Project Proposal and Feasibility Study

Team 2 – 🔄!

Ian Hoffbeck, Tom Kok, Brett Pennings, Christian Swenson
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1 INTRODUCTION

1.1 SENIOR DESIGN

Senior design is a class dedicated to testing the abilities of Calvin engineering students before they enter the work field. The class allows the students the freedom to discern a project that will improve their engineering skills, but also benefit the general public. The class consists of lectures that prepare the students for the work field. These lectures include guest speakers from the industry along with professors speaking on issues like communication and team building. The lectures, combined with this project, will give the students an idea of how a project in the job force will be handled.

1.2 TEAM DESCRIPTION

Our team consists of four undergraduate senior engineers from Calvin College. We are excited about this project and are eager to make progress and see results. Our names and concentrations are listed below our pictures.

![Ian Hoffbeck (EE) Christian Swenson (ME) Tom Kok (ME) Brett Pennings (EE)]

Ian worked at Northrop Grumman this past summer and has an interest in optics. Christian is minoring in mathematics and has interned at Airbus. Tom has a passion for aircraft and has internship experience in optics research. Brett has a computer science minor and internship experience writing in C, an experience which should prove useful to the completion of this project.

1.3 PROBLEM STATEMENT

Humans are good at a lot of things, but they have some real limitations. They typically have trouble staying interested with tedious, repetitive tasks; they have to sleep and eat, and they can’t fly. Humans design and build robots, like Plane!, to do these kinds of tasks. Our goal is to design and construct a prototype of a small, low cost, aerial data acquisition system. Unmanned aerial vehicles (UAVs) have long been used by the military in reconnaissance applications, but they have yet to trickle down into the affordable consumer market. This is surprising as there are significant applications for such a system to be utilized in many fields including scientific research, search and rescue applications, security monitoring and surveying. We aim to create a system that will allow companies and individuals, without defense contracts, to perform data acquisition that would otherwise be impossible.
Our system is specifically intended for use by the Calvin College Biology Department to aide their research of canopy composition for the Calvin College Nature Preserve. The plane must have a flight time long enough to map out the entire nature preserve in a single flight from an altitude of about 100 ft. The plane must be robust enough to repeat this procedure for an entire research season with minimal maintenance. Additionally, the system should have an intuitive enough interface that non-technical users can operate it. We intend for the plane to operate fully autonomously during normal flight. Takeoff and landing will be controlled using the manual controls built into the RC aircraft so as to fit the project within time and budget constraints.

2 Objectives

The final design must meet these design objectives:

1. Design a UAV capable of 5 minutes of sustained flight.
2. Design a UAV capable of autonomous navigation and stabilization.
3. Design a simple, intuitive user interface for programming flight paths.
4. Determine a method of recovery that is safe for both the UAV and the operator.
5. Keep costs below a level acceptable to small research institutions (approx. $500).
6. Design a robust UAV which is simple to maintain and easy to repair.
7. Develop operating instructions.

3 Design Norms

As Christian engineers, it is important to remember that faith in the Lord must play an integral role in every step of the design process. A Christian engineer is responsible to his clients and managers, but ultimately he is responsible to God. This responsibility manifests in many ways throughout the project. He treats his superiors with respect, as God-appointed authorities. He works diligently and honestly. And he continually seeks to understand how this design will affect the world that God has given us and the people who live in it. The process of design from a Christian perspective has been described by a set of design norms, or standards, four of which are explained below in how they relate to this project.

3.1 Transparency

Transparency is achieved by good documentation of this project. A person can look at the documentation and understand how decisions were made. The budget for the project will be documented so that the product will be financially transparent to the public. This project is kept simple so that the user can easily operate the product. This keeps the product transparent for the end user. It is important to keep the design simple to satisfy the customer by having easy operation.

3.2 Stewardship

This project represents stewardship in several ways. The first way is financial stewardship. The aircraft will allow people to capture aerial photography without having to pay as much money. Currently a plane must be rented and a photographer must fly over the designated area to take pictures. This can cost thousands of dollars. This project will allow people to take aerial photographs when necessary for several hundred dollars. It also allows smaller organizations and institutions to do research that would be impossible because of the high prices. It shows
environmental stewardship because it reduces greenhouse gas emissions. With our device, people will no longer need to rent airplanes to take aerial photographs. This reduces the amount of fuel that is burned and thus reduces greenhouse gas emissions.

3.3 Caring
Caring was designed into the concept of the aircraft. This project cares for both the environment and the digital divide. The aircraft shows creation care for the environment because it runs off electricity. This makes the aircraft create less noise pollution and no carbon emission. It also helps make environmental research easier. It applies to caring about people too. The digital divide is the idea that the upper class keeps getting more advanced, while the under classes are left with older technologies that leave them disadvantaged to the upper class. This aircraft closes this divide by allowing researchers with less money to conduct research that was originally too expensive for them. This allows for such projects as removal of evasive species in nature preserves. This improves people’s ability to take care of these nature preserves.

3.4 Trust
The trust is shown by the end user. The biology department is the end user for this project and they trust that the end product will meet the criteria that were requested. The biology department is trusting that the aircraft will perform the necessary tasks that they desire. The project will exhibit trust by completing these requirements set forth by the biology department.

4 Project Management

4.1 Task Specifications
Since our team has split concentrations, we are naturally obligated to specialize in different areas of the project. In a general sense, the mechanical engineers (MEs) will deal with the physical characteristic of the plane and the electrical engineers (EEs) will be responsible for the plane’s hardware and software. We will all be conducting research, testing, and revisions based on test results from various subjects; each subject will be dependent on our concentrations.

4.1.1 Mechanical
The physical traits of Plane! that the MEs will be focusing on include airframe choice and modification, stress-strain analysis, center of gravity calculations, component harnesses and failsafe parachute design. The MEs have already decided on the Bellanca Decathlon 480 RTF airframe. They plan to add structural support to the wings and determine the best placement for the components. The MEs will design a harness to secure the camera to the plane without significantly affecting its aerodynamics or mass.

