MDR Report: Mellivora, an electric vehicle supercapacitor power supply experiment

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***Abstract*—Current automotive technology is shifting towards electric and hybrid drive systems. While the emerging technologies have improved fuel mileage and aided in reducing transportation related greenhouse gas emissions, the majority of automotive manufacturers have taken less than ideal approaches that either limit range, have good efficiency in limited applications, or prohibitive initial cost; all of which make for a vehicle that is less desirable despite a societal shift towards environmental consciousness and a desire to reduce environmental impact in every-day life. Currently, lithium battery technology is the dominant power source in mobile and portable applications, but with emerging graphene supercapacitor technology, lithium batteries will be usurped by a lighter, smaller, less expensive, more power dense package that does not rely on rare or toxic heavy metals and can be manufactured in an environmentally friendly manner. This project aims to show the viability of a supercapacitor bank as the sole power source for an electric vehicle in anticipation of the release of these technologies.**

I. Introduction

THE wide acceptance of electric vehicles by the majority of drivers is inhibited by many factors. The predominant limitations of electric vehicles stems from additional vehicle cost, limited lifetime of battery banks, and range anxiety due to limited range, long recharge times, and limited availability of charging stations[1][2].

Graphene based supercapacitors have the potential to reduce the size, weight, and cost of electric vehicle power supplies due both to the lower cost of raw materials, graphene supercapacitors do not rely on rare metals like lithium battery technology, and not having to oversize the power supply to compensate for limited discharge rates as with a battery bank[3]. Supercapacitors have another distinct advantage over batteries, which is useful lifetime. High quality lithium batteries can typically be charged and discharged 5,000 times before there is a noticeable reduction in available charge, which begins to limit available range in a fully electric vehicle while low quality supercapacitors can be fully charged and discharged on the order of 500,000 times with no noticeable reduction in capacity[4].

Many research experiments have been performed to show the charging and discharge efficiency of supercapacitors over batteries[5][6], as well as the efficiency and lifetime gains of combined battery/supercapacitor power supplies[7], but very few experiments have been performed to show the applicability of stand alone supercapacitor power supplies in an electric vehicle application[8][9]. This project is designed to be a physical demonstration of the capability of a supercapacitor bank in an electric vehicle application by showing the discharge characteristics during acceleration, the charge efficiency during regenerative braking, and the reduced charge times when compared to a similar sized battery bank. We are designing this project as a proof of concept in anticipation of the release of graphene based supercapacitor technology which has been shown to have the potential to exceed the capabilities of lithium battery technology[10].

II. Design

A. Overview

Mellivora consists of several integrated subsystems to control the charging, drive control and user interface, regenerative braking, power delivery, and overall system management. Due to time and budget constraints, Mellivora has been scaled back to a single weighted drive wheel to demonstrate power delivery capability as well as to provide a rotational mass to demonstrate energy recovery efficiency via regenerative braking.

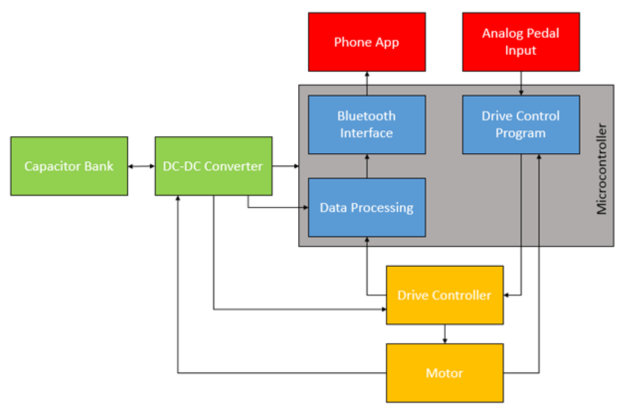

Figure 1: Block Diagram

Figure 1 Shows the block diagram for our project. The project consists of four main parts. The power supply, motor, software, and outside peripherals. The power supply consists of a supercapacitor bank and a DC-DC buck-boost converter. The DC-DC converter has two operating modes; motoring and regenerative braking. In the motoring mode the supercapacitor bank supplies power to the drive controller/motor combination through the DC-DC converter. The DC-DC converter maintains a 36V output while the supercapacitor bank voltage in allowed to vary from 66V at full charge to 24V when considered fully depleted. The regenerative braking mode switches the rolls of the DC-DC converter and the drive controller/motor combination. During regenerative braking the rotational energy of the wheel is converted to electrical energy by running the motor as a generator with the supercapacitor bank as the load. In this mode, the DC-DC converter outputs a constant 66V to the supercapacitor bank to facilitate charging while the drive controller limits the current delivered to control the braking force as determined by the microcontroller. The motor is a brushless DC motor. It is run off of a drive controller which receives signals from the microcontoller. The motor returns hall sensor feedback infomation back to the the microcontoller. The microcontoller runs all of the software for the project. In addition so sending the drive signals to the drive controller in processes the wheel rpm, speed, and battery power which it sends to a phone app which will display the information through bluetooth. Lastly a physical game pedal will be used to control the speed of the wheel.

