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High Level Design: Hybrid Vehicle

1. Introduction

This document outlines the overall design of the proposed smart system for the Notre Dame Formula Hybrid team vehicle. The design delineates the planned communication interfaces between the various components of the system to fulfill its requirements, providing computational capabilities and safety features. All system components were selected under the criteria of the the Formula Hybrid rules for the 2019 competition year.

2. Problem Statement and Proposed Solution

The Formula Hybrid team has a need for a sophisticated electronic system that will be embedded in their car. The system is required to act as an electronic differential, an accumulator management system, and a monitor for the motors. It must be able to activate the regenerative braking system. Lastly, the system must be display the current state of the controller inputs and outputs to the driver through serial communication and to an external computer off the track through RF signals.

An important part of the problem involves the accumulator management system (AMS) which is required by the Formula Hybrid rules to ensure safe operation of the high voltage circuit. The mechanism to shut down the high voltage loop is called the Accumulator Isolation Relay (AIR), of which there are two. The Formula team is designing the AMS, but the device they have asked for is required to be an additional element that can open the AIR's.

The proposed solution will be designed to take inputs from the accelerator and brake pedals, steering wheel, accumulator bank, and IC engine. These inputs will give the system information on the voltage and temperature levels of high voltage components. The central microprocessor (Motherboard) will compute the optimal torque to output to the motor controllers based on computations done using the steering wheel, brake pedal, and accelerator pedal positioning. The separate Accumulator Dedicated Processor (ADP) outputs to the coil of the Senior Design Relay (SDR). The SDR switch is in the accumulator management loop and can open the AIR's if the ADP detects overheating or over voltage in the accumulator. The ADP is connected to the Motherboard via an optical coupler and will communicate the state of the accumulator. This data and the data collected by the central processor will be sent to the LCD and and off-track computer via the RF transceiver.

3. System Requirements

The system must monitor the activity of each of the aforementioned components and provide information on and control of the car's performance. It must provide connectivity between the various electrical systems of the car as well as computational power. The system must also assist the Accumulator Management System (AMS) in monitoring the operation of the energy storage bank. It must be reliable and robust and meet the specifications of the 2019 Formula Hybrid rules.

The chosen sensors use a range of analog and digital communication. The Motherboard must have support for both analog and digital I/O, SPI, and I2C pins for the sensors, LCD, and optical coupler. It must support CAN bus for the Kelly controllers. Lastly, it must be able to read out to the RF transceiver via UART. The transceiver must be able to transmit a minimum distance of ¼ mile (0.4 km). System data such as accumulator voltage, device temperatures, and generator and motor currents will be transmitted over this wireless link to a trackside receiver. Driver feedback will be provided by the LCD, displaying information such as vehicle speed and accumulator voltage.

Power for each sensor and each of the two processors will be provided by the Grounded Low Voltage (GLV) system. The energy storage for the GLV is a 12V motorcycle battery, which is self-sustaining by recharging from the alternator. The sensors and processors all run on either 3.3V or 5V. Two DC/DC converters are required to convert 12V into 3.3V and 5V for this purpose.

The vast majority of safety concerns are covered in the Formula Hybrid rules, including accumulator management, driver security, and system startup/shutdown. The Senior Design system must fulfill the electrical safety requirements as well as some added safety features. All high voltage elements of the system will be physically inaccessible when charged and safety interlocks will be utilized to power down the system before performing maintenance. All high voltage elements are fully isolated from the main low voltage system through DC/DC converters for power and optical couplers for data.

The accelerator pedal is an analog sensor and thus is required by the rules to have error checking for open circuit, short to ground, and short to sensor power faults. The brake pedal simply must produce a 0-5V signal, in addition to mechanical braking.

The danger of overheating in the accumulator is protected against by the temperature sensors as part of the AMS. The ADP is required to shut off the high voltage system if the accumulator bank is unstable. Thermocouples provide information on the temperature of the accumulator and the generator to the ADP. The voltage of every cell in the ultracapacitor accumulator bank must also be monitored to ensure that no cell is being overcharged. The ADP assists the preexisting AMS system, which utilizes relays and fuses to protect the high voltage system.

