Formula SAE
Hybrid Racing Team

University of Notre Dame
Department of Electrical Engineering
EE41440 - Senior Design II

Final Report

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1. DEFINITIONS

Accumulator: Energy storage for the high voltage system. Capacitor bank containing 60 capacitors rated 3000F, 2.7V each.

AMS: Accumulator Management System. Circuitry that continuously monitors accumulator voltage levels and safely shuts down high voltage system if an issue arises.

AIR: Accumulator Isolation Relay. Relay that opens high voltage loop. Must be normally open.

ESF: Electrical System Form. Documentation turned in with competition entry (not included in project scope).

CAN or CAN Bus: Control Area Network. Automotive data bus standard, uses differential channel for (in this case) broadcast type data communications.

Discharge Circuit: Brings the voltage of the intermediate circuit between the accumulators and the tractive system loop down below the required values within the 5 second limit.

GLV: Grounded Low Voltage System. 12V battery circuit powering electronics.

GLVMS: Grounded Low Voltage Master Switch. Controls power to low voltage system.

IC Engine or ICE: Internal Combustion Engine. 250cc engine from Kawasaki Ninja motorcycle.

ISO SPI: Isolated Serial Peripheral Interface. Special SPI protocol with a 2-wire differential signal that allows for reduced susceptibility to noise and longer transmission length, as well as high voltage isolation. Can be converted back and forth between standard SPI and Isolated SPI.

Motherboard: PCB containing system microcontroller and attached circuitry.

Precharge Circuit: Circuitry that protects AIR contacts by charging an intermediate circuit to 90% accumulator voltage capacity before closing the relay.

Shutdown Circuit: Current loop that holds the AIRs closed, disconnects the high voltage system from accumulator when opened.

TSV: Tractive System Voltage. High voltage circuitry powered by accumulators.

2. INTRODUCTION

The Notre Dame Formula Hybrid team is constructing a series hybrid-electric race car that will compete in a number of events in future Formula Hybrid SAE competitions. The team is in need of an embedded electronic system to aid in the monitoring and optimization of various mechanical systems integral to the performance categories defined in the various events. This system must take inputs from the driver and control the motors, engine, and driver displays electronically. It must continually monitor the high voltage vehicle system so as to promptly and safely shut down the system if a problem arises.

The team designed and built a multifaceted embedded system based around a PIC32795 microprocessor to achieve the proposed task. There are three main functions of the system: **controls**, **monitoring**, and **status**. The functionality that **controls** the car includes operation of the charging system and operation of the drive system. The **monitoring** functionality includes continuously measuring the temperature and voltage levels of the system and responding to abnormalities. The **status** functionality provides both the driver and the off-track team live updates of the vehicle diagnostics. These functions will be broken down further to explain the overall problem solution.

2.1 Controls

The Hybrid Car control system takes driver inputs and controls the vehicle functions. The *charge system* is controlled from a switchboard next to the LCD display. The function of the *charge system* is to deliver power from the internal combustion (IC) engine to the ultracapacitor banks (called the accumulator). The driver inputs include switches to turn on the 12V low voltage system, precharge the controllers to match the voltage of the accumulator, enable the high voltage system, turn the ignition on, start the IC engine, and toggle charging/not charging states.

The controls system also operates the *drive system*. This adds the ability to shift between forward, neutral, and reverse drive states via another switch. The *drive system* controls also include a throttle pedal which engages the hub motors in the rear wheels, and a brake pedal which engages regenerative braking in the same rear wheels. Regenerative braking returns power in the wheels back to the accumulator. Finally, the *drive system* controls allow for differential steering. When the steering wheel is turned, the torque of the outside wheel is increased to improve drive performance.

Lastly, the controls system also adds functionality to automatically shut down the high voltage system independent of any driver inputs. This is done in the event of an error detected by the monitoring system, as described below.

2.2 Monitoring

The Monitoring function of the Hybrid Vehicle system is a vital part of the overall design. It continuously measured the voltage across each capacitor cell in the accumulator to ensure even power distribution in both charging and discharging states. The system also measures the temperature of every accumulator cell to detect if any part of the accumulator goes outside of the safe operating temperature. The monitoring system also includes the embedded current and temperature sensors in the Kelly motor controllers. These values as well as related errors are regularly read in to the central microprocessor. In the event of an over voltage, over temperature, or any other fault, the monitoring system will safely shut off the high voltage system from any drive state. As required by the Formula Hybrid SAE competition rules, the system cannot be reset by the driver from within the vehicle, but must be brought back and reset externally.

2.3 Status

The status function of the system includes the onboard LCD and the wireless RF transceiver. The LCD displays the vehicle speed, power levels, engine rpm, accumulator charge level, and drive state, as well as any errors. This functionality is vital for driver feedback ad performance. In addition to the onboard LCD, the status function adds the ability to transmit diagnostics wirelessly to an off-track computer using an RF transceiver. These diagnostics include everything that the driver display is showing, in addition to other information on the controller current and temperature levels. This can easily be added to or altered to meet a need for future vehicle diagnostics.

2.4 Performance

The design was successful in meeting the majority of the required specifications. The drive system works very well, including the drive states (wait, precharge, neutral, forward, reverse) and torque vectoring. The regenerative braking also performs very well. The LCD display turned out to be an excellent addition to the status interface. The precharge, discharge, and shutdown sequences work as they were required. The AMS successfully shuts down the high voltage system when it should and displays the correct error message on the LCD. The thermistors were not installed in the accumulator, but were tested and confirmed to operate as needed.

There are several functions that do not meet specifications in the final design. The information coming from the motor controllers was not able to be reliably identified as coming from a particular controller, so the parameters taken from those messages, including speed and error messages, are sometimes ambiguous. This is especially evident on the LCD speedometer, which does not always display an accurate speed, especially when the wheels are running at different rpms. Another issue is in the IC engine feedback loop. The electrical noise created by the generator and its controller interferes with the pwm signal to the throttle servo motor. When in the charging state, the servo is not able to be reliably controlled.

A challenging aspect of this project was the wide variety of separate devices that were all being integrated. For each input, an appropriate switch or sensor was selected, tested with a breadboard, and then added to the final PCB. A device was also selected for each output where needed. The final design has 4 analog inputs, 1 digital input, and 9 digital outputs from the PIC32. There are 6 SPI, 3 CAN and 1 UART devices also communicating with the PIC. Each of these devices was designed, built and troubleshooted separately and then integrated into the larger system. There was a great deal of wiring done to achieve the necessary functionality. There are also a number of spare pins on the Motherboard PCB to allow for added functionality in the future. Much of the hardware was configured to be good enough to test, but will require more work to be fully rules compliant. The vehicle system was assembled on a table for the purposes of testing and demonstration, but once the Formula Hybrid team constructs a frame for the vehicle, the system must be integrated into the new form factor.

With the system in its current state, the Formula Hybrid team is in a good position to compete in the competition in the coming years. Much of the future work for the Hybrid team and future EE

Senior Design teams that may take up the project will lie in making the wiring rules compliant and integrating it into an actual frame, as well as tuning the various parameters that were left to be tested.

3. SYSTEM REQUIREMENTS

The Formula Hybrid Senior Design project has focused on providing an embedded electronic system that will govern many of the vehicle's mechanical and electrical systems. The goal of this overall electronic system is safely operating and optimizing the vehicle's performance while also providing output data for the driver and the team to utilize during and after competition events.

The design consists of building a microprocessor based vehicle management system that performs the following functions:

- Controls
    - Accepts driver inputs of throttle, brake, steering, and switching
    - Engages the rear hub motors in both forward and reverse directions
    - Safely turns on and off the high voltage system
    - Starts the IC engine and toggles the charging state
    - Maintains engine rpm while charging
- Monitoring
    - Continually measures accumulator voltage and temperature
    - Shuts down the high voltage system in the event of an error
- Status
    - Displays vehicle diagnostics to the driver
    - Transmits diagnostics wirelessly to an off-track computer

The competition involves a technical inspection in which each entry is reviewed for safety and rules compliance. The rules of this inspection were taken to be the design constraints of the project. The following specific constraints served as major requirements for the purposes of the Senior Design project. Please refer to the 2019 Formula Hybrid SAE rulebook (see Appendix 9a) for the complete list of rules and regulations.

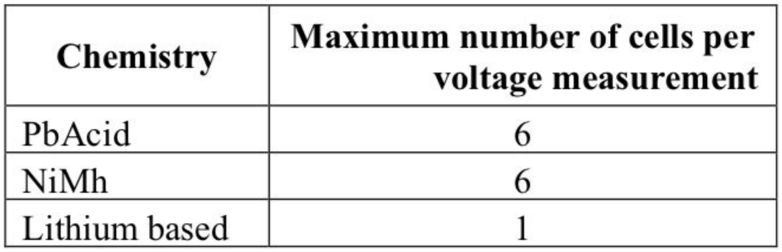
1) AMS

a) Each accumulator must be monitored by an accumulator management system (AMS) whenever the tractive system is active or the accumulator is connected to a charger.

b) The AMS must monitor all critical voltages and temperatures in the accumulator as well the integrity of all its voltage and temperature inputs. If an out-of-range or a malfunction is detected, it must shut down the electrical systems, open the AIRs and shut down the I.C. drive system within 60 seconds.

c) The tractive system must remain disabled until manually reset by a person other than the driver. It must not be possible for the driver to re-activate the tractive system from within the car in case of an AMS fault.

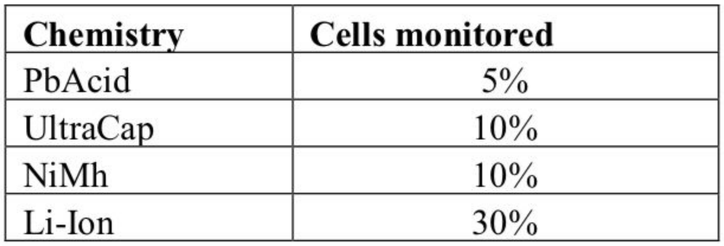
d) The AMS must continuously measure cell voltages in order to keep those voltages inside the allowed minimum and maximums stated in the cell data sheet (See Table 10). NOTE: If individual cells are directly connected in parallel, only one voltage measurement is required for that group



Chemistry	Maximum number of cells per voltage measurement
PbAcid	6
NiMh	6
Lithium based	1

Table 10 - AMS Voltage Monitoring

e) The AMS must monitor the temperature of the minimum number of cells in the accumulator as specified in **Table 11** below. The monitored cells must be equally distributed over the accumulator container(s). NOTE**:** It is recommended to monitor the temperature of all cells.



Chemistry	Cells monitored
PbAcid	5%
UltraCap	10%
NiMh	10%
Li-Ion	30%

Table 11 – AMS Temperature Monitoring

f) All voltage sense wires to the AMS must be protected by fuses or resistors (located as close as possible to the energy source) so that they cannot exceed their current carrying capacity in the event of a short circuit

g) Any GLV connection to the AMS must be galvanically isolated from the TSV. This isolation must be documented in the ESF.

2) **Team-designed AMS Board**

a) Teams may design and build their own Accumulator Management Systems. However, microprocessor-based accumulator management systems are subject to the following restrictions:

- i) The processor must be dedicated to the AMS function only. However it may communicate with other systems through shared peripherals or other physical links.
- ii) The AMS circuit board must include a watchdog timer. It is strongly recommended that teams include the ability to test the watchdog function in their designs.

