DESIGN AND IMPLEMENTATION OF A BATTERY MONITORING SYSTEM FOR THE TCU ENGINEERING DEPARTMENT ELECTRIC VEHICLE

by

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DESIGN AND IMPLEMENTATION OF A BATTERY MONITORING

SYSTEM FOR THE TCU ENGINEERING DEPARTMENT

ELECTRIC VEHICLE

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ABSTRACT

A shift in global energy prices contributed to an increased number of electric vehicles on the roads today, especially in urban environments. Monitoring remaining energy in an electric vehicle proves to be more challenging than determining the remaining fuel in a conventional vehicle. In addition, the range of many contemporary electric vehicles is below that of many conventional vehicles and the time required to "refuel" an electric vehicle is typically on the order of several hours rather than the several minutes taken to refuel a conventional vehicle. The difficulty in determining remaining operating range coupled with the necessity of knowing how much further the vehicle can drive requires a system known as a battery monitoring system.

This paper outlines the process in creating a battery monitoring system for the Texas Christian University Engineering Department Electric Vehicle. The system uses several circuits to measure the voltage across each battery and aggregates the data for later analysis using an Arduino microcontroller. This data can then be imported into MATLAB or another similar programming environment to study battery usage patterns and monitor battery state-of-health. The system outlined is designed to allow for future improvements, including real-time in-vehicle monitoring of battery charge and other vehicle performance metrics. Overall, this system will improve the TCU Engineering EV project by allowing future students to study different usage patterns and even battery types.

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INTRODUCTION

Electric vehicles are becoming more commonplace as the technology matures and gas prices remain higher than in previous decades. While the internal combustion engine still dominates much of the world's roads, electric vehicles and hybrids (vehicles with both an internal combustion engine and some form of electric motor) are more prevalent in urban areas than previous decades. Hybrids operate much like regular cars, requiring periodic refueling to supply the internal combustion engine, but typically with better fuel economy than their pure gasoline-powered counterparts. On the other hand, electric vehicles do not have any onboard power generation and rely solely on stored energy in batteries to power the electric motors during operation.

For an electric vehicle, monitoring the usable energy remaining in the batteries is just as important as knowing how much fuel is remaining in your gas tank for an conventional vehicle. In each case, the operator needs to know how far the vehicle can go before running out of stored energy, be it in batteries or gasoline. Compared to monitoring the remaining usable energy in a battery, knowing how much fuel is left in a tank is relatively simple—the amount of gasoline remaining is proportional to the remaining range of the vehicle. Determining the remaining energy stored in a battery is more difficult as there is no "fuel level" that can be observed. The energy in a battery is stored as chemical energy, much like the energy stored in gasoline, but when a battery provides energy, there is no combustion or exhaust of gases. In other words, while your gas tank empties as you drive, your battery does not lose any mass.

This paper outlines a scalable method of determining the voltage across each battery in an electric vehicle and an eventual path for the development of a real-time battery “fuel gauge” for use in the TCU Engineering Department Electric Vehicle.

BACKGROUND

For several years now, the TCU Department of Engineering has been converting a 1973 Porsche 914 from its original gasoline-powered state to a completely electric vehicle. The project is student-led, but under the supervision of Dr. Stephen Weis, a professor in the TCU Department of Engineering. The motivation behind the conversion centered on the desire to create an experimental environment where students could get hands-on experience during their undergraduate education and explore the opportunities for electric vehicles. The author has been working on the project for almost three years at the time of publication. The Porsche proves to be a suitable target for conversion efforts as Ferdinand Porsche’s first automobile design in 1898 happened to be an electric vehicle with a top speed of 21 miles per hour and an estimated range of 49 miles [1].

The project started with a Jeep Cherokee (donated by Jon Eidson, of the TCU IT Department) that had already been converted to an electric vehicle and the Porsche 914. The Jeep was scavenged for parts and understanding while the Porsche was stripped to bare metal. The first few years were concerned with repairing the body of the Porsche; including patching rusted areas and giving the whole body a new primer coat to protect from future rust. Much of the body work was done in-house at the TCU Physical Plant by James Griffin and in the TCU Engineering Machine Shop by David Yale and Mike Murdock. Several students were involved as well. Once the Porsche was rust-free, the DC series motor from the Jeep was installed where the 4-cylinder engine used to sit, just behind the passenger compartment.

Once the motor was installed, Yale machined an adaptor plate to couple the electric motor directly to the original 5-speed manual transmission in the Porsche. Metal housings for the batteries were also fabricated in the TCU Engineering Machine Shop. The DC series motor from the Jeep needed a high DC voltage to operate effectively. A set of twelve Optima Blue-Top Marine Deep Cycle batteries were purchased to supply the necessary voltage in series and to allow for a decent expected range. These Optima lead-acid batteries were selected over the more energy dense lithium batteries for cost, ease-of-maintenance, and overall safety. The twelve batteries were split between the forward (under the hood) and rear compartment (in the trunk) of the Porsche to distribute the approximately 520 pounds of batteries evenly in the vehicle. With the motor and battery pack chosen, a motor controller was needed to control the speed of the motor. Without a controller, the motor would spin at a single speed, making it unusable for vehicle operation. A Zilla Controller Package, manufactured by Café Electric [2], was chosen to interface between the “gas” pedal and the electric motor. The package includes a Zilla motor controller which controls the flow of current into the DC series motor and a Hairball motor control interface which acts as the “brains” of the motor control, translating pedal movements to changes in motor current. To charge the motive battery pack between uses, an “octopus” style battery charger was mounted in the vehicle. This charger connects to a standard 120 VAC wall outlet and charges each of the twelve motive batteries individually rather than charging the pack as a whole.

With the motive circuit essentially complete, the accessory circuitry was connected as originally designed from the factory with the exception of the HVAC system and radio. Air conditioning would use too much energy, thereby reducing the range, and a ceramic heater would have to be installed to heat the vehicle. All of the accessories, including the vehicle lighting and windshield wipers, are powered by a 12 V standard automotive battery located in the forward compartment of the vehicle. In a conventional vehicle, the accessory battery is charged during operation by an alternator that is connected to the internal combustion engine. Since the Porsche does not have an internal combustion engine anymore, the accessory battery is charged from the motive battery pack using a DC-DC converter. This reduces the overall range of the vehicle by diverting energy normally earmarked for propulsion to the operation of vehicle accessories. A second 12 V battery was positioned in the rear of the vehicle, next to the Hairball motor controller interface, to provide power to the motor controller.