At the start of this project, we were unaware of any companies that were attempting to develop a fully electric vehicle powered by supercapacitors. We were also not aware of any companies currently developing graphene supercapacitors beyond the scale required for portable electronics. As it turns out, Sunvault Energy has been in the process of developing large scale graphene supercapacitors and has paired up with Edison Power to produce a graphene supercapacitor powered fully electric vehicle, the Edison Electron One[11].

Specification	
Efficiency	>86% (greater than that of a lithium ion battery)
Stopping Speed	7.25 Revolutions
Recharge Rate	Greater than charge rate of lithium ion battery

Table 1: Specifications

Our specification, as seen in table 1, are designed to show the effectiveness of the supercapacitor power supply as not only a viable power source, but superior to conventional batteries. We want the efficiency and recharge rate of the power supply to be greater than a lithium ion battery. Additionally we want the stopping distance of the wheel motor to be 7.25 revolutions. This complies with the National Highway Traffic Safety Administrations minimum required braking distance of 19 feet for a passenger vehicle traveling at 20 mph.

B. Motor Controller

The motor controller is responsible for driving the motor and sensing the motor speed via feedback from the motor's hall sensors. It must translate the input from the Central Control Module (CCM) to control motor acceleration and deceleration, via regenerative braking, based on user input through the pedal controls.

The STMicroelectronics L6234 motor driver[12], as seen in Figure 1, is the core of the motor driver. The L6234 is a three phase brushless DC motor driver that is rated for up to 52V and 5A, which is sufficient for driving the 36V 4A wheel hub motor that will be utilized for Mellivora. The motor driver contains three sets of IGBT pairs to form a triple half bridge driver. Each IGBT pair in the L6234 is controlled via enable and input control pins. When the enable pin is high the IGBT pair is powered and the input pin dictates which IGBT in the pair is on. The gate switching allows current to flow to the motor inductor coils creating a north polarity when the upper gate is open and current flows from the motor inductor coils creating a south polarity when the lower gate is open[13]. Figure 2 shows an example of current flowing to the motor. As the rotor spins the gates are switched allowing current to alternate through the coils.

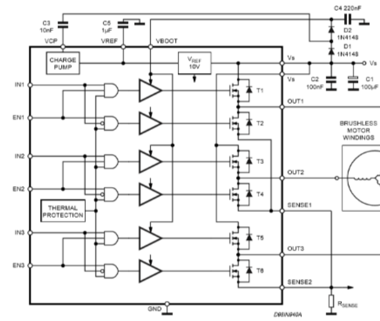

Figure 2: L6234 Block Diagram

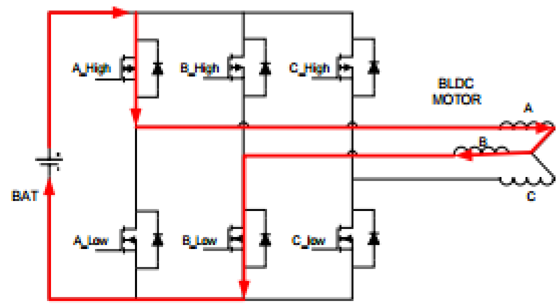

Figure 3: Motor Current Flowing

This gate switching is controlled via feedback from built in hall sensors in the motor. The three hall sensors in the motor provide feedback of the motors position to determine when the gates need to be switched. Figure 4 shows an example of hall sensor to motor state. Hall sensor feedback will also be sent to the CCM for determining current motor speed for the input/output feedback control loop.

