# Dynamic Ferrofluid Lamp

## Design Document

ECE445 Spring 2017

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# Contents

# 1 Introduction

## 1.1 Objective

Invented in 1963, ferrofluid was originally intended to be used to allow liquid rocket fuel to be drawn toward a pump inlet in a weightless environment [1]. It is only in the recent two years that the properties of ferrofluid have been explored and taken advantage of in fields of display and art. However, due to the relatively new concept of using ferrofluid for art, currently existing methods of displaying and manipulating ferrofluid remain somewhat crude and unrefined. Current ferrofluid only uses large and bulky ferrofluid pixels, and artistic pieces that showcase the ferrofluid properties nearly all fall into one of three categories: depending on human interaction, utilizing only one fixed sculpture base, or being too bulky and impractical for average consumers.

Our project aims to refine the design of the artistic display of ferrofluid. In particular, our goal is to create a programmable ferrofluid lamp that enables the manipulation of ferrofluid in artistic ways by modifying the magnetic field of electromagnets. The electromagnets will be arranged such that the ferrofluid can be channeled in both horizontal and vertical motions, allowing potentials for numerous display patterns.

## 1.2 Background

'The Inspiration' Ferrofluid Motion Lamp [2], while being able to manipulate vertical motion, only does so in an uncontrolled manner mimicking a traditional lava lamp with further variety of display requiring the participation of a person with an external magnet. Even the successful Kickstarter project 'RIZE Spinning Ferrofluid Display', raising over 140,000 dollars in crowdfunding [3], only uses a fixed sculpture as a base, limiting the diversity of ferrofluid appearance.

Our dynamic ferrofluid lamp combines the lava lamp and ferrofluid display such that users can not only use it as a lighting source, but also enjoy the amazing visual effects simultaneously. Users can turn on/off the LED array by simply pushing down a LED trigger button. A software audio pass-through interface is provided and a list of music is programmed ahead. While users are trying to select different type of music from the given list, the corresponding magnetic field around the ferrofluid will be modified, resulting in different visual effects.

### 1.3 High-Level Requirements

- The ferrofluid must be able to move in both horizontal and vertical directions. The LED array must be able to be turned on/off while users are pressing the LED trigger button. The ferrofluid must be able to respond to different types of music that users select one at a time.
- Maximum electric current at any time must be less than 2.25 Amps.
- The cost of all parts must be less than 200 dollars.

