# KGCOE MSD Technical Review Agenda

## P10203: Motor Controller for LV1 Land Vehicle Platform

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**Meeting Purpose**

1. Present ability to meet engineering specifications with system analysis.
2. Give a system breakdown and show what each sub-system accomplishes.
3. Present a preliminary test plan.
4. Update risk management status and present new design specific risks.

**Materials to be Reviewed**

1. Engineering Specifications (R#7)
2. Preliminary Test Plan (R#3)
3. Bill of Materials (R#2)
4. Risk Management Document (R#5)
5. Quality Function Diagram (R#1)
6. Schematics of Electrical Designs (R#2)
7. Layout of Designed PCB (R#1)
8. Thermal Analysis (R#3)

**Meeting Date**: February 12th, 2009

**Meeting Location**: KGCOE Design Center, Room 09-4435

**Meeting Time**: 3:00 – 5:00 pm

**Meeting Timeline**

| Start Time | Topic of Review | Required Attendees |
|---|---|---|
| 3:00 | Project Introduction and Overview | Guide, TA, Dr. Hensel, Dr Walter |
| 3:10 | Project Status | Guide, TA, Dr. Hensel, Dr Walter |
| 3:20 | Engineering Specifications | Guide, TA, Dr. Hensel, Dr Walter |
| 3:30 | | Guide, TA, Dr. Hensel, Dr Walter |
| 3:40 | System Analysis and Feasibility – Thermal and Shock | Guide, TA, Dr. Hensel, Dr Walter |
| 3:50 | Feedback | Guide, TA, Dr. Hensel, Dr Walter |
| 4:00 | System Analysis and Feasibility – Electrical Devices | Guide, TA, Dr. Hensel, Dr. Hoople |
| 4:10 | Test Plan | Guide, TA, Dr. Hensel, Dr. Hoople |
| 4:20 | | Guide, TA, Dr. Hensel, Dr. Hoople |
| 4:30 | Risk Management | Guide, TA, Dr. Hensel, Dr. Hoople |
| 4:40 | | Guide, TA, Dr. Hensel, Dr. Hoople |
| 4:50 | Final Feedback: Are we ready to move on? | Guide, TA, Dr. Hensel, Dr. Hoople |

| Engr. Spec # | Customer Need | Specification | Unit of Measure | Marginal Value | Ideal Value | Comments | Reference in Controller |
|---|---|---|---|---|---|---|---|
| ES1 | CN7, CN8, CN9 | Number of Board-to-Board and external wires needed. | Count | 24 | 18 | Will be dictated by final design layout | Internal Boards and Connections |
| ES2 | CN7, CN8, CN9 | Number of PCB Needed. | Count | 3 | 2 | Total number of stand-alone boards used in final implementation | Development Board<br>Designed Board |
| ES3 | CN9, CN13 | Total cost of Controller. | $ | $475.00 | $400.00 | Reduction from $511 in RP1 | Entire Controller |
| ES4 | CN5, CN10 | Mounted Controller drop test surviveability. | Feet | 3 | 5 | Based upon table-top fall | Board Construction and Coating |
| ES5 | CN1, CN9 | Number of Designed Boards Manufactured. | Count | 2 | 4 | Multiple board manufacture for replacement if needed. Varies depending on cost. | Designed Board |
| ES6 | CN3, CN10 | All sensitive components are separated from Noise Generating Components. | cm | > 5 in | > 6 in | Will conform to available dimensions provided by chassis team. | Designed Board Layout and Positioning |
| ES7 | CN4, CN7, CN8 | Distance between controller outputs and interfaces. | cm | < 8in | < 4in | Positioning of connectors in layout will be at edges of board close to interfaces. | Placement of all Boards and Layout of Designed Board |
| ES8 | CN10 | Operating Temperature of Controller Components. | Degrees Celcius | 100 C | 50 C | Maximum temperature of any individual component in the system | On Board Components |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ES9 | CN4, CN12 | Amount of memory on controller. | KB | Code footprint uses ~60% program space and resources, much of the system memory is unavailable for future Improvements | Code footprint uses ~40% program space and resources, much of the system memory remains available | | Development Board and PID Controller |
| ES10 | CN4, CN12 | Number of I/O to be controlled. | Count | 14 | 18 | Quantification of all inputs and outputs to/from the system | Development Board and PID Controller |
| ES11 | CN4, CN6, CN12 | Bandwidth required at input to controller. | Data Rate | 50 Kbps | 250kbps | Based upon available data rate range of wireless technology used by P10205 | Development Board |
| ES12 | CN4 | Data Format at Input to Controller. | Format | 8N1 Bits | 8N1 Bits | Dictated by onboard software from RP1 | Development Board |
| ES13 | CN4, CN12, CN13 | Programming Language used to program Controller. | Language | C++ | C, C++, VHDL, Assembly | | Development Board<br>PID Controller |
| ES14 | CN4, CN6 | Latency of Command Throughput. | ms | 150 ms | 100 ms | Time required to process input and output control signals | Development Board<br>PID Controller |
| ES15 | CN6 | Degrees of Freedom maintained by Controller. | Steering, Traction | 2 | 2 | | Motor Drivers<br>PID Controller |
| ES16 | CN4, CN6 | Controller interfaces with motor modules independently. | Boolean | 1 | 1 | Individual motors are controlled independent of one another. | Motor Drivers<br>PID Controller |
| ES17 | CN11 | Power Consumption of the Processing Sub-system. | Watts | 500mW | 400mW or lower | Loads include MCU Board, PID Board and 2 Driver Boards | Logic Power Boards |

**P10203 Test Plan Excerpt**

Electrical Components

1. Logic Power Distribution Board
    - Values to be tested – Output Voltage and Current for considered loads, (MCU, PID, Motor Drivers).
    - Method for testing – Connect a multimeter to the output of the loaded system and measure the output voltage and current.
    - Pass/Fail Criteria – Voltage = 4.8 to 6V, Current = at most 500mA
2. Motor Power Distribution Board
    - Values to be tested - Output Voltage and Current for considered loads, (DC Motors, Servo Motors, Motor Drivers).
    - Method for testing - Connect a multimeter to the output of the loaded system and measure the output voltage and current.
    - Pass/Fail Criteria – Voltage = 5.5 to 7V, Current = at most 4.2 A
3. DC Motor Driver Boards
    - Values to be tested – Output Voltage and Current for considered loads, (DC Motors). Also test the functionality of the PWM, Enable and Direction inputs.
    - Method for testing - Connect a multimeter and oscilloscope to the output of the loaded system and measure the output voltage and current. Also, apply a varied PWM signal to the device as well as all combinations on enable and direction inputs.
    - Pass/Fail Criteria – Voltage = 5.5 to 7V, Current = at most 1.6 A, varied PWM alteration is exhibited at oscilloscope, enable signal turns motor driver on or off, direction control is exhibited at oscilloscope.
4. Microcontroller Processing Unit
    - Test Programs exist, (provided by the manufacturer and by the P09204 group) to test the functionality of the Development Board. These test programs will be run in order to test the I/O capability of the board.
5. PID Control Unit
    - Test Programs exist, (provided by the manufacturer and by the P09204 group) to test the functionality of the PID Controller. These test programs will be run in order to test the I/O capability of the board.

