MECHANICAL ENGINEERING DESIGN PROJECTS

FINAL REPORT

Team 7

Josh Elkind, Jesse Morzel, Alex Reiner, Fiona Strain, Sophia Stylianos

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PROJECT OVERVIEW

This project will address the need for a low cost UAV that can be easily deployed by military personnel for near-field surveillance purposes. The low cost feature of this system will allow the rocket-launched glider to be considered disposable. Furthermore, the system must be fast and easy to deploy, allowing field units to remain agile and gather the needed information quickly. The camera that will be on board the glider will transmit back to the unit, giving the troops a real time video of the area being surveyed and rendering the retrieval of the plane unnecessary. Lastly, the system must be able to cover a large range so that the use of the surveillance equipment will provide the troops with information they would not be able to easily attain using other means.

The UAV will undergo two distinct phases during its flight: launch phase and flight phase. The launch phase will use rocket engine propulsion to elevate the system to a height that will allow the glider to reach a desirable range. The flight phase will occur after the propulsion is concluded and will carry the surveillance equipment to the sites which must be surveyed. The glider must be able to carry a payload of the battery, camera, transmitter, necessary electronics, and control system (needed for autonomous flight and stabilization).

The challenge in constructing a UAV that can execute both a rocket launch and autonomous flight phase is that these two modes have very different demands on the vehicle. For rocket launch, high forces are present due to the thrust from the engine and the lift and drag forces on the wings. Due to these forces, the glider must have enough structural strength to ensure that the wings and tail survive the launch. These components must also be able to survive the heat generated from the rocket engine. Additionally, the forces acting on the glider must be located properly to ensure stability throughout the launch. For the flight phase, the glider must have the appropriate control surfaces to allow for continuous control from the flight program. These control surfaces will have to be used to ensure that the glider reaches its designated waypoint.

The current state of the art in this field is quite limited. Although the U.S. military currently uses countless drones in the field such as the Predator and Reaper UAVs, these are relatively expensive, slow to deploy vehicles that may not be available to a team in the field. There are many systems that can be easily hand-launched by a small team, though the advantage of a rocket would be the speed of deployment and extended range of the UAV. A senior design team from Vanderbilt University appears to have already successfully implemented a rocket-launched UAV, but they used a very large rocket that would not be suitable for use by a small remote team. A few other teams have developed smaller rocket-launched UAVs, including a project called “Guardian 2.0” and a UAV developed at the University of

Canterbury. However, it is unclear how far these projects got in testing and how capable they are for field use. This team's project will be distinguished by its ease of use and low cost.

The customer has specified several design constraints for this project. The overarching goal is to maximize the loiter time of the UAV given a 100 meter minimum range. This will allow us to prove the concept of an autonomous flight glider launched using rocket propulsion, and future efforts can be applied to extend this minimum range. Additionally, in order to extend this range, rocket engines requiring special licenses would be needed and that is outside the scope of this project. Another customer specification is to use a "G" rocket motor (which has 80-160 N•s), because it is the largest low-power rocket motor that doesn't require additional training. The most important metric of success is that the glider can be successfully launched using this rocket engine and that once in the flight phase the glider can reach its designated waypoint using autonomous flight control. Finally, the UAV should be capable of transmitting real-time video of at least 30 frames/sec.

In order to accomplish these project goals, a carbon-fiber reinforced glider was used as the UAV which carried the onboard camera and necessary electronics for autonomous flight and video transmission. Figure 1 below illustrates the various components of the design.

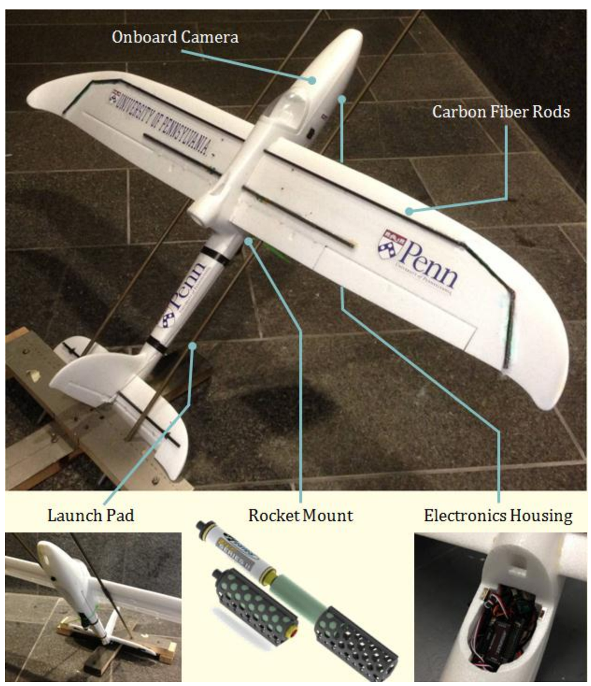


Figure 1: Illustration of the Various Components of the Project Design

Since the glider was made of EPO foam, it became necessary to structurally reinforce the glider using carbon-fiber rods. These rods were attached to the wings and tail of the glider to ensure that these components would not fail due to the high lift forces experienced during launch. Furthermore, the tail was protected from the exhaust of the rocket engine by heat-shielding tape which has the capability of withstanding 1100ºF. The rocket engine was attached to the belly of the glider using a custom-made rocket mount. The rocket mount was 3D printed and designed to align the thrust forces generated by the rocket with the CG of the aircraft. This aspect of the design increased the stability of the glider during the launch phase. The nose of the glider housed the electronics and onboard camera. These electronics were necessary to transmit the video in real time as well as communicate with the ground station. The ArduPilot onboard communicated with the ground station in order to determine destination points, track and log flight data, and receive flight control commands.

OVERALL DESIGN

Rocket Integration

About halfway through the second semester, the team began to focus more on integrating the rocket engine into the design of the glider. Rocket integration presented three distinct challenges: thermal integrity, structural integrity, and flight stability during launch.

The simplest component of the rocket integration was the launch pad. The launch pad was made of 2x4s in a cross configuration covered in 1/8" thick aluminum to prevent the wood from catching on fire. The plane launched off of two six-foot long, 3/8" diameter steel rods inserted into the launch pad at a 45º angle for optimal launch height and range. The plane attached to the guide rails via two custom carbon fiber tubes which were fastened to the bottom of the wings. The interface between the carbon fiber and steel was a slip fit such that the plane could smoothly slide up the guide rails during rocket launch.

Figure #2. Plane mounted on the launch pad.

The rocket mount assembly is comprised of three components: the rocket motor, the protective fiber glass tube, and the 3d printed rocket mount. Fiber glass is extremely durable, heat resistant, and often used in aerospace applications. We 3d printed the motor mount so that we could design a custom shape to most effectively fit into our glider. We placed the rocket mount assembly as close to the center of mass as possible without compromising the structure of the fuselage and tail. To do so we measured the exact center of gravity each time we repacked the electronics. We also wanted the whole mounting system to be removable and adjustable, so we fastened it to the plane with removable zip ties. The zip ties allowed us to adjust for the position of the CG based on modifications made to the electronics system and to accommodate the use of different sized rocket motors which also affected the location of the CG.