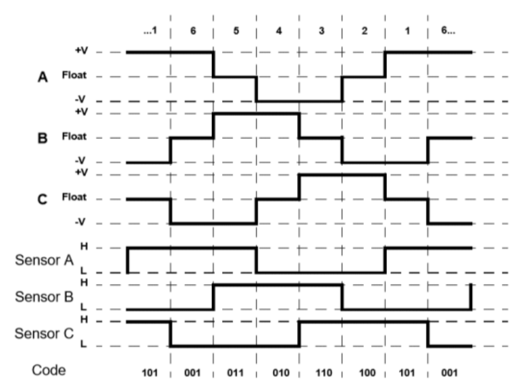

Figure 4: Sensor vs Drive Timing

During regenerative braking, current flows through the freewheel diodes on the IGBTs to the DC/DC converter to be stored in the supercapacitor bank. Figure 5 shows the current path during regenerative braking. Drawing current into the power supply creates back EMF in the motor slowing it down. The braking speed can be controlled by quickly cycling the lower gates. This switches the motor between freewheeling and braking[14]. Regenerative braking is most effective at high speeds due to the larger back EMF created when drawing current from the motor. The braking force becomes less powerful as the motor slows down though. Regenerative braking has not yet been implemented in the motor controller as the motor has not yet arrived due to supply chain delays.

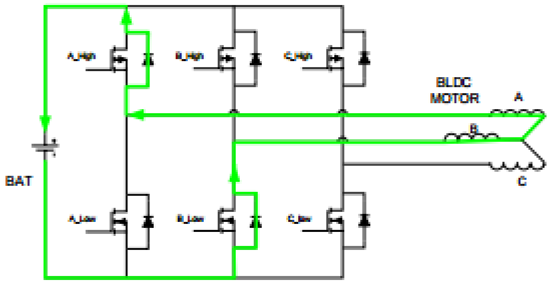

Figure 5: Regenerative Braking Current

For simulation and testing, an Arduino UNO microcontroller is used to run the code required for the motor controller. The hall sensor inputs are read by the Arduino and translated into a specific hall state. Each hall state corresponds to a specific set of gates open. The Arduino sets the required Enable and Input pins on the L6234 to high. A potentiometer is used to control the throttle or braking speed.

C. *User Inputs and Interface*

At the highest level, Mellivora uses physical pedals as inputs and displays system attributes as outputs on an Android device. The Central Control Module (CCM) will use Bluetooth to communicate with the Android application while the pedals sends analog signals to the CCM for processing speed and braking demand. The pedals are adapted from a videogame controller, which makes use of potentiometers to allow simulating standard vehicle inputs. With two analog inputs, the CCM will need to consider fail-safes such as determining actions when both pedals are depressed at the same time. All calculations and inputs are handled in the CCM to prevent errors from external interference and communication errors. The Android application is utilized solely to graphically display data, such as speed, remaining power, etc., to the user.

The application is being designed using Java. The application will break apart the input lines from the CCM and display the information on the Android display. The CCM will output data in a text file. The data represents a specific performance aspect of the system and must be received in a specific order: RPM, Battery Percentage, Mode, Speed, and Pedal Demand Percentage. The Android application then splits up each input and separates them in order to update the visual display on the Android device.

D. *Central Control Module*

The Central Control Module (CCM) is the element that ties all the systems together. Its primary function is the feedback control of all other systems. This means that the program on the Central Control Module must process incoming signals from the other systems and signal other systems correctly in response such that the system runs as intended. Secondary functions of the CCM include safety protocols, data collection and management, error handling, and monitoring other systems. Motor control may also be handled by the Central Control Module depending how system integration proceeds. Most of these functions will be achieved through the manipulation of outgoing signals to achieve the desired result.

The CCM has two primary components, a program and a microprocessor. The program is written in C, a simple streamlined language with few tools, thus reducing the profile of the program and allowing its executable files to be run without a memory expensive operating system. The compiler used is the simplistic Cygwin gcc with standard C libraries. The microprocessor that the CCM program is to be run on is the PIC16F886 manufactured by Microchip Technology. It was chosen to be as small and efficient as possible for the task with just enough memory and processing power for the task. If it proves to be insufficient, it may be swapped out for a more powerful microprocessor.

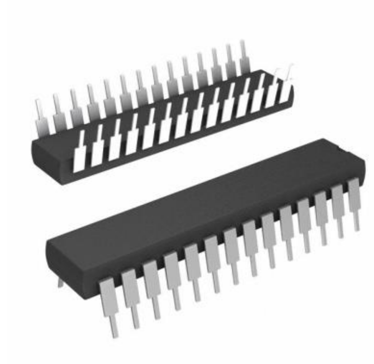

Figure 6: PIC16F886 microprocessor

As the element that connects the other systems together, it is important to stress the flexibility of the programming onboard the CCM. For every change in any other system, the CCM must be adapted to match. The programming and hardware choices were made with these in mind, such that the CCM may easily pick up new tasks as necessary.