3) **Accumulator - Isolation Relays**

a) At least two isolation relays (AIRs) must be installed in every accumulator container, or in the accumulator section of a segmented container (See **EV2.3.4** Note 2) such that no TS voltage will be present outside the accumulator or accumulator section when the TS is shut down.

b) The accumulator isolation relays must be of a normally open (N.O.) type which are held in the closed position by the current flowing through the shutdown loop (**EV7.1**). When this flow of current is interrupted, the AIRs must disconnect both poles of the accumulator such that no TS voltage is present outside of the accumulator container(s).

c) When the AIRs are opened, the voltage in the tractive system must drop to under 30 VDC (or 25 VAC RMS) in less than five seconds.

d) The AIR contacts must be protected by Pre-Charge and Discharge circuitry, See **EV2.10.** If the AIR coils are not equipped with transient suppression by the manufacturer then

e) Transient suppressors must be added in parallel with the AIR coils. AIRs containing mercury are not permitted.

4) **Precharge**

   a) The AIR contacts must be protected by a circuit that will pre-charge the intermediate circuit to at least 90% of the rated accumulator voltage before completing the intermediate circuit by closing the second AIR.
   b) The pre-charge circuit must be disabled if the shutdown circuit is deactivated; see **EV7.1**. i.e. the pre-charge circuit must not be able to pre-charge the system if the shutdown circuit is open.
   c) It is allowed to pre-charge the intermediate circuit for a conservatively calculated time before closing the second AIR. Monitoring the intermediate circuit voltage is not required.
   d) The pre-charge circuit must operate regardless of the sequence of operations used to energize the vehicle, including, for example, restarting after being automatically shut down by a safety circuit.

5) **Discharge**
   a) If a discharge circuit is needed to meet the requirements of **EV2.8.3**, it must be designed to handle the maximum discharge current for at least 15 seconds. The calculations determining the component values must be part of the ESF.
   b) The discharge circuit must be fail-safe. i.e. wired in a way that it is always active whenever the shutdown circuit is open or de-energized.
   c) For always-on discharge circuits and other circuits that dissipate significant power for extended time periods, calculations of the maximum operating temperature of the power dissipating components (e.g., resistors) must be included in the ESF.

6) **Motor Controllers**
   a) The tractive system motor(s) must be connected to the accumulator through a motor controller. Bypassing the control system and connecting the tractive system accumulator directly to the motor(s) is prohibited.
   b) The accelerator control must be a right-foot-operated foot pedal.
   c) The foot pedal must return to its original, rearward position when released. The foot pedal must have positive stops at both ends of its travel, preventing its sensors from being damaged or overstressed.
   d) All acceleration control signals (between the accelerator pedal and the motor controller) must have error checking.

e) For analog acceleration control signals, this error checking must detect open circuit, short to ground and short to sensor power

f) For digital acceleration control signals, this error checking must detect a loss of communication.

g) An error in the acceleration control signal must shut down the torque production in less than one (1) second when a fault is detected. NOTE: If these capabilities are built into the motor controller, then no additional error-checking circuitry is required.

h) The accelerator signal limit shutoff may be tested during electrical tech inspection by replicating any of the fault conditions listed in **EV3.5.4**

i) TS circuitry, even at low voltage levels, is not allowed in the cockpit. All motor controller inputs present in the cockpit must be galvanically isolated. This includes accelerator input, forward/reverse, on/off switches etc.

j) Motor controller inputs that are galvanically isolated from the TSV may be run throughout the vehicle, but must be positively bonded to GLV ground.

k) TS drive motors must spin freely when the TS system is in deactivated state, and when transitioned to a deactivated state.

4. PROJECT DESCRIPTION

4.1 System Theory of Operation

Operation of the Hybrid Vehicle is reliant on a system of sensors, microprocessors, and driver inputs to function safely and effectively. The system design takes in the following driver and vehicle inputs:

Inputs:

- Throttle and brake pedal positions
- GLV and TSV enable, direction, ignition, starter, and charge state switches
- IC engine RPM
- Kelly controller CAN messages
- Accumulator cell voltages
- Accumulator cell temperatures
- Steering wheel position

Outputs:

- Left and right hub motor torque
- AIR control (ability to close relay)
- LCD display (with driver information)
- Wireless RF signal (with off-track information)
- Engine control (start engine, throttle, turn off engine)

All inputs (save for AMS dedicated functionality, see AMS section 4.7) are processed by a PIC32795, located on a PCB designed and assembled by the team called the Motherboard. The general operation of the vehicle system is as follows:

1. The low voltage system is turned on via the GLV switch, bringing up the LCD display and initialising the **wait** state.
2. The enable switch is toggled, initializing the **precharge** sequence which matches the voltage of the controller to the accumulator.
3. After 5 seconds of precharging, the system switched to the **neutral** state from which it can be placed in **forward** or **reverse**. The motor and generator controllers are powered on.
    a. In **forward** mode, the throttle pedal moves the wheels forward and the brake pedal engages regenerative braking. The steering wheel controls the differential speed of the left and right wheels.
    b. In **reverse** mode, the throttle pedal moves the wheels in reverse, and the brake pedal does nothing (no regen needed in reverse).
4. While in **neutral**, the engine can be started by toggling the ignition switch and then flipping the starter switch for 1 second.
5. While the engine is running, the charge enable switch can be toggled between **charge** and **idle** states
    a. In the **charge** state, the engine charges the accumulator. It is automatically throttled to maintain a consistent RPM.
    b. In the **idle** state, the throttle control is not engaged and the engine is **idling**.

In addition to user operation, the system has the following functions:

- If there is an over voltage or over temperature in the accumulators, the high voltage system is safely disconnected by a dedicated microprocessor.
- Live vehicle data containing speed, engine rpm, accumulator status, power draining/generating, steering wheel angle, and error messages are displayed on the LCD and sent wirelessly over an RF transceiver to an off-track computer.

