Programmable Ferrofluid Display

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Abstract

The project is a display designed to manipulate ferrofluid by moving permanent magnets attached to servos. These magnet-servo combos function as individual pixels in a 4-by-4 array, a design which was tested and verified. The programmable ferrofluid display can store programs of unique pixel patterns and control each specific servo, all 16, at a single time; unfortunately, complete ferrofluid control is not entirely successful. Vertical translation of the magnetic fluid is not fully realized due to three possible reasons: the weak strength and polarity of the permanent magnets, the thickness of the fluid enclosure, and the wide spacing between each magnet. For future work, we hope to physically control ferrofluid through tilting the enclosure horizontally, reducing distance between magnets, or reversing polarity of adjacent magnets.

Contents

1. Introduction

The project is a programmable ferrofluid display which manipulates ferrofluid to patterns on the display. This project builds on the results of a similar project created by Group 32 from the Fall 2016 semester [1] [2]. Our goals for the project were to improve upon the functionality of the previous group's ferrofluid display by reducing power consumption and increasing display resolution. We aimed to accomplish this by utilizing servos to mechanically move the permanent magnets influencing the ferrofluid. Group 32 used electromagnets to control a series of permanent magnets. As aforementioned, this required a drastic amount of current draw. By utilizing servos, our display has a low current need (less than 2 A) and can access all 16 magnets at once, allowing for high display resolution.

The project functionality is based on the ferrofluid that is manipulated through a 4-by-4 grid of permanent magnets attached to servos. These servos increase or decrease the magnetic field as they move towards or away from the display in suspension, essentially acting as a "pixel". Figure 1 shows the block diagram of the programmable ferrofluid display.

The project is divided into four main modules: the power module, the control module, the rig module, and the display module. The power module consists of a PSU which provides a steady 5 V DC and sufficient current flow to the control and rig modules. The brain of the project, the control module, is made up of a microcontroller and control logic, which is responsible for addressing each of the 16 servo controllers, individually, and providing the appropriate signals to control them. The 16 servo controllers act as state holders, storing either an ON or OFF state for their associated servo. Depending on the state assigned, the controllers feed the appropriate control signal from the microcontroller to the respective servo, setting its position to either on or off. The servos are attached to permanent magnets, which they move closer and farther from the enclosure to control the ferrofluid within. The enclosure itself is a clear glass tank, filled with a mixture of ferrofluid and a suspension fluid created from 91% isopropyl alcohol and distilled water.