Before this project, the only method of monitoring the state-of-charge (SoC) of the motive batteries was using an off-the-shelf battery monitoring system: the Link-10 E-Meter manufactured by Xantrex (newer model shown in [3].) This E-Meter monitored both the voltage of the entire battery pack and the current flowing through the motor at any given time. To determine how much energy is left in the batteries, the E-Meter essentially “counts” all of the charge that has left the battery by integrating the motor current over time. The “used” charge is then subtracted from the nominal total charge present in the battery pack based on battery specifications. The ratio of “used” charge to nominal total charge is presented to the operator in the form of a percentage of charge remaining, analogous to the fuel remaining in a gas tank. While this might seem like a good solution to the problem of determining remaining range by monitoring the SoC of the motive batteries, there are several drawbacks to this approach. Firstly, battery capacity (how much energy it can store) degrades over time and charge/discharge cycles. Therefore calculating the energy remaining can be difficult since only the nominal total capacity is used and not the actual total capacity. Secondly, the Link-10 only monitors total pack voltage and not the voltages of each individual battery. Monitoring individual battery voltages simplifies battery maintenance as batteries with low resting voltages when charged are nearing end-of-life. Being able to easily monitor the health of each battery *in situ* is important for proper maintenance. If lithium-ion batteries were used instead of lead-acid batteries, monitoring individual battery voltages is even more important since lithium-ion batteries must remain balanced (i.e. all with the same level of charge) across a battery pack or the risk of fire increases dramatically. Finally, the Link 10 does not possess a comprehensive method of saving data on battery usage for future analysis. The experimental nature of the TCU EV project would benefit from a method of saving data on battery usage and other metrics to increase understanding of electric vehicle operation over time, rather than only real-time feedback on usage as is currently the case.

As with many engineering problems, there are multiple ways to determine the state-of-charge of batteries. In this case, a system was designed to take periodic voltage measurements from each of the twelve batteries in the main power pack on the TCU Engineering Department Electric Vehicle (EV). These voltage measurements are then saved on an SD card via an Arduino Uno [4]. Users can then import the voltage measurements to a PC for further processing in MATLAB or another similar computing environment. In this way, data can be saved and the performance of the batteries (and by extension the EV) can be monitored over time. The system is designed for easy adaptation to future needs of the TCU Engineering Department EV, including the possibility of real-time information presented to the driver while operating the vehicle and other measurements of vehicle and battery performance.

CIRCUIT DESIGN

With the overall system in mind, a single circuit needed to be designed to measure the voltage of a single battery in the motive power pack. This circuit could then be replicated and integrated into the system to measure the voltages of all batteries in question.

Basic Design

When beginning the design of the voltage measurement circuit, several considerations were taken into account. First, the main power pack operates at a high DC voltage level (nominally 144VDC) which can be extremely dangerous to those in and around the vehicle if not handled properly. To reduce the electrical hazard, a decision was made to keep all high voltage wiring out of the passenger compartment. Second, an effort was made to reduce power consumption in the battery monitoring system so as not to reduce the effective range of the EV. With an internal combustion engine, there would be less of a need to reduce power because the alternator can keep the battery charged as long as the engine is running and the vehicle can be refueled quickly. However, on the EV, every joule used to power the battery monitoring system is a joule that cannot be used to propel the car. Since electric vehicles already have a shorter range than their gas-powered counterparts and take much longer to "refuel" (on the order of a few hours compared to a few minutes) reducing power consumption is an obvious goal.

The monitoring system will be made up of several different components installed in different locations throughout the vehicle. The Arduino Uno will act as the "brain" of the monitoring system, recording data and allowing for future expansions of the scope of the monitoring. Even though the Arduino Uno is capable of taking direct voltage measurements, it can only do so in the ±5 V range. The high DC voltage of the main power pack (144VDC) leads to the necessity of an intermediate circuit with an output voltage proportional, but much lower than the voltage across the main power pack. Several different methods are available to isolate high-voltage circuitry while

