EE 2810 Final Report

Group 17: We Are ADA Compliant

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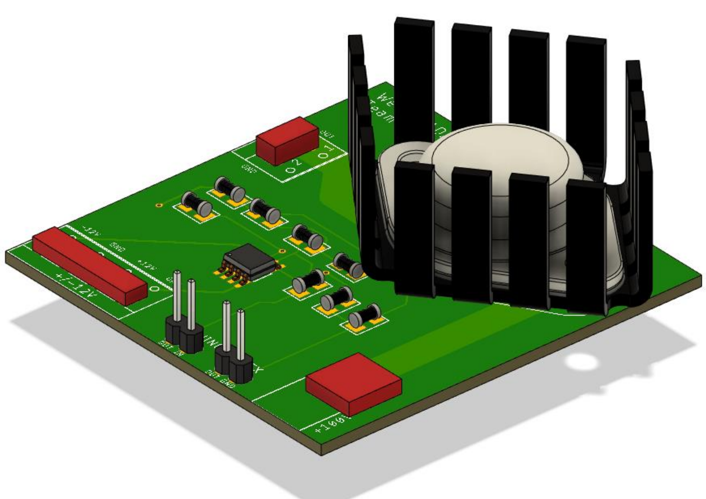
Introduction

The goal of this project is to provide an ample experience to gain insight into Senior Design and the Engineering Design Process. For this project we design a sort of robot arm actuator (as explained in lectures) that could be used in future adaptations and experiments. During the project, certain design criteria must be met to simulate an industrial scale application of the relationship between the consumer, the designer, and the providers. Note, this project is a simulation up to the point of filing order forms and requisitions without actual funding or funds allocation.



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1 Project Usage Description

The objective is to design a circuit that uses a flex sensor (possibly fitted onto a glove) that will generate a signal that when supplied to the pre-programmed Arduino Uno controller provides an output to a power amplifier. The power amplifier will produce enough power and current to run a motor of an unspecified type. Ideas presented in class explain that the motor could possibly be attached to a robotic arm that will move with correspondence to the motion of the flex sensor.

1.1 Design Criteria and Constraints

- Resistors used for the Wheatstone Bridge and the Difference Amplifier circuits must dissipate less than 0.25W.
- Flex Sensor used in Wheatstone Bridge must be by Spectra Symbol and range from 25k-ohms to 125k-ohms.
- Restricted to one of three of the following op amps: LM324, LM358, or LM741.
- The output of the difference amplifier must be no more than 5V and no less than 0V, it must also connect to an Arduino Uno analog input pin.
- The Power Amplifier must be capable of providing up to 10A to the emitter and should be able to absorb 200W.
- Connectors must be used for two 12V batteries, an external DC power supply (for the power amplifier, also capable of carrying 10A), and an external load (which will simulate a motor) that can carry 10A).
- Power Amplifier must use a TO-3 Package Transistor.

2 Wheatstone and Flex Sensor

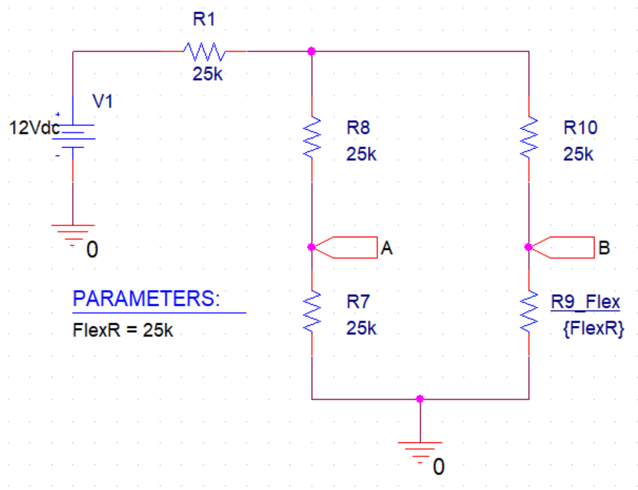

Figure 1. Wheatstone circuit used for analysis.

The purpose of the Wheatstone bridge circuit is to create the voltage difference V_{BA}, this can be measured and used to roughly calculate the resistance of the flex sensor. The sensor in the bottom right acts as a flexible potentiometer and ideally leaves the bridge balanced when no flex is applied, in this case $V_{BA} = 0$.

The flex sensor will theoretically range from $25k\Omega$ to $125k\Omega$ with a $\pm 30\%$ error that becomes $17.5k\Omega$ to $162.5k\Omega$. The other resistors in this circuit have an error of only $\pm 1\%$, which for our purposes is negligible.

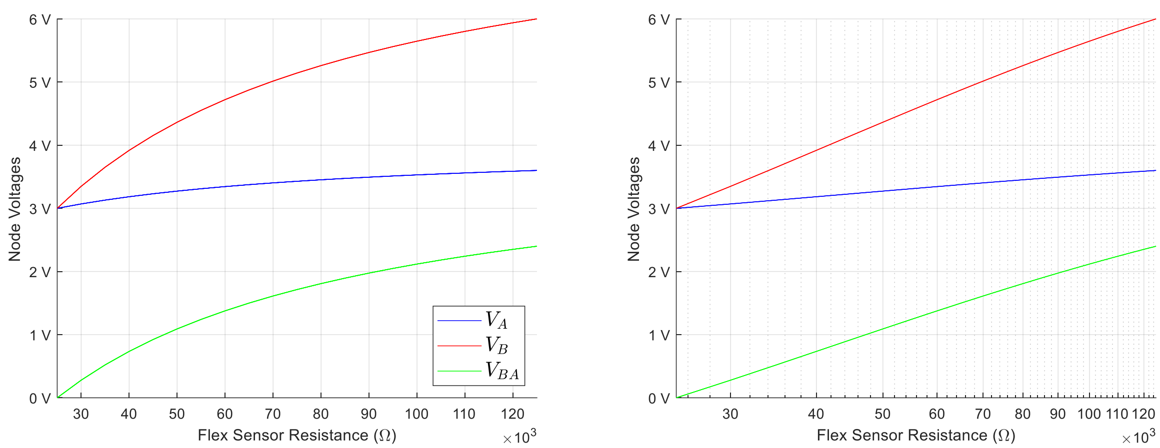

Figure 2. Node voltages V_A, V_B and V_{BA} vs. flex sensor resistance.