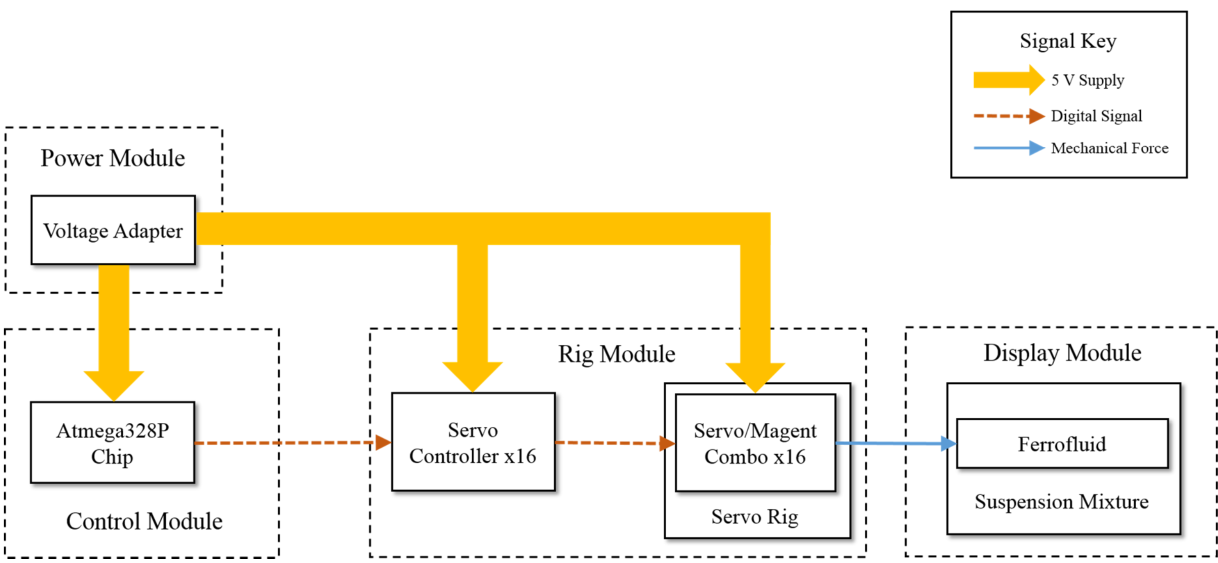


Fig. 1 Block Diagram

2. Design

The design consists of a liquid display (mixture of ferrofluid and a suspension fluid) contained within a clear, glass 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 simple wall adapter PSU which also supplies power to the servo array. The microcontroller has a programming port that allows programs to be uploaded to it. We optimize the spacing and strength of our magnets to maximize the rate at which we can move the ferrofluid into position. The display includes a large amount of ferrofluid within the enclosure to ensure enough ferrofluid is present for at least 12 of the pixels to be active at once. An image of the display's physical design is located in Appendix B of the report.

2.1 Power Supply

2.1.1 Power Supply

The PSU is highly simplified for this project. Each unit (microcontroller, servo controller, and servos) only requires a supply of 5 V DC with minimal current draw. Since there are no discrepancies between voltages, only a single device is necessary to step down main to the desired 5 V DC. Thus, a wall adapter rated at this voltage was utilized. As shown in Figure 2, we use a generic AC/DC power supply wall adapter/transformer. This device step-downs and converts the 120 V AC main to 5 V DC.

Fig. 2 Physical view of the power adapter

Because this is a pre-manufactured device, many requirements and verifications are already provided to us through the data sheet [3]. This information provided is trusted and utilized for further design and calculations. The characteristics in Table 1 must be met or the display will not be properly powered. The requirements and verifications of the PSU must reflect these constraints.

Table 1 Power adapter characteristics

Full Load Rated Voltage	5 V DC ± 0.3 V
Rated Current	2 A
Rated Power	10 W
Operating Temperature Range	-10 °C to + 40 °C
Operating Humidity Range	30-85% R.H.

2.2 Control Unit

2.2.1 Microcontroller

The microcontroller, an ATmega328P chip, is the brains of the display and is shown in Figure 3 [4]. It will run a software program that manages the display and draws preprogrammed patterns to it [5]. The microcontroller sets the state of the 16 servos through six output pins (SELECT 1-5 and ON). The five SELECT pins feed into input pins of a 5:32 multiplexer that allows each individual servo to be selected. ON is a state pin, and it sets the state of the selected servo (enabled or disabled). The two PWM (pulse width modulator) signals are outputs that control the servo position depending on the state of their associated servo controller: pixel OFF/ON equating to disable/enable, respectively. Ultimately, to set a servo module state, set the ON pin to a desired positon, then toggle the select bits on and off to quickly select and deselect the desired servo. This acts as a clock pulse for the JK flip-flop in the selected servo controller, updating its state.

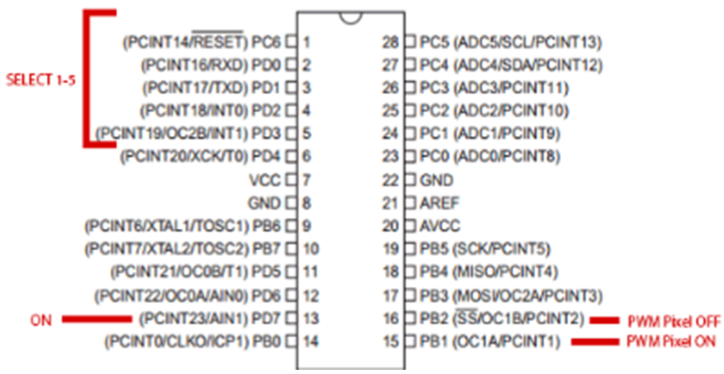


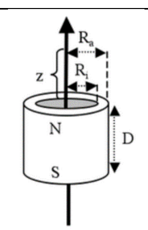
Fig. 3 ATmega328P pinout diagram with signals labeled

2.3 Rig Unit

2.3.1 Servo/Magnet Combos

The servo-magnet combos serve as the pixels for our display. These devices are what capture and influence the ferrofluid in the enclosure utilizing an induced magnetic field. Each servo arm is connected to a rubber "piston". When the servo arm rotates, the piston moves the permanent magnet in a linear fashion towards or away from the fluid enclosure. This signifies a pixel ON or pixel OFF, respectively. Whether a servo-magnet combo is to be turned on is determined by the microcontroller. The microcontroller sends signals that rotate the servo between 0° and 60° relative to its starting position. There are 16 servo-magnet combos in total.