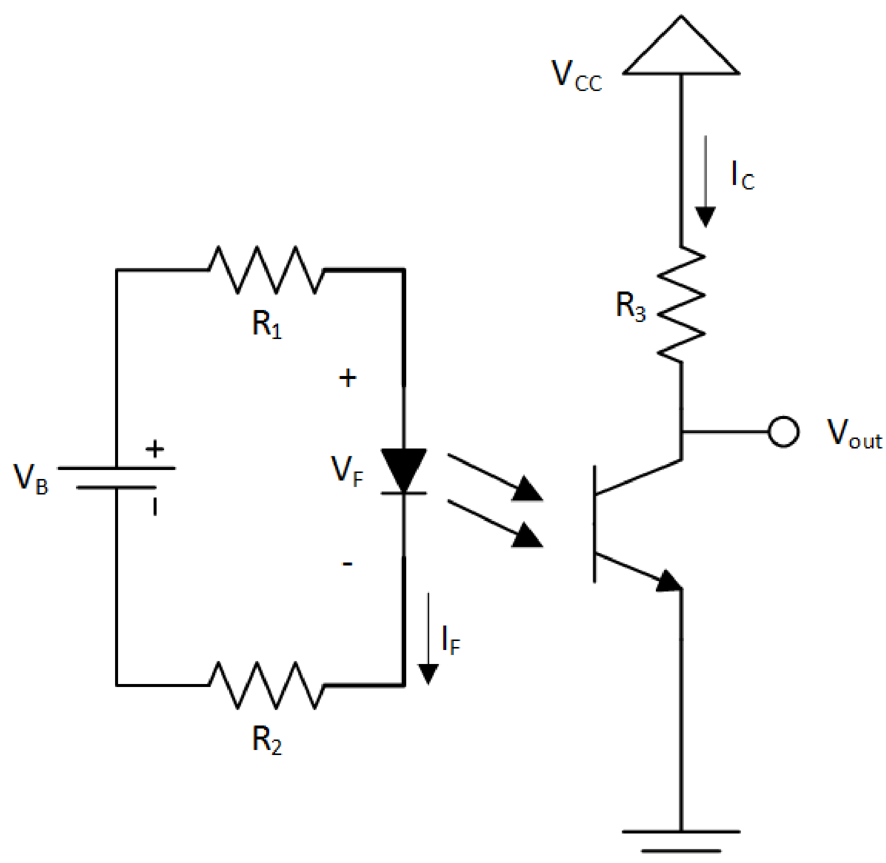

Figure 1 – Battery Monitoring Circuit

simultaneously measuring the circuit itself. In this case, an optically-isolating circuit was designed to both isolate the rest of the battery monitoring system from the high DC voltages of the main power pack and provide an output voltage proportional to the voltage across one of the batteries in the main power pack, as in [5].

The voltage measurement circuit designed for a single battery is outlined in Figure 1. A phototransistor-output optoisolator was chosen for circuit simplicity. An optoisolator is a discrete component that contains a light-emitting diode (LED) and a photosensitive element—in this case a phototransistor—packged monolithically. In this way, the LED and phototransistor can be precisely positioned to control how much light emitted from the LED falls on the photosensitive portion of the phototransistor. In addition to geometric factors, the medium in which the light passes from LED to phototransistor is part of the assembly and therefore its transmission parameters are known to be relatively constant. The amount of light emitted from a LED is proportional to the current through the LED once the diode itself is forward-biased. Similarly, the current passing from collector to emitter in the phototransistor is directly proportional to the light falling on the photosensitive "base" of the phototransistor when it is in the active region. Therefore, the current passing through R_3 is proportional to the current passing through the LED. The addition of several resistors allows the circuit to be tailored to this application, using a simple common-emitter amplifier to provide an output voltage proportional to the voltage across the battery of interest.

Choosing Parameters

After the basic design of the circuit was decided, the operating conditions and consequent device parameters needed to be determined. The Vishay VO618A series of optoisolators was chosen because of its phototransistor output and lack of complicating features. Specifically, the VO618A-3 was selected because of a guaranteed current

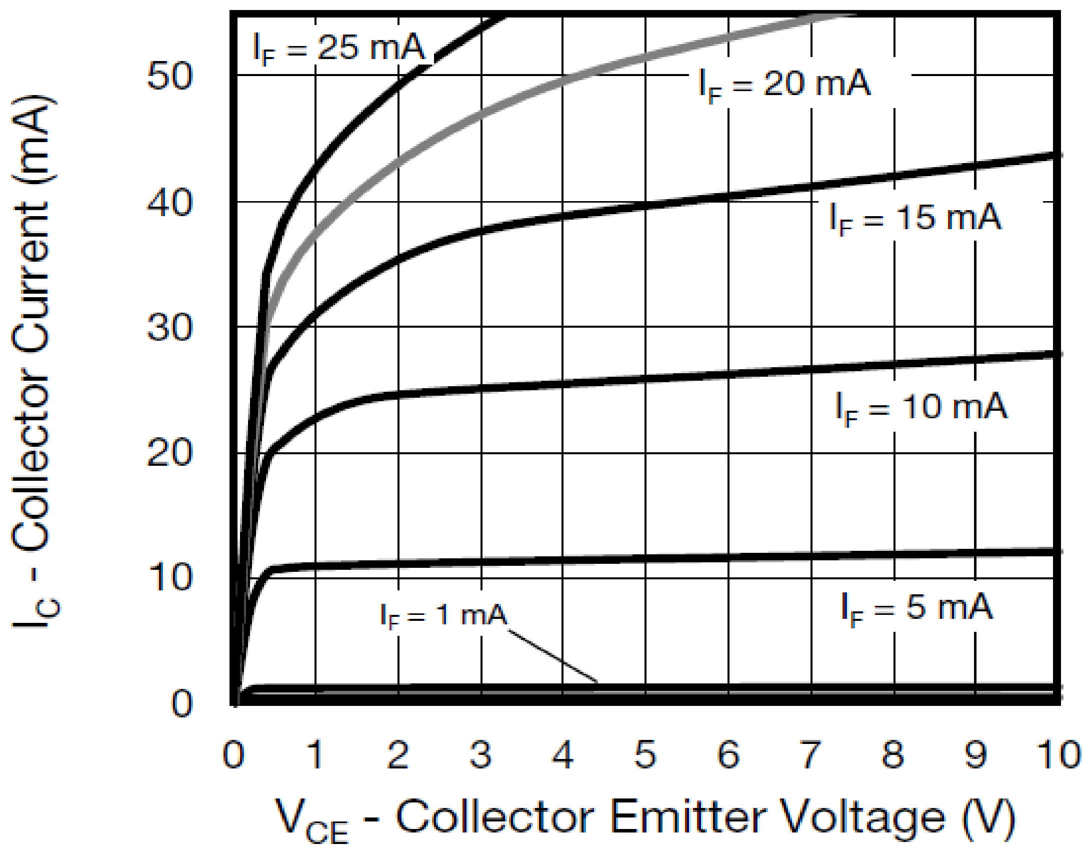

Figure 2 – VO618A Optocoupler Collector Current vs. Collector Emitter Voltage

transfer ratio (CTR or the ratio of the collector current to the diode forward current) of 100-200%, its low cost, and ability to operate well with forward diode currents on the order of a few milliamps. As with any transistor amplifier design, a DC operating point must be established. Figure 2 shows the phototransistor collector current (I_C) vs. the collector emitter voltage (V_{CE}) for several different forward diode currents (I_F). Initial designs looked at setting I_F to be 1 mA, but this was changed to 5 mA in the final design to allow for more stable operation and a larger collector current swing while remaining in the active region of the phototransistor.

