Ferrofluid Clock

Design Review
ECE 445

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1. Introduction

1.1 Motivation and Statement of Purpose:

This project is important because it has the potential to provide viewing and entertainment value beyond what is offered by a standard digital clock (which doesn't really offer viewing pleasure). It will also include the ability to act in a manner similar to a lava lamp, or some other passive display. Admittedly, this project is not revolutionary in the sense that it holds humanitarian or significant research value. Nonetheless, it is still an interesting exploration of what may be the future of dynamic and interactive displays. We selected this project because we wanted to create a product that each group member would consider personally using (stressing entertainment over strict practicality) and that could be described by the average onlooker as "fun."

1.2 Objectives:

The goal of the project is to create a ferrofluid clock that functions similarly to a typical digital clock. The end customer should be able to use the clock to tell time with suitable precision.

Expected Benefits:

- Enhanced viewing pleasure over conventional digital clocks
- Everything offered by a typical timepiece (i.e. ability to tell time)
- General decorative value

Proposed Features:

- Moving ferrofluid display (numbers will be formed using ferrofluid) affected using a large array of electromagnets (at this time, we expect to require 64 separate electromagnets)
- Programming that allows the display to act as a digital clock, as well as a "lava lamp" (characterized by alternating upwards and downwards movement)
- UI that allows the ability to change time manually

2. Block Diagram and Block Descriptions

System Overview:

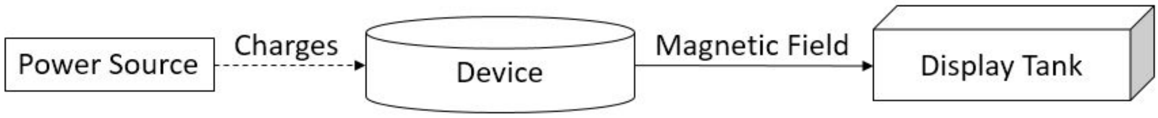

Figure1. System overview

Device:

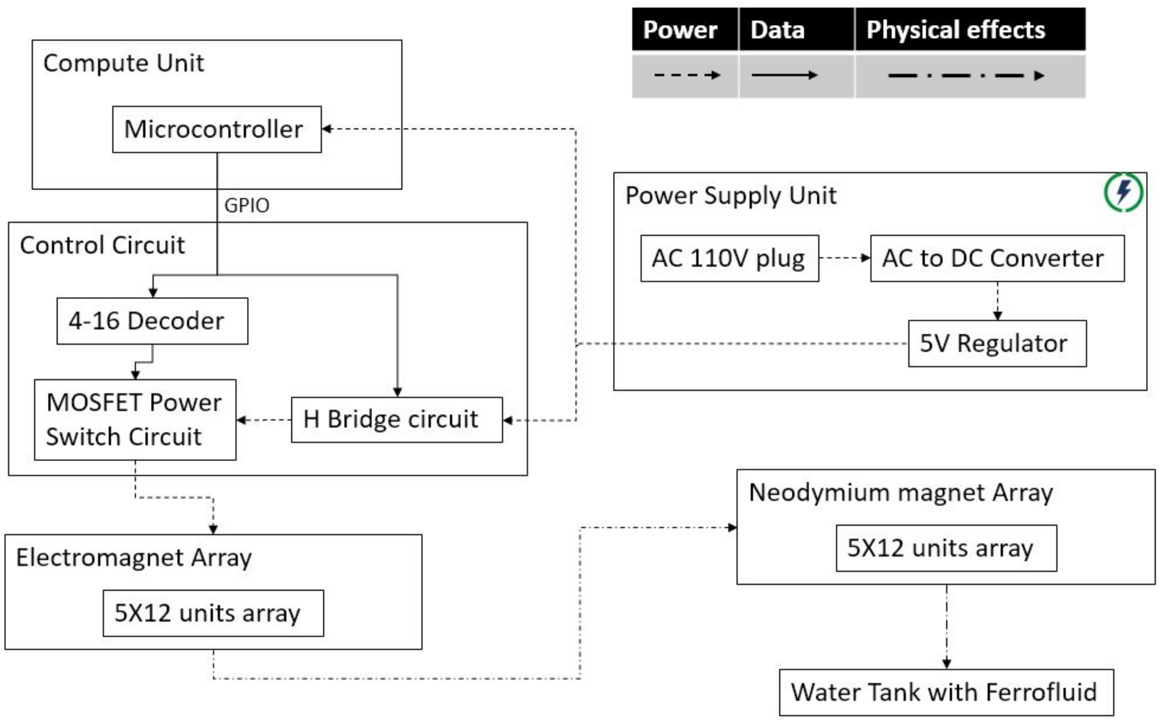

Figure 2. Block diagram

Block Description:

1.Power Supply Unit

110V AC to 5V DC Converter Circuit:

This circuit is the power supply of the device. Its input is the 110V AC and output is the 5V regulated DC voltage. It uses a transformer to first transform the 110 V AC to 5V AC. Then the diode bridge takes in the AC and outputs the DC voltage. The 470 uF polorized capacitor reduces the noise and then the 7805 voltage regulation IC is used to produce a regulated 5V DC voltage.

The 7805 regulator IC can hold up to 1.5 A of current, so it fulfills the current requuirements of our design. Besides, it has the internal short circuit limiting function.

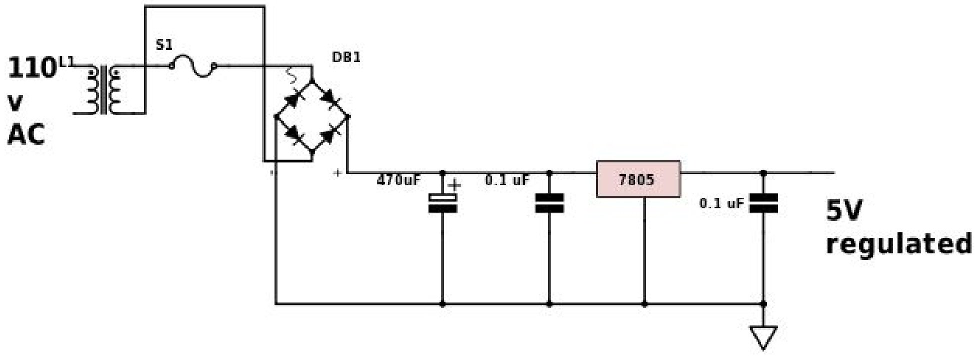

Figure3. Power supply circuit

2. Computational Unit

Microcontroller : ATmega328 (Arduino Nano)

Microcontroller	ATmega328
Operating Voltage (logic level)	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limits)	6-20 V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	8

Table 1. Arduino Nano ATmega328 data

This microcontroller sends 4-bit GPIO signals that represent the location of a electromagnet and tell the power swtich circuit which one to switch on. Then, it sends a 2-bit signal to the H-bridge circuit to control the direction of the power flows. Each 4-bit signal and 2-bit signal control 15 electromagnets, thus, we need 24 digital pins to control the the electromagnet array(total 60 electromagnets).

Therefore, we require two ATmega328s with a total of 28 digital pins to control the electromagnet array.

Two of the ATmega328s communicate with I2C.

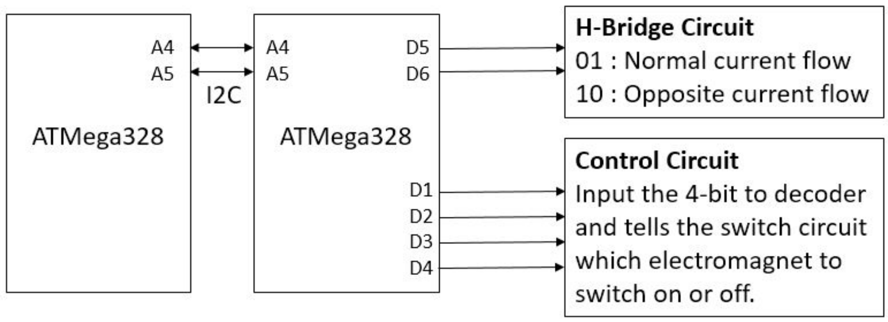

Figure 4. ATmega328 communication

Pin Function

Pin	Function
D1~D4	4-bit location data of 15 electromagnets(Group1)
D5~D8	4-bit location data of 15 electromagnets(Group2)
D9,D10	2-bit Current direction representation of Group1
D11,D12	2-bit Current direction representation of Group2
A4,A5	For I2C communication

