Formula Hybrid: High-Level Design

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1 Introduction

We are working with the Notre Dame Formula SAE Hybrid Racing team to improve the legacy electrical system in their hybrid vehicle. The car is a series hybrid powered by a capacitor bank in series with an internal combustion engine (ICE). An alternator converts mechanical energy from the ICE to electrical energy. The capacitor bank serves as an energy buffer between the alternator and the electric hub motors on the two front wheels. Each of these motors is controlled by a Kelly motor controller.

The system can be broken up into five subsystems:
- driver inputs
- system status interface
- motor controllers/generators/motors
- engine feedback loop
- accumulator management system (AMS)

There are interconnections between these systems, but they represent the major components of functionality. The central motherboard handles almost all processing and communication between and among systems. SAE rules mandate an additional dedicated processor for the AMS, called the Accumulator Dedicated Processor (ADP). Each of the subsystems will be discussed in more detail in section 2 of this report.

2 Current Understanding of the Existing System

2.1 Driver Inputs

The driver inputs currently consists of 2 pedals (throttle and brake pedal), a steering wheel and a switch box. The switch box was designed to take charge of powering the motherboard and the AMS board, start the ICE, the charging sequence and the direction state of the vehicle. The data from the pedals are sent to the motherboard and then this is sent to the rotary encoder which interprets the signal and sends it back to the motherboard which then feeds the information back to the controller. There are a lot of inputs currently and we would be looking at how to streamline them and make it easier for the driver to operate and interact with them.

2.2 System Status Interface

Currently, the system status interface is supposed to show live wheel rotation, system voltage, motor temperature, system state transitions, engine speed, vehicle rpm, and error messages. After review, there are many problems with the transition states and inputs into the current system status interface. When using the system according to the Usage Manual document from the previous year's group, transition states and state changes within the system are not displayed properly on the interface. Also, error decoding and error transmission seems to need adjustments. The LCD/motherboard code needs to be further analyzed and modified along with the current set-up so that the software functions should match accordingly to the hardware devices.

The off-track RF transmitter needs additional work to determine the baud rate of the transmission system. Signals are determined to be sent and received, but our group cannot decipher such signals without the correct baud rate, which was not documented by the previous year's group. Additionally, autosave and a GUI needs to be implemented within the RF transmission system.

Moreover, minor changes can be implemented to the LCD screen such as brightness control, color contrast, and an anti-glare screen.

2.3 Motor and Generator Control System

The motor and generator control system manages the transmission of signals that regulate the movement of the vehicle and the charging state of the accumulator bank. The Kelly controllers on each hub motor send data from the motor to the motherboard via the Broadcast CAN2.0B and SAE J1939 Protocols. With each CAN message, there is a 29-bit extended identifier that specifies the priority of the CAN message, the maximum number of messages, and to which devices the message is broadcast.

The current system is able to differentiate between the generator and the hub motor controller CAN messages, but does not distinguish the difference between the left and right hub motor controller messages. This is an issue for fine-tuning the torque-vectoring method previously developed by last year's design team. We would also like to explore the possibility of implementing torque-vectoring in the regen mode and having distinguished CAN messages from each controller would speed up the debugging process. Lastly, each CAN message contains information about errors occuring in each motor and the ability to determine which motor experiencing the error is necessary.

2.4 Engine Feedback Loop

The engine feedback loop consists of the ICE, a sensor that measures motor velocity, a servo motor connected to the ICE throttle, and the motherboard. The purpose of this subsystem is to keep the ICE at an efficient RPM setpoint through changing loads. This is accomplished through a PID controller implemented on the motherboard.

The feedback in the control system is realized as the output of the motor velocity sensor, which is connected to the output of the alternator and measures the frequency of the output sine wave. This sensor communicates to the motherboard simply by outputting high/low on a wire based on voltage thresholds.The motherboard then converts to RPM.The motherboard has a set desired RPM. Subtracting the feedback gives an error signal. Passing this error signal through the PID controller produces an output, which is converted to a PWM signal to drive the throttle servo. The subsystem block diagram is shown below.