4.1.2 Electrical
The hardware components that the EEs will be dealing with are a GPS receiver module, an accelerometer, IR detectors, an antenna, a microcontroller, and servos. The software components will be the IDE for the Arduino microcontroller and Matlab for the image mapping. Brett will deal mainly with the interfacing of the parts, the algorithms for guidance and general coding. Ian will work on requirements and algorithms for stability as well as image mapping and user interface in Matlab.
4.2 **Team Organization**

Our team consists of two electrical engineers and two mechanical engineers. The project has been broken down into milestones based on critical tasks. Initially the milestones are divided into mechanical tasks and electrical tasks, but as time goes on the milestones integrate the electrical and mechanical components. Each concentration has set a reasonable time limit to complete these milestones. As projects start, each concentration makes their own decisions based on their research and then reports to everyone in the group meetings before taking action. If the entire group is in agreement about the decision, then the decision is acted upon. If the decision is rejected, then more research and alternative options are considered until the group agrees on a decision.

4.3 **Schedule**

Completing the project on time is especially important for our team. Our goal is to deliver a functioning prototype to the biology department by the end of second semester. To do this, the project must have a clear timeline. We broke the project down into a number of critical milestones and divided them between the team members. First, we completed research to give us an understanding of how UAVs are built, and what parts will be appropriate for a project of our scope and budget. Second, we selected several of the important electrical components and ordered them. Then we began the process of designing the critical systems of the aircraft. Each system will be developed through a process of development, testing, and redevelopment. Once a satisfactory design had been achieved, we can then move on to the next system. The Gantt chart below shows the progression of the different processes. The development of the guidance and stabilization systems is especially heavy in electrical engineering work. In order to even the load, we endeavored to do as much mechanical work as possible concurrently with the design of these two systems.

![Figure 1. Project Gantt Chart](image-url)
5 PROPOSED DESIGN

5.1 AIRFRAME

5.1.1 AIRFRAME PROPOSED DESIGN
The airframe that we have chosen is the Bellanca Decathlon 480 RTF. We chose this aircraft because it is a beginner plane. The Decathlon 480 also has a large fuselage, leaving plenty of room for installing the electrical components. It also has enough power to carry the necessary payload of the camera and the electronic components. The aircraft also has three sets of control surfaces. This helps with the guidance system because the plane does not need to be banked in order to turn. If the plane had to be banked, it would make the stabilization system more complicated. The spare parts for the Decathlon 480 can also be easily accessed through the provider. All parts are available from engines, to wings and fuselage. This is convenient because if the biology department breaks the aircraft, they can easily order the necessary spare parts for less than $20 each.

5.1.2 AIRFRAME ALTERNATIVE DESIGN

5.1.2.1 CUSTOM DESIGN
The first alternative design that was considered was a custom made airframe. The mechanical engineers would have designed the frame to meet the specifications of the project. After assessing the necessary time to customize the airframe and the required calculations, it was decided that buying the airframe was the better option. Spare parts are also available. If the airframe was custom made, then spare parts would have to be fabricated, but now the biology department can order parts online if necessary.

5.1.2.2 FLYING WING
Along with a custom design, several types of aircraft were investigated. One option that was discussed was a flying wing. A flying wing consists of a large fuselage, where the entire aircraft acts as a wing. Figure 2 shows an example of a flying wing.

![Figure 2: Flying Wing](image)

Research was done on this type of aircraft and the pros and cons were evaluated. The research found that a flying wing was a good option. It had a wide range of speed that allowed the aircraft to slow down in order to take pictures, but speed up to reach its destination. It had a large fuselage that would have allowed us to fit the components into the body of the plane. It also was very aerodynamic so that the power draw from the propellers would be decreased. Another convenient application is that the aircraft could be launched by hand and landed on the grass with minimal damage to the airframe. There are several cons to this aircraft that outweighed the pros. The first problem was stability. A flying wing is not very stable. The aircraft would be hard to manage in windy conditions and the aircraft would have the potential of flipping over. Since the stabilization system is automated, a
more stable aircraft was preferred. The second con is that the airframe would be one solid piece. If the airframe were to become damaged the entire airframe would need to be replaced. This is different than most model airplanes. If the wings are damaged in a more traditional model airplane, then the wings can be replaced. This would be costly if the body was damaged. After analyzing the pros and cons of a flying wing, it was decided that a more traditional aircraft would be a better choice. The stabilization system will be difficult, so having a more stable aircraft will help when designing the stabilization system. The second reason is because of the fragility of the airframe. It is undesirable to have to replace the entire airframe if a crack forms in a small section. It would be must easier for the end user if he or she could simply buy a replacement for the damaged part. Because of these two reasons, we rejected the idea of using a flying wing as our airframe.

5.1.3 AIRFRAME DESIGN CHALLENGES
There are several design challenges that the airframe presents. The first is attaching the electronic components. The components must fit into the fuselage and they also must be made to withstand the environment. The aircraft will be flying in variable weather and has the potential to collect moister in the fuselage after several usages. So the airframe must allow the electronics to be protected. The airframe must be adapted so that a parachute can be deployed. The airframe will need to be modified to attach the parachute and calculations must be done so the airframe can withstand repeated stress caused by the parachute deployment. The airframe may need to be reinforced to accomplish this task. The airframe will also need center of gravity calculations before we add the electronic components to the airframe. These calculations will be challenging as we try to optimize the position of all the electronics.

5.2 FASTENERS
The electronic components in the design will be secured inside the fuselage by means of fasteners. In designing these fasteners, several requirements were considered. First, the fasteners must hold the electronics securely enough to prevent the electronics from rattling around during sharp turns or turbulence. Failure to secure the electronics could result in impact damage to the electronics or stability issues due to a moving center of gravity. Second, the fasteners should minimize interference with the fuselage design. This ensures that the structural integrity of the fuselage will not be compromised. Third, the fasteners should add a minimum amount of weight to the final design. Any additional weight added to the airframe will decrease flight performance and flight duration. It was decided that bracket style aluminum fasteners would be used in the final design.

