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Formula Hybrid Project Proposal

1 Introduction

This project will be completed for the Notre Dame Formula SAE (Society of Automotive Engineers) Hybrid Racing team as part of an ongoing collaboration of EE Senior Design students and the Hybrid team to improve and expand the electrical subsystems contained within their hybrid vehicle. Due to the nature of this collaboration, the project is based on the documentation and subsystems created by previous year's Senior Design groups to learn what subsystems currently work, what subsystems need improvement, and what new subsystems need to be implemented.

As discussed in previous documentation, the car is a series hybrid powered by a bank of ultracapacitors in series with an internal combustion engine (ICE). A generator motor converts mechanical energy from the ICE to electrical energy, while the capacitor bank serves as an energy buffer between the generator and the two electric hub motors, each of which is controlled by a Kelly motor controller. The combination of the ICE, ultracapacitors and motors is the high voltage system, while monitoring and controlling the high voltage system based on user inputs is achieved by the low voltage system.

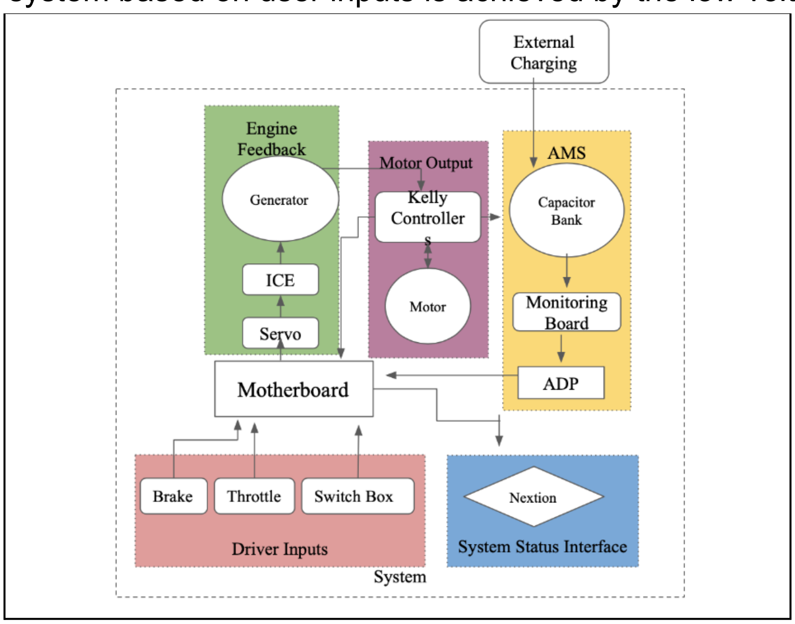

Figure 1. Complete System Diagram (2020-2021)

2 Problem Description

Each of the past three years, an EE Senior Design (EESD) group has worked with the Formula SAE Hybrid Racing team to develop and improve the required electrical subsystems for an SAE sanctioned hybrid vehicle. Therefore, the team will be relying on the previous documentation to inform and guide decisions about continued work on the car. Based on the recommendations of the 2020-2021 EESD team, four electrical aspects of the hybrid vehicle that require ongoing work are the following: AMS (Accumulator Monitoring System), Motherboard Redesign, Systems Status Interface, and Engine Feedback Loop. Each of these aspects of the hybrid vehicle presents certain problems that must be solved.

AMS

The Accumulator Management System is required on the vehicle to meet regulations but has not been completely implemented. Thermistors must be included in the system to monitor capacitor temperatures. Each thermistor will track the temperature of two capacitors, and every capacitor must be in contact with a thermistor.

The AMS system can also be improved by removing the issue of low-power shutdowns. Currently, the discrete transistor power supply for the demo boards requires at least 11V from the capacitors under each demo board to output its 5V regulated power. If the capacitor voltage drops below 11V, the demo board shuts down, preventing the generator from charging the capacitors. Additionally, an active cell balancing system can be implemented to equalize the charge among all capacitors at any voltage, to address inequalities in charge within the bank.

Motherboard Design

The current motherboard that is being used in the vehicle was designed in 2018, and it lacks some of the capabilities needed to fully support the existing system. The board’s current microprocessor lacks satisfactory processing power and the board does not have enough UART connections to support all of the vehicle's systems, as both the Nextion system status display and the RF transmitter use UART, but the board only has one UART module. In addition, the relays on the current board are not functioning properly and cannot set the drive states of the vehicle. As the hybrid vehicle continues development, it is imperative that the motherboard can support the existing systems and can support systems that might need to be introduced in the future.

Systems Status Interface

The Systems Status Interface was designed by previous EESD teams to provide live updates to the driver on a Nextion screen regarding fuel level, ultracapacitor charge, vehicle speed, engine RPM, and relevant error messages. This interface was planned to also include off-track monitoring through the use of an RF transmitter, which communicates to an off-track RF receiver, and writes to a serial monitor. However, due to past project limitations, this off-track monitoring system was not completed. As suggested by the 2020-2021 EESD team, our group will need to work on an off-track monitoring system that communicates data that is displayed on the Nextion to the Hybrid team on the sideline during a race.

