"Affordable Microgravity" a Drone-Based Microgravity Test Platform

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***Abstract* — This document presents the design methodology used to create a drone capable of achieving microgravity conditions for research purposes. There are currently no prominent test platforms available on a low budget for conducting microgravity experimentation. The focus of this project is to design such a solution that is affordable yet scalable in the future for larger payloads or longer microgravity tests. The multirotor drone used as the test platform will incorporate both an off-the-shelf flight controller and a customized microcontroller. The combination of these electronics will allow fully autonomous and microgravity-inducing flights.**

***Index Terms* — Acceleration control, aircraft control, control systems, microcontrollers, mobile robots, research and development.**

I. Introduction

The objective of this project is to create a low-cost multirotor drone capable of autonomously achieving microgravity conditions. This will enable microgravity researchers to conduct experiments in low gravity for short amounts of time. The benefits of this system compared to existing methods of microgravity experimentation are as follows: experimentation can be conducted on a lower budget, wait time between experiments is reduced or eliminated, and travel to a distant facility to conduct experiments may not be required.

Within the past decade the commercial drone industry has grown exponentially. With this technology now easily accessible to the public, people have found innovative ways to use it. From aerial surveillance to crop dusting, these unmanned aerial vehicles are revolutionizing a wide range of industries. Our project's goal is to revolutionize microgravity research using a drone.

The current cost for microgravity facilities is very steep, making them almost inaccessible to those below the top echelon of research groups. Parabolic flight, one largely known way to attain microgravity experiments, is largely expensive and requires booking months to even years in advance. Drop towers, which can achieve microgravity through free fall, have large upfront costs to erect such a facility and are sparsely located in the world. We aim to provide researchers with the ability to conduct low cost microgravity research. With an inexpensive drone platform that can be operated by activating a switch on a radio transmitter, we intend for this drone to be as easy to operate as an elevator. The user will need no prior knowledge of how to fly a drone but merely some simple safety and maintenance knowledge.

The drone used in our project will be used for microgravity experiments like those conducted in drop towers. The drone will accelerate directly downward from a predetermined altitude rather than generate microgravity by utilizing a parabolic path with translational motion in the horizontal plane. The restrictive budget of the project will also prove that this alternative to drop tower-style microgravity research can be affordable for any researcher who wishes to use this method. The microgravity will not be as clean as the conditions seen in a vacuum-chamber drop tower and will certainly not last as long due to physical restraints such as air resistance. It will, however, achieve a few seconds of uninterrupted microgravity conditions that will be suitable for many experiments.

Research projects have been constructed in the past with the intent of creating reduced gravity conditions via drone technology. Georgia Institute of Technology students focused on the design and optimization of an autonomous quadrotor drone to achieve microgravity. Their vehicle, while never actually performing the microgravity flights (as of the end of 2016), was simulated to provide proof-of-concept for 4 seconds of microgravity at an accuracy 10^{-3} G. From their research, they quickly realized that simply letting the craft freefall and attempt to stabilize itself led to catastrophic results. The research led to the development of variable pitch rotors using constant rotor speed, allowing "... a more responsive system capable of fighting drag independent of direction and maintaining attitude control authority independent of the thrust required during a microgravity tracking flight." [1]. These variable pitch motors led the team of students to many unforeseen complications with a high level of complexity, however, leading us to believe a simpler solution is still the better route to take.

Fig. 1. Image of our microgravity drone almost fully assembled. The payload bay will hang below the frame, the mission computer will sit on the payload bay and the battery will be mounted on the top of the frame. This configuration was used to perform an initial flight to test the stabilization PID settings.

Fig. 2. CAD model of our drone fully assembled. The battery is shown mounted to the top of the frame, with the payload hanging below.

