Poppins - The Autonomous Weather Balloon

ECE 445 Design Document Fall 2020

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1 Introduction

1.1 Objective

High altitude weather balloons are an essential part of data collecting for many sciences, ranging from weather forecasting to pollution monitoring. Two weather balloons from about 900 sites around the world are launched every day of the year [1]. They consist of a large balloon, usually filled with either helium or hydrogen, and a payload, which often has sensors and computers to obtain data from the heavens. As the balloon and payload float up the air pressure decreases and the diameter of the balloon expands until it pops.

Once it has popped, the payload then deploys a parachute and safely returns to the ground, where data is collected. Researchers can predict where the weather balloon will land using calculations, but ultimately, due to outside variables such as jetstreams, they have to rely on GPS to retrieve the payload. Unfortunately, this is an issue when balloons often land in hazardous conditions as it often results in the data collected, as well as the payload, getting destroyed or lost.

Our solution is to give the balloon a way to guide itself; a system that allows the balloon to reposition or apply tension to certain parts of its parachute to land at a designated GPS location. Our custom payload, including power, heating, navigation, and steering, and weather balloon must follow FAA regulations for utilization by other weather balloonists.

1.2 Background

Meteorologists, researchers, and the military deploy these balloons with a diverse and expensive payload of equipment that can exceed thousands of dollars. Besides the financial investment, scientists pour countless hours of work to collect this data that can improve the fields of meteorology, photography and astronomy [2].

The landings of these small unmanned aircraft are also important as they can cause fatal damage. The high frequency of weather balloons and growing urban sprawl are increasing the chance a weather balloon could land in trees, bodies of water, residential areas, or even highways. Due to the nature of the electronic payload, there are cases of crash landings where the payload starts a high blaze [3]. In the wrong situation, these balloons could cause wildfires, destruction of property, or vehicle accidents.

The ability to determine a secure landing location for weather balloon payloads provides a potentially invaluable tool to the scientific community. With just a small amount of overhead, researchers can confidently launch their balloons and ensure it will avoid large catastrophes and loss of their valuable data.

1.3 High-Level Requirements

- The ability to steer the parachute payload based on sensor input from the navigation system. Being able to turn the parachute left and right will allow us to direct the payload and autocorrect when it veers off course.

- Lands consistently within a certain threshold distance from our preprogrammed GPS target. Due to FAA restrictions and the scope of the class, we are instead measuring the success of our design by only testing the guided descent of our payload by deploying our parachute at the top of a utility crane. If the height of the crane is 120 ft, then the payload should be able to land with 10 feet of our GPS target.

2 Design

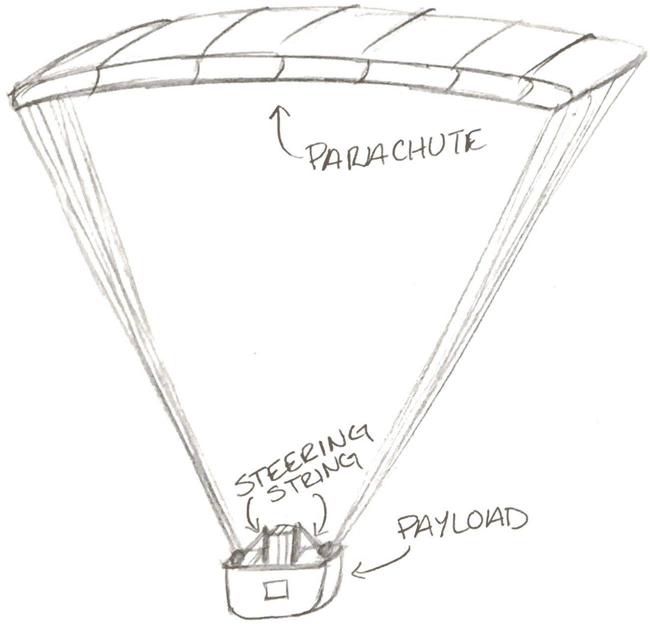

Figure 1. Physical diagram of Poppins parachute and payload systems..