Table 2 Specifications of a permanent ring magnet [6]

Schematic	Material Type	Outside radius (R_a)	Inside Radius (R_i)	Length (D)	Residual Induction (Br)
 [7]	Ceramic	51.5 mm	6.5 mm	7.7 mm	385 mT

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

$$B = \frac{B_r}{2}\left[\frac{D+z}{\sqrt{R_a^2+(D+z)^2}} - \frac{z}{\sqrt{R_a^2+z^2}} - \left(\frac{D+z}{\sqrt{R_i^2+(D+z)^2}} - \frac{z}{\sqrt{R_i^2+(D+z)^2}}\right)\right] \tag{1}$$

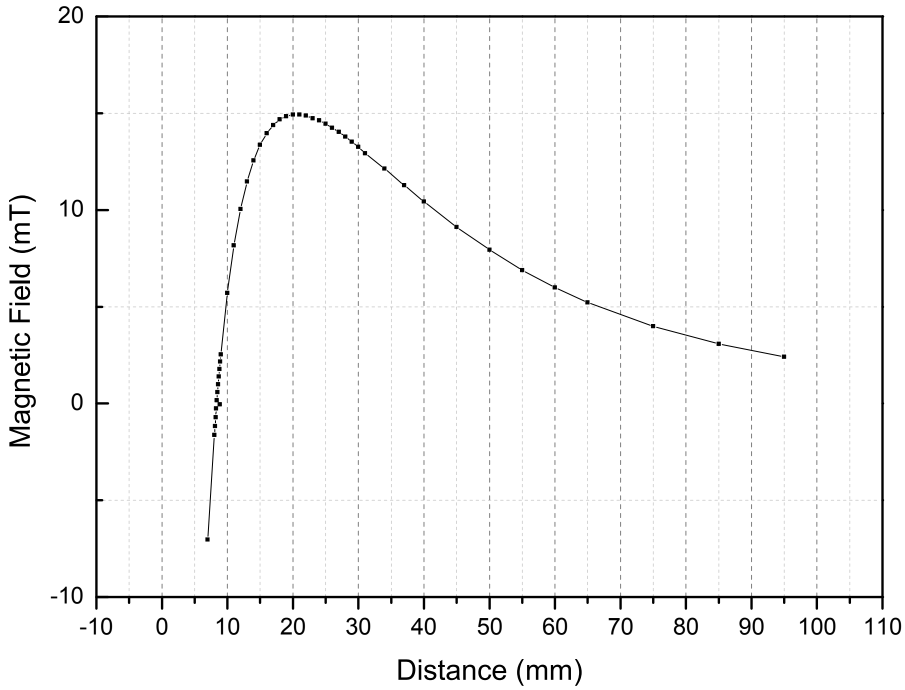


Fig. 4 Magnetic field versus distance

Figure 4 shows a simulation of the magnetic field versus distance of our magnet. We can see that the magnetic field decreases with increasing distance. We can adequately say that the servo, in its rotation, provides enough separation to manipulate the magnet, permitting control of the ferrofluid. Therefore, this simulation was utilized to grasp a better understand of the distance pixel ON and pixel OFF of the project should be.

2.3.2 Servo Controller

The 16 servo controllers are PCBs which are each assigned to an individual servo and manage the servo's state. They consist of a JK-flip flop which stores the servo's state, either ON or OFF. This state is updated to the current value of the microcontroller's ON pin when the servo controller is quickly selected and deselected, which is accomplished by using this select signal as a clock pulse for the flip-flop. The flip-flop outputs its state value and its inverse through its Q and ~Q outputs. These feed into one of the two inputs of two separate AND gates, and are ANDed with PWM Pixel ON and PWM Pixel OFF respectively. This serves to select one of these two signals to send to the servo's signal pin. Since exactly one of Q and ~Q will be true at all times, we ensure that only one these signals is passed through to the servo. For our final design, we added diodes to each of these AND gate outputs to prevent back-current into the output of the other gate. Each servo controller PCB is attached to the tail-end of its respective servo motor. The servo controller schematic is shown in Figure 5.