The plume released by the rocket engine during launch has the capability to compromise the glider's structure by melting the foam and weakening the tail. The solution that the team decided to use was to apply heat-shielding tape to the areas of vulnerability. We applied one strip of two-inch wide Thermaflect Tape, which can withstand 1100°F of continuous radiant heat and 500°F of direct contact, along the fuselage to the tail. The tape proved to be very successful at executing this task when tested during our rocket launch tests. The plume occasionally singed the tape, but never weakened the tail of the glider in any way.

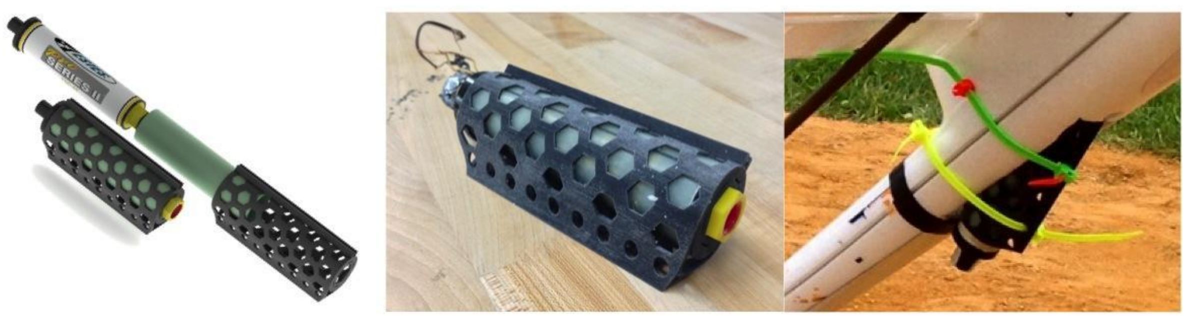


Figure #3. From L to R, CAD of the motor-tube-mount assembly; photo of the actual rocket mount assembly; rocket mount assembly fastened to the glider. Note the silver strip of heat-shield tape at the mouth of the motor.

The next challenges we needed to tackle were structural integrity and flight stability. We found out that these challenges were very much co-dependent. For a G79 Estes rocket engine, maximum thrust reaches 100.7 N, average thrust is 79.0 N, and a total impulse of 108.6 Ns is experienced during a burn time of 1.4 seconds. For an F50 Estes rocket engine, maximum thrust reaches 79.6 N, average thrust is 53.7 N, and a total impulse of 76.8 Ns is experienced during a burn time of 1.4 seconds. The thrust forces caused by the F50 motor exerted approximately 50N of average lift on the wings during rocket launch. After our first rocket tests, our glider structurally survived launch with both an F50 rocket motor and a G79 rocket motor. However, these flights were not stable. We gained stable flight by building the more robust and adjustable motor mount described above, and also by meticulously measuring the center of gravity and positioning the rocket such that the thrust vector pointed directly through the axis containing the CG. For more details regarding the design and redesign of the glider, please refer to the "TESTING/PROTOTYPING RESULTS" section of this report.

The final structural design of the plane can be seen in the photo below. To strengthen the wings and tails to survive the lift forces caused by the thrust of the rockets, we reinforced the plane with lightweight carbon fiber rods. The rods were positioned along the wings to reinforce the locations most vulnerable to fracture due to the lift forces. The max lift experienced by the wings, due to a G79 rocket motor, is approximately 55N. The addition of extra carbon fiber rods through the wings added structural strength with an approximate factor of safety of 2.56. For factor of safety calculations, please see the appendix. The rods are mounted to the tail with small custom carbon fiber hooks and mounted to the wings with West System epoxy because it does not chemically attack the foam of the glider.

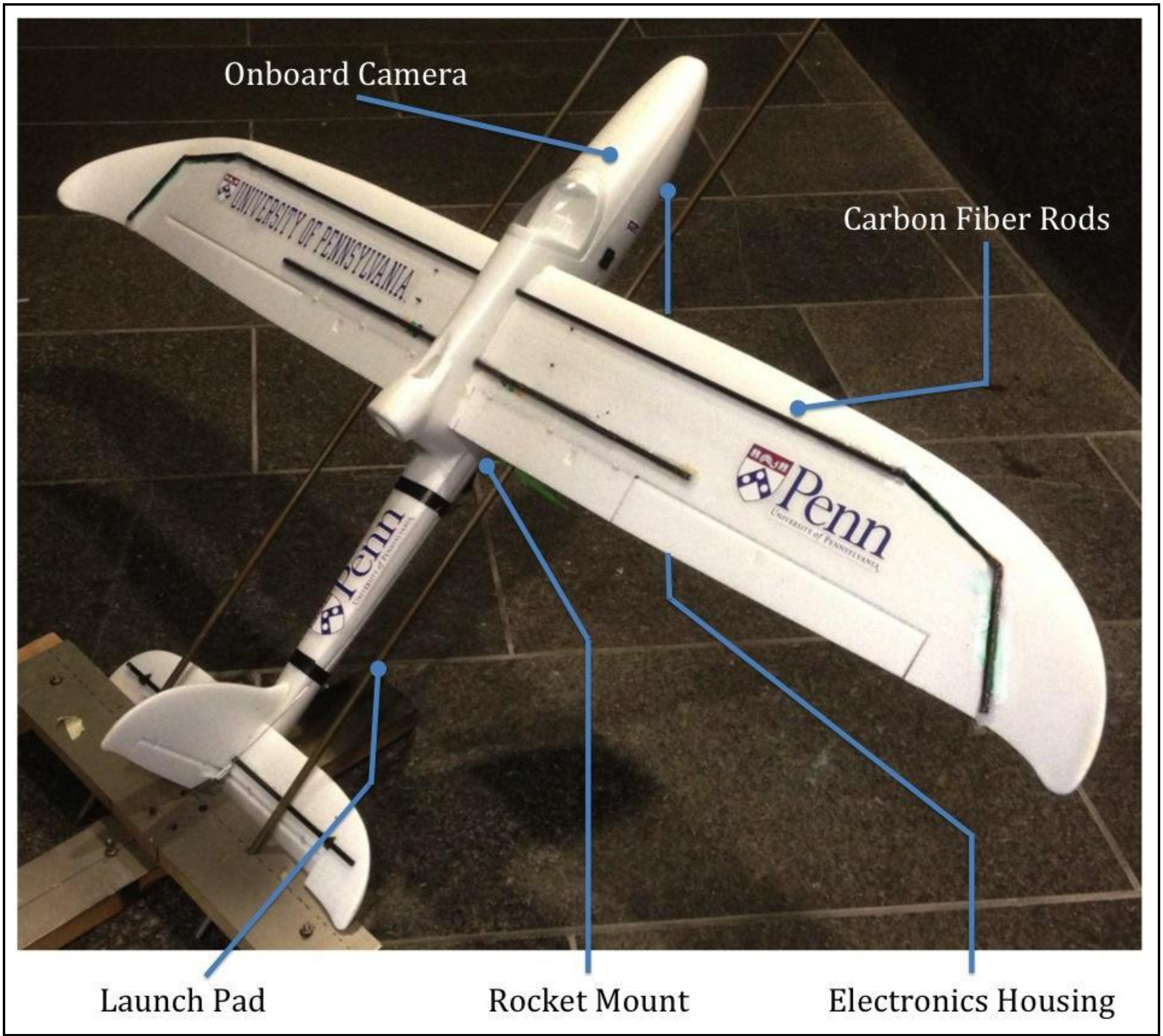


Figure #4. Fully assembled glider and launch pad structures.