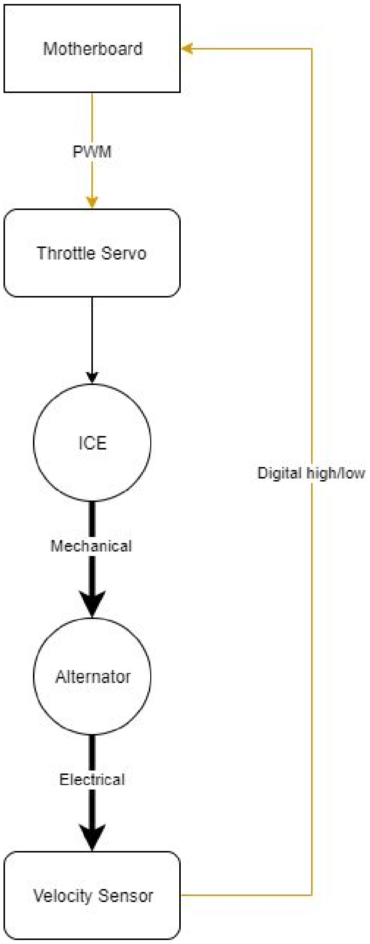

Figure 3.4: Engine feedback loop

The major problem with this subsystem is noise on the cable from the motherboard to the servo when the motors are running. Because of this noise, the ICE cannot be reliably controlled with the motors running. This problem will be discussed further in section 3.4.

2.5 Accumulator Management System

The AMS consists of 4 cell monitoring boards and the Accumulated Dedicated Processor (ADP). The 4 cell monitoring boards monitor voltage and temperature of the capacitors. They are daisy chained using isoSPI, so only one ADP isoSPI connection is needed to monitor all cells. When the ADP detects over-voltage or over-temp, it triggers the Accumulator Isolation Relay (AIR), which is a safety feature that shuts down the high voltage system. The voltage and temperature of the cells are also communicated from the ADP to the Motherboard through isoSPI.

Currently, there is an error with demo board 4 that pertains to “overcharging” of the ultracapacitor even though it doesn’t exceed the maximum voltage according to voltage measurements.

3 Problem Solutions and Upgrades

3.1 Driver Inputs

The current system requires different switches for state transitions and also the brake system is designed using an accelerator pedal. We plan on analyzing the current transitions between states and coming up with a more optimal solution so the driver does not have to focus on many switches that do different things. The brake system would be redesigned to meet the Formula SAE requirements which require hydraulic circuits.

3.2 Engine Feedback Loop

The major problem with this subsystem is the noise on the cable from the motherboard to the ICE throttle servo which carries the PWM signal for servo position. This can be solved simply by using a shielded cable. Once operation with motors running has been established the PID controller will need to be tuned.

The current system only has one RPM setpoint (at maximum efficiency). An upgrade to this system will allow for a higher RPM setpoint that will automatically be switched to when the capacitors are nearing depletion. Implementing this will require using an additional input in the form of capacitor voltage. This information is already passed to the motherboard from the ADP, so no new sensors or communication ports will be needed.