Relationship between Battery and Output Voltages

With a circuit schematic and a DC operating point selected, the relationship between the battery voltage and corresponding output voltage can be determined. Using Kirchoff's Voltage Law (KVL), the voltage around any closed path must be zero, for the right side of Figure 1

$$-V_{CC} + V_{R3} + V_{CE} = 0.$$

If we substitute V_{out} for V_{CE} and solve for V_{out}, we find that

$$V_{out} = V_{CC} - V_{R3}.$$

But, by Ohm's Law, the voltage across *R3* is

$$V_{R3} = i_C R_C.$$

Therefore, the output voltage is related to the collector current by

$$V_{out} = V_{CC} - i_C R_C. \tag{1}$$

The collector current, i_C, is proportional to the forward current of the LED by

$$i_C = (\text{CTR}) \times i_F, \tag{2}$$

where *CTR* is the current transfer ratio of the given optoisolator. Finally, i_F can be related to the voltage across the battery in question with another application of KVL:

$$-V_B + i_F R_1 + V_F + i_F R_2 = 0, \tag{3}$$

where V_B and V_F are the battery voltage and the forward bias voltage of the LED, respectively. If we solve for the forward diode current,

$$i_F = (V_B - V_F)/(R_1 + R_2)\,,$$

then substitute back into Equation (2), we have

$$i_C = (\text{CTR}) \times (V_B - V_F)/(R_1 + R_2). \tag{4}$$

Finally, we can substitute Equation (4) back into Equation (1) to solve for the output voltage in terms of the battery voltage and known "constants." The output voltage, V_{out} is given by

$$V_{out} = V_{CC} - (\text{CTR}) \times R_3\,(V_B - V_F)/(R_1 + R_2). \tag{5}$$

Equation (5) shows that the output voltage, V_{out} is inversely proportional to the battery voltage, V_B, which is to be expected for a single-stage common-emitter amplifier. Once the relationship between output voltage and battery voltage is established, the resistors can be chosen to set the diode forward current and maximize signal swing at the output.

The rail voltage, V_{CC}, was chosen to be 5 VDC because the Arduino Uno operates on a 5V supply and the digital input/output ports of the Arduino Uno are also 5V. Based on the datasheet for the VO618A-3, the CTR will be between 100 and 200% and the typical forward bias voltage for the LED is 1.1 V. Choosing the diode forward current to be 5 mA and setting $R_1 = R_2 = R_D$ we can solve Equation (3) for the resistors necessary to set the forward diode current at 5 mA for a nominal 12 V battery voltage:

$$R_D = \frac{V_B - V_F}{2 \times i_F} = \frac{12\text{ V} - 1.1\text{ V}}{2 \times 5\text{ mA}} = 1.09\text{ k}\Omega.$$

To fall into one of the bins on the standard 5% resistor table, 1.1 kΩ was chosen as the value of R_D. Now that the diode side of the circuit has been established, the operating conditions and collector resistance of the phototransistor side of the circuit need to be defined. In an attempt to maintain output linearity and ensure that the phototransistor always operates in the active region, a decision was made to limit the output voltage between 1 and 4 volts for any expected battery voltage (thus limiting V_{CE} to the same 1-4

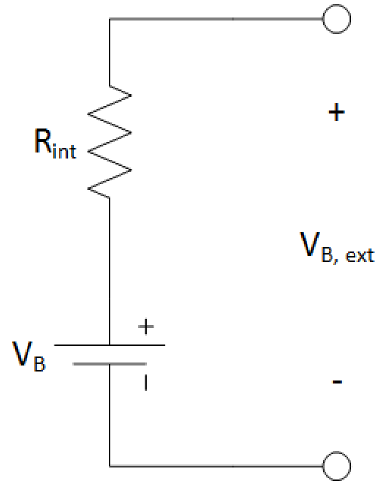

Figure 3 -- Battery model including internal resistance

volt range). The TCU Engineering Department EV uses 55 Amp-hour Optima Blue-Top Deep Cycle Sealed AGM batteries (model D34M) for the main power pack. Optima lists the open-circuit battery voltage for each D34M to be 13.1 VDC when fully charged and 10.5 VDC when fully discharged. It is important to note that these voltages are the open-circuit resting voltages. During operation or charging, the battery voltages could exit these bounds. Because batteries store chemical energy, there must be a conversion to electrical energy before the battery can supply current. This conversion from chemical to electrical energy is not perfectly efficient and the conversion losses are typically modeled as an internal resistance of the battery, as shown in Figure 3. For a given current, the actual output voltage can be modeled by

$$V_{B,ext} = V_B - i_B R_{int}$$

where $V_{B,\,ext}$ is the output voltage at the battery terminals, i_B is the current through the output terminals, V_B is the open-circuit battery voltage, and R_{int} is the internal series resistance of the battery. Optima lists an internal series resistance of 2.8 mΩ for the D34M Blue-Top. Assuming the maximum theoretical current draw (500 A in the TCU

EV) and minimum open-circuit battery voltage (10.5 V), the minimum voltage across the battery terminals can be found by

$$V_{B,ext} = 10.5\text{ V} - (500\text{ A}) \times (2.8\text{ m}\Omega) = 9.1\text{ V}.$$

Similarly, the maximum terminal voltage when fully charged should not exceed 13.1 V per the Optima datasheet. To add margin to both sides of this range, the battery voltage was assumed to always satisfy $8\text{ V} \leq V_{B,ext} \leq 14\text{ V}$ for this design. This voltage range can be used (along with the CTR range of 100-200%, the typical LED forward voltage, and the resistances chosen for R1 and R2, and the specified output voltage range $1\text{ V} \leq V_{out} \leq 4\text{ V}$) in Equation (5) to determine an appropriate value for the collector resistance. However, the load line method of determining collector resistance was used instead, with verification that chosen resistance met prescribed voltage ranges using Equation (5).

