## Dronenet: The Quad Chronicles

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Abstract — A complex electrical engineering project, Dronenet, is a design and system integration of four major subsystems: an unmanned aerial vehicle (UAV), a control terminal for the UAV, a mobile UAV carrier, and a control terminal for the mobile UAV carrier. Dronenet has a unique regenerative charging system based on the design of a Bedini motor to extend the duration of Pb and LiPo batteries. This project will also incorporate a fingerprint scanner to allow for system security, ensuring that only authorized individuals can operate any subsystem.

*Index Terms* — Data security, telemetry, battery management systems

#### I. INTRODUCTION

Dronenet: The Quad Chronicles is a complex integrated project consisting of four main parts: an unmanned aerial vehicle (UAV), a mobile UAV carrier, and two separate control terminals for both the mobile UAV carrier and the UAV. Dronenet was designed and built to have a myriad of real world applications. Some of the applications we had in mind while completing this project include: military intelligence, search and rescue assistance, commercial and residential delivery systems, computer vision integration, and surveillance.

The overall goal of the project is focused on extending the mission time of both the UAV carrier and the UAV itself. The downfall of relying on battery systems is the limited single use time of the system. Our UAV carrier incorporates a new regenerative charging system based on the design of a Bedini motor. The charging system will be able to take one Pb battery and use it to charge three Pb batteries that are used to drive the UAV carrier. With a UAV carrier now that can extend its range much further than before, we are able to utilize the battery life of the UAV. With this system the UAV no longer has to expend its little battery life trying to get to the location where it needs to carry out its task. Essentially our system is similar to how the relationship between a Navy aircraft carrier and the jets onboard. The UAV carrier will incorporate an all terrain drive train and unique wheels that allow us to move in various directions. The UAV carrier will also be secured and only able to be driven and accessed by authorized personnel.

The UAV has autonomous flight modes where we can make preplanned flight routes using Google Maps. Both of the UAV and the UAV carrier have wireless telemetry using Xbee wireless modules and both have live video feeds.

The control terminal for the UAV carrier is a custom built controller that allows us to have security features on the carrier as well as motor controls including individual speed control for each motor. The UAV control terminal is open sourced software where we can view the wireless data and program our UAV.

#### II. UAV

The unmanned aerial vehicle that we used in this project is a quadcopter. The main components of our UAV consist of: a flight controller, four motors, four electronic speed controllers (ESCs), wireless telemetry, and a battery. In addition to the main components we integrated a video transmitter and an on screen display module (OSD), and a sonar module.

#### A. Flight controller

In order to be able to have a UAV we need a powerful brain, we call this brain the flight controller. The flight controller will need to incorporate a gyroscope, accelerometer, altimeter, compass, GPS, and a processor. The flight controller we are using in Dronenet is the APM 2.6 flight controller.

The 6 axis MEMS device that is being used for the gyroscope and accelerometer is the MPU-6000. This device will run on 3.4 volts and has a logic level of 3 volts. During normal operation, using the gyroscope and the accelerometer at the same time, the MEMS device will draw around 3.9 mA's of current giving us a power consumption of 13.2 mW. (MPU 6000 Data Sheet).

The accelerometer and the gyroscope give us the measurements needed to adjust the pitch and roll of the UAV; therefore we are missing a component to give us the yaw. The yaws is perpendicular to the direction of Earth's gravity, see Figure 1, and thus cannot use the accelerometer alone.

The digital compass that is used is the HMC5883L. The electrical characteristics of this part include having a supply voltage of three volts and a current draw of approximately 100  $\mu$ amps. This component has a maximum output rate of 160 Hz.

The APM 2.6 controller is run using an Atmega 2560 which has an open source schematic that we can use, the controller design will allow us to put a 3-axis gyro, an accelerometer and magnetometer, and a barometer included on the board. It also will allow us to use an off board GPS and compass system, we must put these off the board for the purposes stated earlier. The Atmega chip has multiple RX and TX pins which will allow us to use Xbee's for our telemetry.