## 2 Design

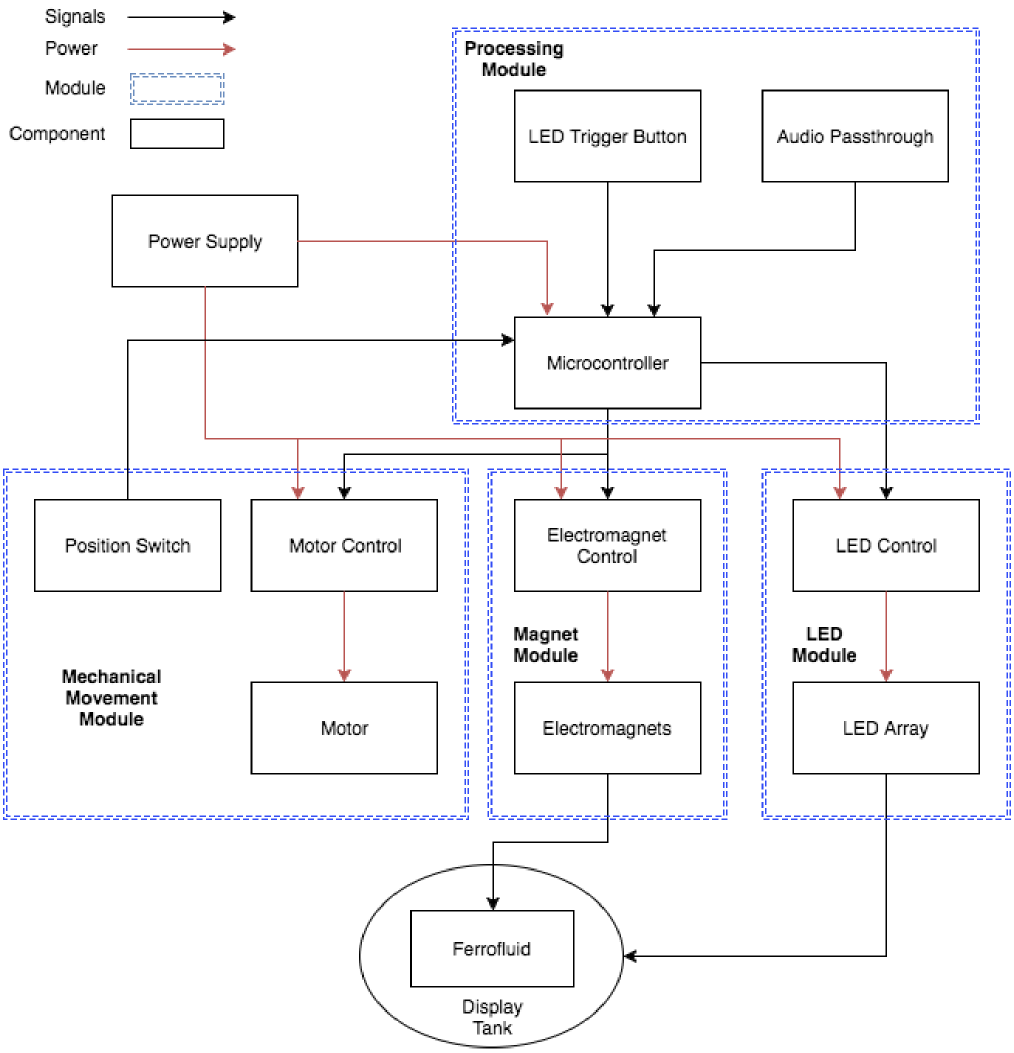


Figure 2: Block Design

## 2.1 Power Supply

As Shown in Figure 2.1, from the work of group 32 in Fall 2016 [4], we have a power supply circuit that Has two 5V ports and two 12V ports. Of which the 5V ports each have a 1.5A maximum current rating, and the 12V ports each have a 2A maximum current rating.

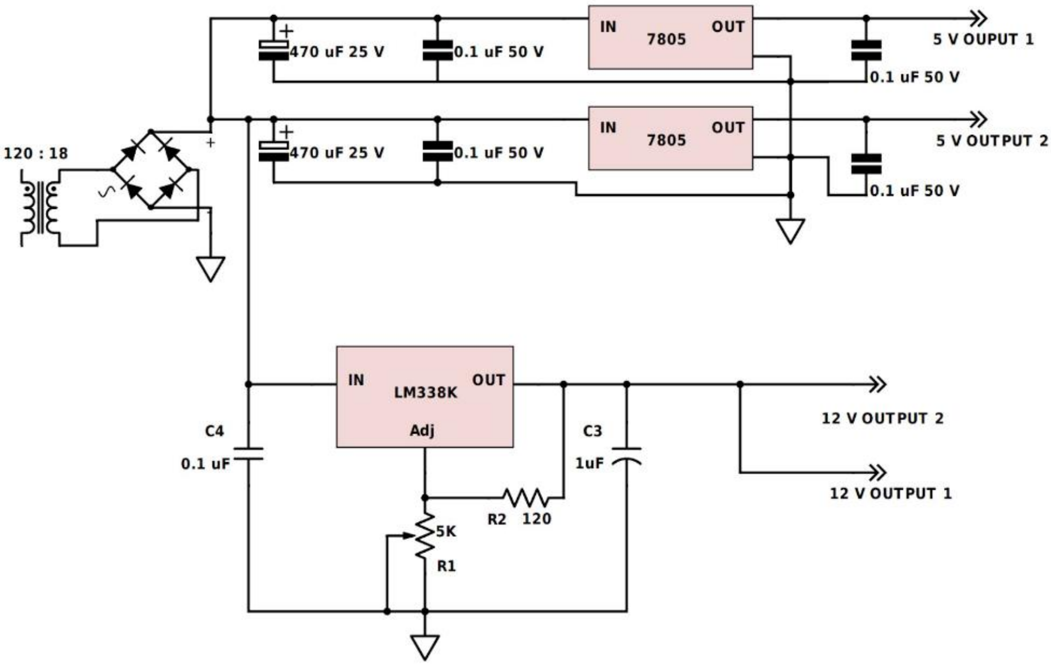


Figure 2.1: Power Circuit Design from Group 32 of Fall 2016 [4]

| Requirement | Verification |
|---|---|
| 1) The electric current passing through the wires is 2A +/- 0.25A | 1)<br>1. Use a multimeter to measure the current passing through the slip ring at the beginning of the experiment<br>2. Use the same multimeter to measure the current passing through the slip ring 5 minutes later<br>3. Use the same multimeter to measure the current passing through the slip ring 10 minutes later<br>4. Make sure that each measurement of the current falls within our intended bound and if not, abort the experiment |

| | |
|---|---|
| | immediately. Let an instructor/TA check the experimental setup again and if approved, re-try the experiment. |
| 2) The voltage provided by the power supply under the expected load of 2A should stay stable at 12V +/- 0.5V | 2)<br>1. Hook up a multimeter to measure both the current the drawn from the power supply port and the voltage it is at.<br>2. In software, adjust the intensity of the magnetic field of the electromagnets so that the the current drawn reaches 2A.<br>3. Measure the voltage supplied and compute the fluctuation to see if it is still within tolerance range. |