2.1 Temperature and Sensitivity Analysis

According to their datasheet our $25k\Omega$ resistors have a temperature coefficient of $\alpha = \pm 200ppm/$℃ and an operating temperature of -55 to 155℃. Likewise, the listed operating temperature for the flex sensor is -35 to 80℃.

The sensitivity analysis below was conducted on the balanced Wheatstone bridge when $R_{Flex} = 25k\Omega$.

DC Sensitivities:		Output V(A)		Output V(B)	
	Element Value	*Element Sensitivity (Volts/Unit)*	*Normalized Sensitivity (Volts/Percent)*	*Element Sensitivity (Volts/Unit)*	*Normalized Sensitivity (Volts/Percent)*
R_R1	2.500E+04	-6.000E-05	-1.500E-02	-6.000E-05	-1.500E-02
R_R2	2.500E+04	-4.500E-05	-1.125E-02	1.500E-05	3.750E-03
R_R3	2.500E+04	7.500E-05	1.875E-02	1.500E-05	3.750E-03
R_R4	2.500E+04	1.500E-05	3.750E-03	-4.500E-05	-1.125E-02
R_flex	2.500E+04	1.500E-05	3.750E-03	7.500E-05	1.875E-02
V_V1	1.200E+01	2.500E-01	3.000E-02	2.500E-01	3.000E-02

3 Arduino Uno

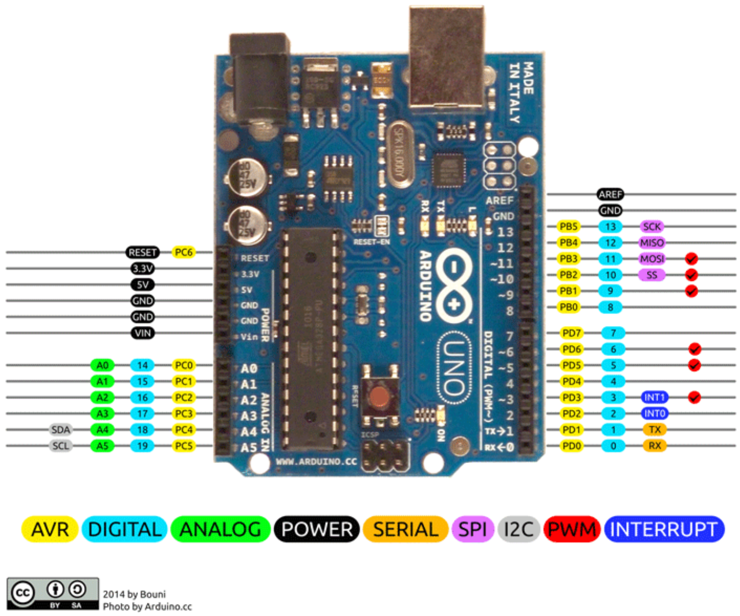

Figure 3. Pinout guide for the Arduino Uno.

The Arduino Uno has a 10-bit analog to digital converter that maps voltages of 0 to the operating voltage $5V$ to a number between 0 and 1024. The board can read an analog signal from 6 pins A0-A5 using `analogRead()` in the IDE. The pins have internal resistance $100M\Omega$.

For output the Arduino also supports the `analogWrite()` function which can write to PWM pins 3, 5, 6, 9, 10, or 11 at 490 Hz (pins 5 and 6: 980 Hz) with 8-bit resolution. The output voltages range from 0 to $5V$. The internal resistance of these output pins is said to be negligible but for our purposes we will assume this to be $100m\Omega$.

4 Op Amp Analysis

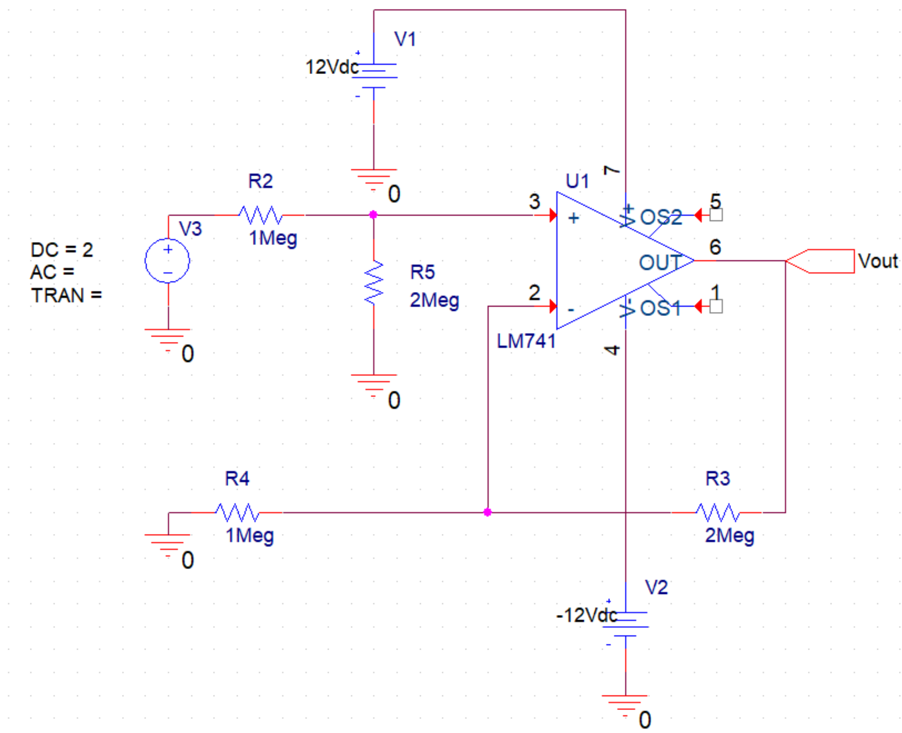

Figure 4. Isolated Op Amp circuit used for sensitivity analysis.