Engine Feedback Loop

The Engine Feedback Loop controls the RPM of the engine. It involves a sensor that measures the RPM of the ICE, a servo that controls the ICE throttle, and the PID (Proportional Integral Derivative) controller on the motherboard. The servo adjusts the ICE throttle to set the RPM of the ICE.

The 2018-2019 group implemented the Engine Feedback Loop, but it has not been modified by subsequent groups due to the pandemic and the technical difficulties with the engine itself. Therefore, the issues associated with the first iteration Engine Feedback Loop have yet to be addressed.

The first issue is noise caused by the EMI generated by the motors. It interferes with the RPM sensor-to-motherboard and motherboard-to-servo signals. The noise causes the motherboard to incorrectly measure RPM and the servo to incorrectly respond to messages from the motherboard. Since the EMI is caused by the motors, the system doesn't work when there is a load. Therefore, the current constants set in the PID controller are set for no-load conditions.

The other issue is that the current Engine Feedback Loop algorithm holds the engine at a set RPM for maximum ICE efficiency, no matter the state of the other systems. The engine at present cannot adjust RPM based on capacitor charge, and the current algorithm cannot run the car in idle mode.

3 Proposed Solution

AMS

The capacitor bank has been assembled since the 2019-2020 EESD team worked on the AMS. Therefore, the thermistors must be incorporated into the capacitor bank and then connected to the monitoring demo boards that already monitor capacitor voltage. Additionally, the single-transistor power supply on each demo board should be replaced with a low-dropout 5V power supply, which will mitigate the issue of low-power shutdowns.

To implement active cell balancing, our group will need to utilize the battery monitor’s capability to transfer charge between each pair of capacitors. This will involve reprogramming the monitor's IC, as well as replacing the current-limiting resistors in the capacitor bank with fuses to eliminate any excess resistance.

Motherboard Design

In order to successfully design a new motherboard, the team must gain familiarity with the current motherboard to see what new features need to be added and what features are already acceptable. A new microprocessor will be implemented into the new board that will have the processing power and communication capabilities that are required for the system. To decrease the complexity of the system, a power supply for the Nextion display will be added to the board so that a separate power supply is not necessary. This will be a 12V-5V converter that supplies power to the display from the board.

Systems Status Interface

Coding adjustments to the 2019 EESD team's MATLAB GUI should be used as a starting point to implement an off-track monitoring system tracking data currently able to be displayed on the Nextion. An RF transmitter should be used in order to achieve this off-track monitoring, as suggested by the 2021 EESD team.

Engine Feedback Loop

The noise issue can be resolved with a quality shield cable. To further limit noise, the RPM control circuit should have its own PCB away from the motherboard. The noise issues currently prevent the Feedback Loop from operating with a load. Once the noise issue is resolved, the PID constants can be set based on load conditions.

The RPM setpoint can be adjusted based on the charge of the capacitors. This would require integrating signals that measure the capacitors' charge into the algorithm that determines the ICE throttle position and RPM setpoint of the engine. When the capacitor change is measured below a certain threshold, the RPM setpoint will increase above the ICE's maximum efficiency RPM setpoint. When the capacitor charge is above a given threshold, the RPM setpoint would decrease below the ICE's maximum efficiency RPM setpoint. Finally, an idle state will also be integrated into the algorithm.

4 Demonstrated Features

AMS

By May, the functionality of the AMS will be verified by demonstrating that the motherboard receives temperature-related errors if the capacitors overheat. Additionally, the AMS must be able to operate on a lower voltage and be able to correct voltage imbalances between capacitors.

Motherboard Design

By May, a new motherboard will replace the current board in the vehicle. It will be able to interface with the RF Transmitter and the Nextion display. This means it will have to show real-time vehicle information to the driver and the off-track team through the RF Transmitter that has already been completed by a past EESD team. In addition, the board will contain enough communication modules, such as UART, to interface with all necessary vehicle subsystems.

Systems Status Interface

By May, the off-track monitoring system that displays similar data to the Nextion will be implemented in order to send data to a PC using a MATLAB GUI. An RF transmitter will be used to realize this aspect of the systems status interface.

Engine Feedback Loop

By May, the team will be able to show that the RPM of the engine is set correctly under a wide range of loads, meaning either at the current setpoint or after the algorithm is updated, according to what the team would expect to be the outcome of the algorithm. This will indicate that the Engine Feedback Loop operates with the motor running, meaning the noise and PID constant issues are resolved. The team will also be able to show that the RPM increases when the voltage of the accumulators is below a certain voltage and the RPM decreases when the voltage is too high. The vehicle will be able to operate in idle state without turning the Engine Feedback Loop off, demonstrating that the limitations on the Engine Feedback Loop algorithm are resolved.