4. System Block Diagram

4.1 Overall System:

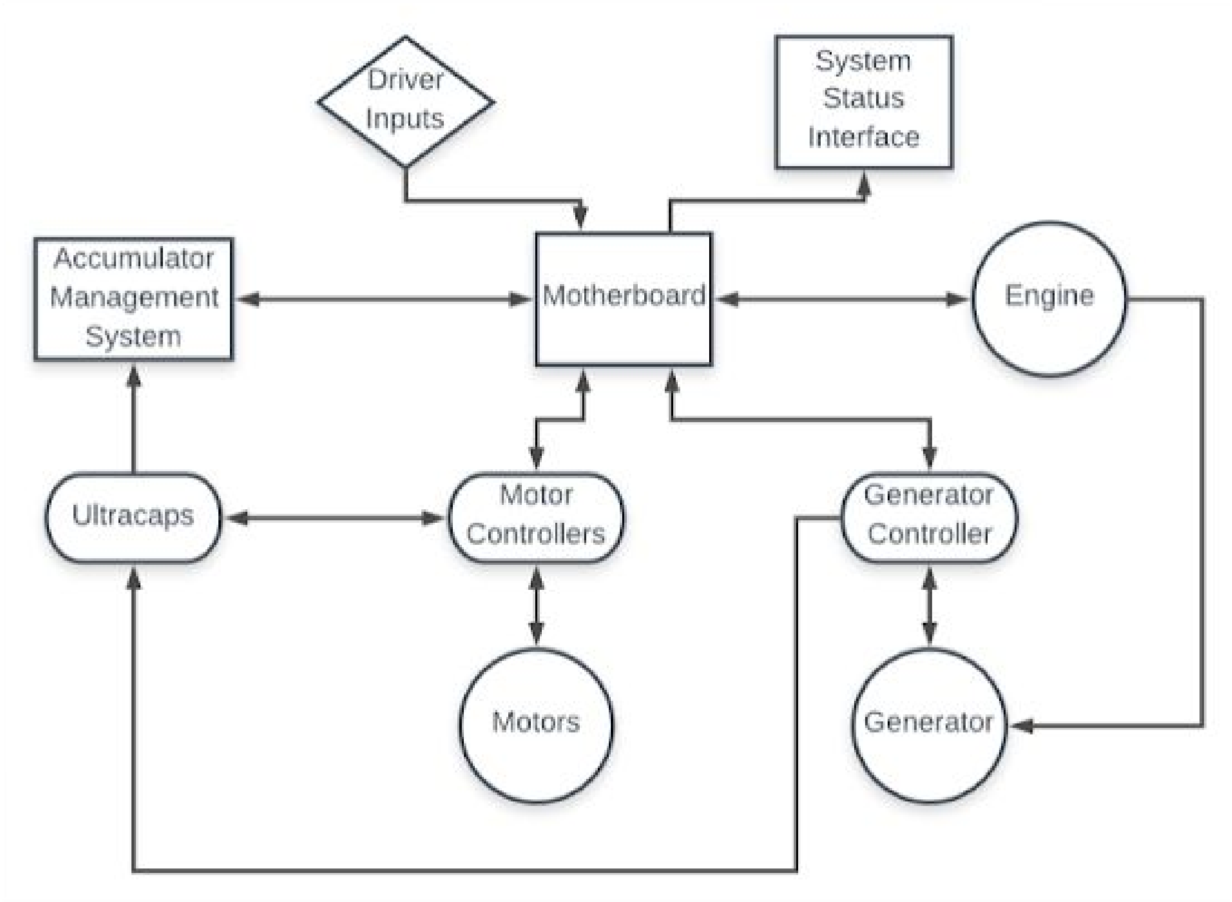

Figure 1: Overall System Block Diagram

The system is centered around a Motherboard that handles the majority of processing and I/O requirements. This central processor is responsible for monitoring the status of all components to detect device malfunctions, using driver input signals to calculate appropriate motor outputs, and controlling the internal combustion engine and generator to maintain appropriate accumulator voltage. An auxiliary microprocessor (the ADP) is dedicated to managing the accumulator as required by the SAE rulebook. This processor takes inputs of capacitor temperature and voltage, and it controls a safety shutdown relay as well as transmitting data to the Motherboard. Information relevant to the driver is outputted to a display on the steering wheel, while other system data is transmitted wirelessly to a trackside receiver.

4.2 Subsystem and Interface Requirements:

1. Driver Inputs

   This subsystem measures inputs from the driver, including throttle, brake, and steering wheel position. Throttle and brake sensors will each generate dual 0-5V analog signals, which allow for error checking. Steering position will be measured by a rotary encoder and must transmit absolute position over a range of at least 2.5 turns via SPI.