The Atmega 2560 will be the brain of our flight controller. The Atmega 2560 is an eight bit AVR architecture which is Atmel's own architecture that is based on the Harvard architecture. The Atmega 2560 runs on five volt logic while most of the sensors that we will be using use I2C or SPI connections which all run on 3.3 volt logic, therefore we will have to use a bi-directional level translator to convert between the 3.3 volt and five volt logic. One of the main reasons that we will be going with the Atmega 2560 is because it has plenty of GPIO, 86, and PWM channels, 12. (Atmega 2560 Data Sheet). The amount of GPIO is important because of all of sensors that we implemented onto the flight controller. The PWM channels are essential for the UAV application because it allows us to control the motors, the additional channels also allow us to put in the two servos that we will need in order to put a camera system on the quadcopter



Figure 1: Yaw, Pitch, and Roll Orientation

The flight controller design will need an altimeter. The altimeter that we are using is technically called a barometric pressure sensor, but it serves the same purpose. The sensor takes in the changing barometric pressure and from there can determine the change in altitude. The altimeter that is being utilized is the MS5611-01BA03 barometric pressure sensor. This sensor, as do most of the sensors that we use, runs on 3.3

volt logic. The operating characteristics of the sensor are perfect for our low power requirements; it runs on 3.6V at  $1\mu A$ .

#### B. Wireless Telemetry

For our UAV design one of the most important features is being able to communicate with our mobile platform and to be able to transmit the data and the video feed that we will be collecting. In order to accomplish this goal, we will set up a telemetry system that will be able to send the data long distances to our mobile platform.

After determining the goals we needed for the telemetry system we decided the major factors to take into account are as follows: low power, the ability to transmit/receive data packets over at least one mile, and be able to transmit large packets of data accurately.

From our research there are mainly two operating frequencies for most telemetry devices, 900 MHz and 2.4 GHz. One of the benefits of using the 900 MHz transmitting frequency is that using the same transmission power it can transmit much farther than the 2.4 GHz version. This is due to the path loss from the attenuating signal, where the path loss is directly proportional to frequency of 2.4Ghz will have higher path loss and will limit its effective transmit distance (Friis Equation). The lower frequency of 900 MHz also gives an added advantage of greater penetration distance, meaning the lower frequency and the longer wavelength the 900 MHz signal can penetrate walls much easier.

$$P_r = \frac{P_t \lambda^2}{(4\pi R)^2}$$
 Watts  
Equation 1: Friis Equation

Because of these factors we will use 900 MHz; we plan on having a relatively clear transmission path, no walls, and a modest transmitting range of one mile.

While researching telemetry options the parameters that were compared were the transmission range and the power consumption. The parameters that we were trying to meet were to be able to have telemetry up to a mile in range and to consume low power relative to all telemetry options. We were able to do this by using Xbee Pro wireless telemetry modules. The Xbee Pro has a range of one mile that we were requiring and with an adjustable transmit power of up to 215mW which is about half the transmit power as other telemetry models we researched. (Xbee Pro Data Sheet).

#### C. Battery

While researching batteries we discovered that we had two plausible options for batteries, LiPo or NiCad.

Lithium Polymer (Li-Po) batteries are essentially made up of the same materials as Li-ion batteries, except that the electrolyte that is sandwiched between the anode and the cathode. The electrolyte found in Li-Po batteries differs in that it is micro porous and the one found in Liion is traditional (Buchmann). Because of the increased specific energy, as well as, the benefits of being lightweight and having a high nominal voltage, Li-Po batteries are the currently the most popular choice for aircraft hobbyists today. This is why we decided they would be the best choice for our project.

The most important characteristic we considered when choosing a battery for our UAV is the energy capacity. This is measured in milliamp-hours (mAh). This number represents the amount of milliamps (mA) the battery could supply at a constant rate for one hour (Bourke, Understanding Electric Power Systems Part 2). For example, a battery with an energy capacity of 2800 mAh could supply 2800 mA of constant current for one hour or 700 mA for 15 minutes.