The maximum output voltage of the Wheatstone bridge will be approximately 2.5V or less, therefore we want to build a difference amplifier with a gain of 2. Using the megaohm configuration as shown in the circuit diagram above, we will be able to maintain this gain across the op amp, while allowing minimal current to flow to avoid damaging components.

4.1 Sensitivity and Temperature Analysis

Using PSPICE to run temperature and sensitivity analysis on the op amp portion of our design, we tested many of the coefficients using a test voltage of 2V to give an idea of approximately how the circuit would operate.

Resistor values with included Temperature Coefficients

	-55°	0°	27°	70°	125°	150°
R2 (MΩ)	0.984	0.995	1.000	1.009	1.020	1.025
R3 (MΩ)	1.967	1.989	2.000	2.017	2.039	2.049
R4 (MΩ)	0.984	0.995	1.000	1.009	1.020	1.025
R5 (MΩ)	1.967	1.989	2.000	2.017	2.039	2.049

Sensitivity analysis with output Vout for LM741 (Resistor values in table above)

	-55°	0°	27°	70°	125°	150°
R2 (ΔmV/%)	-14.38	-14.40	-14.40	-14.41	-14.42	-14.42
R3 (ΔmV/%)	27.19	27.20	27.20	27.20	27.21	27.21
R4 (ΔmV/%)	-25.61	-25.60	-25.59	-25.58	-25.57	-25.57
R5 (ΔmV/%)	12.81	12.80	12.80	12.79	12.79	12.79

All resistors have a ±5% tolerance. For worst case scenarios on both extremes:

$$V_{out,min} = 5(V_{R2} - V_{R3} + V_{R4} - V_{R5}) + V_{out}$$

$$V_{out,max} = 5(-V_{R2} + V_{R3} - V_{R4} + V_{R5}) + V_{out}$$

To calculate the maxima and minima output voltage we can follow the formulas above. For the maximum voltage output of the op amp we calculate it to be approximately 4.4V, while the minimum output voltage will be close to 3.6V based on the 2V input test voltage. This proves the gain is averaging around two, and these extremes are only due to ±5% nature of the resistors.

5 BJT Analysis

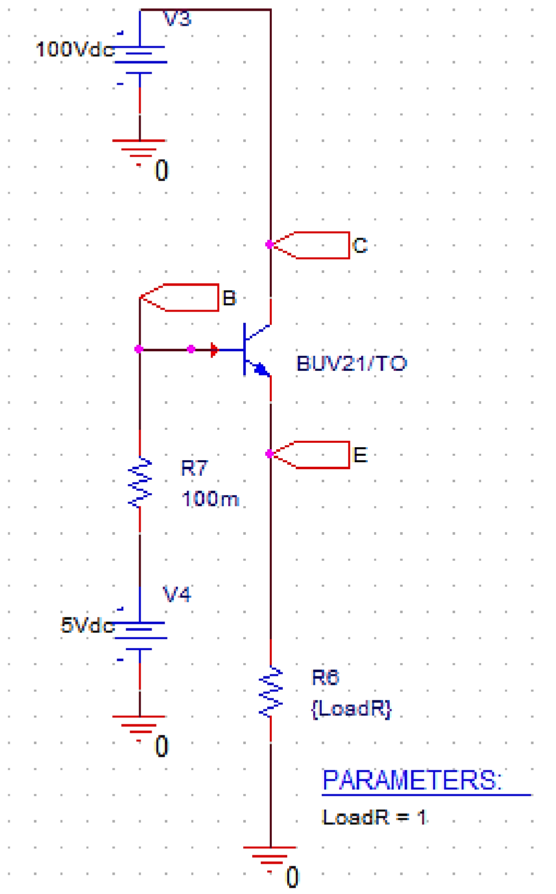

Figure 5. The circuit used to model the BJT.

The Arduino will modulate the analog output between 0-5V in order to deliver power to the motor represented by load resistor R6. In our first analysis of this circuit we will preform a DC sweep of V4 to get an idea of how the Arduino output effects node voltages and power delivered.

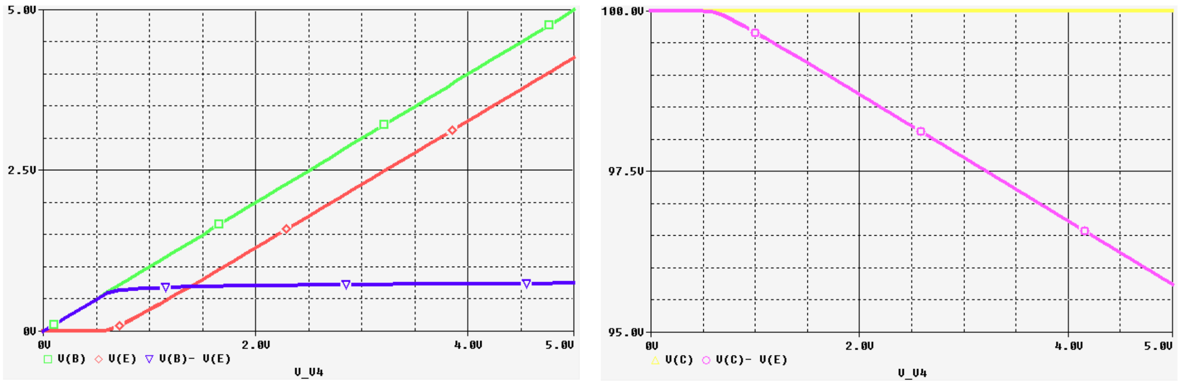

Figure 6. Relevant voltage differences for operation of the BJT for all Arduino output values.