## 2.2 Ferrofluid/Display Tank

This ferrofluid display tank is the actual physical device on which users have direct visions. It consists of two cylinders (inner and outer) and two platforms (top and bottom), and a central rod is placed in the inner cylinder. The inner cylinder is where the electromagnets move around and produce different on/off combinations that could manipulate different magnetic field intensities. The spacing between inner and outer cylinders is where the actual ferrofluid and the suspension liquid reside. The inner cylinder will be covered by an opaque shroud, so that users cannot see the actual mechanism inside but can only see the outside ferrofluid.

| Requirement | Verification |
|---|---|
| 1) The inner cylinder must be watertight and non-conducting | 1)<br>1. Wear rubber gloves before experiment to ensure safety<br>2. Look inside through the outer cylinder. If any apparent gap or crack is detected, abort the experiment and report to an instructor/TA immediately<br>3. If no visual crack is detected, fill in a small portion of distilled water. Close the lid and shake the device gently. Wait 5 minutes, if no exception is detected, plug in the power (must be conducted |

| | |
|---|---|
| | under a TA's supervision)<br>4. If no exception occurs, power off the power supply, replace the distilled water with the actual ferrofluid and suspension liquid. Then plug in the power and enjoy |

## 2.3 Processing Module

The processing module consists of three parts: the LED trigger button, the software audio pass-through interface, and the microcontroller.

### 2.3.1 LED Trigger Button

The LED trigger button has two states: on and off. Because one of the key features of our dynamic ferrofluid lamp is to provide lighting function, users must be able to turn on/off the LED array via this LED trigger button.

| Requirement | Verification |
|---|---|
| 1) The LED trigger button must be easily pressed without any restrictions | 1)<br>1. Press the button to make sure that it is easily pressed without any pressures/obstacles and it does not malfunction after each press |

### 2.3.2 Audio Pass-through

The software audio pass-through interface provides users with the ability to interact with the ferrofluid by allowing them to modify the magnetic field intensities around the ferrofluid. A list of different types of music is programmed ahead into the interface from which users can later select. Since each type of music has its own frequency, the interface would extract and store these different frequencies of different types of music. Each frequency is then mapped to a unique pattern that could generate different magnetic field intensities around the ferrofluid.

| Requirement | Verification |
|---|---|
| 1) Users must be able to clearly understand the interface and easily select each type of music | 1)<br>1. Take a look at the interface description and understand which keyboard key corresponds to which type of music<br>2. Press 1 to enable Blues and a |

| | |
|---|---|
| | feedback of “Blues enabled” should be displayed on the console<br>3. Press 2 to enable Rock and a feedback of “Rock enabled” should be displayed on the console<br>4. Press 3 to enable Jazz and a feedback of “Jazz enabled” should be displayed on the console |

### 2.3.3 Microcontroller

The ATmega328 chip will serve as our microcontroller.

0 - 4MHz@1.8 - 5.5V, 0 - 10MHz@2.7 - 5.5.V, 0 - 20MHz @ 4.5 - 5.5V

| Microcontroller | ATmega328 |
|---|---|
| CPU Speed | 20 MIPS |
| Digital I/O pins | 14 (6 PWM) |
| Analog I/O pins | 8 |

Table 2.3.3-1: ATmega328 Specs [5]

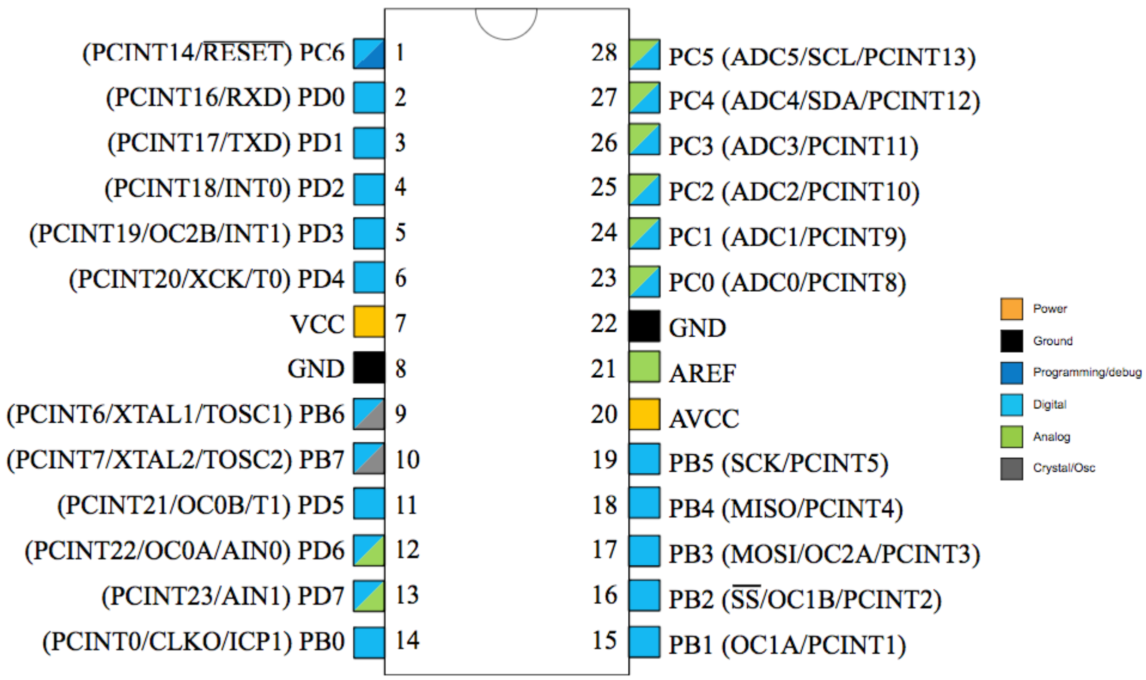


Figure 2.3.3: ATmega328 Pin Map [5]

