Modules for Controlled Power Distribution in an Electric Vehicle

ECE 445 Design Document

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1 Introduction

1.1 Objective

The objective of this project is to improve efficiency by increasing the down-time of PCBs powered by a low voltage bus thus decreasing power consumption of the Illini Solar Car (ISC) team's solar electric vehicles. It will allow the power distribution system (PDS) to individually monitor and control connections to the +12V bus of the solar cars. The existing +12V bus, from which most of the vehicle's PCBs are powered, is just 12 connectors in parallel, with no protection circuitry, power monitoring, or switching. The implementation of our project will allow for specific control of the boards that are powered, which can improve our efficiency by 1.81%.

1.2 Background

Solar electric vehicles are a growing sector in the vehicle market around the world. Companies around the world, like Sono Motors from Germany (Lambert and Lambert, 2019), are trying to break into the market with a sleek, fuel-efficient, and reliable alternative to the gas-based vehicle on the road. Powering cars from solar energy or supplementing their power from solar energy decreases emissions. The project that we implement could have the potential to be applied to another product on the market.

For our purposes, we are focused on the solar car competition. The competition circuit is made up of mostly college teams who enter events around the world every one or two years. Our solar car must be able to drive for thousands of miles during week-long endurance races across United States (American Solar Challenge, ASC) and Australian highways (World Solar Challenge, WSC) in order to compete. The design and implementation of the power distribution system (PDS) that we intend to complete would increase efficiency for the car. Implementing independent switching for the +12V bus will give us more freedom to control what parts of the car receive power and we also plan to monitor the current consumption for all the connections. By updating the PDS firmware and hardware, we will get better monitoring for the system, be able to identify power hungry low voltage systems, and optimize the low voltage power consumption based on the situation.

1.3 High level requirements:

- Each of the +12V bus connections must be able to switch on and off independently of each other, and "on" must be the default or failure state.

- +12V bus must have current sensing on each of the switched outputs and one voltage sense on the main connection in order to understand how much power each connection is drawing.
- +12V bus should communicate over CAN in order to know which connections should be "on" or "off" and to report the current and voltage measurements.

2 Design

The PDS in the scope of our project contains extensive upgrades to our current +12V bus. The bus will have a microcontroller unit (MCU) that will be used to control all the other parts. Our main objective to improve efficiency of our car by being able to turn each connection “on” or “off” on the +12V bus independently. We aim to do this by applying a MOSFET to each connection and having the MCU communicate with each one separately. The MCU will receive signals from the rest of the car and the driver via CAN, and then it will interpret them to switch the MOSFETs accordingly. Aside from controlling the FETs, we will also have current and voltage sensing on the board. There will be a current sense on each of the FETs in order to track which low-voltage part of the car is consuming the most power. By monitoring and gathering this data we can then move to make those specific areas of the car more efficient. We will have voltage sensing on the input to the +12V bus in order to monitor what voltage the bus is normally operating at, and then act accordingly. The main purpose of our +12V board is to control what parts of the car receive power in order to ration energy during tests and competitions, and to reveal what low voltage systems consume significant power.