Testing for the Central Control Module will come in two parts since the program will need to be tested independently of the microprocessor before trying to make it work with the rest of the system. Testing the program is accomplished by running the program on a computer first as an executable to ensure the program runs correctly, and then on a virtual machine without an OS, simulating how it would be run on the microprocessor. The microprocessor's integrity would be tested using Microchip Technology's own debugging program which came with the chip. Passing both of these, the program will then be loaded onto the microprocessor. There are many ways of debugging a microprocessor with a program on it, though the current plan is to use the Xilinx (XMD) microprocessor debugger to control and watch what signals pass in and out of the CCM.

In order to complete the tasks set for the Central Control Module, it must process a number of signals. To find the speed of the wheel and direction, the frequency of the wheel motor's hall sensor must be interpreted. The power remaining in the power supply will be calculated from the voltage sensor in the capacitor bank. The desired speed, direction, and type of movement (which includes forward, backward, braking, and charging from a plug) will come from voltage readings from a game pad.

This data will all be saved in memory to be extracted later as run data, as well as sent to the Android Application to be displayed to the user. The data will also need to be processed such that the motor receives an adjustment signal such that the user's desired speed matches the output wheel speed. While each individual system will deal with error catching in their own systems, the CCM will also watch for problems and send signals to correct the situation.

The Central Control Module is the connection that brings all the systems together, adapting to match the needs of the other systems. As a result, if new and unforeseen requirements appear as system integration proceeds, it is possible the CCM may end up looking entirely different than it does today.

E. DC/DC converter

The DC/DC converter utilizes two Linear Technologies LT8705[15] synchronous 4-switch buck-boost DC/DC controllers. The LT8705 controller has an input range of 2.8V-80V and and output range of 1.3V-80V. The off-chip MOSFETs, voltage, and current monitoring allows for high current power supplies. The LT8705 controller exceeds 98% efficiency as controlled currents exceed 10A. Mellivora should expect to see very high efficiency and good conversion during both motoring and regenerative braking modes as efficiency should still be over 94% at demands all the way into the milliamp range.

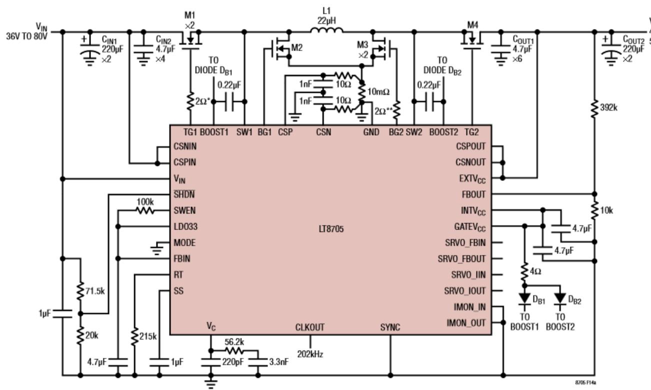

Figure 7: Typical layout of LT8705 configured for variable input with fixed output

The design utilizes two converters, one for motoring and one for regenerative braking. Communications will be required from the CCM to determine which converter will be active. There will be a negligible increase in power consumption of 2.65mA by keeping both converters active while the vehicle is powered up, but the low consumption is an acceptable penalty to allow for immediate switching between motoring and regenerative braking modes to avoid waiting for start-up cycles during emergency acceleration or braking commands.

The converters will be constructed on a single two-sided three ounce PCB that will be routed in house on the Accurate 336 CNC routing machine available in M5, or on the laser PCB machine in the biomedical lab if the proper permission can be obtained. All components will be surface mount and all traces will be on the top side of the PCB with the back side of the board reserved for the ground plane as specified on the LT8705 data sheet.

Testing will be performed by driving each converter individually with a lab bench DC power supply and varying the input voltage with no load connected to verify that the converters operate within the designed operating voltage range, shut down at the designed low voltage cutoff, and maintain the fixed 36V output. Testing will proceed with connecting a dummy load to simulate the motor and capacitor bank while varying the power supply voltage to verify all operating points are maintained under load. Once proper operation has been verified under load, each converter will be tested with it's respective load while being powered by the DC power supply before finally being connected in its final configuration for full system testing and integration.