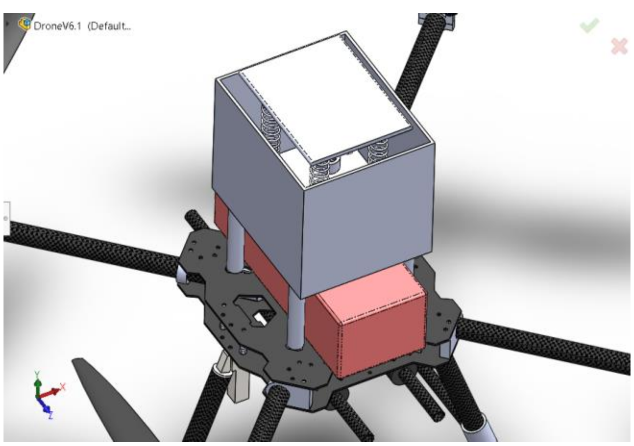


Fig. 3. CAD model of our parachute bay installed on top of the battery. The plate used to eject the parachute is spring-loaded and secured with a strap after the parachute is installed.

II. Goals

A. *Budget*

This project is sponsored by Northrop Grumman with a fixed budget; therefore, the drone construction cost may not exceed $1500. An additional $500 has been offered for research and development funds.

B. *Microgravity Time*

By calculations given later in the paper we predict to achieve around 3 seconds of microgravity conditions each flight.

C. *Experimental Payload*

The payload bay is built to accommodate up to a 3 kg load. Our motors are also able to provide the necessary thrust to carry this payload.

D. *Recoverability*

The drone can land itself needing only a recharged battery before another flight. Failsafe mechanisms are also in place as described later in the paper to allow for minimal damage in the event of any accidents.

E. *Precision*

Our accelerometers give us 0.1G of precision while being minimally affected by noise in this range. We plan to provide microgravity data within this range of precision.

F. *Autonomy*

The drone is designed to be user friendly and minimal experience with multirotor drones is required for operation. We intend the drone to be completely autonomous from the takeoff to landing.

III. Flight Plan

Our research has found that the best way to achieve microgravity with a multirotor drone is through assisted free fall in a downward direction. Since this project will use fixed pitch propellers, the drone will reverse the motor direction just before free fall so the propellers will provide thrust in the downward direction. This allows for sufficient downward acceleration to achieve microgravity.

The flight will begin with a check of all electrical and mechanical systems of the drone. This will verify the integrity of the system to ensure a safe flight. The drone will then be placed on the ground in an open flying field within FAA-approved airspace. It will be powered on, allowing the flight control system to initialize and acquire adequate GPS signal for translational position-hold functionality. When the drone is ready for flight, the system will be armed (motor outputs enabled) and a switch will be activated on the radio transmitter to begin autonomous flight. The craft will ascend to a predetermined maximum altitude. Upon arrival at this altitude, the drone will begin a controlled acceleration directly toward the ground. Once the drone falls to a predetermined altitude floor it will slowly decelerate and return to a hover, then activating a return-to-home feature of the drone to descend safely back to the takeoff location. In the event of an emergency the operator can flip a switch to regain manual control of the aircraft or use another switch to deploy a parachute to slow the drone's downward airspeed and allow the drone to reach the ground at a safe velocity.

IV. Procedure of Operation

Prior to each flight, the drone operator must determine whether they are able to fly. This includes checking the weather conditions in the desired experiment location, checking FAA regulations regarding flight in the desired airspace, and verifying that the drone is airworthy. If these conditions are satisfactory, the flight can be performed. The batteries for the drone and the RC transmitter must be fully charged prior to operation. The microgravity duration for the experiment will be determined and programmed appropriately in the microcontroller, hereafter mentioned as the 'mission computer.' This will allow the drone to fly the autonomous mission in such a way to meet the experimental specifications. The parachute recovery system must also be checked to verify it is ready for operation.

