Formula Hybrid: High-Level Design

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1 Introduction

This project will be completed for the Notre Dame Formula SAE Hybrid Racing team as part of an ongoing collaboration between EE Senior Design (EESD) students and the Hybrid team to improve and expand the electrical subsystems of their hybrid vehicle. As discussed in prior 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 is based on user inputs achieved by the low voltage system.

The vehicle includes five electric subsystems: Driver Inputs, System Status Interface, Motor Controllers/Generators/Motors, Engine Feedback Loop, and the Accumulator Management System (AMS). The central motherboard handles the vast majority of processing and communication between the subsystems, in addition to an Accumulator Dedicated Processor (ADP) mandated by SAE rules. This document serves as an outline of the high level design choices for planned improvements to the functionality of the vehicle's electrical subsystems. All system components are planned to fall under the criteria of the Formula Hybrid rules for the 2022 competition year.

2 Problem Statement and Proposed Solution

2.1 Accumulator Management System

The Accumulator Management System is required by Formula Hybrid rules, but the current implementation is incomplete. Currently, the capacitor bank is only partially assembled due to faulty capacitors, and only half of the monitoring boards have been connected to the bank. Additionally, the current system lacks thermistors to monitor capacitor temperatures, both of which are necessary to ensure safe operation of the high-voltage system. The monitoring boards also have a problem with low-power shutdowns, requiring the capacitor bank voltage to be above 44 volts to operate.

The proposed solution is to finish assembly of the capacitor bank by replacing the faulty capacitors and connecting the remaining two monitoring boards. Then, the thermistors can be installed in the capacitor bank to monitor the temperatures of pairs of capacitors. The existing single transistor power supply on the monitoring boards will also be replaced with low dropout power supplies.

2.2 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 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.

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. 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.

2.3 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.

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.

2.4 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.

The noise issue can be resolved with a quality shield cable. 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. Another possible algorithm would be to have the engine idle if the capacitors reach full charge, and turn on again once the capacitors dip below a given charge.

Past groups have been unable to work on this subsystem because the engine was not functioning properly. It's unclear whether this issue has been resolved, and would need to be fixed before making significant progress on the subsystem.

3 System Requirements

The overall system requirements are based on the 2022 Formula Hybrid Competition rules. For vehicle operation, the braking system must act on all 4 wheels and be controlled by a single source. In the case of braking system failure, two wheels need to be maintained. The acceleration of the vehicle should be controlled under all circumstances. The vehicle must have a way to communicate live data and errors to the user and their team. The system should be able to communicate with the left and right motor independently. The engine of the vehicle must operate in a stable range. Finally the vehicle must monitor the voltage and temperature of the capacitor bank to prevent the overchange of the capacitor bank. Detailed electrical safety requirements are outlined in those rules, but important takeaways include that the system can power down for maintenance, the high voltage requirement is inaccessible while charged and there is a separate high voltage and low voltage system. The end goal is for all these systems (besides the team interface) to be contained within a one person vehicle with power in the system coming from the engine.

Many of these requirements have already been addressed by previous teams, such as the requirement of communicating with the right and left motor separately. The requirements that are not addressed or insufficiently addressed will be discussed in the subsystem requirements below.