4.2 System Block Diagrams

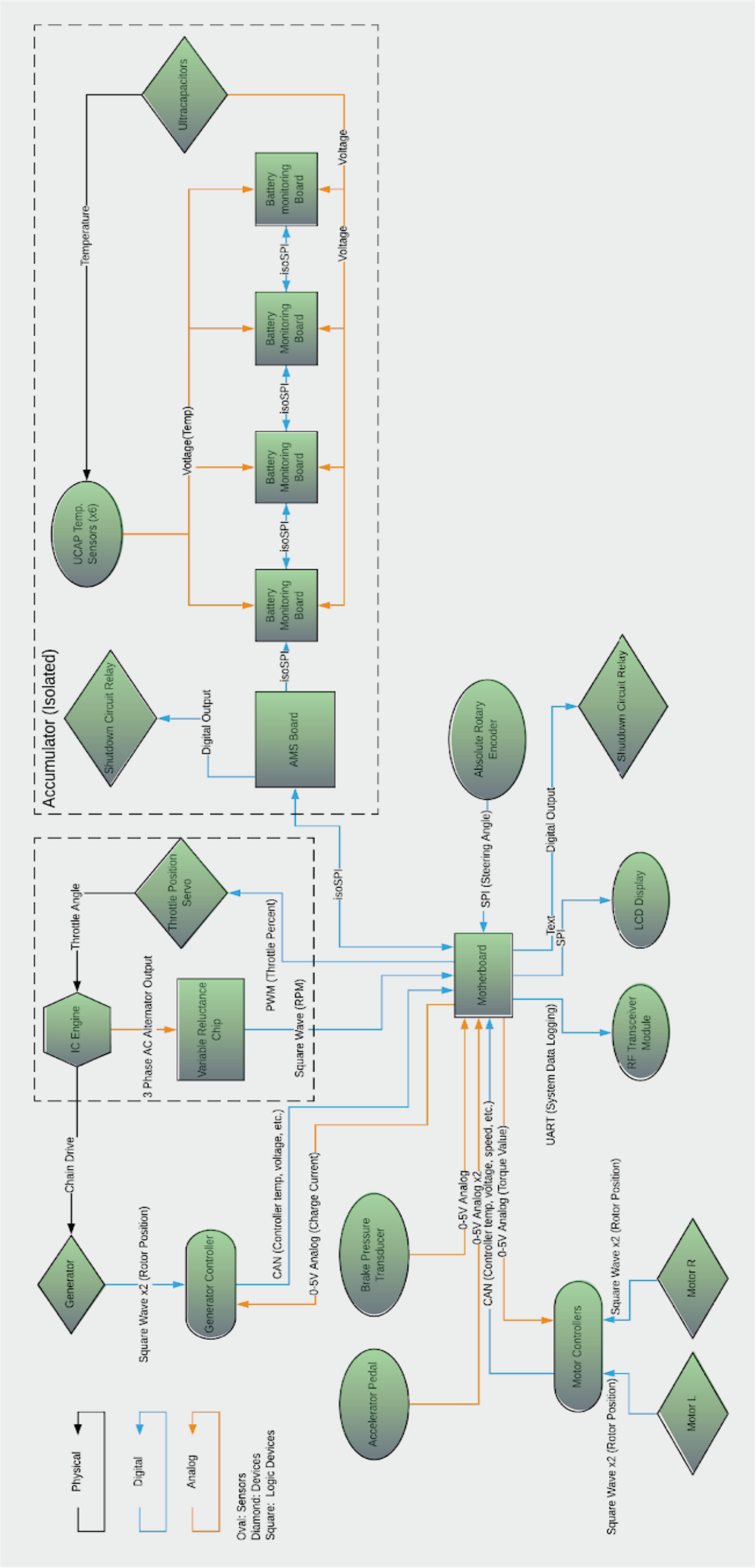


Figure 4.2a Full System Diagram

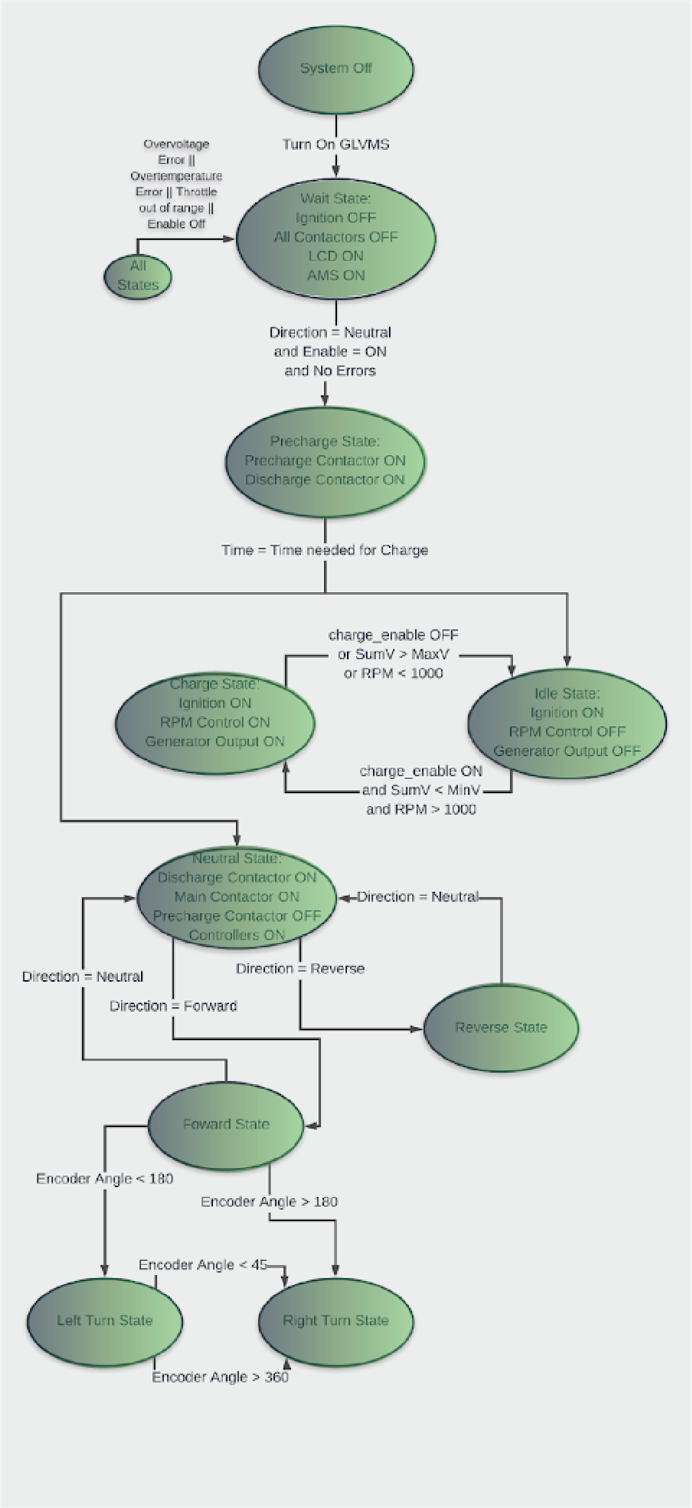


Figure 4.2b Drive System State Diagram

4.3 Driver Inputs

4.3.1 Subsystem Requirements

The driver inputs consist of signals received from the pedals and data for the angle of the steering wheel received from the rotary encoder. These values are used to control the speed of the motors and develop a torque vectoring control system for the vehicle's drivetrain. The drive system software outputs calculated values to the motor controllers to optimize the speed of each wheel, and, in turn, the overall handling of the vehicle. The other component of this system is the switch box which implements the process described in Section 4.1 and enables the switching between states described in Figure 4.2b. Overall, the driver input subsystem satisfies the first part of the design requirement that the system "accepts driver inputs and displays essential information."

4.3.2 Wiring Schematics And Description

The foundation of the driver inputs is the throttle and brake pedals. In the current system these are two identical Toyota Prius pedals. Each pedal is connected through an opamp circuit to the Motherboard in order to implement the correct level of voltage sent to the Motherboard. The throttle pedal has two inputs two the motherboard that are averaged to generate the final throttle value sent to the motor controllers. The opamp circuits output to analog pins of the Motherboard and the signals received here are sent to the motor controllers to set their speeds. This is the interfacing involved between the driver inputs and the controller subsystem. The AMT203 absolute rotary encoder is physically attached to the steer wheel of the system and electrically connected to the Motherboard in order to modify the signals sent to the motor controllers based on the current position of the steering wheel. These aspects of the driver inputs are displayed in Figure 4.3.1.

The other physical setup required in the driver input subsystem is the switch box. This controls the powering of the Motherboard and AMS board, start and ignition of the ICE, the charging sequence, and the direction state of the vehicle. All of these are implemented as switches on a control panel and their connections are described in Figure 4.3.2. The driver has access to these switches and the implementation of their use by the driver is described in Section 4.1.

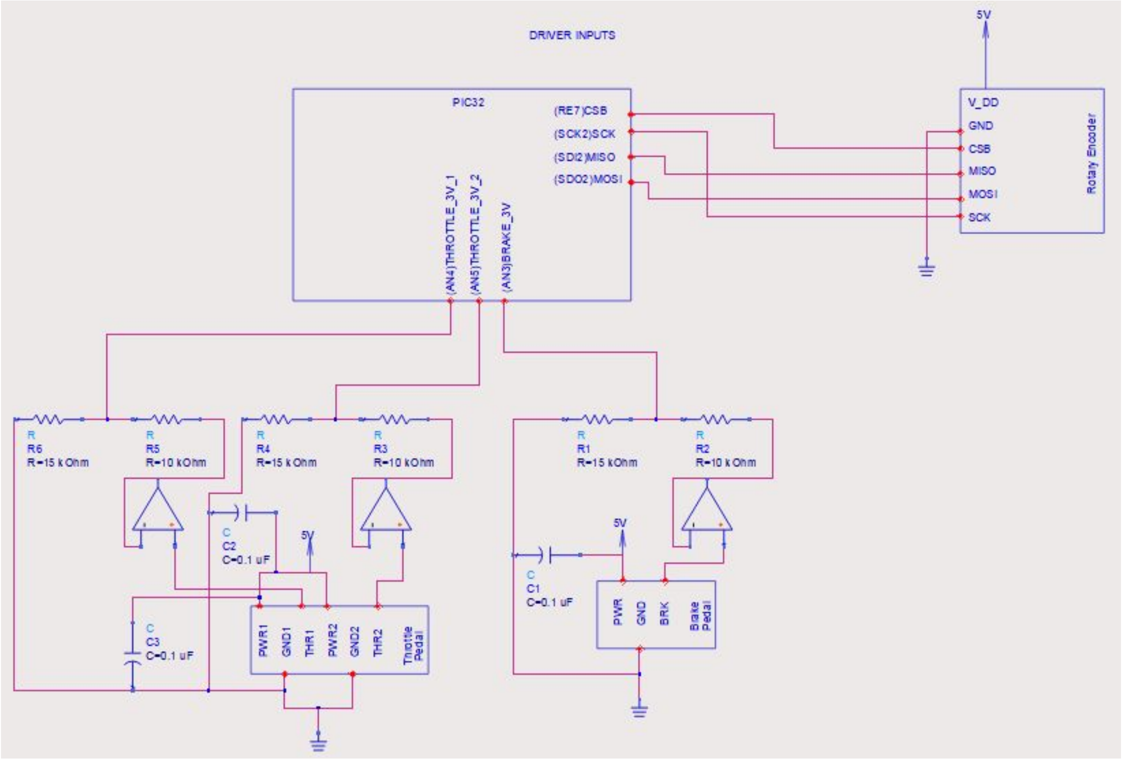


Figure 4.3.1: Driver Inputs Schematic - Encoder and Pedals

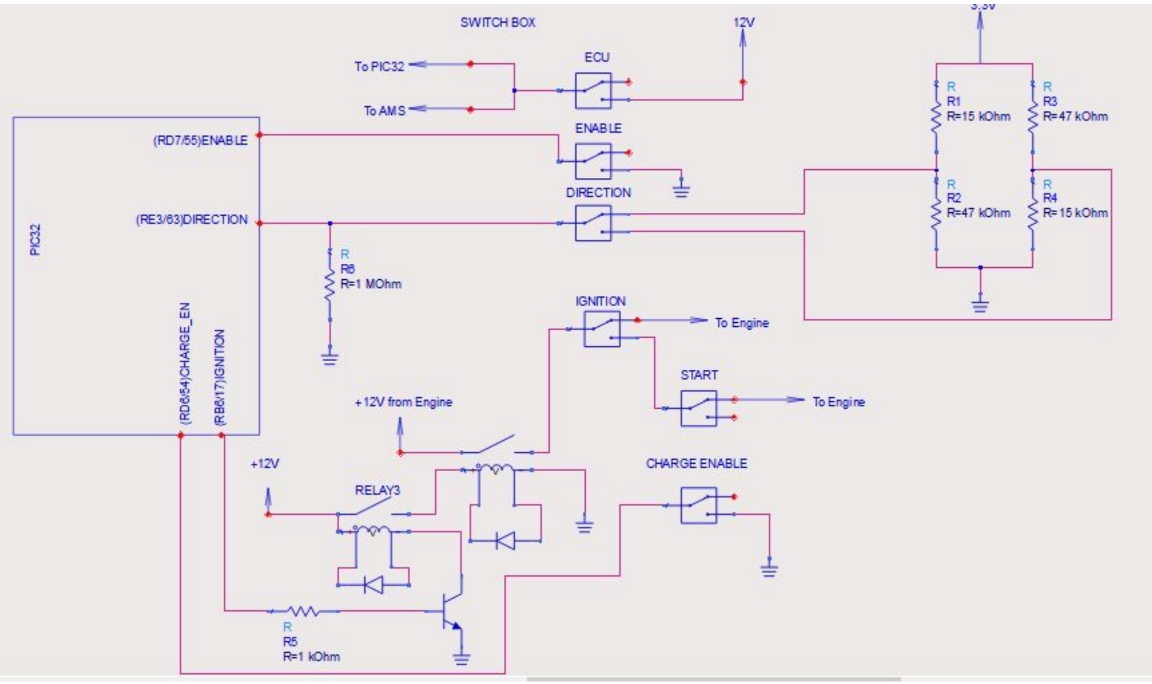


Figure 4.3.2 Driver Inputs Schematic - Switch Box

4.3.3 Software Description

The structure of the software implementation for the actual driving and motor control aspect of this subsystem combines the functionality of the pedals, encoder, and switches. Namely, the direction switch is used in this part of the subsystem. When the system is powered up and the precharge sequence completes, the system enters the neutral state based on the software. The direction switch shown in Figure 4.3.2 can flip between forward, neutral, and reverse. Each direction implements a different control scheme. In the neutral state the signals sent to the controllers are set to the minimum so that the controllers register no value. In the forward state, the function of the rotary encoder is utilized. The rotary encoder is an SPI device so this protocol was configured and initialized in the implementation of this software subsystem. The checking of the angle took place in a timer interrupt of length 20us in order to comply with the delay between reads noted in the encoder datasheets. The rest of the driver input software configuration involved switching between various states the vehicle could be in to implement different features from charging to driving to starting the ICE.

The control scheme is based on the position of the steering wheel which is read by the rotary encoder. The angle reading determines the turn state of the vehicle as shown in Figure 4.3.3. The throttle and brake signals are modified by an experimentally determined constant based on the current value of this angle, tuned to implement the correct motor speed in each wheel. These modified signals constitute the torque vectoring to improve handling in turns. The forward state also implements regenerative braking via software. In the reverse state, the baseline signals from the throttle and brake pedals are sent to the motor controllers.

The other aspect of the driver input software implementation includes the switching of states based on the positions of the switches in the switch box. The implementation of this state diagram is shown in Figure 4.2b. The driving states are a subset of the states available in this code configuration. The vehicle waits in a wait state until precharging is enabled by the enable switch and from there the the vehicle goes to the neutral state and is prepared to drive by flipping the Direction switch if the capacitors are charged. The Ignition and Start switches factor into the software in order to activate the engine and enable autonomous charging.

