

“Extended Reach” Haptic Array

Design Review

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1. Introduction

1.1 Description

The motivation for this project stems from a desire to extend and expand human sensory perception. There are many signals that humans simply don't have the capacity to sense; ultrasound, infrasound, the vast majority of the electromagnetic spectrum, and the temperature of distant objects are all invisible to humans. Our project aims to allow humans to experience these signals by translating them into a form that humans can recognize.

Specifically, this project will provide the tools to map any quantified characteristics of a signal detected by a sensor into a haptic response on an arm-worn array of motors. This haptic feedback system will use an array of micro-transducers to stimulate the user's arm, utilizing the body's haptic perception of different intensities, locations (two dimensions), and frequencies. Every tenth of a second, the haptic device will accept a packet of information from the sensor. This packet will give values for up to three signal characteristics, which will then be intelligently mapped to haptic intensity, location, and frequency. The mapping will be modular and easy to use; the user will have the ability to decide what signal characteristic gets mapped to each haptic quality. The end result will be a "natural" psychophysical stimulus to a signal imperceptible to humans.

This project is a continuation from a previous semester's project (60 Hz Electromagnetic Field Detector/Interface System). We are focusing on improving the haptic array. The previous project's haptic array was only capable of changing intensity, and was also flimsy. We aim to expand the haptic stimulus to include location and frequency, and use durable build techniques for a robust haptic device.

1.2 Goals

The primary goal of this project is to create a robust haptic biofeedback device that delivers a continuous stimulus to the user's arm, allowing the user to become aware of sensory data normally outside the range of human perception. This device will include a simple Arduino program that will facilitate the mapping of sensory data to haptic stimulus. Also, the device will include circuitry to amplify and control the motors such that they deliver natural and repeatable feedback to the user.

1.3 Benefits

- Augments human sensory perception
- Delivers "natural" psychophysical haptic feedback
- Provides four dimensions of biofeedback (intensity, frequency, x/y location)
- Modular device driver works with any quantified signal characteristics
- Unobtrusive haptic feedback works in noisy and bright environments.

- Modularity allows expansion and integration into other human augmentation designs

1.4 Features

- Arm-worn haptic feedback array
 - Sturdy, compact design
 - Four dimensions of haptic feedback
- Haptic feedback driver with simple programmable interfacing with signal characteristics
 - Modular, simple user interface
 - Supports any quantifiable signal qualities

2. Design

2.1 Block Diagram

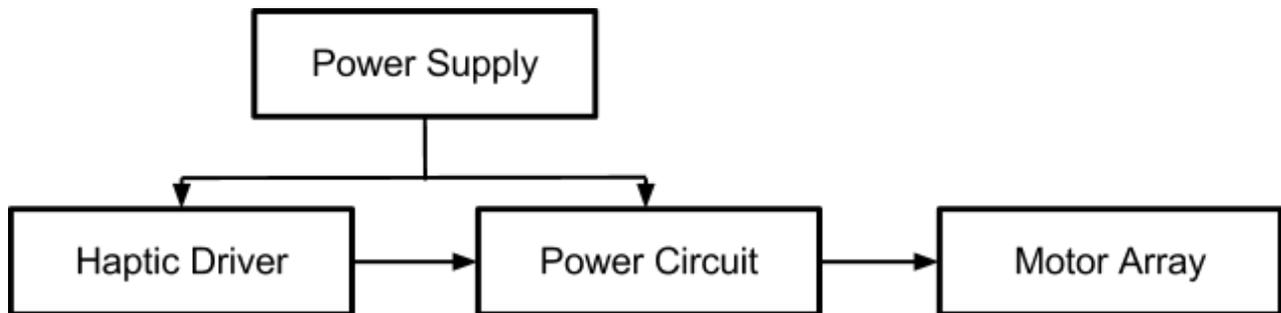


Figure 2.1: Haptic Array Block Diagram

2.2 Block Descriptions

Power Supply: Power will be supplied by DC battery sources.

Inputs: None

Outputs: 4.8V and 9V DC

Haptic Driver: An Arduino Uno microcontroller will take in quantified signal characteristics and map these characteristics to haptic features of the array. PWM values for every motor will be calculated to achieve the haptic stimulus. This values will be outputted through the digital I/O pins of the Arduino board.

Inputs: 9V DC (9V battery)

UART data from sensor

Outputs: PWM signals for every motor through digital I/O pins

Power Circuit: The power circuit will maintain, amplify, and control the PWM signals from the Haptic Driver such that they can be used to drive the motor array. The TI TLC5940, a 16 Channel LED Driver, will be used to amplify and control the PWM response of the motors.

Inputs: 4.8V DC (4 NiMH AA batteries)

PWM signals from Haptic Driver

Outputs: Amplified PWM signals for every motor

Motor Array: The motor array will be two 5x3 arrays of shaftless vibration motors (one for the top of the forearm, and one for the bottom). The motors will be secured in a robust armband.

Inputs: Amplified PWM signals from Power Circuit

Outputs: Haptic stimulus on user's arm

2.3 Performance Requirements

- Achieve a robust device by employing durable build techniques
- Achieve continuous perception (motors indistinguishable from one another)
- Achieve repeatable results for dependable feedback
- Achieve large range of frequency and intensity across entire array

2.4 Schematic

2.4.1 Hardware

Sub-circuit Descriptions

The circuit for the haptic feedback array will make use of an Arduino Duemilanove, two TLC5940 LED driver IC chips, thirty shaftless vibration motors, thirty diodes, thirty 17.4 Ohm resistors, two 650 Ohm resistors to set the channel current to 60 mA, a 9V power source for the Arduino, and a 4.8V power source for the TLC5940 chips and motor array.

