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UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

CLIMATE & SPACE SCIENCES & ENGINEERING
1005 DOW
ANN ARBOR, MI 48109

To: Dr. Aaron Ridley, Technical Instructor, University of Michigan
Dr. Alan Hogg, Technical Communication Instructor, University of Michigan

From: David Arnett, Engineer in Training, University of Michigan
Rithika Ganesh, Engineer in Training, University of Michigan
Alex Pohlman, Engineer in Training, University of Michigan
Pedro Zamora, Engineer in Training, University of Michigan
Arthur Zhang, Engineer in Training, University of Michigan

Subject: Final report regarding the design, execution, and completion of a scientific investigation on turbulence at specific altitudes in Earth's atmosphere.

Date: April 19, 2019

FOREWORD

We were tasked to build a payload system centered around a scientific question related to the atmosphere. Provided this, we concentrated on investigating wind shear forces at different altitudes throughout Earth's atmosphere. The real world focus of our investigation was to identify the least turbulent regions of air to give a more optimal path for aircraft to fly in. We designed a weather balloon payload equipped with atmospheric sensors to measure the differences in accelerations as the payload travels through the atmosphere. The collected data was analyzed to determine which altitudes in our flight path contain less turbulent air. This report contains notable aspects of our payload design process and analysis of multiple plots with measured accelerations at specific altitudes.

SUMMARY

We designed and launched a payload to measure wind shear forces in the atmosphere by collecting sensor data, such as acceleration and GPS location, over a region above southeast Michigan. The resulting data from our payload shows oscillation with increasing frequency and amplitude as it rises through the atmosphere, reaching a maximum magnitude of acceleration near the upper border of the jet stream. Since our objective is to minimize encounters with turbulent air, we recommend that airplanes avoid this area - the upper border of the jet stream - to improve the efficiency of flights and reduce potential airframe stress. If desired, a potential avenue for further investigation would be single-package balloon launch. This would eliminate more noise regarding acceleration, allowing for a more concrete and precise conclusion.

DISCUSSION

Introduction

Turbulence is characterized by tiny chaotic changes in the air, which can lessen the performance and safety of an airplane during flight. This can be measured by analyzing wind shear forces, which are the differences in wind speeds over small distances. In order to measure these forces, we designed and tested a payload which contained a circuit board that integrated a multitude of calibrated sensors. The payload recorded important numerical features, such as acceleration and location during a 2.5-hour weather balloon flight. Through our analysis of the collected acceleration data, we determined the turbulence at certain regions above Michigan.

Schematic and Block Diagram

The schematic for our circuit board was created in Altium and shows the specific connections between the board components (see Appendix A). The system block diagram in Figure 1 outlines the flow of information in our circuit. All of the 3.3-volt components are laid out on the left, and all of the 5-volt components are laid out on the right.

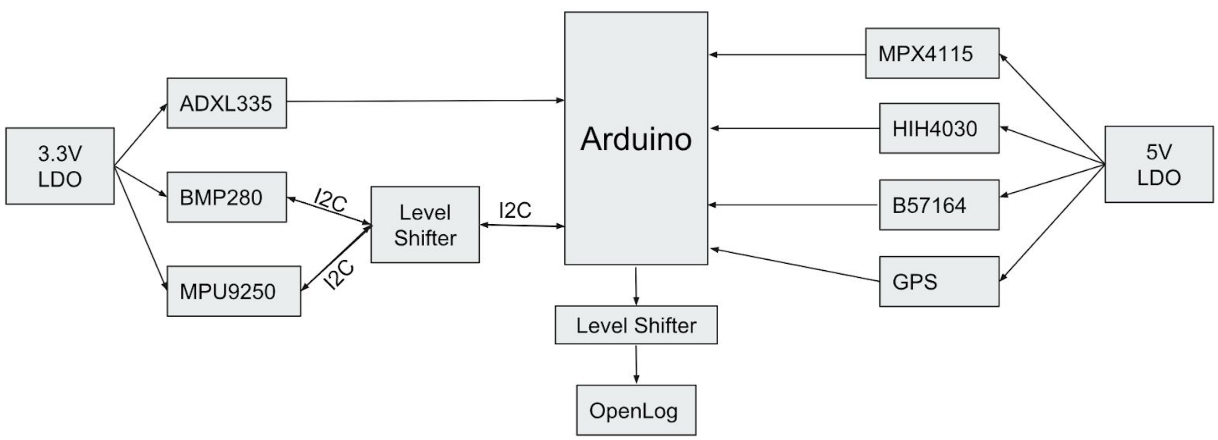

Figure 1. System block diagram.