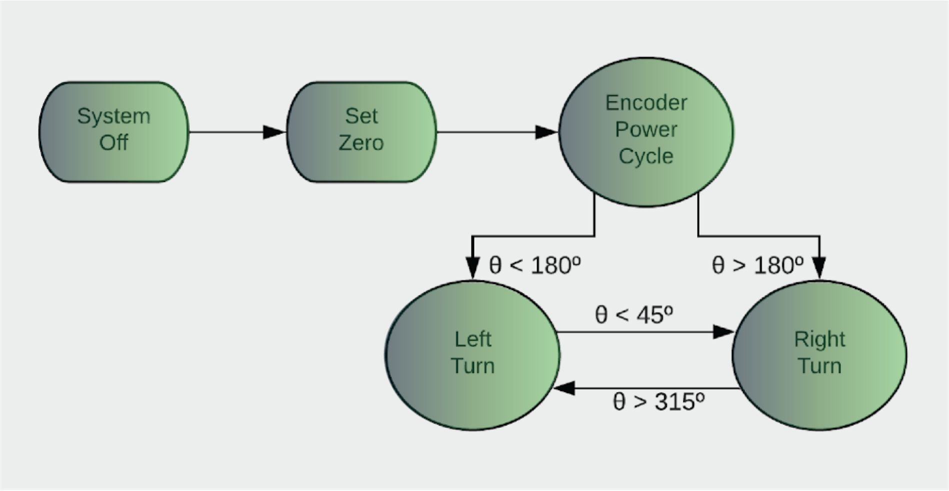


Figure 4.3.3: Rotary Encoder State Diagram

4.3.4 Choice of Components

The Toyota Prius pedals were selected as they were simple to integrate into our design and inexpensive. The rotary encoder was selected for its precision and for its style of absolute measurement. The AMT203 reads the value of the position as an angle on a 360 degree circle. This allowed the team to design a control scheme knowing the exact position of the steering wheel and sending this measurement as a signal. The other type of rotary encoder involves incremental measurement which relays information about the motion and direction of the encoder. The absolute style of measurement was ideal for this application as the current position was necessary for calculations and provided this measurement to utilize directly. Finally, the single throw single pole switches were used to simply implement the changing of states required in the software configuration.

4.3.5 Subsystem Testing

The main testing needed for this subsystem revolved around ensuring the state diagram implemented by the software worked properly and integrated with the pedal and encoder signals. This was tested by repeating the switching initialization sequence and noting the states of the relays on the Motherboard impacted by each switch flip. The Motherboard was powered, the system enabled, and the state of the direction relay noted when switching between forward and reverse. Once this sequence was complete and without issue, the drive control system was tested. This was done in order to tune the torque vectoring implemented by the rotary encoder and to ensure the direction relay implemented the correct rotation and drive scheme for the different drive states. This testing yielded a complete drive system for the left and right wheel implementing the changing of states based on switch inputs and the correct signals to the motor controllers based on pedal and encoder inputs.

4.4 System Status Interface

This system is designed to provide live updates to the driver and off-track team about relevant data pertaining to fuel level, ultracapacitor charge, vehicle speed, engine RPM, and pertinent error messages. This includes direct updates to the driver sent via an LCD display inside the car. The second component is the off-track transmission by an RF transmitter communicating to an off-track RF receiver writing data to a serial monitor.

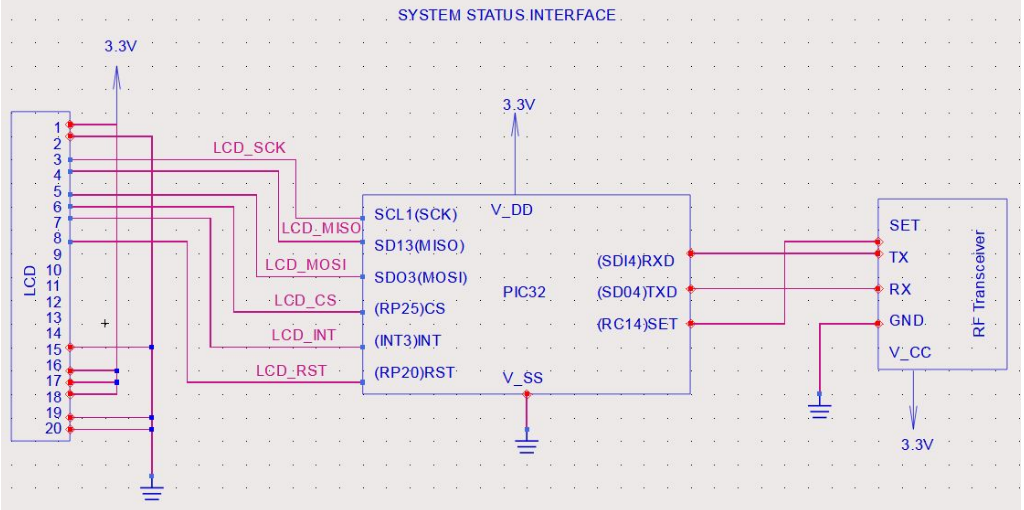


Figure 4.4.1: LCD Wiring Schematic

4.4.1 LCD

The LCD screen is used to communicate information on the state of the vehicle to the driver on board. The team picked this specific LCD because it is equipped with a controller that makes it easy to communicate with through SPI. The 7-inch size was also ideal for the team’s purposes to output a large amount of data that is easy for the driver to see. Additionally, the available libraries are intuitive, making it simple to create graphics such as gauges and progress bars. It supports various forms of RGB interfacing, which makes it flexible as well.

The display takes in constantly changing values of the vehicle speed and power and shows them in two gauges that update accordingly. The power gauge starts in the middle and moves clockwise when the net power is positive (draining the acumulator) and counterclockwise when the net power is negative (regenerative braking, adding power to the accumulator). The current charging state of the capacitors is displayed in a progress bar in percentage value; the RPM is displayed the same way. There is also a list of diagnostics including the accumulator temperature, steering wheel angle, accumulator voltage, and charge state. The top right displays a 1 if the AMS is Lastly, there is a section of the screen dedicated to displaying any errors that the monitoring system detects. In order to display the errors, the LCD program interprets the CANbus messages it receives. Every type of error is allocated to a bit, therefore the program performs bit masking to identify which errors have been set and then display the corresponding text error on the screen.

4.4.2 RF Transceiver

The transceiver circuit is used to transmit diagnostics on the state of the vehicle to an off-track computer via RF. The team selected the transceiver kit because it communicates through UART, a communication protocol the team members are familiar with. Additionally, it has a range greater than a kilometer, which is sufficient for the competition. The RF transceiver is installed close to the LCD display, which in the finished vehicle will be next to the steering. The formula team will be able to receive the signals through a computer equipped with the same transceiver from the side of the track during the race displayed on a serial monitor.

4.5 Motor and Generator Controllers

The motor and generator controllers subsystem deals with all input and output signals to and from the three Kelly controllers. This includes CAN message reading, analog throttle and brake signals, generator charging current signal, and forward/reverse switching.

4.5.1 Subsystem Requirements

The motor controller subsystem must manage the controllers for the left and right hub motors and the generator. The hub motor controllers must be provided with two 0-5V analog signals for throttle and regenerative braking. These controllers must also be connected to two 12V switches to toggle forward and backward modes. The generator controller must be fed a 0-5V signal for charging current. The Motherboard must be able to read signals transmitted from all three controllers over a CAN bus and interpret the contents of the message and which controller it was send from. These include rpm, motor and controller temperatures, motor current, controller and switch status, and error messages.

4.5.2 Wiring Schematic

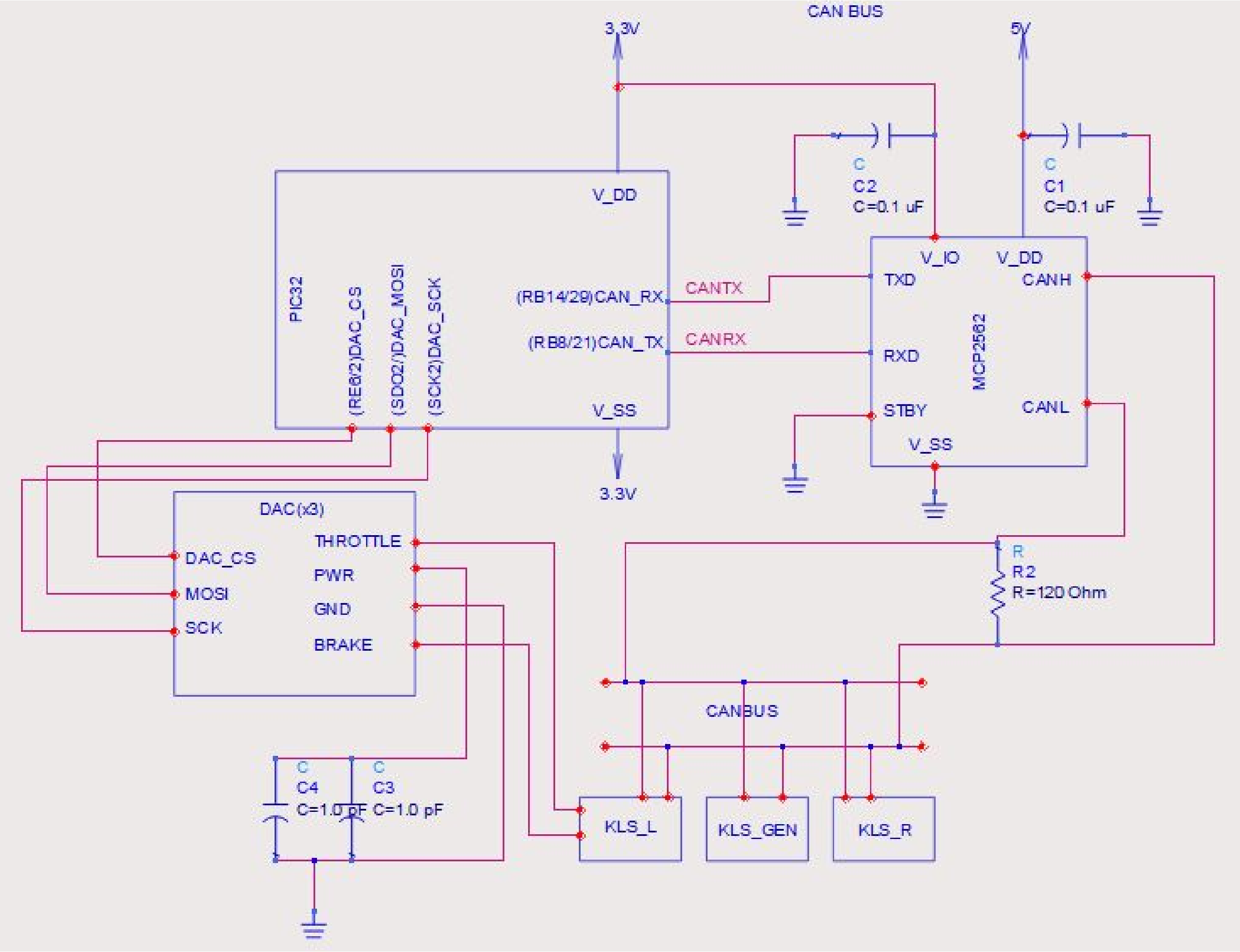


Figure 4.5.2: Wiring Schematic Diagram

4.5.3 Design Choices

The left and right hub motor controllers used in the project are of the model KLS8080I (Kelly Controls, LLC). The controller for the generator is of the model KLS8080IPS (Kelly Controls, LLC). These were chosen and purchased by the Formula Hybrid Racing team before the project had begun.

The throttle and regenerative braking inputs for the motor controllers could have been directly hooked up to 0-5V pedals, but the team chose to do something different. The throttle and brake pedals (part of the Driver Inputs subsystem, see section 4.3) are interpreted by the Motherboard and a signal is sent from the Motherboard to each of the two hub motor controllers via two of the three digital to analog converters onboard the Motherboard PCB. The third DAC is used to turn on the generator controller, which does not receive any throttle or braking data.

