ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Senior Design Project 445 of Electrical and Computer Engineering

Programmable Ferrofluid Display

By

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Design Review for ECE 445, Senior Design, [Spring 2017]

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Project No. 45

Content

I. Introduction

1.1 Objectives

1.1.1 Goals

1. Create ferrofluid display of lower cost than currently available on the market.
2. Improve upon the design of Group 32, an ECE 445 team that created a programmable display the semester of Fall 2016
3. Allow computer connectivity to the display which grants manipulation of the ferrofluid pixels via programming
4. Generally pleasant aesthetic of finished enclosure and liquid (suspension fluid and ferrofluid)

1.1.2 Functionalities

1. Ferrofluid manipulated through a 5x5 grid of permanent magnets attached to servos which increase/decrease the magnetic field as they move toward/away from the display (function as "pixels")
2. Suspension fluid that allows for quick and efficient movement of ferrofluid without causing buildup or scum to pile on the display
3. Microcontroller provides API for the computer-to-display interaction, which includes functions for enabling/disabling individual magnets, and allows for simple programmed images using the ferroflu

1.2 Background

Ferrofluid is a type of liquid that, when in the presence of a magnetic field, becomes strongly magnetized. Invented by Steve Papell of NASA in 1963, it was first incepted as a liquid rocket fuel. The idea was to draw the fluid towards a pump inlet by applying a magnetic field in a weightless environment. Ferrofluid is considered a colloidal liquid composed of nanoscale ferromagnetic particles suspended in a carrier fluid (mainly water or some organic solvent) [1].

Our idea for a programmable project was greatly inspired by the Ferrolic display. Ferrolic is a high-end ferrofluid display that seeks to connect digital screens and tangible reality into a beautiful magnetic painting. It functions by utilizing a basin that allows ferrofluid to be manipulated freely. Behind this aquarium, strong electromagnets control the shape of fluid. Ferrolic is controlled in software by an internal system that is web-browser accessible. This allows users to create unique animations through the display. As for its characteristics, Ferrolic is completely silent and produces zero light. Its best qualities are represented through time and text displays. Currently, Ferrolic is in ongoing development and is projected to be quite expensive [2]. Ferroflow is another ferrofluid display but operates on a much simpler scale [3].

Another area of inspiration was from a past ECE 445 group. They attempted to create a ferrofluid clock. Some noted information is discussed above in the Objectives. Ultimately, they utilized electromagnets to manipulate an array of permanent magnets, thus allowing movement of the ferrofluid. So far, their extensive reports have given us vital information on how to approach our project and will likely provide more insight in the future.

1.3 High-level requirements list

The following is a list quantitative characteristics that this project must exhibit to be considered successful.

1. The project must be able to respond to computer input to move ferrofluid to any pixel on the display within 5 seconds of receiving the command.
2. The project must be able to operate with at least 10 of the display's 25 pixels active (holding ferrofluid) at once (40%).
3. The microcontroller, servo controller, and a single servo must be powered at all times with 5V $\pm$ 5% voltage and 100 - 500 mA current.