Table 2. Pin function of Arduino Nano

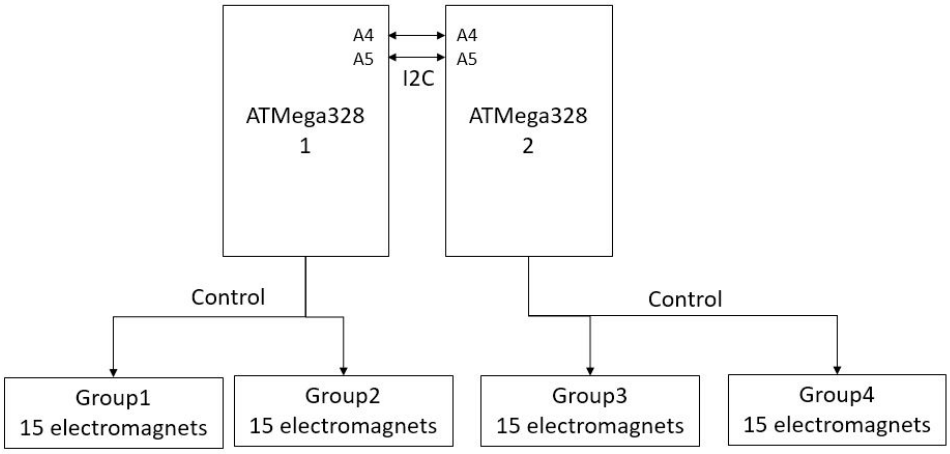

Figure 5. Illusrtration of control scheme

3. Control Circuit

<u>4-16 Decoder</u>:

IC used : 74HC154 4-to-16 line decoder [1]

Function diagram:

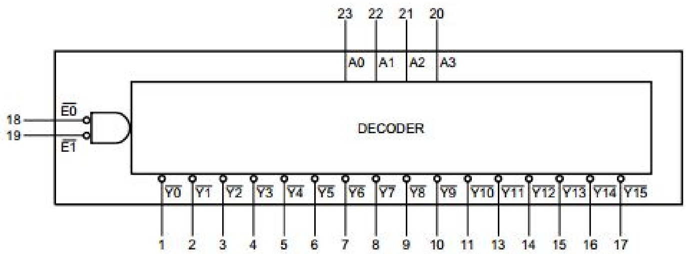

Figure 6. 4-16 Decoder function illustration

Inputs: 4-bit location signal from microcontroller

Output: 16-bit signal that represents which electromagnets will switch on is sent to the power switch circuit. Thus, there will be only one electromagnet activated in one group.

<u>H-Bridge Circuit</u>:

Module used : L298N Dual H Bridge DC Stepper Motor Controller

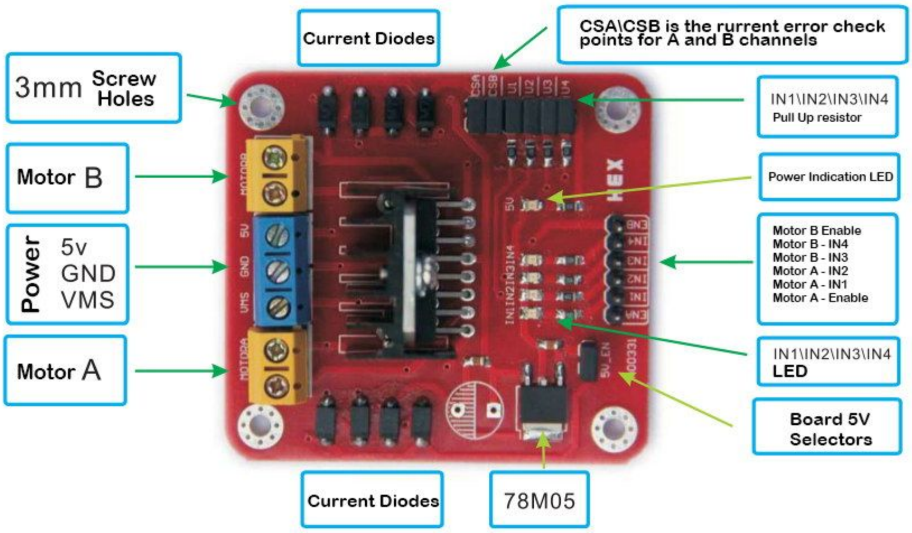

Figure 7. H-bridge [2]