All three of the Kelly controllers have a USB connector for programming the devices, but while running the only way to communicate with them is via CAN bus. CAN is an automotive standard in which devices all hook up to the same bus and broadcast information to be read by any of the other devices. The PIC32MX795 has two CAN enabled channels, but requires a CAN transceiver to convert the differential signal into CAN transmit and CAN receive signals. For this purpose, the MCP2562 (Microchip Technology Inc) was selected. This chip was relatively easy to set up and functioned well at the voltages that were available to run it. It was added to the Motherboard PCB as a surface mount part and connected to the CAN channel 2 Rx and Tx pins on the PIC.

The CAN protocol used for the KLS8080I and KLS8080IPS controllers is based on the the SAE J1939 protocol. This protocol runs at 250 bps. All CAN protocols use a filtering process for message handling. There are two types of messages that each controller sends, each with a corresponding extended identifier (EID) and respective data bytes. The filter used by this program takes messages with a type 1 EID and puts them in FIFO0, while placing messages with a type 2 EID in FIFO1. The data bytes for each message type are thus processed separately. After the ID segment of the CAN message there is a control field that specifies how many bytes of data are contained in the message. The program checks that this control field (DLC byte) is 8 (the length of a correctly read CAN message) before processing the data bytes.

While different message types have different extended identifiers, there is no segment of the EID that contains information about the specific controller that the message came from. Since these CAN messages are of the broadcast type, there is no way to determine which controller's message will be read in to the FIFO next. To deal with message handling, the fifth data byte in message type 2 is read in. This byte is listed as reserved on the Kelly data sheet, but it was determined experimentally that it is consistently 0x41 for the generator controller and 0x1E for the left and right hub motor controllers. To determine the speed of the whole vehicle, the rpm values (located in message type 1) is read in for only the hub motor controllers. The average rpm is calculated by averaging the last two rpm messages read and computing the speed using a wheel diameter of 20.5''. The power consumed/generated is calculated by first determining whether the brake pedal is being pressed by comparing its value to the minimum brake value. If the brake is being pressed, regenerative braking is activated and the hub motors are adding current to the system. If it is not pressed, the power consumed is calculated as the sum of the hub motor currents minus the generator controller current. If the brake is being pressed, the power generated is calculated as negative sum of all three current values. Note that the "power" displayed to the driver is calculated via the currents, which are proportional to power but not quantitatively the same.

The errors coming from the Kelly controllers over CAN bus are transmitted as two error bytes, with each bit corresponding to one of 15 error messages. The program decodes the error MSB and LSB and stores them in a string to be displayed to the driver (see System Status Interface section 4.4).

The entire CAN message reading process occurs in a 4ms timer that turns on CAN, initializes it, reads a message of each type, turns CAN off, interprets the messages, and then resets the timer. This was done so that the process is not interrupted by the logic of the broader program. A CAN message done not need to be read as often as, for example, the rotary encoder position. It was placed in an interrupt timer so the whole process can occur without being held up by printing to the LCD or the RF transceiver.

The two motor controllers take in two 0-5V analog signals for throttle (torque provided to motors) and regenerative braking (proportion of power to take from motors). The generator controller takes in one 0-5V analog signal for charging current (proportional to power added to accumulators). The Motherboard uses three MCP4922 digital to analog converters (Microchip Technology Inc) to produce these signals. These DACs were chosen because they communicate over SPI, which the team was familiar with, and they were the highest resolution for their price. In the program, the DACs are written to sequentially starting with the DAC for the left hub motor controller, then the right motor, then the generator. The SPI2 channel is configured for the DACs before writing to the left controller DAC, and reconfigured for the other SPI2 devices after writing to the generator.

The forward and reverse switches are wired to a three way 12V switch located in on the driver-controlled switchboard (see Driver Inputs section 4.3). The forward switch for the generator controller is hard wired to 12V so as to always operate in the forward state.

4.5.4 Programming State Diagrams

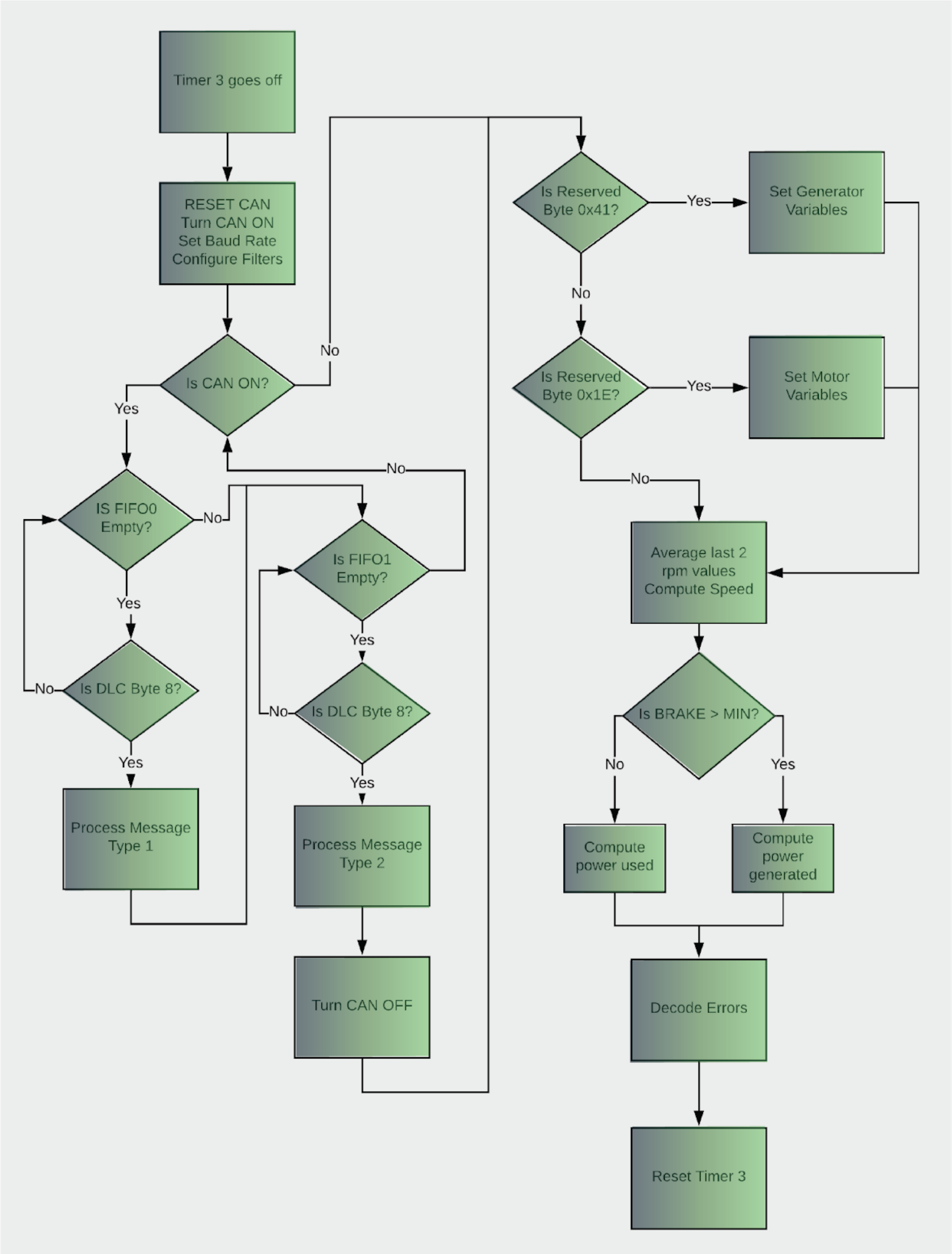


Figure 4.5.5: CAN Message Read State Diagram

4.6 Engine Feedback Loop

This subsystem refers to the internal combustion engine (ICE) used to power the generator that supplies power to charge the ultracapacitors used to supply voltage to the vehicle’s drive system. The loop includes the engine itself, a servo motor used to physically adjust the angle of the engine throttle, and a sensor to monitor the throttle value set by the servo and compare it to the desired throttle value at the time. This loop sets the ICE RPM to the desired value to optimize the charging of the ultracapacitors.

4.6.1 Subsystem Requirements

To control engine speed, the throttle must be modulated to deliver the correct amount of fuel for a given mechanical load. A servo allows the throttle to be electronically opened or closed on demand. A signal representing the current engine speed is also necessary, so that the appropriate throttle adjustments can be determined. The system must be able to compensate for changes in load such that the engine RPM remains stable. This means that the transient response must be quick enough to avoid engine stalling. Excessive overshoot when the control desired RPM changes is also unacceptable, as the engine has an upper limit of permissible running speed of about 14,000 RPM. The control algorithm must be able to allow the engine to run at idle speed when capacitor charging is not required. In addition, the system should allow the user to bypass it for the purpose of warming up the engine or other testing.

4.6.2 Wiring Schematic

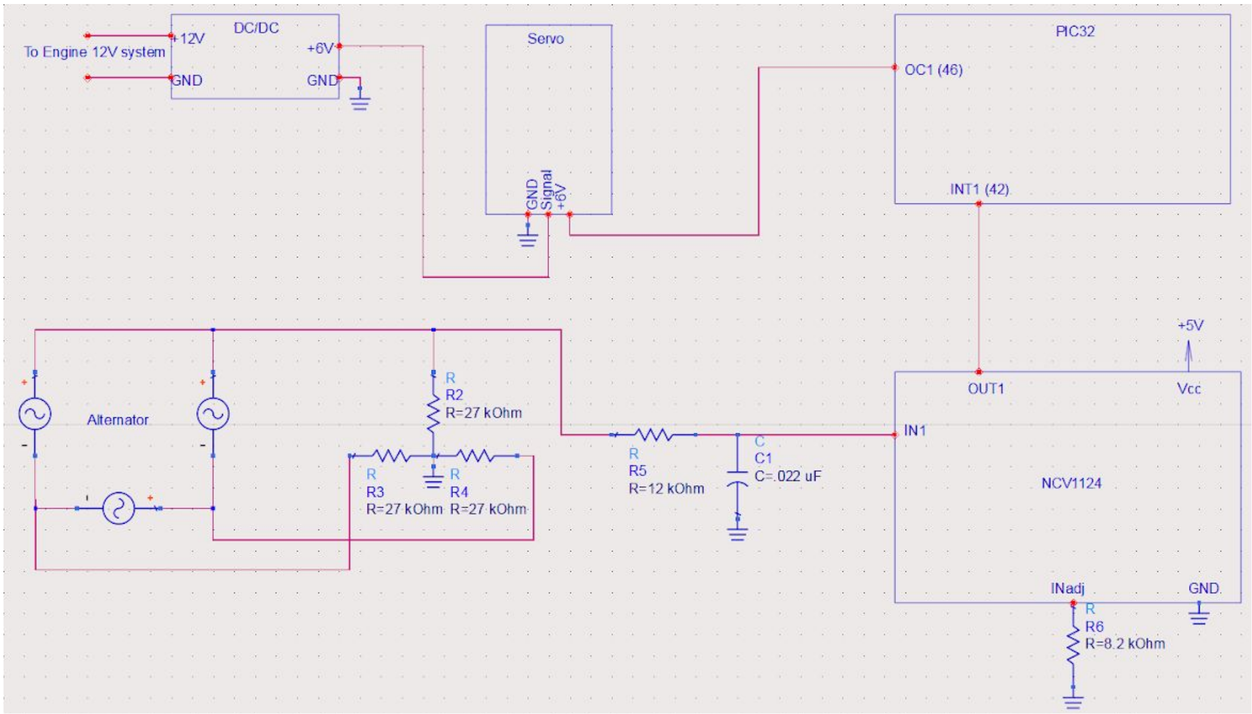


Figure 4.6.2

4.6.3 Design Choices

The throttle servo was selected for the minimum feasible size that would maintain sufficient torque to counteract the throttle return spring. The servo must be able to hold the throttle open against the force of the spring without overheating or damaging its gears. The throttle return spring must still be able to overcome the servo and return the throttle to its fully closed position when the servo is off. The Hitec D485HW servo was selected to meet these requirements. Since small servos utilizing a 12V supply voltage are difficult to obtain, a 12V to 6V DC-DC converter was utilized to power the servo. This also provides ground isolation between the ICE 12V starting/ignition system and the microcontroller 12V system.