In the images above, our BJT begins as off and then spends most of the DC sweep in activation mode. This gives a consistent model of behavior, as saturation would not occur until $V4 \approx V3 = 100V$ which is physically impossible for the Arduino.

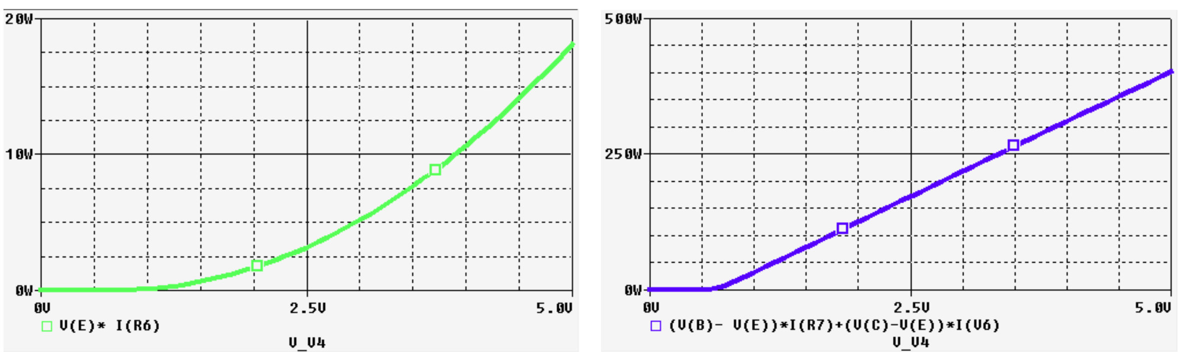

Figure 7. (a, left) Power delivered to motor. (b, right) Power dissipated by the BJT.

A key observation from the traces above is that the transistor dissipates maximum power when the Arduino is outputting $5V$. This fact will be used to test absolute maximum conditions in section 5.2 on usage constraints.

All simulations in throughout this section will be performed with default values $V3 = 100V$, $V4 = 5V$ and $R6 = 1\Omega$ unless otherwise specified.

5.1 Temperature and Sensitivity Analysis

In order to get a rough idea of how our circuit will respond to small changes in various parameters at different temperatures, we performed a temperature sensitivity analysis. Because this circuit is designed to deliver power, we will be considering both voltage and current sensitivities.

DC Sensitivities of Output V(R6)

	0 °C	27 °C	70 °C	125 °C	150 °C	200 °C
R6 (ΔμV/%)	298.1	323.9	365.2	418.0	442.1	490.3
V4 (ΔmV/%)	49.64	49.61	49.57	49.52	49.49	49.45

DC Sensitivities of Output I(R6)

	0 °C	27 °C	70 °C	125 °C	150 °C	200 °C
R6 (ΔmA/%)	-41.89	-42.26	-42.87	-43.66	-44.03	-44.77
V4 (ΔmA/%)	49.64	49.61	49.57	49.52	49.49	49.45

Note that because we used default parameters for this analysis $R6 = 1\Omega$, and the sensitivity of I(R6) and V(R6) with respect to $V4$ is the same.

5.2 Power Ratings and Usage Constraints

In electrical components, rise in temperature is proportional to power dissipated. According to the datasheet of the BUV20, the **maximum power dissipated** at room temperature is $250W$ and the **maximum junction temperature** is 200℃. Because *npn* transistors have two input currents, the total power dissipated is calculated by

$$P = V_{BE}I_B + V_{CE}I_C.$$

In this section, we will be measuring the maximum power dissipated by our transistor with respect to various user-dependent parameters of our circuit.

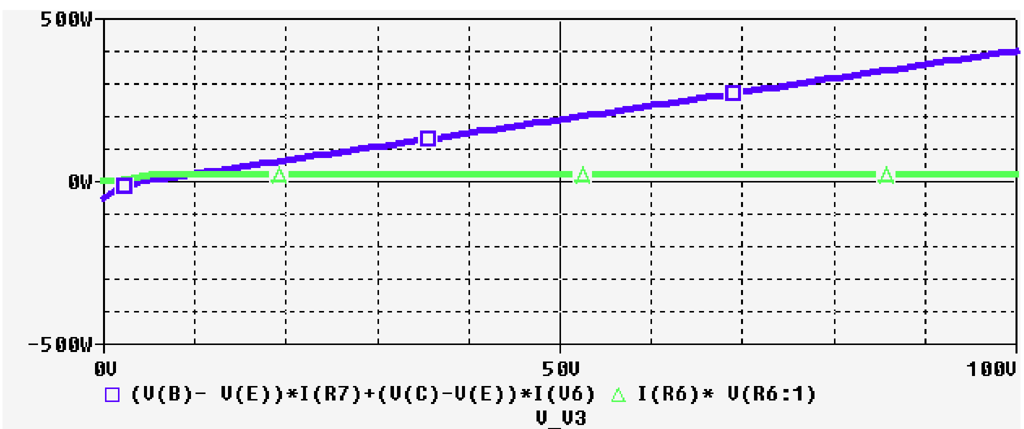

Figure 8. DC sweep performed on $V3$, voltage input to the DC jack. The power delivered to the motor (green) maxes out at $18.5W$ when $V_3 = 6V$ whereas the power dissipated by the transistor (blue) continues to rise to $404W$ when $V_3 = 100V$.