Load Line Determination of Collector Resistance

The load line method of determining collector resistance involves using the graph of collector current (I_C) vs collector-emitter voltage (V_{CE}). Because transistors are non-linear over their entire range of operation, the load line method is more intuitive and typically easier than solving a system of equations that may not be accurate at all of the solutions. To use the load line method, two points must be established: the collector-emitter voltage when the collector current is zero and the minimum possible collector-emitter voltage while the transistor is both in the active region of operation and subjected to the highest possible collector current. In the simple common-emitter amplifier of Figure 1, the relationship between the collector current and collector-emitter voltage is given by Equation (1), where $V_{out} = V_{CE}$. When the collector current is zero, the collector-emitter voltage goes to the rail, i.e. $V_{CE} = V_{CC} = 5V$. Using Equation (4) and known values of R_1, R_2, V_F, CTR_{max}, and $V_{B,\,max}$ we can solve for the maximum possible collector current at the saturation voltage (the collector-emitter voltage below which the transistor exits the active region):

$$i_C = (\text{CTR}) \times (V_B - V_F)/(R_1 + R_2),$$

where $R_1 = R_2 = 1.1\ \text{k}\Omega$, $CTR_{max} = 2$, $V_{B,\,max} = 14$ V and $V_F = 1.1$ V per the VO618A-3 datasheet and previous calculations. Therefore,

$$i_{C,max} = (2) \times (14\ \text{V} - 1.1\ \text{V})/(2.2\ \text{k}\Omega) = 11.7\ \text{mA},$$

which corresponds to a V_{CE} of approximately 0.4 V. Now that two points along a line have been established, we can determine the unique equation that represents the line itself. The slope of the line can be found algebraically with two points as follows:

$$m = (y_2 - y_1)/(x_2 - x_1)$$

where (0.4 V, 11.7 mA) and (5 V, 0 mA) are (x_1, y_1) and (x_2, y_2) respectively. In this case, the slope of the line is

$$m = (0 - 11.7)/(5 - 0.4) = -2.54\ \text{mA/V}$$

or $-1/393\ \ \Omega$. This corresponds to $-1/R_C$. Normally, this would indicate a R_C value of 390 Ω per the standard 5% resistor tables, but a resistance of 330 Ω was chosen to increase the slope of the line and thus reach the maximum collector current before the transistor enters saturation. We could continue to solve the unique equation representing the load line, but the y-intercept does not relate to a physical occurrence in the transistor and is unnecessary for this application. The graphical representation of the load line method is shown in Figure 4.

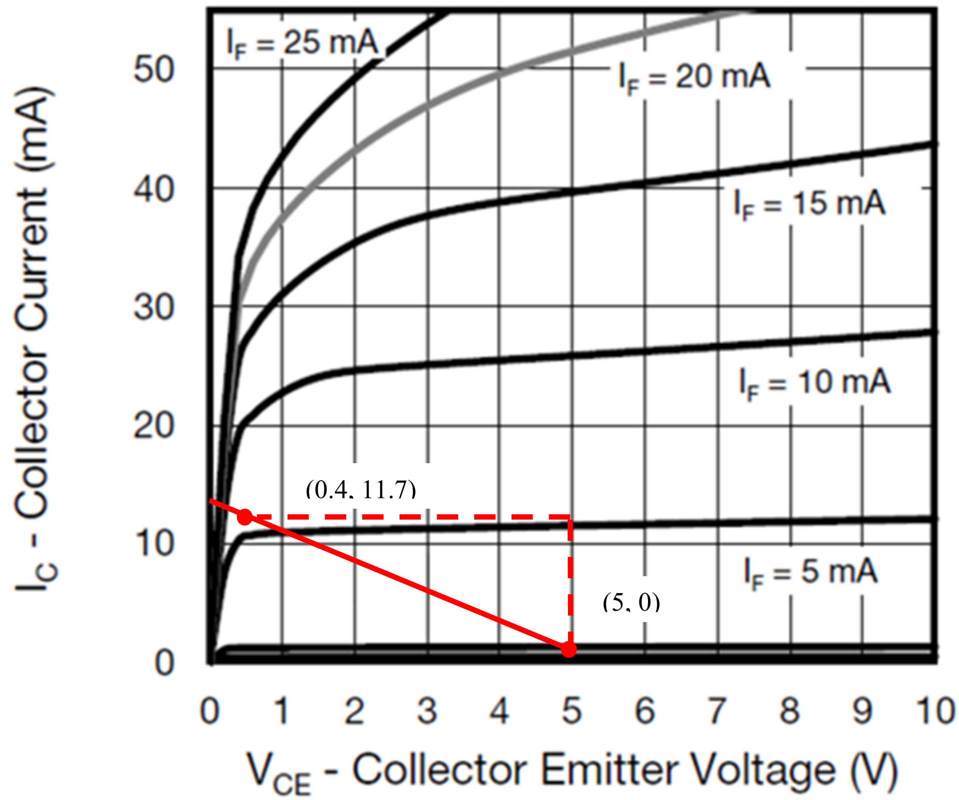

Figure 4 – Load Line Method for Determining Collector Resistance

Twelve of these circuits will be used to measure the voltage of each of the twelve batteries in the main power pack and the same circuit will also be used to monitor the voltages of the main accessory battery and the controller battery. There will be variances in the parameters for each component that will result in unique proportionalities between the input and output voltage of each circuit, but the general operation will be similar between all such circuits. The code for data acquisition and processing will account for the differences between circuits.

SYSTEM DESIGN

The circuit designed above can only measure the voltage across a single battery and even then requires more equipment before the voltage output can be understood by the vehicle operator. In addition, the voltage monitoring circuit has no provisions for storing previous battery voltages; it only outputs a voltage proportional to the current battery voltage. To complete the design of the battery monitoring system for the TCU EV, a stand-alone system is needed, including provisions for data processing and storage.