Each component sends readings (either digital or analog) to the Arduino Nano microcontroller, which in turn sends the processed information to the OpenLog that logs the data onto an SD card. The components that use the I2C communications protocol are indicated by the I2C label that sits above their respective communication lines.

Mass, Power, and Data Budgets

Our mass budget (Table 1) outlines the distribution of weight for our overall package.

Component	**Mass(lb)**
PCB board	0.102
ADXL335	0.002799871
BMP280	0.002866009
MPU9250	0.00286601
FGPMMOPA6H GPS	0.00881849
MPX4115	0.00881849
HIH4030	0.00110231
B57164	0.00081571
Battery	0.12
Structure(including carabiner)	0.7519
Total	1.000
Margin (%)	0.00

Table 1. Outline of mass contributions in the payload.

The sensors and PCB board jointly contribute approximately ~0.128 lb to the total weight. Most of the weight comes from the structure (composed of insulated foam, hot glue, and duct tape), the attachment system, and the battery. Together these elements contribute ~0.872 lb to the total weight. The final weight of the package comes to precisely 1.000 lb.

Component	**Bytes per Measurement**	**Measurements per Minute**	**Bytes per Minute**	**Minutes per flight**	**Kilobytes per flight**	**Contingency (%)**	**Grand Total (kilobytes)**
ADXL335	14	60	840	180	151	5	159
BMP280	22	60	1320	180	238	5	249
MPU9250	60	60	3600	180	648	5	680
GPS	42	60	2520	180	454	5	499
MPX4115	4	60	240	180	43	5	45
HIH4030	4	60	240	180	43	5	45
B57164	14	60	840	180	151	5	159
Total							1837
Card Capacity							8,000,000
Margin (%)							435374%

Table 2. Outline of predicted data usage after a three-hour flight.

Our data budget (Table 2) predictions closely match the actual flight data usage, which was 1,888 kilobytes. This is because we used software interrupts to precisely time the intervals we logged data in. This improves the accuracy of the predicted measurements per minute for each sensor. The small variation in file size can be attributed to extra lines of data logged by the GPS that were not correctly parsed by the Arduino mid-flight.

The power budget in Table 3 outlines the power consumption of each component on our circuit, as well as the total energy consumption of the system compared to the battery capacity.

Component	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Duty Cycle (%)**	**Total Power (W)**	**Contingency (%)**	**Grand Total (mW)**
ADXL335	3.3	0.35	1.155	100%	1.155	10%	1.27
BMP280	3.3	1.12	3.696	100%	3.696	5%	3.88
MPU9250	3.3	3.5	11.55	100%	11.55	15%	13.28
FGPMMOPA6H GPS	5	25	125	100%	125	5%	131.25
MPX4115	5	10	50	100%	50	5%	52.50
HIH4030	5	0.5	2.5	100%	2.5	5%	2.63
B57164	5	5	25	100%	25	15%	28.75
OpenLog	3.3	20	66	100%	66	15%	75.90
5V LDO	5	15.5	77.5	100%	77.5	10%	85.25
3.3V LDO	3.3	49.97	164.901	100%	164.901	10%	181.39
Arduino Nano	5	400	2000	100%	2000	10%	2200.00
Total							2776.10
Time of Flight							3 hours
Total Energy Used							8328.30
Battery Capacity							16280.00
Margin							95.48%

Table 3. Outline of power consumption in the system.

Estimating for a flight time of 3 hours, we calculated that we had a 95.48% margin, which gave us confidence that power would not be an issue during the flight.

Finished Board and Payload

Components were soldered onto the board over about one and a half weeks. All capacitors and resistors were surface mounted, while the rest of the components were connected using through-hole female headers. As each connection was soldered, it was tested for continuity using a digital multimeter. Once the entire board was soldered, each component was thoroughly examined to ensure that it was receiving the correct voltage, was connected to ground, and was connected to the correct pin on the Arduino.