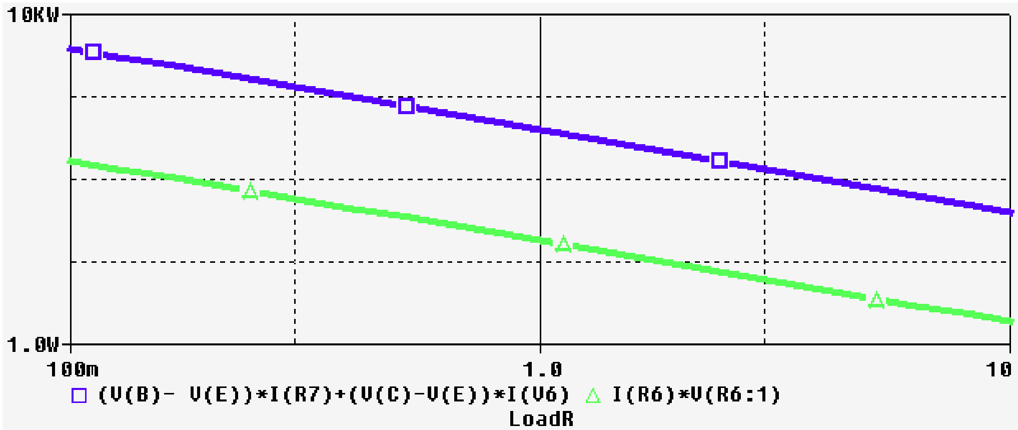

Figure 9. Log-Log plot of power delivered to motor (green) and power dissipated by the transistor (blue) as the load resistance R6 varies by $\pm 1\ dB$.

The traces above together with information from the BUV20 datasheet give safe operating values of $R6 \geq 1.6\Omega$ with $V3 = 100V$ or $V3 \leq 70V$ with $R6 = 1\Omega$.

5.3 Heat Sink Considerations

Temperature analysis is analogous to typical circuit analysis where instead of $\Delta V = IR$, we have $\Delta T = P_D \Theta$ where P_D is **power dissipated** and Θ is **thermal resistivity** between components. The datasheet lists maximum power dissipated as $250W$ and junction case thermal resistance $\Theta_{JC} = 0.7℃/W$. This gives $\Delta T = 175℃$ on the transistor case.

The figure below shows the components of our heat sink configuration with models and parameters used in our fusion 360 simulation.

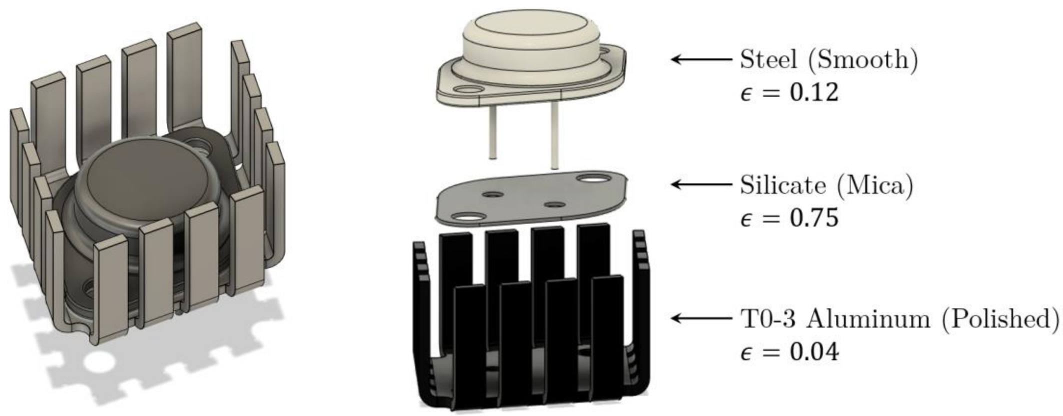

Figure 10. (a, left) CAD model retrieved from grabcad.com. (b, right) Components of the model labeled with material and emissivity used in the thermal simulation.

The simulation took into account the internal heat as calculated above, radiation caused by material emissivity, thermal contact resistance and convection throughout the components taken to be at a standard 12 $W/(m^2K)$. The ambient temperature for each load was considered to be 27℃.