Mechanical Components

1. Board Coating
    - Values to be tested – Survivability of a 3 foot drop test after board has been coated.
    - Method for testing – Coat a sample board with the coating and drop the device from a height of 3 feet.
    - Pass/Fail Criteria – Board exhibits no external damage after the drop and all components remain securely in place.
2. Thermal Resistance
    - Values to be tested – Temperature of all heat sensitive and heat generating components.
    - Method for testing – Using a thermocouple, measure the temperature of all components in consideration for a 30 min. time period, (normal operation of controller).
    - Pass/Fail Criteria – All components remain at or below 100 C.

| **Risk Item** | **Effect** | **Cause** | **Likelihood** | **Severity** | **Importance** | **Action to Minimize Risk** | **Owner** |
|---|---|---|---|---|---|---|---|
| *Describe the risk briefly* | *What is the effect on any or all of the project deliverables if the cause actually happens?* | *What are the possible cause(s) of this risk?* | *L* | *S* | *L * S* | *What action(s) will you take (and by when) to prevent, reduce the impact of, or transfer the risk of this occurring?* | *Who is responsible for following through on mitigation?* |
| Power Distribution or Driver Boards are not able to provide the correct power to run the motors. | Motor functionality will suffer or completely fail. | Poor communication with motor team. Unexpected Power losses in circuitry. | 2 | 2 | 4 | Prevent by performing software simulations and hardware prototyping of circuitry prior to final product manufacture. | EE's |
| Decision to change an aspect of RP1 snowballs into redesign of entire system. | Customer needs are not met. Project is unable to advance properly. | Improper design choices to improve previous design. | 1 | 3 | 3 | Reduce by only changing design where absolutely necessary or the change will produce a significant cost reduction or performance increase. | All |
| Several Components including the PID Controller do not have footprints and symbols for their packages. | Layout of Board cannot be completed or will be incorrect. | Layout Software does not come with these packages in library. | 3 | 3 | 9 | Reduce by either drawing the symbols and footprints by scratch, or finding an alternative way of mounting the components. | Kory |
| Incorrect Routing on designed PCB | Board will not function as intended. Could potentially cause failure of components. | Poor design procedure by team or poor board production by layout company. | 2 | 3 | 6 | Prevent by performing checks of layout. Electronic tests (DFM Report) and human tests will be used. | EE's |
| Coating on Boards causes failure of components. | Components or entire boards will need to be replaced. | Unexpected reactions between components and coating material. | 2 | 2 | 4 | Prevent by testing suggested coating on a prototyping board before coating essential controller components. | ME's |
| Component failure due to overheating | Components require replacement. Other electronics may be damaged in the process. | Not enough thermal resistance on heat sensitive or heat generating components. | 1 | 3 | 3 | Prevent by performing thermal analysis of components using hardware emulation and hand calculations based on component datasheets. | ME's |

| | Linear Regulator | Switching Regulator |
|---|---|---|
| Function | Step Down Only | Buck, Boost, Buck-Boost, Inverting |
| Efficiency | Low, at most about 40%, depends on Load Current and Vin-Vout difference | High, except at low load currents where switch-mode quiescent current is higher |
| Waste Heat | Can be high, dependent on operation parameters | Low, switcher does not generate much heat at low power levels |
| Complexity | Low, requires only external low value bypass capacitors | Can be quite complex, requires accurate timing analysis for switching. Also requires additional discrete components and/or transistor. |
| Size | Low overall, but external heatsink required adds to size | More PCB size required due to additional discretes |
| Cost | Low, more expensive to drive higher loads | Medium to high, mostly due to additional discretes |

*Linear vs. Switching Regulator – Functionality*

| Power | Vin | Vout | Max Load Current |
|---|---|---|---|
| Logic | 7.4 V | 5 V | 500 mA |
| Motor | 7.4 V | 6 V | 4.2 A |

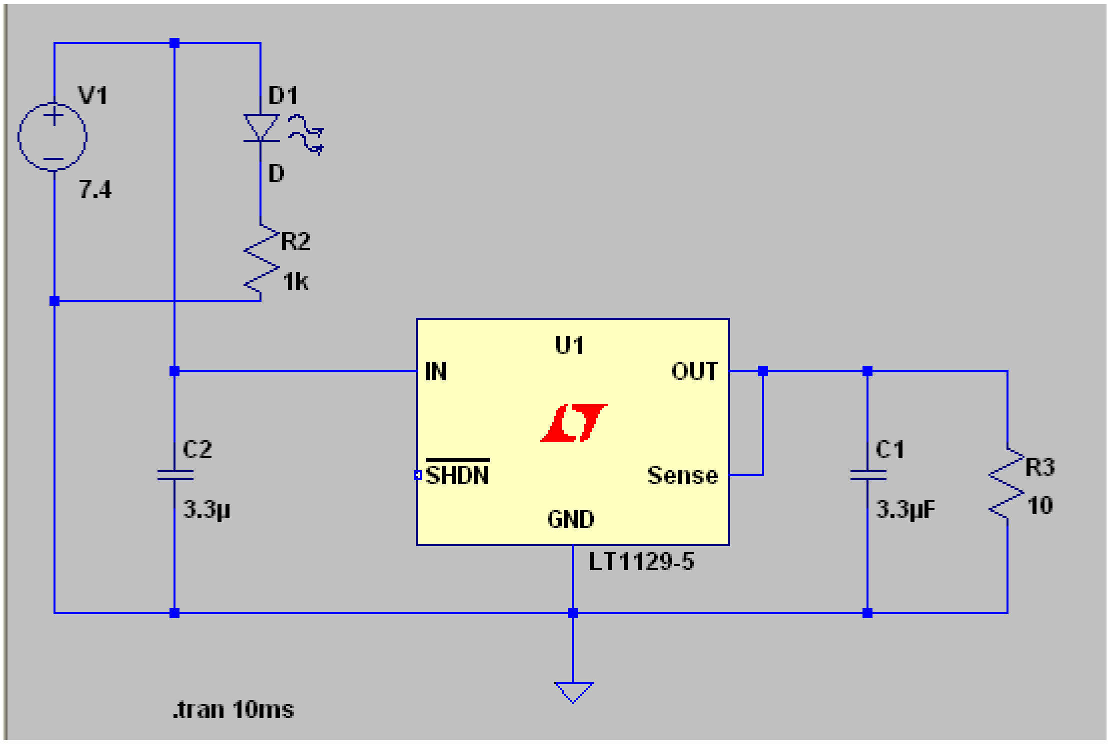
*Applications for Regulators*

| Switching Regulator | | | |
|---|---|---|---|
| Component | Part Number | Distributor | Cost |
| Switching Regulator | LTC1771EMS8#TRPBF-ND | Digikey | $5.38 |
| PMOS Transistor | SI6435ADQ-T1-E3 | Mouser | $0.97 |
| Schottky Diode | UPS5817E3TR-ND | Digikey | $0.15 |
| 5 Capacitors | Multiple | Digikey | $2.50 |
| 1 Inductor | TBD | Digikey | $4.00 |
| 4 Resistors | Multiple | Digikey | $0.40 |
| TOTAL | | | $13.40 |