F. *Power Supply*

The power supply consists of 24 series connected 3000F supercapacitors to produce a 75Wh (eqn. 1) power supply. Minimum cell voltage will be limited to 1V, leaving 63 Wh of available energy. The 3000F KamCap capacitor[16]\ was chosen due to the high energy density of 12kW/kg. While 12kW/kg pales in comparison to typical lithium battery energy densities of around 100-150 kW/kg, these supercapacitors surpass the energy densities of other supercapacitors, which average 3-9 kW/kg.

Special considerations need to be taken to prevent overcharging of individual cells when bulk charging series connected supercapacitors. As capacitors age, individual cell capacitance and equivalent series resistance (ESR) drift. These differences in capacitance and ESR cause a difference in charge and discharge rates leading to a difference in cell voltages. A cell balancing/voltage limiting circuit, Figure 8, will be built into the power supply to prevent overcharge conditions. The op-amp is used as a comparator with a 1.235V reference voltage at the negative V_{in} terminal and a voltage divider on the positive V_{in} terminal. As the current drops off at the end of the charge cycle, voltage begins to climb. When the cell voltage reaches 2.7V, the voltage at the positive V_{in} terminal reaches 1.235V, which causes the comparator to trigger the MOSFET and shunt current around the supercapacitor, preventing an over voltage condition.

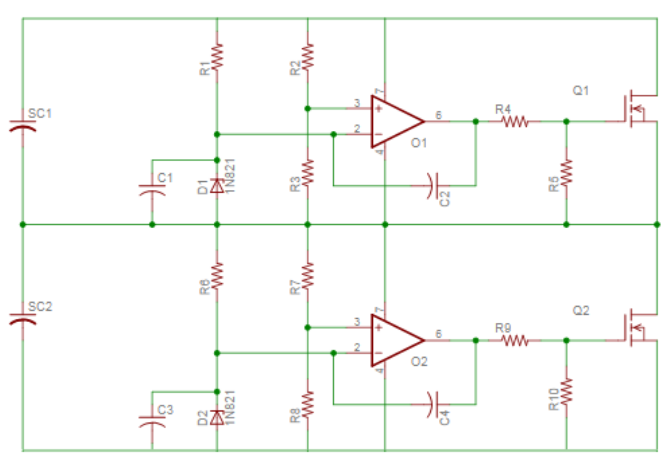

Figure 8: Schematic of the charge limiting circuit.

While there will be power losses in the MOSFETs when current is shunted past individual cells, the power losses are considered acceptable to prevent overcharge conditions and cell damage. This should typically only occur late in the power supply life during charging or under very limited conditions where the vehicle is in regenerative braking mode with a fully charged power supply, such as coasting downhill immediately after unplugging, where regenerative braking would not be able to be utilized to store additional charge in the supercapacitor bank.

The power supply will be constructed in four rows of six capacitors with rows offset to construct a slightly smaller package. Supercapacitors will be oriented vertically with alternating polarity. Each row will have a top and bottom PCB to act as interconnects between supercapacitors as well as to contain the charge limiting circuitry. These PCBs will be constructed from the same three ounce material as the DC-DC converter and will be routed on the same machinery.

Testing will consist of verifying that the individual charge limiting circuits function properly prior to installing the supercapacitors and completing construction of the power supply. Prior to system integration, the charge and discharge characteristics will be tested utilizing a lab bench DC power supply and a dummy load, respectively.

III. Project Management

Subsystem	Status
Central Control Module	Programmed and simulated, not tested on device
Phone App	Programmed, not tested on device
Motor Controller	Designed and prototyped, not tested with motor.
Power Balancing Circuit	Designed, Gerber file in process
Pedal Interface	Designed, prototype and testing pending
DC-DC Converter	Designed, Gerber file in process

Table 2: MDR Deliverables

Our MDR goals, shown in Table 2. Our group aimed to have one of our two subsystem done by MDR and to demonstrate viability of the project. The android app has been coded and can accept data sent from the CCM as well as display it. The game pedals have been modified to work in our current design. The CCM code has been completely written and tested. The motor controller has been demonstrated to work on a simulated load. Lastly supercapacitors have been demonstrated to be able to run a motor load.

The team has been working together well. We have a weekly team meeting to discuss the progress of our portion of the project and how it is progressing. We have a additional meeting every week with our faculty advisor Professor Leonard. Overall the team works well together and each member is good about helping other out if they have problems. The one area our team need to work on is explaining what we are doing to each other and keeping each other accountable for staying on track with work. We were slow in starting our work for PDR and MDR. For the Spring semester we are going to be working on keeping track of what each team member is working on and tracking to make sure they complete their work when they say they will.