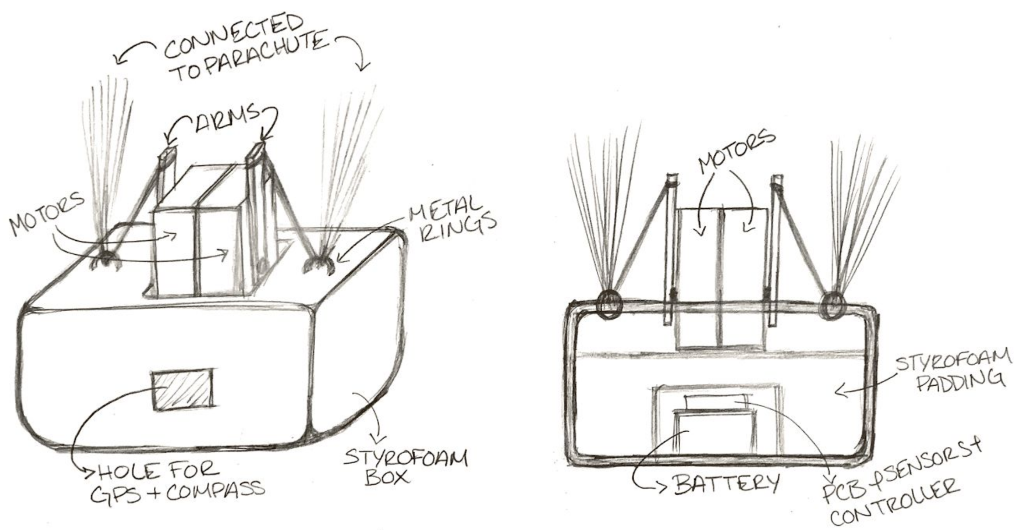

Figure 2. Physical diagram of payload with outer view (left) and inside view (right).

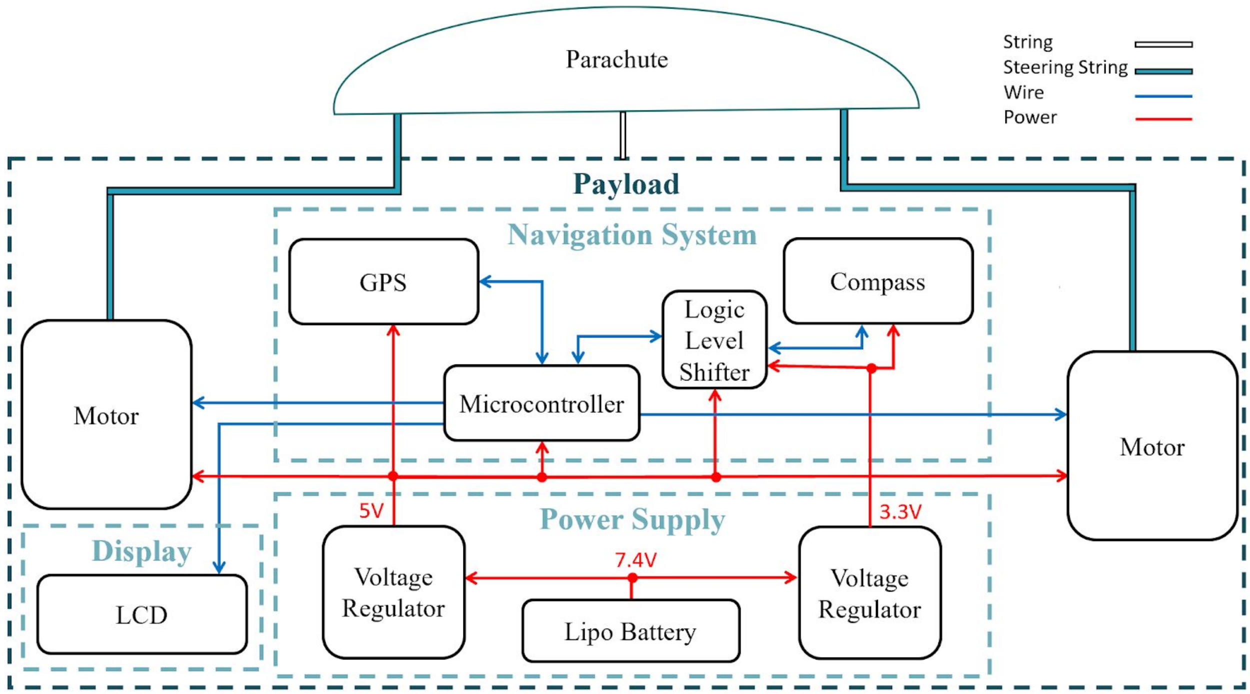

Figure 3. Poppins High Level Block Diagram

Figure 3 shows that our design will be made up of a small ram-air parachute and custom payload. We will be able to achieve our requirement to control the movements of the descending payload to a specified location through the navigation system using a microcontroller, sensors, and motors. Within the ascension system, the parachute will be specifically designed to achieve our goal to steer the payload 360 degrees by attaching it to the payload for support and the motors for steering. Each of these block components will be discussed further in the following section.

2.1 Navigation System

The main deliverable of this project and what allows us to compute the logic for steering and landing requirements is the navigation system. This system will take in input from the various sensors and use a microcontroller to decide how to power the motors to steer the parachute. This system has its data and power wires connected to our custom PCB board, which is powered by the power supply. The PCB also outputs the power calculated by the microcontroller to the motors in the steering subsystem.