The next specification used to categorize Li-Po batteries are the discharge rates. Because of the sensitive nature of Li-Po batteries, they have limited discharge rates. These rates are directly related to the capacities of the batteries. For example, a battery with a 2800 mAh capacity that can safely supply a constant rate of 28A would be specified with a 10C continuous discharge rate (RC Helicopter Fun).

For Dronenet we went for the Nanotech Turnigy 5000 mAh battery. This nanotech battery has a burst discharge rate of 70C and a constant discharge rate of 35C and weighs 409g. We compared this nanotech Turnigy battery to an equivalent Turnigy 5000 mAh battery that was not a nanotech. The plain Turnigy battery had a burst discharge rate of 30C and a constant discharge rate of 25C and weighs 531g. The higher discharge as well as the lighter weight and smaller dimensions of the Nanotech battery made it our preferred battery for our UAV.

What separates Nanotech batteries from traditional LiPo batteries is in the fabrication technology. Traditional LiPo batteries use particles in the range of size between 5 to 20 micrometers while Nanotech batteries use partilices smaller than 100 nanometers. The advantages of the

Nanotech batteries include: a increased available power, faster charge times, longer shelf life, and they are safer.

#### E. Electronic Speed Controller

The flight controller is also responsible for controlling the speed and direction of the motors for flight. In order to control the motors, there must be a bridge between motors and the flight controller called the electronic speed controller (ESC). This process of controlling the electronic speed controller is very similar to controlling a servo. The flight controller will be using the pulse width modulation outputs of the controller to send a pulse that will turn the speed controller on and send the correct power to the motors to adjust its speed and direction.

The ESC's that we used in this project are DJI OPTO ESC's that are rated for 30A. We used the 30A DJI OPTO ESC's because they do not have to be calibrated before flying. The DJI OTPO ESC's are brushless speed controllers which is important since our motors are also brushless. Our motors are rated for a current draw between 15-25A, therefore in order to supply enough current we needed ESC's with a current rating of at least 25A. We decided on the 30A to ensure that we do no not risk burning up the ESC.

#### III. UAV CONTROL TERMINAL

Our goal is for our UAV to be autonomous and hands off during missions, we needed a way to program mission parameters before takeoff. Since we are using the APM 2.6 flight controller based on the Atmega 2560 chip, we needed to use a supported software package for uploading the mission plans.

Michael Oborne's Mission Planner software is currently the most supported software for completing this task. Mission Planner is, by far, the most used open source software for configuring and planning autonomous missions. This results in a large online community with many resources for developing an autonomous vehicle. This also means we can add features, if we so desired, in the future.

Mission Planner is a software package that allows us to configure the APM's settings for our particular airframe setup, so we can achieve the best stability and control for manned and unmanned flights. This software package also supports calibration of the compass and our accelerometers. Mission Planner also allows us to test our motors as well as our sensors such as the sonar module. Mission Planner allows us to plan missions with waypoints planned using a Google Maps interface within the software. Mission Planner makes this very easy with point-and-click waypoint entry. We also have the ability to download mission log files for analysis after our missions are completed and the copters have safely returned.

#### IV. UAV CARRIER

The UAV Carrier consists of multiple subsystems housed within its shell. The mecanum wheeled drivetrain, the Bedini based regenerative charging system, and platform with the quad-locking system have all been designed to be the mobile base for the UAV. With it, we can deliver our UAV to a location and service the UAV's energy needs all on location, extending the use of the UAV out in the field.

#### A. Mecanum Wheels

Mecanum wheels are a very unique type of wheel. They were created back in the 90's by Bengt Ilon, a Swedish Engineer for Mecanum AB and have not been widely adopted into the commercial and robotic industries until the last few years. They are most commonly used in forklifts and at airports. They offer several advantages of traditional wheels such has the ability to strafe left and right, move in diagonal directions and circle around objects while still facing them. All of these maneuvers are performed without any type of steering system. They are controlled by simply adjusting the direction and speed at each wheel independently. They offer a simple and in most applications cost effective solution to steering a vehicle. Figure 2, shows the wheels from a first person point of view to help the remaining explanation and figures make more sense.