The project was divided into eight subsystems with each member having two. Derek Clougherty is responsible for the super capacitor bank and power contoller as well as being the team leader. Derek Wang in responsible for the code in the central control module and bluetooth interface. Lubin Jian is responsible for the phone app and physical pedals. Nathan Ball is responsible for the motor contoller and regenerative braking. No member of the team was an expert in the their subsystems area to begin with. The project has required all member of the team to do a considerable amount of outside research. Research into supercapacitors, microprocessors, electric motors had to be done for the project

Progress to this point has been slow and has been met with some difficulty, mostly stemming from supply chain issues. Parts had been ordered before the Thanksgiving Break, but it wasn't found out that parts were not ordered until two days after the break ended. No prototyping or testing was able to begin until the week prior to MDR. Due to time zone differences and slight language barriers, after two and a half months of back and forth with suppliers in China (no motors that were affordable and suited our needs were found in the US), the motors were finally ordered, so no physical testing has been performed as the motors should finally arrive as the semester closes. Other difficulties have arisen due to a lack of parts in the SDP lab and in M5. Other groups had taken all available components of certain types leaving nothing to mock up and test, even on a scaled down version, for several weeks. With the scale and complexity of our project, our budget is fairly constrained, so we were hesitant to order components that were not going to be utilized in the final project.

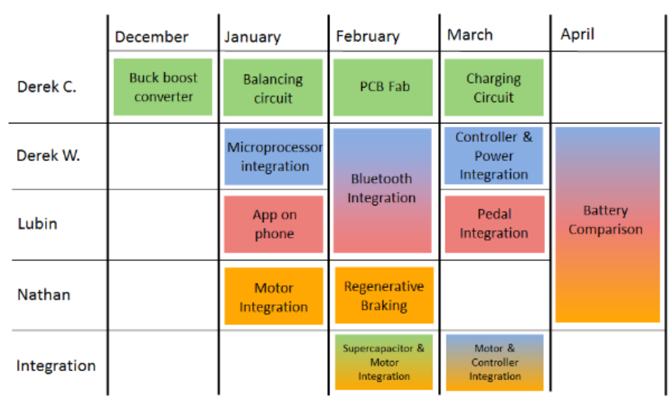

Figure 9: Gantt Chart

IV. Conclusion

While each team member did complete their desired MDR deliverable we still have a lot of work moving into the Spring semester. The early part of the semester will be spent completing our second subsystem. Final prototypes will be completed in the first couple of weeks of the Spring semester. It is vital that our specific subsystems are working and have been tested before integration can happen. Our Gannt chart of work for the spring semester can be seen in Figure 9**.**

As noted in Figure 9, Lubin will first focus on completing the mobile interface before moving on to Bluetooth capabilities in February. We estimate that Bluetooth integration will be completed by early March where Lubin can then focus on connected the pedals with the rest of the system. On completion, the whole group will then move on to looking at a battery comparison.

Derek Wang will be working first on getting the Central Control Module program loaded onto the microprocessor for testing. Before moving forward, the microprocessor must be able to show that it can successful generate and send signals that the motor controller can use. Once this is successful, Bluetooth integration will be worked through to the end of February. At this point the CCM will be able to communicate wirelessly with Android application, allowing Android feedback and control of all systems through the CCM. In March, the Central Control Module will be tuned to adapt to any changes in any other subsystems, hooked up to the gamepad pedal and other systems in an attempt to get our final product. There is likely to be a lot of troubleshooting. As with the rest of the team, Derek W. will also then move on to work on the battery comparison portion of our project.

Due to supply chain problems mentioned earlier the motor controller was not able to be tested on the motors. Nathan will integrate the motor with the motor controller in January. February will be reserved for designing and implementing the regenerative braking functions of the drive controller.

During the last half of January Derek Clougherty will be creating the Gerber files and begin PCB routing for the DC-DC converter and supercapacitor interconnects with the integrated charge limiting circuitry. Final assembly and testing should occur by mid February to allow for troubleshooting and time for integrating the power supply and DC-DC converter prior to the full system integration phase in March.

We will be moving into the system integration phase of the project starting in February and continuing through the rest of the semester. The two software and two hardware parts of the project will begin integration in February. The CCM and the phone app will be integrated with Bluetooth. The motor, motor driver and supercapacitor power supply will be integrated in the first week of March. The final weeks of March will be utilized for integrating the hardware and software portions of the project. Then finally in April the team will work on a battery comparison that will be used to demonstrate the effectiveness of s supercapacitor power supply vs. a battery in a side by side comparison.

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