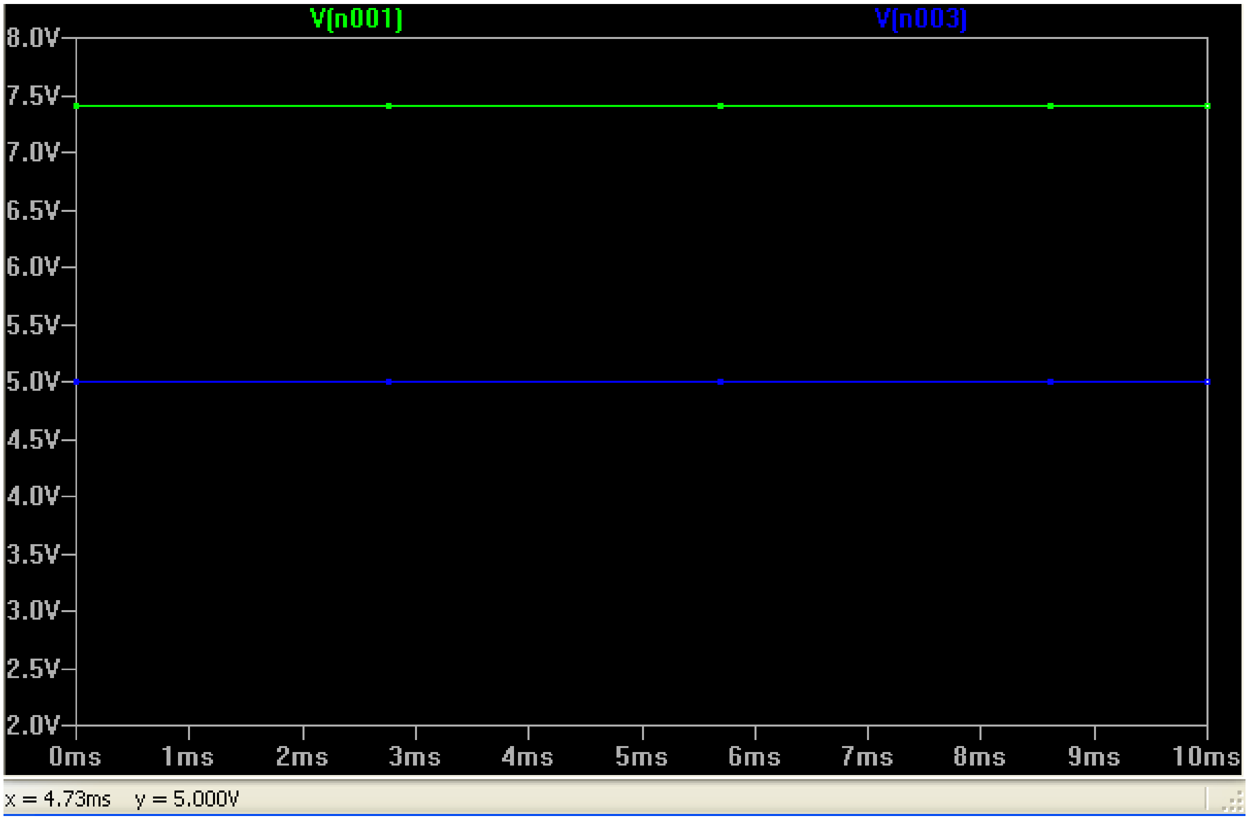
| Linear Regulator | | | |
|---|---|---|---|
| Component | Part Number | Distributor | Cost |
| Linear Regulator | LT1083 | Digikey | $8.83 |
| 2 Capacitors | Multiple | Digikey | $1.00 |

| | | | |
|---|---|---|---|
| 2 Resistors | Multiple | Digikey | $0.20 |
| TOTAL | | | $10.03 |