I/O Pin Requirements:

| | |
|---|---|
| Motor Speed Control | 1 PWM |
| Motor Direction Control | 1 Digital |
| Electromagnet Magnitude Control | 4 PWM |
| Electromagnet Select Signal | 4 Digital |
| Top Switch | 1Digital |
| Bottom Switch | 1 Digital |
| Audio Passthrough | 2 Analog |
| LED Trigger Button | 1 Digital |
| LED PWM Control | 1 PWM |
| LED Shift Register Control | 4 Analog (used as digital) |

Table 2.3.3-2: I/O Pin Requirements

As shown in Table 2.3.3-2, we need 6 PWM pins, 8 digital pins and 6 analog pins. The I/O pins the ATmega328 provides satisfy the needs of our design.

## 2.4 Mechanical Movement Module

The mechanical movement module consists of three components: the motor control, the motors unit, and the position switch. This module utilizes these three components to provide the electromagnets platform with vertical motion, in turn providing us with the ability to manipulate the ferrofluid along the vertical axis.

### 2.4.1 Motor Control

Input:

PWM signal from the microcontroller

Direction signal from the microcontroller

Output:

Power signals that control speed and rotation direction of the motor

An H bridge will be used to convert the control signals from the microcontroller into power signals to control the speed and rotation direction of the motor. The specific H bridge chip used is the TB6612FNG [6].

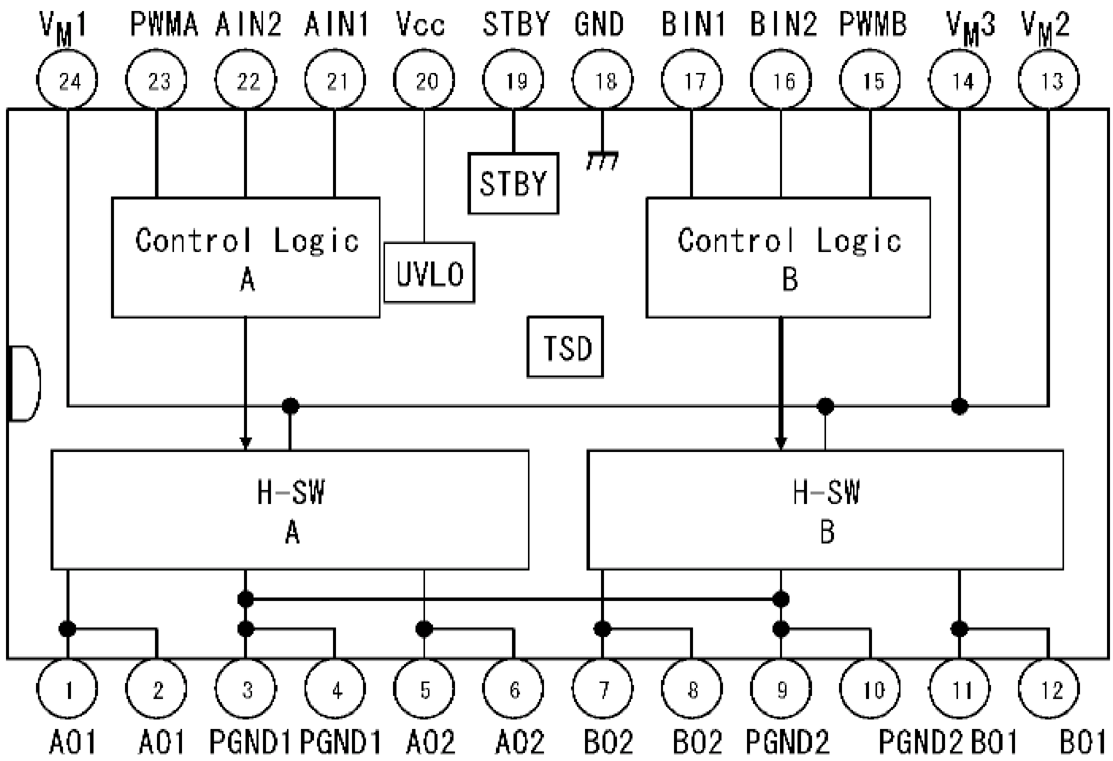


Figure 2.4.1-1: TB6612FNG Block Diagram [6]