Theoretical Model

In order to theoretically analyze both the launch and gliding dynamics of the Rocket Glider, we developed MATLAB simulation software (in conjunction with work done by previous senior design group Airtonomy 4) in order to understand how the glider would perform under varying parameters. The full model can simulate launch with any choice of thrust curve and any rocket placement, as well as the autonomous gliding phase. The simulation of the autonomous gliding phase includes a guidance system incorporated into the controls system that can avoid circular obstacles or "no fly zones."

The controls systems utilized are variations of the PID controller including one full PID controller and one PI controller. The PID controller is used to control the rudder control surface to obtain a glider heading angle while in autonomous guided flight, and the PI controller is used to control the elevator control surface during the rocket launch phase. The PID controller aims to match the heading angle of the glider with the output set point given by the guidance system, and the PI controller aims to maintain the change in pitch angle at zero so the glider maintains a straight heading in its original orientation from launch.

Launch Phase Simulation

The simulation of the launch phase does not require extensive alterations to the dynamic glider model. If we give the initial conditions of the glider to be at rest with a certain roll pitch yaw as determined by its orientation on the launch pad (the simulations shown later will launch the glider at an initial pitch of 45 degrees), and we create a function that can call thrust when given a time, we can then add this time dependent force to the force summation along the longitudinal axis of the glider. In our current rocket engine configuration we have the engine located at an offset from the gliders center of gravity. Therefore we also must add in an additional moment on the glider.

With the forces and moments added into the dynamic model, we then can move to creating the controls system. Since the glider is initially set in a position with a neutral rudder angle, a roll angle of 0 degrees, and a thrust perfectly aligned with the longitudinal axis of the body, we in theory don't have to worry about lateral control. Therefore, as far as the simulation is concerned, we are only focused on trying to counteract the unbalanced moment created from the rocket offset as well as the additional lift created by the thrust. We can attempt to counteract these moments by affecting the elevator, and the control system accomplishes this by attempting to maintain the same pitch angle that it was launched from by maintaining the change in pitch angle at zero.

One aspect of the launch that is currently being determined through observing the simulation is at what point the glider goes from the launch phase to the autonomous glider phase. This essentially marks the transition from constant ascent with strictly elevator control to guided descent with strictly rudder control. This transition occurs at about the peak height of the glider and can possibly be determined in later iterations of the simulation automatically.

Autonomous Glider Phase

The simulation of the gliding phase is done by selecting a destination waypoint, programming in obstacle positions and sizes, and inputting this information into the guidance system which will output a desired heading. This desired heading is then fed into the rudder control system to ensure the glider is adhering to a course that will simultaneously bring the glider closer to its destination and avoid obstacles. Upon reaching the waypoint, the glider will circle the destination until descending to the ground.

The guidance system works as follows. The system primarily measures what heading the glider must take to head directly in a straight line to the waypoint and will output that desired heading in the absence of nearby obstacles. However, if there is a nearby obstacle, the glider may begin to alter its course. There is a manually set threshold that measures radial distance from obstacles. If the glider is within this threshold, it will perform a few checks. Firstly, it will check if its current heading will pass through the obstacle. If it is on a collision course with the obstacle, the heading set point is output to be perpendicular to the radial vector starting at the center of the circular obstacle and ending at the glider. It will veer around the obstacle until the option of heading straight to the waypoint is no longer impeded by the obstacle. Once it is clear of the nearest obstacle it will then check to see if it is in the threshold of the next nearest obstacle and will perform the same checks until it is not near any obstacles.

The control system very simply attempts to match the output heading of the guidance system with the current global heading of the glider.