TLC5940:

The main purpose of the TLC5940 is to maintain the PWM signals to the motors. This way, the Arduino is free to process future PWM values instead of working to maintain current PWM signals. The TLC5940 has 28 pins, which can be seen in the schematic. The notable ones are as follows¹:

- XERR: this output indicates that the TLC5940 has overheated or has a burnt out LED. We are not using this output.
- SOUT: this is the serial data output pin. We are using it for the daisy-chaining functionality to chain the two chips together. It is connected to the SIN of the second chip.
- DCPRG: this input selects the source of the current limiter register. We will be keeping it high.
- IREF: This sets the current output of every channel. The equation for determining the value of this current is as follows:

$$I_{max} = \frac{V_{(IREF)}}{R_{(IREF)}} \times 31.5 \quad [2.1]$$

Using this formula, we determined that a 650 Ohm resistor is necessary to achieve a channel current of 60 mA.

- XLAT: this input is used to latch data after shifting. The TLC5940 library functions control what is input to XLAT.
- SCLK: this input is used to clock data shifting. The TLC5940 library functions control what is input to SCLK.
- SIN: this is the serial input pin for the TLC5940. For the first chip, this pin is connected to the Arduino. For the second chip, it is connected to the first chip's SOUT.
- VPRG: this selects the chip's mode of operation. We will tie VPRG to ground to select GS (grayscale) mode.
- GSCLK: this is the grayscale clock for the PWM. It will be driven by the Arduino's digital I/O pin 3.
- BLANK: this indicates that a grayscale PWM cycle has completed, and also blanks the output. We will tie this to the Arduino's digital I/O pin 10.
- OUT: there are 16 current-sink output pins. These are the channels that will maintain the PWM on our motor array.

Flyback Diode Circuit:

A best practice for connecting small motors to a current sink is to use a Flyback Diode Circuit design. Because motors have not only real impedance, but an imaginary component from the wire coil as well, the circuit must be designed to deal with the inductive properties.

The voltage across the motor is defined (modeled as an inductor) :

$$V_L = -L \frac{dI}{dt} \quad [2.2]$$

The voltage the TLC5940 maintains is controlled by a resistance R_c :

$$V_{IC} = I \cdot R_{IC} \quad [2.3]$$

When the TLC5940 stops the current, the voltages are equal:

$$I \cdot R_{IC} = -L \frac{dI}{dt} = V_{IC} \quad [2.4]$$

Above it can be inferred that as the TLC5940 attempts to stop the current, R_{IC} jumps very high as it is designed to mitigate I . However, $\frac{dI}{dt}$ will jump as the inductive part of the motor

attempts to maintain the current. This will cause a large negative spike in V_{IC} and place the TLC5940 in danger.

We can solve this problem by putting a diode in parallel in the motor. Normally, as the motor is forward biased, the diode is reverse biased and does not allow current to run alongside the motor. Without the diode, when the motor loses its bias, an excess of charge spikes the voltage down at the TLC5940 end of the motor. However, with the diode, the diode becomes forward biased and allows the current to flow back into the motor. The excess energy gets dissipated as work by the motor and heat by resistance in series with the motor.

Note that the Flyback Diode Circuit is only shown four times in the Hardware Schematic. Furthermore, note that OUT15 for both TLC5940 chips is not used.

Arduino Duemilanove

The Arduino Duemilanove is a small Arduino microcontroller that has five analog in/out pins (that we won't use), 14 digital in/out pins (including two serial TTL pins and four PWM pins). It is programmable using a C-like language. It also can connect to computers via USB, and can be powered via USB or a 7-12V power source.

We will be using the Arduino to process all of the motor PWM information. It will be receiving serial data, interpreting the data, computing new PWM values for the motors, and then outputting the new values to the TLC5940 chips.

Motor Array

The motor array will consist of 2 arrays of 15 motors each, arranged in a 5x3 pattern with each motor having a distance of 3 cm from center to center. We arrived at this distance by using the arm's Two-Point Discrimination, which is at best 3.07 cm.⁴ The motors will be driven by the PWM outputs of the two TLC5940 chips. Each motor has a typical operating current of 60mA and a typical operating voltage range of 2.5V – 3.5V.⁵

9V Power Supply

The 9V Power Supply is a power supply capable of delivering 9V to the Arduino. We plan to use a 9V battery for this element, but if that fails we will use a bench-top power supply to supply the Arduino with 9V.

4.8V Power Supply

The 4.8V Power Supply is a power supply capable of delivering 4.8V and 2A to the Power Circuit and the Motor Array. We plan to use 4 AA NiMH batteries for this element. These AA NiMH batteries deliver 1.2V each, are rechargeable, maintain a stable voltage during discharge, and can discharge 5A.³

Decoupling Capacitor

A decoupling capacitor is placed between the VCC and GND pins of both TLC5940 chips. Inevitably, an IC's power requirements will fluctuate as it operates. Usually, a power supply is

not capable of meeting the demands for more or less current quickly enough. To resolve this issue, a decoupling capacitor is placed between VCC and GND. This capacitor stores a small amount of energy and is able to quickly supply a small amount of energy to the IC when it is needed. That is, the decoupling capacitor acts as a short-term, fast-response power supply for the IC. The value of 100nF was chosen because it is the recommended value in Texas Instrument's Application Example.¹

Serial Interface

The Arduino has serial TX and RX pins. However, we would like to use the RS232 standard instead of the TTL standard. Thus, we will use a TTL-RS232 converter to convert RS232 serial input to TTL serial input that can be used by the Arduino. Furthermore, for testing purposes, we can use a USB-RS232 converter to send serial signals from a computer to the Arduino.