5.3 ANTENNA
5.3.1 ANTENNA PROPOSED DESIGN
An antenna is required for the GPS system to receive displacement information. Our team ordered two different antennas. The first one is a simple, magnetic mount, patch antenna with an SMA connection. To interface this antenna with the GPS chip we also purchased an edge-mount SMA connector. The second antenna is a much smaller and lighter, but more complicated, chip-scale antenna. This will be difficult to interface with because of its size and requirements on the printed circuit board. In an ideal case, we would be able to use both antennas depending on the situation; the chip-scale antenna could be used in flight because of its minimal footprint and the more dependable magnetic mount antenna could be used for debugging purposes on the ground because of its reliability and size. The use of two different antennas is recommended by other developers. The expected radio frequency signal for the GPS is the same frequency that is detected by both of the antennas.
5.3.2 Antenna Alternative Design
Because the chip-scale antenna is small, and the printed circuit board layout it requires is complex, the alternative may be to use the large patch antenna instead. We may have to remove the magnet from the larger antenna to reduce its footprint on the airframe. This may not be a significant alteration in the design, but having two separate antennas to choose from would still be preferable.

5.3.3 Antenna Design Challenges
The antenna could present a very large difficulty if the patch antenna doesn’t work the first time we connect it. Since this antenna is so modularized, it will be nearly impossible to identify a problem if one arises. However, assuming that we can get the patch antenna to work, more difficulties are expected to occur in the chip-scale antenna because we have to build the complex printed circuit board for it.

5.4 Photographic System
5.4.1 Photographic System Proposed Design
*Plane!* uses an onboard camera to take pictures at the given waypoints. We selected the GE A830 because of its light weight, low cost and high pixel count. Even if there is some blurring of the images due to movement of the aircraft, the 8.0 megapixel image should still have enough resolution to be used for foliage detection and classification. The photographic system will be mounted to the bottom of the aircraft facing downwards. In order to increase the modularity of the system, the camera will have only minimal changes. The image capture button will be removed so that it can be directly wired into the airplane control system, and the case may be removed to reduce the total weight of the camera payload.

5.4.2 Photographic System Alternative Design
One possible alternative for the imaging system is a hard wired camera. This could potentially allow the plane to carry a lighter payload. For example, if an integrated camera did not have a LCD, or the hardware necessary to run a basic operating system, it could potentially be smaller, lighter and cheaper. However, *Plane!* is intended to be a modular system, so the simpler the interface, the better. The modular camera also necessitates a high level, low footprint, sensor interface. A hardwired camera requires power, integrated media storage and the like, requiring a reconfiguration if the sensor ever needed to be changed. Connecting different sensors is easier with the chosen interface.

A number of different sensors could have been used in lieu of the optical camera, including IR sensors, temperature sensors, or even a radio tracking device as suggested by the biology department. However, the optical camera has more intuitive and varied uses than any other. Additionally, tracking canopy composition was a primary goal of the biology department, and the optical camera filled this need well.

5.4.3 Photographic System Design Challenges
The primary concerns for the photographic system are the weight of the imaging payload and the clarity of the images. First, the airframe must be powerful enough to keep the camera aloft for the entire time of the flight. The airframe only has so much power, meaning that there is a definite maximum weight for the imaging payload. Staying within this constraint could be difficult. Second, the camera must take clear pictures. No stabilization system is planned for the camera, again due to time and budget constraints. The movement of the plane inherently is not ideal for image capture. In order to take sharper images the camera must have a short shutter speed, a narrow aperture, little movement, and be a sufficient distance away to have all targets in the same depth of field. This means that the plane must fly at a high altitude, with good stability, at low speed, in laminar wind
conditions, with as much light striking the ground as possible. Speed, stability and altitude are the only constraints that can be considered for our design. Developing a solid stabilization system and ensuring that we fly at the maximum height allowable by the FAA will help to improve image quality.

5.5 RECOVERY SYSTEM

5.5.1 RECOVERY SYSTEM PROPOSED DESIGN

One of the objectives of this project is to safely recover the UAV after a mission. Potential obstacles to accomplishing this objective are objects or people in the flight path and failure of one or more of the guidance systems. To ensure the safe recovery of the UAV under all conditions, it was decided to use a parachute recovery system. The parachute recovery system provides several advantages:

1. Allows for recovery in the event of guidance/power failure
2. Allows operation in areas with limited open space
3. Protects the airframe from high speed impacts during landing
4. Autonomous fail-safe operation
5. Reduces danger from obstacles at low altitudes

The main advantage of a parachute recovery system is that it provides a means of recovery in the event of power or guidance failure. The parachute system will be composed of a parachute and an electromagnet. During flight, the parachute will be folded and held to the fuselage by the electromagnet. Once the flight is finished, the control board will cut power to the electromagnet. This will allow the parachute to fall free of the airplane and deploy. Similarly, if a diagnostic check (such as the number of GPS satellites in range) returns an unsatisfactory answer, or if the power fails, the power to the electromagnet will be cut and the parachute will deploy.

An important secondary advantage of the parachute system is the ability to operate without a runway. This makes the UAV compatible with field work in a wide range of environments, from city parks to remote wilderness.

5.5.2 RECOVERY SYSTEM ALTERNATIVE DESIGN

5.5.2.1 CONVENTIONAL LANDING

As an alternative to the proposed parachute recovery system, the UAV could be recovered using a conventional landing technique controlled either autonomously or through the manual override.

5.5.2.2 AUTONOMOUS CONTROL

If the conventional landing where autonomously controlled, before takeoff the user would enter the landing coordinates as part of the complete flight plan. At the end of the flight plan, the onboard controller would gently reduce motor speed and altitude until the UAV landed. The advantages of this system are:

1. No additional hardware is required
2. The airframe is subjected to minimal stresses
3. The pre-made airframe comes with landing gear attached

However, the advantages of an autonomous landing system are offset by some obvious disadvantages:
1. Not all operational areas have sufficient room for conventional landing
2. The UAV risks collision with stationary and movable obstacles, including the user.
3. Software to control landing is extremely time consuming to write

The most noteworthy disadvantages of autonomously controlled landing are the increased risk to both the UAV and the user, and the additional cost in time and labor. The design team concluded that the cost of additional hardware for a parachute system was less than the cost of the additional time to create an autonomous landing system.