4 System Block Diagram

4.1 Overall System

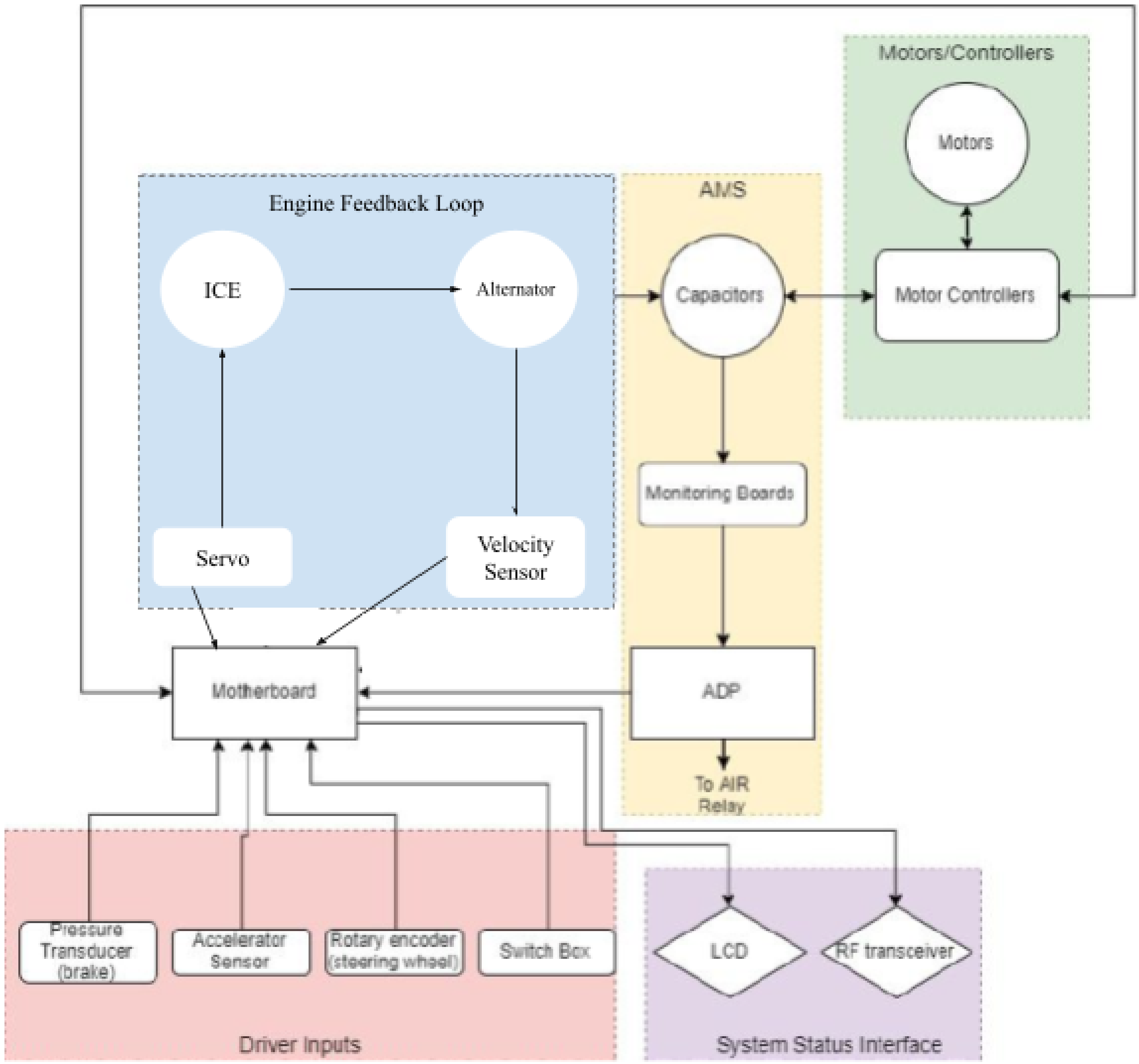

Figure 4.1.1. Overall system block diagram copied from 2019-2020 HLD Figure 5.1a

4.2 Subsystem and Interface Requirements

According to previous years' documentation, the Driver Inputs and Motor/Controller subsystems already have most of their functionality, so the team will not be focusing on them this year.

4.2.1 - AMS

The AMS must measure the temperature of the capacitor bank in at least 6 locations and the voltage of every capacitor in the bank. If the AMS detects high temperatures or voltages beyond the specifications of the capacitors, it must shut down the high-voltage system and send an error to the main motherboard.

4.2.2 - Motherboard Design

The redesigned motherboard must retain all the capabilities of the current motherboard, while adding an additional UART connection, functioning relays, and a power supply for the Nextion display. The microcontroller selected for the motherboard must be able to support all the existing connections as well as the planned additions.