Upon further testing, it was discovered that the SDA and SCL connections were flipped, as in they were connected from the I2C components to the incorrect pins on the Arduino. To fix this, the relevant traces were severed, and external wires were soldered on to correct the connections. Hot glue was applied to insulate these new connections. More testing was completed, and it was determined that the fix was successful. The wire configuration is shown in Figure 2.

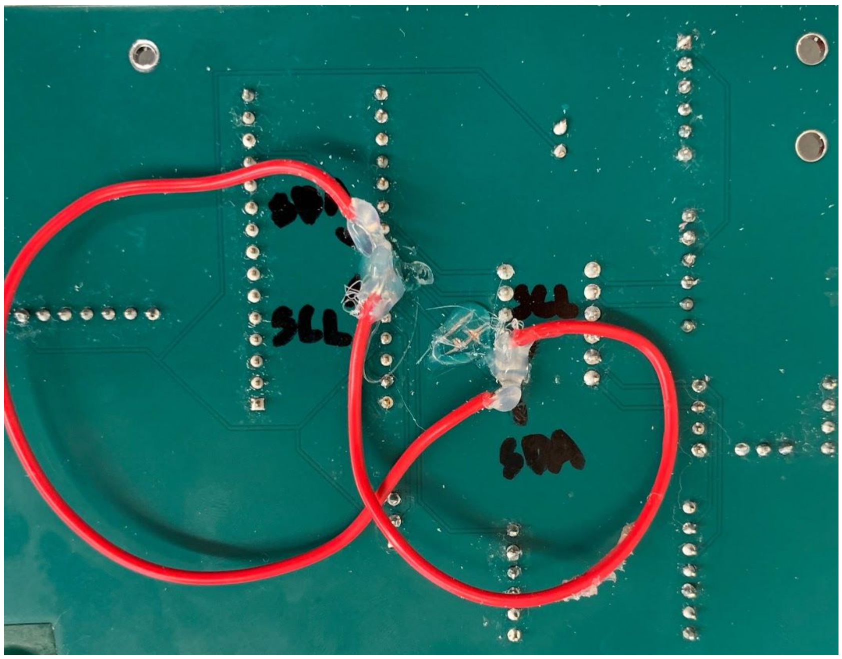

Figure 2. External wire configuration to enable I2C communications with Arduino Nano.

Software

To accurately measure the wind shear forces around our payload, we allotted more of our Arduino Nano's limited memory and processing to the GPS, altitude, and accelerometer sensors. Additionally, we implemented I2C communications between several sensors to reduce the complexity of our PCB. On our MPU 9250 9 axis accelerometer, we used I2C communications to read data from the external magnetometer, gyroscope, and accelerometer. Originally, we planned on processing this data to determine the orientation of our payload, allowing us to remove the effects of gravity on our acceleration readings. However, because of time constraints, we were not able to do this. We compensated for this by smoothing our acceleration data first to remove the noise, then subtracting the resultant smoothed acceleration data from the unsmoothed data to obtain a normalized acceleration. This also significantly reduced the noise in our acceleration data, as depicted in Figure 3.