II. Block Design

2.1 Block Diagram

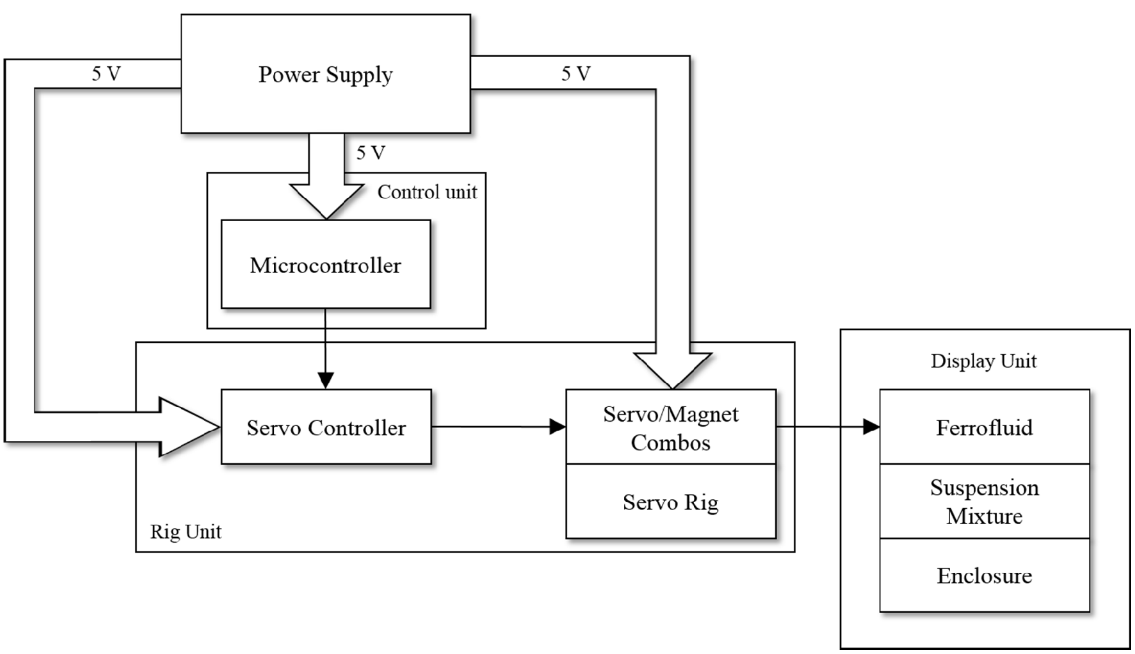


Figure 1 Block diagram of design

The design consists of a liquid display of a mixture of ferrofluid and a suspension fluid, contained within a clear enclosure. Behind this is our Servo Rig, which contains all of our permanent magnets attached to servos, arranged in an even grid. This rig is controlled by our microcontroller, which moves the magnets closer and farther from the display using the servos. This will from now on be referred to as enabling and disabling magnets. The microcontroller is powered by a power supply which also supplies power to the servo array through a current-limiting circuit. The microcontroller has an I/O port for control from a computer. Upon receipt of a command from the computer to turn a pixel on, the microcontroller will enable and disable magnets in order to move ferrofluid to the pixel, and will disable the pixel's magnet when instructed to turn the pixel off. We will optimize the spacing and strength of our magnets to maximize the rate at which we can move the ferrofluid into position. The display will include a large enough amount of ferrofluid in the enclosure to ensure that there is enough ferrofluid to allow for at least 12 of the pixels to be active at once.

2.2 Physical Design

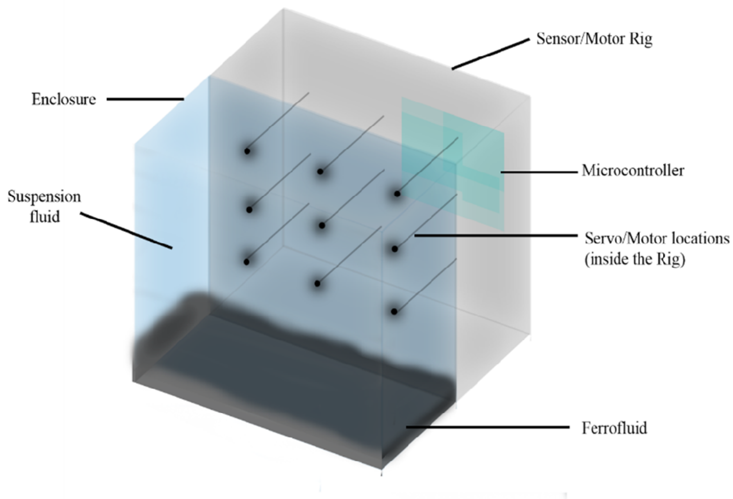


Figure 2 Physical diagram of display

As Fig. 2 shows, our project will consist of two distinct interconnected sections: the display and the servo rig. The display contains the fluid mixture (ferrofluid and suspension fluid) and the rig contains the hardware (servos and magnets). The servo controller and microcontroller will be mounted behind the rig.

2.3 Functional Overview

2.3.1 Power Unit

Power Supply

The PSU provides continuous and steady power to the device. It consists of twelve AAA alkaline batteries connected in series to create an 18V source. The batteries are rated at 800 mAh and would allow for approximately 3 hours of 250 mAh draw. To step down the DC voltage, the source will be connected to two voltage regulators (MC7805). These are available in ECE Electronics Services Shop. The MC7805 voltage regulators output 5V DC and are current limited up to 1.5 A, well within the needed current draw. The 470 uF and 0.1 uF capacitors are connected to reduce the noise of the circuit and allow for smoother output. This voltage regulating circuit is similar to the past group's (32) design.