Pin Assignment

| No. | Pin Name | Assignment |
|---|---|---|
| 1 | AO1 | Motor positive lead power |
| 3 | PGND1 | Ground for power lane |
| 5 | AO2 | Motor negative lead power |
| 18 | GND | ground |
| 19 | STBY | standby signal, set to high to enable chip |
| 20 | Vcc | control signal logic high |
| 21 | AIN1 | direction signal |
| 22 | AIN2 | negation of direction signal |
| 23 | PWMA | PWM signal for controlling the motor |
| 24 | VM1 | Motor voltage supply |

Table 2.4.1: Motor Control Pin Assignment

### 2.4.2 Motors

Inputs:

Positive PWM power lane from motor control unit.

Negative PWM power lane from motor control unit.

The motors component provides the mechanical movement that drives the rod and in turn moves the electromagnet platform up and down. This directly gives us the ability to manipulate the ferrofluid along the vertical axis.

### 2.4.3 Position Switch

This component consists of two switches that are positioned at the top and bottom of the electromagnet platform's movement path. When the platform reaches the top, the top switch activates and sends a signal to the microcontroller that the top has been reached. Likewise, the bottom switch sends a bottom has been reached signal to the microcontroller when the platform reaches the bottom.

| Requirement | Verification |
|---|---|
| 1) The position switch must be de-bounced such that when the signal transitions from logical low to high, there is one and only one instance of the voltage rising above 0.6V, and when transitioning from logical high to low, there is one and only one instance of the voltage dropping below 2V. | 1)<br>1. Connect switch component to an oscilloscope. Set the trigger to single trigger at 1.0V.<br>2. Press and hold down the switch manually and record the waveform.<br>3. Check the to see if there is indeed only one instance of the voltage rising above 0.6V.<br>4. Set the trigger to single trigger at 1.0V again.<br>5. Release the switch and record the waveform.<br>6. Check if the second waveform has only one instance of the voltage dropping below 2V |

## 2.5 Electromagnet Module

The electromagnet module consists of two parts: the electromagnet control and the electromagnets. We have a total of eight electromagnets that are arranged evenly and uniformly in a circular platform attached in the middle of the rod in the inner cylinder. The electromagnet control unit receives PWM signals from the microcontroller and controls which electromagnet(s) are on and off. Depending on different on/off combinations of these eight electromagnets, the magnetic field around the ferrofluid can be manipulated accordingly, resulting in its different shapes and visual effects.

### 2.5.1 Electromagnet Control

Inputs:

PWM signals from the microcontroller.

Select signals from the microcontroller.

Output:

Power signals that control magnetic field intensities.

This component converts the PWM signals from the microcontroller into power signals that power electromagnets. Due to the limited number of PWM pins in affordable microcontrollers, the electromagnet control unit uses one single PWM signal to control two electromagnets, selecting which electromagnet to activate using a regular digital output signal from the microcontroller as a selection signal.

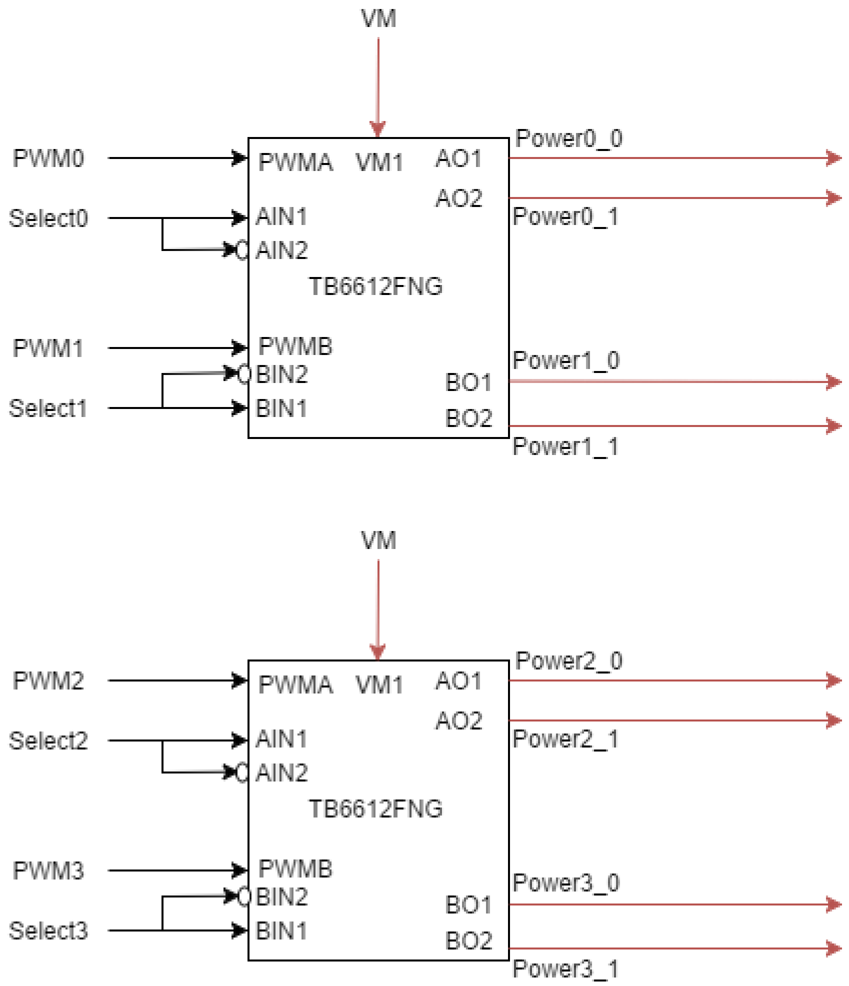


Figure 2.5.1: Electromagnet Control Unit

As seen in figure 2.5.1, the H bridge module used to control the motor is used here as a MOSFET power switch. Two TB6612FNG modules will be used to provide 8 power signals to control 8 electromagnets.

Pin Assignment:

| No. | Pin Name | Assignment |
|---|---|---|
| 1 | AO1 | electromagnet control signal |
| 3 | PGND1 | Ground for power lane |
| 5 | AO2 | electromagnet control signal |
| 7 | BO2 | electromagnet control signal |
| 11 | BO1 | electromagnet control signal |

| | | |
|---|---|---|
| 15 | PWMB | PWM signal for controlling BO1 and BO2 |
| 16 | BIN2 | negation of selection signal 1 |
| 17 | BIN1 | selection signal 1 |
| 18 | GND | ground |
| 19 | STBY | standby signal, set to high to enable chip |
| 20 | Vcc | control signal logic high |
| 21 | AIN1 | selection signal 0 |
| 22 | AIN2 | negation of selection signal 0 |
| 23 | PWMA | PWM signal for controlling AO1 and AO2 |
| 24 | VM1 | electromagnet voltage supply |

Table 2.5.1: Electromagnet Control Pin Assignment

| Requirement | Verification |
|---|---|
| 1) The duty cycle of the output of the electromagnet control must be within an error of less than 5% compared to that of the input PWM signals | 1)<br>1. Measure the duty cycle of the input PWM signals using an Oscilloscope<br>2. Measure the duty cycle of the output power signals using the same Oscilloscope<br>3. Ensure that the two duty cycles must be at least 95% match |

### 2.5.2 Electromagnets

Inputs:

Pulse width modulated power signals from electromagnet control unit

The electromagnets component is the main component that directly manipulates the ferrofluid. By using electromagnets, we are able to control the magnetic field intensity through pulse width modulation. Also, through sequentially turning on and off the electromagnets in a clockwise or counterclockwise order, we can achieve rotational motion of the ferrofluid.

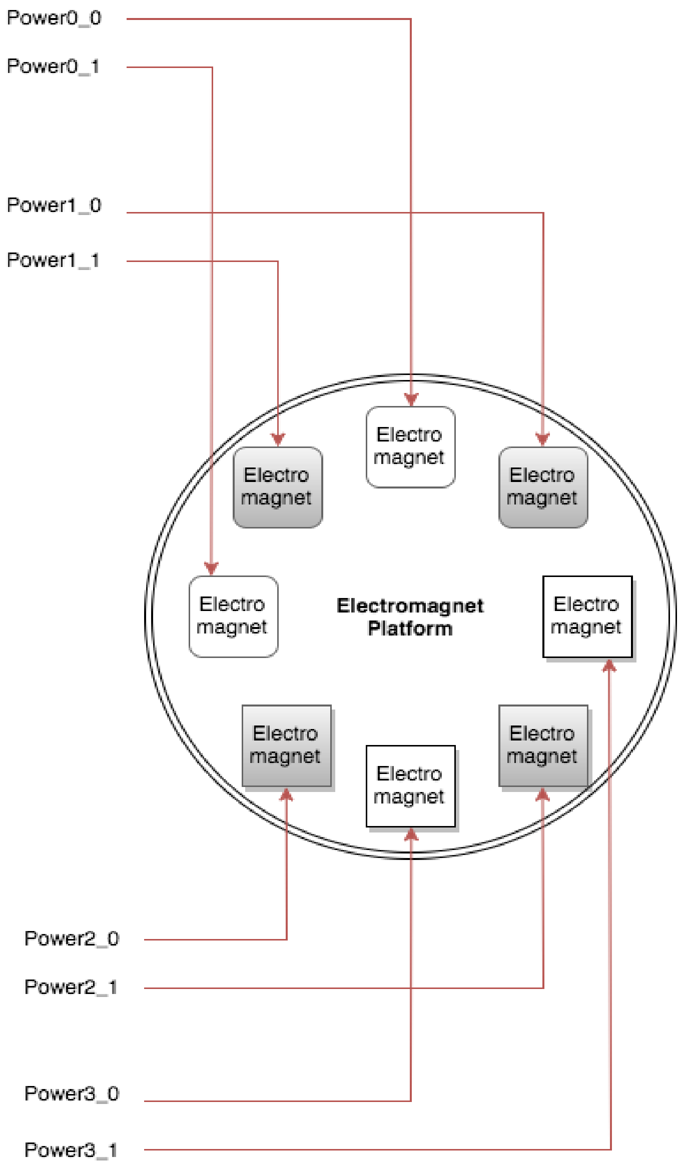


Figure 2.5.2: Electromagnets

As shown in figure 2.5.2, similarly shaped and shaded electromagnets in the diagram can only have one powered at the same time. That is, only one of the electromagnets controlled by Power0_0 and Power0_1 can be powered at the same time etc. This limitation is due to the affordable microcontrollers not having enough PWM pins. However, with this design, a large variety of effects can still be achieved.

We are planning to use 22 AWG copper wire to wrap our electromagnets. The wire has a diameter of 0.0253 inches and an expected resistance of 52.939 Ohms/Kilometer. As for the number of wire loops around each electromagnet, we plan to have 250 loops on each electromagnet. Thus the length of the wires in total should be less than 5 centimeters. The magnetic field intensity can be calculated by following the equation:

$$B = \mu n I$$

where $B$ is the strength of the magnetic field, $\mu$ is the magnetic permeability of space, and $n$ is the number of turns of wire per meter, and $I$ is the current through the wire.

Because iron has a relatively large permeability, we would use iron as the core rod to drive the electromagnet. Therefore, $\mu$ is replaced with the permeability of the iron, which is $6.3 * 10^{-3}$ H/m. Since we have 250 loops for 5 cm, the loop density is 250/5 = 50 turns/cm, which is 5000 turns/m. Together with the maximum current of 2A, we should have an estimated magnetic field strength of:

$B = (6.3 * 10^{-3})(5000)(2) = 63$ Tesla

## 2.6 LED Module

The LED module consists of two parts: the LED control and the LED array.

### 2.6.1 LED Control

The LED control unit receives PWM signals from the microcontroller and controls the on/off functionality of the LED array. Depending on whether users want lighting or simply intend to see the lighting/ferrofluid combination, the LED array can be turned on/off through the LED trigger button.

| Requirement | Verification |
|---|---|
| 1) Through the LED control mechanism, the LED trigger button must be able to trigger on/off the LED array when users press the button | 1)<br>1. The LED array is initially off. Press the button to see if the LED array is turned on<br>2. If it is turned on, press the button again, and the LED array should be turned off<br>3. Press the button again, and the LED array should be on again<br>4. Each time the button is pressed, the LED array should switch between the on and off states |

### 2.6.2 LED Array

This is the physical LED array located at the very bottom of the device. It sits right above the bottom platform of the device, and should be triggered on/off through the LED control mechanism each time when users press the LED trigger button.

## 2.7 Tolerance Analysis

The biggest tolerance we have to maintain throughout our project is the amount of current passing through the wires. Because we are dealing with the current and water/alcohol combination, we have to restrict the current to be as low as possible. Therefore, we are restricting the current passing through the wires to be a maximum of 2.25 Amps, which is 2 Amps + 0.25 tolerance Amps. The 2 Amps come from the fact that the maximum possible current passing through the wires could potentially reach ~2 Amps. If at any time the current value exceeds 2.25 Amps, we will abort the experiment immediately and re-try only after the setup is checked by an instructor or TA.

# 3 Cost

## 3.1 Labor Cost

| Name | Hourly rate($) | Total hours(hrs) | Total($) |
|---|---|---|---|
| Chen Huang | 30 | 200 | 15,000 |
| Chong Lu | 30 | 200 | 15,000 |
| | | | 30,000 |

Fig. 3-1. Labor Cost

## 3.2 Parts Cost

| Part | Unit($) | Quantity | Total($) |
|---|---|---|---|
| Microcontroller: ATmega328 | 1.96 | 1 | 1.96 |
| H bridge: TB6612FNG | 2.11 | 3 | 6.33 |
| Motor | 12.95 | 1 | 12.95 |
| Electromagnet | 8.97 | 8 | 71.76 |

| | | | |
|---|---|---|---|
| RGB LED | 1.95 | 9 | 17.55 |
| | | | 100.55 |

Fig. 3-2. Parts Cost

### 3.3 Total Cost

| | |
|---|---|
| Labor Cost($) | 30,000 |
| Parts Cost($) | 100.55 |
| Total Cost($) | 30,100.55 |