MATLAB Simulations

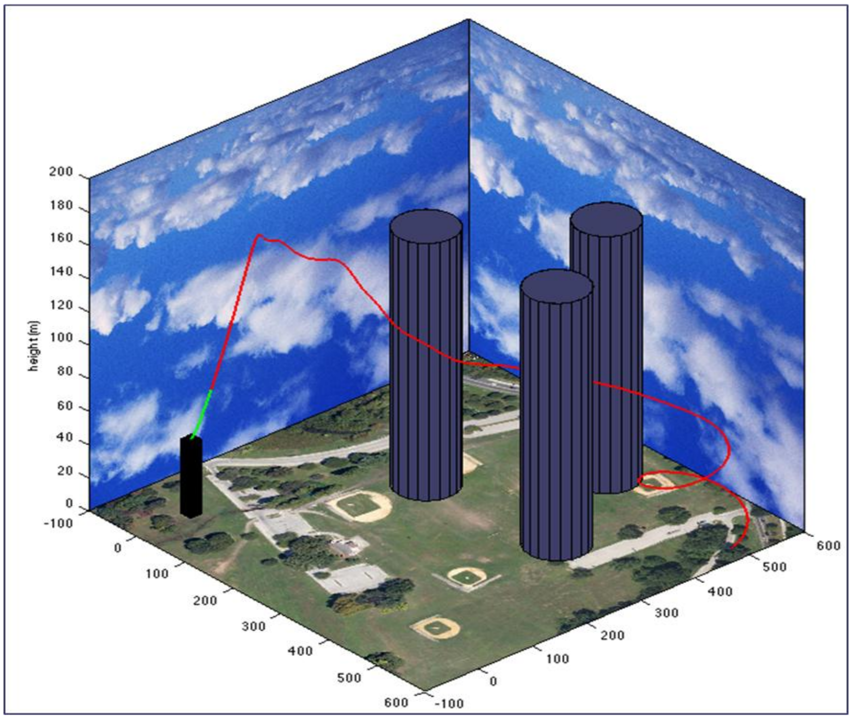


Figure 5: Fully simulated flight path from top-down view

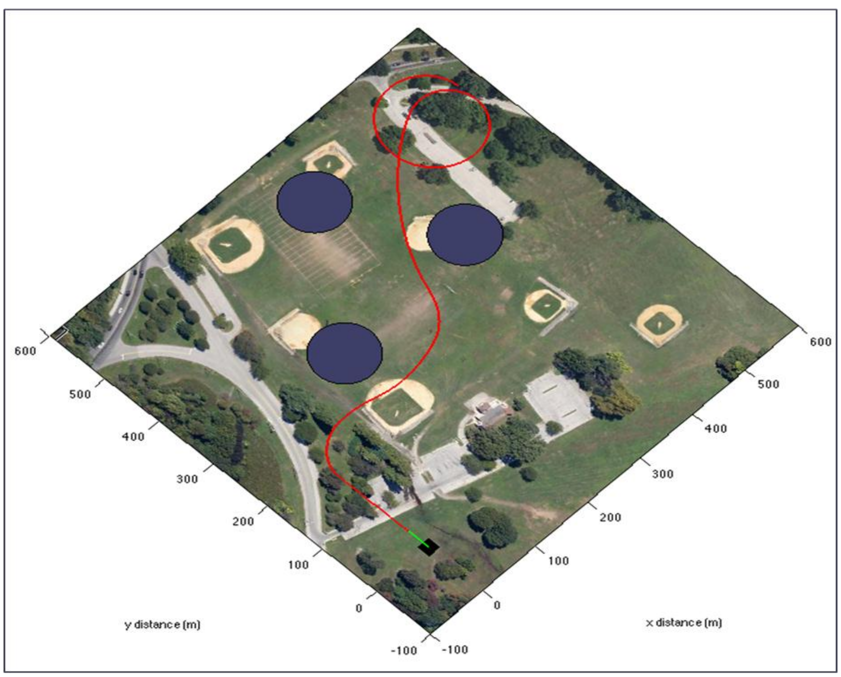


Figure 6: Fully simulated flight path from side-view

Electronics Systems

The electronics for the glider (see Figure 7 for high-level schematic) are comprised of two primary subsystems: the video transmitter/camera subsystem, and the microcontroller subsystem based around the ArduPilot Mega 2.5 microcontroller. The reason for this segmentation is that the video subsystem requires 11V while the microcontroller subsystem requires 5V. Furthermore, our team decided that the relatively insignificant added benefits of integrating the video subsystem with the microcontroller would be outweighed by the additional complexity required to do so.

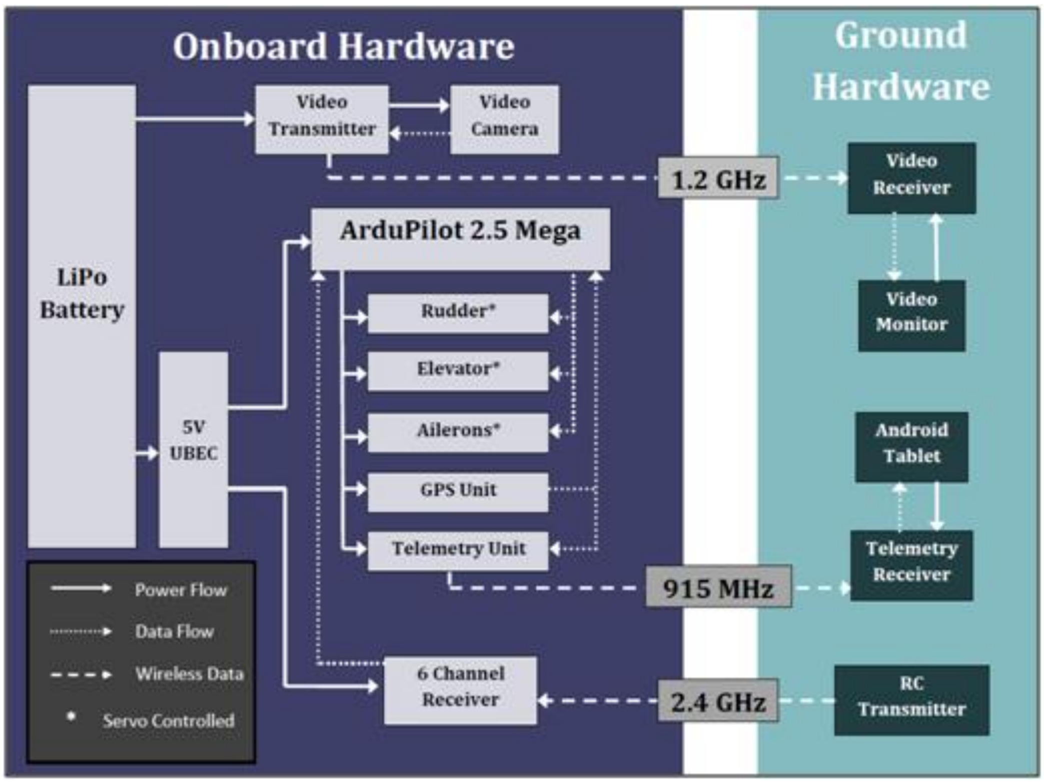


Figure 7: High-level Electronics Schematic

The microcontroller subsystem is designed to be very easy to switch between manual and autonomous mode. If manual mode is desired, the 6 channel receiver will relay commands from a human-operated remote control on the ground to the microcontroller. If autonomous mode is desired, embedded code on the microcontroller will take over control of the servos. This subsystem must execute four primary tasks: process the data from the GPS unit, relay commands from the 6 channel receiver to the servos controlling the rudder, elevator, and ailerons of the glider (if the glider is flying in manual mode), calculate the desired servo outputs based on our simulation model of the glider (if the glider is flying in autonomous mode), and send and receive data to the ground station via the telemetry unit. All electronic components for both subsystems were field tested. Complete system functionality was demonstrated through balloon drop tests. Most importantly, the team demonstrated the ability to control the glider using the ArduPilot, log data during flight for later analysis, and stream live video to the ground station. In total, the electronics components collectively weighed roughly 250 grams.

TESTING/PROTOTYPING RESULTS

Testing was the most essential part of our project since many aspects of the design that determined its ultimate success were only verifiable through full-scale testing. Thus, we performed multiple tests over the course of this semester. For each test, the same HobbyKing Bixler 2 glider was used, with modifications for rocket attachment, electronics integration, and added strength in the wings to ensure structural integrity. All of the tests were performed at the Belmont Plateau field in Fairmount Park, which provided enough empty space for safe flight-testing. Testing results were the primary motivations for changing the design, components, and customer requirements, so the chronology of testing displays the changing design of the glider and rocket system throughout this semester.

The first tests on December 13th and February 2nd consisted of a balloon and glider system to release the glider from the weather balloon at a desired height. The goals of these tests were to characterize the glider flight, collect data used to verify our MATLAB simulation, and gain knowledge about the controls inputs for autonomous flight. Additionally, the tests confirmed functionality of the onboard camera system, the ArduPilot Mega system, and the transmitters and receivers for both. The setup primarily consisted of a helium balloon, the glider with electronics and camera integrated, and a mechanism to release the glider from the balloon at the desired height, about 300 ft. Some tests were performed successfully using a hook-in-slot mechanism controlled with a motor and radio control, but the motor failed at some point during this test, rendering it unusable for future tests. For other tests, the team rigged a pulley-knot system of string to release the glider. However, the same height could not be achieved using this method, leading to a 75-ft altitude test.