2. System Status Interface

   Feedback on system performance and status will be given to both the driver and trackside crew. Driver relevant information, such as accumulator voltage, temperature, and speed, will be displayed on an LCD screen located near the steering wheel. All other data will be wirelessly transmitted over a minimum range of ¼ mile. Transmission speed requirements are negligible, as data updates need not arrive more frequently than about once per second.

3. Accumulator Management System

   The AMS must monitor the temperature of the accumulator in 6 locations as well as the voltage of each individual cell. Temperatures about 65 degrees Celsius, voltages above 2.6V, and large voltage variations between cells will trigger a shutdown of the high voltage system by opening the shutdown relay and sending error data to the Motherboard. The AMS circuitry will be galvanically isolated from all low voltage system components.

4. Motor, Generator Controllers

   Each motor controller requires 0-5V analog signals for for throttle and braking torques, and the generator controller requires a 0-5V input for desired charging current. The controllers internally manage power transfer between the accumulator and their respective motors. Speed and temperature data is transmitted back to the Motherboard over CAN.

5. Internal Combustion Engine

   The ICE management system is a feedback loop that keeps the engine at the appropriate RPM to maintain the ultracapacitor voltage. Necessary charge current is determined by the accumulator voltage, and from this value the necessary engine speed can be calculated. Current engine speed is determined by converting the AC alternator output to a square wave signal and measuring its frequency. Then, the throttle position servo is actuated to increase or decrease fuel delivery, resulting in a corresponding change in RPM.

6. Motherboard

   The Motherboard will be responsible for all decision making and calculation except for the automatic shutdown triggered by an AMS error. Functions include determining the appropriate engine RPM and generator current output to keep the accumulator charged, implementing a torque vectoring system that reads throttle position and steering angle to determine the optimal torque outputs of each drive wheel, and sending the corresponding commands to the motor and generator controllers. The motherboard will also send system data to the LCD display and RF transmitter.

4.3 Future Enhancement Requirements

This system will be constructed with future expansion in mind. The AMS will be expandable to include a larger number of cells in the pack by leaving additional pins available for a second transistor array and more temperature sensors. The Motherboard will also have additional pins available for general I/O and communications, so future teams who wish to add additional sensors or driver feedback systems will be able to do so. These pins will be brought out to headers for easy connection. All software will be well commented for clarity and ease of modification. An external programming connector will allow quick software updates, which is important when tuning the control algorithms.

5. High Level Design Decisions

The basic understanding of the subsystems of our project come from the system block diagram present in Section 4.1. The individual components of each make up a subsystem requiring specific devices, sensors, and interfaces. This section describes the specific components chosen for each subsystem.

5.1 Motherboard:

The Motherboard microcontroller must take input from all sensors except those strictly a part of the Accumulator Management System. This requires the microcontroller to be powered from the vehicle 12V system through a 3.3V DC-DC converter. The I/O and interface requirements include UART, SPI, I2C, and CAN. With these requirements needing to be implemented from multiple other subsystems, a microcontroller in the PIC18F family from Microchip would be suitable. A consideration of sufficient I/O pins for each type of interface is necessary when deciding upon the specific board, however, the power and basic I/O capabilities of this family of microcontrollers satisfy the requirements of our system.

5.2 System Status Interface:

This subsystem includes the LCD screen used to communicate information on the state of the vehicle to the driver on board as well as the transceiver circuit which transmits diagnostics to an off-track computer via RF. We picked this specific LCD (see section 7.1) for three reasons: First, the LCD is equipped with a controller that makes it easy to communicate with through SPI. It supports various forms of RGB interfacing, which makes it flexible as well. Second, the LCD is large enough for our purposes. The 7-inch size is essential since we plan on outputting a lot of data on it. Third, it is cheap when compared with other displays. The transceiver circuit is also very practical because it accomplishes everything we need. It can communicate over 1 km, which is sufficient for this competition. It also communicates through UART, a protocol that our group is familiar with. We also need a receiver to receive and display the signal on a computer, and we will do this by using an Arduino equipped with the same transceiver. The Motherboard family that we chose will have the ability to interface through I2C and SPI, therefore it falls within specs, and we are using the pins as efficiently as possible.