Schematic

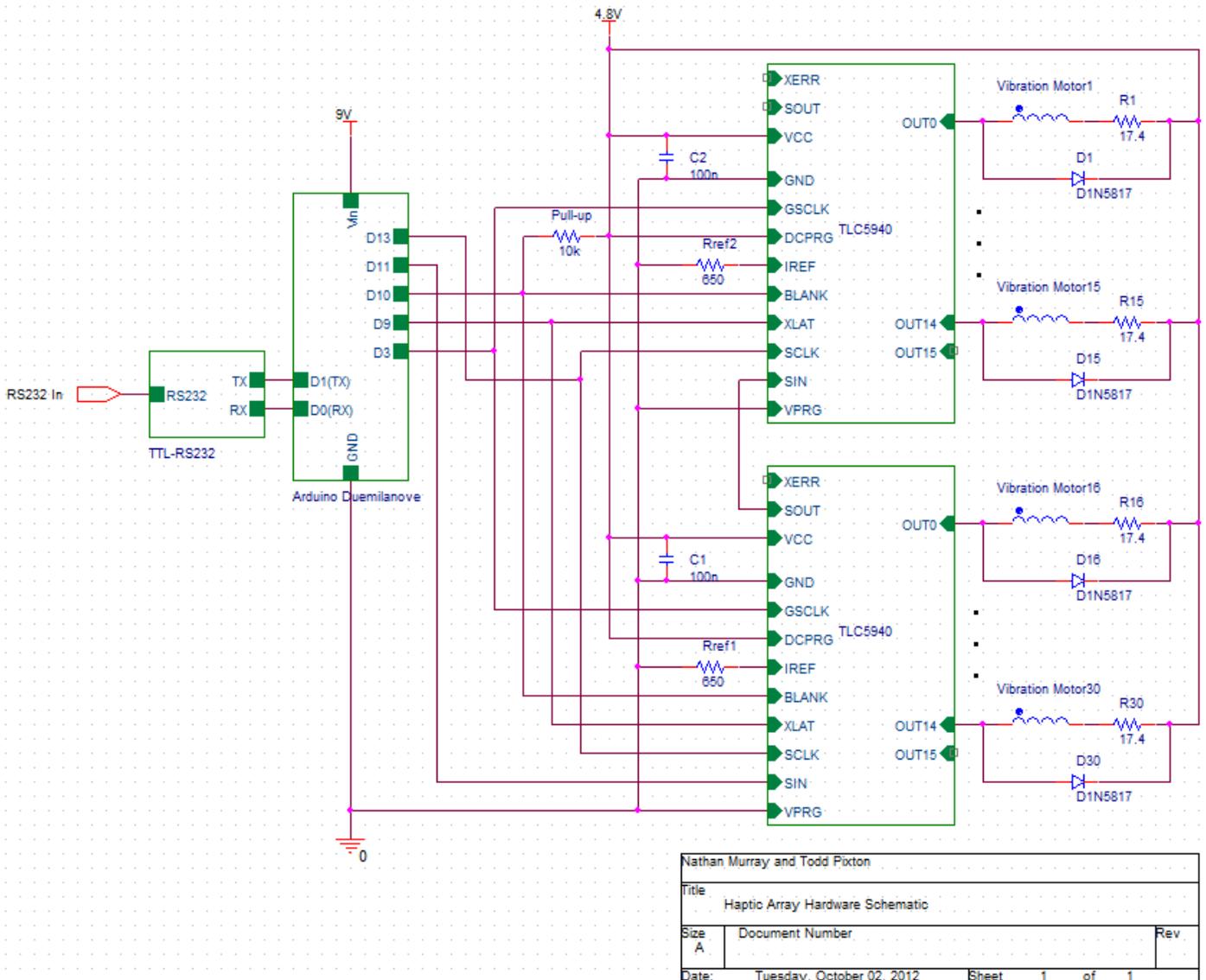


Figure 2.2: Haptic Array Hardware Schematic

2.4.2 Software

Flowchart

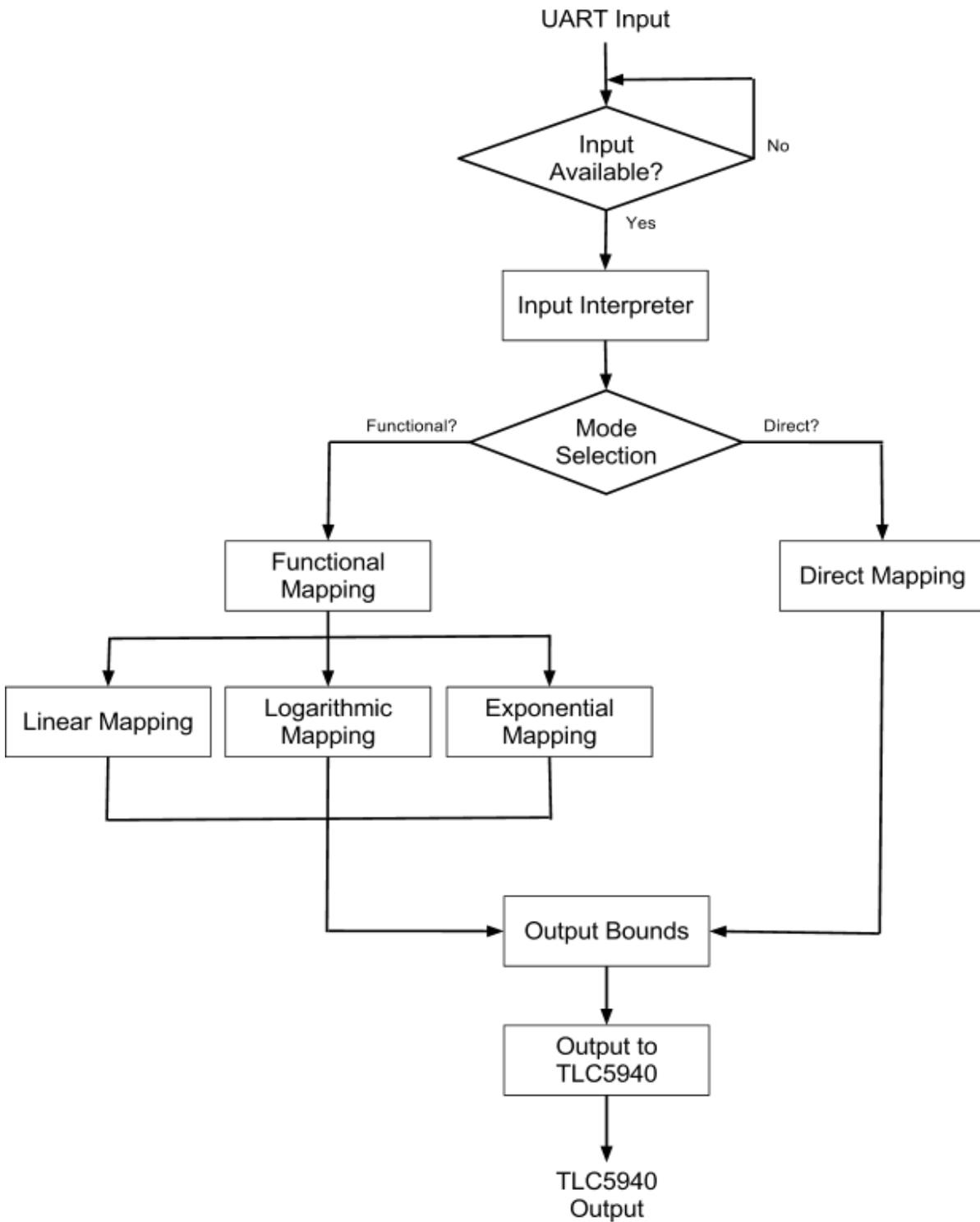


Figure 2.3: Software Flowchart

User Interface

The code will be written as an Arduino sketch. We will make use of a library provided at the Arduino playground code wiki [2]. This library provides functions for setting the grayscale PWM values for the channels of the TLC5940. There are four main functions. `Tlc.init()` initializes the PWM values to zero. `Tlc.clear()` sets every grayscale PWM value to zero. `Tlc.set(channel, value)` will set the grayscale PWM value for the specified channel. For our application, the channels are 0 to 31, although we will only be using thirty. The grayscale values can range from 0 to 4095. However, `Tlc.set` commands do not take effect until `Tlc.update()` is called. `Tlc.update()` sends the updated channel values to the TLC5940 chips.

Following is example code for how a value obtained through serial input can be mapped to vibrational intensity of a single motor. The final code will need to account for the dimensions of the motor array, of course.

```
/*
 * This function defines the range for the value obtained through serial
 * input, the range for the output values, and then maps the input value
 * to the output range using the function linearMapping.
 */
void mappingOne(int input)
{
    int expectedMin = 0;
    int expectedMax = 9;
    int outputMin = 0;
    int outputMax = 90;

    int newPWM;

    if(input < expectedMin)
        input = expectedMin;
    else if(input > expectedMax)
        input = expectedMax;