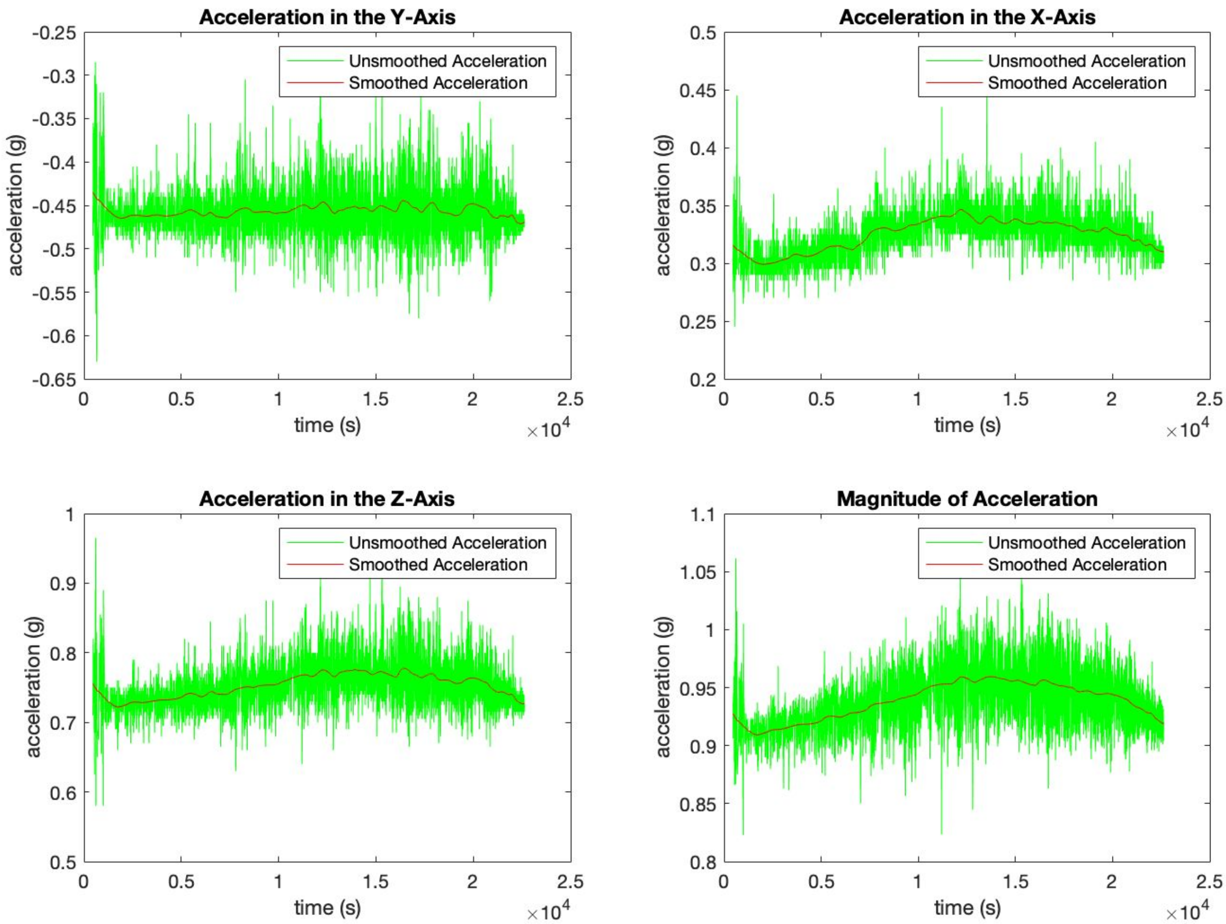

Figure 3. Comparison between smoothed and raw acceleration data.

Our payload software also features interrupts, which help us precisely time the logging of data. This is critical in ensuring that we continuously log data throughout the flight regardless of external interferences. The only potential inaccuracy comes from drift in our processor's crystal oscillator, which is minimal.

We created libraries for each of these sensors to improve code readability and thereby reduce bugs in our code. During our cold, benchtop and blue bus tests, we did not encounter any errors and logged reasonable data. The only exception occurred with our GPS, which sometimes took a while to find a lock and often dropped out during the blue bus test. We determined that this was simply an internal issue with the GPS sensor itself, and decided that a fix was not feasible. During the flight, our tests showed that they were indeed indicative of actual behavior during the flight. Overall, our software correctly logged sensor data during the entire flight without significant issues.

Summary of Testing

Our team's payload went through a multitude of testing to guarantee its performance in an environment experienced in a weather balloon flight. Testing included a three-hour power & data test, a shock test, a GPS test, and a cold test. The first three-hour long test was to ensure that our payload would remain under power and record data for at least the duration of the weather balloon flight. The next test was a shock test, in order to test how our payload responded to abrupt acceleration and ensuring it would withstand a 2.5 G shock. For our purposes, this meant throwing it down three flights of stairs and then confirming the integrity of our internal components. The first two tests were passed with acceptable results. Moving on, our third test was for the GPS - asserting that we can record valid position data for over an hour. In order to perform this test, the payload was taken on a university bus and properly recorded the resulting bus route for 65 minutes. The last test for our payload was the cold test - this test was comprised of our payload sitting in a -40 degree Celsius chamber for at least two hours, and proving that it could successfully perform its data collection during the entire test. After recording reasonable data for 138 minutes with an internal temperature reading of -31 degree Celsius, we were confident in our payload's ability to survive in the colder regions of Earth's atmosphere. After our payload was confirmed to pass the testing stage of our design, our team was ready to move on to launch.

