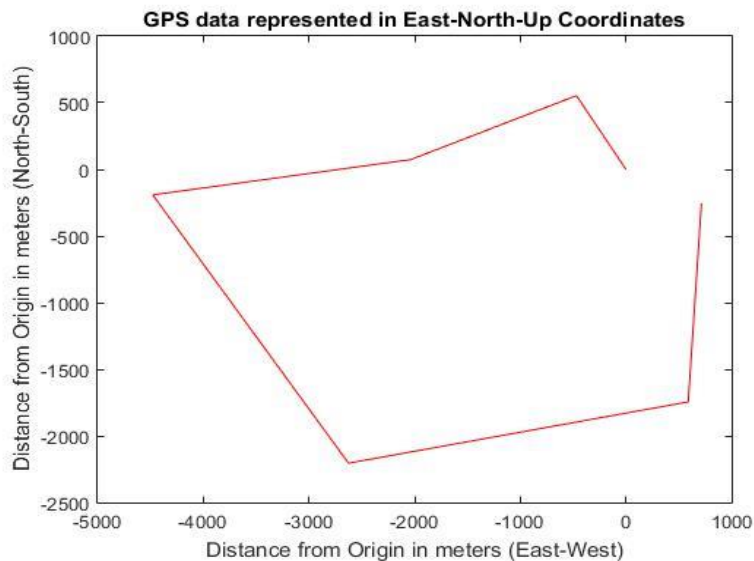
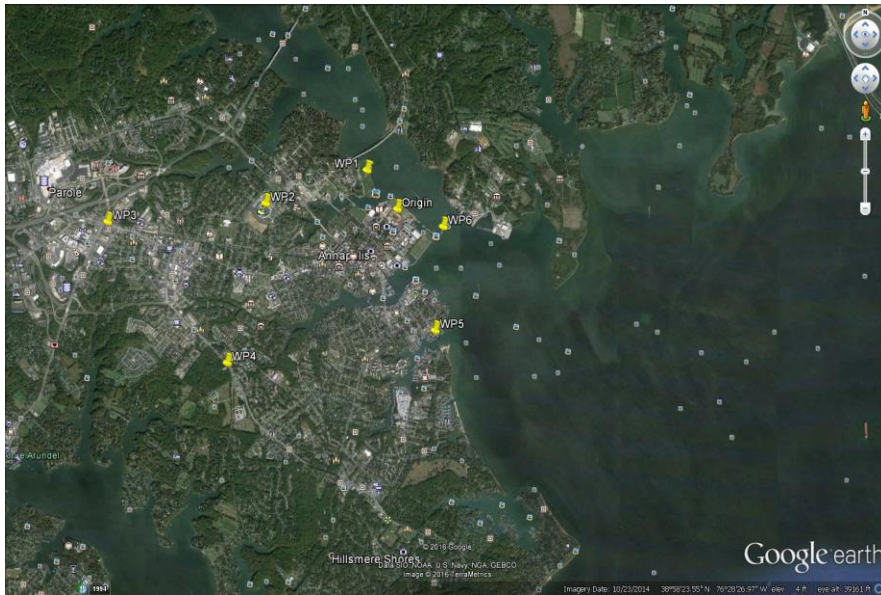
Autonomous Target Detection

Assumption for this task is that the competition allows us to acquire photos of the target before the competition day. The code will automatically detect the same targets obtained prior to the competition on the ground. Autonomous Target Detection code distinguishes photos by using Extract Feature Descriptors at the interest points of images. Then find putative points matches by using RANSAC (Random Sample Consensus). These features are matlab built-in function. The code works well with distinguished and ununiformed color images. The code and the result is in Appendix A.

Antenna Pointing Subsystem (final design and results/testing for each)