*Cost Analysis of Linear vs. Switching Regulator*

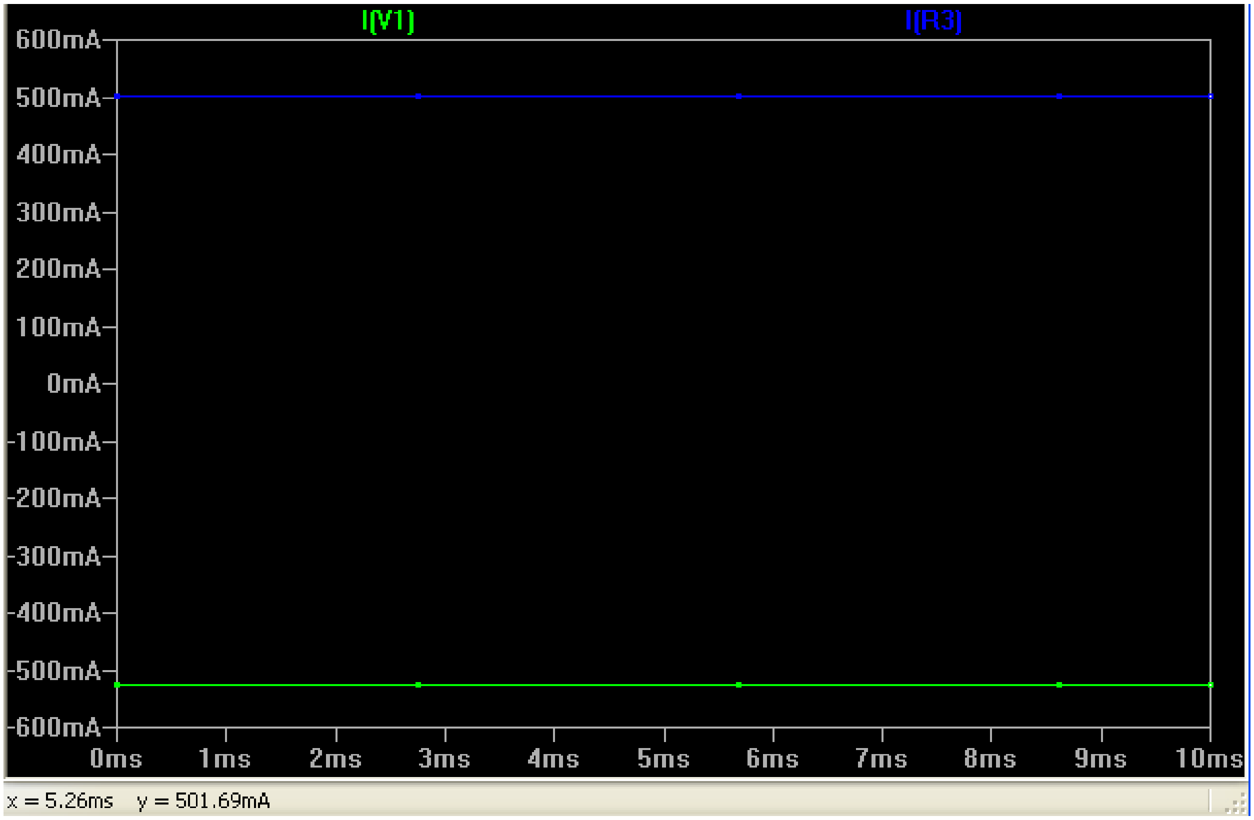


*Logic Power Distribution Schematic*



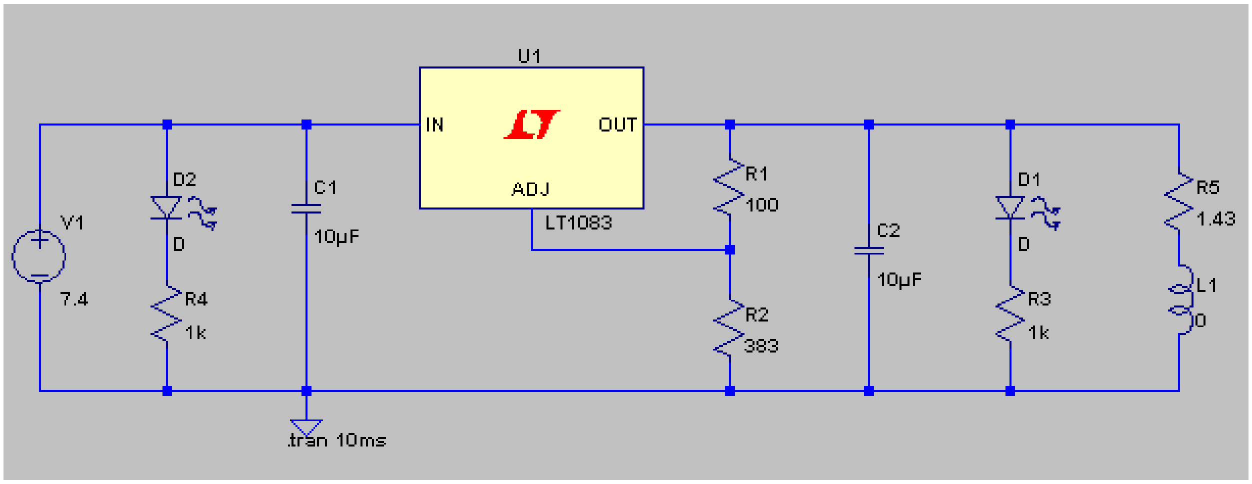
x = 4.73ms y = 5.000V

*Logic Power Output Voltage*

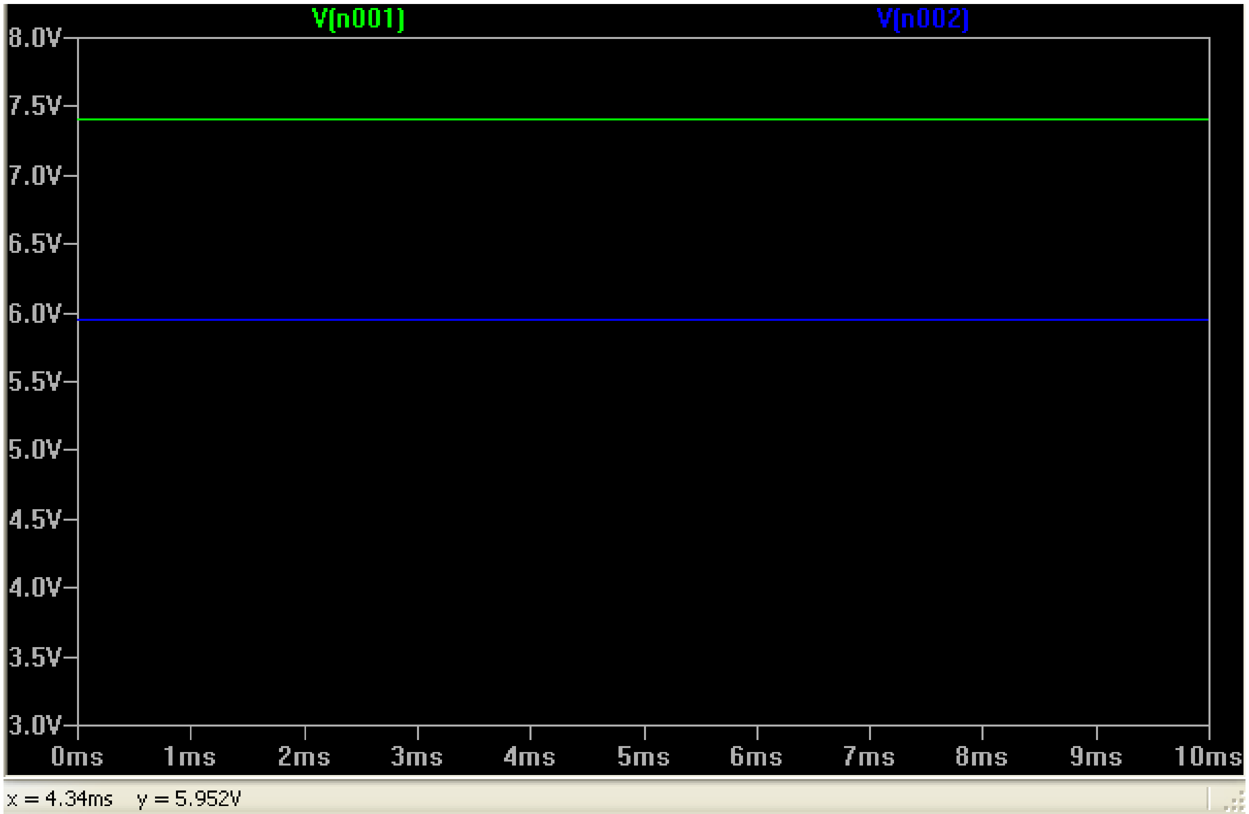


x = 5.26ms y = 501.69mA

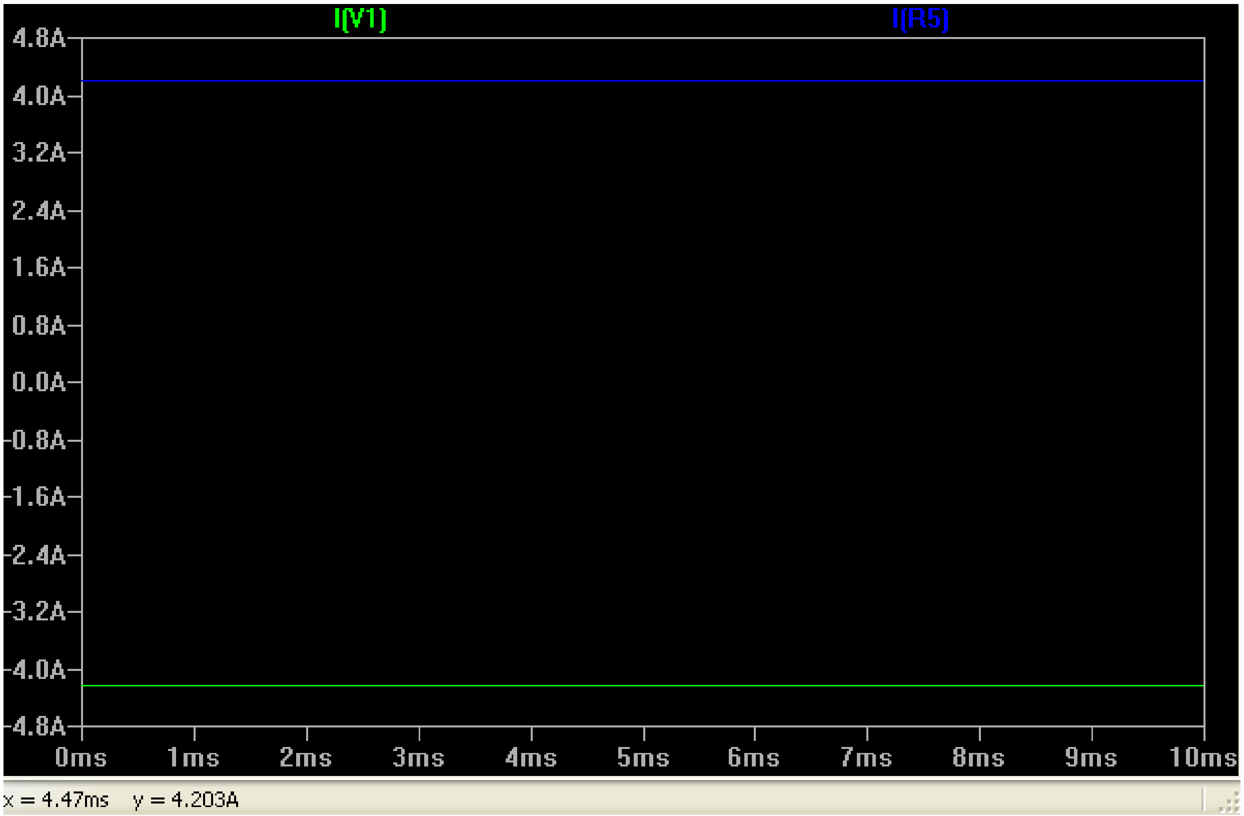
*Logic Power Output Current (Fully Loaded)*