Launch Day

Before the weather balloon carrying our payload could've been launched, an optimal date had to be chosen. The weather and jetstream speed had to be assessed so that the balloon's flight path and distance traveled would be conducive to a successful recovery, making sure the payload train didn't land in an inaccessible place, like a lake. Choosing a day, flight predictions were made taking into account things like weight, launch location, parachute size, and amount of helium utilized. Our initial predictions had the balloon starting at Union City, MI and traveling southwest to land near Adrian, MI.

For launch day each person on our team was given a role, to ensure smooth operations when tracking the balloon: a driver, a navigator, a communicator (to keep in contact with other teams), and a tracker (to track the balloon). On launch day, payloads, balloons, and helium tanks were loaded into vehicles and transported to the launch site. After leaving the University of Michigan, our team met with the other teams at a school in Union City to prepare for launch. We laid out the payload train with each team securing their payloads. This was attached to a weather balloon, which was filled with helium. People were assigned to hold each package before launch. The packages were turned on, everything was checked to be secure, and the balloon was released, carrying the payload train into the atmosphere.

Following a successful launch, teams packed into their vehicles and headed for the predicted landing spot. Throughout the ride, predictions were updated multiple times to keep with the balloon’s current position. At the end, the payload train landed near Monroe, rather than the initially predicted Adrian. The train was seen falling into a field, where it was retrieved. Our payload was still secure and actively collecting data. It was disconnected from the train after a successful flight and brought back to Ann Arbor with its data to be analyzed.

Flight Path

Figure 4. A map of the payload's flight path.

Our payload had a flight time of approximately 3 hours and traveled due east (Figure 4). The payload was launched in Union City, Michigan and was recovered north of Monroe. The payload landed safely in an empty field, about 2 miles away from the edge of Lake Erie.

Additionally, the payload reached a maximum altitude of 26,039.6 meters, where the weather balloon popped. A detailed path is shown in Figure 5, with the light areas indicating where the location data was more sparse, and the blue areas indicating where the location data was more dense.

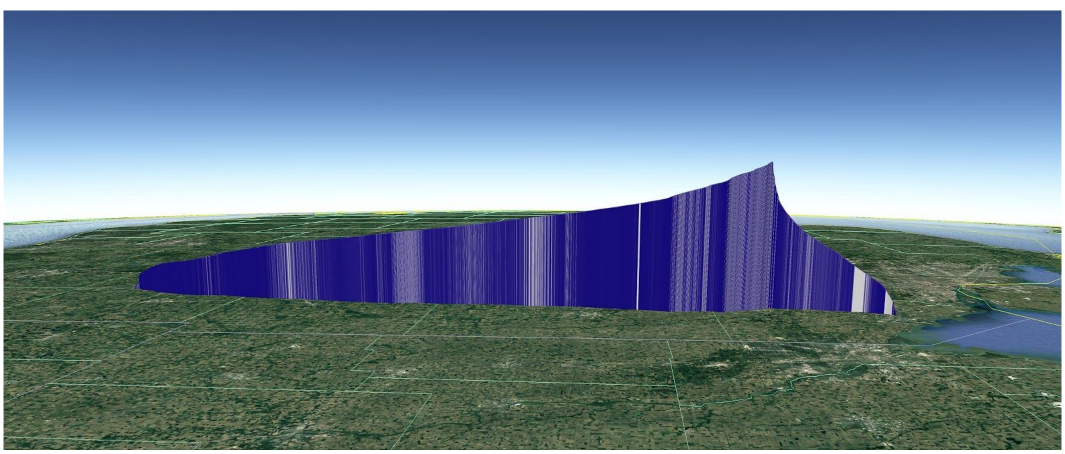

Figure 5. A map of the payload's altitude during flight.

Flight Data

The first notable observation to make was that the payload's acceleration remained relatively stable on the ascent. This is in part due to our inability to remove acceleration from the accelerometer readings. Because we computed the magnitude of acceleration, the axis affected by gravity heavily skewed the results since it is weighted more heavily. Regardless of this, we were able to determine peak acceleration points during our payload's ascent, shown in Figure 6.