2.1.1 Microcontroller

The navigation system will need a brain to compute how to control the motors based on the data from the sensors. This is accomplishable on an AVR microcontroller because it will be compatible with all the logical sensors required for our design.

Requirement	Verification
1. Capable of executing at least 12 Mhz single level instructions per second. *2. At least 12 IO to interact with all sensors.*	*1. Can make a sample program with a similar workload, and see if microcontroller can handle it. Can just use LEDs to verify output of the program.* *2. We can count the IO on the datasheet, and verify each work by using a test program.*

Table 1. RV Table for Microcontroller.

2.1.2 GPS Device

The GPS device is used to know the location of the payload. We will have to find a good balance between weight, accuracy, and cost. Since our design has short windows of error for navigation, we need a GPS device that will update quickly and accurately.

Requirement	Verification
1. Needs the ability to calculate coordinates with margin of error with less than 50 meters. *2. Updates location at a minimum of 1 Hz*	*1. Go to known coordinates and measure the coordinates with the GPS, then compare them to the known.* *2. Connect to ATmega and LCD to read out the speed of updates.*

Table 2. RV Table for GPS Device.

2.1.3 Digital Compass

For the navigation system to know which direction to go, it must first be able to tell which direction it is facing. This can be accomplished with a digital compass.

Requirement	Verification
1. A digital compass with I2C connections for our microcontroller .	*1. Connect to the microcontroller and verify heading direction accuracy is within 0.5 degrees.*

Table 3. RV Table for Digital Compass.

2.2 Steering System

The steering system will be the main mechanism for accomplishing our tasks of steering the balloon in a full 360 degrees and landing our balloon consistently on a designated GPS location. The steering system will consist of two servo motor arms, powered by the microcontroller, that pull on the steering strings of the ram air parachute. By having these two arms we can make the parachute turn left, turn right, and slow down descent velocity. The motors must meet the parachute's minimum steering pull weight, which in our parachute is 15 kg/cm per string.

2.2.1 Motors

The steering system will consist of two separate servo motors, each connected to a metal arm that is connected to one of the parachute's brake strings. By activating the motors, we are able to tighten the lift string to turn left and the right string to turn right. By tightening and loosening the strings, the design has the ability to position the parachute in the direction most beneficial toward getting the whole system to move in a wanted direction.

Requirement	Verification
1. The motors must be able to hold their rotational position against the force of the wind on the parachute. Minimum pull of 15 kg each. *2. Lighter than 8 ounces each.*	*1. Can verify 1 by attaching a 15 kg weight to a string, and seeing if a motor can pull it.* *2. Use a scale.*

Table 4. RV Table for Motors.

2.2.2 Parachute

In the experiments we will manually deploy the parachute by holding it above the payload before dropping it. The parachute we need for our project will have to be highly maneuverable and light weight. A small Ram-Air parachute will serve our requirements of being able to carry the payload and have steering strings that can be fed into our internal steering system [7].

Requirement	Verification
1. A ram-air parachute capable of holding the full weight of the payload (max 6 pounds). *2. A left and right brake to toggle the parachute's yawl.*	*1. We can verify the parachute's weight and brake yawling through our 120 ft drop tests.* *2. Observing the parachute's glide ratio stays within the golden mark of 5:1 by comparing the drop height to the distance traveled.*

Table 5. RV Table for Parachute.

2.3 Power System

The power system must be able to power the two stepper motors as well as the whole navigation system. All components of the navigation system can operate at 5 volts, except the compass at 3.3 volts. Also the digital servo motors can run from 4.8 - 6 volts. The power system will then consist of a 7.4 volt lipo battery with a minimum 1000 mAh charge and an adjustable step down DC-DC buck converter.

2.3.1 Lipo Battery

The main battery for the power system will be a rechargeable 7.4 volt lithium polymer battery with around 1000 mAh of charge. The lipo will connect directly to the buck converter and then power the steering and navigation system. The storage amount of 1000 mAh is based on calculations used for a standard 2-4 hour weather balloon flight.

Requirement	Verification
1. A rechargeable battery that supplies enough current for the circuit which has a total 150 ma draw. *2. A recharge battery that stores at least* 1000 mAh of charge. *3. A recharge battery that supplies 7.4 volts. Highest operating voltage is 5 volts.*	*1. Connect the battery to a sample circuit and verify using a multimeter.* *2. Leave the battery connected to the sample circuit for 4 hours and observe voltage stays above 7.4 volts with a voltmeter.* *3. Connect the battery to a sample circuit and verify using a multimeter.*

Table 6. RV Table for Lipo Battery.

2.3.2 Step Down DC-DC Buck Converter

The DC-DC buck converter will be used to step down the main 7.4 V lipo to 3.3 V for the Compass and 5 V for the motors, microcontroller, LCD, and GPS.