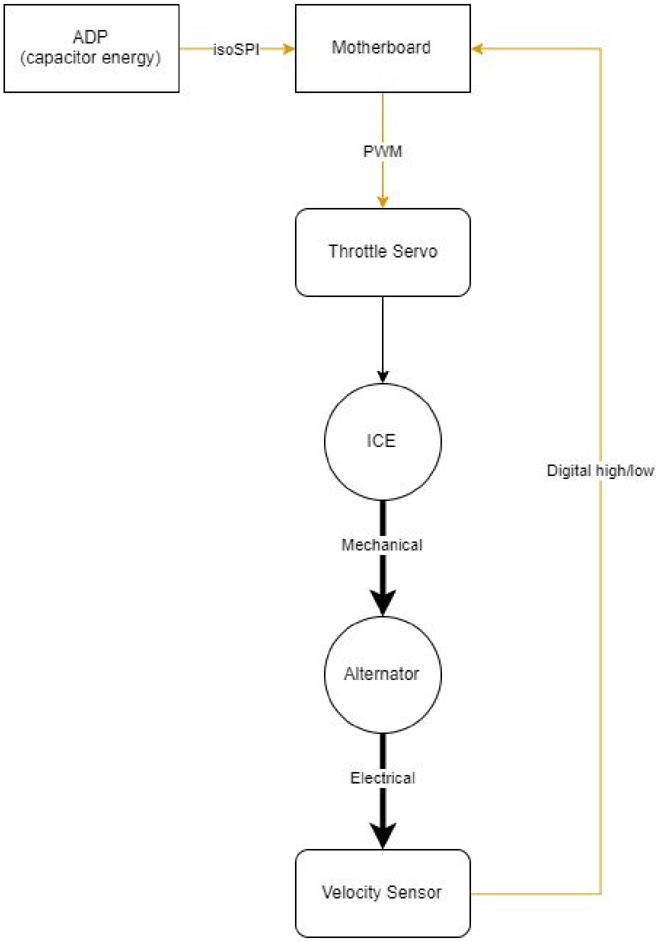

Figure 3.2 Figure shows improved engine feedback loop

3.3 Accumulator Management System

The current system requires active balancing of voltages across the ultracapacitors and monitoring the voltages and temperatures across each cell while making sure that any detection of over voltage or high temperature will enable the AMS to shut down for the safety of the driver.

After having recently looked at the AMS, the AMS seems to not be functioning due to an "overcharged" ultracapacitor from demo board 4. In the previous years, the Hybrid team had worked on ultracapacitors, thus, the group plans on reviewing any additional procedures in order to resolve the error message. After solving this issue, the group can continue to implement an active cell balancing system in order to prevent similar issues by transferring current among capacitor cells in order to balance the charges.

3.4 Motor and Generator Control System

Our design must contain a method to separate CAN messages from the left and right hub motors. There are two possible ways to accomplish this. The preferred method involves modifying the 29-bit CAN extended identifier included in each CAN message. The Kelly KLS Configuration Program from Kelly Controls, Inc. contains an option to change the “Preferred CAN address” which will set these identifying bits in the 29-bit identifier. To identify and test these unique codes or addresses, the Saelae Logic Analyzer decodes the CAN High or CAN Low message which will isolate the 29-bit identifier. Currently, the modification of the “Preferred CAN address” field in the Kelly program does not propagate to the logic analyzer output. Debugging efforts of this issue are ongoing. An alternative method of determining the source of the CAN message from the motor controllers involves implementing 2 separate CAN buses, one for each motor controller. This would require 2 separate CAN transceiver interfaces and 2 concurrent operating loops. The generator controller would remain on one CAN bus. The PIC32MX795 currently on the motherboard can accommodate 2 CAN bus systems.

3.5 System Status Interface

Major issues within the system status interface revolve around transition state coding such that the GUI relays the proper information as described in the legacy usage manual. This can be solved through continual testing of hardware-software integrated systems and code adjustments.

Additionally, RF transceiver baud rate decoding is highly necessary. Further research and contact with legacy teams will be required. The RF transceiver also needs a GUI implementation and Autosave feature, which will be solved through code adjustments.

Display/Physical clarity adjustments within the system can be fixed through code and implementation of additional materials such as an anti-glare screen.

4 System Requirements

Most of the safety concerns within this project are covered in the *Formula Hybrid* rules, such as accumulator management, driver security, and system startup/shutdown. The final system should strive to adhere to these electrical safety requirements as much as possible when handling the overall system. High voltage equipment will be physically inaccessible when charged, and previously implemented safety interlocks for powering down the system before maintenance will continue to be used. High voltage elements are isolated from the low voltage system through DC/DC converters.

4.1 Driver Inputs

Braking:

The car must be equipped with a braking system that acts on all four wheels and is operated by a single control.

Hydraulic circuits are needed to make sure that if one braking system fails, effective braking power is maintained on 2 wheels.

Acceleration:

The system needs to be fail safe so that the failure of any component will not result in an uncontrolled acceleration of the vehicle.

Accelerator pedal must have a positive pedal stop incorporated on it to prevent over stressing the accelerator cable or any part of the actuation system.

All acceleration control signals (between the accelerator pedal and the motor controller) must have error checking.

4.2 System Status Interface

LCD Screen:

The LCD screen is used to clearly communicate all errors and status/conditions of the vehicle. Live data such as vehicle speed and accumulator voltage is supplied through the LCD. The LCD is also supposed to display transition states when flipping the switches on the vehicle, such that one can tell if the car is in neutral, waiting, charging, or other states.

RF transmitter:

The RF transmitter uses UART in its communication system, so proper circuitry and overall set-up is required. The motherboard must be able to connect and send messages through UART to the RF transmitter. The transceiver must be able to achieve a minimum distance of 0.25 miles (0.4km).