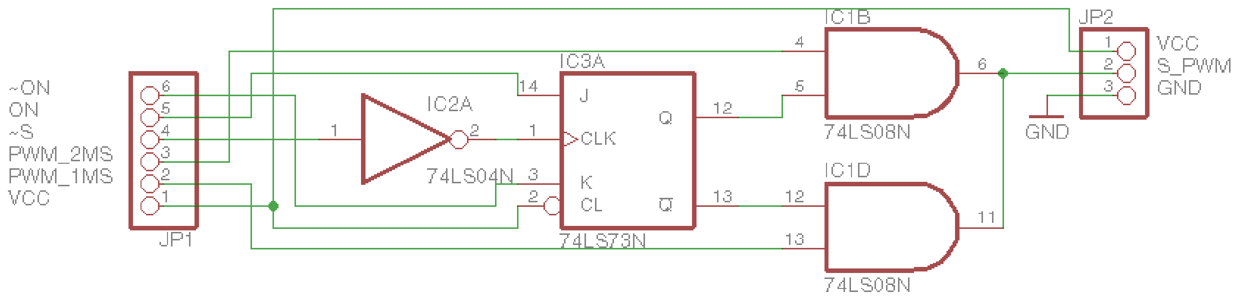


Fig. 5 Servo Module Schematic

2.3.3 Servo Rig

The servo rig is a static, fabricated wooden rig upon which the servos are mounted. Sixteen holes the size of the magnet diameter (51.5 mm) are cut into the rig and evenly spaced in a 4-by-4 array. The magnets are placed inside and allow for the linear motion desired for ferrofluid manipulation. The servos, attached to the magnet piston, are screwed into metal brackets on the back side of the rig. This ensures the stability of the servo motor. The ferrofluid enclosure sits in front of the servo rig.

2.4 Display Unit

2.4.1 Enclosure

The enclosure contains the ferrofluid and suspension mixture. It is a clear, waterproof squared tank with a removable but sealed lid. Plexiglass was used as the material for the enclosure at first, but the ferrofluid stained the inside surface of the container and every suspension fluid tested was unable to reduce the staining property. Therefore, we were forced to purchase a glass tank on the market. This square tank did not cause the ferrofluid to stain the walls and works well with all kinds of suspension fluid. The enclosure is attached to the front of the servo rig. Figure 6 shows the difference between the plexiglass and glass tanks.

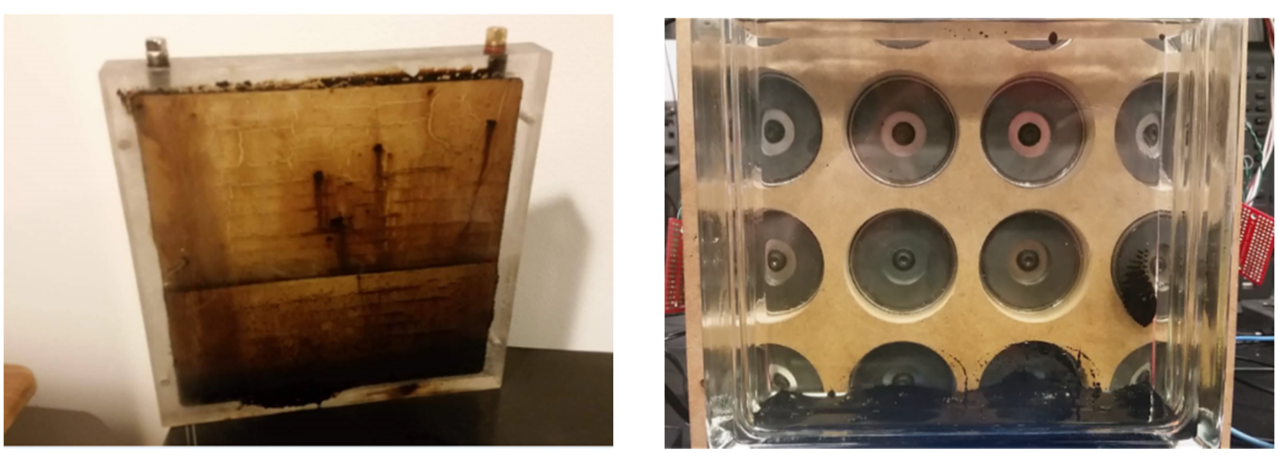


Fig. 6 Stained plexiglass container (left) and glass container in front of servo rig (right)

2.4.2 Ferrofluid

Ferrofluid is the liquid medium our project manipulates on the display. It is a black, magnetic fluid that follows the path of the field lines. Our linearly moving permanent magnets in the servo rig attract the ferrofluid. It is contained within a suspension mixture. This mixture is a transparent liquid, of similar density, that allows the ferrofluid to freely traverse through the enclosure.