Fig. 3-3. Total Cost

## 4. Schedule

| Week | Chen | Chong |
|---|---|---|
| 2/6 | Start ordering parts | Finalize project proposal |
| 2/13 | Prepare for Mock Design Review | Discuss high-level requirements with TA and mechanical difficulties with Machine Shop |
| 2/20 | Finalize ferrofluid/suspension liquid composition | Finalize design document and prepare for Design Review |
| 2/27 | Finalize the outer and inner cylinder dimensions, top/middle/bottom platform dimensions and report to Machine Shop | Experiment with finalized ferrofluid to be familiar with its properties and susceptibility to various magnetic field intensities |
| 3/6 | Begin mechanical movement module design | Begin processing module design |
| 3/13 | Finish mechanical movement module design | Finish processing module design |
| 3/20 | Continue programming microcontroller, motor control and rotation position detection units | Continue programming LED trigger button, audio pass-through, and LED control units |
| 3/27 | Finalize the above units and start electromagnet control with Chong | Finalize the above units and start electromagnet control with Chen |

| | | |
|---|---|---|
| 4/3 | Finalize eletromagnet control and start integrating parts together | Finalize eletromagnet control and start integrating parts together |
| 4/10 | Debug with Chong and prepare for Mock Demonstration | Debug with Chen and prepare for Mock Presentation |
| 4/17 | Final revision | Final revision |
| 4/24 | Perform environmental testing with the actual device | Prepare for demonstration and refine final papers |
| 5/1 | Prepare for final presentation | Finalize final papers |

Fig. 4. Schedule

## 5. Ethics and Safety

Because ferrofluid is a relatively new area when related to aesthetics, it still has a lot to be explored. During our experiment with the ferrofluid, we will follow closely to the IEEE Code of Ethics, #3, “to be honest and realistic in stating claims or estimates based on available data.” [7] We will not include any unrealistic data or result in our report in order for it to look good or persuasive, we will instead be honest and respectful to the data we have acquired even if it is not perfect.

We choose ferrofluid-related field as our primary research project because we are interested and want to dive deeper into it. Thus, we will closely follow the IEEE Code of Ethics, #5, “to improve the understanding of technology; its appropriate application, and potential consequences,” [7] as we work along with our project. Our intention is to understand more about the properties of ferrofluid and how it can be applied in real industry to further contribute to our society.

Although our ferrofluid lamp is a product of aesthetics, it unavoidably comes with several potential safety hazards. The first safety issue comes with the nature of the ferrofluid. Because ferrofluid itself is dangerous to manipulate with depending on its type, we will only select safe ferrofluid to play and test with. We will gather reliable information about various ferrofluids from different sources, narrow down to the one that is relatively safe in its nature, and investigate it carefully throughout the entire project.

Another important safety issue comes with the fact that we are experimenting with the current and water/alcohol combination. The maximum possible current passing through the wires could potentially reach ~2 Amps, which is already lethal to humans under certain conditions. Worst of all, if the inner cylinder breaks, then the liquid may leak into it, resulting the wires to be exposed to water/alcohol. This is dangerous because of the potential electric shock it could cause to humans and the flammable nature when current encounters alcohol. Therefore, we would have to be extremely careful when testing our experimental setup. We understand the safety issues associated with our project, thus promise that we will be testing in a watertight non-conducting box during our initial experiment [8], and potentially wear non-conducting gloves to eliminate the risk as much as possible. Most importantly, we will have an instructor and another TA approved before plugging in our physical device for the first time. We will not bring any parts of the device home, and will only experiment with it under a TA's supervision in senior design lab.

## References

[1] N. Nada, "A brief history of Ferrofluid," in Concept Zero, Ferrofluid Displays | Concept Zero, 2014. [Online]. Available: https://www.czferro.com/news1/2014/10/27/history-of-ferrofluids.

[2] K. Haines, "Inspired Designs," in KICKSTARTER. [Online]. Available: https://www.kickstarter.com/projects/1880422811/ferrofluid-a-symbol-of-the-future.

[3] M. Robinson, "RIZE Spinning Ferrofluid Display," in KICKSTARTER. [Online]. Available: https://www.kickstarter.com/projects/ferroflow/rize-spinning-ferrofluid-display.

[4] H. Zhang, T. Hsu, Z. Yao, “Ferrofluid Clock Final Report for ECE445”, supervised under Luke Wendt, [Online]. Available: [online] https://courses.engr.illinois.edu/ece445/getfile.asp?id=8701.

[5] "ATmega328," in MICROCHIP. [Online]. Available: http://www.microchip.com/wwwproducts/en/ATmega328.

[6] "Semiconductor & Storage Products for TB6612FNG," in TOSHIBA Leading Innovation. [Online]. Available: http://toshiba.semicon-storage.com/ap-en/product/linear/motordriver/detail.TB6612FNG.html.

[7] "IEEE IEEE code of ethics," in IEEE Advancing Technology for Humanity. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html.

[8] C. Huang and C. Lu, “Dynamic Ferrofluid Lamp ECE445 Project Proposal”, comments added by Luke Wendt. [Online]. Available: https://courses.engr.illinois.edu/ece445/pace/getfile.asp?id=8826.

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[1] Scott A. McDonald, Electrical and Computer Engineering Machine Shop, 1049 ECE Building