5.5.2.3 Manual Control
If the landing were manually controlled, at the end of the flight the user would push the manual override switch and guide the UAV to the landing strip. This method would have all the advantages of an autonomous landing system without the disadvantage of additional time lost in programming. However, a manual landing would require the end user to spend hours practicing the difficult art of flying a model airplane. This represents added risk to the UAV during both the practice flights and the operational flights. Additionally, a solely manual landing system provides no fail-safe recovery for the UAV in the event of a power loss. Because manual override is included in the proposed design the end user will have the option of manually landing the UAV, but the design team concluded that the extra effort to design and install a parachute recovery system was worth the reduced risk the UAV.

5.5.3 Recovery System Design Challenges

5.5.3.1 Induced Airframe Stress
Using a parachute to recover the UAV after every flight will place significant stresses on several parts of the airframe. Because the premade model airplane was not designed to handle this level of stress, it will be necessary to reinforce the airframe in several key areas:

- A brace will be placed across the top of the wings to prevent the wings from shearing off when the parachute opens
- The fuselage will be reinforced with several braces, solidly connecting the parachute to the engine mount, airframe, and electronics
- Braces will be placed in the vertical stabilizer and the horizontal stabilizers

All of the braces will be constructed from aluminum to reduce airframe weight. Calculations of the location and dimension of the braces will be performed when the force exerted by the parachute has been adequately determined in testing.

5.5.3.2 Deployment
Another challenge in designing the parachute recovery system is parachute deployment. A partially inflated or uninflated parachute will result in serious damage to UAV. Therefore it will be necessary to perform extensive tests to determine the best method of parachute deployment. Most parachute systems currently in use rely on a smaller guidance parachute to pull the larger parachute out. A similar system will probably be used to operate the parachute recovery system, but alternatives such as using a small weight or spring loading the parachute are also under consideration.
5.5.3.3 Electro-Magnet Strength

While the use of an electro-magnet in the recovery system design does provide fail safe operation, it has the serious drawback of consuming additional power during flight. To improve flight time it will be necessary to determine a way of minimizing the amount of power consumed by the electro-magnet. The most promising option currently under consideration is using a small lever to give the electro-magnet a mechanical advantage. This will allow the design team to use a smaller electro-magnet, which will consume less power.

5.6 Stabilization

5.6.1 Proposed Design

Our research has indicated that UAV stabilization will be the most difficult task in creating a functioning prototype. The stabilization system controls both the roll and the pitch of the plane in order to maintain level flight. To preserve level flight, we decided our plane should bank as little as possible when changing headings. Many planes use banking to change heading, or pitch up and down during normal flight; however, we believe that a flat level flight in all conditions will provide easier operation in a project so constrained by time and budget. Additionally, level flight should provide the navigation system a stable platform to control, and provides the stability necessary to take clear pictures. To do so the system must be able to handle inconsistencies in air flow, changes in wind velocity and direction, compensate for banking during turns, and maintain a steady altitude. Our stabilization system uses a combination of inertial measurement and objective reference sensors to detect the roll and pitch attitudes of the plane. Next the digital control system of the plane takes these readings and calculates the necessary compensations to sustain a cruise attitude. These compensations are then sent to the control surface servos via pulse width modulation, which physically correct the orientation of the aircraft. Figure 3 shows the layout of the aircraft control system with the stabilization components emphasized.

![Stabilization System Configuration](image)

**Figure 3. Stabilization System Configuration**

5.6.1.1 Sensors

Our design includes a four sensor stabilization system with a two servo output. The three axis accelerometer and the two-axis rate gyro comprise the inertial measurement unit (IMU) and GPS and IR determine an objective reference for the plane's stabilization. This sensor redundancy helps to maximize the reliability of our system. To maximize the reliability of this system, our design utilizes sensor redundancy. First, the three axis accelerometer and the three axis rate gyro comprise an inertial measurement unit (IMU) and second the GPS and IR determine an objective reading of the plane's stabilization. IMUs are a ubiquitous technology used in planes and boats of all
types. The accelerometer reads the acceleration of the aircraft in all three dimensions. This determines whether any force is pushing the airplane left, right, up, down, forward or backward. However, since the accelerometer only detects acceleration, the plane could be moving at a steady velocity in any one of the directions without being detected, producing a disastrously inaccurate reading of the plane's location. In order to compensate for this the rate gyro is added. The rate gyro detects the change in pitch, roll and yaw of the aircraft. Together, this system can determine the velocity of the plane in each direction at any given time. For example, if the UAV is in a banked turn, a component of the centripetal acceleration of the aircraft will offset the force of gravity vector, resulting in an inaccurate reading of acceleration. However, the rate gyro will be able to sense the change in roll required for a banked turn, and indicate that the plane is not level. From this reading, the microprocessor can control the elevators to resist the turn and level the plane's flight. In this way the IMU provides sufficient information to determine whether or not the plane is in steady level flight. In our design, we chose the ADXL330 accelerometer from SparkFun Electronics as it was low cost and has been used in several successful open source projects and is also used in the Nintendo Wiimote. We chose the IDG300 rate gyro also from SparkFun Electronics as it has been combined with the ADXL330 in other IMU systems.

While IMUs provide accurate and quick readings, each measurement is measured relative to the previous measurement. Small errors in these measurements accumulate resulting in a drift error. In order to correct this, a more accurate and objective system must be used. The IR sensor is designed to mitigate this problem. The sensor itself consists of four infrared thermopiles mounted orthogonally with one each facing forward, backward, left and right relative to the flight direction of the aircraft as shown in Figure 4.

![Figure 4. IR Sensor Configuration](paparazzi.en.fr)

The sensor operates on the principle that the ground is distinctly warmer than the sky. Therefore, a thermopile pointed at the ground will give a significantly higher reading than one pointed at the sky, as shown in Figure 5.