Fig. 7 Ferrofluid

2.4.3 Suspension Mixture

As aforementioned, the suspension mixture is a transparent liquid that allows for the free translational movement of the ferrofluid when exposed to a magnetic field. The mixture should also be such that it does not allow staining on the enclosure walls. It is of a slightly lower density than the ferrofluid to allow the ferrofluid to pool at the enclosure bottom. Lastly, the mixture did not react chemically with the ferrofluid. We use a mixture of 91% isopropyl alcohol and distilled water in a ratio of about 60% IPA to 40% water.

Fig. 8 distilled water (left) and 91% isopropyl alcohol (right)

3. Design Verification

The requirements and verifications for our modules are explicitly stated in Appendix A of this report. These following verifications present additional data and information on each module's testing.

3.1 Power Supply

Our requirements for the power supply were primarily ensuring that enough power is supplied to enable our display to simultaneously manipulate our minimum number of servos while maintaining consistent voltages throughout our circuitry. We verified this by running a program which continually toggled all 16 servos on and off so that all 16 servos were constantly rotating, our maximum possible current-draw state, and testing voltages throughout our circuitry with a multimeter. We found that voltages throughout the circuitry while all servos were rotating were indistinguishable from corresponding voltages with no servos rotating, and all servos behaved as expected while running in this state. Thus, we verified that our power supply fulfills our requirements.

3.2 Microcontroller

A major verification of the microcontroller was in the two PWM output waveforms. These requirements are necessary to ensure that the PWM signals correspond to the correct rotation of the servos for our on and off positions. After speaking with the machine shop, it was decided to switch the pulse width of the pixel ON from 1 ms to 1.2 ms and pixel OFF from 2 ms to 1.8 ms. This was due to the piston device used to linearly move the magnets. Therefore, our requirements and verification table is a little off, but it is still correct in theory with the minor change. Pixel ON must have a PWM pulse width of 1.2 ms ± 0.05 ms of each 20 ms cycle. Pixel OFF must have a PWM pulse width of 1.8 ms ± 0.05 ms of each 20 ms cycle. As shown in Figure 9, the oscilloscope outputs for both PWM signals are shown. The signals are well within the requirements.

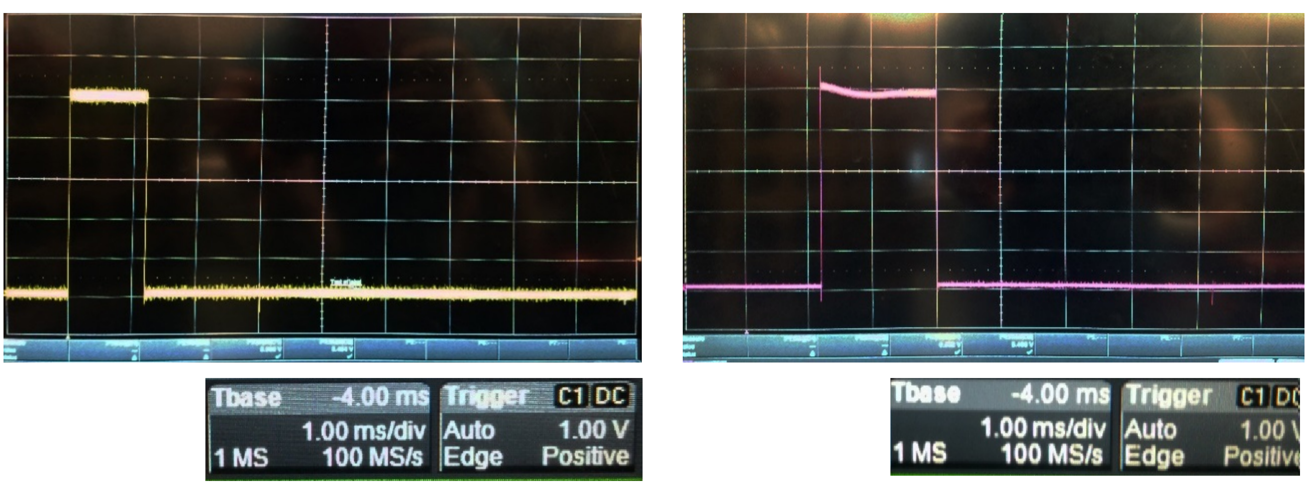


Fig 9 PWM signal for pixel ON (left) and PWM signal for pixel OFF (right)

Also, the microcontroller can control and access all 16 servos at once. This passes the verification of manipulating 10 servos at a single time.