4.2.4 - Systems Status Interface

The Systems Status Interface is responsible for communicating information such as fuel level, capacitor charge level, vehicle speed and motor speed in RPM to the off-track team. These updates are also displayed to the driver on a Nextion screen. An RF transmitter is required in order to efficiently communicate this data to the off-track team.

4.2.4 Engine Feedback Loop

The engine must operate a stable RPM under a wide range of loads. The RPM setpoint of the engine must respond to changes in capacitor voltage. The engine responding to capacitor voltages will help the AMS system prevent an overcharge and also ensure that the engine is not producing energy that will never be used.

4.3 Future Enhancement Requirements

This semester, the group is focusing on getting each subsystem to work on a table in the basement of Fitzpatrick. However, the end goal is that all these subsystems are contained within a vehicle that can work without connections to wall outlets and does not bear excess equipment weight. Transferring the system to a vehicle is a bit unrealistic for this semester, since it seems like previous teams had their hands full just getting the subsystem to work. However, it is important when designing the systems that the group accounts for the future possible that this will need to be put in a one person vehicle without connections to wall outlets or easy access to individual components.

5 High Level Design Decisions

5.1 Accumulator Management System

The monitoring boards and the AMS motherboard have already been implemented by previous teams. To implement temperature monitoring, thermistors will be connected to the capacitors, which will send analog signals to the monitoring boards. Additionally, since there are 20 defective cells in the capacitor bank, new capacitors will be installed as replacements and connected to the monitoring boards. The purchase of these replacement capacitors and thermistors has been handled by the Formula Hybrid club and is outside the scope of this project. However, their implementation is necessary for the safe operation of the vehicle. Overall, the system must comply with the 2022 Formula Hybrid rules.

5.2 Motherboard Design

The existing motherboard uses a PIC32 microcontroller. This microcontroller is expected to have sufficient memory and serial connections for this application, so the redesigned board will likely use the same controller. Because the new board needs to preserve all the existing functionality of the current board, the current design will be used as a reference, in order to avoid negatively impacting the performance of the existing systems.

5.3 System Status Interface

The motherboard currently communicates Nextion via a UART protocol, as implemented by the 2020-2021 team at a baud rate of 31250, but could be changed if necessary. As of right now, the communication between the Motherboard and Nextion does not need any fixing, as the previous year's team had fixed every issue. As mentioned above, 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. Therefore, in order to build a complete off-track monitoring system that successfully communicates data from the

Nextion to the off-track team, the System Status Interface will need that second UART module as proposed above.

5.4 Engine Feedback Loop

Most of the hardware for this system is already in place, including the velocity sensor, throttle servo, and capacitor change sensor, as well as the parts that support them. The major change to hardware are the cables. The cables should be replaced with shielded cables to resolve the noise issue.

The software determining the RPM setpoint needs to accommodate capacitor change. So before the software enters the loop that positions the throttle for the correct engine speed, it will first need to calculate what that engine speed will be. A start to this algorithm is that if the voltages are above a certain threshold the engine will slow down significantly or idle and it will turn back to the RPM of maximum efficiency once the capacitor changes dips below a certain point. Figure 5.4.1 reflects the new algorithm for setting RPM. The Kp, Ki and Kd constant in the figure also need to be set for the load condition.