Requirement	Verification
1. Supplies 3.3 V or 5 V +/- 5 % from a 7.4 V DC source. *2. Draws current in a range of 0-275 mA*	*1 & 2. Connect the battery to a sample load circuit and verify with an oscilloscope that the voltage stays within 5% of 3.3 V or 5 V, while also drawing 275 mA.*

Table 7. RV Table for Voltage Regulator.

2.4 Display System

The display system is necessary to visualize all the navigation system outputs for testing and debugging. With the ability to see what is retrieved from the logical sensors and microcontroller, users can customize the design to meet their needs and log data from test flights.

2.4.1 LCD Display

Our design will utilize a small LCD display that can interface with our microcontroller and have enough space to display all of our data.

Requirement	Verification
1. Compatible with microcontroller *2. At least a 16 x 2 character display*	*1. Verify with the datasheet that the mircocontoller has all the data pins to support the display.* *2. Verify by checking data sheet of LCD*

Table 8. RV Table for LCD Display

2.5 Physical System

The physical system will host our navigation, steering, power, and display system during flight. It needs to fit the requirements of being both durable and lightweight. Two metal rings will also be attached to the top of the structure so the parachute has a means of lifting the design.

2.5.1 Styrofoam Box

In nearly all weather balloon designs, a simple styrofoam box is used because it fits all necessary requirements. We will also look for a styrofoam box that is capable of holding our PCB, battery, and motors.

Requirement	Verification
1. Minimum dimensions of 6 inches x 6 inches x 12 inches (length, width, height).	*1. Verify with a ruler or datasheet*

Table 9. RV Table for Styrofoam Box

2.6 Software

The payload will have to make decisions based on the information provided by the sensors, meaning a microcontroller will have to be used. It will be programmed based on the FSM and control flow below.

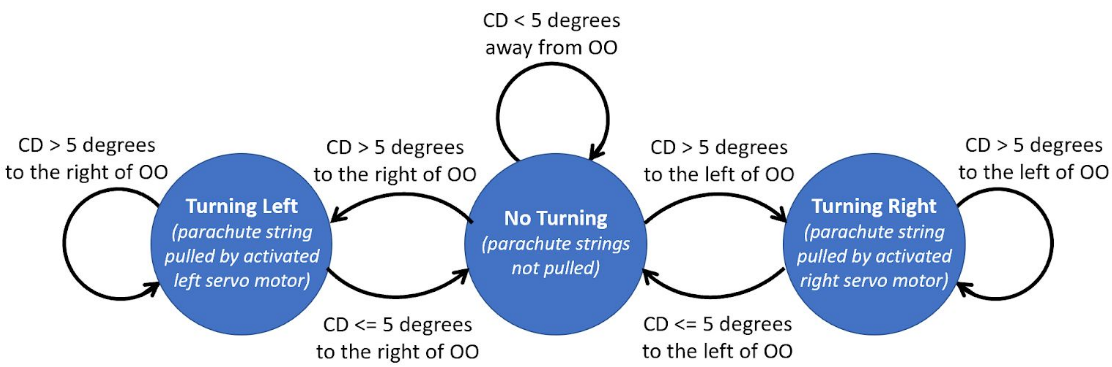

Figure 4. Finite State Machine for project software.