In order to monitor the engine RPM, a signal must be obtained that corresponds to the speed of a rotating shaft. There are several methods for accomplishing this, including hall effect sensors, which require a magnet to be affixed to the shaft, rotary encoders, which also require physical attachment to the shaft, and optical encoders, which could not operate on the oil submersed crankshaft. The team chose to use an existing signal from the engine’s alternator, which is permanently connected to the crankshaft. This decision allowed the team to avoid any kind of mechanical connections, which can be difficult to make reliable given the extremely high speeds seen at the crankshaft. The alternator provides a three phase sinusoidal output, which varies in frequency proportionally to the speed of the crankshaft. In order for the microcontroller to interpret this signal, it needed to be converted into a logic level (3.3V) square wave of the same frequency as the original signal. This presents several challenges, including the switching noise present in the sine waves and the variable voltage of the alternator output, ranging from about 16 to 75 volts. The NCV1124 "Variable Reluctance Sensor Interface IC" was designed to address similar concerns in automotive applications, where an inductive sensor gives a periodic output that must be interpreted by a microcontroller. The IC includes two stages. First, an active clamping circuit reduces the input voltage to logic level. Then, a comparator circuit converts the sinusoidal input into a square wave. To reduce the amount of high frequency noise which enters the chip, an RC filter with a cutoff frequency equal to the maximum expected frequency is placed before its input.

Another challenge which arose was the lack of a neutral lead from the alternator. The alternator output is three phase AC, while the NCV1124 requires a single phase referenced to ground. To solve this issue, a "floating ground" was created by connecting three resistors across the phases in a wye configuration. These resistors must also be accounted for when designing the RC filter.

4.6.4 State Diagram

The theory of operation for the engine speed PID controller is shown below. The difference between the desired RPM and actual RPM (error) is calculated. Then, this error is multiplied by Kp, the proportional gain. This error is also integrated over time and multiplied by Ki, which eliminates steady state error. The derivative of the error is also calculated, which allows the system to smooth out oscillations and transients.

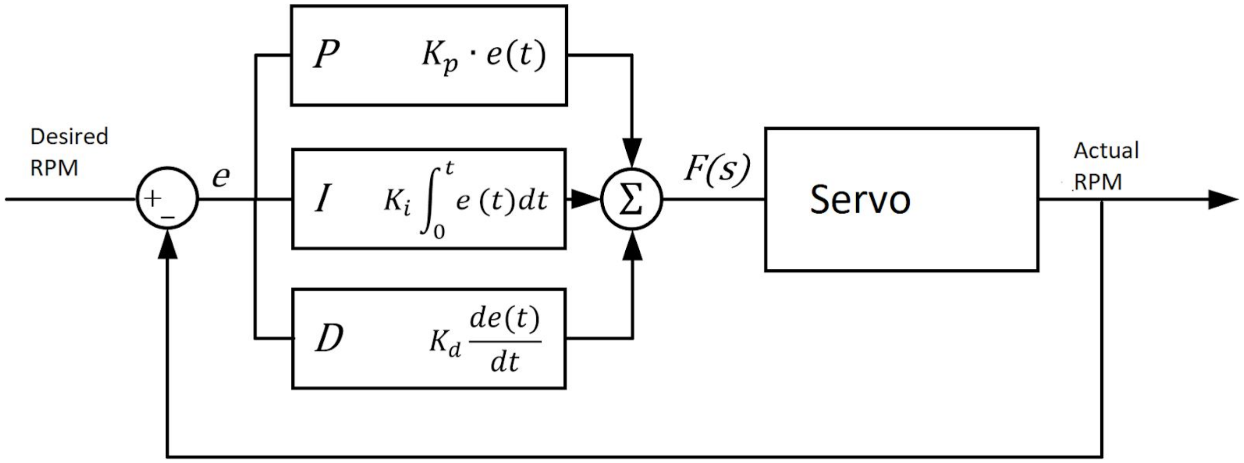


Figure 4.6.4

(For a block diagram of the charging and engine idle states, see Figure 4.2b.)

4.7 Accumulator Management System

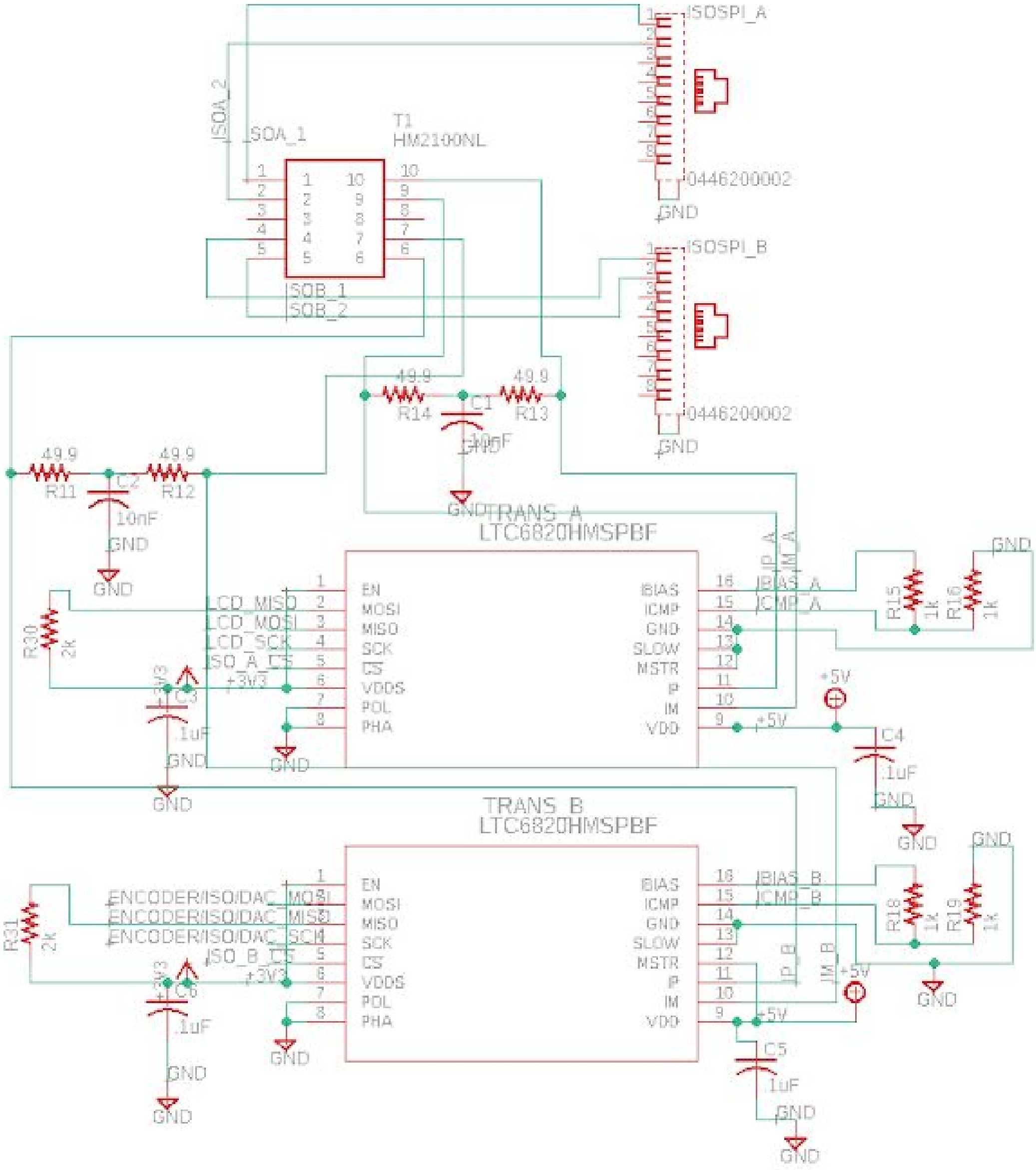


Figure 4.7.1

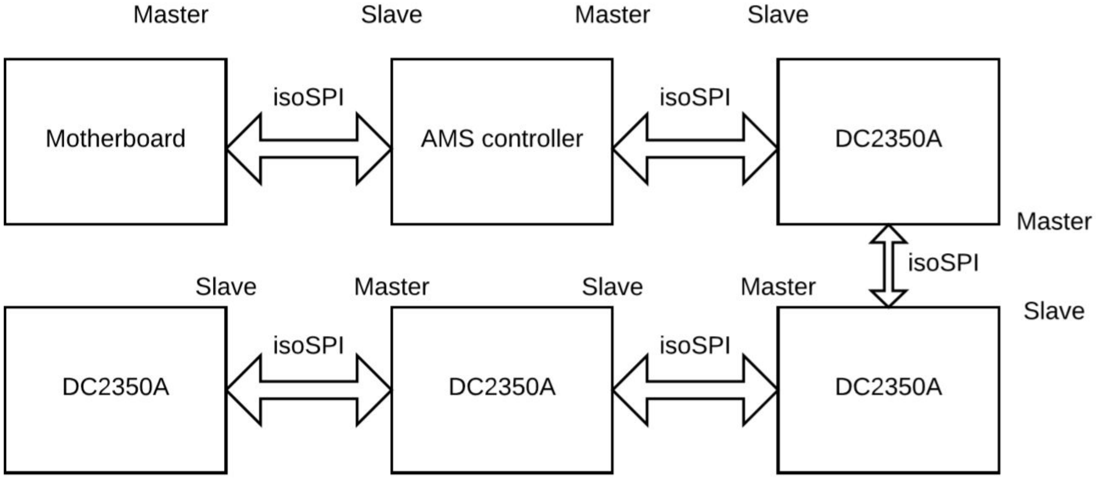


Figure 4.7.2

The AMS is composed of an AMS controller and four daisy chained demo boards, all of which together handle the monitoring of the cell voltages and the temperature of the cells. The AMS controller is built from the same board as our motherboard, but they're different in that the AMS controller has less components, and two isoSPI translators instead of one. One of the isoSPI translators is used as a master to communicate with the demo boards, and the other is used as a slave to communicate with the motherboard based on the motherboard's requests.

The LTC6812 based demo boards were chosen because they met all of our needs for monitoring the ultracapacitors. Our system had to be able to monitor the voltage of all cells and the temperature of at least 10% of them. Each demo board is capable of measuring 15 batteries, as well as 9 temperature sensors. Therefore, by getting four of these, we were able to meet our requirements for both temperature and voltage sensing. If we wanted to (as recommended by the data sheet), we could monitor the temperature of all cells as well by using a mux. The demo boards also have the ability to detect over voltages, under voltages, as well as the ability to balance the cells. Therefore, it can be expanded beyond the minimum requirements. Also, our system had to be electrically isolated from the rest of the system, and these boards fulfill that requirement by communicating through isoSPI.