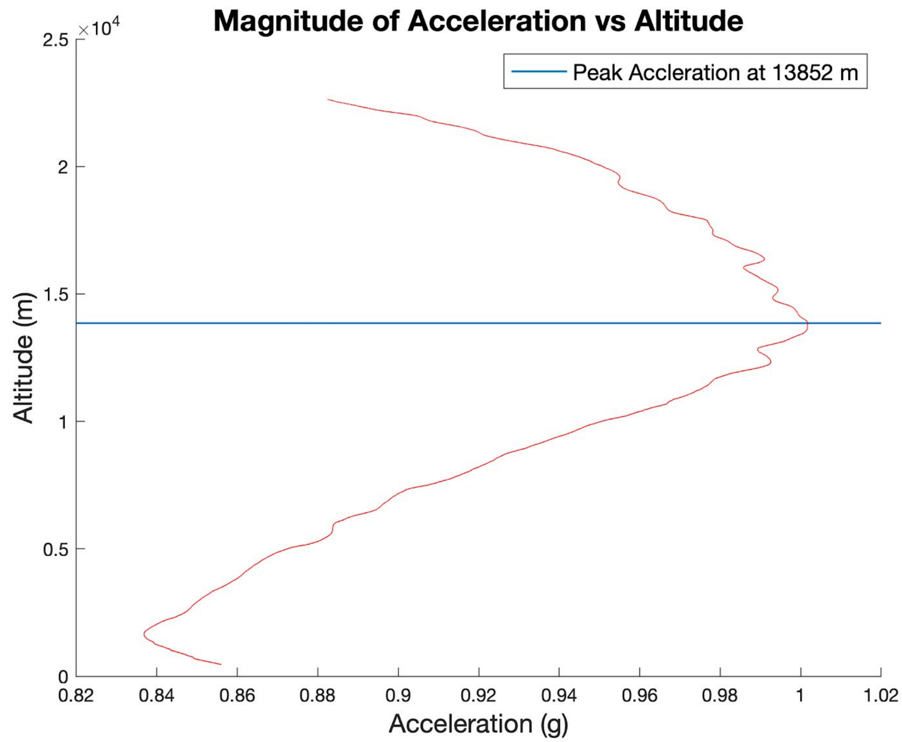

Figure 6. Averaged payload acceleration on ascent.

The acceleration continuously increased until 13,852 meters, at which point it peaked at roughly 1 g. The important thing to note is that between 13,000 and 20,000 meters, the acceleration rapidly oscillated. Because small acceleration changes in axes not affected by gravity are reduced when calculating the magnitude of acceleration, this indicates that the acceleration dramatically oscillates between 13,000 to 20,000 meters above sea level. The high-frequency oscillations in acceleration are clear indicators of shifting wind shear forces. Based on this data, we recommend that planes fly below 13,000 meters to avoid violent wind shear forces.

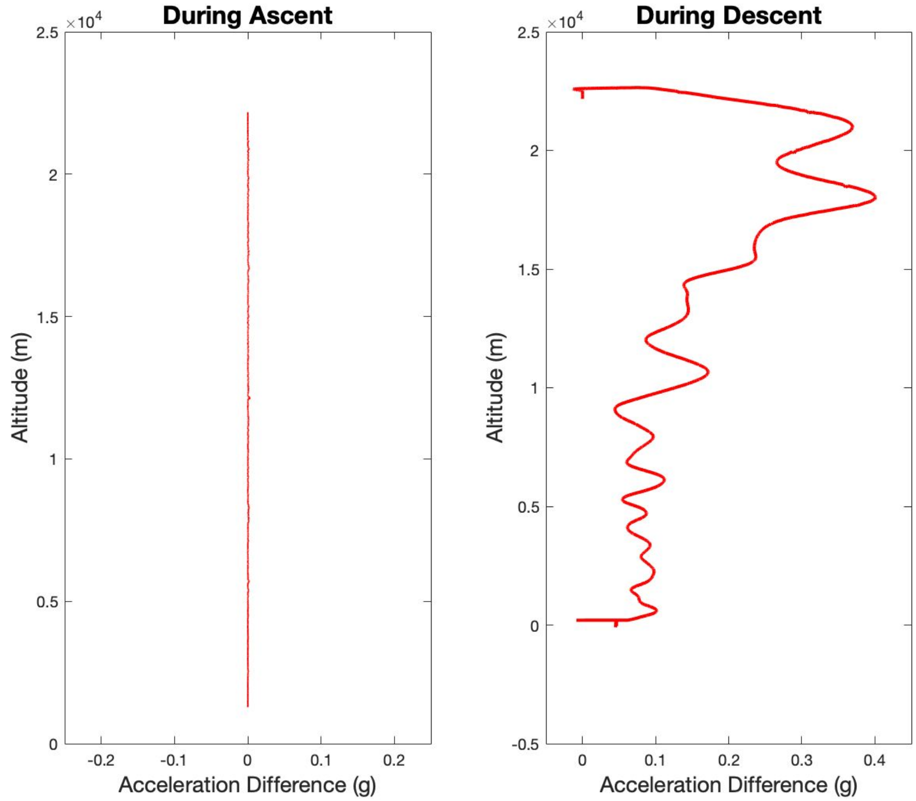

Figure 7. Normalized payload acceleration at different altitudes.