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1 Figure 4 from paparazzi.en.fr

2 Figure 5 from paparazzi.en.fr
In this way, two opposite sensors can only have the same reading if they are both pointed at the horizon, that is, if the plane is level. The IR sensor takes readings from two opposite thermopiles and feeds them into a differential amplifier. This difference is read by the microcontroller using the built-in analog to digital conversion ports and interpreted as an undesired roll or pitch. We chose the CDP4 Co-Pilot from FMA Direct as it has been successfully used in the ArduPilot UAV autopilot.

The second sensor in the objective reference is the GPS. While many of the GPS readings are useful to the navigation system, altitude, heading and airspeed are of primary importance to the stabilization system. The altitude determines the height of the plane and can instruct the stabilization system to increase or decrease pitch as necessary to correct altitude. As the airspeed of the plane is a critical component in determining lift, the GPS will also determine the regulation in the motor speed controller. The heading of the plane is another useful GPS reading, which can be calculated quickly using the current and previous position of the plane. Any detected change in heading means that some manner of turning must be occurring, and therefore the plane must be banking. This will help to correct any drift from inaccuracies in the rate gyro reading. While both of these readings can be very accurate, they take longer to calculate than the readings from the IMU. A combination of the signals from the IMU, the IR sensors and the GPS module give an objective reading with a detailed resolution of changes in pitch, roll and acceleration.

5.6.1.2 PROCESSING
The readings from the sensors must then be interpreted in order to correct the stabilization of the plane. Our design utilizes proportional integral derivative (PID) feedback control loops to maintain the stability of the system. Figure 6 gives the proposed feedback control loop for the three axis accelerometer.
The desired net acceleration is subtracted from the current acceleration as determined by the accelerometer. This difference is detected by the PID and a new pitch and roll is determined to compensate for the current acceleration. This new desired acceleration is fed to the servos controlling the elevators of the aircraft. The proportional, integral, and derivative gains must be trimmed to obtain a feedback response that is rapid with little overshoot. This tuning process will likely be the most time consuming element of the stabilization system design process. For this reason it is important for us to conduct flight tests as early as possible.

5.6.1.3 Output

The combined output from the PID controllers then must be sent to the elevators to control the plane. The roll and pitch of the plane are controlled simultaneously using the two elevators located on the tail of the aircraft. Most large aircraft have these two axes regulated by two sets of control surfaces. The ailerons on the wings of the plane control the roll of the plane and the elevators on the tail of the plane control the pitch. However, the Bellanca Decathlon, like many other model aircraft, has only three control surfaces: two elevators and a rudder. As the rudder is not used in the stabilization system, the elevators must control both pitch and roll. This need technically makes the elevators elevons, but the term elevator will be maintained for this document. The change in pitch and roll of the aircraft are related to the angle of the elevators as shown in Figure 7.

\[ \frac{d\theta}{dt} = k_p \left(\frac{\alpha_r + \alpha_l}{2}\right) \quad \text{and} \quad \frac{d\phi}{dt} = k_r (\alpha_r - \alpha_l) \]

Figure 7. Mathematical Relationships between Attitude and Elevators

Where \( \theta \) is the pitch attitude, \( \phi \) is the roll attitude, \( \alpha_r \) and \( \alpha_l \) the deflections of the right and left elevators relative to the horizon, and \( k_p \) and \( k_r \) constants of proportionality for pitch and roll respectively. So the change in pitch attitude is proportional to the average of the elevator deflection, and the change in roll attitude is proportional to the difference between the elevator deflections. We propose to have the desired change in pitch and the desired change in roll calculated separately within the microcontroller, and then combined to get the displacement sent to
the servos. In order to determine the desired deflection for the elevators, we solved for the system of equations in Figure 7 to yield the relationships in Figure 8.

\[
\alpha_t = \frac{1}{k_p} \frac{d\theta}{dt} - \frac{1}{2k_r} \frac{d\phi}{dt}
\quad \text{and} \quad
\alpha_r = \frac{1}{k_p} \frac{d\theta}{dt} + \frac{1}{2k_r} \frac{d\phi}{dt}
\]

Figure 8. Calculating Elevator Deflection given Pitch and Roll

We will use these equations to combine the desired change in pitch and roll of the aircraft. The time interval over which we desire the rudder to change, \( dt \), remains variable in this relationship. By varying the parameter \( dt \) we can control how quickly or slowly the aircraft responds to the calculated change in desired attitude. Once the desired deflection of the rudders has been calculated, the microcontroller instructs the servos, via pulse-width modulation, to fix the elevators at the desired deflection. As shown by the feedback control loop, these deflections will determine a new attitude of the aircraft and once again be used in calculating a new heading.

5.6.2 ALTERNATIVE DESIGNS

As the stabilization system is potentially the most difficult system to implement, it is also the most likely to not be completed by the allotted deadline. For this reason we chose a number of alternative designs that can be completed as discrete milestones. We believe this approach provides two primary benefits. First, setting milestones means some manner of operable prototype may be delivered to the end user. If unforeseeable problems prevent the timely completion of the project, the user will receive a functional system, even if it does not have all of the intended features. Second, by setting the bar high we are more likely to push farther during the semester. Setting for a simpler goal may allow us to let deadlines slip. While we have rejected all of the design alternatives as final products, we do intend to pass through them on the way to our goal.

5.6.2.1 REMOTE CONTROL

The Bellanca Decathlon functions as a remote controlled aircraft right out of the box. While autonomous stabilization is the end goal of this project, it would be possible to operate the system by remote instead of autonomously. This provides the ability for the user to take aerial photographs, but requires more input on the part of the user. We have rejected this option as a final objective for this project, but we intend to utilize it as a contingency plan in the event of an incomplete or buggy stabilization suite.

5.6.2.2 SOLELY INFRARED SENSOR

In our research, we found some systems capable of operating solely using the infrared detectors. Additionally the CDP4 Co-Pilot advertises the ability to return the aircraft to a cruise attitude simply by centering the control stick. For this reason, it is possible to operate the aircraft solely using the IR stabilizer. We do not believe that this will provide a robust system, as a fault in the sensor could cause a system failure.