After the mission computer has been programmed, the experimental payload must be installed into the payload bay. If electronics are required for the experiment, a voltage regulator may be installed and connected to the craft battery to power the electronics. 5V power from the mission computer's voltage regulator may be used for low-power applications not to exceed 2.5W. Total payload mass is not to exceed 3kg and any equipment not being subjected to free fall conditions should be secured to the walls of the payload bay.

When the drone is ready to fly, it must be set up in the field. It is advisable to leave the propellers off the motors until the drone is at the flight location and prepared for takeoff. Always turn on the RC transmitter before powering on the drone to ensure there is a valid control signal being sent to the drone from the operator. With the motors off, the flight controller must be connected to a computer with INAV Configurator installed. In the receiver tab of the configurator, the drone operator must verify that the drone is receiving valid control inputs from the RC transmitter and the mission computer. If no signals are being sent to the flight controller, the mission computer should be reset. If this issue persists after a reset, it may be due to a lack of signal from the RC transmitter or a sensor malfunction on the mission computer. The telemetry radio pair may also be installed on the drone and onto a laptop if the researcher intends to monitor the flight details of the drone in real time. A telemetry monitoring program such as Mission Planner may be used to view this data.

The GPS signal health can be monitored from the Setup tab of INAV, and the drone is ready to fly with a lock onto at least six positioning satellites. A safe wait time is at least three minutes for this process to occur. When the system is ready to fly the drone battery can be connected, then the USB can be disconnected, and finally the propellers may be installed onto their respective motors.

All individuals must step back to a safe distance from the drone prior to takeoff. The drone operator must then ensure the flight mode on the RC transmitter is set to 'manual flight' and the throttle stick is in a neutral position representing 0% throttle. Upon switching to an armed state, the operator must verify that the propellers are not spinning or are spinning slowly in the forward direction. The pilot can then change the flight mode to 'autonomous flight.' The drone will then begin its ascent to the maximum altitude. Altitude can be monitored through the telemetry viewer; however, it is advisable to have a visual observer present so the pilot can maintain a line-of-sight view of the drone and flight analysis can be performed by the visual observer.

Once the drone has reached maximum altitude, it will automatically begin its acceleration downward, attempting to achieve a constant acceleration rate of $9.81 m/s^2$. The drone will exit this control loop after any one of four conditions: the altitude floor has been reached, the time limit for the free fall has been reached, the maximum negative throttle has been achieved, or the pilot interrupts the process to regain manual control. After one of the first three conditions has been met the drone will slowly decelerate to minimize stress on the frame. Once it has stopped its descent it will return to its takeoff coordinates in the horizontal plane and make a controlled descent to the ground. As soon as the drone reaches the ground the operator must disarm the craft.

The drone operator may safely power down the craft after it has reached the ground and been disarmed. The battery must be disconnected, and the propellers removed before the drone can be considered safe to pack up and transport.

It is important to note that only one flight should be conducted with a fully charged battery since the drone's power decreases because of battery drain. The figure below shows the discharge curve of a battery as a function of voltage and time. Since maximum thrust output is a function of voltage applied to the motors, the available thrust decreases as the drone battery drains.

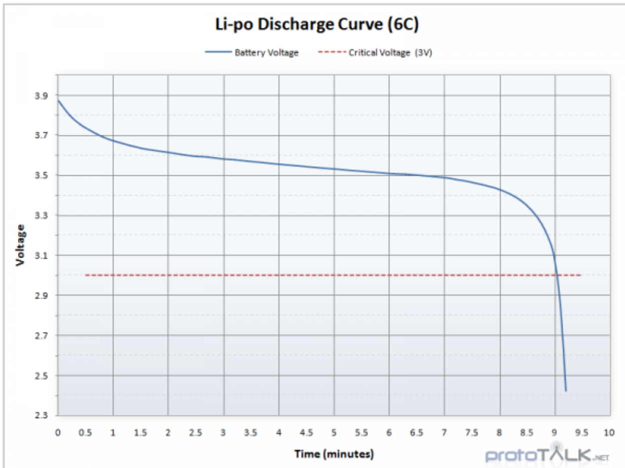


Fig. 4. Graph of a lithium-polymer battery discharge curve. The blue line represents battery voltage drain with respect to discharging time. Each battery cell begins fully charged at 4.2 volts and reaches critical voltage at the red dotted line, 3.0 volts.

V. Specifications and Features

The drone has been constructed with experimental versatility in mind. A payload bay is mounted to the bottom of the craft. It is a transparent acrylic box capable of holding a maximum payload of 3kg. It has inner dimensions of 110x110x116.5mm, which is slightly larger than a 1U cube satellite. The payload bay incorporates a data and video recording device for convenience of data collection during the experiment. This experimental data recorder consists of a Raspberry Pi Zero computer, a ribbon camera, and an inertial measurement module. It is set to automatically record video and log data throughout the flight and save the sensor data in a .CSV format for ease of post-processing and analysis. The camera is mounted to a leg of the craft and will point directly into the side of the payload bay to observe the experiment. The Pi will save its data on a USB stick allowing the user to simply plug it into a computer after the flight to view the data. The flight controller also has a built-in black box which records data from its sensors and stores the data onto a MicroSD card and can be read with a black box viewer program. This could be analyzed in the event of data loss or a crash to view flight data, but it is not as easy to manipulate due to its file format.

The flight controller of the drone is programmed with firmware that handles stabilization of the drone by sensing its orientation with an IMU and sending PWM signals to each of the electronic speed controllers to individually drive the motors to level the craft. It also incorporates the sensors used for maintaining horizontal position, monitoring altitude, and returning the drone to its home position.

The mission computer uses an ATMega2560 microcontroller which is programmed with an Arduino (C++) sketch to control the autonomous and manual commands to the flight controller. The chip runs at 16MHz (up to 16 MIPS) and has 256 KB of programmable memory allowing for scaling to more intricate flight missions in the future. Our current autonomous code only inhabits 5% of the program memory. The system also uses a BMP180 barometric pressure sensor to determine altitude and an MMA8451 triple-axis accelerometer to determine acceleration. Real-time averaging and normalization are incorporated into our code to reduce inaccuracy of sensor readings due to noise. The mission computer board is powered by a 5V 3A switching regulator to provide a constant voltage to the electronics of the craft, driven by a LM2576 regulator chip.

The autonomous code for the free fall sequence involves a PID control loop which takes the vertical acceleration as an input, 0G as the setpoint, and drives the downward throttle as the output. The motivation for using a control system to drive our downward acceleration is to maintain a constant acceleration regardless of changing conditions such as wind gusts. A static code to ramp up the throttle would not account for such real-world conditions and would be subject to error accumulation. Fig. 5. shows the general form of a PID control system. This system continuously calculates the difference between the input and the setpoint, applying a correction to the output value based on proportional, integral, and derivative control terms in effort to minimize the error.

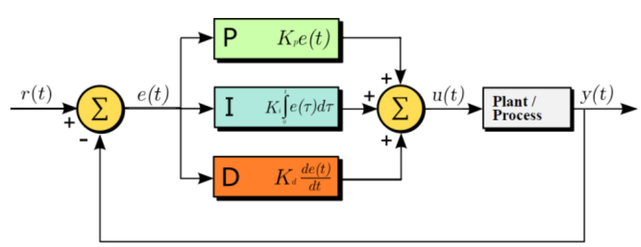


Fig. 5. General design of a PID control system [3].

At a maximum altitude of 400 ft, the flight ceiling allowed for recreational drones, we expect to get a free fall time of approximately 2.9 seconds. To calculate terminal velocity in each direction, an equation derived from the equations for linear acceleration and drag force, which was derived by NASA's Glenn Research Center is used [2]. For this application, weight has been replaced with combined thrust and weight in this equation. These modifications can be seen (1) and (2), where T and W are thrust and weight, respectively,

$A_{frontal}$ is the frontal area of the drone with respect to the drone's movement, C_D is the drag coefficient, ρ is the density of air, and λ is the efficiency of the rotors on the downwards trajectory.

$$t_{\text{fall,down}} = \frac{V_{\text{terminal,down}}}{g} \tag{1}$$

$$V_{\text{terminal,down}} = \sqrt{\frac{2(W+\lambda T)}{\rho A_{\text{frontal}} C_D}} \tag{2}$$

Using this analytical method, a duration of 2.9 seconds has been calculated. The results of this calculation could be made much more accurate through finding the drag force on the drone experimentally.

Safety features are also included on the craft in the event of unforeseen issues. The program has two separate hardware interrupts triggered by switches on the RC transmitter that allow the user to either take back manual control of the drone or disarm the craft, actively stopping the motors. There is another dedicated switch on the RC transmitter to deploy a parachute. The parachute bay, a 3D-printed box, is spring loaded and mounted on top of the drone's battery. A servo holds a pin in place that will release the parachute, launching it away from the craft when the parachute switch is activated. A final failsafe mechanism is incorporated into the flight controller that will tell the drone to drop, descend, or return to home (user preference) if it loses signal from the mission computer.

VI. System Components

This section highlights the various components that make up our electronics system. Details will include the following: the component, its function, why it was chosen, and the specific part that is used in our final build.

A. Battery

The battery is the sole source of power on our multirotor drone. It has the highest demand placed upon it of all the components on the craft. It is therefore extremely important that the right battery is selected for the aircraft for its specific mission. A few factors make up the formula for the right battery - chemistry, voltage, capacity, and discharge rate. Battery technology has improved immensely in the last few decades and the most popular battery chemistry for drones is the Lithium Polymer battery, or LiPo, for short. The LiPo battery boasts an incredibly high discharge rate and the absence of a quirk called 'battery memory' that would diminish the capacity of some older batteries. LiPo batteries are perfect for multirotor drones by providing the quick bursts of energy and maintaining a relatively linear voltage drop rate for most of its discharge process. LiPo batteries provide a voltage source of 3.7V per cell nominal, with a maximum voltage of 4.2 volts per cell. These cells can be wired in series to create higher voltage battery packs for use in large aircraft with higher-voltage power systems. Lower-KV motors often require higher voltage to maintain optimal speed, so many multirotors such as ours might require six-cell batteries or greater. Capacity of the battery is determined by calculating the current drawn by the aircraft and the duration of the flight required. For a simple example, an aircraft that draws 20A of current would require a 20,000 milliamp-hour (mAh) battery to fly for one hour. In the case of our project, we will need to decide the time required to perform the flight, and factor in the average current drawn by the craft during the flight. The Turnigy Graphene battery has a continuous discharge rate of 180A and peak discharge rate of 360A. This is suitable for our application, since we should be drawing a maximum of approximately 120A of current during flight.

B. Power Distribution Board

An often-overlooked portion of the multirotor power system is the power distribution board. Some flight controllers include it on their circuit board, and sometimes ESCs, or electronic speed controllers, are designed as an all-in-one package with a battery input and motor outputs. For our project, however, we utilize a discrete power distribution board to support our high-power needs. Like the battery, the power distribution board will need to be able to handle the current of the entire aircraft power system. This is achieved by including terminals/solder pads for the battery as well as all the outputs.

C. *Electronic Speed Controllers*

The electric speed controllers (ESCs) are very simply chosen by finding an ESC rated for 20-30% higher current than the motor will typically draw. This allows enough headroom for the ESC to power the motor in the event of momentary high current draw without destroying the power circuitry. ESCs are additionally considered for extra characteristics such as govern the motor speed at a high rate, heat dissipation, and firmware/programmability. ESCs generate large amounts of heat when pushed to their limits of performance and we intend to run the motors at maximum speed during portions of our flight. We will need to pick ESCs that can dissipate this heat effectively. "ESC firmware is the software running on every ESC, which determines the ESC's performance, and what configuration interface can be used. The firmware you can use depends on the ESC's hardware." [5]. ESCs are often programmed via computer software and firmware/hardware determines the features of the ESC such as PWM frequency. This is the frequency at which the flight controller communicates the motor speed to the ESC, and higher frequency is better. Other features of the ESC include active braking, low-voltage cutoff, and bidirectional motors. Active braking is a feature that allows the motor to actively decrease motor speed when throttle is reduced. Low-voltage cutoff protects the craft from draining the LiPo battery down to an unsafe level. The Lumenier ESCs we are using utilize all these features. They can provide 50 amps continuous current and 60 amps burst current which is suitable for our application.

D. *Motors*

Brushless DC motors are the most popular type of multirotor motors, due to their high power and efficiency versus outdated brushed motor technology. "Brushless motors offer several advantages over brushed motors thanks to the design. Much of it has to do with the loss of brushes and commutator. Since the brush is required to be in contact with the commutator to deliver a charge, it also causes friction. Friction reduces the speed that can be achieved along with building up heat. ...This means that brushless motors run cooler and more efficiently so they're able to deliver more power." [6]. Brushless motors are rated most generally by a unit called KV, which translates to the rotations per minute per volt applied to the motor. Higher-KV motors are often used in smaller craft to achieve higher motor speeds with small propellers. They also require lower voltage to achieve sufficient speed, since lower voltage batteries are most commonly used in small craft. Adversely, lower-KV motors are used often with larger craft and batteries with higher voltage. They provide the torque that large propellers need to lift heavy payloads. Besides KV, motors can be further compared by their individual performance through thrust tables. These tables offer the thrust provided and the current drawn for one or a few combinations of propeller and battery. The KDE motor brand we chose offer a 400KV motor that lists a maximum thrust of up to almost 4 kg per motor with a similar propeller to ours. This would give ample power to our propellers to accelerate and recover our drone.

Static motor testing was able to determine the empirical value of thrust that will be provided by the motors with our selected propellers. Our testing was conducted up to 60% of the total voltage. This testing also shows about 30% efficiency when the motor is spinning in the opposite direction, as seen in Table I.

TABLE I
Motor Testing Values

% of Full Thrust	**Forwards Direction Thrust (g)**	**Backwards Direction Thrust (g)**
25	590	190
50	1500	475
60	1950	570

E. *Mission Computer*

As detailed in section VII, our mission computer is a custom circuit board used to automate our flight. It consists of a two-layer PCB with a microcontroller, voltage regulator, and I/O pins to interface with the other aircraft electronics.

Fig. 6. Image of the mission computer circuit board.

F. Voltage Regulator

The design of our switching voltage regulator is based off the LM2576 reference design shown in Fig. 7. As seen in Fig. 8., we implemented this design directly onto our PCB.

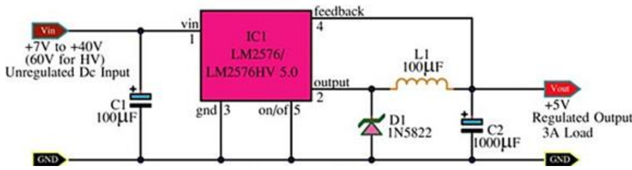


Fig. 7. Image of the LM2576 reference design [7].

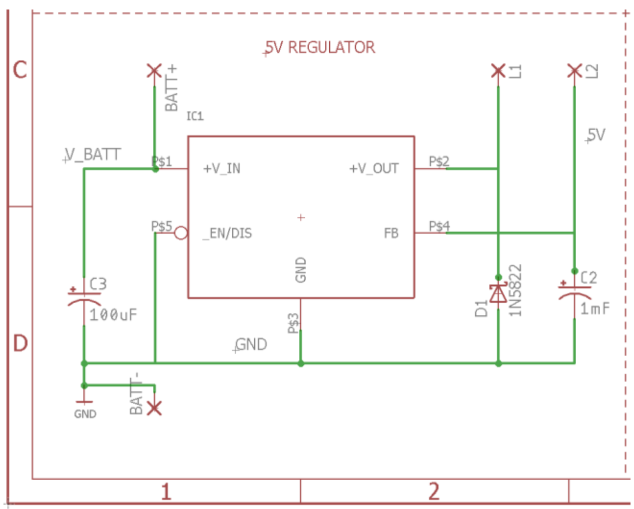


Fig. 8. Image of the mission computer implementation of the LM2576 reference design.

G. Camera

The camera used to record the payload during flight is a webcam module made to be compatible with the Raspberry Pi Zero. The video quality will be set to be 720p at 60 fps. The camera will be mounted upside down on the leg of the craft, but post processing will allow the video to be oriented to rotate the video as well as add a millisecond-precision timestamp on the video.

VII. Board Design

The mission computer was designed to allow fully autonomous mission functionality to our microgravity drone. This provides the dual benefit of mission repeatability and ease of use. Flight controllers have been developed over the last decade to stabilize aircraft and fly to specific GPS coordinates, but they were never intended to fly the drone at a constant acceleration. Therefore, we needed to develop our own system to pass the flight controller the control signals required to achieve this goal. A microcontroller was the perfect solution; it can compute the desired throttle values with adequate speed, low overhead, and minimal power consumption. We specified the ATMega2560 chip for its program memory size and I/O options. The mission computer board also doubles as a low-voltage power source for the whole drone, providing the 5V regulated power source.

The I/O connections of the mission computer are as follows: a drone battery input to drive the voltage regulator, an ICSP connection for burning the bootloader through the SPI port, a serial interface for code uploading through a USB-to-Serial adapter, PWM inputs for manual user controls, a PPM output for passing signals to the flight controller, and telemetry passthrough from the flight controller to the telemetry radio module. The voltage regulator was selected to handle ~25V input from a 6-cell lithium polymer battery. The in-circuit serial programming port was used for burning the Arduino bootloader to the chip for programming our code through the Arduino IDE. The serial I/O port was chosen as our programming interface to eliminate the need to include a USB-to-Serial adapter on our board. This reduces the number of components on our board which lowers production cost and weight. A PWM interface was chosen to communicate from the RC transmitter to the mission computer due to its simplicity. PPM output to the flight controller was a necessary alternative to PWM because the flight controller only has one input pin for user control. Telemetry was passed through the mission computer board because the flight controller's telemetry output was not connectorized nor did it provide 5V power to the telemetry radio module.

The mission computer board was laid out in such a way to isolate the power electronics from the signal traces. This was done to minimize noise in the signals. The board layout is shown in Fig. 9. below. The yellow box outlines the voltage regulator, and the signals are sent along the top half of the circuit board, seen outlined in green.

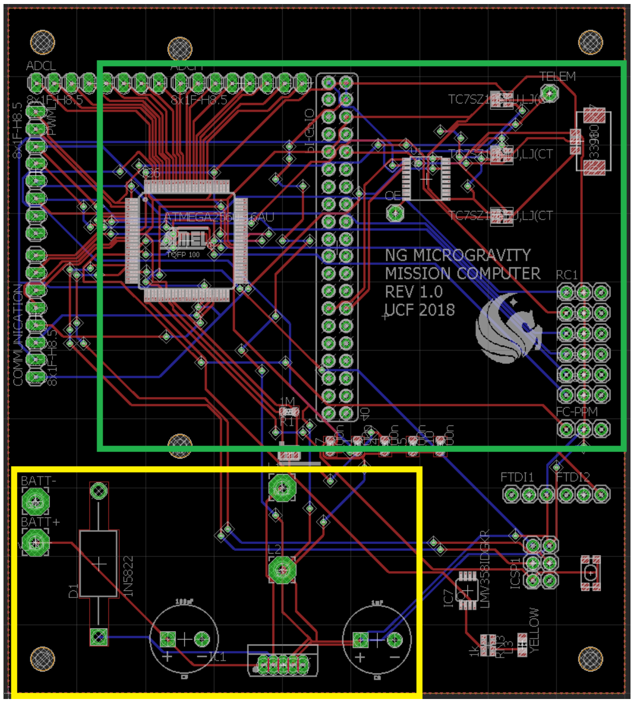


Fig. 9. Image of the mission computer board layout, highlighting the power system (yellow) and signal path (green).

VIII. Conclusion

Although the design of the design outlined in this paper has proven to be an adequate solution to providing a low-cost microgravity experimentation platform, there are many improvements to be made. A custom-built frame could provide increased durability of the drone. Additionally, higher precision sensors and more elaborate filtering could be incorporated into the system to achieve cleaner and more accurate microgravity.

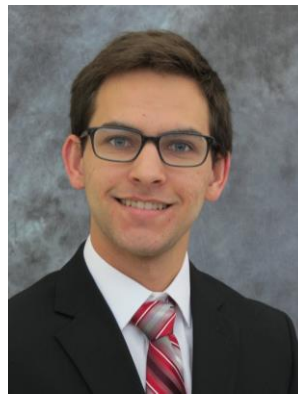
This project has taught us many things about working as a large team of engineers and with members of different engineering disciplines. Some examples of challenges we've faced while working on this project include the following: organizing the members of our team, scheduling times to meet, budgeting, and conflicting design ideas. With these challenges that we have overcome to be successful in this project, we are have gained invaluable experiences that are more than likely to arise in our future endeavors as engineers.

Acknowledgement

The authors wish to acknowledge the assistance and support of Northrop Grumman, Eliot Ramey, Marino Nader, Chris Tate, and Hoverfly Technologies, Inc.

Biography

Adam Brockmeier is a 25-year-old graduating Electrical Engineer at the University of Central Florida. He is currently working at Hoverfly Technologies, Inc. in Orlando's Research Park and plans to continue work developing drones.



Jacob Knepper is a 22-year old graduating Computer Engineer at the University of Central Florida. Jacob is currently studying to apply for an officer position in the US Air Force. He hopes to pursue a career in the computer engineering field with an interest in embedded systems.

References

[1] J. Afman, J. Franklin, M. Mote, T. Gurriet and E. Feron, On the Design and Optimization of an Autonomous Microgravity Enabling Aerial Robot. Atlanta, GA, 2016, pp. 1-8.

[2] N. Seidle, “Battery Technologies” Sparkfun. [Online] Available: https://learn.sparkfun.com/tutorials/battery-technologies/battery-options/ [Accessed: 10-Apr-2018]

[3] "PID Controller", En.wikipedia.org, [Online]. Available: https://en.wikipedia.org/wiki/PID_controller. [Accessed: 10-Apr-2017].

[4] NASA Glenn Research Center, "Propeller Thrust," May 5, 2015. [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/propth.html. [Accessed: 30-Nov-2017]

[5] O. Liang, “ESC Firmware and Protocols Overview,” July 10, 2017. [Online] Available: https://oscarliang.com/esc-cfirmware-protocols/. [Accessed: 12-Oct-2017].

[6] K. Koehler, “Brushed vs. Brushless Motors: What’s the Difference?” Pro Tool Reviews, 2015. [Online] Available: https://www.protoolreviews.com/news/brushed-vs-brushless-motors/18990/. [Accessed: 11-Oct-2017].

[7] “5V 3A Switching Regulator circuit by LM2576,” ElecCircuit, November 28, 2016. [Online]. Available: https://www.eleccircuit.com/5v-3a-switching-power-supply-by-lm2576/. [Accessed: 13-Oct-2017].