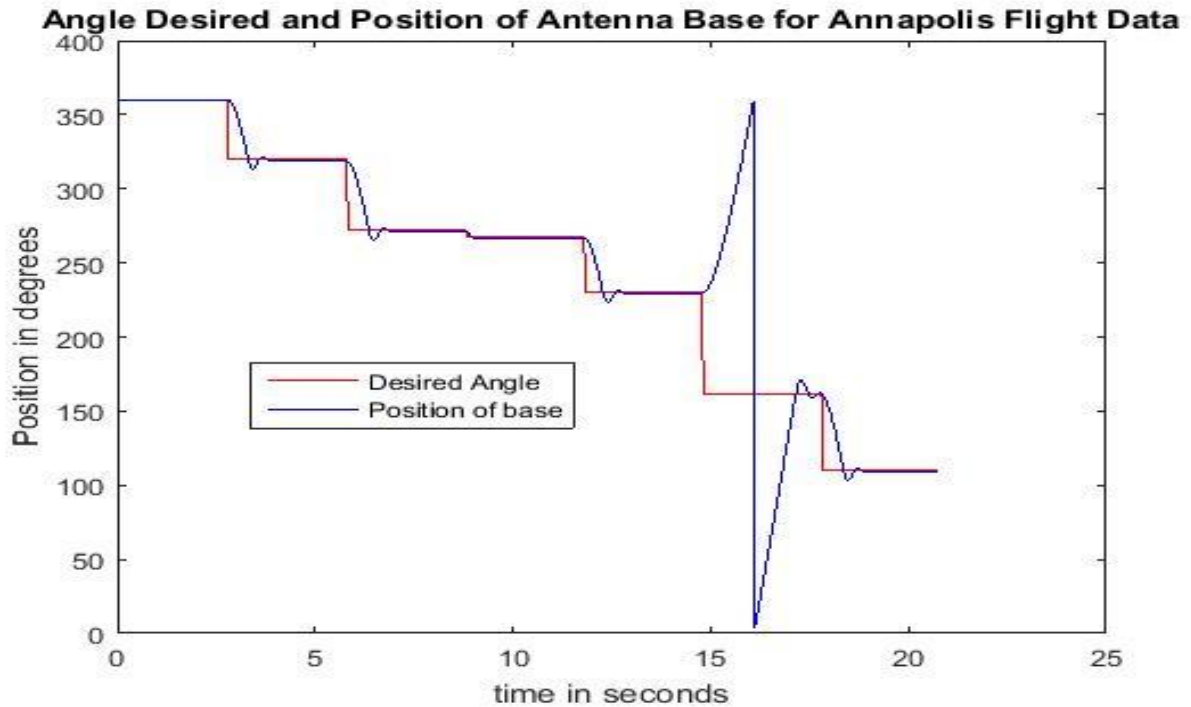
The Antenna Pointing Subsystem was critical for the tasks of acquiring, identifying, and localizing ground-based targets. For the best possible transmission of images over the 2.4 GHz Ubiquiti link, pointing the AirGridM© toward the aircraft was essential. To accomplish this, a subsystem that would orient the ground dish towards the aircraft in a timely and efficient manner was developed.

For the performance of the GPS to ENU conversions, using simulated waypoints in Google Earth©. Below is an example of the waypoints in Google Earth and the accompanying conversion into ENU coordinates in MATLAB.



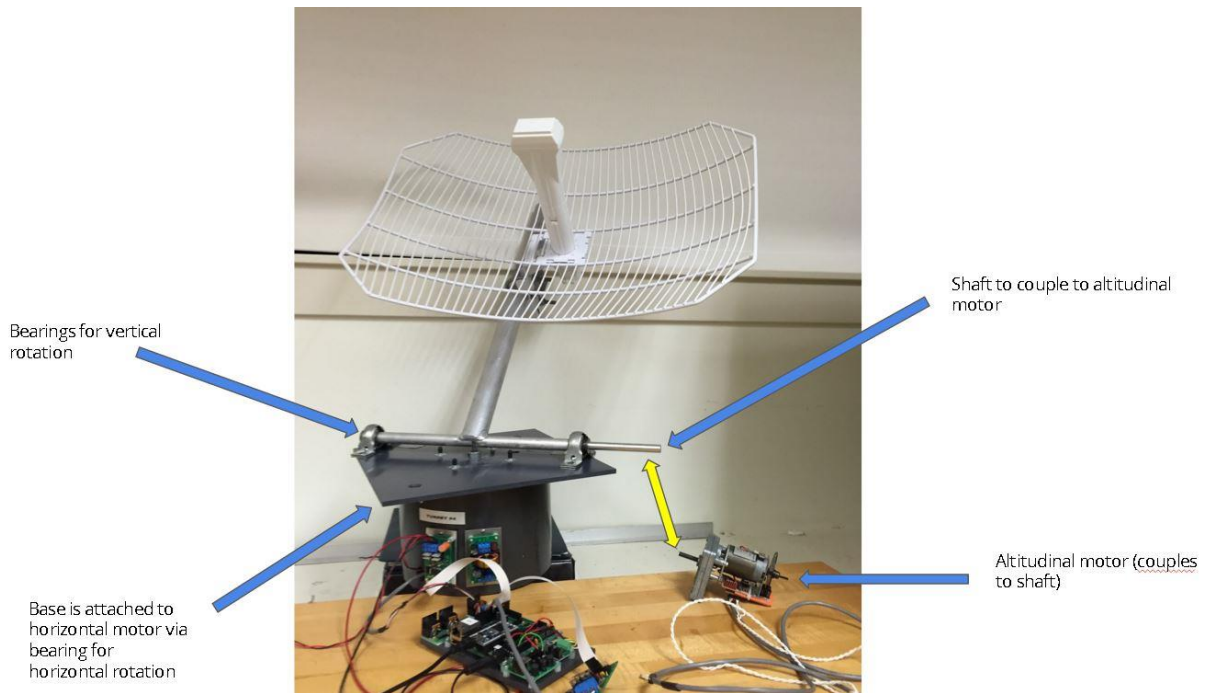
The waypoints in Google Earth and the accompanying conversion in MATLAB to ENU coordinates from GPS waypoints.