5.6.3 DESIGN CHALLENGES

First, the aforementioned fine-tuning of the PID feedback control loops will require careful work. We will attempt to reduce this work by simulating the PID controllers on Matlab and Simulink. This measure is not guaranteed to give perfect answers, but it will likely reduce the time spent testing the system. Second we could experience difficulty from driving one set of servos with multiple sensors. A conflict between sensors could cause the system to become unstable. These problems can be mitigated by developing robust software routines to calculate which inputs to consider. A third challenge is the lack of realistic ground tests for the stabilization system. The elevators can only control the motion of the aircraft if there is wind passing over the control surfaces. A failure of the stabilization system at a full flight height and speed could irreparably damage the airframe or electronics. For this
reason, we must take care to perform tests at low speeds and altitudes, in favorable weather conditions. Finally, the stabilization system will be most limited by the number of flight tests conducted. The more flight tests, the more bugs can be fixed before the project is completed. While designing a fully functioning stabilization system will be a challenge, we believe that it is a feasible goal with greater rewards for its pursuit.

5.7 NAVIGATION

5.7.1 PROPOSED DESIGN

5.7.1.1 LAYOUT

Our approach to navigation is to use a GPS receiver module to obtain the necessary position, velocity, and heading. Based on similar small-scale autonomous UAV projects, GPS readings alone are sufficient for a plane to navigate. The layout of the electronics for the navigation system is shown in Figure 9. The radio controls from the user are multiplexed with the automatic controls from the microcontroller. The control line to the multiplexers determines whether or not the autopilot is engaged.

![Figure 9: Layout of Navigation System](image)

5.7.1.2 ALGORITHM

The current GPS coordinates and the next waypoint coordinates will be needed to calculate the desired heading. The GPS also returns current heading. These two heading measurements will be adequate for determining the appropriate rudder angle to perform successful horizontal navigation. Shown below is a simplified algorithm for determining the rudder angle from preloaded waypoints and current GPS readings.

Nomenclature:

- **Constants:**
  - $\tau_{gps}$ = period of GPS refresh rate
  - $k$ = proportionality constant

- **Preloaded variables:**
  - $x_{desirec}$ = next waypoint coordinates
  - $y_{desirec}$

- **GPS-obtained variables:**
  - $x_{current}$ = current GPS coordinates
  - $y_{current}$ = current GPS heading
  - $\theta_{current}$ = current GPS heading
The desired heading can be found from the current and desired positions.

\[ \theta_{\text{desired}} = \arctan \left( \frac{y_{\text{desired}} - y_{\text{current}}}{x_{\text{desired}} - x_{\text{current}}} \right) \quad \text{and} \quad \Delta \theta = \theta_{\text{desired}} - \theta_{\text{current}} \]

The angle of the rudder is directly proportional to the change in heading over time.

In analog terms:

\[ \theta_{\text{rudder}} = k \frac{d}{dt} \theta \]

In digital terms:

\[ \theta_{\text{rudder}} = k \frac{\Delta \theta}{\tau_{\text{gps}}} \]

This is a known as a greedy algorithm: it makes the locally optimal choice at each stage with the hope of finding the global optimum. Because of its simple nature, it is a prime choice for a narrow small-scale UAV application. We have limited computing power and space, restricting us from more involved guidance techniques such as Lyapunov vector fields. The relative simplicity of our guidance model will require many flight tests to calculate the unknown proportionality constants. Also, as depicted in Figure 10, the speed of the UAV is part of the proportionality. However, we plan to hold our speed relatively constant so that this factor will be absorbed into the ‘\( k \)’ term.

![Figure 10: Navigation Control Algorithm](image)

**5.7.1.3 Pulse Width Modulation**

The target rudder angle will be proportional to the duty cycle of the pulse width modulated signal for the rudder control servo. To prevent unnecessary complications in automation, the navigation system is only able to control the rudder so that the navigational control surface is isolated from the stability control surfaces. Figure 11, to the right, shows four different PWM signals. In most cases, the period is a unit of time and the duty cycle is expressed as a percentage.

![Figure 11: Pulse Width Modulation Signals](image)
5.7.1.4 GPS Receiver and Protocol

We chose a 20 channel ET-312 SiRF III for our GPS: it is a relatively inexpensive module that can communicate with up to 20 satellites. The Arduino Pro Mini microcontroller takes the readings from the GPS receiver serial port at a rate of 4800 bits per second in the NMEA 0183 protocol. This protocol includes *talkers* (sensor classes) and within *talkers* are sentences. For our purposes, the GGA and VTG sentences from the GPS sensor class will be plenty. The GGA sentence provides longitude, latitude, and altitude readings and the VTG sentence provides heading and velocity. The formats of these sentences are shown in Figures 12 and 13.

![Figure 12: GGA Sentence Format](image)

1) Time (UTC)  
2) Latitude  
3) N or S (North or South)  
4) Longitude  
5) E or W (East or West)  
6) GPS Quality Indicator  
7) Number of satellites in view (00 to 12)  
8) Horizontal Dilution of precision  
9) Antenna Altitude above/below mean-sea-level  
10) Units of Antenna Altitude (meters)  
11) Geoidal Separation  
12) Units of Geoidal Separation (meters)  
13) Age of Differential GPS Data  
14) Differential Reference Station ID (0000 to 1023)  
15) Checksum

![Figure 13: VTG Sentence Format](image)

1) Track Degrees  
2) T = True  
3) Track Degrees  
4) M = Magnetic  
5) Speed Knots  
6) N = Knots  
7) Speed Kilometers per Hour  
8) K = Kilometers per Hour  
9) Checksum

Before the GPS receiver knows what data to relay to the microcontroller, it must be sent GPS selection and initialization commands. Since the GGA and VTG sentences are needed, the ET-312 needs to receive the following selection strings:

"$PSRF103,00,00,01,01*25\r\n" (gga on)
"$PSRF103,01,00,00,01*25\r\n" (gll off)
"$PSRF103,02,00,00,01*26\r\n" (gsa off)
"$PSRF103,03,00,00,01*27\r\n" (gsv off)
"$PSRF103,04,00,00,01*20\r\n" (rmx off)
"$PSRF103,05,00,01,01*20\r\n" (vtg on)
The initialization command helps the GPS receiver connect to satellites by providing an initial timestamp and an approximate GPS location. The string that is specific to our project provides the GPS coordinates of our Senior Design Station:

"$PSRF104, 42.93113,-85.590127,0,96000,237759,1946,12,3*0C"

Once all of these commands are sent, the GPS is ready to send data to the microcontroller once per second. The data that is seen should be in the GGA and VTG formats shown earlier.