2.1 Block Diagram:

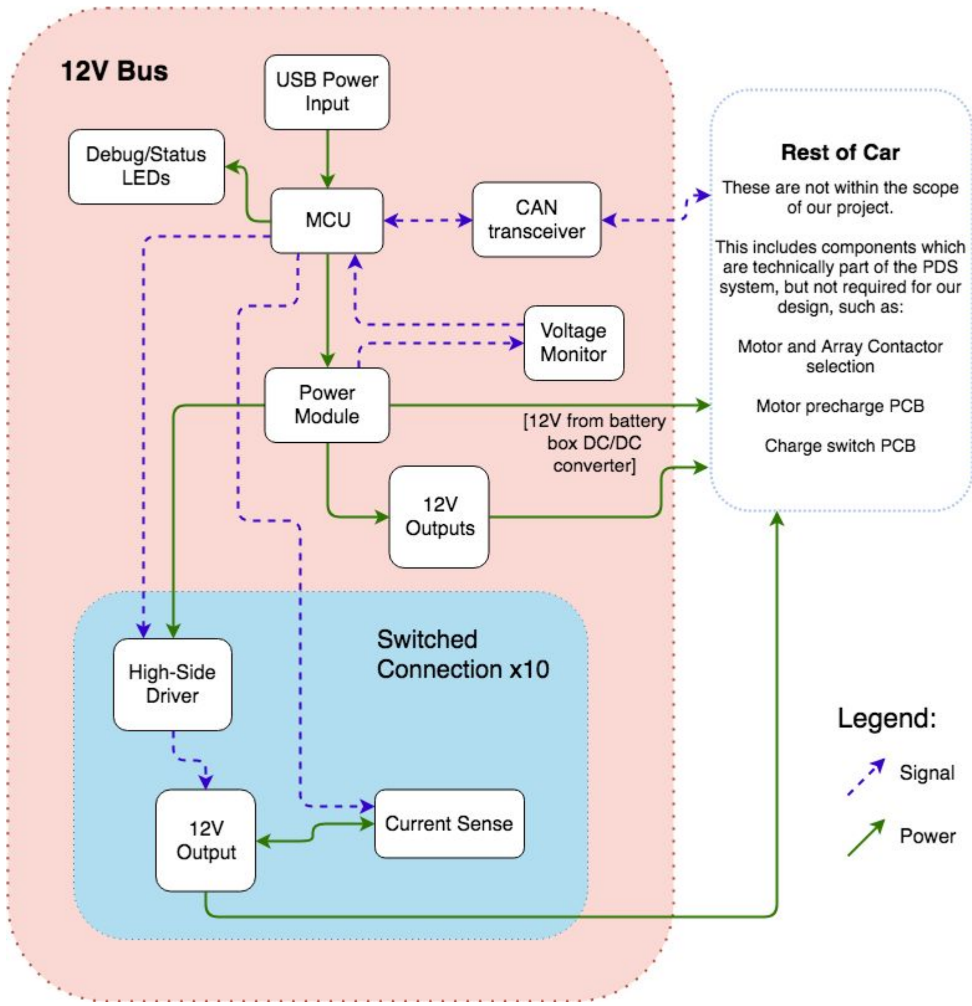

Fig 1. Block Diagram

2.2 Low-Voltage Bus Board

2.2.1 Input Protection & Conversion

The low voltage bus 12V input is from the DC/DC converter inside the battery box, which is outside the scope of our project. We are mindful of the fact that the DC/DC converter current limit is 8.5 A, which means all of the input circuitry and protection should be able to handle that current. Voltage after protection and regulation should not exceed 14V for inputs from 9-18V. 9-18V is the range of possible voltages we could see on 12V bus based on DC-DC converter output range from datasheet (vicorpower, 2019). The design should also convert 12V for the LV bus to 3.3V for IC power using onboard conversion IC.

Requirement	Verification
• Voltage after protection should not exceed 14V(+/-0.1V) for inputs from 9-18V.	1. Sweep voltage at the input connector from 9-18V using an oscilloscope 2. Voltmeter at the output of the protection circuitry should not read more than 14V(+/-0.1V).
• This module should convert 12V for the LV bus to 3.3V(+/-0.02V) for IC power.	1. Voltmeter at the output of the conversion circuitry should read value 3.3V(+/-0.02V).

2.2.2 Voltage Monitoring Module

This module is connected to the output of the input protection module. It should be able to sense the voltage and report the information to the MCU when it is queried. Capability to request the voltage will be applied to the MCU as part of our firmware update. The reported voltage data should have +/- 0.01V precision.

Requirement	Verification
• This module should have LV bus voltage sensing ability and can report to MCU when queried.	1. Request bus voltage data using the MCU.
• The reported voltage sensing data should have +/-0.01V precision.	1. Connect external oscilloscope at testing point on PCB. 2. Compare voltage reading of the monitoring module with external oscilloscope reading.