    newPWM = linearMapping(input, expectedMin, expectedMax, outputMin,
outputMax)

    Tlc.set(newPWM, 0);
}

/*
 * This function linearly maps the input value from the input range to the
 * output range. If the input range is not one dimensional, then it will
 * output the minimum output value.
 */
```

```
*/  
void linearMapping(int in, int eMin, int eMax, int oMin, int oMax)  
{  
    int out;  
    if(eMin != eMax)  
        out = (in-eMin)/(eMax-eMin)*(oMax-oMin)+oMin;  
    else  
        out = oMin;  
    return out;  
}
```

2.5 Simulations and Calculations

2.5.1 Flyback Diode Circuit

As discussed previously, when an inductive motor loses its bias, a strong negative bias is seen across the element. This flyback EMF can be simulated in PSPICE. Note that this simulation was designed to mimic how the TLC5940 controls the bias at the negative terminal of the motor. The negative voltage seen when the inductive motor loses its bias peaks near 200V, which is far too much for the TLC5940.

By adding a diode in parallel with the motor, a pathway is opened up for the current to flow after the motor has lost its bias, allowing the motor to safely run down its stored energy. Furthermore, by adding a resistor in series with the motor, we are able to accomplish two goals: we further reduce the effect of the flyback EMF, and we introduce another voltage drop between the 4.8V source and the TLC5940, reducing power dissipation of the chip. The 17.4 Ohm resistor choice is discussed in the next section.

On the following three pages are the circuits and simulations for the Flyback Diode Circuit.