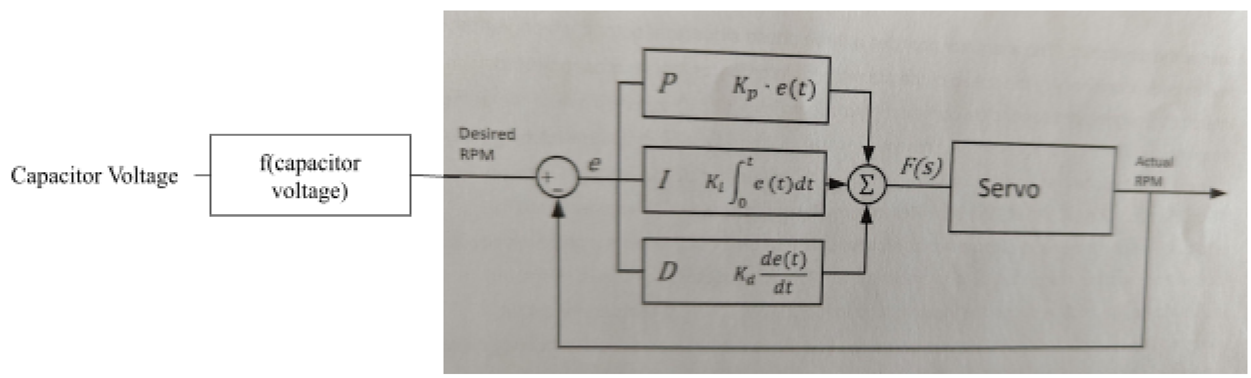

Figure 5.4.1. Modified Engine Feedback Loop algorithm based on 2018-2019 Final Report Figure 4.6.4

The computation for this system is done by the motherboard. The new microchip on the motherboard will need interfaces pins to accommodate this system. First there needs to be an input pin that accepts a square wave from the alternator communicating the RPM of the engine. The motherboard also needs to host the NCV1124 and high pass filter that supports the alternator interface. Second is an output pin that controls the servo. The capacitor voltage sensor communicates with the motherboard using an isoSPI system. Multiple subsystems use capacitor voltage, so doing all the processing on the motherboard limits the sensors and wires going to and from the capacitors.

6 Open Questions

6.1 Motherboard Design

Currently, microcontrollers similar to the one used on the current motherboard are out of stock on the Microchip website. It may be difficult to obtain an appropriate microcontroller. More investigation will be necessary to determine if it is appropriate to purchase either a lower-spec or a more expensive microcontroller.

6.2 System Status Interface

The 2020-2021 group was unable to implement the off-track monitoring system that displays data from the Nextion to the off-track team. RF transmission must be used in order to implement this process. By using the 2019 team's matlab GUI as a starting point, our team may be able to finish developing the RF transmitter that previous teams were hoping to implement. Other than using the matlab GUI as a starting point, the team is somewhat unsure how to solve this issue, but we will prioritize this as a prominent issue needing to be addressed.

6.3 Engine Feedback Loop

The 2020-2021 group was unable to make progress on the subsystem because the engine was not functioning properly. It's unclear whether this issue is fixed. Fixing an engine might be outside the scope of electrical engineering, so if the engine is still broken, the group might not be able to make progress on this subsystem.

The group has not worked significantly with the engine or the throttle servo. The 2018 - 2019 Final report specifies that the servo was the smallest servo that would provide significant force to counteract the spring. That servo was making small adjustments to its position to get to a set RPM. With the set RPM changing more that requires a servo that can support bigger changes, so the group might need to look into a more powerful servo to accommodate a changing RPM setpoint.

7 Major Component Costs

New microcontroller for motherboard: ~$11 if available

New PCB for motherboard: 2 layer PCB quickturn prototype $33 each (student deal) 4PCB

Shield Cables: Less than $1 per foot, but will likely be sold in higher quantities than what the team needs.
https://www.homedepot.com/p/Southwire-By-the-Foot-18-2-Gray-Stranded-CU-CL3R-Shielded-Security-Cable-57573199/204725192

Bridge Diode that can withstand ~100V and 5-7 Amps of current: ~$10 (Might be able to obtain from Dr.Bauer) https://tinyurl.com/2xjwu6xr

The 2020-2021 team suggested the team buy a new 110V voltage source: https://tinyurl.com/2229v57m . The one they suggested was not available, but similar models were $60-$100.

RF Transmitter for Off-Track Monitoring System: ~ $4.95
https://www.sparkfun.com/products/10534

8 Conclusion

This high level design provides an outline of what the team would like to accomplish this year as well as how they plan to do it. It is heavily based on previous teams documentation and their comments on what needs to be fixed and improved. Many of these problems have been around since the 2018-2019 Formula Hybrid Design team. Hopefully this will be the year those problems finally get resolved the team will finally have a working vehicle.

9 References

2018-2019 Senior Design Formula Hybrid Documentation
2019-2020 EESD Formula Hybrid Documentation
2020-2021 Senior Design Formula 1 Documentation