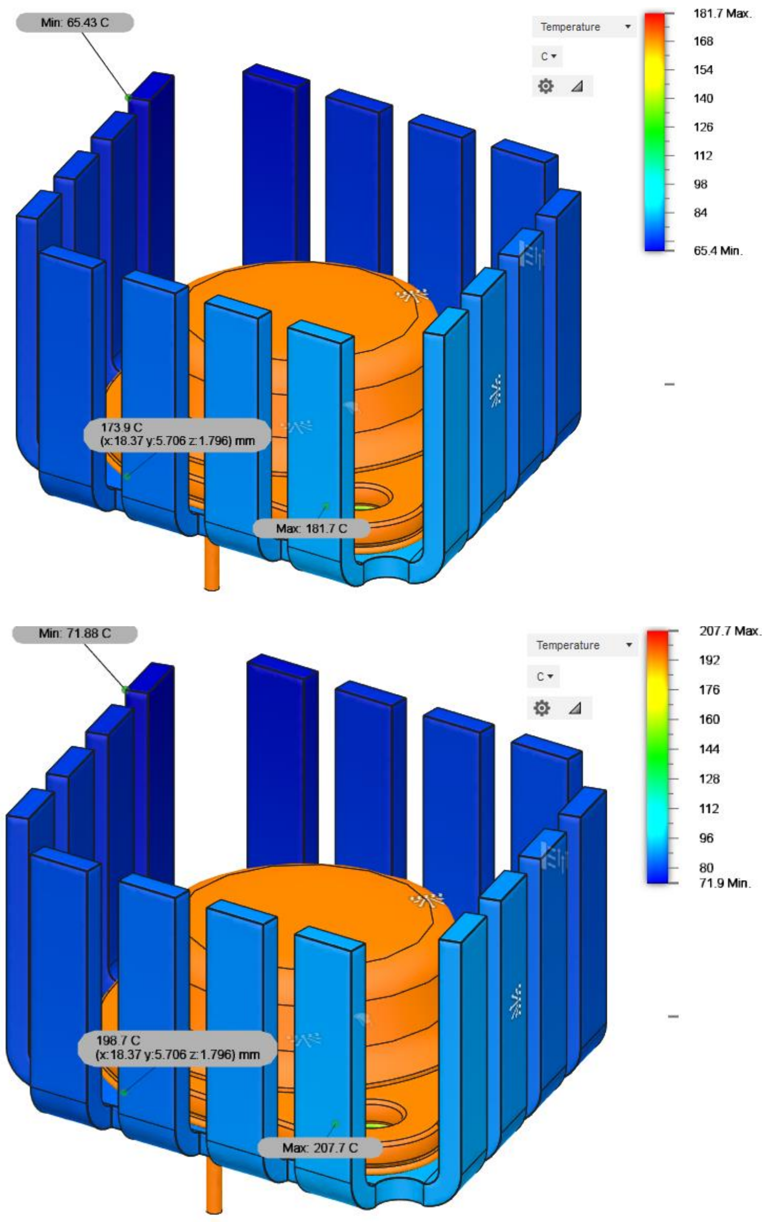

Figure 11. (a, top) Simulation ran at case temperature calculated from maximum power dissipation. (b, bottom) Simulation ran at maximum case temperature specified by datasheet. In each image, temperature pins are placed on the BJT body, the mica insulting pad and the heatsink.

6 PCB Design and Analysis

Our PCB aimed to be as small as possible, while still supporting the constraints of our vendor and the design itself. The size of the board is 70x70mm. If this board needed to be assembled manually, we have included a silkscreen layer with outlines of all the parts with their names (excluding resistors) and values labelled.

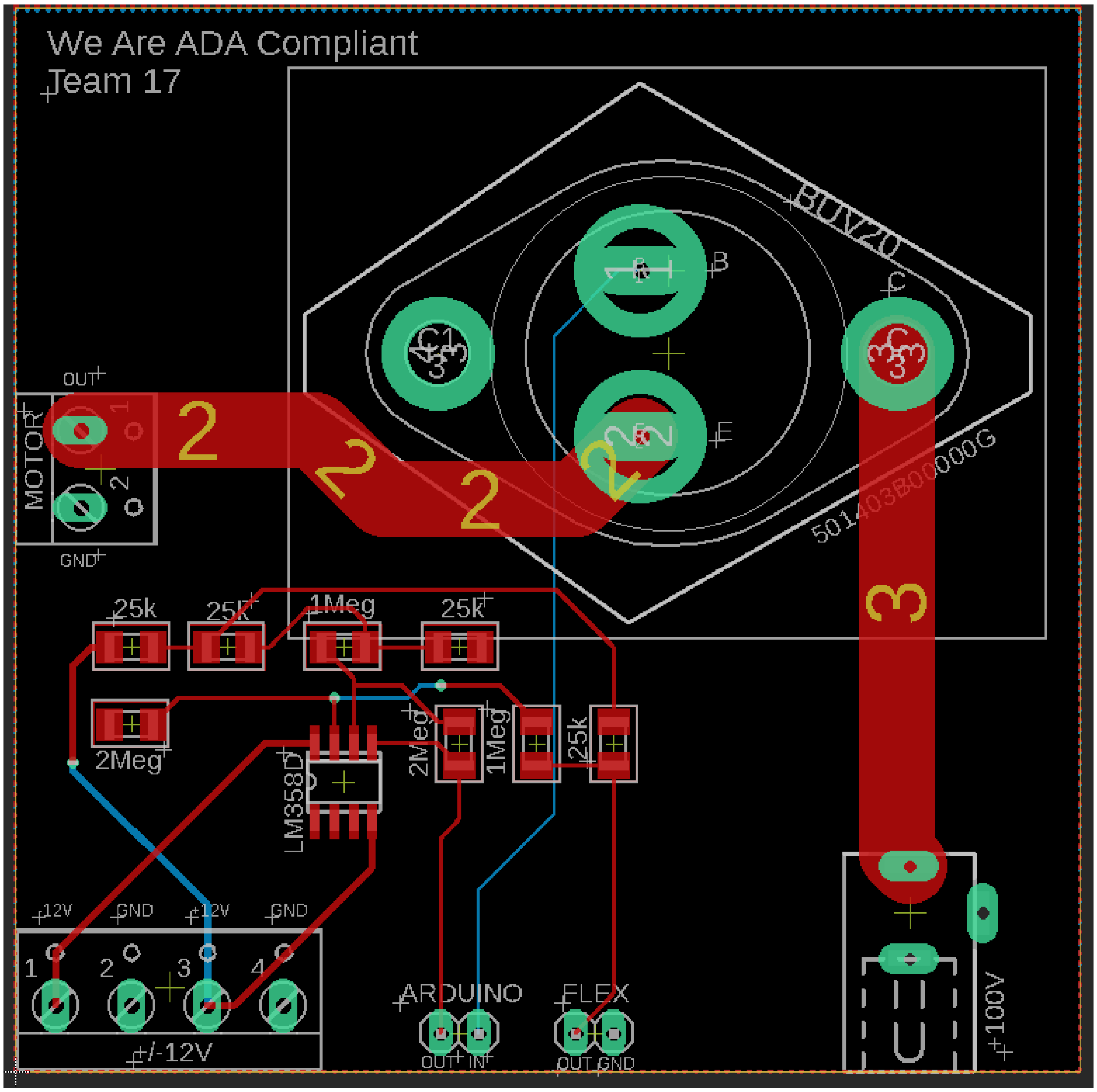

Figure 12. Image of our board. Heatsink footprint sourced from componentsearchengine.com and converted to an eagle library via the Altium Library Loader.

6.1 Trace Widths

12V and -12V supply	15mil
+100V supply	196mil
All other connections	10mil

While we could have gone for smaller signal trace widths on the small connections, we felt it was not necessary. For a board with relatively few components, the larger the traces the better. Of course, the 12V supply traces need to be larger than the small signal ones to differentiate the two, as well to be able to handle the current and voltage flowing through them.

Due to finding that the maximum current going into the BJT can never reach 10A, the trace width for the collector input and emitter output is 196mil (can handle 7.6A). This information was found using this trace width calculator.