3.3 Servo/Magnet Combo

The magnets can manipulate the ferrofluid within the enclosure from over 2 mm away. The thickness of the glass enclosure is 1.2 cm, and the magnets are still able to effectively influence the ferrofluid. Additionally, the servo motors, when screwed tightly into the metal bars of the servo rig, do not move horizontally at all during arm rotation. Thus, both requirements for the servo-magnet combo are met.

3.4 Display Unit

The enclosure is a commercial made glass tank. It does not leak any fluid whatsoever during normal operation and has held liquid without leaks for days at a time. The diameter of each ferrofluid pixel is well over the required 2.5 mm. The pixel diameter is equal to the magnet diameter which is 51.5 mm. With the glass enclosure, the suspension mixture does not allow the ferrofluid to deposit on the interior walls. Also, there are no significant chemical reactions as the ferrofluid is suspended in the mixture.

4. Costs

4.1 Parts

Table 3 Parts Costs

Part	Manufacturer	Retail Cost (USD)	Items	Actual Cost (USD)
Generic AC/DC Power Adapter	D-Link	$10	1	$10
Power supply			**1**	**$10**
ATmega328p	Atmel	$2.25	1	$2.25
Microcontroller			**1**	**$2.25**
Futaba S3003 Servo Motors	Amazon	$12.33	16	$197.28
Magnets	Magnet 4 Less	$1.99	16	$31.84
Servo Controller PCB	PCBWay	$0	20	$0
Main Board PCB	PCBWay	$0	5	$0
Mounting Rig	ECE Machine Shop	$0	1	$0
Various Electronics Components	Various (Digikey)	Various	Many	$228
Rig unit			**1**	**$457.12**
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**
Total				**$523.70**

4.2 Labor

Table 4 Labor Cost

Service	Hourly Rate	Qty.	Total
Computer Engineer I (Bradley Anderson)	$60.00	225	$13,500.00
Engineering Physicist 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**

Table 5 Grand Cost

Labor Sub-Total	$40,500.00
Part Sub-Total	$523.70
GRAND TOTAL	**$41,023.70**

5. Conclusions

5.1 Accomplishments

All the electrical and mechanical components of our project were tested and verified. Our PCBs could function as intended with each module of our design. The microcontroller was connected and soldered appropriately to the servo controllers which allowed for desired control over the servo motors. The servos rotated appropriately when connected to the linear piston-magnet devices created with the ECE aid of the machine shop. The servo rig operated as intended, permitting a sound structure for the servos to be placed. Lastly, the glass enclosure allowed for free movement of the ferrofluid when suspended in mixture with zero staining.

5.2 Uncertainties

Our project had a major uncertainty in its inability to vertically translate ferrofluid between magnets. When enabling a pixel above an adjacent one, the ferrofluid does not communicate adequately; instead, the ferrofluid falls back into the bottom pool. Several forces appear to be working against our design. Since our display stands upright, the effect of gravity on the ferrofluid is at its maximum. Tilting the display horizontally might lessen this effect. Also, the electromagnetic force between adjacent magnets seem to repel one another. This is likely due to the shared polarity of every permanent magnet. Reversing polarity between adjacent magnets in a checkerboard-like fashion would most likely fix this issue.

5.3 Ethical considerations

Our project has a couple of components that require special care to ensure safety. Foremost is the liquid mixture. Ferrofluid stains easily, but fortunately the fluid utilized in our project is nontoxic and can be disposed of similarly to everyday trash. The suspension mixture is also of relatively low harm. It is composed of 91% isopropyl alcohol and distilled water. IPA is flammable so great care is undertaken to ensure the enclosure is properly sealed from the outside world and away from open flames. These align with #1 of the IEEE code of ethics. We mitigate potential harm of our project and disclose the safety or health issues that could arise from its use or misuse [8].

The project, as a whole, does not have any ethical issues for consideration. It is intended solely for entertainment and was created to improve upon Group 32's design. Aside from the potential issue of someone removing the liquids from our display and ingesting them, or lighting the project on fire, there are very few risks to 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 inspired 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.