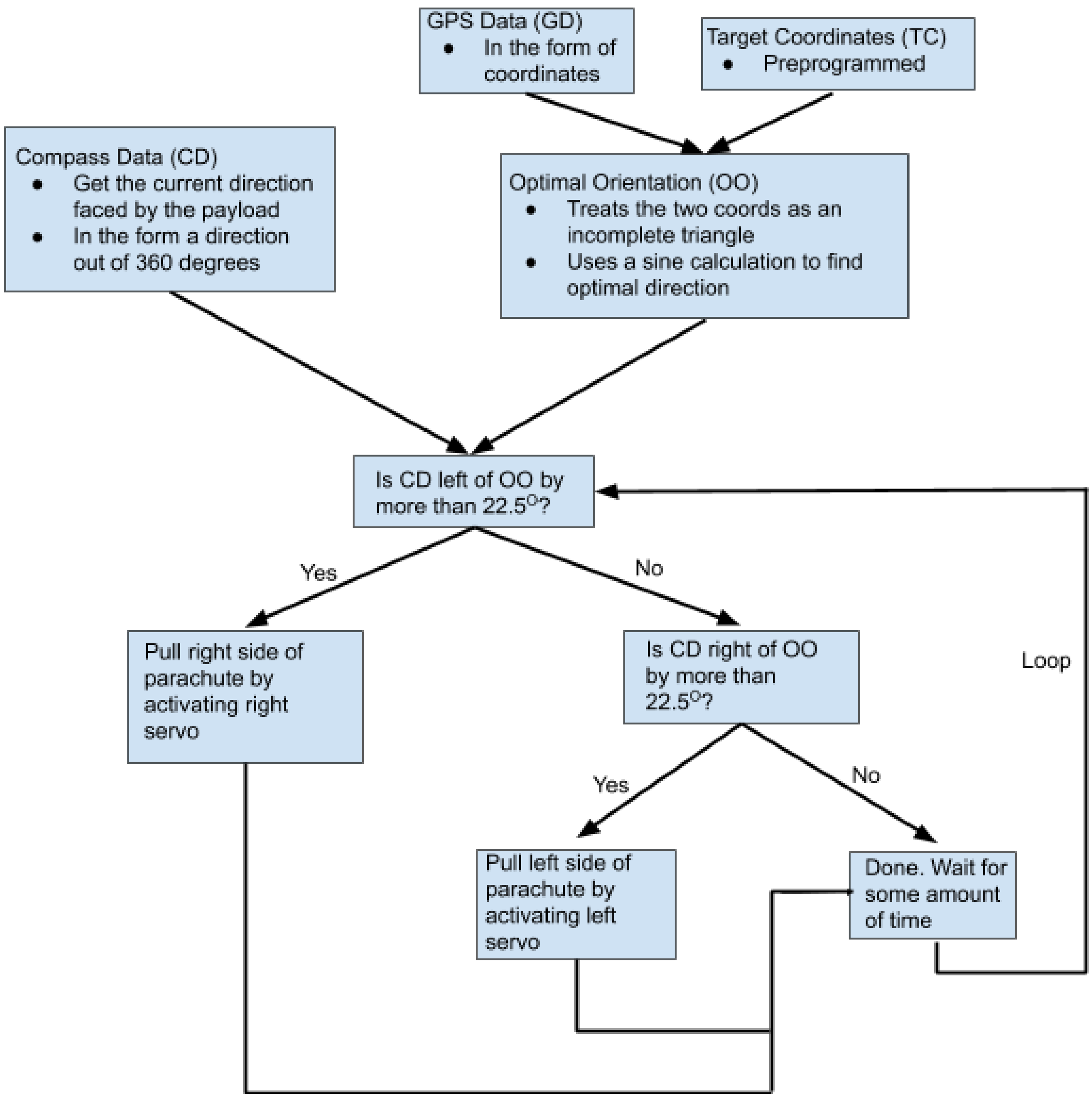

Figure 5. Flow Diagram of project software.

2.7 Schematic Block Diagrams

The Schematic Diagrams referenced below are from the component data sheets, and will be used when designing our PCB encompassing all the sensors and microcontroller.

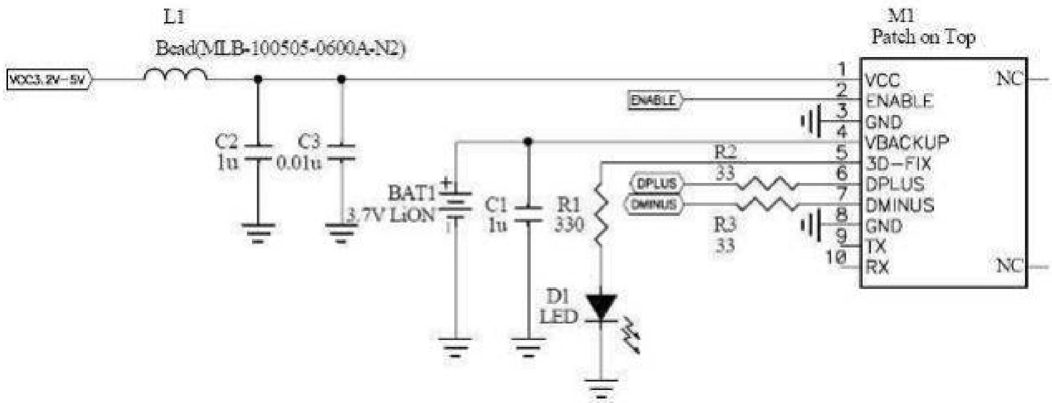

Figure 6. GPS Schematic from Adafruit Ultimate D GPS Breakout data sheet [8]. This diagram is for USB interface. A UART interface is also available.