System Overview

As stated previously, this project uses an Arduino Uno (board pictured in Figure 5) as the “brain” of the system. The Arduino Uno itself is capable of digitizing analog

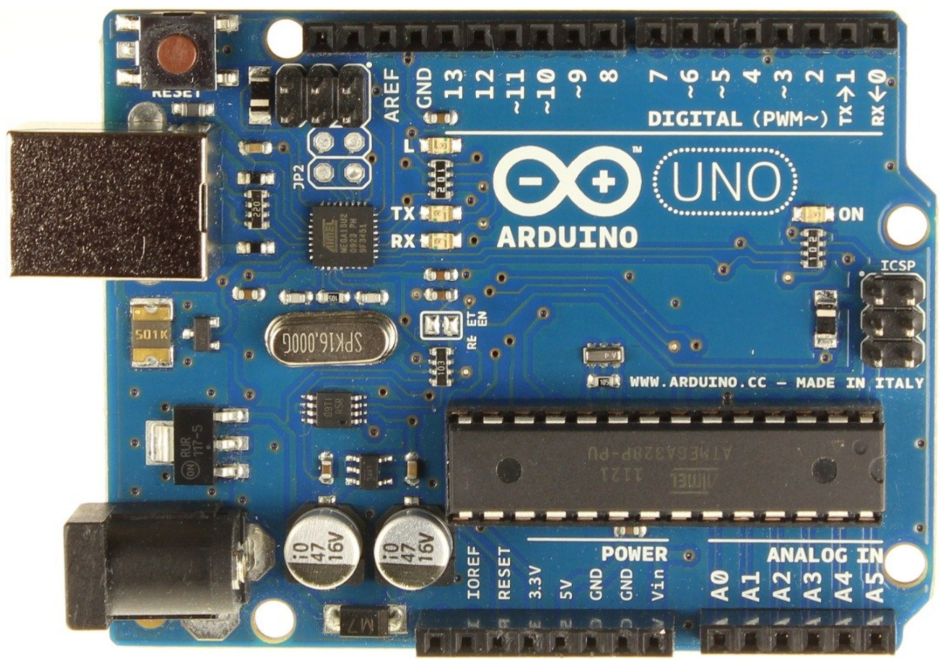

Figure 5 -- Arduino Uno Rev. 3 Microcontroller Board

signals (like those from the battery monitoring circuit) over the range of +/- 5 V. However, the Uno only has six analog inputs and the EV needs fourteen inputs for the batteries alone. Another intermediary circuit is needed to offload the digitizing process and instead make use of the numerous digital inputs and serial data capability of the Uno. A multi-channel analog-to-digital converter (ADC) will be used in conjunction with an external voltage reference and discrete power supply. These components will be co-located on a printed circuit board (PCB) in both the front and rear compartments of the

EV, with a wired connection running from each to the Uno located in the passenger compartment of the vehicle.

Selecting a Microcontroller

Today, there are many different low-power, high-performance microcontrollers in the market. A push towards embedded processing and an effort to build low-cost systems that children and hobbyists could begin tinkering with spurred the creation of several different systems, including the Arduino lineup and the Raspberry Pi. While not nearly as powerful as a typical desktop computer or even a smartphone, these miniature computers can perform simple tasks including data acquisition, data processing, and even system control tasks. The Arduino lineup itself has a wide range of devices, each with differing performance characteristics and capabilities. For this project, a low-power, low-cost microcontroller was needed to capture, collate, and process data coming already digitized from the battery monitoring circuits and save to some medium for later analysis. The microcontroller also needed room to grow the system in future to include more monitoring capabilities.

An Arduino Uno Revision 3 was chosen for this project. The Uno operates from a 5 V supply, as does the battery monitoring circuit, and has numerous analog and digital inputs for future expansion. In addition, the Uno is capable of using the Serial Peripheral Interface (SPI) to communicate with other digital devices and can accommodate data storage on SD cards with an additional off-the-shelf component. Furthermore, programming the Uno is made simple with the use of Arduino's integrated development environment, while the programming of other microcontrollers can sometimes even require writing code to on-chip memory using an ultraviolet light source. Should the scope of this monitoring system greatly increase in future years, the Uno can even be replaced by more powerful brethren within the Arduino family without the need to completely re-write any of the already written code. For these cost, performance, and ease-of-integration factors, the Uno is an obvious choice for this project.

Building the Circuit to Microcontroller Interface

With 14 batteries to monitor and only 6 analog inputs on the microcontroller, some form of multiplexer is needed to enable the Uno to capture data from every battery. Instead of using a simple multiplexer and the Uno analog inputs, an 8-channel ADC from Linear Technology was selected to capture, collate, and digitize individual battery voltages before passing them on to the Uno via a digital interface. The LTC1863 has 8 channels, samples at to 200,000 times a second with a 12-bit resolution, and operates from a single 5 V supply like the battery monitoring circuit. Perhaps more importantly, the LTC1863 is capable of communicating with any device capable of SPI communication, such as the Uno. The SPI communication occurs over a three-wire bus with a fourth wire controlling the start and stop of the conversion process. The three-wire bus establishes a communication clock and allows for signals to be passed from the Uno to the ADC and back. The clock is provided by the Uno on the serial clock line, or SCK. The serial data input, SDI, line transmits a channel selection and format from the Uno to the ADC. The final line in the bus is used for serial data output (SDO), passing the voltage measured from each circuit back to the Uno in a digital format. The fourth wire in the communication process is used to control which device on the SPI bus is communicating with the Arduino via a method known as “chip select.” In total, there will be three devices on the SPI bus not including the Arduino: an ADC for the front batteries, another ADC for the rear batteries and a SD card reader to store the data. Each of these devices has a separate wire connecting the device to a digital port on the Uno. This fourth wire is used for chip select and allows the Arduino to tell one of the two ADCs or the SD card that the instructions being passed on the SDI line are for it and the response should be passed over the SDO line. Aside from the ADC, two other integrated circuits (ICs) will be used in the interface between battery monitor circuits and the Uno. The first is a LT3082 200 mA low-dropout regulator from Linear Technology that will provide power to the ADC and act as the V_{CC} rail for the battery monitoring circuits. The LT3082 will convert the fluctuating accessory battery voltage (nominally 12 V) to a more stable 5 V necessary for the proper operation of each individual battery monitoring circuit. The second IC is a LT1461 precision voltage reference for the ADC. While the LTC1863 has an internal reference, the external reference can easily be integrated into the circuit and provides more accuracy and lower drift for the conversions. These three ICs require several different resistors and capacitors for proper operation, most notably the LT3082 which requires a precision set resistor to set the output voltage for V_{CC} to 5 V. A 500 kΩ set resistor will be used per the LT3082 datasheet to properly set the output voltage. Several bypass capacitors are also needed for proper operation and are included per the datasheet recommendations for each device.