5.4 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 voltage and current rating (5V DC and 2 A, respectively) large enough for the requirements of the circuit. The modules 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. Many factors are considered with concerns to the actual casing of the project:

- Use sturdy, glass 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 (isopropyl alcohol mixed with distilled water) 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 passed the lab safety training before building and testing of our project. We are all well-versed and properly updated on the laboratory and electrical safety protocols.

5.5 Future work

The biggest challenge our project still faces is to allow for vertical control over the ferrofluid. There are two types of improvements which we have found will address this problem: increase the strength of the magnetic field in the enclosure and slope the enclosure of the display downhill towards the ground.

The most effective and easily engineered solution to attempt for future work is to increase the strength of the magnetic field in the enclosure. This can be accomplished in a number of ways, the simplest of which is to arrange the magnets with alternating polarity in a checkerboard pattern, so that each magnet has an opposite polarity facing the enclosure as each of its surrounding magnets. This will work because ferrofluid moves along magnetic field lines, and a checkerboard pattern will optimize the strength of the magnetic field between adjacent magnets. We were unable to implement this in our own project due to the magnets we used being encased on all but one side in a metal cup which absorbed the magnet's flux, however magnets purchased with a checkerboard pattern in mind could avoid this problem. Other methods of increasing magnetic field strength in the enclosure include reducing the thickness of the glass to reduce the distance between the magnets and the ferrofluid, and reducing the distance between adjacent magnets to further increase the strength of the magnetic field between magnets.

While testing our display, we found that when the display is tilted towards its back, with the enclosure sloping downwards toward the ground, we were able to "launch" the ferrofluid up the enclosure by quickly alternating magnets on and off in an upward, vertical line. This uses the fluid's momentum to help it bridge the gap between magnets, allowing us to carry it upwards farther than we are able to do with the display standing upright. Steeper slopes (closer to horizontal with the display laying on its back) further increases this effect, however a completely horizontal display would negate the effect of gravity, preventing fluid from being able to return to the bottom of the display.

References

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Appendix A Requirements and Verification Table

Table 6 System Requirements and Verifications

Requirements	Verifications	Verification status
Power Unit		
1. Power Supply **a.** The display must not consume more than the adapter power rating of 5 W at any point during operation. **b.** The display must not draw more than the adapter current rating of 1 A at any point during operation.	**a.** 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 **b.** 1. Connect a resistor (< 5 Ω) to the PSU output 2. Use a multimeter to check the current draw	**a.** Y **b.** Y
Control Unit		
1. Microcontroller **a.** 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 **b.** Must be able to manipulate 10 out of the total pixels (40%) at once.	**a.** 1. Connect oscilloscope to PWM outputs from microcontroller 2. Measure pulse widths through oscilloscope. 3. Ensure pulse widths are within required range. **b.** 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	**a.** Y **b.** Y
Rig Unit		
1. Servo/Magnet Combos **a.** Magnets are able to manipulate and control the ferrofluid from at least 2 mm away through the walls of the enclosure. **b.** Stay in position with ± 5° rotation while not operating	**a.** 1. Measure distance between magnet and enclosure wall by ruler. 2. Watch to see significant movement of the ferrofluid from varying distances. **b.** 1. Connect waveform generator to servo and input a signal 2. Use the protractor to measure the rotation	**a.** Y **b.** Y

2. Servo Controller **a.** Ensure adequate current draw 2 mA ± 0.1 mA, as specified by the used multiplexers	**a.** 1. Operate servo controller 2. Use multimeter to measure the current	**a.** Y
3. Servo Rig **a.** Servos do not move by more than 0.2 cm from their initial position during operation.	**a.** 1. Operate the servo and adjacent servos operate. 2. Measure the position of each servo before and during operation using a ruler	**a.** Y
	Display Unit	
1. Enclosure **a.** Does not leak any liquids.	**a.** 1. Fill the enclosure with liquid. 2. Measure the mass of the liquid. 3. Place the enclosure overnight and measure the mass again.	**a.** Y
2. Ferrofluid **a.** When displaying pixels, the diameter of each pixel must be at least 2.5 mm.	**a.** 1. Run a program on microcontroller which will display the maximum number of pixels 2. Measure each pixel with a ruler directly	**a.** Y
3. Suspension Mixture **a.** Cannot oxidize the ferrofluid and have chemical reaction with ferrofluid. **b.** Doesn't make the ferrofluid deposit on the enclosure.	**a.** 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 **b.** 1. Connect waveform generator to servo and input a signal 2. Use the protractor to measure the rotation	**a.** Y **b.** Y