Figure 2: 3D Representation of Mecanum Wheels

The concept behind mecanum wheels takes advantage of basic trigonometry. The wheels operate off a rotated XY axis by 45 degrees. Each wheel has a set of rollers that are evenly spaced going around the wheel. These rollers are then rotated 45 degrees. However, the direction in which they are rotated is important and must follow suite. Depending on what maneuver you are trying to do, these wheels "cancel" each other's angles causing it to force itself to push or pull in a direction. Figure 3 shows the wheels after the rotated axis. You will see that the rollers on the wheels line up after the axis are rotated 45 degrees.

The flexibility of driving modes with the mecanum wheels has opened up a whole new realm of possibilities for us. Due to the fact that we are essentially trying to catch a flying object, the ability to be able to perform small and tight maneuvers with a large vehicle became important. As previously mentioned the direction you turn each motor will determine the direction the whole vehicle will move.

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Diagonal Front Right	Diagonal Rear Left	Diagonal Rear Right	Strafe Left	Strafe Right

**Table 1: Mecanum Turning Direction for Driving Mode** 



Figure 3: Mecanum Wheels on 45 degree rotated XY axis Table 1 defines the standard driving modes of the mecanum wheels. After the platform was built, we had trouble getting it to drive in a straight line. However, with the way the code was written for the motor controls, we were able to control each motor speed individually. We then implemented a secondary speed control that would control the two left motors independently of the two right motors. This now gave us the ability to correct the speed offset to drive straight as well as the ability to perform a full radial turn. Before, we were only able to pivot and turn on a dime. While this is useful, we also discovered that a variable turning radius was essential for driving on any type of slightly curved surface.

While discovering the radial turns, we also then realized it should be possible to do a radial strafe mode. We applied the same concepts above while we were strafing, but realized that we were controlling the wrong motors. Instead of controlling the left and right independently, we now control the two front and two back motors independently. We can now circle around an object while facing the object the whole time.

#### B. Motor Control System

We have already reviewed the basic requirements to drive the mecanum wheels. Now we will go into more specifics on how all of that data is determined. As previously discussed, in order to move the wheels you need to have three digital lines, one Pulse Width Modulated (PWM) line, and one analog input.

Two of the digital lines are what determines the direction of the motor. They are based on simple logic shown in the table below. The bit values refer to driving the digital lines High (1) and Low (0).

Direction	Bit 0 (Digital)	(Bit 1 Digital)			
Forward	1	0			
	0	1			
Reverse					
Off	0	0			
Table 2: Motor Control Table					

The third digital line is required for the motor driver fault handler. If a motor faults out in cases such as over temperature or a shorted output, it will drive the signal Low(0) to let you know the motor driver is faulting out. If no process is running on the motor driver, it will still read Low. This requires a combined monitoring system that just requires knowing if you are trying to drive the system by looking at the bits being sent to the motor driver IC.

The PWM signal is for speed controls. The higher the PWM, the faster you go. These PWM values are ranging between 0-255. The motor driver IC will support up to 20kHz PWM. However we are currently only running it at around 900Hz due to the limitations of the motor controller MCU and keeping it stable.

The last remaining signal is the analog input. This signal determines the amount of current the motor is pulling from the motor driver. The current is read in as a ratio of the output current.

Where Isense is the current read at the MCU analog input, Iout is the actual current being pulled, and K is a parameter determined in the datasheet to be ranging from 9,665-13075 depending on the current draw.

The original design sent commands to the motor controller that it would then parse and determine the direction. This required an entire list of commands and a fairly large finite state machine to handle all the commands. Every time a new mode was discovered, we had to reprogram the device. We wanted the motor controller to be more of a firmware to provide a more robust system. We have a unique custom parser that handles all the logic for the motors. Since each motor requires two bits to determine the direction and we have four motors, we need eight bits to determine the direction for all of the motors. Since four bits represents one byte, and one byte is the minimum value you send over our communication system, the parser was written to just handle the two bytes and parse every two bits to assign them to the motors for the direction. The parser for each individual motor can be shown in the table below.