Figure 3: Physical view of MC7805 Voltage Regulator

2.3.2 Control Unit

Microcontroller

The microcontroller, an ATmega328P chip, is the brains of the display. It will run a software program that manages the display state and provides a high-level API to a computer, which can be plugged into the microcontroller through an I/O port and allow for drawing to the display. The microcontroller will be able to set the state of the 25 servos through 6 output pins. The microcontroller will also move ferrofluid to any pixel on display by enabling/disabling magnets along a path from the bottom of the display to the desired pixel. Lastly, the controller will be wired into the servo controller and will be powered by the power supply.

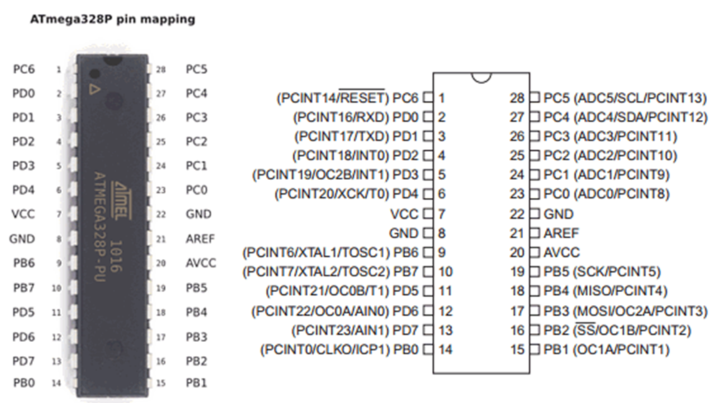


Figure 4 ATmega328P Pinout Diagram

2.3.3 Rig Unit

Servo/Magnet Combos

The servo/magnet combos serve as the individual components the microcontroller will control in order to manipulate the enclosed ferrofluid. There will be 25 mounted to the servo rig, and they are each composed of a single magnet attached to the arm of a servo. The servo will toggle the rotation of the arm between 0° and 180°, with 0° defining the magnet away from the display and 180° defining the magnet close to the display. These will be wired into the servo controller.

Figure 5 (Left) Magnets; (Right) Simple servo

Servo Controller

The servo controller is the interface between the servos and the microcontroller. It acts as a multiplexer, allowing the microcontroller to address individual servos for enabling/disabling without the need for separate pins. This will greatly reduce the complexity of our project. The component will receive six pins of input from the microcontroller: five of which will be used for addressing each of the 25 servos and the remaining will be utilized for setting the state of the addressed servo. The array will then enable and disable the servos wired into it.

Servo Rig

The servo rig is a static, fabricated plastic rig upon which the servos and sensors will be mounted. It will provide mounting points with which the components are attached. This rig will be connected to the enclosure and will ensure that the components do not move relative to one another or the enclosure.

2.3.4 Display Unit

Enclosure

The enclosure contains the ferrofluid and suspension mixture. It is a clear, waterproof tank with a removable but sealed lid. The enclosure will be attached to the front of the servo rig.

Ferrofluid

The ferrofluid is the medium which our project will manipulate to form patterns on the display. It is a black, magnetic fluid which we will manipulate by shifting permanent magnets through the back wall of the enclosure. It will be contained within a suspension mixture. This mixture will be a transparent liquid that will allow the ferrofluid to freely traverse through the enclosure. This liquid must be of similar density to the ferrofluid.

Figure 6 Ferrofluid

Suspension Mixture

The suspension mixture is a transparent liquid which will be mixed with the ferrofluid inside the enclosure. This liquid will be of similar but slightly lower density to the ferrofluid so that the ferrofluid falls to the bottom of the enclosure, but can be easily manipulated. The fluid must also not react in any way with the ferrofluid. We will use a mixture of 75% isopropyl alcohol (91%) and 25% distilled water, as this will be immiscible with the ferrofluid's solvent (mineral oil).

2.4 Requirements and Verifications

The Table II represents the requirements and verifications of each block.