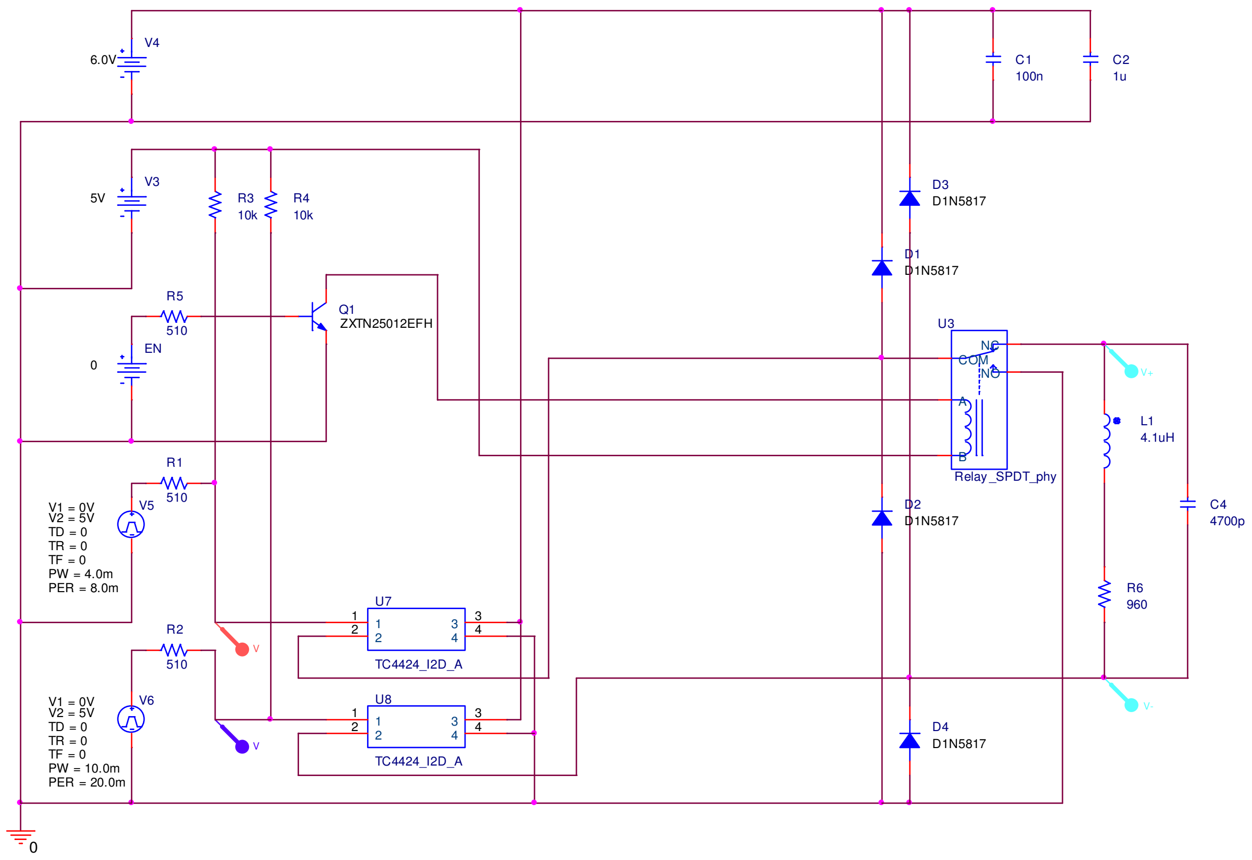
*Motor Power Distribution Schematic*



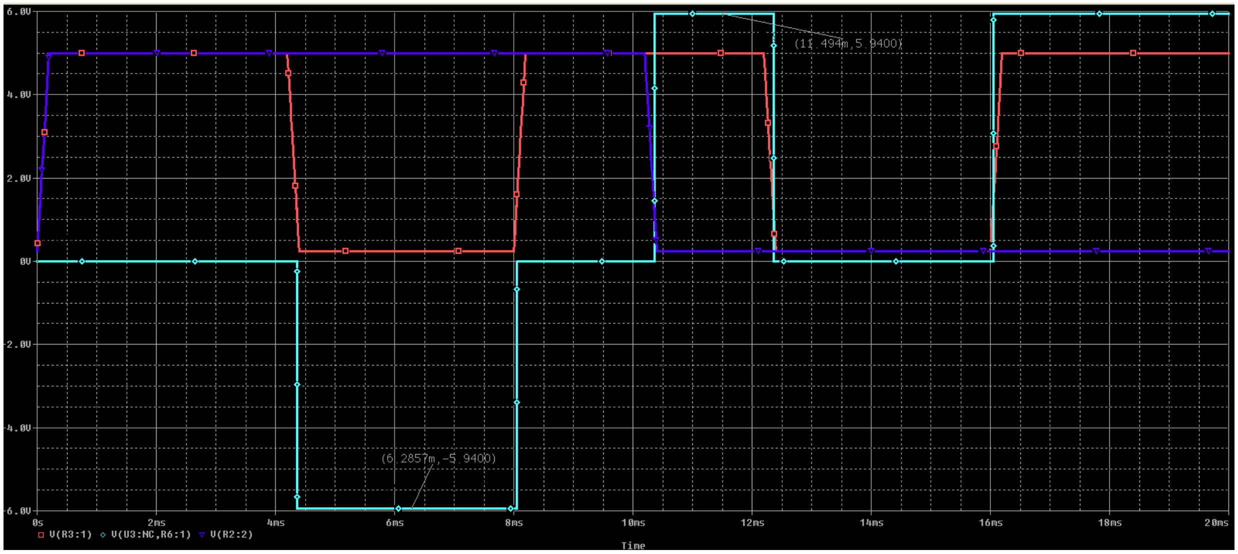
*Motor Power Output Voltage*



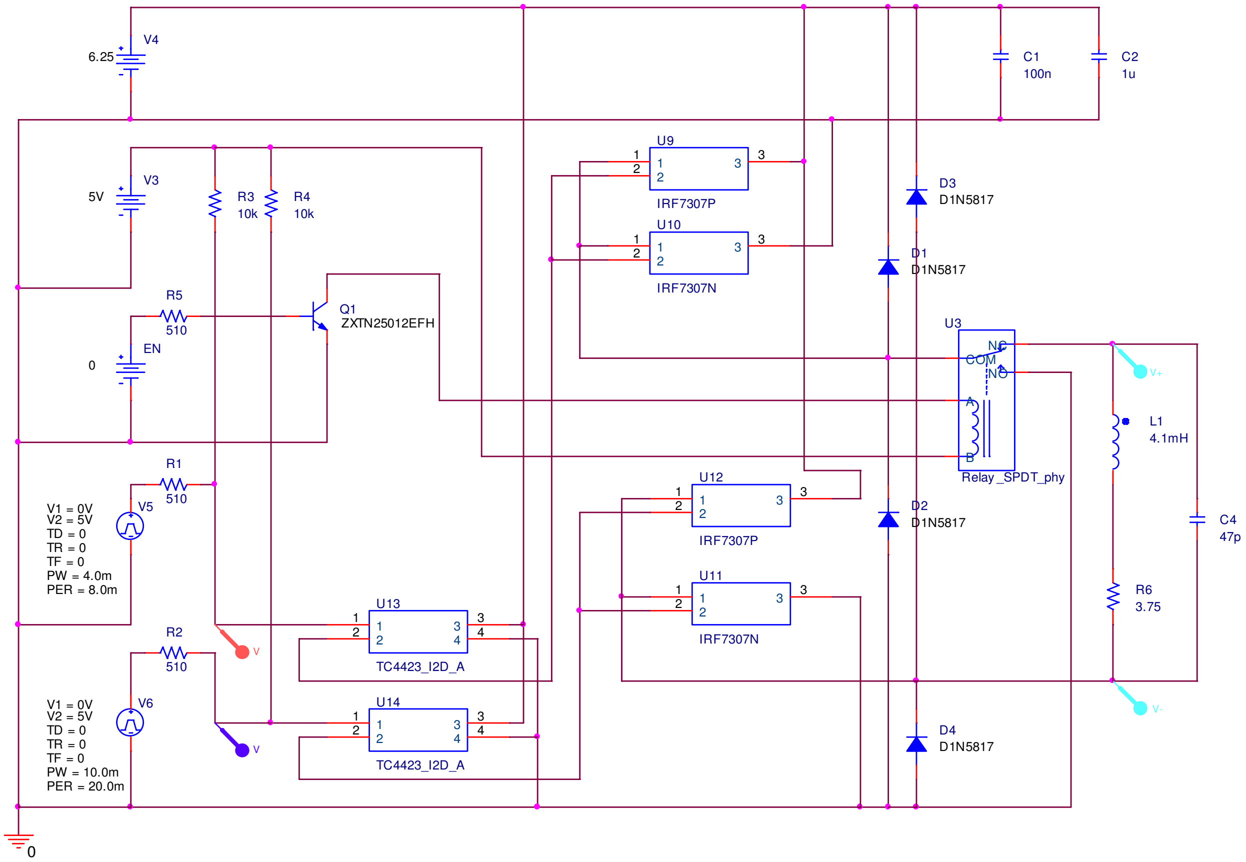
*Motor Power Output Current (Fully Loaded)*