5.3 Accumulator Management System:

This subsystem requires a dedicated microprocessor as required by the Formula Hybrid competition rules. Since the AMS is a high voltage subsystem, then it must be isolated from the rest of the system. Therefore, we require a slave microcontroller (the ADP) that will communicate with the Motherboard either with SPI or I2C. This will give us flexibility to use the protocol that is available. The AMS must be isolated from the rest of the car since it deals in high voltages, and therefore we will use an optical coupler to couple the communication between the motherboard and the ADP. The ADP will output 6 bits which will control an array of transistors which are responsible for connecting the appropriate cell to an analog input on the ADP for voltage measurement. This same system is needed for both the positive and the negative voltage of each capacitor, so we can couple each capacitor with its ground reference. The ADP is also responsible for being able to turn the Shutdown Circuit Relay on, in the case of an out of range voltage or other safety risks. Temperature, which needs to be monitored since it is a safety risk, will be measured by temperature sensors which will send out a proportional-to-temperature analog signal to the ADP.

5.4 Ultracapacitors:

The ultracapacitor subsystem consists of the physical capacitor banks receiving power by getting charged by the generator and powering the motors by discharging when necessary. The Accumulator Management System accounts for the monitoring of these components necessary for this project. The ultracapacitors themselves are Maxwell Technologies BCAP3000 connected in two groups of thirty (each individual capacitor in series). Each group of ultracapacitors have balancing boards meant to equalize the amount of charge of each capacitor to ensure there is not an uneven distribution. The purchasing of these capacitors and balancing boards lie outside the scope of this project, though their function and continual monitoring is a necessary component of the Accumulator Management System and thus the sensors tracking the characteristics of temperature and voltage are important to that subsystem.

5.5 Engine:

The purpose of the internal combustion engine is to power the generator that, in turn, charges the ultracapacitors used to power the motors of the vehicle. To achieve this function, the engine must receive and transmit information interfacing with the Motherboard microcontroller so as to run at the desired rpm. Adjusting the throttle angle providing gas to the engine will require a physical input from a servo motor adjusting the position of the throttle based on the Motherboard's calculations. The actual rpm of the engine must then be outputted to the variable reluctance chip, which converts the engine's alternator output to a logic level square wave representing the current rpm in order to transmit whether a shift in the current throttle angle is needed to achieve the desired rpm. This output will inform the necessary throttle angle in a feedback loop based on the desired rpm. The reason for using the variable reluctance chip is twofold. It transforms the output 3 Phase AC alternator waveform from the engine into a square wave that the microcontroller can understand. The chip also serves to convert to a 3.3V signal the output from the engine that can be upwards of 60 volts. These functions make the chip suitable to interfacing between the output waveform of the engine and the necessary input waveform compatible with the microcontroller.

5.6 Generator/Controller:

The generator operates as a subsystem with one input and one output. The engine sends the intended physical rpm output as detailed in the "Engine" subsystem and outputs a square wave representing the rotor position to the Kelly Controllers which control both the generator and the motors. The generator requires a digital interface to send the necessary square wave signals to the generator controller which will in turn interface with the Motherboard microcontroller. The choice of microcontroller is the most integral to this subsystem as it must be able to process the square waves from the generator controller.

The generator controller subsystem serves to communicate the status of the generator directly to the Motherboard microcontroller as well as receive data of the necessary charge current from the microcontroller. The generator and its associated controller take a 0-5V analog command from the Motherboard about how much current to output to the accumulator. The microcontroller needs to be able to incorporate this function, however, the controller and generator have already been ensured to accept this communication from the microcontroller when specified as they were selected by the Formula Hybrid Team. The controller is powered by the existing 12V system of the overall vehicle.

5.7 Motors/Controllers:

The Kelly Controllers will require a power supply from 8V to 30V. These controllers will interface between the motor and the selected Motherboard microcontroller from the PIC18F family. The Kelly Controllers are capable of supplying power to the wheel, as well as regenerative braking. The motherboard will supply the Kelly Controller with four inputs, which are the brake percentage, whether the car is braking, the throttle, and the direction the motor should turn. Apart from this, the Kelly Controllers communicate with the microcontroller through CAN2.0B to transfer certain data such as the rpm, the internal temperature, etc. This information will then be transferred to the motherboard (and then to the LCD). Also, the motherboard, which is communicating with the rotary encoder, will use this information to tell the ADP to communicate to the Kelly Controllers how much power they should supply.

5.8 Driver Inputs:

The driver inputs all send their outputs directly to the microcontroller. These consist of the steering wheel and the accelerator and brake pedals. The rotary encoder is placed on the steering wheel shaft and outputs the absolute position of the steering wheel to the Motherboard via SPI for use in optimal torque calculations. The accelerator pedal also outputs to the Motherboard. Its 0-5V analog output tells the Motherboard how much acceleration the driver is requesting, which goes into the calculations for what torque to give the motor controllers. Choosing the Motherboard to be an intermediary between the accelerator and the motors was an important step in the design, and will allow the car to operate at a much higher efficiency, while improving performance characteristics. The brake pedal also gives and analog output to the Motherboard, which can turn on regenerative braking in the motor controllers.