Another notable feature from the flight was the heavy turbulence we encountered during the descent. In the plots above, we sampled 20 acceleration points and averaged them to remove noise from the acceleration data. After doing this, we computed the difference between the smoothed and unsmoothed acceleration to reduce the effect gravity had on the acceleration data. Upon doing this, we noticed that the acceleration is remarkably smooth on ascent and highly volatile on descent. While it follows a sinusoidal pattern throughout the descent, the amplitude is the highest above 15,000 meters. This behavior is especially dangerous for airplanes. The volatile sinusoidal behavior is indicative of a high difference in wind speeds across relatively short distances in the atmosphere. Wind patterns like this essentially shear the airplane - this reduces performance, creates a potential for damage, and produces uncomfortable flying conditions. The plots in Figure 6 support those in Figure 7 and support our recommendation that planes avoid flying around a height of 13,000 meters to increase efficiency and reduce the chance of the previously mentioned problems occurring.

Results

In short, our payload flight was a success. We were able to accurately deduce optimal regions of air in which commercial airplanes could fly where they would be less susceptible to wind shear forces, and therefore turbulence. Specifically, we concluded that our payload reached a maximum magnitude of acceleration at 13,000 meters - in the upper border of the jetstream. This follows the logic that the area in which the fast-flowing air of the jetstream collides with the surrounding, slower air would more likely cause rough eddies of air, or turbulence. However, due to gravity and our payload's launch system - a chain of multiple scientific packages attached to a single balloon - our data was suffused with noise. This made it difficult to extract discernible data from our flight, resulting in a conclusion that was less significant than we had hoped.

Improvements

Given that launching a balloon chain comprised of multiple payloads linked together caused a great extent of noise in our data, shown in Figure 3, this is one of the most significant factors of improvement to be considered in future investigations. We propose launching a single-payload weather balloon flight to remedy this. Furthermore, we would like to design a way to more easily filter out acceleration due to gravity from our measurements. These improvements are the most apparent advancements for a similar future study.

CONCLUSION

Our scientific objective of finding the optimal regions of air in which commercial airplanes can fly was achieved, with our data revealing that our payload reached a maximum acceleration around 13,000 meters. To achieve our scientific objective, we designed a printed circuit board (PCB) with attached sensors that recorded acceleration, GPS location, and altitude. This payload was placed inside of a structure built with insulated foam that protected the board during its flight. The attached sensors collected atmospheric data during its 3-hour flight over southeast Michigan, which was later analyzed to answer our scientific objective. Possible errors that might have occurred include the acceleration data during the ascent not being significant. Despite this, when determining the optimal height at which commercial airplanes should fly to receive the least amount of turbulence, our conclusions were based on acceleration data related to the descent of our payload. In future iterations of this experiment, we recommend launching the payload more than once to receive multiple sets of data to analyze. Additionally, the payload experienced a large amount of noise during its flight, which could have skewed our data. Next time, we recommend filtering our acceleration to remove the effects of gravity to gain more accurate data readings regarding acceleration and altitude. Our final recommendation regarding our scientific objective is that commercial flights should avoid fly at an altitude near 13,000 meters - the upper border of the jetstream - to reduce the amount of turbulence experienced.