PCB Design

With growing circuit complexity and an eventual permanent installation, the decision was made to mount on a printed circuit board (PCB) all of the circuitry needed for monitoring battery voltages and converting the analog signals to digital values that can be sent over an SPI bus to the Arduino. Since the batteries in the EV are split between the forward and rear compartments of the vehicle, the PCB will include 8 battery monitoring circuits (6 for motive batteries, 1 for accessory, and 1 spare), a LT3082 power supply, a LT1461 voltage reference, and a LTC1863 ADC. Each battery will be wired directly to the PCB, with power being supplied from the accessory batteries, and additional wiring connecting the PCB and the Arduino. The PCB will be enclosed in a plastic enclosure to protect the board from the environment and prevent objects from shorting leads on the circuit board. The PCB itself will be a two-layer design, with all of the components and signal routing on the top surface. The bottom is reserved for a ground plane and some power routing. Instead of including discrete headers on the board itself, copper pads are laid around the board with the intention of directly soldering wires to the pads. Because of some routing complexities and surface mount components, the PCB will be manufactured by Sunstone Circuits (www.sunstone.com) before being assembled by Screaming Circuits (www.screamingcircuits.com). The PCB design was done using PCB123, Sunstone's free proprietary PCB layout software.

DESIGN TESTING

Before the PCB could be fabricated, the calculations performed in the Circuit Design section were experimentally checked. A prototype of the battery monitoring circuit was built for this purpose.

Checking the Circuit Design

The circuit was prototyped and verified exclusive of a lead-acid battery and any of the Arduino interface circuitry. Instead of using the LT3082 to provide the rail, an HP 3612A DC power supply was used. A Fluke-Phillips PM5138A function generator was used to sweep the "battery" voltage between 5 and 15 volts. The output voltage and “battery” voltage was measured using an Agilent oscilloscope and is plotted in Figure 6. The data was linearly fit in in Microsoft Excel with a resulting slope of -0.3126 V/V, corresponding to the ratio between the output voltage and battery voltage, V_{out}/V_B . If we separate the “constant” and variable terms in Equation (5), we find

$$V_{out} = V_{CC} + [V_F\,(\text{CTR})(R_3)]/(R_1 + R_2) - V_B\,[(\text{CTR})(R_3)]/(R_1 + R_2). \qquad (6)$$

Taking nominal values of $V_{CC} = 5$ [V], $V_F = 1.1$ [V], CTR $= 2$, $R_1 = R_2 = 1.1$ kΩ and $R_3 = 330\ \Omega$, we can solve Equation (6) for the expected slope and y-intercept:

$$\text{y}_{\text{int}} = V_{CC} + [V_F\,(\text{CTR})(R_3)]/(R_1 + R_2) = 5 + [1.1(2)(330)]/(2 * 1100) = 5.33\text{ V},$$

$$\text{slope} = -[(\text{CTR})(R_3)]/(R_1 + R_2) = -[(2)(330)]/(2 * 1100) = -0.3\ [\text{V/V}].$$

Comparing these values to those shown in Figure 6, we see that magnitude of both the

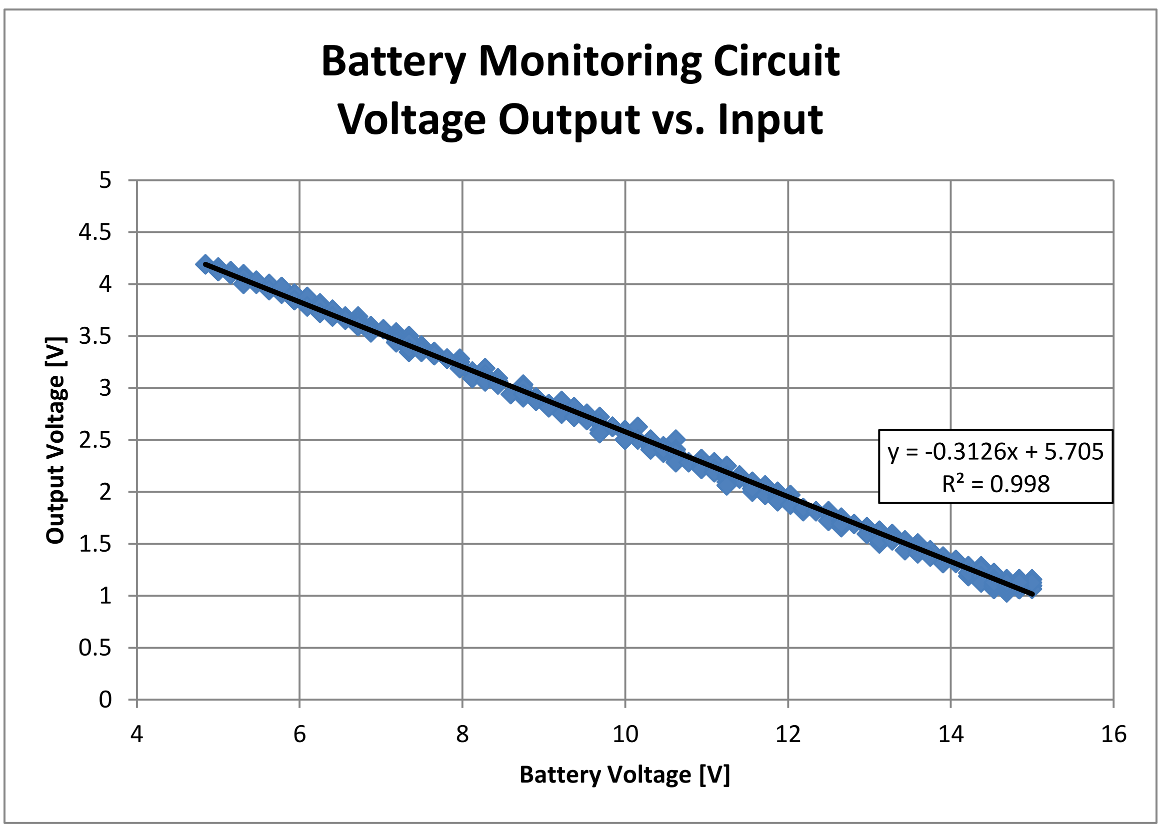

Figure 6 -- Prototype Battery Monitoring Circuit Input/Output Relationship

slope and intercept match are similar to the expected values. In fact, the percent error of the actual slope from the expected slope is:

$$\% \text{ error} = [\text{actual} - \text{calc.}]/\text{calc.} * 100 = [-0.313 - (-0.3)]/-0.3 * 100 = \ 4.33\ \%$$

which can be corrected during data processing. Each battery monitoring channel on the final design will have a different calibration constant relating the output voltage to the battery voltage being measured. These calibration constants will be determined using the same procedure used on the prototype circuit and integrated into the Arduino code so that the data saved is converted back to equivalent battery voltage. The prototyping process outlined above validates the calculations made when designing the battery monitoring circuit.