Table II Module requirements and verifications

System	Module	Requirements	Verifications	pts
Power Supply	Voltage Regulators	Must be able to supply a consistent 5 V $\pm$ 2.5 V (5%) DC power at 100 - 500mA draw to the microcontroller, PCB logic, and one rotating servo at all times.	Utilize a multimeter to check if the voltage and current outputs are within the specified values. Measure it over a period of one minute while running the servo. Use an oscilloscope to check if the voltage signal is steady	5
	Batteries	12 AAA batteries connected in series to supply 18V $\pm$ 5% power at 100 – 500 mA draw. Lifetime of batteries should exceed 2 hours.	Utilize a multimeter to check if the voltage and current outputs are within the specified values. Use oscilloscope to check voltage steadiness. Measure, through use of a timing mechanism, the lifetime of the batteries during usage of the device.	10
				15
Display Unit	Ferrofluid	Must be able to cover 10 - 20 (40% - 80%) of the 25 pixels at once.	Run test program on microcontroller which cycles ferrofluid up from bottom along each column. Must fill the pixels of the display up to and between the second and fourth row before running out of ferrofluid to carry upwards	5
		When the system is considered to be "on", pixels contain a splotch of ferrofluid with a diameter of at least 2.5 mm.	Measurements will be taken of each pixel's ferrofluid splotch using a ruler to verify diameter requirement. Results will be presented as a photo of the test passing accompanied by overlaid diameter of each pixel.	5
	Suspension Mixture	Cannot oxidize the ferrofluid and have chemical reaction with ferrofluid.	Mix the suspension mixture with the ferrofluid and allow to sit overnight. Ensure appearance and behavior of ferrofluid remains unchanged.	3
		Doesn't make the ferrofluid deposit on the enclosure.	After mixing, monitor the solution overnight and note any deposits that form on the enclosure.	2
	Enclosure	Does not leak any liquids.	Place enclosure in a tray, fill with liquid, measure volume of liquid contained, and allow to sit overnight. Ensure that tray contains no liquid and that volume inside container is equal to initial volume.	4
		Cannot be magnetized to prevent manipulating the ferrofluid.	Measure thickness of walls of container with a ruler.	1
				20
Rig Unit	Servo Rig	Servos do not move by more than 0.2cm from their initial position during operation.	Measure the position of each servo before and during operation using a ruler as adjacent the servo and adjacent servos operate. Ensure difference in positions is within tolerance.	2
	Servo/ Magnet Combos	Magnets produce magnetic field strength of to manipulate ferrofluid through the walls of the enclosure.	Utilize ruler to measure distance between magnet and enclosure wall. Watch to see significant movement of the ferrofluid from varying distances.	5
	Servo Controller	Ensure adequate current draw, approximately 2 mA, as specified by the used multiplexers	Utilize ruler to measure distance between magnet and enclosure wall. Watch to see significant movement of the ferrofluid from varying distances.	2
				9
Control Unit	Microcontroller	PWM pulse width for 1ms pulse must be between 0.75ms and 1.25ms wide and 2ms pulse width must be between 1.75ms and 2.25ms wide	Connect oscilloscope to PWM outputs from microcontroller and measure pulse widths.	6
				6

2.5 Supporting Materials

2.5.1 Calculatioins

Power Supply

The 18 V source will be stepped down by voltage regulators to create two 5 V outputs. These outputs will power the microcontroller/servo controller and individual servos. One servo will be powered at a time and the controllers will be powered at all times. The current will be held somewhere between 100 to 500 mA. Suppose the total current is 200 mA; therefore, in terms of power consumption, the active servo will consume approximately 1 W of power.

$$Power = Voltage \times Current = 5\ V \times 200\ mA = 1\ W \quad (1)$$

This is assuming that the current draw would be 200 mA, which falls within the estimated range. As aforementioned, both controllers also require 5 V inputs for power. Therefore, their respective power consumptions should be in a similar range to that of the individual servos.

Enclosure Size

Most calculations are associated with ferrofluid. Since the ferrofluid is still in delivery, we are not able to start any calculation for servos. Nevertheless, we can calculate the minimum size of the enclosure by measuring the space that each servo occupies. The small servo has a torsional moment of 1.5 kg/cm and a dead band width of 10 microseconds, so the small servo can easily support the permanent magnet and move fast without affecting the output/servo arm. Each pixel operates with a servo and a permanent magnet. The diagram of a pixel is shown in Fig. 7.