After choosing the board, we decided to use isoSPI for our motherboard-to-AMS controller communication as well. The requirements state that these need to be isolated, and being able to put the translator on an already used SPI bus seemed efficient in regards to pin allocation. The AMS controller was made with reproducibility and efficiency in mind. By using the same board for both the AMS controller and the motherboard, we can have boards and components for replacement on hand.

Our AMS controller sends commands to the monitoring boards to get information about the ultracapacitor voltages and temperatures. This data is passed through isoSPI to the motherboard whenever the motherboard sends an information request. If the temperature is above the rated maximum or an overvoltage is detected, the AMS board will shutdown to protect the driver and components. It will also pass along the error to the motherboard. Figure 4.7.3 illustrates the software flow of the program.

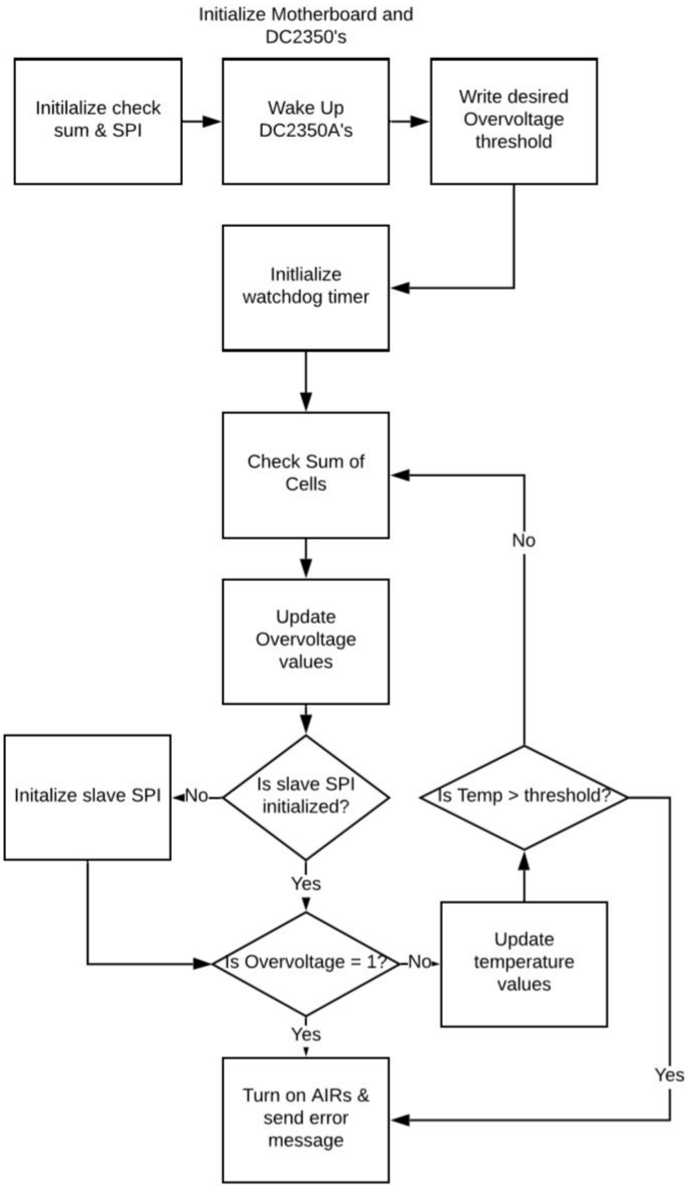


Figure 4.7.3

5 SYSTEM INTEGRATION TESTING

5.1 System Integration Overview

The subsystems described above were designed and tested individually before being integrated into the full system from both the hardware and software side. For each software integration, the several considerations were taken. Firstly, timing was a major concern. It was essential that time sensitive processes were able to function without being interrupted. For this purpose, the CAN message reading, rotary encoder, and servo functions were put in separate timers. This allowed them to operate without being bogged down by the slow processes of the UART and LCD printing. Secondly, the devices that shared channels, such as the 4 SPI 2 devices, were ensured to work in harmony. This involved making sure that the configuration bits for each SPI function were correctly set at the time at which the functions were called. The Saleae Logic analyzer was especially useful to ensure that the correct information was being sent to the correct pins.

In addition to software integration, there was a good deal of hardware integration that occurred. This all comes together on the Motherboard PCB, which contains the circuitry for most of the input and output devices. Once wired, the subsystems were again tested individually and then added to the final program one by one.

Final testing consisted of running the full process from start to finish. Please refer to the user manual section 6.2 for a step-by-step list of the process that was used to test the device.

5.2 System Requirement Check

The following requirements were checked using the described test process, and returned the following results:

Requirement	Test

Accepts driver inputs of throttle, brake, steering, and switching	Functionality verified for all switches. Brake and throttle inputs measured on Logic analyzer. Steering angle measured and outputted to LCD.
Engages the rear hub motors in both forward and reverse directions	Verified throttle pedal functions in forward and reverse modes mode, brake pedal functions in forward mode, and neither pedal engages motors in neutral or any other states.
Safely turns on and off the high voltage system	Verified that high voltage enable switch triggers wait state for 5 seconds, then switches to neutral state. Relays verified functioning.
Starts the IC engine and toggles the charging state	Verified that ignition and starter switches turn on engine, charge enable switch engages generator controller.
Maintains engine rpm while charging	Engine throttle servo verified when not charging, but failed during charging state due to electrical noise
Continually measures accumulator voltage	Verified voltage levels in accumulator match those read by the system. Temperature measurements tested on one thermistor, but not connected to accumulator.
Continually measures accumulator temperature	Temperature measurements tested on one thermistor, but not connected to accumulator.
Shuts down the high voltage system in the event of an error	Shorted accumulator during operation and verified system shutdown
Displays vehicle diagnostics to the driver	LCD functionality demonstrated
Transmits diagnostics wirelessly to an off-track computer	RF transceiver tested individually and integrated with full system

6 USERS MANUAL/INSTALLATION MANUAL

6.1 How to install your product

The final design for this project includes a functioning drive system for the Formula SAE Racing Team to install in their future overall vehicle design. The prototype also functions as a test bench from which to add other software features and electrical components to continue the optimization of the overall system. Therefore, the installment of this system into the overall future vehicle design is twofold. The first aspect of installment is physical. The subsystems will each need to be mounted in the body of the car and where electrical connections exist the subsystems must be in close proximity to each other. This is especially important for the serial communication protocols used for the various devices connected to the Motherboard.

Given that most of the physical devices will need to be accessed by the driver, installment is focused on mounting components in a manner suitable to use by the driver. This begins with installing the driver input components. The steering wheel and pedals will be situated in the traditional locations of a car, the throttle and brake controlled by the right foot and the wheel at arm level when the driver is in a sitting position. Mounted by the steering wheel must also be the Switch Box used to implement the state diagram controlling the overall start-up of the system. The driver must also have access to viewing the LCD at all times. This should be installed in the style of a dashboard that a traditional car would have. With all these devices requiring power from the Motherboard, this should also be installed in the cockpit of the vehicle alongside the AMS board. This accounts for most of the physical installment of the additional components included due to the scope of this design project.

The components of the more sizable subsystems, namely the ICE feedback loop, the motor controllers, and the motors themselves will be installed in the locations allotted for in the frame design pending completion. This installment guide is not strict as the design of the vehicle is still in flux. Therefore, the main understand a user must have is that all the electrical components must be in close proximity, accessible to the driver, and implemented in a way that allows the vehicle to function correctly with the larger physical components remaining in the places specified by the team designing the physical car.

6.2 How to setup the product, know if its working, and troubleshoot it

The following describes a system initialization process as well as the signs that the system is working properly and what to do if the system is not working as intended.

1. Connect all components (peripheral devices and boards):

This initial step involves connecting all the devices that run off the Motherboard to their designated connector. Each connector is noted by name (Ex: Encoder, Throttle, L_DAC, etc.) and is already wired to a female connector housing to be attached to the male pins on the board. Connect a 12V supply or battery to the Motherboard and AMS board.

2. Turn on main power and upload code:

In this step, flip the leftmost switch on the switch control box labelled “ECU” to establish connection of the 12V source to the Motherboard and AMS Board. Upload the software file “main.c” using the PickIt3 from the Hybrid_Car_Final.X MPLAB project. Upon uploading this code you should see the LCD turn on with the display described in Section 4.5 of this document. If the LCD display screen does not turn on cycle the power by flipping the ECU switch off then on again. The LCD will be integral to understanding if the entire system is working properly as it displays system diagnostics as well as what state the vehicle is in (i.e. Wait, Precharge, Neutral etc.). The LCD will also display errors in text. At this point the LCD should display “Wait” and “No Errors.” If at any point in the following steps the LCD state changes back to Wait or text other than No Errors displays, a critical error has occurred. To troubleshoot these, note the error description and check the appropriate connection or system component. Errors that will cause the system to revert to the Wait state include and overvoltage on a capacitor, the throttle pedal being out of range, or the temperature of a capacitor or controller being too high. Another check throughout this process that can assist troubleshooting is having the serial monitor open as data is relayed from the RF transceiver about system diagnostics if the LCD does not provide complete information about an issue.

3. Turn on the Enable switch and listen closely:

Flip the switch labelled “Enable” on the switch control box (second from the left). You should note a few changes in the system upon flipping this switch. The Precharge and Discharge relays should click on. Also, the LCD state display should change from “Wait” to “Precharge”. Then, after five seconds the main relay should click on and the state on the LCD should change to “Neutral”. See step 2 if at any point in this process there are more than three clicks or the LCD state changes to Wait again. To test the functionality of the direction states after the enable functionality is confirmed, turn off the enable switch. Then, turn the large red switch on the ultracapacitor housing to ON (WARNING: This activates the high voltage capabilities of the system). Turn the enable switch back on and press down the throttle and brake pedals, there should be no response from the motors in the neutral state.

4. Test the Direction switch:

Once the functionality of the Neutral state is noted, test the setup of the other drive system directions by flipping the Direction switch between “FWD” and “REV” (going through Neutral each time). When in the forward position, there are multiple tests to check correct functionality. Pressing the throttle should spin the motors, this is the basic functionality of the forward state. Turning the test steering wheel to a set position and then running the motors below full throttle should result in one motor turning faster than the other (Ex: when turned to the right the right motor should spin slower than the left). This tests the functionality of the torque vectoring. If no change is noted check the connection of the rotary encoder to the Motherboard. Finally, to test the regenerative braking feature run motors at full throttle and then press the brake pedal, you should note the motors come to a halt immediately rather than spinning freely down to zero. This tests the forward state. Flip the Direction switch to “REV” and note the sound of the direction relay clicking then check by pressing the throttle pedal that the wheels do in fact spin the other direction. If there is any deviation from the functionality described here, note that the software may need to be investigated for completeness.

5. Test the Start and Ignition switches:

WARNING: This functionality must be tested and setup in an outdoor open space. This will be very loud.

Flipping the Start and then the Ignition switches in that order will turn on the ICE. Testing the functionality of the ICE can be done by monitoring the RPM via an additional LCD screen to test the effectiveness of the RPM PID setting the throttle angle based on the servo attached to the ICE. Issues with this may come from noise of the system interfering with the signal going to the servo. Troubleshoot by tuning the servo to the correct angle and noting whether this makes sense for the RPM readout.