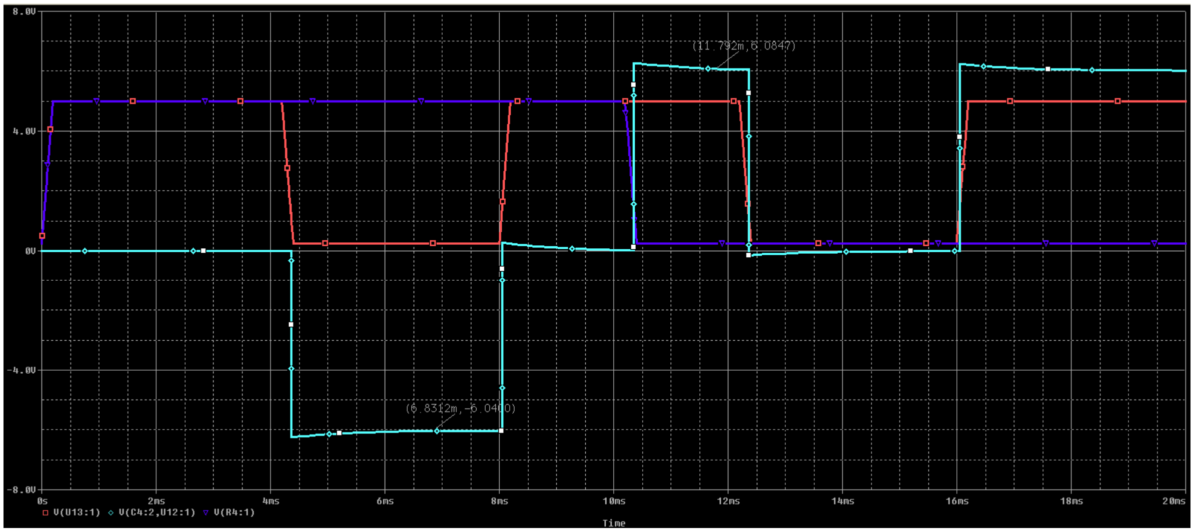
*DC Brushed Motor Driver Schematic using solely MOSFET Drivers (TC4424)*



*Simulation results for DC Brushed Motor Driver using solely MOSFET Drivers (TC4424)*



*DC Brushed Motor Driver schematic using MOSFET Drivers (TC4423) with additional POWER MOSFETS (IRF7307) for reduced power dissipation on the MOSFET Drivers*



*Simulation results for DC Brushed Motor Driver schematic using MOSFET Drivers (TC4423) with additional POWER MOSFETS*

### Power Dissipation of MOSFET Driver without dedicated power mosfets:

At maximum acceleration and maximum current draw of 1.6A:

From TC4424A datasheet:
Typical @$T_A = +25^\circ C$, $R_{DS(ON)} \cong 4.25\Omega$ (@ Output Low), $R_{DS(ON)} \cong 4.75\Omega$ (@ Output High)
Minimum High Output Voltage, $V_{OH} = 6V - 0.025V = 5.975V$
Maximum Low Output Voltage, $V_{OL} = 0.025V$

Power Dissipation of MOS. Driver = $\{I_{SS}^2 * R_{DS(ON)}$ (@output Low)$\}$ + $\{ I_{SS}^2 * R_{DS(ON)}$ (@output High)$\}$
= $\{(1.6A)^2 * 4.25\Omega\} + \{(1.6A)^2 * 4.75\Omega\} =$ **23.04W**
Power loss of MOS. Driver = 0.025V * 1.6A = **40mW**

At zero acceleration and minimum current draw of 370.96mA:

From TC4424A datasheet:
Typical @$T_A = +25^\circ C$, $R_{DS(ON)} \cong 4.25\Omega$ (@ Output Low), $R_{DS(ON)} \cong 4.75\Omega$ (@ Output High)

Power Dissipation of MOS Driver = $\{I_{SS}^2 * R_{DS(ON)}$ (@output Low)$\}$ + $\{ I_{SS}^2 * R_{DS(ON)}$ (@output High)$\}$
= $\{(370.96mA)^2 * 4.25\Omega\} + \{(370.96mA)^2 * 4.75\Omega\} \cong$ **1.2385W**
Power loss of MOS. Driver = 0.025V * 370.96mA = **9.274mW**

### Previous Years Power Dissipation of the MOSFET Driver (worst case):

From TC4424 datasheet:
Typical @$T_A = +25^\circ C$, $R_{DS(ON)} \cong 3.5\Omega$ (@ Output Low), $R_{DS(ON)} \cong 3.5\Omega$ (@ Output High)

Power Dissipation of MOS. Driver = $\{I_{SS}^2 * R_{DS(ON)}$ (@output Low)$\}$ + $\{ I_{SS}^2 * R_{DS(ON)}$ (@output High)$\}$
= $\{(1.5A)^2 * 3\Omega\} + \{(1.5A)^2 * 3\Omega\} \cong$ **15.1875W**
Power loss of MOS. Driver = 0.025V * 1.5A = **37.5mW**

### Power Dissipation of MOSFET Driver with dedicated power MOSFET:

$P_{TOTAL} = P_{GATE} + P_{DYNAMIC} + P_{QUIESCENT\text{-}CURRENT\text{-}DRAW}$

$P_{GATE} = C_G * V_{DD}^2 * F_{SW} * n$
Where:
$C_G$ = MOSFET Gate Capacitance.
$V_{DD}$ = Supply Voltage of MOSFET Driver (V).
$F_{SW}$ = Switching Frequency.
n = number of driver channels.

$P_{DYNAMIC} = CC * F_{SW} * V_{DD} * n$
Where:
CC = Crossover constant (A*sec).