5.7.1.5 FailSafe and Manual Override
Before the UAV can leave the ground, it must have a steady connection to GPS (4 or more satellites) even though the system will only need the altitude reading until the user brings the UAV to its destination height with manual controls; this reading will be used to determine when to activate the autopilot. If the GPS receiver loses its lock on all satellites in mid-flight, the plane will straighten the rudder for a moment and then, if the lock isn’t recovered, it will circle its current location until the user changes the plane back to manual control and brings it down safely. This manual override will be available at anytime and the user can engage it by pressing left on the fourth channel joystick on the radio control meant for optional ailerons. Our current plan for autopilot initialization is to have it engage in the same fashion; the pilot would press left on the optional aileron joystick. In this way, the pilot would be able to manually fly the plane form the ground to an acceptable height and then activate the autopilot. Similarly, the landing will also be accomplished by the pilot. The shift back to manual control will be triggered either by the plane’s arrival at the last waypoint or manually by the pilot.

5.7.2 Alternative Design
Using a GPS receiver for our design is almost essential because of its accuracy and universality. Therefore, we don’t have alternatives for navigation, but rather supplementations. Three additional sensors for navigation are a compass, an altimeter, and a rate gyro. We plan to start our project by having a photo-taking prototype that is controlled entirely by the user. Once we accomplish this, it will serve as a fall back in the event of unforeseen, imminent challenges.

5.7.2.1 Compass
Compasses are never given good reviews for UAV applications. It is because they spiral into a positive feedback loop when the plane rolls. If the platform of operation was flat, then the compass could be used to determine instantaneous heading as corrective data. This method has potential to be very accurate, but this accuracy could also be compromised by electromagnetic interference from the rest of the device as well. Interfacing with a compass would require more time, money, power, code, ports, and space. This is the least attractive alternative.

5.7.2.2 Altimeter
An altimeter could be used to determine the height of the aircraft based on air pressure. This is more reliable than GPS because it will always give a reading. The altimeter could actually be a viable addition to our project because it would allow us to send the plane up before it has a lock on any satellites. However, the accuracy of the unit depends on the surrounding weather conditions and, similar to the compass, it would require more time, money, power, code, ports, and space.

5.7.2.3 Rate Gyro
A rate gyro is a device that measures angular velocity. The integral of this measurement would yield the instantaneous yaw for the time between GPS refresh intervals. Once the GPS is read again, the actual yaw is
corrected and the gyro uses it as its new offset. Using a rate gyro for heading is strongly encouraged when wind interference is an issue. We expect to use this design alternative if the GPS proves to provide insufficient data.

5.7.3 **Navigation Challenges**

This is a challenging project. As there will certainly be many challenges in terms of navigation, we are trying to become as familiar with the system as possible. The next difficulty to overcome is to figure out if any GPS input commands are missing from the current test program; we’ve been able to talk to the GPS receiver with the microcontroller, but we haven’t been able to connect it to any satellites yet. The control systems for running navigation are a lot more difficult than expected. Figure 14 shows a yaw control system including GPS and a rate gyro with a washout filter. Also, multiplexing the manual controls with the autopilot and implementing the proposed design conditions for its control bit will be a difficult. We expect the biggest challenges to arise from flight tests and implementing changes based on the results.

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![Figure 14: Yaw Control Diagram](image)

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5.8 **User Interface**

While robots can perform many useful operations autonomously, the job of defining those tasks is still left to humans. For this reason our prototype must have a user interface that allows a user to select where the plane should fly. The ideal solution for this is a full graphical interface which allows the user to select these waypoints in real time. However, this is not feasible given the time and budget constraints of this project. Instead the user will use a computer to download the desired waypoints into Plane! before the flight. Upon return from the flight, the user can download the pictures taken, with their embedded GPS locations, and run them through a software script that stitches the images together. The user interface is then a combination of the software used to download the coordinates onto the computer, and the software used to combine the images.

6 **Design Alternatives**

6.1 **Flight System Alternatives**

A variety of aerial vehicles were considered at the outset of the project. These vehicles included; airplanes, helicopters, blimps, hot air balloons, and ornithopters. Most of these were rejected because of our project constraints. The blimps and hot air balloons were rejected because in an outdoor environment the craft is subject to wind conditions. The size of our model and the power of the engines would not be significant enough to correct any mistakes in the flight path if there was wind acting on the blimp. Blimps and hot air balloons also presented a
problem for landing. The ornithopters were rejected because the motion to cause flight would disrupt the ability of the camera to take pictures. The ornithopter also consumes a lot of power to sustain flight. The helicopter did have potential because it would allow for easy take off and landing. It could slow down and hover for pictures and it would be able to turn easily. We did not choose a helicopter because it was harder to automate than an airplane. The airplane constantly moves in one direction. A helicopter must lean forward to start moving forward. This would make the stabilization system difficult. The stabilization system would have to be able to recognize when the helicopter was leaning forward to move and when it was being pushed by the wind. The carrying capacity for the helicopter was also a problem. Once the payload was added, it was unclear if the helicopter could sustain flight for more than five minutes. This led us to choose an airplane as our flight platform for this project.

6.6.2 Alternative to Autonomous Flight
An alternative option for the aircraft navigation is using a remote control. The aircraft will be controlled on the ground by a person. The person will have to fly the aircraft over the desired area to get an aerial picture. The picture will be triggered by a set of commands on the controller. When the aircraft performs a specific maneuver, the camera will be triggered to take a picture. Since the camera uses a SD chip for memory, the aircraft can contain over 4 gigabytes of memory. This allows for hundreds of pictures to be taken in flight. This is the best option because the remote control does not need to be modified to have pictures taken. This helps reduce the complexity of the project if the contingency plan must be used. This also helps reduce the cost of the contingency plan because parts from the original project are being reused for the alternative option. The microprocessor that would have been used for the autonomous system will be used to manage the camera picture taking; and the accelerometer that would have been used for stabilization will be used to trigger the picture taking. This is the best alternative if the autonomous system cannot be completed.