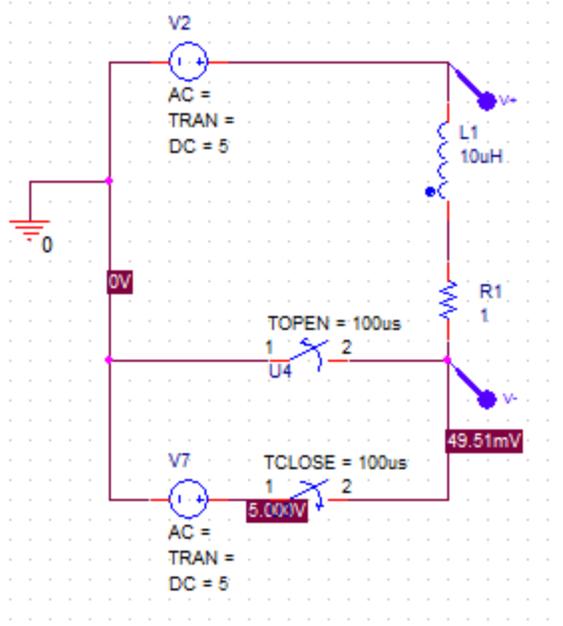


Figure 2.4: Motor circuit without flyback diode.

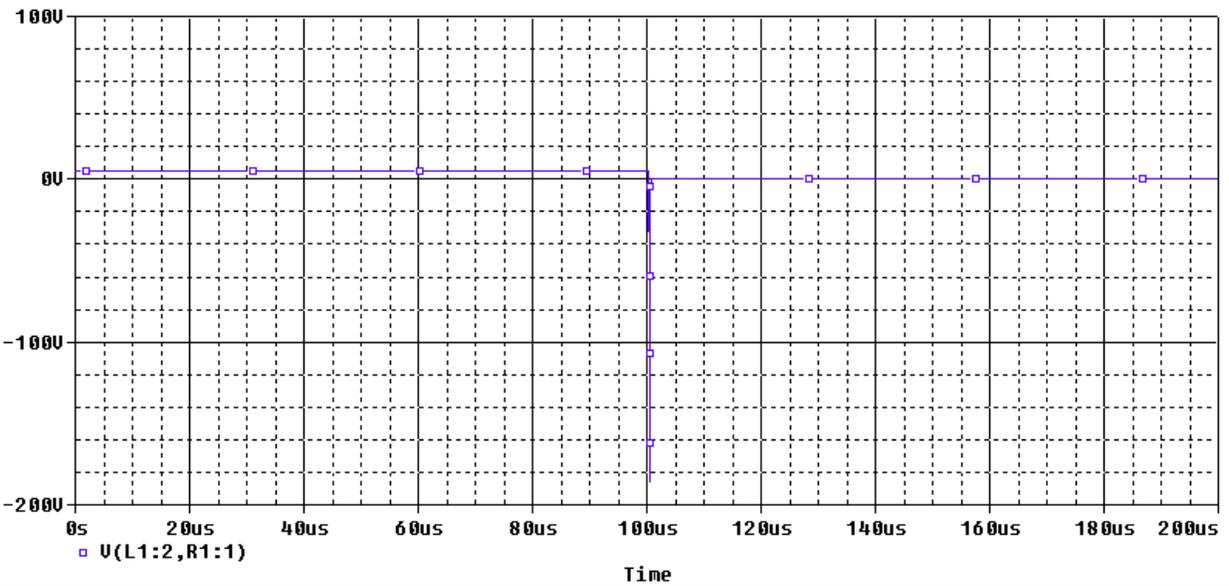


Figure 2.5: Plot of the voltage across the supply and the drain, without flyback diode. The motor loses its external bias at 100µs.

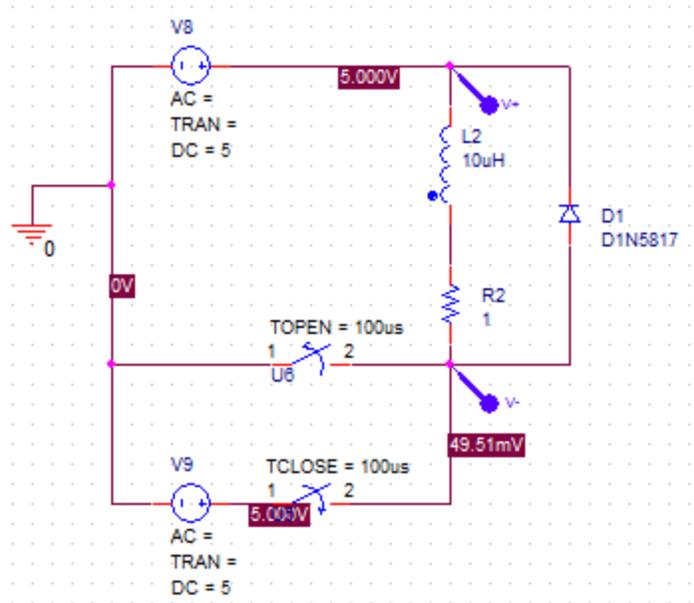


Figure 2.6: Motor circuit with flyback diode.