Pin Function

IN1	Input signal of Motor A
IN2	Input signal of Motor A
IN3	Input signal of Motor B
IN4	Input signal of Motor B
Motor A Enable	Enable Motor A output
Motor B Enable	Enable Motor B output
Motor A	Connect to Group 1 electromagnet array
Motor B	Connect to Group 2 electromagnet array

Table 3. Pin function of H-bridge

Pin Reaction

EN	IN1	IN2	Reaction
HIGH	HIGH	LOW	Motor A outputs a positive current direction
HIGH	LOW	HIGH	Motor A outputs a negative current direction
LOW	Ignore	Ignore	No output at Motor A

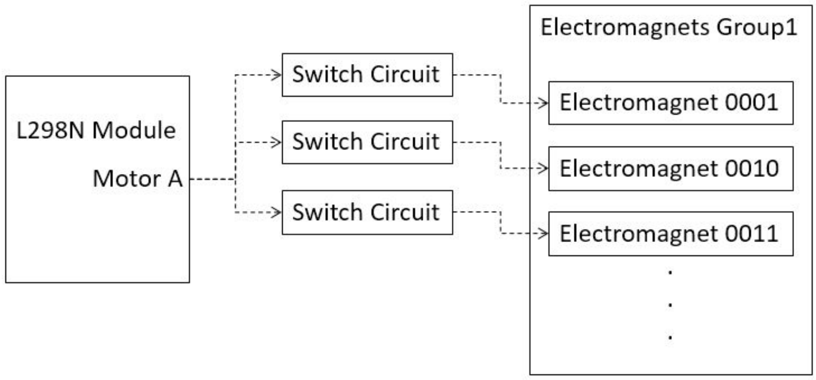

Figure 8. Pin reaction of H-bridge

MOSFET Power Switch Circuit

Input: Control signal from Arduino Nano output pin.

Output: Switching action that controls the ON/OFF of the electromagnet.

This unit controls the single electromagnet using a MOSFET as the switch. The control signal comes from the Arduino output pin. When the MOSFET is turned on, the current goes into the electromagnet. The voltage to the electromagnet is at 5V and the 0.2A at maximum. The resistor power rating should be at least 1 Watt. For the whole device, at most four electormagnets should be operating at the same time.