4.3 Motor and Generator Control System

Our system must differentiate between the CAN messages from the left and right hub motors.

4.4 Engine Feedback Loop

The motor RPM will be stable through the expected load range. Large overshoot and stalling will not be acceptable. In addition, RPM set values will automatically adjust based on capacitor charge values.

4.5 Accumulator Management System

Requirements for this subsystem includes the monitoring of the AMS whenever the system is active or the accumulator is connected to a charger. High voltage system must be galvanically isolated from low voltage systems.

AMS has to monitor all critical voltages and temperatures in the accumulator and must shut down the electrical and I.C. drive systems, open the AIRs within 60 seconds and send an error data to the Motherboard if there’s detection of voltage above maximum voltage, a cell temperature of about 65 degrees Celsius or a large variation of voltages between cells. This way the voltage of every cell can be monitored to prevent overcharging of a cell. Additionally, the driver may not enable reset in case of an AMS fault.

5 System Block Diagram

5.1 Overall System

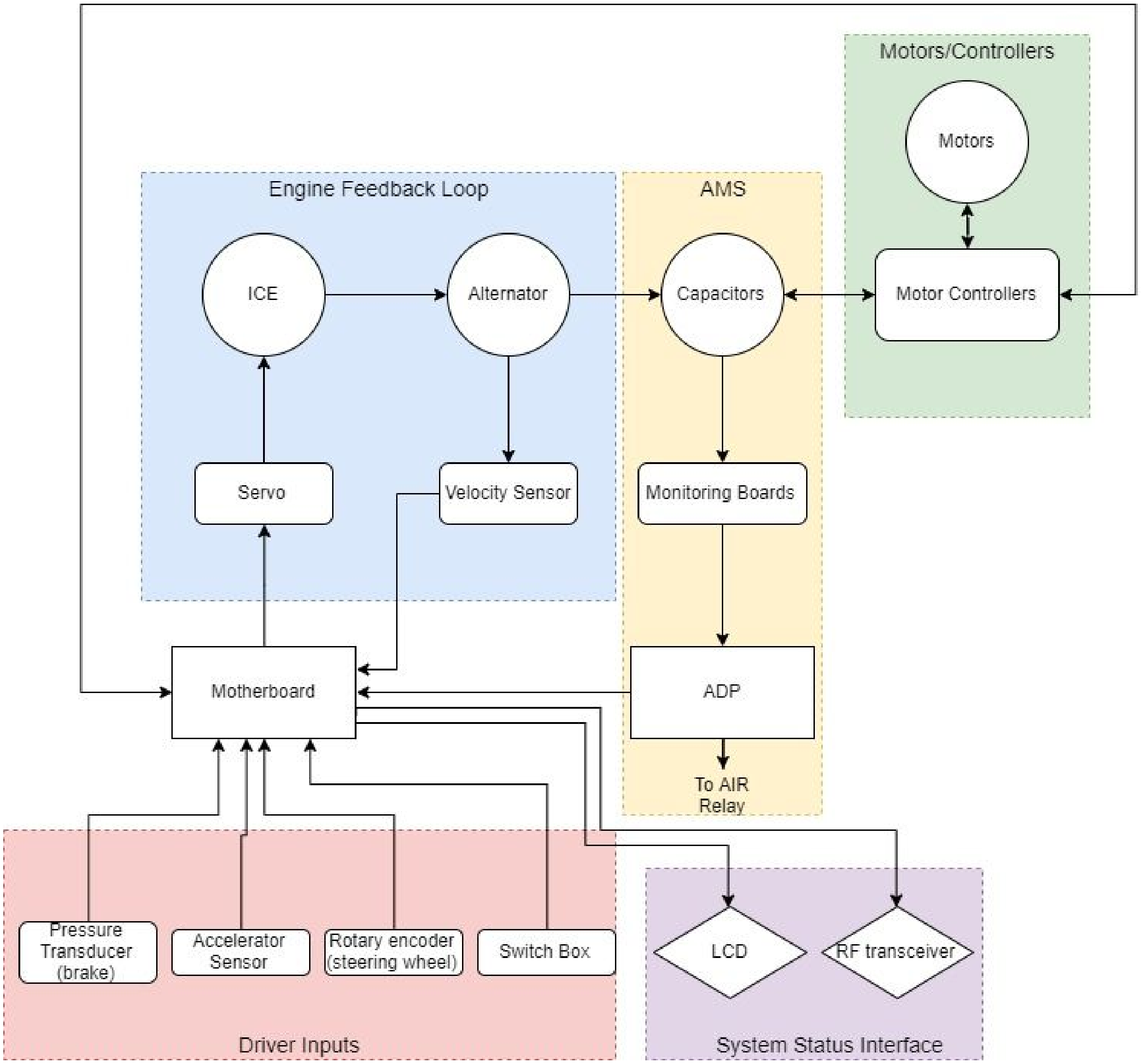

Figure 5.1a The figure above shows the overall system with the subsystems

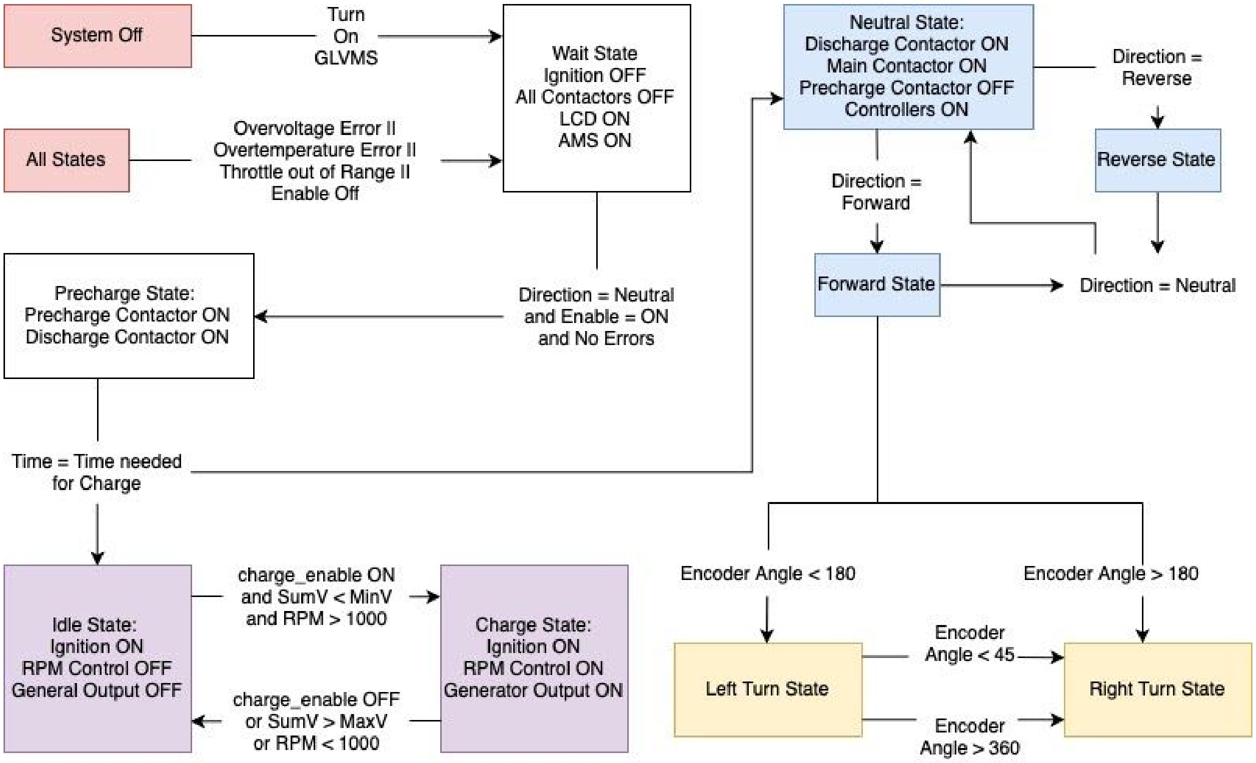

Figure 5.1b The figure above shows the drive system state diagram, copied from the 2018 EESD Formula SAE Final Report

5.2 Future Enhancements

Instead of a switch box, we would like to implement a touch screen user interface. This would create a more intuitive system for the driver, and would also allow control of software elements such as changing RPM setpoints.