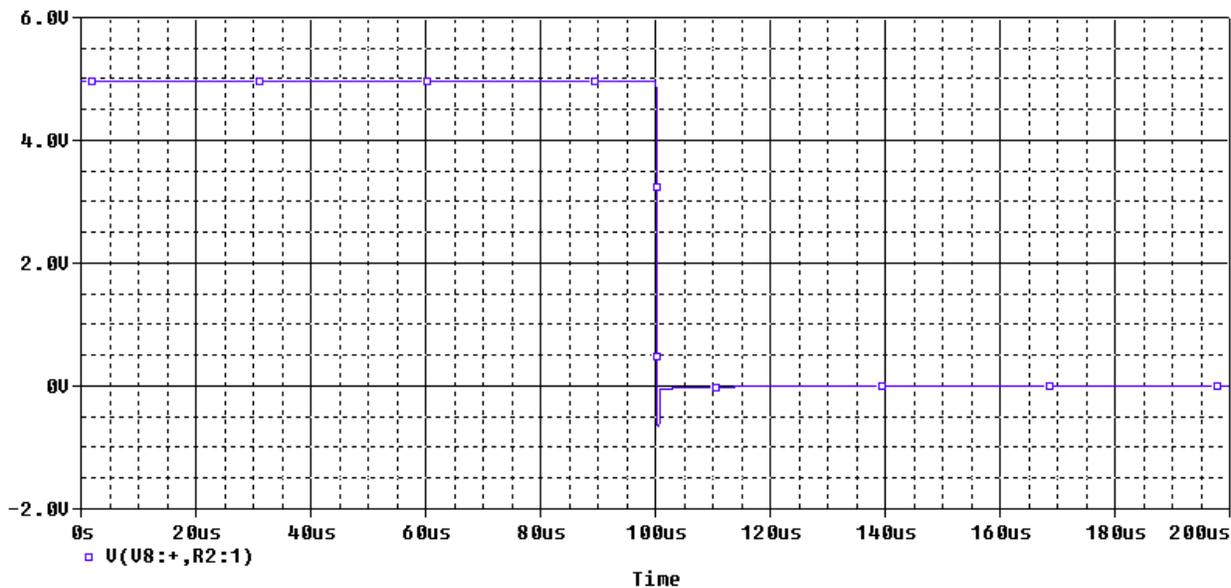


Figure 2.7: Plot of the voltage across the supply and the drain, with flyback diode. The motor loses its external bias at 100us.

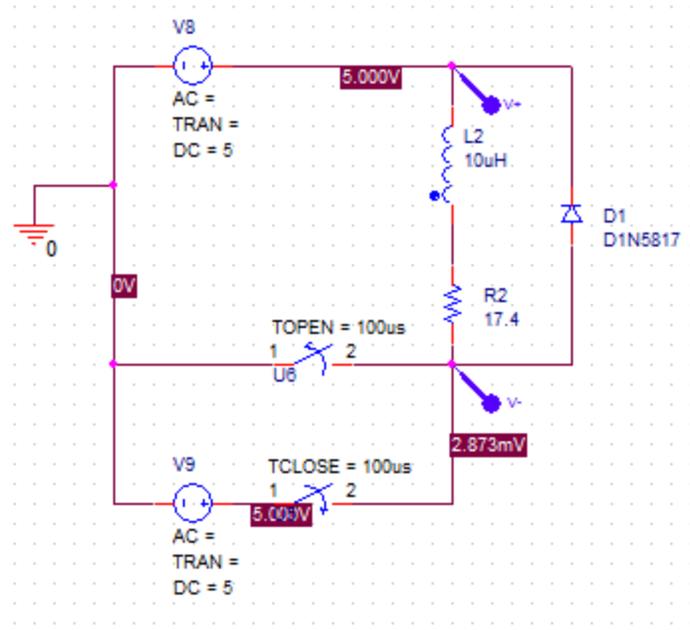


Figure 2.8: Motor circuit with flyback diode and series resistance.

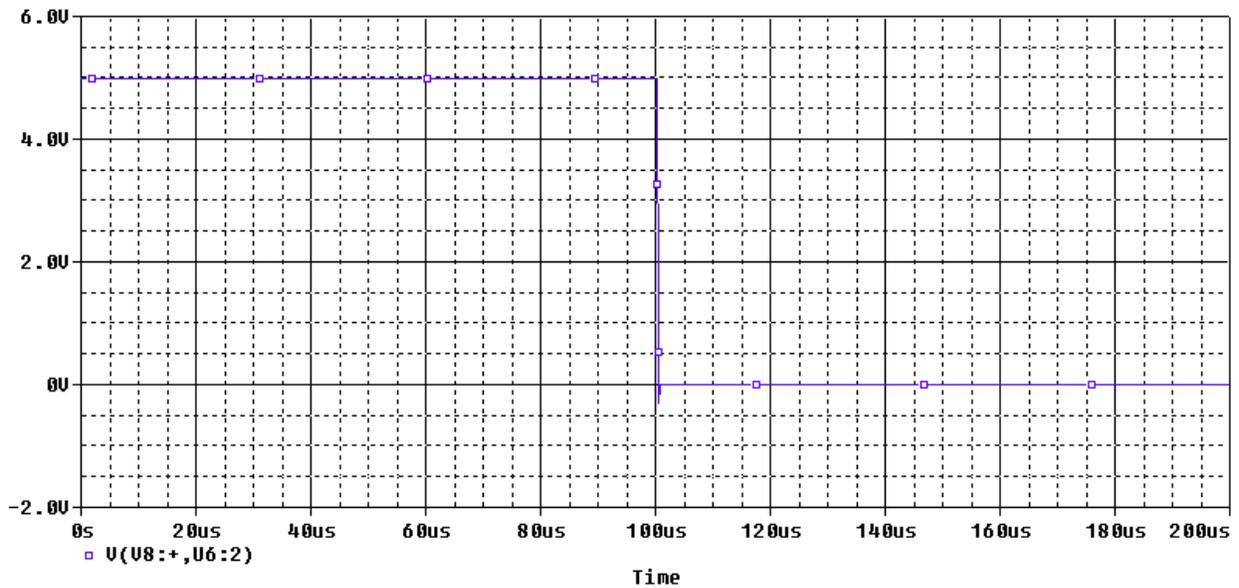


Figure 2.9: Plot of the voltage across the supply and the drain, with flyback diode and series resistance. The motor loses its external bias at 100us.