As for ground planes, there is a top and bottom plane using 1 oz. copper (same with traces).

6.2 Connectors

12V and -12V supply	2 2-pin screw-clamp terminal blocks	PRT-08432
+100V supply	Standard DC barrel jack	CON-SOCJ-2155
Motor I/O	1 2-pin screw-clamp terminal block	PRT-08432
Arduino I/O	2-pin female wire socket pin header	PPPC021LFBN-RC
Flex sensor I/O	2-pin female wire socket pin header	PPPC021LFBN-RC

For our 12V supply blocks, we have 4 inputs due to having two external 12V batteries. Each battery has a positive and negative wire, so to supply +12V, the positive wire goes into pin 1 and the negative wire goes to pin 2 (GND). To supply -12V, the negative wire goes into pin 3 and the positive wire goes to pin 4 (GND).

As for how the batteries are positioned physically, we are using 2 single A23 battery holders with wire leads. This gives us flexibility to put them wherever they are needed, such as on a chassis or sticking them to the bottom of the board.

For the motor i/o block, we will be using 18-gauge wires, since they are able to handle 8A flowing through them in air. The terminal block is able to fit 18-gauge wires. As for all other connections, we will be using 22-gauge wires since they are more accessible (and we have used them in the past with other labs in LSU). [Chart we used to determine size]

6.3 Design Rules

Our vendor of choice is JLCPCB. We chose this vendor because they were the cheapest to order from. They are well-prepared for enormous orders, since the highest option for a *single* order is 90,000 units. Other vendors we found did not have an option for such a larger order and would result in contacting them directly for a special quote. As for each vendor, they have a specific set of rules for PCB fabrication.

Element	*Our Board*	*JLCPCB design rule*
Trace widths	Min: 10mil, Max: 196mil	>3.5 mil
Copper plating	1oz	1-2oz
Board size	70x70mm	400x500mm
Layers	2	1-6
Via size	Min: 30mil	>7.87mil
Drill hole size	Min: 40mil, Max: 230mil	>7.87mil and <248.03mil
Text character length	Min: 6mil	>6mil
Text character height	Min: 35mil	>32mil

*A relevant list of design rules compared to our specs. The full list can be found here.

7 Component Requisition

Subcircuit / Misc. Components	*Description*	*Model Number*	*Total Cost (for 100,000 complete units)*
Wheatstone Bridge	25kΩ Resistor $\pm$1% 1/4W	RVC1206FK25K0	$26,880.00
	25k-125kΩ Flex Sensor	SEN_FLEX2P2_DE3	$795,000.00
Op-Amp	1MΩ Resistor $\pm$5% 1/4W	RMCF1206JG1M00	$465.18
	2MΩ Resistor $\pm$5% 1/4W	RMCF1206JG2M00	$465.18
	Dual Channel Op-Amp LM358	LM358LVIDR	$6,400.00
BJT	TO-3 NPN PWRBJT 125V 50A	BUV20	$2,711,000.00
	TO-3 Heatsink	501303B00000G	$69,120.00
Connectors	2-pin Screw-Clamp PCB Terminal Block	PRT-08432	$285,000.00
	DC Power Barrel Jack	CON-SOCJ-2155	$100,000.00
	2-Pin Female Wire Socket Pin Header	PPPC021LFBN-RC	$26,000.00
Voltage Supply	12V A23C Battery	A23C	$77,140.00
	A23C Battery Holder	BH23AW	$184,886.00
PCB	70x70mm board by JLCPCB	n/a	$40,252.74

8 Conclusion

For our complete and assembled board, the total cost for 100,000 units comes out to be $4,351,172.47 and $43.52 per unit. If we wanted to make a 25% profit, each board would have to be sold for $54.40 and we would profit ~$1,088,000.

Our research and simulations have definitely taught us on how industry circuit analysis works. We did research all the way from doing a basic analysis on a circuit to deciding what size and layers of PCB traces are needed. The key to this project was o never gloss over the small things, as the small errors in design can accumulate to make an entire schematic fail.

Appendix I: Op Amp Decision Matrix

When deciding our op amp, we had a few to select from. As suggested, we came up with a decision matrix as seen below to help rectify our choice.

Pairwise Matrix	Speed	Price	Accuracy	Geometric Mean	Normalized Mean
Speed	1	2	0.33	0.870658769	0.261943831
Price	0.5	1	0.5	0.629960524	0.189528066
Accuracy	3.03030303	2	1	1.823218359	0.548528101

To define a metric for accuracy, we first performed a temperature sensitivity analysis on each option. Refer to resistance values in section 4.1 for specific calculations.

LM741	**-55°**	**0°**	**27°**	**70°**	**125°**	**150°**
R2 (ΔmV/%)	-14.38	-14.40	-14.40	-14.41	-14.42	-14.42
R3 (ΔmV/%)	27.19	27.20	27.20	27.20	27.21	27.21
R4 (ΔmV/%)	-25.61	-25.60	-25.59	-25.58	-25.57	-25.57
R5 (ΔmV/%)	12.81	12.80	12.80	12.79	12.79	12.79

LM358	**-55°**	**0°**	**27°**	**70°**	**125°**	**150°**
R2 (ΔmV/%)	-12.72	-12.74	-12.74	-12.73	-12.72	-12.73
R3 (ΔmV/%)	26.35	26.34	26.34	26.34	26.34	26.34
R4 (ΔmV/%)	-27.23	-27.24	-27.24	-27.25	-27.25	-27.25
R5 (ΔmV/%)	13.62	13.62	13.62	13.62	13.62	13.62

LM324	**-55°**	**0°**	**27°**	**70°**	**125°**	**150°**
R2 (ΔmV/%)	-12.75	-12.74	-12.74	-12.73	-12.72	-12.73
R3 (ΔmV/%)	26.35	26.34	26.34	26.34	26.34	26.34
R4 (ΔmV/%)	-27.23	-27.24	-27.24	-27.25	-27.25	-27.25
R5 (ΔmV/%)	13.62	13.62	13.62	13.62	13.62	13.62

We then defined accuracy in terms of the worst-case extremes, $V_{out,max} - V_{out,min}$, see section 4.1 for expressions and details.