2.2.3 Microcontroller Unit

The MCU reads messages from the CAN bus transceiver and controls outputs, such as LED indicators and contactor controls, based on those messages and its states. It should be an ARM chip which can support I2C, SPI, and CAN communications. It should have at least 10 GPIO pins in order to support the debug LEDs, contactor controls, and communications on the board. To comply with the ISC code base, the microcontroller will be from the LPC15xx family (wiki.illinisolarcar, 2019). The MCU will also have a reset button to restart the firmware.

Requirement	**Verification**
• MCU is able to send and receive messages	1. Ensure no other processes are happening 2. Send a message to a specific module 3. Verify that the receiver then acts as it was instructed
• MCU has >10 GPIO pins	1. Confirm existence on datasheet
• MCU can be programmed over JTAG SWD	1. Verify with the datasheet 2. Upload a hello world or blinking lights program to the MCU through the JTAG connection 3. Verify the Debug LEDs flash in the programmed sequence as the code runs
• When pressed, the Reset button should restart the firmware on the MCU.	1. Press the button 2. The on-board debug LEDs will indicate beginning of the code.

2.2.4 Switching Module

Each of the connections from +12V bus to the low-voltage PCB in the electrical system should have a FET module built in. The FET module should fail short since we need power connection to all boards even if we sacrifice efficiency. Otherwise, crucial parts of information or road-legal requirements may fail unexpectedly, resulting in violation of rules. The switching circuit should not introduce significant losses into the low voltage power flow and be rated for at least 50% above desired voltage level (+12V) for safety margin. For verification testing purpose, we will use LED test circuitry at each output connector, with 100mA current limit. LEDs should light up if the connection is enabled.

The MCU on the +12V bus will be responsible for controlling the FETs. It will process signals from other parts of the car and from the driver in order to control the FET in each module should be able to turn on and off individually. FETs in the modules should be picked based on following requirements: 1. FET in each module should fail short under fault condition; 2. FET should at least be rated for 50% above desired voltage level +12V; 3. FET should at least rated for 2A continuous current draw (to accommodate for the most power draining light board).

Requirement	**Verification**
• While the 12V input is powered, the default state of the switch connections is that they are connected/on.	1. Connect the 12V input while the communication circuitry is disconnected. 2. Verify that each module connection has 12V power. 3. Connect the communication circuitry but do not send any commands to the switching chip. 4. Verify that each module connection has 12V power. 5. Command the chip to switch off the power to all modules. 6. Disconnect the communication circuitry and verify that each connection has 12V power after 5 seconds.
• FET in each module should be able to turn on and off individually within 0.25 seconds in response to signals and driver input processed by MCU	1. Connection should be enabled if the CAN message signals MOSFETs to do so within 0.25 second. Output voltage should be tested under following conditions (various test cases): i. Command the chip to stop power to all 10 connections. ii. Toggle firmware through 10 states: one connection powered at a time. iii. Cycle firmware through five other possible combination of 10 connections off and on. Check that the outputs are at 12V when they are supposed to be on.

2.2.5 Current Sense

Each of the switched connections from the +12V bus to the PCBs it powers in the electrical system should have a current monitoring module connected to it and be able to report current information to the MCU whenever queried. Typical quiescent current draw of the whole car ranges from 400 mA to 700 mA. One exception is that when light board is on, it can draw up to 5A at peak. Current monitoring at each connection should be within +/-10mA accuracy for the entire range. A reach goal for future design is to implement current monitor for all connections on the low voltage bus. To avoid extra hardware complexity, this version of the board (for senior design purpose) will only have switched connectors' current monitored.

Requirement	**Verification**
● Each of ten current monitoring modules connected should be able to report current information to the MCU when queried.	1. Request each module's data using the MCU.
● At normal voltage (+12V) current monitoring on each output connection should be within +/-10mA accuracy ranging from 0.4A to 5A.	1. Test module with different loads within range: low point and upper bound 2. Verify loads can draw constant 500 mA and 5 A at 12V. 3. Connect loads and external oscilloscope at each output. 4. Compare current reading of the monitoring module with external meter reading.

2.2.6 The 12V Outputs

The new design of the board needs to have a sufficient number of connections on the +12V bus for all boards on the car, as well as extra ones for jump start and other debugging purposes. Two types of connections will be used: Molex KK396 and KK254, to match ISC standards. Ideally have five Molex KK254 and five Molex KK396 switched output connectors on the board, with additional 4 unswitched connectors. We have needed more than the 12 available connections on the existing 12V bus, and need room for expansion. These output connectors will have different current carrying capabilities and will be able to handle different wire types compatible with different subsystem PCBs.

Requirement	Verification
• Use two types of standardized connectors compatible with current car: 10 switched output connectors (5+5) on the board to handle different currents and wire types on subsystem PCBs.	1. Check the PCB design and schematic to verify correct number of connections 2. Plug into the existing electrical system test bench to verify compatibility.
• One KK396 input connector (easily identifiable) and 4 unswitched connectors.	1. Check the PCB design schematic and layout.

2.2.7 Firmware

The firmware (FW) running on the microcontroller will process signals from the CAN transceiver and control the drivers on the bus board. The FW will send measurement data from the current sensors to the CAN bus five times every second. We assume that in driving operation of the car, the most regular high-current that will switch on and off is the vehicle's turn signals, which due to regulations can flash at no more than 120 times per minute (4 switches per second). In order to ensure that enough data can be collected on the current consumption of the boards we will send the current consumption data five times a second.

Requirement	Verification
• Latch the switching state until a new signal is received or the board loses power.	1. Send command to switch every other module on, every other module off. 2. Wait for 2 hours 3. Meter the module connections to verify they are the same as when the command was initially set
• Switch the power on each of 10 connectors independently	1. Connection should be enabled if the CAN message signals MOSFETs to do so. Output voltage should be tested when toggle firmware through 10 states: one connection powered at a time.

2.2.8 CAN transceiver

The CAN transceiver connects the PDS control to the vehicle's CAN bus. This allows the PDS control board to send and receive messages from other boards. The IC for the CAN transceiver converts 3.3V MCU logic to 5V logic, and it isolates the microcontroller from noise on the CAN bus.

Requirement	**Verification**
● Should be able to withstand +/- 18V spikes on the CAN_HIGH and CAN_LOW pins.	1. Use oscilloscope to send +/- 18V on the CAN bus pins 2. Measure the voltage at the receiving end to monitor what is received at the pins 3. Use a CAN bus analyzer to verify the chip can still send and receive messages

2.2.9 Debug/Status LEDs

The PDS control board should have on-board LEDs for debugging and status indicating purposes during operation and fault states. Each LED will be controlled by a GPIO pin on the MCU. Therefore, they will be able to turn on and off based on firmware.

Requirement	**Verification**
● On-board LEDs should be able to turn on and off based on firmware for debugging and status indication.	1. Test MCU can turn on and off LEDs with GPIO. 2. Test LED can indicate fault state.

2.2.10 USB Power Input

This input provides power to the microcontroller when we wish to program the board through a JTAG connection. It is not able to power the full board, only the 3.3V net, which provides power to the MCU.

Requirement	**Verification**
• The 3.3V connections on the PCB should have power.	1. Connect the board to a computer via USB. 2. Check that the 3.3V indicator LED is on.

2.3 Risk Analysis

The greatest risk to our project is the design and implementation of the PCBs themselves, specifically the +12V bus PCB. Should anything be designed on the boards incorrectly, it will be much harder to fix and take more time in comparison to connections between boards or firmware problems. We are completely redesigning the +12V bus board, which will not only take time but also a lot of careful planning. The board that we intend to design is significantly more complex than before, which has higher risk for error. Realistically with the time that we have, we do not have many opportunities to redo our PCBs, so because of the time and complexity factor, production of the +12V bus PCB is the biggest risk we have. We would like to point out one risk of our design interface with the power converter on the battery system. The current rating of the standardized connector type (7A) on current generation vehicle is lower than current limit of the DC-DC converter 8A (vicorpower, 2019). For the purpose of this project, we are not going to change the connector standard and the battery DC-DC converter of this solar vehicle since it has been established during building process. If this project is successful and the team ends up implementing the board onto the next solar vehicle, this risk should be carefully evaluated and addressed.

2.4 Supporting Materials

2.4.1 Schematic for single Current monitoring module

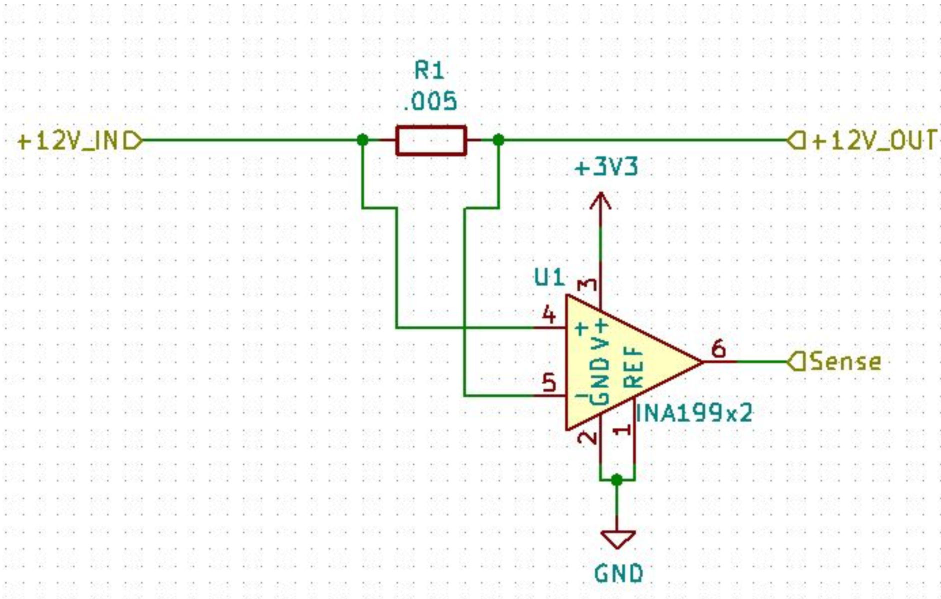

Fig 2. Single Current sense module

2.4.2 Schematic for USB Power Input module

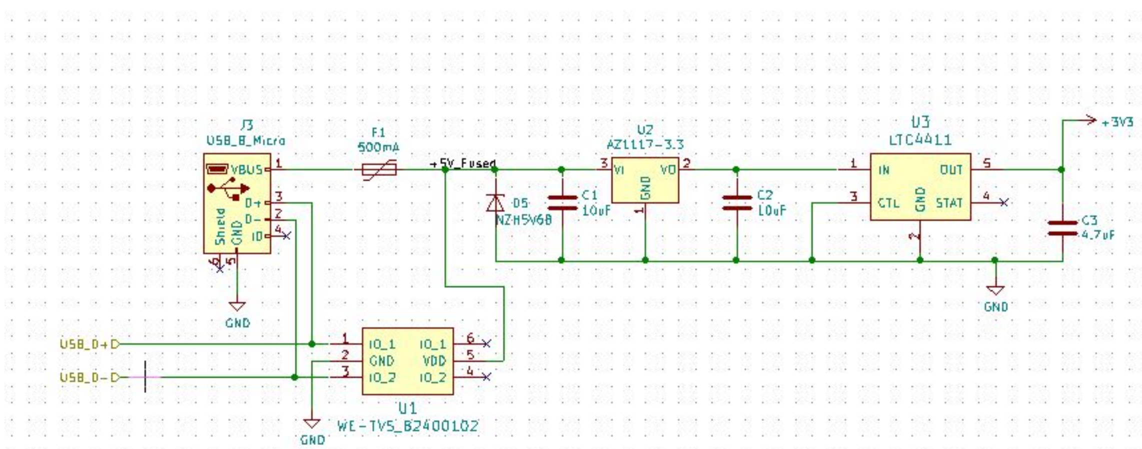

Fig 3. USB Power Input

2.4.3 Schematic for CAN transceiver module

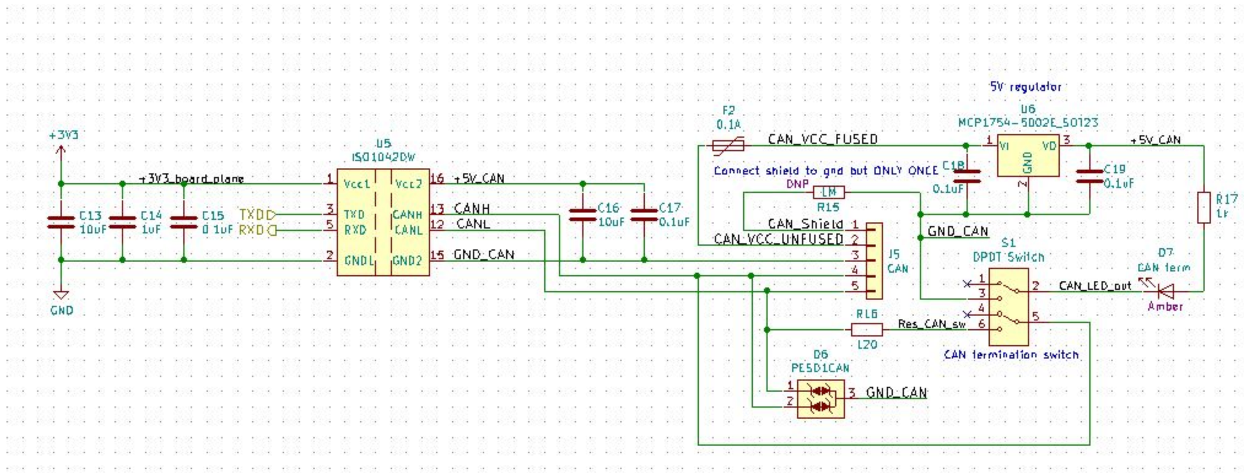

Fig 4. CAN transceiver

2.5 Tolerance/Numerical analysis

Power savings are very important for an endurance race that spans long distances and lots of time. In order to stay on track and meet checkpoints with a calm pace, steady speed is required while the driving. However, in order to maximize the efficiency of the solar vehicle during the endurance road race, it is our goal to make sure that most of the power that is consumed is during the driving state for the motor. To do this, we need to reduce power consumption while the car is idle. In a typical race day during the American Solar Challenge and World Solar Challenge, the car will be idle in the charging state or at checkpoints. The intention for this project is to be able to turn off specific subsystems on the car during these idle times. Some of the subsystems include rearview camera, rearview camera screen, the dash screens, and vehicle lights (front, back and rear). A solar vehicle during the charging state doesn't require these subsystems to be on. When we have control over subsystems, we can save power and improve the efficiency of the car during the race.

The typical quiescent current draw of the whole car ranges from 400 mA to 700mA (average current draw is 550mA) at battery pack voltage (117V). The typical power consumption during the charging stage can be calculated as follow.

$$P = 550mA \times 117V = 64.4W$$

Charging hours are 6-8am, 4-6pm on a normal ASC competition day. In addition to that, checkpoints last 45 minutes (American Solar Challenge, 2019). In total, the solar car is in the idle stage for about 4.5 hours per day. Total energy savings is 289.8 Watt-hour.

$$E = 64.4W \times 4.5hr = 289.8\ Watt \cdot hour$$

With two 1kW motors running, this power can help us to run for an extra 0.145 hour (detailed calculated shown below). This helps to improve the efficiency by 1.81 percent.