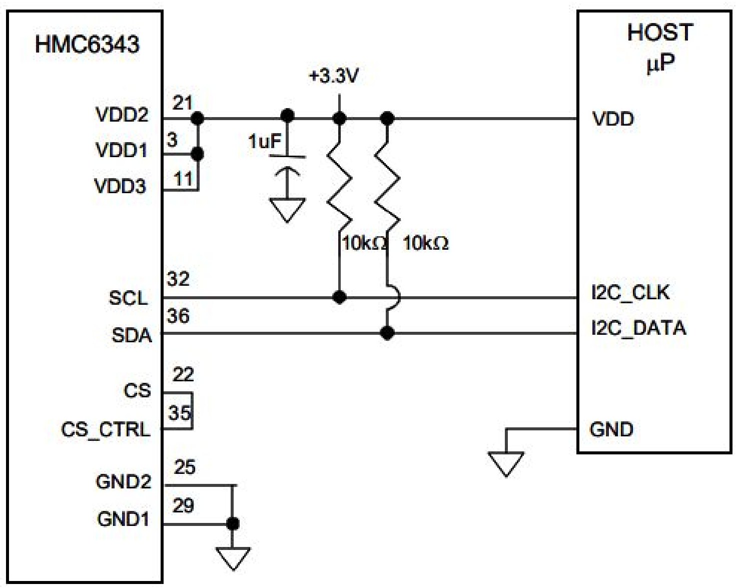

Figure 7. Electric Compass Schematic from HMC6343 Breakout data sheet [9].

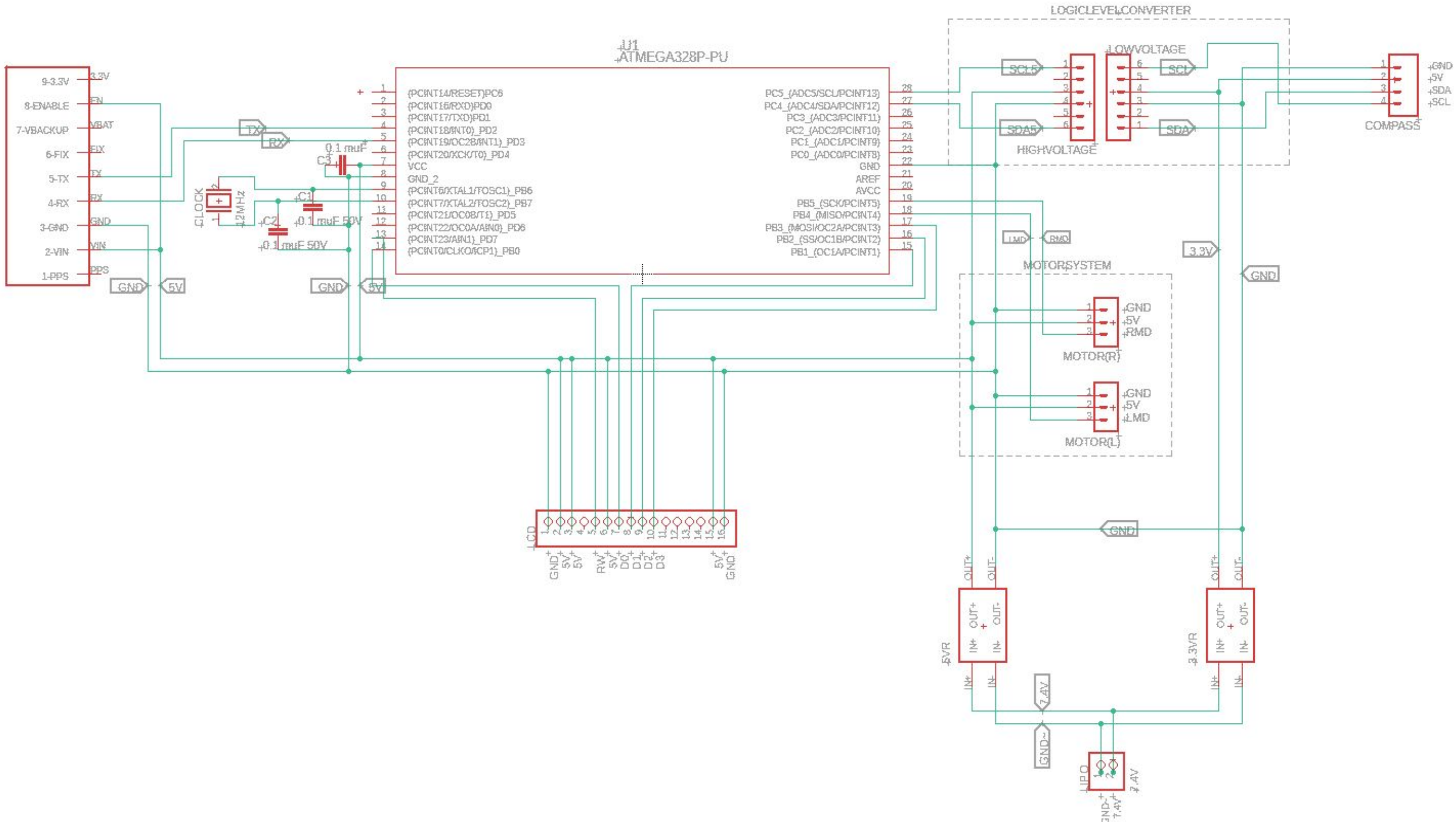

Figure 8. Schematic layout of digital components to be organized on a PCB.