18 Bits						
2 bits	8 bits	7 bits	1 bit			
Direction	Speed	Current	Fault			
Table 3: Motor Driver Parser						

We still have the "legacy controls" implemented in our motor controller, but we were able to reduce the original state machine by almost 50%.

The actual motor drivers IC's (motor drivers) are part of an automotive IC line by ST Semiconductor. These are used to drive high current 12V motors in vehicles. Our motors have a stall current of up to 22 Amps and have a nominal running current of around 5-10 Amps at full speed based off our testing. The motor drivers are designed to handle up to 30 Amps for 150 seconds and have an "infinite" runtime if you are running under 14 amps. Since we very rarely spike above 5 amps per motor driver IC, our motor drivers run surprisingly very cool and are yet to overheat even after driving for over an hour in the sun. We used an infrared laser thermometer to measure the IC's after our operations and have never seen them rise above 102°F.

#### C. Bedini Motor Theory of Operation and Construction

The Bedini motor works on a principle of a pulsed DC voltage. The idea is that an electromagnet circuit is switched on and off based on sensing the proximity of a permanent magnet as it rotates on a rotor. Initially when the rotor is not spinning, the system is "off" and no current energizes the electromagnet. As can be seen in Figure 4, once the rotor starts spinning; the permanent magnet moves towards the center of the coil, an induced voltage into the sense winding (red) biases a NPN transistor and increases the base voltage such that the transistor turns on. This supplies current to the



Figure 4: Bedini Motor Schematic

electromagnet and produces a magnetic field that is the same polarity as the permanent magnet. The repelling magnetic field accelerates the rotor in the same direction that it was moving. As the permanent magnet moves away from the center of the coil, the induced voltage starts to reduce, eventually below the turn on voltage of the transistor. When the transistor turns off, no current flows through the coil, but the rotor continues to spin due to momentum.

The battery charging comes from two mechanisms. The first mechanism occurs due to the magnetic field developed in the coil. When the power is removed, there is an inductive kick from the coil due to the collapsing magnetic field. However, since the transistor is off, the only path allowed for current flow is directed into the capacitor bank.

The second mechanism happens due to the interaction of the rotor and the coil. Generator action happens when a magnetic field is moving relative to a conductor. The magnets on the rotor induce a voltage into the windings of the coil, aiding the current flow into the capacitor bank. The voltage produced by these mechanisms is rectified to ensure the proper polarity for charging the batteries. A controlled switching mechanism allows the energy to build up in the capacitor bank and periodically dumps this stored energy into the battery to be charged.

What differs about this device from other charging devices is that this is designed to charge batteries using a pulsed DC voltage. Traditional battery chargers utilize continuous DC current as their charging mechanism. The problem with using continuous current as the charging mechanism is that the  $I^2R$  losses generate heat in the battery and cause a variety of issues. These include sulfate buildup and evaporation of water (Pistoia). With the Bedini motor, the pulsed DC voltage can be much higher because it is not continuous which means the heat generation will be significantly less from the  $I^2R$  losses.

The permanent magnets are  $\sim 1$ " x 2" x 3/8" and are mounted in a 3D printed rotor assembly. The spool holder for the dual coil was also printed using a 3D printer and has holes for inserting ferrous rods for the coil. Additionally, the spool holder was printed in two pieces and zip tied together to hold the coil on the spool. The coil consists of 20 & 24 AWG magnet wire, with approximately 900 turns for each.

In this system, we have four batteries to swap between. In order to automatically switch between charging batteries and the driving battery, a monitoring system measures the input voltage of the driving battery. This monitoring system is composed of a voltage divider circuit that is connected to the ADC of the Atmega chip. From this, the Atmega compares the relative voltage of the driving battery and compares it to a programmed value. Whenever the driving battery falls below this programmed value, the next battery in sequence is placed into the driving side of the circuit. A 5 second delay ensures that the voltage value settles to minimize unnecessary swapping of batteries. By cycling through the batteries sequentially, it ensures that each battery is given the longest possible charge time prior to be placed back into the driving side of the circuit.