2.5.2 TLC5940 Power Dissipation

Power dissipation in the TLC5940 chips is a concern. They are designed to work with LEDs, which operate at lower currents than the coin vibration motors. Therefore, it is important to confirm that the TLC5940 chips will be able to safely operate even in the worst case scenario. The power dissipation equation is given as¹:

$$P_D = (V_{CC} \cdot I_{CC}) + (V_{OUT} \cdot I_{MAX} \cdot \frac{DC_n}{63} \cdot d_{PWM} \cdot N) \quad [2.5]$$

where, for the worst case scenario,

$$\begin{aligned} V_{CC} &= 4.8V, \\ I_{CC} &= 60mA, \\ I_{MAX} &= 60mA, \\ \frac{DC_n}{63} &= 1, \\ d_{PWM} &= 1, \end{aligned}$$

and

$$N = 15$$

One area of concern is V_{OUT} . If we can reduce V_{OUT} , then we can drastically reduce power dissipated in the chip. We reduce V_{OUT} by adding a resistor in series with each motor. We want to drop about 1V across this resistor when the motor is operating at 60mA, so the resistor needs to be about 16.7 Ohm. We were able to find a cheap 17.4 Ohm resistor that works with PCB. Therefore, the voltage drop across our series resistor is 1.044V. Furthermore, the operating voltage of the motors is given to be between 2.5V and 3.5V. We will assume the worst case, 2.5V. Therefore,

$$V_{OUT} = 4.8V - 1.044V - 2.5V = 1.256V \quad [2.6]$$

and the worst case power dissipation can be found:

$$P_D = (4.8V \cdot 60mA) + (1.256V \cdot 60mA \cdot 1 \cdot 1 \cdot 15) = 1.4184W \quad [2.7]$$

Given that the maximum power dissipation is 2.026W, we can find what percentage of maximum power we will dissipate in the worst case scenario:

$$\begin{aligned} \% P_{D,MAX} &= \frac{P_D}{P_{D,MAX}} \cdot 100\% \\ &= \frac{1.4184W}{2.026W} \cdot 100\% \\ &= 70.01\% \end{aligned} \quad [2.8]$$

Therefore, we are well within the specifications and should be able to operate the motor array without power dissipation concerns.

3. Verification

3.1 Testing Procedure

Every block in the above diagram will need to be tested for completeness and operability. Each block will also need to be tested with the other blocks to make sure that the entire system works as a whole. In order to test the Haptic Driver, we will use a simple test that will cause all of the PWM signal outputs to exercise their full range of intensity and frequency, which we will then measure for correctness using an oscilloscope. For the Power Circuit block, we will supply input signals from a function generator and measure the output signals using an oscilloscope to ensure that they are being amplified correctly. For the Motor Array block, we will use a function generator to test the boundaries of motor behavior, and eventually test the functionality of the entire array after the previous blocks have been constructed and tested.

Robust design techniques will be evaluated for their durability, such that we can ensure a robust design.

3.2 Tolerance Analysis

The Power Circuit block for this project must work to a tight tolerance. The motors can not run when powered by the Arduino. The motors require more current than the Arduino can supply without burning out. For this reason, we need to ensure that the Power Circuit block is capable of amplifying the signals from the Arduino into the range of operation for the motors.

In order to verify that the Power Circuit block works as intended, we will need to subject it to a variety of PWM signal scenarios and measure the output. We will then analyze the output signals to confirm that they conform to the acceptable range of inputs for the motors.

3.3 Verification Table

Module	Requirement	Verification
Power Supply	<ol style="list-style-type: none"> 1. A 9V battery must supply the Arduino. It must supply 200mA and not drop below 7V. 2. A 4.8V portable power supply for the TLC5940 	<ol style="list-style-type: none"> 1. <ol style="list-style-type: none"> a. A 45 Ohm resistor will be connected from power to ground for the 9V power supply. b. The power supply will be tested with a digital multimeter to check if they can maintain a voltage +/- 5% of their

	and motor array must supply up to 2A and maintain a voltage between 4.7V and 5V.	<p>expected value.</p> <p>2. a. The power supply will be tested with a digital multimeter to check if it can maintain a voltage within the given range of 4.7V – 5V. It will be tested after charging, after 10 minutes of use, and after 20 minutes of use to make sure that it maintains 4.8V.</p>
Haptic Driver	<p>1. The Haptic Driver must drive a serial communication pin of 5V +/- 0.1 V.</p> <p>2. The Arduino must be able to respond to serial communication.</p>	<p>1. a. The Arduino will be powered with 9V from the bench to VCC.</p> <p>b. The Arduino will be programmed with a “serial communication on” program, that constantly modulates pins 3, 5, 10, 11, and 13 on the Arduino.</p> <p>c. An oscilloscope will measure the voltage from each pin above to ground to verify that each pin drives at 5V +/- 0.1 V.</p> <p>2. A computer will send serial data to the Haptic Driver via USB to RS232 to TTL converters. The Arduino will confirm via LED that it is receiving data.</p>
Power Circuit	<p>1. The TLC5940 chip requires that a current reference resistor will be selected at 650 Ohms +/- 10% to ensure current sink draws 60mA.</p> <p>2. The TLC5940 must supply 60mA +/- 10% at each output, when each output is turned on.</p>	<p>1. An ohmmeter will verify the resistance of the IREF resistor to be at 650 ohms +/- 10%.</p> <p>2. a. 4.8 V will be supplied from the bench to VCC.</p> <p>b. A resistor of value 650 Ohms will be connected between pin IREF to GND.</p> <p>c. The haptic driver will turn each output on individually via serial communication to the Power Circuit.</p> <p>d. A resistor of 10 Ohms will be placed between VCC and each pin which is turned on. The voltage across the resistor will be verified to be .6 V +/- 10%.</p>
Motor Array	<p>1. The motors must maintain vibration when driven with 60mA.</p>	<p>1. 60mA will be supplied from the benchtop source. Each motor will tested via a voltmeter and by feel.</p>