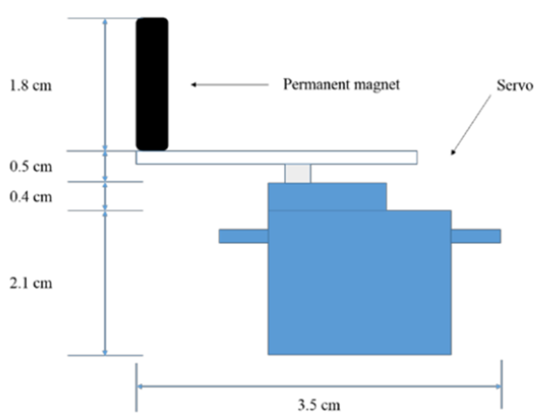


Figure 7 Physical diagram of pixel

From the physical diagram, the minimum height of each pixel is

$$Minimum\ Height = 1.8 + 0.5 + 0.4 + 2.1 = 4.8\ cm \quad (2)$$

and the minimum width of each pixel is 3.5 cm. For a device with at least a 5x5 grid of permanent magnets attached to small servos, the absolute minimum front size of the enclosure is

$$Height = 4.8 \times 5 = 24.0\ cm \tag{3}$$

$$Width = 3.5 \times 5 = 17.5\ cm \tag{4}$$

$$Area = Width \times Height = 24.0 \times 17.5 = 420.0\ cm^2 \tag{5}$$

However, it will be more aesthetically pleasing to have square pixels rather than rectangular pixels. As such, we intend to have a minimum pixel width of 4.8 cm to match the minimum pixel height. Additionally, we would like to add at least an additional 0.2 cm of spacing along each dimension to prevent servo collisions. Therefore, the minimum front size of the enclosure using square pixels is

$$Height = 5.0 \times 5 = 25.0\ cm \tag{6}$$

$$Width = 5.0 \times 5 = 25.0\ cm \tag{7}$$

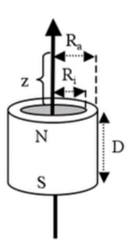
$$Area = Width \times Height = 25.0 \times 25.0 = 625.0\ cm^2 \tag{8}$$

We will not be able to determine the ideal depth of the enclosure until we receive our ferrofluid, but we expect it to be less than 1 cm deep.

Magnetic Strength

We want to simulate the magnetic field strength to see how far the permanent magnet should be in order to understand the force between the magnet and the ferrofluid. Suppose the enclosure is 0.5 cm thick, the component of a common ring permanent magnet is neodymium iron boron, and the movement of the magnet is linear and is on the symmetry axis of the magnet. The basic information of the magnet is shown in Table I [5].

Table I Specifications of a permanent ring magnet

Schematic	Material Type	Outside radius (R_a)	Inside Radius (R_i)	Length (D)	Residual Induction (Br)
 [6]	Nd-Fe-B	8.75 mm	5 mm	5 mm	52 mT

The formula for the magnetic field on the symmetry axis of an axially magnetized ring magnet is

$$B = \frac{B_r}{2}\left[\frac{D+z}{\sqrt{R_a^2+(D+z)^2}} - \frac{z}{\sqrt{R_a^2+z^2}} - \left(\frac{D+z}{\sqrt{R_i^2+(D+z)^2}} - \frac{z}{\sqrt{R_i^2+(D+z)^2}}\right)\right] \tag{9}$$

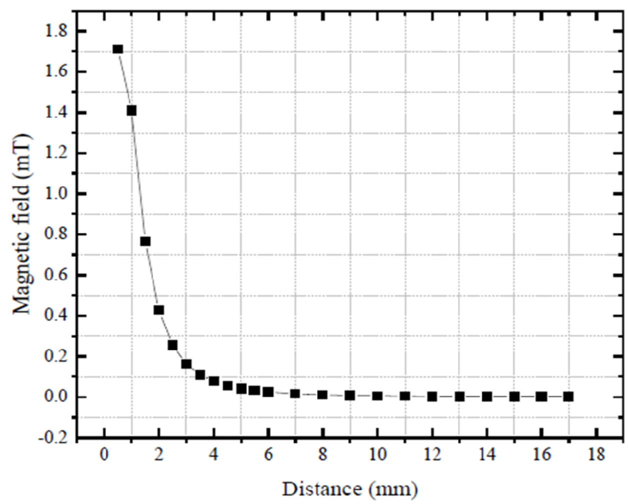
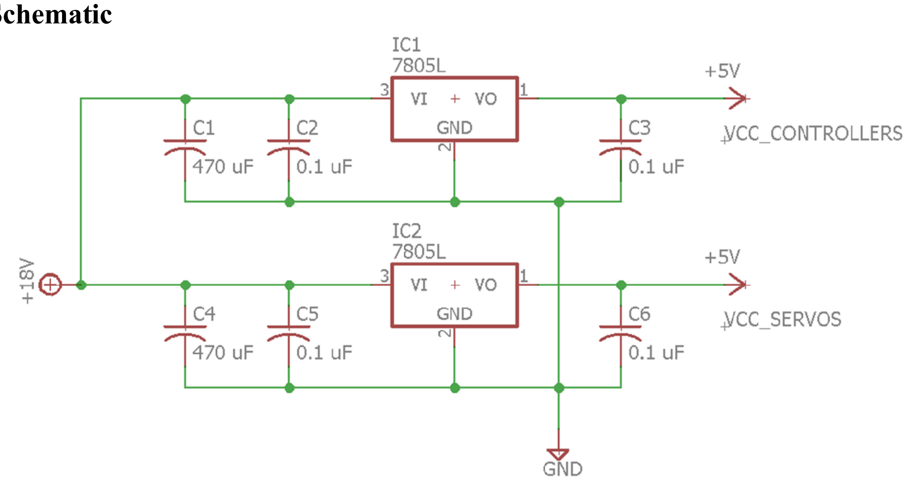


Figure 8 Magnetic field versus distance

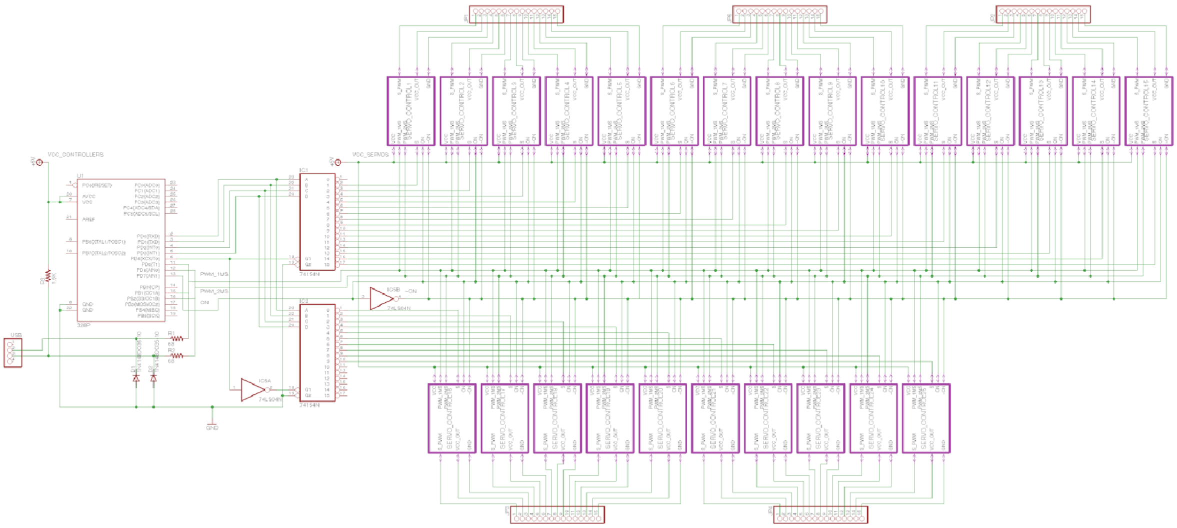
We can see that the magnetic field decreases rapidly through distance in Fig. 8. When the distance is 4 mm, the magnetic field is almost zero. The actual movement of the magnet is rotation, which means the actual distance is farther than the assumption of linear movement. In conclusion, we can say that the micro servo can provide enough separation for the user to manipulate the magnet in order to control the ferrofluid.

2.5.1 Schematics

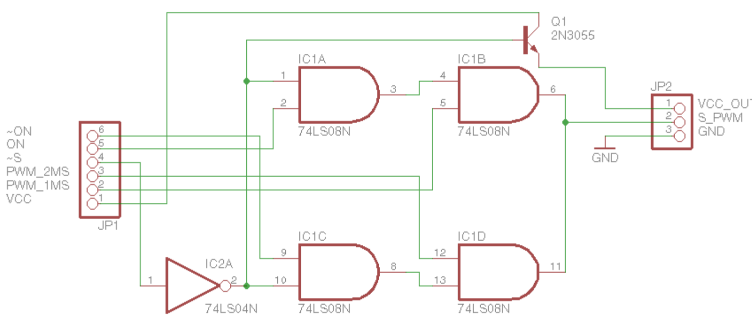
Power Supply Schematic



PCB Schematic (Microcontroller and Servo Controller)



Servo Module Schematic



2.6 Tolerance Analysis

The greatest risk to the successful completion of our project is clearly the servos and magnets. It is essential to our project's functionality that the magnets manipulate the ferrofluid reliably, which requires precise optimization of magnet spacing. Since we are unable to locate data sheets for most of the ceramic magnets found, physical characteristics will be difficult to calculate; therefore, we will need to experiment to determine this data. Furthermore, interactions between magnets could become problematic and increase the torque required of servos to move the magnets. This could potentially force us to use more powerful servos than initially planned, which will increase project cost as well as power consumption. We do not envision these difficulties causing serious problems as far as project completion is concerned; however, the difficulties could become quite high and will require extensive trial and error to solve.

As mentioned, since the servos control the proximity of the magnets and thus the strength of the magnetic field, it is vital the accessed servo receives a stable current. When activated, a servo in the array should receive a 5V input within a 5% error from the PSU. This error value will account for small fluctuations in voltage while still allowing for proper current production. If these conditions cannot be met, then the servo will likely not receive adequate current and thus imprecisely manipulate the ferrofluid. This will result in improper pixel display and the failure of our product.

III. Cost and Schedule

3.1 Cost Analysis

The cost includes the labor cost and the part cost, as shown in Table III.

Table III Cost analysis

LABOR			
Service	**Hourly Rate**	**Qty.**	**Total**
Computer Engineer I (Bradley Anderson)	$60.00	225	$13,500.00
Engineer Physician I (Hao-Jen Chien)	$60.00	225	$13,500.00
Electrical Engineer I (Thomas Coyle)	$60.00	225	$13,500.00
Labor Sub-Total			**$40,500.00**

Note: The hour rate includes a 2.5 multiplier.

PARTS				
Part Name	**Distributor**	**Unit Cost**	**Qty.**	**Total**
12-Pack AAA Rechargeable Batteries	Amazon	$11.99	1	$11.99
MC7805 Voltage Regulators	ECE store	$0.94	2	$1.88
Power supply			**1**	**$8.86**
Arduino Uno (ATmega328P)	Arduino	$24.95	1	$24.95
Microcontroller			**1**	**$24.95**
Futaba S3003 Servo Motors	DealExtreme	$4.26	25	$106.50
Round Disk Magnets (25 pieces)	Amazon	$7.99	1	$7.99
Servo Controller PCB	ECE Machine Shop		1	$10.00
Mounting Rig	ECE Machine Shop		1	$20.00
4:16 MUX (SN74154N)	ECE Store	$3.62	2	$7.24
Hex Inverter (SN74LS04N)	ECE Store	$0.70	5	$3.50
Quad AND Gate (SN74LS08N)	ECE Store	$0.71	25	$17.75
High Power Transistor (2N3055)	ECE Store	$0.82	25	$20.50
Rig unit			**1**	**$193.48**
Distilled water (0.5 gallon)	Walmart	$2.00	1	$2.00
91% Isopropyl alcohol (0.5 gallon)	Walmart	$2.58	1	$2.58
Enclosure	ECE Machine Shop	$15.00	1	$15.00
Ferrofluid (125mL)	Amazing Magnets	$34.75	1	$34.75
Enclosure			**1**	**$54.33**
Part Sub-Total				**$286.63**

Labor Sub-Total	$40,500.00
Part Sub-Total	$281.62
GRAND TOTAL	**$40786.62**

3.2 Schedule

No.	Week	Bradley Anderson	Hao-Jen Chien	Thomas Coyle	Team
1	01/16	Search partners	Search partners	Search partners	Post initial post.
2	01/23	-	-	-	Form design matrix of potential parts for determining design. Begin design.
3	01/30	Determine project objectives	Determine project objectives	Determine project objectives	Project page setup Purchase lab notebook.
4	02/06	Create list of part. Begin block design.	Finalize project proposal. Begin physical design	Finalize project proposal.	Finish lab safety training. Begin purchasing parts. Complete, edit and turn in the design proposal.
5	02/13	Finalize mock design document	Finalize mock design document	Meet ECE shop. Sign up mock design review	Complete mock design review and turn in on Wednesday.
6	02/20	Sign up for design review. Complete circuit design for project.	Finalize design review document	Design power circuitry. Order ferrofluid.	Finalize design and complete the design review document. Eagle assignment.
7	02/27	Unavailable. In San Francisco for professional conference.	Test the proportionality of the suspension mixture. Meet machine shop for enclosure.	Finalize power circuitry. Meet machine shop for assembly of magnet and servo.	Purchase the rest of parts. Revise design based on comments. Begin PCB design in Eagle.
8	03/06	Integrate rig unit and microcontroller and test microcontroller for a servo	Test servos and ferrofluid for visual effects.	Test voltage regulators. Test power connection and reliability.	Complete soldering assignment. Complete first version of PCB
9	03/13	Continue testing the microcontroller for 25 servos. Finish corrections of PCB.	Test	Test	Finalize PCB.
10	03/20 break	Work on individual progress report	Work on individual progress report	Work on individual progress report	Complete individual progress reports.
11	03/27	Test PCB	Test applications	Aid in testing of PCB and applications	Integrate all parts of project together.
12	04/03	Continue testing PCB	Continue testing applications	Work on integrating all parts of project	Test the entire product
13	04/10	Prepare mock demo demonstration	Prepare presentation for mock demo	Black-box testing of the individual components	Prepare for mock demo.
14	04/17	Finish final presentation	Finish final presentation	Continue planning demo. Finish final presentation	Prepare for DEMO
15	04/24	Finalize project demonstration	Prepare final paper	Aid in finalize paper and demonstration	Finalize final paper.
16	05/01	Finalize presentation	Finalize final paper.	Lab checkout and help with presentation/paper if needed	Complete final paper.

IV. Ethics and Safety

4.1 Ethical Considerations

Our project has a couple of components which will require special care to ensure our safety. The first of these is the liquid mixture. Ferrofluid can be messy and stains easily, but most ferrofluid can be safely handled and will not cause serious harm unless ingested. We should be mindful of what we use for the suspension mixture. Certain liquids, when mixed with ferrofluid could become toxic or react in other dangerous ways. We will need to research to make sure we use a safe material for our suspension mixture which will not interact with the ferrofluid, which is transparent, and which will not corrode the enclosure. This aligns with #1 of the IEEE code of ethics. We want to mitigate potential harm of our project and disclose and safety or health issues that could arise from its use or misuse [4].

We do not envision our project having any potential ethical issues, since it is intended solely for entertainment. Aside from the potential issue of someone removing the liquids from our display and ingesting them, or lighting the project on fire, there should be very few risks to anyone arising from our project.

Overall, our project encompasses the statement presented in the IEEE Code of Ethics, #5. We want to improve the understanding and use of ferrofluid technology. Its lack of use in the consumer industry and its often outrageous price range are factors that inspire us to better engineer the magnetic display [4].

To summarize, our project outlines the following IEEE codes of ethics:

(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; (3) To be honest and realistic in stating claims or estimates based on available data; (5) To improve the understanding of technology; its appropriate application, and potential consequences; (6) To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations; (7) To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others; and (10) To assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

4.2 Safety

Overall, our programmable ferrofluid display has low power consumption, this ideal especially when working with potentially harmful liquids. Our usage of batteries instead of the main source also lowers potential risks that occur when working with a high voltage. Ultimately, there a few things to consider concerning the safety of the batteries:

- Do not short circuit the battery or connect it in reverse polarity
- Keep batteries in a safe environment (ie. dry and cool areas)
- Do not exceed 600 mAh of capacity discharge of battery

The other area of concern lies with the enclosure and fluids. We must keep in mind many factors when considering the actual casing of the project:

- Use a sturdy casing for the front display to avoid shattering or leaking of fluid (do not want liquid to interact with the electronics)

- Use non-toxic ferrofluid and safe suspension material (such as a mixture of isopropyl alcohol) while avoiding the possibility of flammable material wherever possible
- Ensure casing can withstand varying environments of hot/cold and damp/dry

All members of our team have passed the lab safety training and are properly updated and laboratory and electrical safety protocols.

V. References

[1] *Ferrofluid, Wikidepida*, 3 Feb. 2017 at 11:02, [Online].
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