From IRF7307(example Power MOSFET) datasheet:
Worst case gate charge, $Q_G$ = 22nC → $C_G = \frac{Q_G}{V} = \frac{22nC}{5V} \cong 3.67nF$

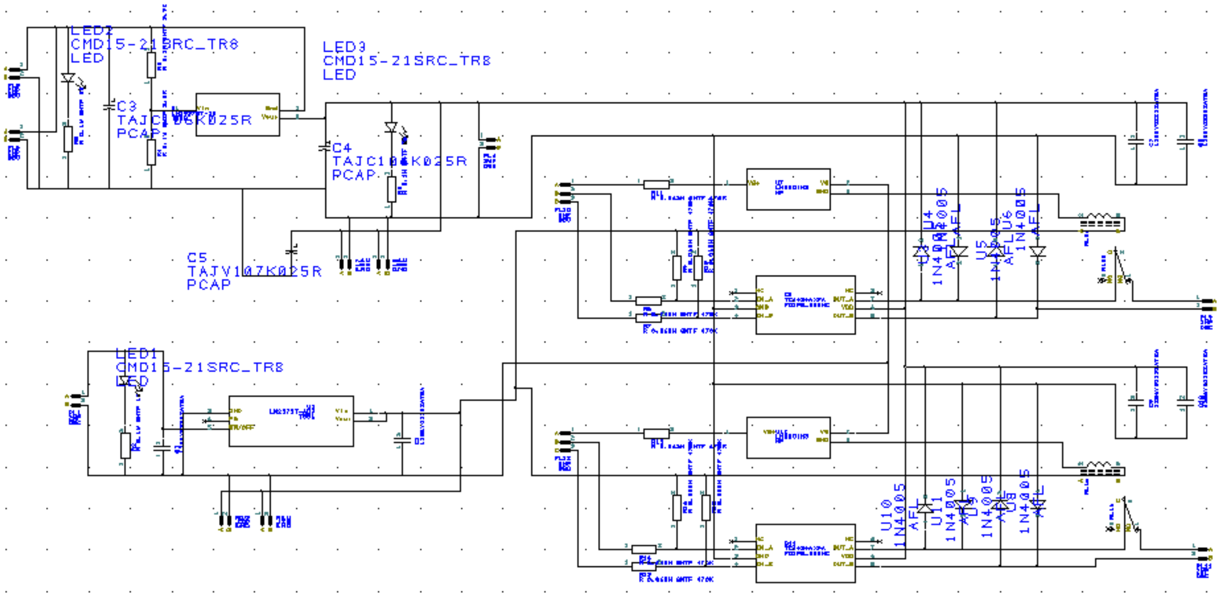
Assuming $F_{SW}$ = 300KHz;
$P_{GATE}$ = (3.67nF)*($6^2$)*(300E3)*2 ≅ 79.272mW

From TC4424A datasheet:
CC = 7E-9

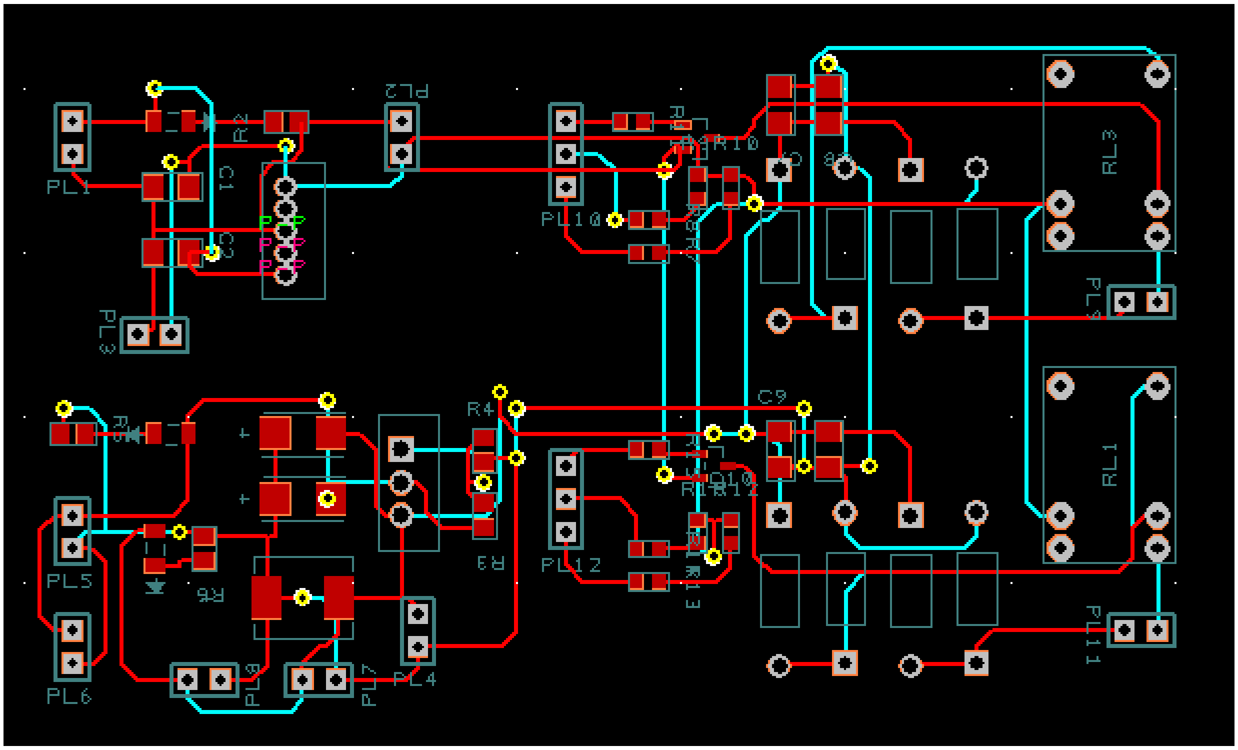
Assuming $F_{SW}$ = 300KHz;
$P_{DYNAMIC}$ = (7E-9)*(300E3)*(6V)*2 ≅ 25.2mW

$P_{QUIESCENT\text{-}CURRENT\text{-}DRAW}$ is generally very low and sometimes left out in power loss calculations. For the purposes of this rough power estimate the value was calculated which was:
$P_{QUIESCENT\text{-}CURRENT\text{-}DRAW}$ = 1.1208mW

$P_{TOTAL}$ = (79.272mW) + (25.2mW) + (1.1208mW) ≅ **105.5928mW**



*Combined Voltage Regulators and Motor Drivers Schematic*



*Preliminary PCB Layout*

| Development Board | PID Controller | Function |
|---|---|---|
| D_0 | A4 | SDA |
| D_1 | A5 | SCL |

| Development Board | Driver Board | Function |
|---|---|---|
| C_0 | P1A | Enable |
| C_1 | P1B | Enable |

| PID Controller | Driver Board | Function |
|---|---|---|
| D6 | P2A | Motor A PWM |
| D7 | P3A | Motor A FWD/REV |
| D8 | P3B | Motor B FWD/REV |
| D11 | P2B | Motor B PWM |

| PID Controller | Motor | Function |
|---|---|---|
| D2 | Encoder | Motor A Encoder A |
| D3 | Encoder | Motor B Encoder A |
| D4 | Encoder | Motor A Encoder B |
| D5 | Encoder | Motor B Encoder B |
| D9 | Servo | Servo A |
| D10 | Servo | Servo B |

*Remaining Connections Concerned in Layout*

| External Connections Required | | |
|---|---|---|
| Interface | Reference 1 | Reference 2 |
| Power | Battery | Logic Power Input |
| | Battery | Motor Power Input |
| | Logic Power Output A | MCU Power In |
| | Logic Power Output B | PID Power In |
| | Motor Power Output A | Servo A |
| | Motor Power Output B | Servo B |
| | Motor Power Output C | DC Motor A |
| | Motor Power Output D | DC Motor A |
| Driver - Motor | Motor Driver Output 1 | DC Motor A |
| | Motor Driver Output 2 | DC Motor B |
| MCU - Driver | MCU Pin C_0 | Motor Driver Enable 1 |
| | MCU Pin C_1 | Motor Driver Enable 2 |
| MCU - PID | MCU Pin D_0 | PID Pin A4 |
| | MCU Pin D_1 | PID Pin A5 |
| PID - Motor | Encoder Output A | PID Pin D2 |
| | Encoder Output B | PID Pin D3 |
| | Servo A | PID Pin D9 |
| | Servo B | PID Pin D10 |

*External Controller Connections*

## Thermal Considerations

In order to ensure the performance and longevity of the controller board, components must be examined for thermal output. These output temperatures must be kept below the maximum junction temperature of the component to ensure safe operation and maximum life of the board. According to Brian Dean, and expert at BD Micro LLC, our chosen development board, BD Micro Mavric IIb, has no appreciable heat generation. Therefore the heat generated by our designed voltage regulators will of primary concern.