Verifying System Design

To validate the design of the whole system, a prototype of the circuitry located on one of the printed circuit boards needs to be created and multiple battery voltages swept across their operating range. Because of equipment and IC packaging limitations, the circuit including the ADC and SPI connection with an Arduino Uno could not be verified before manufacture. To verify proper operation across all 8 channels would require a prototype system to be connected to the EV itself or have the impractical requirement of needing 8 separate voltage sources, one for each monitoring channel. System verification will be left until the completed PCBs are received.

Possible Design Revision

As a means to simplify the PCB design, a different Arduino could be used to handle both the ADC and data storage tasks. A limited supply of analog inputs on the Arduino Uno (pictured in Figure 5) necessitated the external ADC and precision voltage reference on the battery monitoring PCB. The Uno has only 6 analog inputs while the battery monitoring system would require 14, one for each battery. However, the Arduino Mega 2560 (pictured in Figure 7 supports 16 separate analog inputs, more than enough for this design with 2 spare for future improvements [6]. Upgrading the microcontroller to the Arduino Mega 2560 would simplify the PCB design and fabrication, as well as coding the serial communication between devices, at the expense of wiring complexity. Moving to the Mega 2560 would enable the PCB to be fabricated in-house as the remaining components (VO618A, LT3082, various discrete resistors and capacitors) have relaxed routing and placement requirements compared to the LTC1863, which has a pin spacing of under 25 mils. Being able to fabricate the boards at TCU would allow for faster testing of design iterations in future projects relating to the TCU EV. Aside from the difference in PCB design, the Mega 2560 would be a drop-in replacement for the Uno, using similar code and the same power supply.

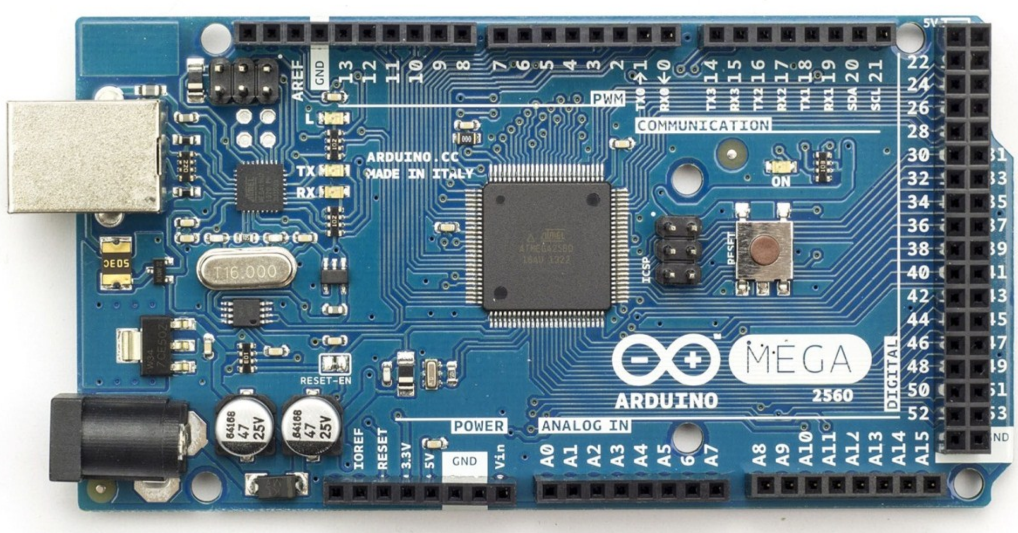

Figure 7 -- Arduino Mega 2560 Microcontroller Board

CONCLUSION

With the system outlined above, the TCU Engineering Department will be able to accurately measure and record the voltage on each individual battery used in the EV. This data will allow future students to study the usage patterns of the batteries in the EV and improve maintenance efforts by improving the detection of underperforming batteries in the motive power pack. In addition, the system can be adapted and expanded for future work in the Engineering Department related to the EV, specifically monitoring other performance metrics, both electrical (motor current, charging efficiency) and otherwise (vehicle acceleration, battery temperature, inertial measurements) with minimal interfacing requirements. In effect, additional features could be added in parallel with the voltage measuring system already in place, using the SPI bus to communicate with other sensors and circuits around the vehicle. Using the Arduino family allows for easy upgrades to more powerful microcontrollers without relegating previous work to a state of obsolescence. Improvements could even include real-time display of information to the vehicle operator. The battery monitoring system outlined herein improves the TCU Engineering EV by collecting battery usage data and improving maintenance procedures.

REFERENCES

[1] BBC News Business. (2014, January 28). BBC News [Online]. Available: http://www.bbc.com/news/business-25934289

[2] Zilla Controller Package. (2014, April). Café Electric [Online]. Available: http://cafeelectric.com/zilla.php

[3] LinkLITE Battery Monitor. (2014, April). Xantrex, Inc. [Online]. Available: http://www.xantrex.com/power-products/power-accessories/linklite-battery-monitor.aspx

[4] Arduino Uno. (2014, March). Arduino [Online]. Available: http://arduino.cc/en/Main/arduinoBoardUno

[5] Stallings, Gordon. (2001, January). Gordon Stallings' Home Page [Online]. Available: http://genki.home.ionet.net/BattMon/BattMonArticle.html

[6] Arduino Mega 2560. (2014, April). Arduino [Online]. Available: http://arduino.cc/en/Main/ArduinoBoardMega2560