APPENDIX A - WIRING

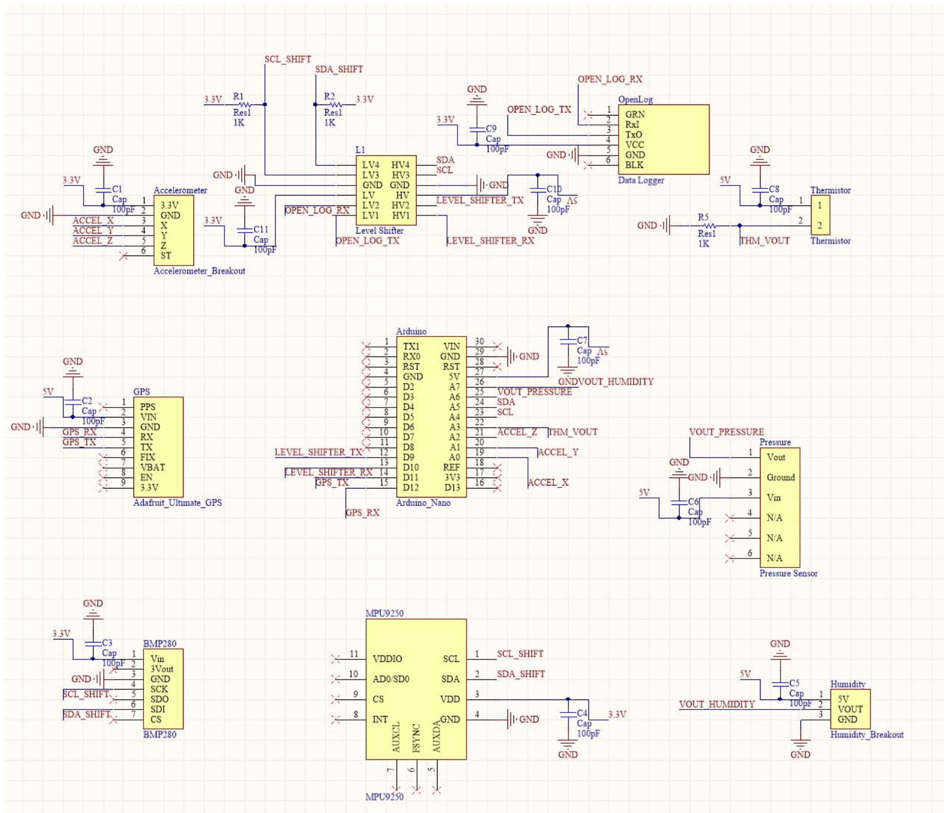

Figure A1. Schematic of Microprocessor and Peripherals

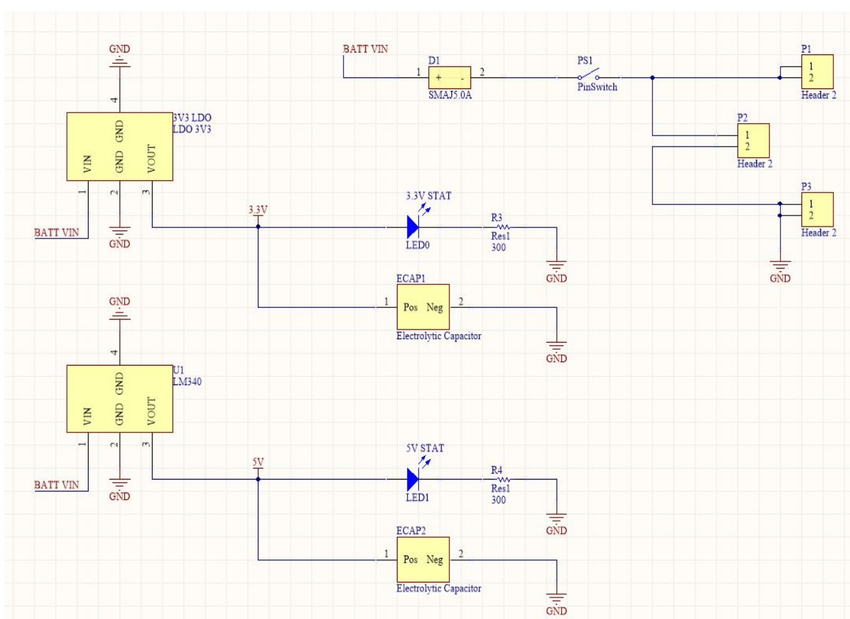

Figure A2. Schematic of Power System

APPENDIX A - WIRING

The schematic laid out in Figure A1 and Figure A2 shows the connections between components on our circuit board. Figure A2 shows the matter in which the battery was connected to the board: through a system of 3 through-hole headers. Figure A1 shows the connections between the onboard computer (an Arduino Nano) and the rest of the board components. The red “net labels” indicate the connections between pairs of pins.

REFERENCES

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