**Voltage Regulators:**

From Linear Technologies micropower low-dropout regulator data sheet, we obtained a set of equations relating voltage and current to the junction temperature of the device.

$$P_d = I_{outMAX}\left(V_{inMAX} - V_{out}\right) + (I_{gnd} \times V_{inMAX}) \quad \text{.......................(1)}$$

$$P_d * R_t = \Delta T \quad \text{.......................(2)}$$

$$T_j = T_{amb} + \Delta T \quad \text{.......................(3)}$$

Where the input and output values are given as $I_{outMAX}$, $I_{gnd}$, $V_{inMAX}$ and $V_{out}$. When applied to constants $R_t$, the thermal resistance between the junction and ambient air and $T_{amb}$, the ambient temperature, $P_d$, the power dissipated and $T_j$, the junction temperature can be obtained.

For logic power the voltage needs to be regulated from 7.4 V to 5 V with a maximum output current of approximately 500mA. The ground current for the chosen regulator package, Linear Technologies LT1129-5 w/TO-220 package, can be obtained from the following chart.

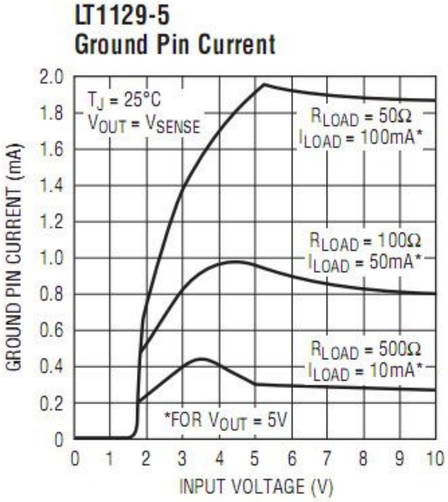


Figure 1: Ground pin current for Linear Technologies LT1129-5

From Figure 1 an approximate ground pin current of 0.3mA was obtained. The input and output values can be used in equation (1) to obtain the power dissipated.

$$P_d = 500mA(7.4v - 5v) + (0.3mA \times 7.4v) = 1.20W$$

The power dissipated can then be used in conjunction with the thermal resistance (50°C/W for TO-220 package) to find the junction temperature rise above ambient. This temperature can then be used with the ambient temp (90°F /32.22°C) to calculate the total junction temperature.

$$\Delta t = 1.20W \times 50\frac{°C}{W} = 60°C$$

$$T_{jMAX} = 60°C + 32.22°C = 92.22°C$$

The maximum junction temperature calculated is well below the maximum junction temperature listed in the datasheet of 125°C and therefore, pending temperature testing, no additional heat dissipation will be needed for this component.

For motor and servo power the voltage needs to be regulated from 7.4 V to 6 V with a maximum output current of approximately 4A. The data sheet for our second chosen voltage regulator, Linear Technologies LT1083 w/TO-3P package, provides an equation for calculating the power dissipated in both the control section and power transistor.

$$P_d = (V_{in} - V_{out})(I_{out}) \quad \text{.......(4)}$$

$$T_j = T_{amb} + P_d(R_{jc}) \quad \text{.......(5)}$$

Coupling equation (4) with equation (5) the junction temperatures can be obtained and compared to the maximum allowable junction temperature (125°C).

$$P_d = (7.4V - 6V)(4A) = 5.6W$$

$$T_j = 32.22°C + (5.6W)(0.5)\frac{°C}{W} = 35°C \text{ - Control Section}$$

$$T_j = 32.22°C + (5.6W)(1.6)\frac{°C}{W} = 41.18°C \text{ - Power Transistor}$$

The maximum junction temperatures calculated, for both the control section and power transistor, are well below the maximum allowable junction temperature listed in the datasheet of 125°C. Therefore, pending temperature testing, no additional heat dissipation will be needed for this component.

**MOSFET Drivers (H-bridge):**

Another board component deemed to produce a significant amount of heat are the MOFSET drivers used in the H-bridge. The data sheet of the chosen MOFSET driver, Microchip TC4424 8-pin PDIP, provides a thermal resistance, from junction to ambient, of 125°C/W for 4.5V<$V_{DD}$<18V and a maximum junction temperature of 150°C. From equations (6) and (7) the junction temperature can be obtained.

$$\Delta t = (P_{d\max}) \times R_{jc} \quad \text{.......(6)}$$

$$T_{jMAX} = \Delta t + T_{amb} \quad \text{(7)}$$

$$\Delta t = 739mW \times 125\frac{°C}{W} = 92.38°C$$

$$T_{JMAX} = 92.38°C + 32.2°C = 124.71°C$$

Another variation of the MOSFET driver is the Microchip TC4424A 8-pin PDIP. This driver was also taken into account because it will most likely be chosen over the TC4424 due to the current demands of the DC motors. The data sheet for the TC4424A, provides a thermal resistance, from junction to ambient, of $84.6^{o}$C/W for $4.5V<V_{DD}<18V$ and a maximum junction temperature of $150^{o}$C. From equations (6) and (7) the junction temperature can be obtained.

$$\Delta t = 1.2W \times 84.6\frac{°C}{W} = 101.52°C$$

$$T_{JMAX} = 101.52°C + 32.22°C = 133.74°C$$

*Note concerning the MOSFETs:*
It may be necessary to exceed the maximum recommended conditions of the MOSFET drivers in order to achieve desired functionality. Since the above calculations due not take into account the additional heat created by overdriving the MOSFETs, additional calculation as well as testing will need to be done in order to ensure the safety and reliability of the driver board.

Assuming that the additional heat will require the use of a heatsink on the MOSFET driver, a maximum heat sink thermal resistance can be calculated in terms of the heat dissipation in watts.

$$R_{HS} = \frac{T_{jMAX} - T_{amb}}{P_d} - \left(R_{jc} + R_{chs}\right) \quad \text{(8)}$$

$R_{jc}$ is the thermal resistance from the junction to the case, given by the data sheet, and $R_{chs}$ is the thermal resistance from the case to the heat sink which can be assumed to be a thermal paste of 0.02 $^{o}$C/W.

**Heat Due to Coating:**

Typical silicone conformal coatings have a thermal conductivity (the inverse of thermal resistance) of 0.04 and 0.12 W/$^o$C-m. The meter unit comes from the thermal conductivities dependency on the exposed area as well as the coating thickness.

For example for the LT1129 TO-220 package, the exposed area is 2500 mm$^2$ and a maximum coating thickness of 210um. The maximum thermal conductivity of the coating is 1.43e6 W/$^o$C which corresponds to a thermal resistance of approximately 7e-7 $^o$C/W. This thermal resistivity, for all intensive purposes, will add no significant increase in heat to the components.