6. Open Questions

6.1 Microcontroller Questions:

- How to connect to and work with the Accumulator Management System dedicated microprocessor (ADP)?
- What is the necessary (aka: minimum) microcontroller requirements to incorporate all types of communication protocol and have enough inputs of those types to incorporate our features?
- How much processing power do we need for the microcontroller chips (both Motherboard and ADP)? Are these different amounts or could the same chip be used for both?
- How will we decode the CAN bus signal?

6.2 Mechanical Component Questions:

- How will we attach the rotary encoder to the wheel shaft?

- Would a full pedal box design be possible or is it better to find individual pedals?
- How will we convert the rotary encoder position to measured output at each wheel?

7. Major Component Costs

7.1 Components:

- AMT20 Modular Absolute Encoder
    - Qty. 1: $48.65
    - Datasheet
    - An absolute rotary encoder can provide information about the angle of the steering wheel. The sensor communicates via serial connection.
- NCV1124 Dual Variable−Reluctance Sensor Interface IC
    - Qty. 1: $2.57
    - Datasheet
    - To monitor the rotational speed of the internal combustion engine, the waveform from it's alternator will be converted to a square wave, which can be read by the microcontroller. The NCV1124 Dual Variable−Reluctance Sensor Interface IC can perform this conversion.
- 433MHz Wireless Serial Transceiver Module
    - Qty. 2: $14.08/module
    - Datasheet
    - Information about the state of each system will be sent wirelessly to a transceiver located trackside. This data will be viewable on a laptop for real-time monitoring of vehicle performance. The following readily available transceiver circuit communicates via serial connection.
    - Another consideration will be a team Arduino or other device to attach the receiving transceiver module.
- 7" Inch Serial SPI TFT LCD Display Shield Module ST7735S SSD1963
    - Qty. 1: $42.95
    - SSD1963 Datasheet
    - A LCD display will be used to give the driver feedback.
- Motherboard Microcontroller
    - Qty. 1: ~$10
    - This is the PIC18F family of microcontrollers. The specific microcontroller will depend on aspects still variable including processing power and number of I/O pins available for the various necessary

- Optical Coupler
    - Qty. 1: $4.95
    - Datasheet
    - Isolating high voltage from the low voltage between the two microcontrollers (Motherboard and ADP) over SPI because they operate at different levels
- Accelerator Pedal
    - Qty. 1: $74.99
    - Datasheet
- Shutdown Circuit Relay
    - Qty. 1: $2.67
    - Datasheet
- UCap Temperature Sensor
    - Qty. 1: $0.91
    - Datasheets
- Brake Pressure Transducer
    - Pressure Transducer
        - Qty. 1: $72.80
        - Datasheet
- Accumulator Dedicated Processor (ADP)
    - Qty. 1: ~$10
    - A board in the family of the Motherboard microcontroller could be used, however, that level of processing power is not necessary for this board which performs fewer functions. The high end estimate is used for this board and set equivalent to the Motherboard microcontroller.

Working Component Cost Total: $300.85

7.2 Specialized Equipment

Much of the specialized equipment surrounding the demonstration of this project are expenses the Formula Hybrid Vehicle team will take on itself. These include component selections currently in discussion or already made by the team including components such as the steering wheel, motor controllers, and the body and other mechanical systems for testing and racing needs. Below are to those components most directly tied to the scope of this project.

- Balancing Boards
    - Datasheet
    - The ultracapacitors will be balanced automatically by a board made specifically for this purpose. The Hybrid team has already obtained these boards.

- Kelly Motor Controllers
    - These controllers are used to control both the generator and motors to interface with the Motherboard microcontroller.

8. Conclusions

8.1 Conclusion:

By defining the scope of the project and examining specific requirements, the team has assembled this high level design. At this point, we are ready to pick specific components and begin assembling parts. We recognize the unknowns that were stated in Section 6, and are prepared to address these questions before a low level design is realised. Completing the high level design has allowed the team to have a clearer vision of the project. We have begun to lay the groundwork so as to to move forward with even more specific goals.

8.2 References:

- Formula Hybrid Website: https://formula-hybrid.org
- Proposal Document: https://docs.google.com/document/d/1quBJzKQb407Fgqj2xN-G38M3Zi85ODDGcvG8qoTXqKE/edit?usp=sharing