3 Analysis

3.1 Tolerance Analysis

The most critical component to our design spawns from the navigation system. Without all the devices working at a high precision, our adjustments to the motors could be catastrophic to the flight and result in a mid-air stall. The tolerance we should concentrate our focus on is the degree of accuracy our digital compass is related to the GPS target location.

At deployment, our payload could be up to 25 miles away from our GPS target. At this distance, if our compass is off target by a mere 5 degrees with each iteration our payload could be off course by up to 2.18 miles. That is why it is mission critical we calibrate our system to be accurate to at most 5 degrees off target.

3.2 Risk Analysis

The component that poses the most risk to the project is the navigation system. It is easy to program a microcontroller to spin a few motors to pull string, but it will be extremely difficult to make our navigation system such that it determines what strings to wind and when. Since our design depends on the variable factors of the wind , it will not be as straightforward as it is with drones, where simply making certain rotors spin faster can alter position and direction, because if the wind is not blowing in the direction we need it to, the parachute will have tremendous trouble fighting it.

It will be necessary to program the navigation system to use the wind rather than fight it. It will have to be a system capable of accepting failure and making the best out of worst-case situations, as there will be many cases in which it will be impossible to overcome the circumstances. The system's goal must not be to get within X distance of a target, but just to get as close to X as possible, given wind conditions.

Even when the wind conditions are favorable, the problem of moving in certain directions is still difficult. Sometimes it may be beneficial to tilt the parachute in a non straight direction depending on which way the wind is flowing, and even then the wind direction and speed can change quickly as altitude increases.

3.3 FAA Regulations Analysis

If our design is FAA approved as a weather balloon, our device and team must adhere to these regulations under FAA Part 101 [10]. If a free air balloon meets the exempt requirements, no further contact with FAA or ATC (Air Traffic Control) is mandatory, but still strongly recommended.

Non-exempt balloons are required to meet the listed launch conditions, contact FAA and ATC, and include additional safety equipment. These new safety precautions include a flashing light and two independent cutdown systems that separate the payload from the balloon.

4 Cost and Schedule

4.1 Cost Analysis

4.1.1 Labor

Factors that determine the labor cost:

- Average UIUC graduate engineer hourly wage = $50/hour
- Overhead multiplier = 2.5 *WHAT IS THIS*
- Estimated hours worked to complete project = 8 hr/wk * 6 weeks = 48 total hours
- Number of team members = 3 people

We use the following equation to calculate the labor cost for one person:

Labor Cost = (hourly wage) x (overhead) x (total hours) x (team members)
= ($50/hour) x (2.5) x (48 hours) x (3 people)
= $18,000

Therefore, our total labor cost is estimated to be $18,000.

4.1.2 Parts

Component	Description	Distributor	Price
Parachute	2.4 m Paramotor Sail	Hobby King	$33.67
Servo Motor x2	20 KG Digital Servo	Amazon	$33.98
Microcontroller	ATmega328P-PU	Amazon	$5.99
Lipo Battery	7.4 V Lipo Battery	Amazon	$17.99
GPS Receiver	Adafruit Ultimate D GPS Breakout	ECE445 Lab	$0
Electronic Compass	SparkFun HMC6343 Breakout	ECE445 Lab	$0
Logic Level Shifter	SparkFun Logic Level Converter - Bi-Directional	Sparkfun	$3.00
LCD Display	Standard LCD 20x4	Digikey	$27.06
Voltage Regulator x2	5 A DC-DC Adjustable Buck Converter 4~38 V to 1.25-36 V	Amazon	$8.99
Styrofoam Box	Insulated Foam Container	Amazon	$10.00
Crystal Oscillator Clock	Bojack 16 Mhz Crystal Oscillator Clock	Amazon	$9.95
Ceramic Capacitors	2 x 22 pF 1 x 100nF	Personal Inventory	$0.00
PCB	100 mm x 80 mm Printed Circuit Board	PCB way	$23.18

Table 10. Cost of project components.

The total cost of the physical components in our project is $173.81

4.1.3 Total

Adding up the previous totals from labor and components, the entire project's final cost is:

$18, 000 + $173.81 = **$18,173.81**

4.2 Schedule

Complete By:	Finished Tasks:	New Tasks:
10/02	Design Document	Begin purchasing parts
10/05	All parts purchased	Begin designing PCB based on parts (Katie)
10/10		Begin designing accurate depiction of payload (Marc)
10/15	All parts acquired except parachute, PCB design finished (Katie), Depiction of payload finished (Marc)	Begin assembling payload (All)
10/25	Payload assembled (All)	Begin unit testing the completed payload (All)
10/30	Finish unit testing payload	
11/02	Parachute acquired	Begin drop tests on parachute
11/04	Drop tests finished	Begin filming demo
11/08	Demo finished	

Table 11. Development Schedule

5 Safety and Ethics

The success of our project can only be measured if we can follow all safety and ethics guidelines. Conveniently, the United States Federal Aviation Administration (FAA) and Air Traffic Control (ATC) have already established requirements for all aircraft. We have contacted the district FAA office in Springfield, IL and the FAA official requested we send the capabilities of our design to determine whether the device is considered a high altitude weather balloon or small unmanned aircraft [11]. If our design is classified as a weather balloon then we only have to contact ATC before flying in an approved air space [12]. If our design is classified as a Small Unmanned Aircraft (similar to a drone) then we are limited to flying under 400 ft in the majority of air spaces. Fortunately, the Springfield official said we could test our “high altitude drone” in their FAA testing field.