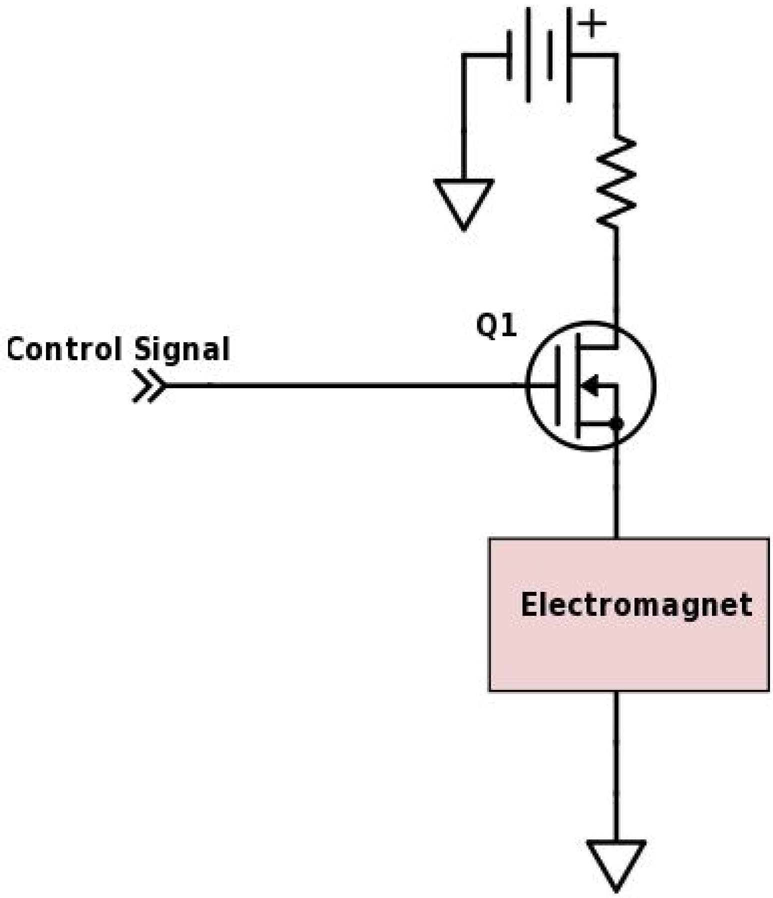

Figure 9. MOSFET switch circuit diagram

Based on the design requiremnt stated above we made the MOSFET choice: CSD13306W 12 V N Channel NexFET Power MOSFET.

Below is the data sheet of the MOSFET model we have chosen [3]:

T_A = 25°C		TYPICAL VALUE	UNIT
V_{DS}	Drain-to-Source Voltage	12	V
Q_g	Gate Charge Total (4.5 V)	8.6	nC
Q_{gd}	Gate Charge Gate-to-Drain	3.0	nC

$R_{DS(on)}$	Drain-to-Source On-Resistance	V_{GS} = 2.5 V	12.9	mΩ
		V_{GS} = 4.5 V	8.8	mΩ
$V_{GS(th)}$	Voltage Threshold	1.0		V

Table 4. CSD13306W 12 V N channel NexFET power MOSFET statistics

Since we will have 5V control signal from the Arduino, here from the data sheet of the chosen MOSFEt, we can see that the resistance through Drain and Source does not change much when the voltage across Gate and Source. This facts ensure that the current would not change much given a fixed voltage across gate and Source.

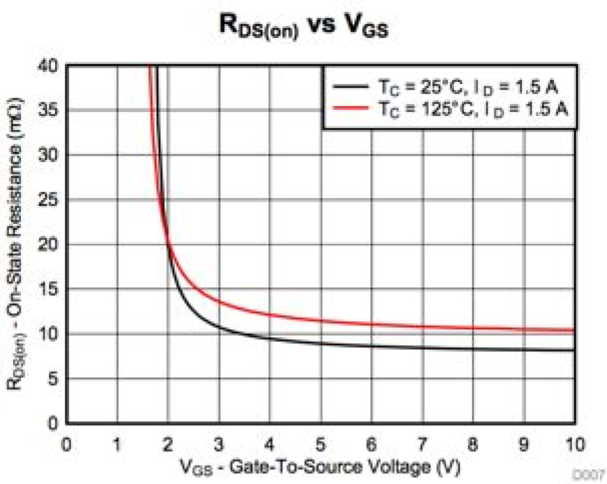

Figure 10. CSD13306W 12 V N channel NexFET power MOSFET characteristisc

4. Electromagnet array and Neodymium array:

The arrangement of our setup is as follows, as seen from a sideways view:

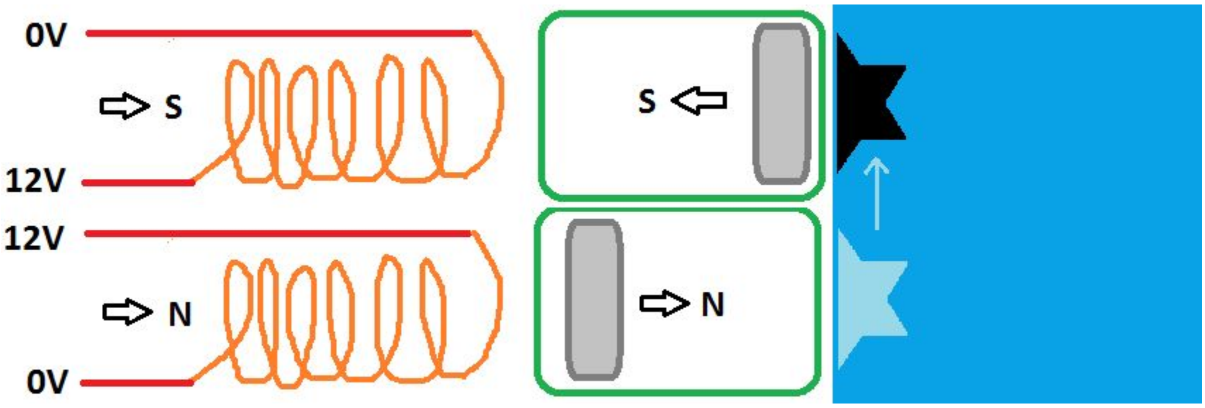

Figure 11: Illustration of how the electromagnet-magnet mechanism works in the context of our implementation. Courtesy of Luke A. Wendt [4].

In essence, the electromagnet and magnet, together, create an on-off switch. By running current one way through the electromagnet, we are able to generate an attracting force, which pulls the neodymium magnet away from the display casing, at which point the ferrofluid will no longer be held in place. Likewise, by running the current through the electromagnet the other way around, we are able to generate a repelling force, which in turn pushes the nedymium magnet towards the display casing - in this case, the ferrofluid (if in a reasonable vicinity) will be pulled to the magnet's location, and held in place.

Using this method, we are able to creat ferrofluid pixels without needing to keep an electromagnet running the entire time.

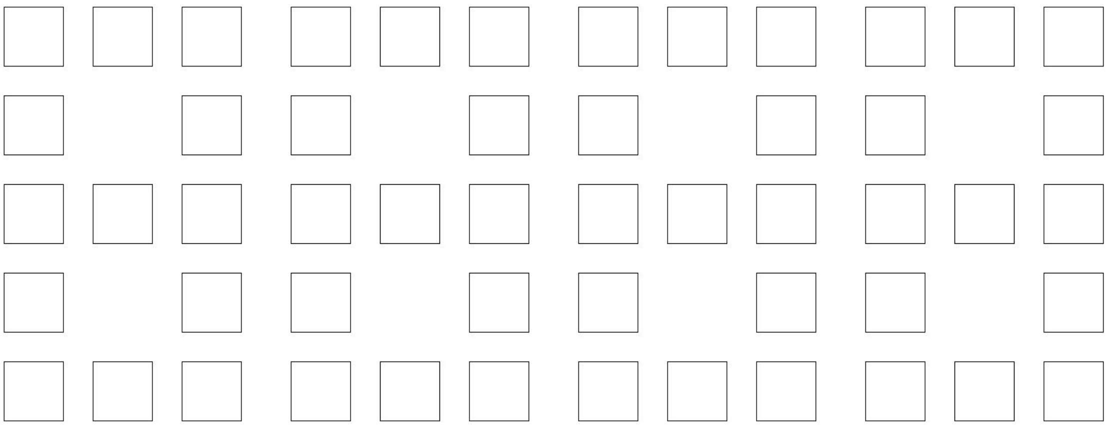

Figure 12. Front panel structure

Frontally, the arrangement of our magnets will be as shown in the above image. The array can be split up into 4 separate "blocks" (i.e. all the magnets required to generate a single digit), each with as many magnets as needed to create the likeness of an "8".

3. Calculations

Power calculations:

At most, 4 electromagnets will be switched on at any given time. We expect each electromagent to consume about 1 Watt of power in a worst case scenario (0.2 Amps over 5V). It follows, then, that this portion of our circuit should consume about 4 Watts of power.

Our Arduino Nano boards will be powered via the same 5V source (pin 27) as the rest of the display. As the upper bound of the power we will allow the display to consume is 7.5 Watts (refer to R&V section), we find that the power consumption of the display will fall well within acceptable bounds.

Strength of electromagnets:

We are using 22AWG copper wire to make our electromagnets. At a diameter of 0.0253”, the wires have an expected resistance of 52.939 Ohms per kilometer.

For our calculations, we note that the points on the field we are most concerned with are those at the then end of the magnet, and that at the maximum distance our neodynium magnets can be from the electromagnet.