6 High Level Design Decisions

BRAKE PRESSURE TRANSDUCER

The brake pressure transducer would allow us to meet the rules indicated by the Formula SAE guidelines. Introducing the brake pressure transducer would require the adjustments of signal thresholds which as indicated in the rules above need to allow for a fail safe system. The use of the transducer should allow our system effectively brake as desired and should result in a more ideal braking system. The current system is a brake by wire system which is not ideal and discouraged by Formula SAE.

ENGINE FEEDBACK ALGORITHM

More advanced engine control algorithms are needed to allow for operation in different racing environments. These will be implemented using the same PID controller that is currently on the system. However, information about the energy remaining in the buffer will be included before the control loop. This added information will allow the development of an algorithm that will prevent the capacitors from overcharging and prevent depletion.

CAN BUS ADDRESSING

In order to ensure unique addressing for each Kelly Controller, the continued use of the PIC32MX795 device is optimal. This microprocessor has 2 separate CAN bus inputs which would allow the implementation of 2 CAN buses on the system if the Kelly KLS Configuration Program method was determined to be faulty. An identical additional CAN transceiver would be necessary on the motherboard to provide this functionality. Since the Kelly controllers themselves are very costly, replacing the controllers solely because of this issue would not be feasible when workarounds are possible.

ACTIVE CELL BALANCING

In order to implement active cell balancing on the AMS, SAB MOSFET Arrays can be implemented to regulate a group of 4 ultracapacitors. Since there are 60 ultracapacitors in series in the AMS, 15 SAB MOSFET Arrays are necessary to balance the entire system. The maximum input voltage to the MOSFET array is +/- 15 V. Since each capacitor has 2.7 V across it, a group of 4 series capacitors would be under 15 V. Combining these MOSFET Arrays in series to accommodate an entire ultracapacitor bank is possible per the datasheet (linked below).

7 Open Questions

What are the variations in voltage between the ultracapacitors in the AMS while the bank is charging and what is the quantified improvement of charge conservation with the Active Cell Balancing?

If we cannot change the preferred CAN address of the Kelly controllers through the provided GUI or find another method for identification, we will contact the manufacturer for help. If unique addresses still can't be achieved, we will need to use two CAN modules on the PIC. While this defeats the purpose of CAN to a certain extent, it will allow us access to the necessary information. If this is the case, we will need to verify that the CAN1 pins are not being used on the PIC, or that they can be made available.

8 Major Component Costs

Quad/Dual Supercapacitor Auto Balancing (SAB™) MOSFET Array:

- $3.47 each
- Qty: 15
- Quad Supercapacitor Auto Balancing MOSFET Array (ALD810025)
- Total component cost: $52.05

Brake Pressure Transducer (*assuming this was not purchased last year)

- Qty. 1: $72.80
- Brake Pressure Transducer

Total Proposed Component Costs: $124.05

9 Conclusions

The high level design provides a background for laying out the scope of the project and what needs to be upgraded upon or completely re-designed in the legacy system. We have begun testing and understanding the legacy documentation, software, and hardware and would be ready to address problems within the system based on the team priorities. The high-level design allowed the creation of a set goals for the team with regards to different subsystems and we would be ready for a more robust and better-designed system before a low-level design is realized.

10 References

Our Preliminary Design Proposal: (uploaded on Sakai)

SAE Guidelines:
https://formula-hybrid.org/wp-content/uploads/2020-Formula-Hybrid-Rules-Rev-1-1.pdf

Previous Team’s High-Level Design:
http://seniordesign.ee.nd.edu/2019/Design%20Teams/ecar/High_Level_Design.pdf

Previous Team’s Final Report:
http://seniordesign.ee.nd.edu/2019/Design%20Teams/ecar/Final_Report.pdf

Kelly Controller Datasheet:
https://kellycontroller.com/wp-content/uploads/kls-8080i-ips/KLS8080I-IPS-Opto-isolated-Sinusoidal-BLDC-V1.10.pdf

Kelly Broadcast CAN Protocol:
https://kellycontroller.com/wp-content/uploads/kls-8080i-ips/Sinusoidal-Wave-Controller-KLS-D-8080I-8080IPS-Broadcast-CAN-Protocol.pdf

PIC32MX795 Datasheet:
https://www.sparkfun.com/datasheets/Components/SMD/PIC32MX.pdf