$$T = 289.8\ W \cdot hr \div 2kW = 0.145\ hour$$

$$Efficiency\ Improvement = 0.145hr \div 8hr = 1.81\%$$

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

The hourly rate was determined using the average salary for an electrical engineer that graduated from UIUC from the ECE Illinois website (Engineering Services, 2019). The average salary for a someone with a BS in Electrical Engineering from UIUC between 2014-2015 was $67,000.

$$\frac{\$67000}{52\ weeks} * \frac{1\ week}{40\ hours} = \$32.21/hour$$

Name	Hourly Rate	Total Hours	Total	Total * 2.5
Siye Lynn Cen	$32.21	300	$9663	$24157.50
Amalia Dungey	$32.21	300	$9663	$24157.50
Richa Vijayvergiya	$32.21	300	$9663	$24157.50
Total				$72472.50

3.1.2 Parts

Description	Part Number	Manufacturer	Vendor	Cost/unit	QTY	Total Cost
MCU	568-11349-ND	NXP USA	Digikey	$7.29	5	$36.45
MOSFETs	DMP3056L-7DICT-ND	Diode Incorporated	Digikey	$0.395	40	$14.36
Current sense	296-27329-1-ND	Texas Instrument	Digikey	$0.748	40	$29.92
3-pin KK254	WM4201-ND	Molex	Digikey	$0.226	50	$11.30
3-pin KK396	WM4621-ND	Molex	Digikey	$0.358	50	$17.90
FET gate drive	MIC5891	Microchip Technology	Digikey	$2.72	5	$13.60
PCB manufacture	--	Bay Area Circuit	Bay Area Circuit	$30	10	$300
P-MOS	785-1106-1-ND	Alpha & Omega	Digikey	$0.56	5	$2.80

		Semiconductor Inc.				
Tactile Switch	CT3093CT-ND	CTS Electrocomponents	Digikey	$0.322	5	$1.61
Mosfet Array 2 N-Channel	IRF7503TRPBFCT-ND	Infineon Technologies	Digikey	$0.63	10	$6.30
Isolated CAN Transceiver	296-52306-ND	Texas Instruments	Digikey	$5.83	5	$29.15
Switch Load Driver	F2110CT-ND	ON Semiconductor	Digikey	$1.03	5	$5.15
Resettable Fuse	F8130CT-ND	Littelfuse Inc.	Digikey	$0.59	5	$2.95
Zener Diode	1727-5076-1-ND	Nexperia USA Inc.	Digikey	$0.21	10	$2.10
Total						**$473.59**

Note: This part list is preliminary based on current design, and it does not include surface mount passive components such various values of resistor and capacitors. PCB manufacture for this Illini Solar Car associated project is sponsored by Bay Area Circuit.

3.1.3 Grand Total

Section	**Cost**
Labor	$72472.50
Parts	$473.59
Grand Total	**$72946.09**

3.2 Schedule

Week #	Deadlines	Lynn	Amalia	Richa
Week 6 (2/18)	1. Design Review Sign up 2. Design Document Check (2/18) 3. Design Document (2/21)	Design Document	Design Document	Design Document
Week 7 (2/25)	1. Design Review (2/25)	Single & combined switch module schematic	Firmware process diagram finalized	Current sensing schematic for high-side driver
Week 8 (3/4)	1. Team Evaluation (3/4) 2. Soldering Assignment (3/8)	Schematic for switch & current monitor unit	Code outline, including CAN message structure	Power protection schematic for +12V bus
Week 9 (3/11)	1. First Round PCB orders (3/14)	Combined bus board schematic	Finalize firmware code	Voltage sensor schematic, send out all designs for review
Week 10 (3/18)	**Spring Break**	Bus board layout with CAN & USB & MCU & LED	Review schematic, test CAN communication	Verify bill of materials
Week 11 (3/25)	1. Individual progress reports (3/25)	Layout review & Order boards	Order parts	Order current and voltage sensing devices
Week 12 (4/1)		Assemble 3 PCBs	Test board communication: switch	Test the power protection and both sensors
Week 13 (4/8)		Testing and validating switch default	Test board communication: sensors	Test high-side drivers with the current and voltage sensors, put it all together
Week 14 (4/15)	1. Mock Demo	Testing and validating switch independence	Test code stability	Test precision: current & voltage monitor