Our biggest safety concerns during the construction of our project include working with the high power supply and the motor drive. We need to follow best practices for not blowing out our circuit and ensuring no one is harmed by a motor accidentally turning on.

The accidental issues that can rise during our deployment are the same problems we are trying to solve. These include our device veering off course and causing a crash that would lead to fires, vehicle accidents, or damage to personal property. To limit the probability of these incidents, we have to research the safest launching site for our project.

On the side of ethics, when our device is fully operationally we now face issues with privacy and public safety. Weather balloons are useful tactic devices for military surveillance operations because they do not show up on radar and are silent. Also, the additional capability to land a payload at a GPS location also means this device could be used as a weapon. These concerns will be weighed by both our team and the FAA to ensure we keep the safety of the community and environment in mind [11].

6 COVID-19 Contingency Planning:

Thankfully due to the nature of our project, a switch to online classes will not greatly affect the development of our project. The only equipment we will need from the lab is an oscilloscope for verifying the behavior of our circuit components. Thankfully we can buy a small and affordable oscilloscope to use at home.

As for the construction of the project, all members of our team are able to collaborate on the physical design while still following the appropriate health guidelines. The only issue in debate is whether we will still be able to use the 120 ft utility crane from the University's Facilities and Services department. If we do not have the permission to drop from that height, then we are limited to testing on the ground for our final demo.

Appendix 1: FAA Regulations

Part 101 - Unmanned Free Balloons

Exempt Requirements:

• Payload weighs less than four pounds.
• Or, payload weighs less than six pounds and the smallest surface is more than 36 square inches.
• Or, two payloads that weigh less than 12 pounds together.
• All rope connected to the payload takes less than 50 pounds of force to break it off.

Non-Exempt Requirements:

• No active telephones on the aircraft during takeoff and landing.
• Do not launch in a prohibited or restricted area, or in a place where the balloon is likely to fly into a prohibited or restricted area.
• Do not drop objects if they could be hazardous to people or property below.
• Do not launch where the cloud cover is greater than 50% or if horizontal visibility is less than five miles.
• The first 1000 ft of ascent is not over a congested urban or residential area.
• Do not launch without a prior waiver from the ATC if your balloon will pass through Class B, Class C, Class D, or Class E airspace.
• Two independent cutdown systems that separate the payload from the balloon. Operators must be able to manually activate if cloud cover increases above 50% or if payload malfunctions and might cause a hazard to planes.
• Lights which are visible for at least five miles and flash between 40 Hz to 100 Hz.
• All trailing antenna lines or other suspension devices must be attached to colored pennants or streamers that are alternating bands of highly conspicuous colors, spaced 50 feet apart, and visible for at least a mile.
• A radar reflective plate that can echo a range of 200 MHz to 2700 MHz.

The following communication guidelines are also a part of the non-exempt requirements set by FAA Regulations in Part 101.

Launch Specification Notification:

A formal "launch speciation" containing important launch details must be sent to the regional FAA Flight Standards office at least three days prior to launch. The document should include:

• Location of launch site in degrees, minutes, seconds (latitude/longitude).
• Estimated launch date and time.
• Target burst altitude.

- Estimated ascent rate.
- Estimated flight duration.
- Balloon identification.
- Balloon diameter.
- Rope length.
- Payload weight.
- Trailing antenna length.
- Map of the predicted balloon trajectory.

Notice to Airmen (NOTAM):

Upon FAA command, operators may need to file a NOTAM, a notice to airmen, between three days and 24 hours prior to launch. This notification goes out to all pilots operating around the launch site and must include the following information:

- Location of launch site in degrees, minutes, seconds (latitude/longitude).
- Estimated launch date and time.
- Target burst altitude.
- Estimated ascent rate.
- Estimated flight duration.
- Any additional information requested.

ATC Balloon Position Reports:

ATC may mandate that operators record the location of the balloon at least every two hours. If communication with the balloon is lost for more than two hours, the ATC must be given the last recorded position and projected trajectory. One hour before descent, ATC must be notified with:

- Current location.
- Current altitude.
- An estimated time when the balloon will reach 60,000 feet.
- The forecast time and location of landing.

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