Once this conversion was proven mathematically, the next step was to develop a controller that efficiently transmitted the angles computed in MATLAB over the serial port to the mbed LPC1768 microcontroller on the WSESBC. Using the WSESBC's native capabilities to interface with encoders and the TD340 motor driver boards, the motors themselves were turned to the appropriate angles. Below is the performance of the horizontal motor using the angles calculated for the previous waypoints shown.



The performance of the horizontal motor when angles were transmitted from MATLAB via serial port corresponding to angles calculated for pointing from one waypoint to the next. It is important to note the asymptotic measurement at around 15 seconds; this measurement change was intentionally designed to ensure the motor pointed to the correct corresponding angle on the other side of the polar plane without crossing the 180° threshold. This was done to prevent the “wrapping” of cables.

Knowing that the control system was correctly designed and that the physical system was sufficient for the design goals, the final goal was to assemble the system and test it. However, assembly had to be delayed due to a problem with the in-house motor electronics of the Brevet motors; the issue has been resolved and assembly has continued. The system assembled conceptually is shown below.



The system assembled to near final completion, only lacking the coupling of the altitudinal motor.

Project Management

Work Breakdown Structure

Due to the large number of tasks needed to accomplish the many objectives in our project, during the first semester of our project we developed a high level work breakdown structure to delineate who did what work and when. Creating our original draft work breakdown structure was admittedly quite difficult since we had not even selected parts or had any idea when we would receive funding; however, at the beginning of the second semester, we had a much better idea of what was possible and how we should focus our efforts to maximize our performance. Our final work breakdown structure we implemented divided up the work by subsystems and weeks, since we met as a team weekly. Our final work breakdown structure is located in the appendix and completion is shown using color coding.

Cost Analysis and Parts List

The proper consideration of costs for any project is vital to ensure that we do not run over budget and get rendered unable to complete our mission. Though minimizing costs was one of our lowest priorities during planning, in order to be able to complete our project we need to be able to spend our money wisely. First, we estimated our cost for parts we wanted. Among our desired parts, the airframe, autopilot, imaging system, and ground station computer were the most expensive. We

also made sure to factor in parts for several redundant systems for our estimates. Among the miscellaneous costs are items such as transportation cases, tables, tents, and travel costs for the competition. Our original cost estimate is listed below.

Airframe	\$3,236.36
Flight Control	\$4,654.74
Supply Drop	\$1,255.60
Imaging Systems	\$5,606.88
Onboard Communications and Computing	\$1,517.84
Ground Station	\$8,348.85
Miscellaneous	\$7,258.37
Total	\$31,878.64

The next consideration to be made is of labor costs. Our team broke labor estimates into three categories: midshipman, faculty, TSD, and shop. Midshipman labor is the projected amount of time our team will spend to complete this project. Faculty labor is the time our advisors, professor Kutzer and Devries, will spend working with us. TSD and shop labor is the amount of time the respective facilities will have to spend making parts and supplying components. Below is our estimate for labor costs, if everyone that contributed had been paid for their direct contribution rather than a salary.