The ArduPilot system consisted of the ArduPilot Mega 2.5 board, the GPS unit, connectors to the control surfaces, the manual control receiver, and the 2.4 GHz data transmitter. The camera system is powered by the battery and consists of the camera, its connectors, and the 1.2 GHz transmitter. For these tests, manual control was used for gliding flight, while flight data was recorded for analysis.

On the ground, a Windows laptop was used as the primary ground station. To obtain data from the flight, we used ArduPilot's Mission Planner software to live monitor several important parameters, such as flight direction, speed, control inputs, GPS location, and altitude. The Mission Planner software also records all of the data from the flight in a telemetry log file that can be re-loaded in Mission Planner to 'watch' the flight again, or exported into another file format for data analysis (such as Excel). The camera's receiver was powered on the ground using another battery, and it provided an RCA video out functionality. We used an EZ-cap video to USB converter device to input this video signal to the laptop ground station. This feed was then viewable live through media software, as well as recordable. However, it seems likely that the video feed's quality is affected by this conversion from analog to digital, and the software used to record the video often incorrectly identified the flight's video as a violation of copyright protection. Due to this issue, a full video of this flight test was not recorded.

From this test, we were able to confirm successful and accurate data collection using the ArduPilot that could then be compared to the MATLAB simulation. We were also able to confirm the functionality of the onboard camera system, its transmitter, and receiver. It was also determined that a better ground station system would provide more reliable and mobile testing. Using a Windows laptop as the primary ground station device limits portability, length of tests due to short battery life, and ease of use, as laptops are not designed for outdoor use. Moreover, the issues with the video feed input to the laptop also suggested the need for a better video feed ground station as well. These were considerations that we have taken into account for future tests and ultimate product use. For future tests, a separate video system and an Android tablet ground station were used to improve portability and reliability. A summary of these tests can be seen in this video link (https://vimeo.com/62582765).

All subsequent tests focused on obtaining a successful integration of the rocket launch phase and the glided flight phase. The first rocket test on March 17th had three main goals. First, as the team was inexperienced with rockets, we wanted to obtain general rocket-launching experience with the assistance of expert Thomas Castner, enabling us to perform future tests independently. Second, the team wished to verify that the structural integrity of the glider could be maintained while experiencing a wide range of forces on different parts of the plane during rocket launch. Finally, we hoped to learn the effect that the placement of the rocket motor on the glider had on the ultimate glider flight path and if any major modifications would have to be made to ensure the glider would launch successfully to the desired height.

The setup and results of the first rocket launch were also detailed extensively in previous reports, but will be summarized here. A rocket mount made of a PVC tube and two faces of ABS plastic was attached to the glider with duct tape to allow for repositioning as necessary. The rocket was positioned to aim through the center of gravity of the glider. The rocket mount also had holes to allow for the glider to be attached to the launch pad, which consisted of a plywood base covered in sheets of aluminum with 45 degree inclined guide rails to position the glider for launch. The rockets were ignited using rocket igniters, a launch controller, and a LiPo Battery. The setup for this test also included the removal of electronics so as to protect them from damage, as well as the addition of heat shielding tape that can withstand up to 1100 degrees Fahrenheit to the body of the glider to prevent burn damage. Manual control of the glider was maintained by incorporating just a receiver for the radio control. The rockets used included two F50 motors that weigh 83 grams, have a 1.6 second burn time, a max thrust of 79.6N, an average thrust of 53.7N, and a max lift-off weight of 1020 grams. The third rocket was a larger model, the G79 motor that weighs 125 grams, has a 1.3 second burn time, a max thrust of 100.7N and average thrust of 79N.

These tests demonstrated unstable rocket launch, but the glider's structural integrity was maintained throughout the three launches. The moment causes by an offset between the rocket motor and the center of gravity caused the plane to loop instead of launching straight at a 45-degree angle (http://vimeo.com/62568548), Thus, it was determined that the positioning of the rocket was the most essential design change to be made. For later tests, a new rocket mount was designed that allowed for more accurate positioning through the center of gravity. Moreover, the launch pad's rails were unstable and the method of glider attachment did not allow for the glider to have the support of the guide rails for more than a few inches into the launch. It was thus decided that the launch pad should have more stable and longer guide rails positioned farther apart to allow for a more stable attachment of the glider and longer flight course over the rails.

Our next set of tests on April 7th consisted of a similar set-up, but with a new rocket mount and more accurate determination of the center of gravity. We used a pin-and-string method to continually move the point until the plane was balanced on each axis to determine the CG. The new rocket mount consisted of a fiberglass tube encased in a 3D-printed structure that allowed for easy maneuvering of position through the use of zip-ties. As can be seen in the testing videos (http://vimeo.com/63542682), launch stability was achieved during these tests. The glider launched as desired at about a 45-degree angle. However, the glider experienced greater lift forces and much higher velocities during the stable launch, about 40 m/s. These increased forces caused the wings to break during launch. Previous stress calculations and initial testing had caused us to not consider structural integrity as a prime issue, but these tests altered the design course. After these tests, it was determined that the glider wings would have to be reinforced with carbon fiber.

The final set of tests on April 15th resulted in a successful rocket launch due primarily to the design changes made after the previous tests. The same rocket mount from the April 7th tests was used to position the rocket accurately through the CG, resulting in stable launch. As mentioned above in the "OVERALL DESIGN" section of the report, the addition of extra carbon fiber rods through the wings added structural strength with an approximate factor of safety of 2.55. As can be seen in the final launch test videos, the glider launched at a stable 45 degrees and remained intact throughout flight (https://vimeo.com/64600988). However, the structural additions to the glider seemed to have affected its flight characteristics, causing the glider to not achieve stable gliding flight after rocket launch. This is something that future testing could confirm, and if a new team investigated this in the future, they might consider using a stronger glider or a custom-built glider.

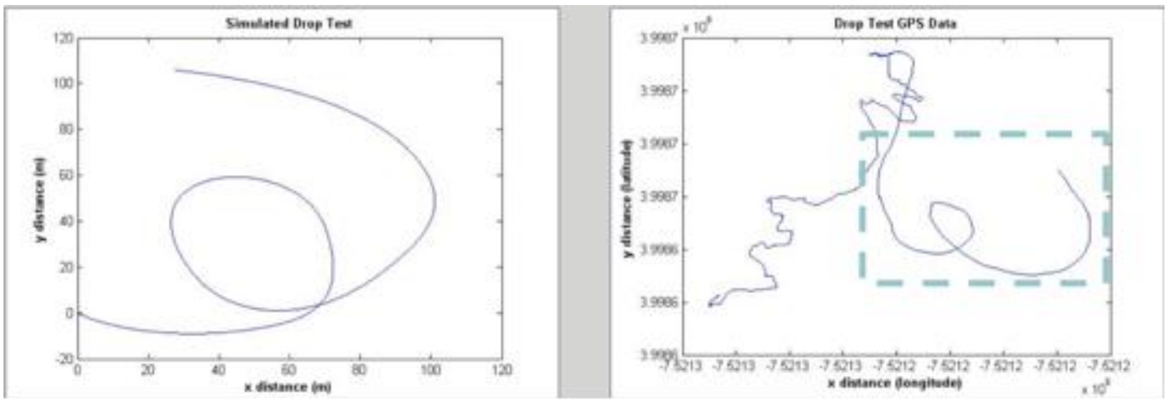
Alongside the rocket tests, we also performed several tests of the autonomous flight system. Small scale tests were performed on the ground to test the interaction of the Android ground station with our custom ArduPilot flight mode to ensure selecting a waypoint would trigger action from our controls system based on a PID controller for the rudder, causing the glider to attempt to fly towards the waypoint. This system seemed functional, but a full-scale helium balloon drop test with the autonomous system resulted in unstable flight and subsequent crash. This seemed to be caused by both the changing flight characteristics due to the addition of the carbon fiber rods and the inherent difficulty of tuning the controls system, especially with flight controlled purely by the rudder. Moreover, the release mechanism from the balloon means that the glider does not begin its flight in a stable position, which causes the autonomous system to overreact to control the glider, ultimately leading to completely unstable flight. The subsequent crash during this flight on April 4th resulted in irreparable damage to the ArduPilot transmitter. This rendered future tests impossible until a new transmitter was received about a week later. This delay ultimately meant that fully autonomous flight was not achieved before the Design Day on April 17th.

The customer requirements changed purely for altitude and loiter time. For our tests, we used F50 and G79 motors. The stable tests on April 15th were achieved using the F50 motors, as a precaution, so less altitude was achieved, about 200 ft. The maximum altitude with the G79 motor would be about 344 ft. The loiter-time with successful gliding flight would also be about 77 seconds. Both of these values are slightly lower than previous customer requirements, but the customer stressed stable rocket launch to flight with data verifiable by the MATLAB flight simulation over actual altitude and range goals, which we did achieve.

Validation of Testing using MATLAB Simulation

After our first drop test, we were able to extract time series of data from the Ardupilot that included the time dependent angles of the various control surfaces, the orientation of the glider, as well as the GPS position of the glider. We can further validate the simulation by creating an interpolation function that will feed in the rudder angles as a function of time into the ODE45 simulation and comparing the simulated path to the actual path as determined by the onboard GPS.

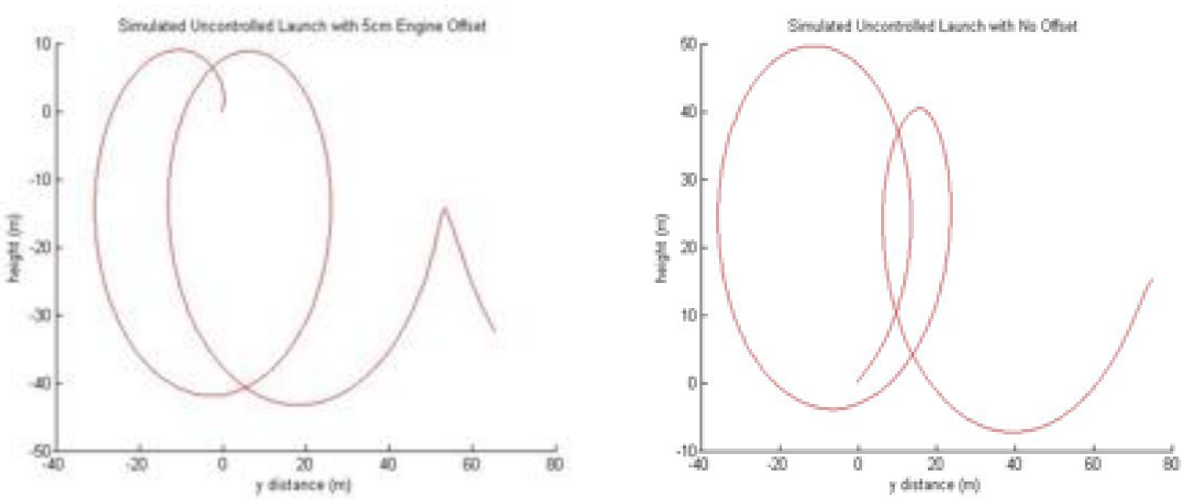
While we didn't expect the simulation to be exact, we were able to see that the simulation produced a flight path that closely imitated the shape of the actual drop test path. Discrepancies can be accounted for by varying environmental conditions (primarily wind), non-exact geometric specifications from out particular glider that are inputted into the model, as well as measurement error of the Ardupilot.



Figures 8 and 9: Simulated Drop Test (left) and GPS position data from drop test (right)

Validating Rocket

We also used the simulator to see if we could generate a flight path similar to the one observed in the video of our first rocket launch. When setting all control angles to zero we simulated these resulting flight paths which mimic our observations:



Figures 10 and 11: Simulated uncontrolled launches with no rocket offset (left) and a 5 cm offset (right)

PROPOSED IMPROVEMENTS/LESSONS LEARNED

As a direct consequence of the nature in which our team tested the autonomous flight aspect of the project separately from the rocket integration component, the final design is limited in its capability to combine both a successful launch with stabile and autonomous flight. Future improvements should be concentrated on optimizing the design in such a way that allows the glider to reach the necessary altitude after launch and then transition into autonomous flight mode. A major limitation of our final design is that it is customized with the aim of improving structural integrity necessary for a successful launch, but as a result is not ideally designed to sustain gliding flight. The reinforcements along with the other onboard components add too much additional weight to the glider. This weight inhibits the glider from reaching greater altitudes and also shortens the loiter time the glider can sustain. Furthermore, the carbon-fiber rods alter the aerodynamic properties of the air foil, which has a negative impact on the ability of the glider to reach its designated waypoints.

In order to address these shortcomings of the design, two easily identifiable solutions exist. First, the carbon-fiber reinforcements could be embedded in the wings of the glider as opposed to being attached to the top of the air foil. This will eliminate any negative effects to the aerodynamic properties of the wing while still providing the structural reinforcement necessary to survive launch. However, this solution doesn't address the need to decrease the weight of the aircraft in order to improve flight performance. The second proposed solution, integrating a wing deployment mechanism, would allow for the use of more light-weight materials. A wing deployment mechanism would allow the wings to remain tucked against the body of the aircraft during the launch phase. Once the glider reaches its maximum altitude, the wings would deploy to their flight position which would allow the glider to fly as originally designed. By being tucked during launch, little to no reinforcement would be necessary since the wings would be subjected to much lower lift forces. Additionally, this design would improve the stability of the glider during launch by moving the center of pressure further backwards. By using this type of system, less material would be needed for reinforcement which would decrease the weight of the glider and improve its ability to autonomously fly.

If the team had managed to achieve initial success with the autonomous flight controls system, several improvements could have been made to improve the system and the ground station for controlling the system. First, the controls could be extended to use the elevator and ailerons. The addition of controllers for these surfaces could allow for better navigational control, as well as stability control. The Android ground station could also have been further modified to allow for obstacles to be programmed via the Google Maps UI similarly to how waypoints are chosen.

If we were to do the project again, we would start rocket testing earlier. We focused the first semester entirely on characterizing gliding flight and programming autonomous flight. We falsely assumed that incorporating the rocket would be a simple process. The process turned out to contain many more variables and be a much more involved process. Had we began rocket testing earlier, we could have spent more time characterizing rocket flight. Given more time, we would design and build a wing deployment system. Reinforcing the wings to survive rocket launch affected the glider's flight during the gliding portion. We would not have to reinforce the wings if we deployed them once the launch phase was complete; therefore, the plane's behavior during gliding flight would be more similar to that of our first drop tests.

Alternatively to building a wing deployment system, we considered building a plane entirely of carbon fiber. We feel that this would have been feasible because we were able to build and test an airfoil constructed out of carbon fiber. The plane survived launch and glided briefly with the custom carbon fiber airfoil.

REQUIREMENTS COMPLIANCE

Functional Requirements Summary

Requirement	Metric		Final Status
	Simulation	*Testing*	
500m Minimum Range	800m	300m	Partially Successful
Use a G Rocket Motor	N/A	Tested in field, not 100% successful	Partially Successful
Glider must be Fast and Easy to Deploy	N/A	Roughly 5 min setup time	Successful
Real time video of the surveyed area	N/A	30 fps	Successful

Functional Goals Summary

Goal	Metric		Final Status
	Simulation	*Testing*	
Autonomous Flight	Fully modeled	Not yet implemented	Partially Successful

Simulation Based Apparatus Specs

Max Altitude	344 ft	**Max Possible Range**	0.5 Miles
Total Weight (w/out rocket)	760 g	**Average Drag**	47.8 N
Total Weight (w/ rocket)	850 g	**Max Lift**	34.31 N
Max Velocity	51.71 m/s	**Max Tensile Strength on Carbon Support Rod**	3.5 GPa
Average Velocity Over Rocket Burn	39.81 m/s	**Realized Stress on a Single Carbon Support Rod**	3.67 GPa
Average Velocity	12.46 m/s	**Realized Stress on Three Carbon Support Rods**	1.22 GPa
Loiter Time	77 s	**Factor of Safety**	2.55

Analysis of Requirements Compliance

- 500m Minimum Range:

The customer initially established 1km as the minimum range of the glider, but during the course of the year this was revised downwards to 500m. This revision was partially due to the fact that the customer was more interested in proving the concept rather than having a finished product. Further, any longer flight ranges than 500m would have required the team to find a testing site much further away than the one it used, Fairmount Park. The team was partially successful in meeting this functional requirement. The MATLAB simulation of the full flight projected a range of 800m, well beyond the minimum range functional requirement. However, in the course of field testing the maximum distance the glider flew was around 300m. This discrepancy can be explained by a variety of factors. First and foremost, the team never conducted a test in which the glider flew in a straight line as it would to maximize range. Due to the size constraints of the testing field, the team always landed the glider by flying it in a looping pattern which obviously reduced the range. Also, as explained in more detail in the following section, the team was unable to conduct a flight test with G rocket motors, settling instead for F size motors. This reduced rocket size would have had a significant effect on glider range. In summary, the team was close to meeting this requirement, and may have been able to meet it with proper testing conditions, but never fully validated a minimum range of 500m outside of in simulation.

- Use a "G" Rocket Motor

The customer established using a "G" rocket motor as a functional requirement because this was the largest size rocket motor that the team could obtain without a special permit. This lack of special permits was important to the team because it meant that they could test the glider in a public park instead of traveling into a much more rural, distant setting. Throughout the rocket testing process the team used both F (53.7 N average thrust) and G (79.0 N average thrust) size rocket motors. However, the only completely successful flight tests performed used F size motors. In the prototype iteration phase in which the team was validating its glider design, structural tests were run with both size motors and both sizes seemed to be fine. When the team moved onto stability tests the structural strength problems re-emerged. Due to time constraints, the team focused on proving the functionality of the final product with F size motors, in which it was generally ultimately successful. Near the end of the semester the team attempted to use G rocket motors but all 5 rockets we tested misfired. The team believes this malfunction was due to the fact that the rockets had been left exposed to air and moisture for several weeks which meant that they could not ignite. In summary, the team was only fully successful using the class of rocket engines directly below G size. Given more time it is quite likely that the team would have been successful with G rocket motors as well.

- Glider must be fast and easy to deploy

In order to justify using rockets to launch the glider, short deployment time would have to be extremely important to the user. As such, the customer established "fast and easy to deploy" as a functional requirement. Though no specific criteria were given by the customer to measure this requirement, the team is confident that it successfully met this requirement. Once the team ironed out some kinks, the total time to setup and launch the glider was about 5 minutes. The procedure was as follows: (1) set the rocket on the launch rails, (2) using the rocket mount attach a rocket to the glider, (3) setup and turn on the live video streaming equipment, and (4) launch the rocket. No real technical training whatsoever would be required to operate this system (besides possibly actually flying the plane if the user desired to use manual mode). Further, once launched the glider would be ready to stream surveillance video in a matter of seconds.

- Real time video of the are being surveyed

The primary functional purpose of the rocket launched glider is to provide almost instantaneous surveillance to users on the ground, so one of the most important functional requirements established by the customer was the ability to stream live video back to the user. The team was completely successful in meeting this requirement. As evidenced in clips at various portion of this video, http://vimeo.com/64600988, the final version of the glider transmitted high-quality at 30 fps back to the user. This would be fully adequate to identify targets of interest in the areas being surveyed to the end user. Further, this portion of the system was tested and found to be extremely robust. Even on launches in which the glider had a hard landing there was no apparent damage to the video equipment. Also, the video streaming is completely independent of the microcontroller portion of the electronics system (see Figure 7) so any damage to the microcontroller or its associated components would not hinder video streaming.

Analysis of Functional Goals

- Autonomous Flight

The customer listed autonomous flight as a goal rather than a strict requirement because the system would be completely operable and useful with or without autonomous flight. The only advantage to having autonomous flight is that it would simplify and streamline the user experience. Further, it would allow users with no prior flight experience to operate the glider. The team was able to fully implement and demonstrate autonomous flight in simulation (see Figures 5 and 6) though not in full scale testing. The primary reason for this were time constraints of the project. Due to setbacks in the rocket integration phase of the project and a general underestimate of long this phase would take, the team was left with no time at the end of the semester to fully integrate the autonomous flight mode with the rest of the glider. However, the team did conduct some promising simple ground tests which indicated that the autonomous fight mode was generally correct. After setting a waypoint in software, perturbing the plane would cause the control surfaces to react as they should have. For example, if the autonomous mode instructed the plane to turn right, the rudder would deflect the correct way. To summarize, autonomous flight was accomplished in simulation but not validated through testing. Given more time, the team is confident that they would have been able to integrate it with the other systems.

COST

As of our midterm report, the total cost of our project– as outlined below– was $1193.57, which still left about $300 in our budget. The remaining expenses included the order of the recording device and video screen, which has a total cost of $93.90, and four more rocket motors, two F50s and two G79s, for a total cost of $108.46 (including the $25 Hazmat fee required for shipping of the rockets). For the motor mount, we ordered a 29mm G12 Fiberglass Tube for $9.95 and a ⅛ inch G10 fiberglass sheet for $17.10 from Wildman Rocketry. We will also replace the launch pad rods with two Low-Carbon Steel Rods, 3/8" diameter from McMaster-Carr for a total of $15.56. These three items total $42.61 bringing our grand total to $1448.54, leaving us $61.46 for the remainder of the semester.

Item	***Category***	***Component Name***	***Cost ($)***
11.1V LiPo Battery	Electronics	ZIPPY Flightmax 2200mAh 3S1P 25C	8.99
5V Voltage Reg. (2)	Electronics	HobbyKing UBEC 3A	7.42
Microcontroller	Electronics	ArduPilot Mega 2.5	199.99
Servos (6)	Electronics	Power HD-1900A	23.94
Telemetry Unit	Electronics	3DR 915MHz Kit	74.99
Video Transmitter	Electronics	FPV1012 Plug and Play 1.2Ghz 1000mW	199.99
Video Camera	Electronics	Sony WDR770	129.89
6 Channel Receiver	Electronics	Tactic TR624	Donated

RC Transmitter	Electronics	Tactic TTX600	Donated
Servo Jmpr. Wires (10)	Electronics	3DR 15cm Female-Female Servo Cables	17.50
Servo Ext. Wires (10)	Electronics	Futaba 30cm Servo Extension Cables	19.90
Servo Ext. Wires (10)	Electronics	Futaba 30cm Servo Extension Cables	19.90
LiPo Battery Charger	Electronics	Hobbyzone LiPo Battery Charger/Balancer	Donated
A/V HDMI Converter	Electronics	Sabrent Component Video/RCA Audio to HDMI	42.86
Test Glider #1 (3)	Structures	Hobbyking Bixler 2 EPO	209.97
Test Glider #2	Structures	Skywalker Falcon Flying Wing	35.99
Drop Test Balloon	Structures	Kaymont Cons. Ind. 1500 gram Weather Balloon	Donated
Drop Test String (3)	Structures	Premier Kites 500 ft of 30 lb test string	20.97
Drop Test Spool	Structures	Uxcell 7.5" Kite Reel	15.99
Pre-Preg Carbon Fiber	Structures	NB301 3K 2x2 Twill 50" 45+5/-3% Black 1% TIP, 10 linear feet (50" wide roll)	Donated
G79 Rocket Motor (2)	Structures	G79-10 29mm, Hazmat Required	$43.48
F50 Rocket Motor (2)	Structures	F50-4 24mm, Hazmat Required	$39.98
Rocket Igniters (3)	Structures	First Fire jrs, Requires 12V	$28.77
Launch Controller	Structures	INTERLOCK CONTROLLER 12VDC	$47.95

Hazmat Fee	Structures	Shipping Company Hazmat Fee	$25
Plywood	Structures	Rocket Launch Pad	Donated
Aluminum	Structures	Launch Pad Heat Shield	Donated
Steel dowels (2)	Structures	Launch Pad Takeoff Guide Rails	Donated
Video to USB converter	Electronics	EzCAP116 USB 2.0 VHS to DVD Converter	$31.95
Heat Shield Tape	Structures	Thermaflect Tape	$29.02
Heat Shield Tape	Structures	Cool Foil Tape	$17.99

During testing after the midterm report, we crashed our last fully functional plane. The Ardu Receiver broke during this crash. Additionally, four of our rockets were “duds” and did not ignite. The crash plus the duds required us to purchase three new planes, four new rockets, and a new Ardu receiver. We purchased the rockets on our own, but we purchased the ardu receiver and rockets through the business office for a total of 269.24. Additionally, the business office purchased six new planes instead of three. Upon receiving six new planes, we assumed that HobbyKing made an error in our favor, so we used them all. We did not realize that the business office covered the expense of all six planes with project funds until we received our final financial analysis. Below is our final Financial Analysis from the business office:

FINANCIAL ANALYSIS

MEAM Design Team 7 - Rocket UAV

Joshua Elkind, Jesse Morzel, Alexander Reiner, Fiona Strain, Sophia Stylianos

July 1, 2012 - June 30, 2013

Revenues:			
Departmental Funds - $300/member		1,500.00	
Income - Other		0.00	
Total Funds Available for FY2013:			1,500.00
Expenditures - 07/01/2012 - 03/31/2013:			
DIY Drones - 3D Robotics 33483	205.65		
HOBBY KING - Hextronik 2005580325	182.73		
Hobby Wireless	329.88		
DIY Drones - 3D Robotics 34395	80.65		
PAYPAL UHOBBIES (Hobby King) 2005685195	68.58		
Hobby King - Hextronik	83.24		
3d Robotics 3406-37466	198.15		
Chief Aircraft.com 100026716	36.17		
HOBBY KING - Hextronik 2006077799	207.98		
HOBBY KING - Hextronik 2006084090	207.98		
Amazon 103-0633200-0450607	31.95		
Hobbyzone HZ-5277537	52.03		
Red Arrow Hobbies	186.18		
RACEPROUSA	69.01		
	0.00		
Total Expenditures		1,940.18	
Commitments:			
Amazon 110-7521683	68.90		
Ebay/FishingCali 7MW01814C	33.50		
McMaster Carr PO 2964922	15.56		
Wild Rocketry 2430	40.87		
3D Robotics 44762	62.24		
	0.00		
Total Commitments		221.07	
Total Expended and Committed			2,161.25
Uncommitted Balance:			(661.25)

D.Sokalczuk
04/11/13

APPENDIX

Wing Factor of Safety Calculations

Because the foam bears a negligible amount of the stresses due to lifting, we modeled the wing as three carbon fiber rods. The rods we used had a diameter of .25" or .00635m. We found the maximum lift force experienced by the wings during the rocket launch to be 53.7N via the MATLAB simulation. Each wing is .75m long. According to Hexcel Corporation, the yield strength of carbon fiber is 6140 MPa.

$$\sigma = 3*[\frac{Mc}{I}] = 3*[\frac{(Fd)(r)}{(\frac{\pi(2r)^4}{64})}] = 3*[\frac{(53.7)(.75/2)(.00635/2)}{(\frac{\pi(.00635)^4}{64})}] = 3*[\frac{0.0639}{7.9811e-11}] = 3(8.01e8) = 2.403e9Pa = 2403MPa$$

$$FS = \frac{MaterialStength}{DesiredLoad} = \frac{6140}{2403} = 2.54$$