However, as our electromagnets are not used for variable adjustment (it merely needs to either pull or push a magnet towards a “wall”), we find that is is sufficient to simply set a “lower bound” on the magnetic field produced at the center of the electromagnets, the strength of which we have obtained expirementally. While this may not be the single most efficient approach, it allows us to be flexible with the spacing of the components in our design, should we decide to make minor adjustments, or run into unforseen problems. We believe that this is a justified tradeoff.

As such, we found expirementally that about 200 loops on each electromagnet would be sufficient. We look to achieve this concentration with a length of 4cm.

The calculation can be done using the following equation:

$$B = \mu_0 n I.$$

As we are not working in a vacuum, and will instead by using iron cores for our electromagnets, we replace μ_0 with $\mu = 6.3\times10^{-3}$.

I, current, is 0.2 Amps. With a loop density of 50 loops per centimeter (5000 loops per meter), we arrive at a magnetic field of:

6.3 Teslas

at the center of the solenoid.

Frame Volume

We also finished the calculation and design of the fram as well as the container that holds the ferrofluid. The whole front panel dimension is 284 mm in width and 107 mm in height. Detailed calculation process is as below.

The holes that hold the permanent magnets have diameter of 13mm and the depth of 30mm. The distance between two individual holes is 4mm.

To achieve four figure eight, we need to have totally fifty-two holes. From the dimension of the holes mentioned above, the area of the corss section of one hoe, which is also the area of one pixel, is 113.11 square milimeters and the total area of all the fifty-two pixels is 1470.3 square milimeters.

Because we desigend the four containers to be separate from each other, including the reserv for the ferrofluid when the device is off, we designed the width of each container to be 71mm, so the height for the reseve needs to be at least 20.708 mm, and we took 21mm here. Adding the distance of 2mm of distance from the bottom row of pixels to the reserve, we reached to a 107mm in height and four of the containers made the width being 284 mm.

Program Size:

Our program will need to be able to handle the on/off values for 56 separate electromagnets, as well as store the current time and go through the required calculations to advance that same time counter.

With this in mind, we will require at least 56 + 5*4 bits for storage alone, not accounting for variable names and the like. Note that this is split evenly between 2 microcontrollers with a memory of 16 KB each. With an expected program size of no more than 10 KB on each microcontroller (a comparable program from one of our team member's portfolios that kept time on a hexadecimal digit display came in at precisely 4076 bytes), we find that our program size will not exceed the maximum combined memory of our chosen microcontrollers.

4. Tolerance Analysis

Power Supply

The project goal is to display numbers using ferrofluid attracted by permanent magents which are actuated by electromagnets set within an array. Since the electromagnet controls a permanent magnet, it is the most cruicial part of the project. The magnetic field gnerated depends on the current going through given a fixed number of loops. Thus, we need to ensure that the current going through does not change much even in fluctuating AC voltage conditions. We have established that the power supply should output 5V with a 5% error. If the power supply output cannot reach the required level, the electromagent cannot have enough current to produce the required magnetic field to push or pull the permenant magnet into desired positions, casusing the pixels on the display to effectively lose their function.

Another important object is the Gate input of the MOSFET. Since MOSFET can be considered as a voltage controlled current source, the voltage that goes into the gate is very crucial when a certain amount of current is reiquried throughe the Drain.

Electromagnet control mechanism

The core function in the whole design is to achieve control on the permanent magnets using the elctromagnets. Tubes are made to contain the permanent magnets. To ensure the smooth movement of the magnets, we designed the tube diameter to be only one milimeter larger than the diameter of the magnets, which is twelve milimeters, and we believe this could prevent the magnets from flipping inside the tube.

In addition, in order to ensure that the ferrofluid can transit from one picel to another, we designed the distance between two holes being 4 mm. This is a distance we experimented to be able to transfer ferrofluid between neighboring magents while minimizing the attraction/repulsion effect between two magnets.