Appendix B

Schematic

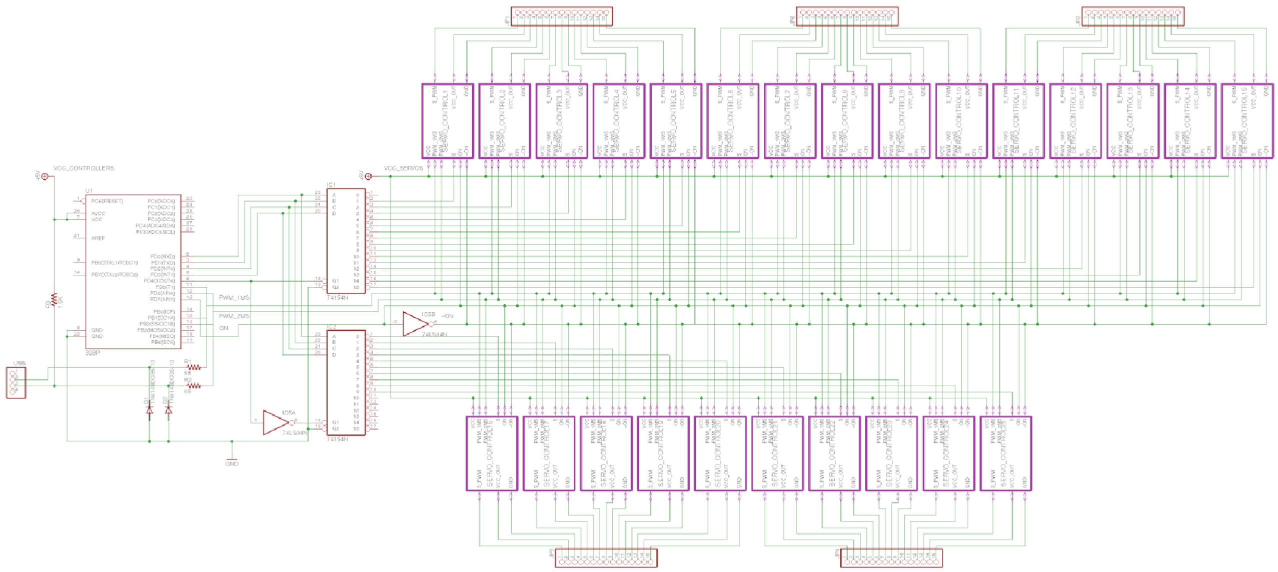

Fig. 10 PCB Schematic (Microcontroller and Servo Controller)

Fig. 10 shows the complete schematic of our project. It shows the microcontroller (right part of schematic) and servo controllers (left part of schematic) working together in tandem.

Physical Design

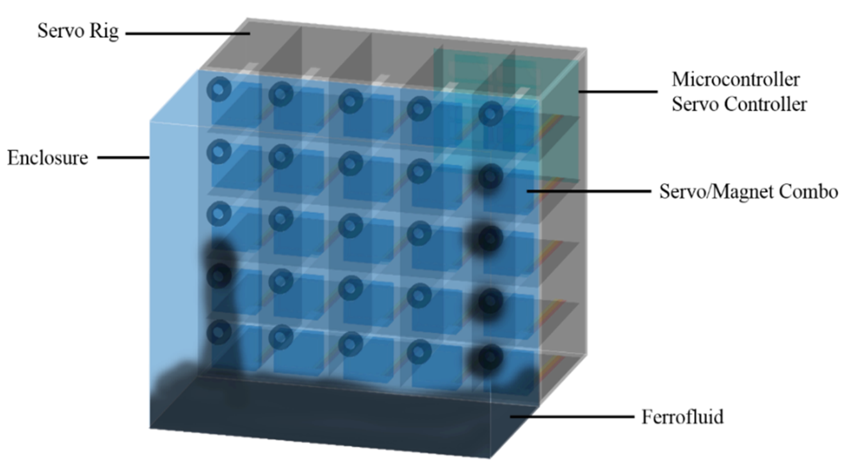

Fig. 11 Physical design sketch

As Figure 11 shows, our project consists 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 controllers are mounted to the backs of the servos, and the main board is mounted to the top of the display.