Metrics that define cost had to be corrected so they would have the appropriate impact.

Price			Accuracy			
Values	Normalized	Corrected	Values	Normalized	Corrected	Op-Amp Types
11,000.00	0.461215932	0.538784067	0.7994	0.333263851	0.66673614	LM324
5,600.00	0.234800838	0.765199161	0.7994	0.333263851	0.66673614	LM358
7,250.00	0.303983228	0.696016771	0.7999	0.333472297	0.66652770	LM741

In the end, we had the final decision matrix pictured below.

Criteria	Weights	LM324	LM358	LM741
Speed	0.261943831	0.33333333	0.33333333	0.33333333
Price	0.189528066	0.538784067	0.765199161	0.696016771
Accuracy	0.54852810	0.666736148	0.666736148	0.666527702
Output		0.55515282	**0.59806484**	0.58483849

Appendix II: MATLAB Numerical Modeling for Microcontrollers

The purpose of the Arduino is to take in the ratio $2V_{BA}$, use this to calculate the resistance caused by the flex sensor and deliver power to the motor proportional to the indicated flex (or change in flex). This relation could be derived analytically but will most likely take the form of a rational function with a computationally costly inverse. For this reason, MATLAB will be used to derive an inexpensive approximation of $V_{BA}(R_x)$ and its inverse.

The code below could be used to approximate $V_{BA}\;R_x \approx aR_x^b + c$ over the operating resistances from a FlexSweep.csv output file from PSPICE.

```
FlexR = FlexSweep.FlexR;
VBA = FlexSweep.VB-FlexSweep.VA;
y = @(B,x)  B(1).*x.^B(2) + B(3);   % B is an unknown vector
beta0 = [1;1;1];         % initial value of B used for SGD
nlinfit(FlexR, VBA, y, beta0)
```

This file output $V_{BA}\;R_x \approx -54.04R_x^{-0.158} + 10.87$ with scores $R^2_{adj} = 0.9998$ and $RMSE = 0.0094$.

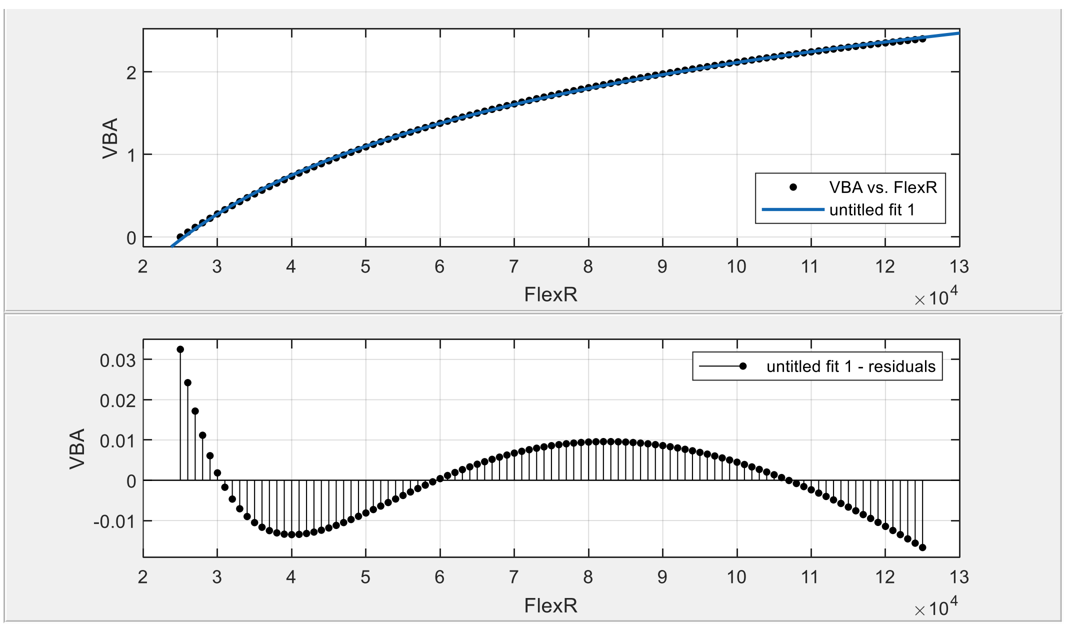

Figure 13. Our fit model plotted with residuals subplot rendered in the Curve Fitting App.

Appendix III: Circuit Design Netlist (PSPICE A/D Code)

```
*Wheatstone Bridge:

V1      1       0       12Vdc
R1      1       2       25k
R2      2       3       25k
R3      3       0       25k
R4      2       4       25k
R5      4       0       *Varies from 25k-125k ±30% (Represents Flex Sensor)
```

```
*Difference Amplifier Using LM358

R6      4       5       1Meg
R7      5       0       2Meg
R8      3       6       1Meg
R9      6       7       2Meg
V2      8       0       12Vdc
V3      0       9       12Vdc
X1      5       6       8       9       7       LM358
.LIB    NOM.LIB;        *Takes the model of the LM358 from the PSPICE Library.

**Using Node 7 as the output, in the Power Amplifier circuit, 7 will represent the output running
**from the Difference Amplifier & Arduino Uno Combination. Please note that in actual
**implementation of this code, a 100Meg resistor can be used to simulate the Arduino Output
**Pin internal resistance.
```

```
*Power Amplifier Using BUV-20 (TO-3 Package)

V4      10      0       100Vdc          *Simulates very high voltage input to collector of BJT
R10     12      0       1               *Simulates motor, to provide output current and power
Q1      10      7       12      BUV20
.LIB    NOM.LIB;                        *Takes the model of the BUV20 from the PSPICE Library.
```

The above circuit design netlist/PSPICE A/D code will generate a circuit similar to the following: