Programmable Ferrofluid Display

ECE 445 Design Document

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I. Introduction

1.1 Objective

Our goals for the project are to create a ferrofluid display of lower cost than is currently available on the market and improve upon the design of Group 32, an ECE 445 team that created a programmable display the semester of fall 2016. It is also desirable for the ferrofluid display to have computer connectivity, granting manipulation of the ferrofluid pixels via programming. Lastly, a generally pleasant aesthetic of the finished enclosure and liquid (suspension fluid and ferrofluid) must be acquired.

The project functionality is based on ferrofluid that is 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") in suspension. The suspension fluid allows for quick and efficient movement of ferrofluid without causing buildup or scum to pile on the display. A 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 ferrofluid.

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).

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 17[1]. Ferroflow is another ferrofluid display but operates on a much simpler scale [2].

Another area of inspiration was from a past ECE 445 group (Group 32 of Fall 2016). 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

- The project must be able to respond to computer input to move ferrofluid to any pixel on the display at any time.
- The project must be able to operate with at least 10 of the display's 25 pixels active (holding ferrofluid) at once (40%).
- Fluids within the display should not react with each other, stick to the walls of the enclosure, or leak from the enclosure at any time.

II. Design

2.1 Block Diagram

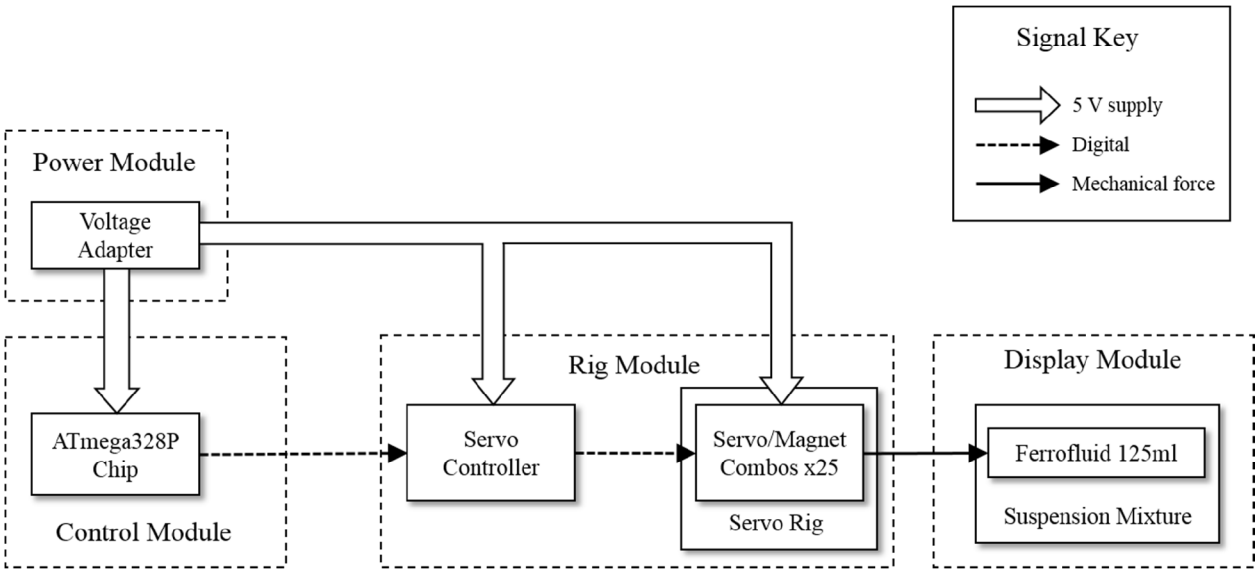


Fig. 1 Block Diagram

The design consists of a liquid display (mixture of ferrofluid and a suspension fluid) contained within a clear enclosure. Behind this display is the Servo Rig, which contains all of the 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 amount of ferrofluid within the enclosure to ensure enough ferrofluid is present in order for at least 12 of the pixels to be active at once.

2.2 Physical Design

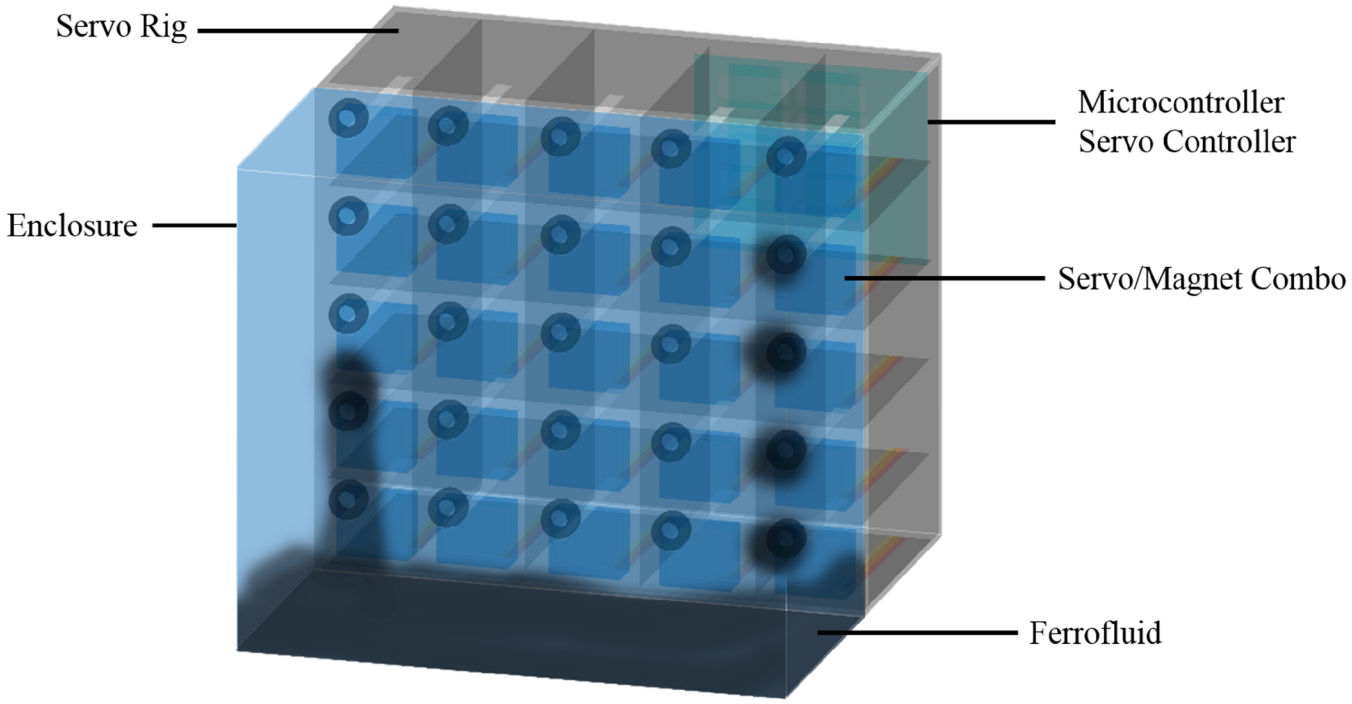


Fig. 2 Physical design sketch

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 Power Supply

The PSU is highly simplified for this project. Each unit (microcontroller, servo controller, and servos) only requires a supply of 5 V with minimum current draw. Since there is no discrepancies between voltages, only a single device is needed to step down main (a wall plug will be utilized) to the desired 5 V DC. We will be using the Jamesco DDU050100M2270 AC/DC power supply wall adapter/transformer. This device will step-down and convert the 120VAC main to 5 V DC.



Fig. 3 Physical view of the Jamesco power adapter

Because this is a pre-manufactured device, many requirements and verifications are already provided to us through the data sheet. This information provided will be trusted and utilized for further design and calculations.

Table 1 Power adapter characteristics

Full Load Rated Voltage	5 V DC ± 0.3 V
Rated Current	1000 mA
Ripple Voltage (Vpp)	50 mV MAX
Rated Power	5 W
Primary Exciting Current I/P: 120VAC 60Hz	90 mA MAX
Primary Load Current I/P: 120VAC 60Hz	200 mA MAX
Operating Temperature Range	-10 °C to + 40 °C
Operating Humidity Range	30-85% R.H.

The characteristics in Table I must be met or the display will not be properly powered. The requirements and verifications of the PSU must reflect these constraints.[3]

Table 2 Power Module requirements and verifications

Requirements	Verifications
The display must not consume more than the adapter power rating of 5 W at any point during operation.	1. Connect to an output and measure the voltage and current at the PSU. 2. Ensure the calculated power does not exceed 5W. 3. Measure at onset, 30 minutes, and 1 hour of operation time
The display must not draw more than the adapter current rating of 1 A at any point during operation.	1. Connect a resistor (< 5 Ω) to the PSU output 2. Use a multimeter to check the current draw

2.4 Control Unit

2.4.1 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.[4]

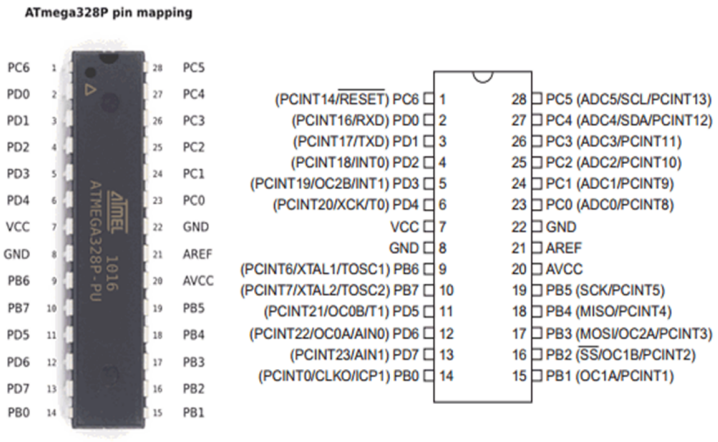


Fig. 4 ATmega328P Pinout Diagram

The microcontroller will be supplied with 5 V from the PSU. It also provides PWM to the servo controller to toggle the individual servos. For toggling, the servos must be supplied with 1 to 2 ms. Therefore, the frequency must be adequate to fulfill these requirements. The frequency and the current draw of chip at 5 V is 1 MHz and 6.75 mA.[6]

Table 3 Control module requirements and verifications

Requirements	Verifications
PWM pulse width for 1 ms pulse must be between 0.95 ms and 1.05 ms wide (±5%) and 2 ms pulse width must be between 1.95 ms and 2.05 ms wide (±5%) to ensure proper operation of servos	1. Connect oscilloscope to PWM outputs from microcontroller 2. Measure pulse widths through oscilloscope. 3. Ensure pulse widths are within required range.
Must be able to manipulate 10 out of the total pixels (40%) at once.	1. Run test program on microcontroller which cycles ferrofluid up from bottom along each column. 2. Observe the display unit to see if there are enough pixels displayed

2.5 Rig Unit

2.5.1 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 composed of a single magnet attached to the arm of a servo. The servo will toggle the rotation of the arm between 0o 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.

2.5.2 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 servos wired into it.

2.5.3 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.

Table 4 Rig module requirements and verifications

Blocks	Requirements	Verifications
Servo/Magnet Combos	Magnets are able to manipulate and control the ferrofluid from at least 2 mm away through the walls of the enclosure.	1. Measure distance between magnet and enclosure wall by ruler. 2. Watch to see significant movement of the ferrofluid from varying distances.
	Stay in position with ± 5° rotation while not operating	1. Connect waveform generator to servo and input a signal 2. Use the protractor to measure the rotation
Servo Controller	Ensure adequate current draw 2 mA ± 0.1 mA, as specified by the used multiplexers	1. Operate servo controller 2. Use multimeter to measure the current
Servo Rig	Servos do not move by more than 0.2 cm from their initial position during operation.	1. Operate the servo and adjacent servos operate. 2. Measure the position of each servo before and during operation using a ruler

2.6 Display Unit

2.6.1 Enclosure

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.

2.6.2 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.



Fig. 5 Ferrofluid

2.6.3 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 sugar and distilled water, as this will be immiscible with the ferrofluid's solvent (mineral oil). The exact molarity of the sugar in the distilled water with be determined in future testing.

Table 5 Display module requirements and verifications

Blocks	Requirements	Verifications
Enclosure	Does not leak any liquids.	1. Fill the enclosure with liquid. 2. Measure the mass of the liquid. 3. Place the enclosure overnight and measure the mass again.
Ferrofluid	When displaying pixels, the diameter of each pixel must be at least 2.5 mm.	1. Run a program on microcontroller which will display the maximum number of pixels 2. Measure each pixel with a ruler directly

Suspension	Cannot oxidize the ferrofluid and have chemical reaction with ferrofluid.	1. Mix the suspension mixture with the ferrofluid and allow to sit overnight. 2. Test the magnetic property through permanent magnet and see if appearance of ferrofluid remains unchanged
	Doesn't make the ferrofluid deposit on the enclosure.	1. Mix suspension and ferrofluid in the enclosure 2. Shake the enclosure and note any deposits.

2.7 Calculation

2.7.1 Power Supply

The power adapter is rated at 5 W. Therefore, it is desirable to ensure that the display does not draw or consume power over this limit. Three areas are powered at all times when the display is on: the microcontroller, servo controller, and servos themselves. From the microcontroller datasheet, during active mode the device draws 0.2 mA at 1.8 V. Since we will be providing a voltage of approximately 5 V, our current draw for the microcontroller will be higher. A good estimate for the current draw would be 1 mA. Therefore, the power consumption of the microcontroller during active mode can be calculated:

$$Power = \text{Voltage} \times \text{Current} = 5\ \text{V} \times 6.75\ \text{mA} = 33.75\ \text{mW} \tag{1}$$

This power draw is quite low and well under the upper limit. The servo controller also has a relatively low power consumption. For the two MUX chips utilized, there is an approximated draw of 170 mW at 5 V [5]. Therefore, adding these two power calculations together still gives the servos a wide margin of possible consumption. Ultimately, we feel confident that the power rating (and current rating) will be met for the display.

2.7.2 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. 6.

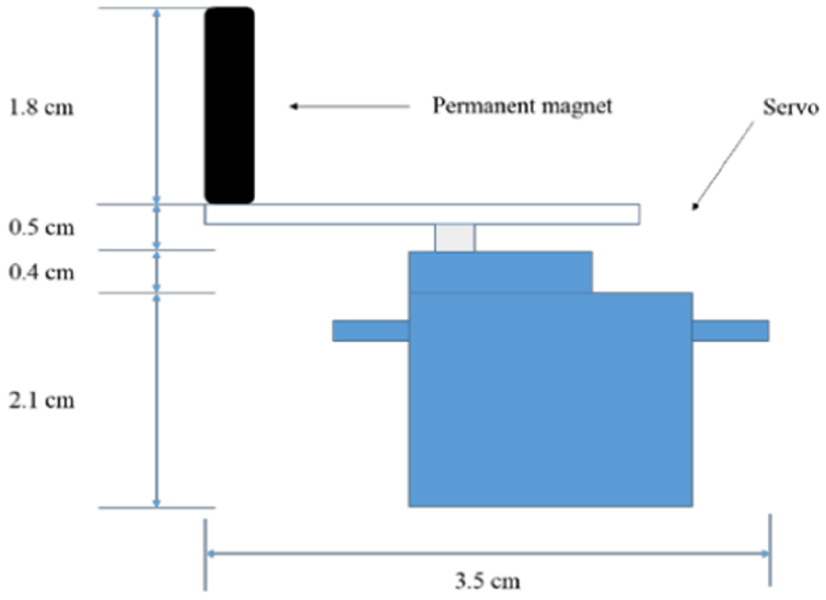


Fig. 6 Physical diagram of pixel

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

$$\textit{Minimum Height} = 1.8 + 0.5 + 0.4 + 2.1 = 4.8 \text{ cm} \tag{2}$$

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

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

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

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

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

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

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

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

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.

2.8 Schematics

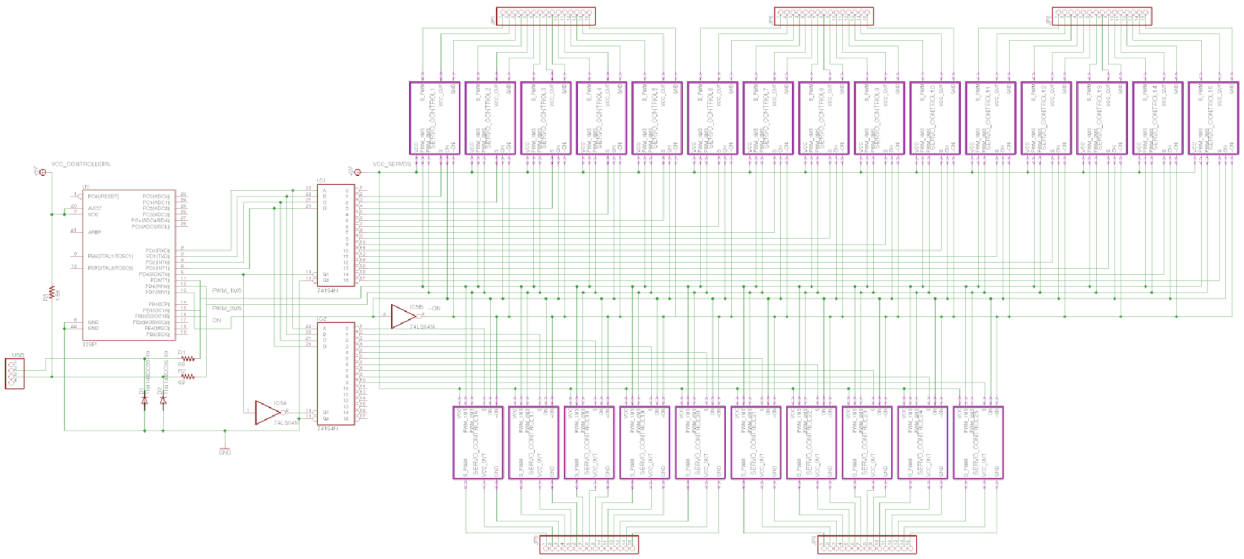


Fig. 7 PCB Schematic (Microcontroller and Servo Controller)

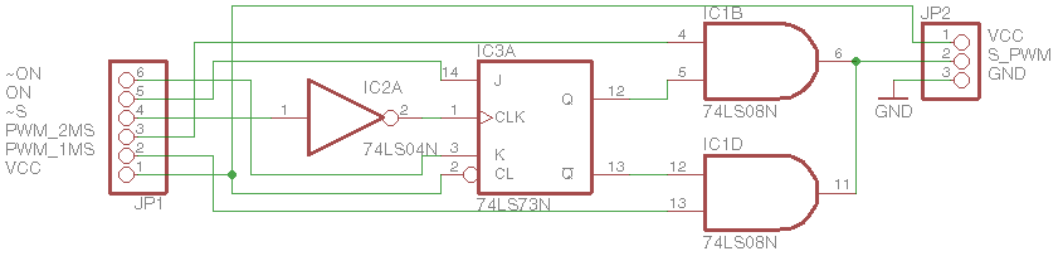
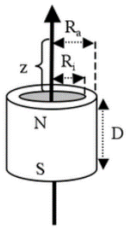


Fig. 8 Servo Module Schematic

III. Tolerance Analysis

The greatest risk to the successful completion of our project is 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, 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 6 [6].

Table 6 Specifications of a permanent ring magnet

Schematic	Material Type	Outside radius (R_a)	Inside Radius (R_i)	Length (D)	Residual Induction (Br)
 [7]	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

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

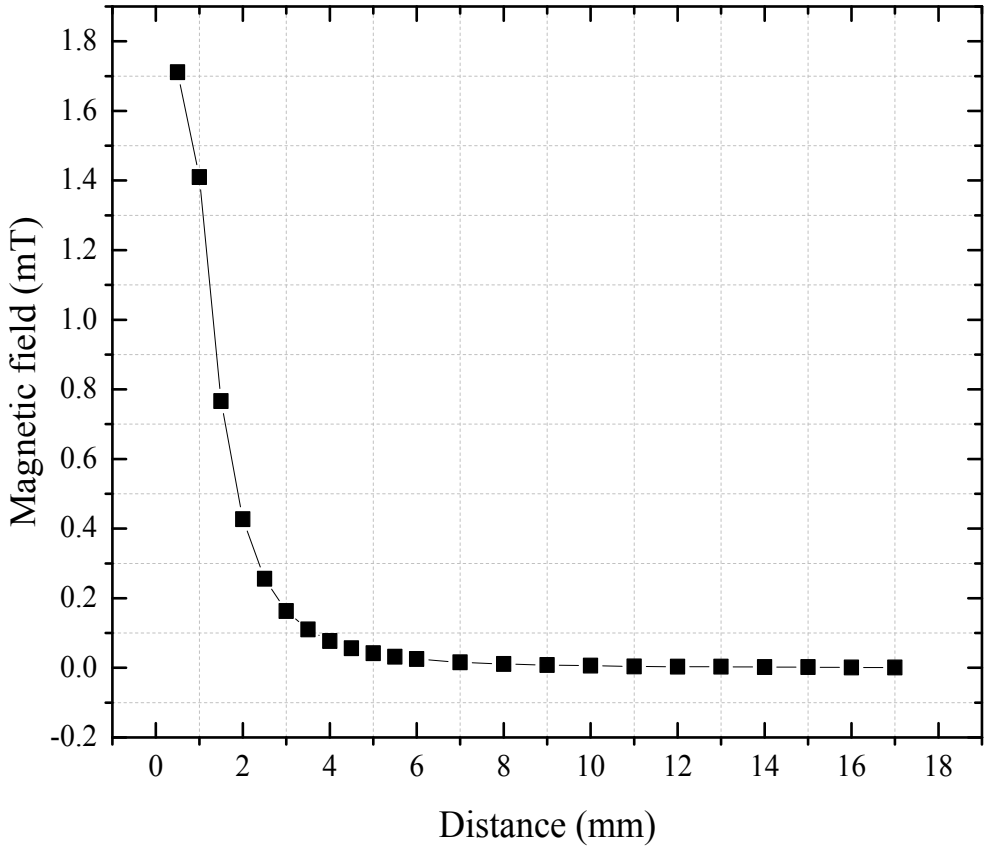


Fig. 9 Magnetic field versus distance

We can see that the magnetic field decreases rapidly through distance in Fig. 9. When the distance is about 1.6 mm, the magnetic strength is about 10 times lower than that at the origin. The actual movement of the magnet on a servo is rotation, which means the actual distance is farther than the assumption of linear movement, so the magnetic will be decrease more rapidly. We can say that the micro servo can provide enough separation for the user to manipulate the magnet in order to control the ferrofluid. Suppose we want to turn on a pixel (which means to move the magnet close to the ferrofluid). The servo arm has a radius of 1.5 cm and the effective distance to not turn on a pixel is 2 mm. We can approximate the tolerance angle for the servo:

$$\theta = \frac{distance}{radius} = \frac{2\ mm}{15\ mm} = 0.133\ \text{rad} = 7.64° \tag{10}$$

The turned-on angle of 180º has a tolerance of 7.64º, a variation of 4.2 %.

IV. Costs

Our fixed development costs are estimated to be $60/hour, 10 hours/week for two people. We consider approximately 60% of our final design in this semester (16 weeks), neglecting the central server, mesh network optimization, and partnerships with NGOs:

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**

PARTS				
Part Name	**Distributor**	**Unit Cost**	**Qty.**	**Total**
DDU050100M2270 Jamesco Power Adapter	Amazon	$17.48	1	$17.48
Power supply			**1**	**$17.48**
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 store	$15.00	1	$15.00
Ferrofluid (125mL)	Amazing Magnets	$34.75	1	$34.75
Enclosure			**1**	**$54.33**
Part Sub-Total				**$290.24**

Labor Sub-Total	$40,500.00
Part Sub-Total	$290.24
GRAND TOTAL	**$40790.24**

V. 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. Enclosure design.	Test voltage regulating of PSU. 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.	Finish corrections of PCB. Work on individual progress report	Finalize power design. Work on individual progress report	Finalize PCB. Complete individual progress reports.
10	03/20	Spring break			
11	03/27	Test PCB	Continue testing servos and ferrofluid effects.	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 the final paper	Aid in finalizing paper and demonstration	Work on final paper.
16	05/01	Finalize presentation	Finalize the final paper.	Lab checkout and help with presentation and paper where needed	Complete presentation/paper

VI. Ethics and Safety

5.1 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 [8].

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 [8].

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.

5.2 Safety

Overall, our programmable ferrofluid display has a simplified power supply unit that requires the use of a single device. This power adapter has a power and current rating (5W and 1A, respectively) large enough for the requirements of the circuit. The units of our display have low power consumption, which is ideal especially when working with potentially harmful liquids. In terms of voltage/current supply, main is desirable over the use of batteries in that it displays steady voltage characteristics and does not produce harmful byproducts such as acid; however, since main supplies such a high voltage, careful consideration must be made to ensure the circuit does not fry. Ultimately, there are a few things to consider concerning the safety of the power supply:

- Do not short circuit the PSU
- Keep PSU and unit in a safe environment (ie. dry and cool areas)
- Do not exceed rated current draw or rated power consumption from the power adapter

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 I 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.

References

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