5 Available Technologies

A previous EESD team has already purchased thermistors for the AMS, but their temperature-resistance curves will be helpful in calibrating the demo boards.

https://www.amphenol-sensors.com/hubfs/Documents/AAS-913-318B-Temp-Resistance-Curves-091614-web.pdf

12V - 5V DC to DC converter capable of supplying up to 1A to be used on the new motherboard to power the Nextion display. This will be used on a new circuit board that is designed and built for the vehicle:

https://www.mouser.com/ProductDetail/TRACO-Power/TMR-9-1211?qs=MJt07Qdd3dLQ8QwPTc%2FkWQ%3D%3D

The wires from the PID controller to the servo and the sensor to the motherboard need to be shielded from EMI. In order to figure out the size of the wire, it is necessary to determine the current going through it. The initial approach would be to look at the size of the wire that is currently in the vehicle for these signals, determining if the sizing is correct and then ordering a replacement shielded wire.

https://www.homedepot.com/p/Southwire-By-the-Foot-18-2-Gray-Stranded-CU-CL3R-Shielded-Security-Cable-57573199/204725192

Off-track monitoring will require the use of an RF transmitter module, which is a small PCB sub-assembly that transmits a radio wave and modulates that wave to carry data.

https://www.digikey.com/en/products/detail/sparkfun-electronics/WRL-10534/5673761?utm_adgroup=RF%20Transmitters&utm_source=google&utm_medium=cpc&utm_campaign=Shopping_Product_RF%2FIF%20and%20RFID_NEW&utm_term=&utm_content=RF%20Transmitters&gclid=Cj0KCQiAhMOMBhDhARIsAPVml-GFkmilCsDFVkNNwHRQBOSvfpoX-z2dqlY6zQEBCzZBEHJx2c9lsC0aAimpEALw_wcB

6 Engineering Content

AMS

Existing circuit boards will need to be modified or replaced to incorporate thermistors, new power supplies, and voltage balance circuits. Additionally, the demo board microcontrollers and the AMS motherboard will both need to be reprogrammed to support these modifications.

Motherboard Design

The motherboard design will require the PCB design skills learned over the course of the fall semester to switch the board to a new microprocessor and include new features, connectors, and a power supply. The new microprocessor will also need to be programmed with both legacy and new features, so code will be developed for the microprocessor to retain its previous functionality while adding new options.

System Status Interface

The System Status Interface will require knowledge from Embedded Systems to implement UART communications to transmit data to the off-track monitoring system by sending existing diagnostic data to an off-track computer, including considerations such as implementing the correct baud rate between devices.

Engine Feedback Loop

The Engine Feedback Loop will require a new PCB board for the PID controller. Most of the work of designing the circuit and the communications protocols needed to acquire and respond to various signals was already done by previous EESD teams. However, the circuit needs to be modified to accommodate the capacitor voltage sensor information, and communications need to be set up between the PCB board and the voltage sensors. Currently, the NCV1124 "Variable Reluctance Sensor Interface IC" conditions signals sent between the sensors and the microcontroller. However, it is designed for sensors that monitor rotating parts, so it may not be the best choice for a voltage sensor. Therefore, changes to the engine feedback loop system will require the PCB design skills learned over the course of the fall semester, and will also necessitate decisions about which, if any, additional devices need to be added to the board to accommodate new features.

The team will also need to modify the embedded system that determines the throttle position to consider capacitor voltage when setting the engine RPM and will need to determine new PIC constants for the case where the motor is operating. Such considerations involve measuring how the engine and the capacitors respond to a load being added.

7 Conclusions

Therefore, by the end of this EESD group's project, the hybrid vehicle will ideally have a fully functional AMS that monitors both capacitor voltage and temperature, a redesigned motherboard with better processing power and the ability to interface to both an RF transmitter and the Nextion display, a Systems Status Interface that implements off-track monitoring via an RF transmitter, and an Engine Feedback Loop that addresses the issues of noise and modifying the RPM setpoint based on capacitor charge level. The breadth of this project is appropriate for the size of the team, addresses existing problems and solutions in the ongoing evolution of the hybrid vehicle over time, and can be solved using available technologies that fall within an acceptable budget.

In addition to technical and design requirements, the project is interesting due to the existence of a real customer -- the Formula SAE Hybrid team -- and its nature as an iterative process, as each year's EESD group improves and adds subsystems to the hybrid vehicle while documenting changes and future needs. Working with the Hybrid team to solve pressing problems with the car is closer to the engineering process in industry than an EESD project that is entirely self-defined, as the SAE Formula Hybrid Rules serve as customer requirements, and this year's EESD team will work on a few select subsystems within a larger product that contains other electrical and mechanical elements maintained and built by other engineering students. By the conclusion of the project, all demonstrated features will ideally be realized and incorporated into the hybrid vehicle, and documentation and next steps for future EESD teams will be identified and recorded.