Week 15 (4/22)	1. Presentation Sign-up	Final Paper	Final Paper	Final Paper
Week 16 (4/29)	1. Final Papers due (5/1) 2. Lab notebook due (5/2) 3. Lab checkout due (5/2) 4. Teamwork Evaluation (5/2)	Final Paper	Final Paper	Final Paper

4 Point Summary

Module	High level requirement	Points
Power protection & conservation	● Voltage after protection module should not exceed 14V for inputs from 9-18V. ● The board should be able to convert 12V to 3.3V for signal.	5
Standard modules	● USB power: The 3.3V connections on the PCB should have power. ● CAN transceiver: Should be able to withstand spikes on the CAN_HIGH and CAN_LOW pins. ● Debug/status LEDs: On-board LEDs should be able to turn on and off based on firmware for debugging and status indication.	5
Microcontroller Unit/firmware	● MCU is able to send and receive messages ● MCU has >10 GPIO pins ● MCU can be programmed over JTAG SWD ● Firmware should take signals from system inputs to turn on and off individual switches on LV bus board.	10
Connections	● Ten switched output connectors on the board to handle different currents and wire types on subsystem PCBs. ● One KK396 input connector (easily identifiable) and 4 unswitched connectors.	5
Switching chip & module	● Switch the power on each of 10 connectors independently. ● Latch the switching state until a new signal is received or the board loses power. ● While powered, the default state of the switch connections is connected/on ● FET in each module should be able to turn on and off individually within a short time in response to PDS control signal.	10
Current Monitor	● Current monitoring modules connected should be able to report to the MCU. ● Current reading should be accurate.	10
Voltage Monitor	● Current monitoring modules connected should be able to report to the MCU. ● Current reading should be accurate.	5

5 Ethics and Safety

The IEEE Code of Ethics 7.8.1 (IEEE.org, 2019) that lays out the rules regarding health, safety, and public welfare will be the code of ethics we intend to follow. Building a solar electric vehicle from scratch is a very challenging task that comes with a lot of safety risks. From designing the proper PCBs with correct connections to machining all of the parts that will come together to make the car, a lot of problems have, and will, occur. Should there be injuries, we intend to take them seriously. After the car is built and ready for testing, our priority is to ensure the safety of the driver. The driver should be able to control the car properly and the car should be reliable over long-periods of time, which will be the conditions for the races we compete in. Our goal is to make a quality, efficient, and reliable car while protecting the components as well as the drivers and crew that will take care of the car.

For our specific project, we will only be working with low voltages (+12V, logic levels) and nothing will require more than 50V. By working with low voltage modules, we will have an inherent level of safety. Within our project, will have current sensing on each of the connectors on our +12V bus in order to monitor the power that will be delivered. We also want to implement power protection for each power input to mitigate the chance of damage to sensitive components, like the microcontroller. This is to be proactive and prevent problems before they materialize. Despite the relative safety in +12V power, we are implementing a switching system that is normally closed and fails closed instead of open.

Another part of our personal code of the ethics is to cite our sources properly to give credit where it is due. This goes for any outside research we do to expand our knowledge, and it includes for responsibilities among this team itself. There are a number of circuits which the solar car team has standardized across boards, and we will clearly indicate when that is where our design comes from and where we have improved on those or actually come up with a new design.

There are many challenges in designing an electric vehicle that will operate outdoors under various conditions. Overheating due to high temperatures (>50°C) and moisture from humidity or inclement weather could cause damage to the board and the connections, leading to fault states and short circuits. The redesign of our +12V bus and additional firmware, and CAN and I2C connections, should reduce the risk of damage to multiple components should the environment cause unavoidable risks.

6 Citations

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