Type	Cost/Hour	Hours	Cost
Midshipmen	\$26.00	1152	\$29,952.00
Faculty	\$50.00	128	\$6,400.00
Shop	\$30.00	10	\$300.00
TSD	\$30.00	19.55	\$586.50
Total	-	1309.55	\$37,238.50

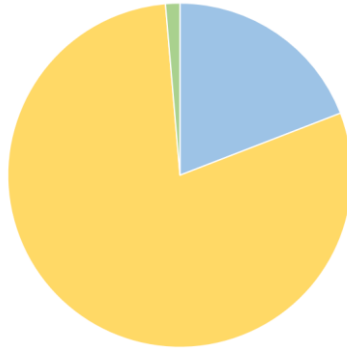
Finally, we estimated the indirect labor associated with our project. The fringe costs are items like holidays, leave, health insurance, and social security. To calculate this, we took 35% of our direct labor cost as our instructor suggested. Overhead costs are the facility costs, electricity, heating, research and development. We used a cost factor of 50% of direct labor costs for this estimate. The last indirect labor cost is general and administrative (G&A) which includes labor like secretaries, attorneys, and management. These steep costs are listed below.

Type	Cost Factor	Cost
Fringe	35%	\$13,033.48
Overhead	50%	\$18,619.25
G&A	25%	\$9,309.63
Total	-	\$40,962.35

Combining the costs for materials, labor, and indirect labor the total estimated cost for the project is approximately \$110,080. While this sum may seem extremely steep, it is important to remember the many number of people involved and the long hours required to complete all mission areas.

After some refinement and discussion with our advisors, we ended up requesting \$34,250.00 from the Program Executive Office Integrated Weapons Systems (PEO/IWS), a part of the Department of the Navy. Of this, we received funding of \$17,250--approximately 50% of our requested amount. Of this \$17,250 budget, \$3,300 was required to be used for travel costs, leaving \$13,950 to spend on materials. The magnitude of this data is shown below.

Funding Requested	\$34,250.00
Funding Granted	\$17,250.00
Travel Costs	\$3,300.00
Funding left for Materials	\$13,950.00
Funding Spent	\$13,717.77
Funding Remaining	\$232.23



Throughout the semester, the project team leader maintained the budget and kept track of the many orders placed. Approximately 28 unique orders were placed over the semester and are shown below with the associated costs and parts in each. Additional parts were borrowed in-house from the Technical Service Division of the Weapons and Systems Engineering department. Additionally, the customized antenna on the modified Ubiquiti antenna was designed and built by the satellite communications lab in the Aerospace Engineering department.

Order (parts)	Price
Amazon (HobbyKing, Gimbal)	\$199.99
3DR (pixhawk and bonus parts)	\$519.01
Event38 (telemetry radios)	\$189.22
PointGrey (flea camera)	\$2,020.00
PointGrey (cables)	\$100.00
Ubiquiti (antennas)	\$197.44
Horizon Hobby (servos and sport cub)	\$251.93
Hobby Express (telemaster, prop, amp, motor)	\$634.27
L-Com (rubber duck antenna)	\$36.90
Amazon (HobbyKing Batteries & Charger)	\$188.48
Newegg (network switch, PoE)	\$36.66
Grayson Hobby (hinge)	\$17.49
Horizon Hobby (T horn, iron)	\$34.87
McMaster Carr (machine equipment)	\$34.97

Horizon Hobby (9 channel transmitter)	\$539.99
Amazon (airspeed sensor)	\$31.98

Amazon (shop-vac and accessories)	\$104.26
3DR (2 pixhawks)	\$417.94
Lenovo (ThinkPad P70)	\$2,529.10
Event38 (2 telemetry radios)	\$379.98
Dell (USB to ethernet PXE)	\$49.99
Point Grey (GPIO connector)	\$80.00
Lenovo (ThinkPad P70)	\$2,576.10
Amazon (Tables, Chairs, Fire Extinguisher, etc.)	\$808.71
Horizon Hobby (ESCs and RC Receiver)	\$369.97
RMA Electronics (Camera Lens)	\$303.46
Amazon (Laptop Cases)	\$66.92
Chief Aircraft (Props and Charging Bags)	\$149.30
Surveillent LLC (lens)	\$848.84

Discussion and Conclusion

Each subsystem individually meets requirements for the competition before the integration together on the Senior Telemaster. However, the flight testing with the entire system integrated was never conducted due to Federal Aviation Administration (FAA) restrictions. One major concern is the weights of the subsystems that the aircraft is carrying. The Senior Telemaster is originally built as an RC aircraft, and not to be modified to carry excessive weight. The team decided that the final design is safe to fly after consulting with RC plane enthusiasts and Professors intimately involved with UAV research, as well as 3/C Redito who has extensive experience with the Telemaster. Dimensional analysis, simulation, and extensive calculations have shown that the plane is flight-ready and the next group to undertake this project will be well on their way to flight testing and system integration after FAA regulations are appropriately addressed.

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Appendix A: Autonomous Target Detection Code