7 Business Plan
Plane! is a prototype to test and develop a modular aerial data acquisition architecture. While potentially marketable as an affordable picture-taking aircraft, we believe that this project could solve more problems by offering a system that can be quickly and simply adjusted to meet a number of needs. Initially, this prototype can be used to test control software necessary to operate a robust UAV. Once the hardware works well, new sensors can be developed. Another alternative could be to work on a system which allows multiple aircraft to work together to complete a task in a shorter amount of time. Our business model is not to sell a plane that takes pictures, it is to design a system that can grow and evolve to solve problems that are as large or as small as the customer needs.

7.1 Feasibility
As indicated by the Biology Department’s interest, there is a market for a small scale, autonomous UAV. Using the parts indicated in this report it is likely that a UAV could be delivered to the user for thousands of dollars less than currently available UAVs, which are designed to operate higher and longer. The economic feasibility of this project is based on filling a unique market niche for inexpensive low-altitude aerial photography.

7.2 Budget
We began with an allotted budget of $300 from the Engineering Department. Since then, we have adjusted our scope and pitched our idea to the Biology Department for additional funding and are currently working with a total budget of $500. This initial budget will be used solely for the parts necessary to develop a working prototype of
our product. Below is breakdown of the budget for these parts; we have ordered and received everything listed below except for the Bellanca Decathlon 480 RTF airframe.

<table>
<thead>
<tr>
<th>Budget:</th>
<th>Senior Design Allotted</th>
<th>$ 300.00</th>
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<tbody>
<tr>
<td>Senior Design</td>
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<td></td>
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<tr>
<td>Biology Dept.</td>
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<tr>
<td>Supplement</td>
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<td></td>
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<tr>
<td>total budget</td>
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<table>
<thead>
<tr>
<th>Cost:</th>
<th>Bellanca Decathlon 480 RTF</th>
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<tbody>
<tr>
<td>GE A830 Camera</td>
<td>$ 79.99</td>
<td></td>
</tr>
<tr>
<td>ET-312 SiRF III GPS Receiver</td>
<td>$ 59.95</td>
<td></td>
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<tr>
<td>Antenna GPS Chip-Scale</td>
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<tr>
<td>SMA GPS Patch Antenna</td>
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<tr>
<td>SMA Connector</td>
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<tr>
<td>Triple Axis Accelerometer</td>
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<tr>
<td>Two Axis Rate Gyro</td>
<td>$ 54.95</td>
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<tr>
<td>Arduino Pro Mini</td>
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<td></td>
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<tr>
<td>FTDI Basic Breakout</td>
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<tr>
<td>total cost</td>
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<td></td>
</tr>
<tr>
<td>remaining budget</td>
<td>$ 113.21</td>
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</tr>
</tbody>
</table>

We hope to make a profit off of our product after all production and selling costs. All retained earnings will be held within the company to further research and development of a more competitive product. We will pursue limited investments by related parties for initial paid in capital, but do not have short term goals of investing company profits. Since patents and copyrights are costly and impose a time limit on intellectual property, we plan to risk its protection by imposing a “trade secret” policy on our methods, parts, and algorithms. We do not feel that pursuing any extensive means of property protection will be worthwhile to our business goals.

<table>
<thead>
<tr>
<th>Income Statement</th>
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<tr>
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<tr>
<td>Revenues</td>
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<td>Costs and Expenses</td>
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<td>Gross Operating Income</td>
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<tr>
<td>Income Tax Expense</td>
</tr>
<tr>
<td>Net Income</td>
</tr>
</tbody>
</table>

### 7.3 Market Potential

This project brings the ability to take aerial pictures at a reasonable price, a desirable goal for a variety of individuals from surveyors to farmers to researchers of various types. Applications for this project are especially prevalent in research done at smaller institutions with more limited budgets.

Another promising market is model airplane enthusiasts. People in the general public may want to own one of these aircraft just because they find it interesting. Some photographers may want this aircraft to add variety to their photography.
A third application is for mapping property. The airplane could be used to identify property lines, fences, or other landmarks. It could also be used to identify the ecosystem distribution on a plot of land. An owner could identify the percentage of the land that is covered with forest, marsh, or grasslands.

8  **FUTURE WORK**

8.1  **MODULAR PAYLOAD**

In future versions of this UAV, it would be a good investment to develop several different payloads which could be easily swapped in and out of the airframe. This modular platform would allow users to upgrade their UAV for different tasks without investing in a new airframe. Examples of possible payloads are an antenna for radio tracking, an infrared camera for search and rescue, or video camera for live aerial pictures. Any of these options could find a market, and the ability to plug in a variety of modules would make the UAV much more appealing.

8.2  **IMPROVE AIRFRAME**

Because of budget constraints, the airframe chosen for this project is a durable, all-purpose radio controlled airplane. If a larger budget could be obtained in future revisions, it would be beneficial to purchase an airframe with a higher glide ratio. A glide ratio is the ratio of distance an airframe travels forward to the distance it travels downward when the airframe is without power. Airframes with high glide ratios are very stable and require only a small amount of power to keep them airborne. Upgrading to this kind of airframe would allow the UAV to spend more time on target and would reduce any stability issues the current airframe might experience.

9  **CONCLUSION**

*Plane!* is a very ambitious project, about on which all four group members are excited to be working. This initial design review has shown that *Plane!* can be accomplished within the time frame of Senior Design, and under budget with assistance from the Calvin Biology Department. However, the control loops required for stabilization and navigation of the aircraft are intensive undertakings, which could prove more difficult than initially anticipated. In the event that autonomous controls cannot be completed by the project deadline, the design team plans to switch to a remote controlled aircraft which will still be capable taking aerial pictures. Either way, the team is excited to be working on this project and confidently expects to deliver a working prototype for aerial photography by the end of the school year.
10 REFERENCES