6. Test the Charge Enable switch:

Once the Engine is running as expected, monitored and adjusted by the servo to optimize RPM, flip on the rightmost switch labelled “Charge EN” to enable the charging capability of the ICE to the ultracapacitors. Attaching a voltmeter across the leads of a set of 30 ultracapacitors after a short time should allow you to see whether the capacitors have been charged. Note on the LCD the battery percentage level and the voltage sum value as a bar and text number respectively to confirm value with voltmeter. This completes the overall system functionality setup and testing if issues are encountered.

7 TO RACE DESIGN CHANGES

7.1 Driver Inputs

To improve system reliability, error margins should be included in the minimum and maximum acceptable values of Throttle 1 and Throttle 2. These limits are in place to detect hardware malfunctions, such as a signal shorted to power or ground. In the initial iteration of the system, faults are triggered and the system shuts down whenever the throttle or brake signals fall outside their nominal range. As a result, small variations in supply voltage and any electrical noise are likely to trigger a false fault condition. To rectify this issue, error margins should be added to the minimum and maximum values. For example, a fault condition could be triggered by a throttle value that is more than .2 volts outside the nominal range. This would reduce the chances of a false error while still allowing the system to detect open circuits, shorts, or other hardware failures.

The brake system, as implemented in the prototype, utilizes a second Prius accelerator pedal for its signal. In the actual vehicle, this signal will be provided by a hydraulic pressure transducer. This device converts the hydraulic pressure in the mechanical braking system into a 0-5V analog signal. To accommodate the transducer, the minimum and maximum signal thresholds will need to be adjusted.

In addition, a brake signal gain factor should be added to the software and tuned according to physical testing. The pressure transducer outputs its maximum signal at a pressure far higher than normal driving conditions create. In order to realize 100% regen capacity during normal driving, this gain factor must be adjusted so that full regen corresponds to a realistic pedal pressure and amount of mechanical braking. Care should be taken to ensure that regenerative braking does not exceed mechanical braking so much that the rear tires begin to slide before the front tires, as this will cause the vehicle to spin.

Additional vehicle performance may be achieved by implementing torque vectoring during regenerative braking. Since heavy braking is utilized at corner entry, torque vectoring during regen increase cornering ability in the same way as torque vectoring during acceleration. Again, care must be taken to tune the torque vectoring such that the rear tires do not lock and cause a loss of control. The proper values for brake gain and torque vectoring constants can only be determined by physical testing under similar conditions as the actual race. Torque vectoring constants for braking and acceleration should be tuned independently and will be different values. Since weight transfers to the rear tires during acceleration, the amount of torque bias on acceleration can be much greater than during braking.

7.2 System Status Interface

The utility of the LCD display can be increased by ensuring that the driver can adequately see what is written. A higher current 3.3V supply (as provided in the revised Eagle files) will allow increased brightness settings, as configured in the software. In addition, a high contrast color scheme and a glare reducing shield will improve visibility.

Further improvements to the LCD include the addition of extra data and clarification of error messages. Information such as individual motor and controller temperatures would allow the driver to more closely monitor the status of the system. Engine coolant temperature could also be monitored by connecting the engine’s factory temperature sender to one of the spare analog inputs on the motherboard. The display format for error messages could also be improved by ensuring that multiple simultaneous errors do not appear on top of each other or overflow off the screen. For controller error messages, identification of which controller sent the message would also be useful.

The RF data system currently sends system status information in the form of a comma separated list. In order to easily interpret this data, it would be useful to create a GUI on the receiving computer that displays the values in real time, as well as creating a datalog which automatically saves the information as it is sent for later viewing.

7.3 Motor Controllers/Motors/Generators

In order to achieve accurate information about motor speed, current, and controller errors, a method for determining the source of a CAN message needs to be designed and implemented. In the current configuration, each CAN message appears in the same format, making it difficult to determine which controller sent it. Without this information, the vehicle speed and accumulator current cannot be determined accurately.

The team's research indicates that the Kelly controllers do not send identifying information in either of the two possible CAN messages. This needs to be verified by utilizing the CAN interpreting function of the oscilloscope while changing the "CAN preferred address" parameter in the Kelly Controller GUI.

If it is determined that no addressing is available from the Kellys, there are other possible solutions to determine the source of the message. The CAN messages include a series of bits marked "reserved" in the datasheet, which may allow the receiver to interpret which controller sent the message. Message 2 could also be utilized for identification by checking the "Switch Status" bits. An unused switch could be set high on one controller and low on another to differentiate the left and right controllers. The generator controller is unique in that the Hall A, Hall B, and Hall C bits are simultaneously zero at all times, while the drive motor controllers never have all three Hall sensors set to zero. These methods of identification are dependent, however, upon the ability of the receiver to associate each Message 1 (which contains speed and current data) with the corresponding Message 2 (which contains the switch and Hall states) from the same sender.

To produce full output from the motors and generator, a liquid cooling system will be necessary. The system will require a water pump and radiator, as well as auxiliary fans to cool the radiator when airflow is insufficient. Future team members may also wish to consider adding a liquid cooling system for the controllers and accumulator as well. This system will require chill plates (heat exchangers which bolt to a flat surface) to be fixed to the respective devices. The water pump and auxiliary fans can be controlled by the spare relay outputs or digital pins from the motherboard. Temperature information for thermostatic control is available from the internal sensors in the motors, generator, and controllers, and from the thermistors employed by the AMS.

7.4 Engine Feedback Loop

The engine feedback loop suffers from interference issues caused by the EMI generated by the Kelly Controllers and motors. When the tractive system is off, the motherboard is able to effectively regulate engine RPM by using a PID controller. When the tractive system is on, however, EMI causes the servo to respond incorrectly to the messages being sent, and the motherboard is sometimes unable to accurately measure the current engine RPM. Proper shielding against electrical noise is needed for both the servo and engine RPM signals. With quality shielded cable, these issues should be resolved.

To further increase reliability of engine RPM measurement, a dedicated PCB should be developed for the NCV1124 chip and associated circuit. This circuit is located away from the motherboard to avoid introducing electrical noise from the alternator to the other circuits. Currently assembled on a prototyping board, this circuit would benefit from a PCB with a convenient mounting solution and protection from the elements.

Once EMI concerns are rectified, the PID controller for the engine RPM should be optimized for performance under loading from the generator. Since the team was unable to operate the RPM control and generator simultaneously, the PID was tuned to work at a no-load condition. The PID constants will need to be adjusted for optimal performance with the generator at maximum capacity.

Future team members may also consider implementing an algorithm that utilizes multiple power output levels, so that the engine runs at a more efficient speed when the accumulator is mostly charged, and increases to maximum power output when the accumulator is nearly empty. This algorithm may also make use of information about the race track layout to optimize the charging and discharging cycle.

7.5 Accumulator Management System

Due to packaging concerns, the cell temperature monitoring thermistors were not included in this project. The accumulator containers, which serve to support the ultracapacitors as well as isolate them from the environment, need to be constructed before the thermistors can be appropriately packaged. The thermistors can be integrated into the support structure between the cells, which will hold them in contact with the surface of the cells. Each thermistor will be in contact with two cells, allowing every individual cell to be in contact with a thermistor.

The AMS can be made more robust by eliminating the problem of low voltage shutdowns. In its current configuration, the monitor boards are powered by a discrete transistor driven by the management IC, which provides the 5V regulated supply they need to run. If the voltage across all cells monitored by the board (15 total) drops below 11V , the board shuts down and triggers an AMS error. This prevents the high voltage system from operating, so the cells cannot be charged by the generator. A simple fix for this issue would be to implement software which prevents the drive motors from draining the accumulator below 44V (11V x 4 boards). A better solution would be to replace the single transistor power supply with a high voltage low dropout regulator, allowing the cells to be drained to just above the 5V regulated voltage. This would allow more energy to be extracted from the accumulator before shutting down.

To further improve the functionality of the AMS, active cell balancing could be implemented using the native functionality of the battery monitor ICs. Each battery monitor IC is capable of driving an external transistor between each pair of cells, which can transfer charge between them when they are out of balance. This scheme of active balancing can support higher balancing currents of one to two amps, and allows for a more proactive balancing approach than the Maxwell balancing boards currently in place. Unlike the Maxwell balancing boards which drain a cell if its voltage limit is exceeded, active balancing using the battery monitor ICs allows the cells to be balanced among themselves at any voltage. This reduces the risk of having one cell charged to a far greater level than the rest, which would make it prone to exceeding its limit during high current charging.

If active balancing is implemented, the current limiting resistors located between each cell junction and the sensing leads for the monitor boards would need to be replaced with fuses. The resistors are meant to limit current to a safe level if one of the sense leads becomes shorted to another cell or ground. They can only function correctly when current in the sense leads is minimal, as is the case for voltage measurements. With the addition of balance currents, this resistance in the circuit is unacceptable. Fuses and fuse holders must be selected to meet voltage, current, and packaging requirements.

8 CONCLUSIONS

The team completed and demonstrated the first functioning implementation of the monitoring and drive system for the Notre Dame Formula SAE Hybrid team. The team was able to meet most of the system requirements, successfully test their functionality in an integrated format, and provide specifications for future areas of needed improvement. Undertaking this project was a constructive learning experience and a chance to implement the knowledge and skills that were acquired throughout the past four years to solve a complex engineering problem.

The project will require further development and improvement as integration with the overall vehicle design continues. Certain subsystems, namely the ICE feedback loop and motor controllers, will need to be integrated with the completed physical and mechanical systems yet to be implemented. The final product prototype fulfilled the requirements set forth at the beginning of this project to accept driver inputs, process these into signals usable by the motor controllers, and display essential information about the state of the system as it undergoes various state changes. The system also serves as a monitoring system for the motor controllers. The final requirement of managing the ICE and energy storage is complete to a point of tuning and handling the noise of the signals impacting the throttle control servo. The testing conducted, first of each subsystem, and then as an integrated system as a whole displayed a robust result prepared for installation. The team hopes the groundwork set with this initial project, which tackles the main electrical components and interfaces, will prove useful for the SAE Formula team as design of a competition-ready vehicle continues.

9 APPENDICES

9.1 References and Data Sheets

Formula Hybrid 2019 Rules: https://formula-hybrid.org/students/rules-and-deadlines/
Rotary Encoder: https://www.cui.com/product/resource/amt20.pdf
RF Transceiver:
http://statics3.seeedstudio.com/assets/file/bazaar/product/HC-12_english_datasheets.pdf
DAC: http://ww1.microchip.com/downloads/en/devicedoc/22250a.pdf
Monitoring Board:
https://www.analog.com/media/en/dsp-documentation/evaluation-kit-manuals/DC2350AF.PDF
Monitoring Board:
https://www.analog.com/media/en/technical-documentation/data-sheets/LTC6812-1.pdf
CAN Transceiver: http://ww1.microchip.com/downloads/en/devicedoc/20005167c.pdf
Dual Variable Reluctance Chip:
https://www.onsemi.com/pub/Collateral/NCV1124%20DATA%20SHEET.PDF
Kelly Controller:
https://kellycontroller.com/wp-content/uploads/kls-8080i-ips/KLS8080I-IPS-Opto-isolated-Sinusoidal-BLDC-V1.10.pdf
Kelly Controller CAN Protocol:
https://kellycontroller.com/wp-content/uploads/kls-8080i-ips/Sinusoidal-Wave-Controller-KLS-D-8080I-8080IPS-Broadcast-CAN-Protocol.pdf

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