	<p>2. The flyback diode circuit must dissipate power from the stored current in the motor when the constant current is cut off from the motors.</p>	<p>2. a. Measure the voltage across a motor with an oscilloscope. Wire a diode in parallel with a resistor in series with the motor. 60mA will be supplied to the motor, reverse biasing the diode.</p> <p>b. The voltage induced by the motor when the current is terminated can be no greater than 17V.</p>
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Contingency Plan:

Motor Array: If the array does not work with motors, LEDs can be used to test the Power Circuit.

Power Circuit: If the Power Circuit does not work, then 4 motors can be driven directly by the Arduino.

Haptic Driver: There is no contingency plan for the haptic driver. This block must work.

Power Supply: If portable power supplies can not be achieved, then we will use a benchtop source.

4. Ethical Considerations

We will abide by the IEEE Code of Ethics. Specifically:

1. To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment

We will consider safety of the user. Considering we are using electronics that will be worn on the user, we will take every precaution to ensure that the user is not subjected to electric shock or burnt. Furthermore, we will not compromise the user's comfort.

3. To be honest and realistic in stating claims or estimates based on available data

We will accurately and promptly report all results of our calculations and tests, not hiding results or misrepresenting any calculation results.

5. To improve the understanding of technology; its appropriate application, and potential consequences

We will document the entirety of our project such that it can be understood and continued after completion.

7. To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others

We will work to resolve and criticism or issues brought to us. Furthermore, we will properly cite and credit all sources that we use for our design or any other aspect of the project.

5. Cost And Schedule

5.1 Cost Analysis

5.1.1 Labor Cost

Billable Hours Per Week Per Engineer	Weeks Of Contract Per Engineer	Total Billable Hours Per Engineer	Multiplicity Factor	Per Hour Billing Rate Per Person	Total Contract Cost
9	13	117	2.5	\$34.00	\$9,945.00
No. Of Engineers in Team					2
Total Labor Cost of Project					\$19,890

5.1.2 Parts Cost

Part	Quantity	Unit Cost	Total Cost + Shipping
Shaftless Vibration Motor 8x3.4mm	50	\$2.79	\$146.45
Arduino Duemilanove	1	\$29.95	\$33.59
TI TLC5941 16-Channel LED Driver	2	\$2.32	\$12.64
22 Gauge Wire	10 ft	\$0.30/ft	\$3.00
Resistors	50	\$0.10	\$5.00
9V Battery	12	\$1.40	\$16.80
AA NiMH Battery	4	\$16.52	\$16.52
1n5817 Schottky Diode	50	\$0.11	\$5.50
Total Parts Cost			\$239.50

Total Cost of Project: \$20,129.50

5.2 Schedule

Week	Date	Task	Member Responsible
1	9/10/2012	Write Proposal	Todd Pixton
		Haptic Array Design	Nathan Murray
		Haptic Driver Design	Todd Pixton
2	9/17/2012	Decide Array Parts	Nathan Murray
		Design Sensor Interface	Todd Pixton
3	9/24/2012	Order Power/Motor Parts	Nathan Murray
		Order Arduino, Interface Parts	Todd Pixton
		Design Review	Nathan, Todd
4	10/01/2012	Build Power Circuit	Nathan Murray
		Build Arduino Interface, Testing Code	Todd Pixton
5	10/08/2012	Build Motor Array	Nathan Murray
		Test Motors with Arduino	Todd Pixton
6	10/15/2012	Signal Group Communication Collab.	Nathan Murray
		Code Motor Interface Protocols	Todd Pixton
7	10/22/2012	Build Arduino Enclosure	Todd Pixton
		Build Motor Array Enclosure	Nathan Murray
8	10/29/2012	Test Connections and Functionality	Todd Pixton
9	11/05/2012	Mock Up Demo	Nathan Murray
10	11/12/2012	Mock Presentations	Nathan Murray
11	11/19/2012	Thanksgiving break	
12	11/26/2012	Resolve Problems from Mock Ups	Todd Pixton
		Prepare Presentation	Nathan Murray
		Prepare Final Paper	Todd Pixton

13	12/03/2012	Demo	Nathan Murray
		Presentation	Nathan Murray
14	12/10/2012	Final Paper	Todd Pixton

6. Citations

- [1] Texas Instruments. October 2007. 16 CHANNEL LED DRIVER WITH DOT CORRECTION AND GRAYSCALE PWM CONTROL. <<http://www.ti.com/lit/ds/slvs515c/slvs515c.pdf>>.
- [2] Arduino Playground. Arduino. <<http://www.arduino.cc/playground/learning/TLC5940>>.
- [3] PowerStream. Discharge tests of AA Batteries, Alkaline and NiMH. <<http://www.powerstream.com/AA-tests.htm>>.
- [4] Physical Therapy. Journal of American Physical Therapy. <<http://www.physther.net/content/62/7/965.full.pdf>>. p967.
- [5] Robotics and Electronics. Pololu. Shaftless Vibration Motor 8x3.4mm. <<http://www.pololu.com/catalog/product/1637>>.