The last aspect of the monitoring system is a RPM sensor for the rotor. Because of the presence of the permanent magnets in the rotor, a Hall Effect sensor is used to calculate the RPM. By counting each magnet as it passes the sensor and timing them, we can determine the approximate speed of the rotor and convert it to RPM.

In addition to cycling through batteries and recharging them, there are two solar panels on the mobile platform to supplement the power needed. With the goal of extending the operational lifetime of this system in the field, the solar panels provide us a large reservoir of energy to use. The solar panels will replace the driving battery in the Bedini motor, allowing us to charge all of the batteries, if needed, while still providing enough power for the rest of the electronics (except the motors for moving the platform). Combined with the regenerative ability of the Bedini motor, we should be able to extend the duration of this system greatly.

#### D. Landing Platform and Quad-Locking System

The landing platform consists of a sheet of Plexiglas that is of sufficient area to allow us room to land on the platform. In order to keep the UAV on the platform while it moves, we had to create a system that would allow us to hold the UAV without having to be present to release it. Additionally, we needed a way to do this while protecting the electronics from the weather of the environment it would be operating in.

The simplest solution that we could come up with involved using magnets to hold the UAV down. Having a way to remove the magnets and allow the UAV to fly its mission became quite complicated. After several different ideas, we came up with two servo driven platforms that would hold a pair of magnets for each side of the UAV and lower them when we want to allow the UAV to take off. When we want to land, we raise the platforms so that the magnets are near the surface of the Plexiglas, attracting the magnets on the legs of the UAV. To hold the magnets in place on the UAV, we designed some "feet" that would hold the magnets to the UAV. We then printed them using one of our 3D printers and attached them to the UAV.

A servo control board was created to control the servos from the main communications board inside the UAV Carrier. This allows us to remotely control the servos for releasing the UAV when we are ready to fly and locking it down when we need to relocate it.

#### V. UAV CARRIER CONTROL TERMINAL

The UAV Carrier Control Terminal is a self-contained system that forms the brains of the UAV Carrier. From this system, we can monitor, in real-time, most of the subsystems for the UAV Carrier, control the unique drivetrain, and lock and release the UAV from the platform.

A PIC32 forms the actual brain of the system. An eightway joystick and two slide potentiometers allows us freedom of direction and speed to control the UAV Carrier and its unique drivetrain. Three buttons with LED feedback help us to determine the many modes that it can drive in; including strafing, pivoting, tank-like steering, and diagonal movement. The PIC32 takes all of these as inputs and transmits the signals necessary via the onboard Xbee.

An onboard LCD has three main screens that we can switch to, depending on what aspect of the UAV Carrier we want to control at any given point. These screens are the motor control, monitoring, and turret control screens. The motor control screen allows us to monitor the control signals that are being sent to the UAV Carrier. The touchscreen display also permits a form of backup control should any of the other components stop working unexpectedly. The monitoring screen allows us to see various aspects of the UAV Carrier subsystems, mostly for checking on the charging level of the regenerative charging system. The turret control screen allows us to lock or release the UAV when it's ready to land or fly, respectively. It also demonstrates the ability to place a defensive turret on the UAV Carrier.

The final piece of the UAV Carrier Control Terminal is the fingerprint scanner. The scanner allows us to have custom profiles that give each operator specific access to any or all of the subsystems on the UAV Carrier. If a potential operator does not have a profile, then it will deny them access to controlling any aspect of the UAV Carrier.

#### VI. CONCLUSION

When we started this project, we knew that we would need to be aggressive in our research, design, and implementation. The schedule we came up with proved to be very challenging, but we were up the task. The key lesson that we learned from this is to make solid plans from the beginning, and to keep checking the progress compared to the plan every step of the way. One thing we did not anticipate was how much impact the mechanical aspects of our system would have on our schedule. Anyplace where we got off track with this project can be attributed to a mechanical issue.

Overall we feel that this project was a great success. The accomplishment we feel for completing such a large project proves our capability and will help us as we transition into our careers.

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THE ENGINEERS

# Brandon Frazer is graduating from

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