5. Requirements and Verificaitons

Requirement	**Verification**
The display does not consume more than 10 Watts at any given time over 2 hours of continuous operation.	Measure the voltage and current at a shared entry point (i.e. point of origin for all arduino boards) while the clock is running and confirm power never exceeds the required amount.
The power supply provides 5V +/- 0.25V	Plug the power supply into the AC power outlet and set the AC input to range from -5% to +5% of 110V and check if the output is within the required range using a multimeter. Repeat at beginning of operation, ten minutes after operation and half an hour after operation.
Ferrofluid can be moved to any required “pixel” on the display. Being on a pixel constitutes the presence of ferrofluid covering at least a 1 cm diameter around the center of the generated magnetic field from a forward-facing view.	Display all possible shapes of digits on each display and check using a ruler placed on the face of the display that all “on” pixels have the required amount an position of ferrofluid over it. Note that precision is not particularly important in this portion of our verification.
Each pixel in the display will not hold more ferrofluid than 1.5 times 1/13th of the total ferrofluid in compartments 1,2,4, and 5, or ½ of the total ferrofluid in compartment 3.	Display all potential shapes on each display (i.e. 0-9, :) as well as all possible transitions. We will measure the sizes of all ferrofluid “pixels” in every case, checking that it is within tolerable levels. Size will be calculated from volume.
All compartments of the display are leak-proof and can withstand a reasonable amount (tentatively 20 pounds) of trauma during common indoor use.	Drop from 2 meters of height and pressure test from all sides of the outer shell can be done on the compartments. We will test in high/low temperatures to stress the sealing material. High temperature means 113 degress and low temperature means 30 degrees. We will apply around 30 KG of pressure on each side and then use dyed water to do leakage test.
The maximum time required to change numbers on the display does not exceed 15 seconds.	Test every possible transition (e.g. 1 to 2, 5 to 6) 10 times each. Measure how long each transition takes and ensure that no trials fail the requirement.
Required programs fit within our microcontrollers’ memories. That is, program and data size must not exceed 15 KB (this allows a 1 KB cushion).	Inspect the program size to check if the size meets the requirement.
Number of electromagnets comes out to 52, each with 200 loops of wire around iron cores.	Simply count the total number of electromagnets accross all arrays when

	complete, and maintain a count of loops in all electromagnets as they are wound.
Magnitude of the current through any operating electromagnet averages at .2 A, +/1 .01 A.	Using a multimeter, measure the current entering (or leaving, as it may be) an operating electromagnet at the very begnning of operation, 5 minutes after continuous operation and 15 minutes of continuous operation. Find the average over all the measures and confirm that the obtained value falls within our required range.
Dimensions of the frame fall within 28 x 12 cm	Measure the dimensions of the frame using a meterstick for three times, and take the average of all the measrements. Compare the average with the required dimension.

6. Cost and Analysis

Item	Unit Price (USD)	Quantity	Total (USD)
EFH1 Ferrofluid (60mL)	19.5	2	38
Magnets (Size 12mm * 0.3mm)	0.6	60	36
Magnetic wire	12	2	24
Breadboard	10	1	10
Plastic glass frame	~12	1	12
Power supply	9.5	1	9.5
Arduino Nano	4.5	3	13.5

Table 5. Part cost

Labor: 35 USD/HR * 600 HR = 21000 USD
Grand total: 21143 USD.

Analysis: The product itself does not cost very much. The ferroluid and the permanent magnets are the main body of the total part cost. Besides the part, the labor cost is calculated using regular average hourly pay after graduation.

7. Schedule

Week	Task	Responsibility
10/3	1. Complete design review 2. Touch up any remaining high priority design issues (e.g. flaws, errata)	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
10/10	1. Start design of the user interface 2. Finalize composition of ferrofluid mixture 3. Continue work on all outstanding (if any) design components	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
10/17	1. Continue work on all outstanding (if any) design components 2. Start making prototypes of the front panel and the electromagnet arrays. 3. Finish the power supply design	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao

10/24	1. Finish the first draft of the Arduino control program 2. Finish first draft of user interface design 3. Finish assembly of arrays and test their basic function	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
10/31	1. Finish drafts of all design related work	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
11/7	1. Debugging and revision 2. Run complete tests on final prototype	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
11/14	1. Further debugging and revision	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
11/21 (Thanksgiving)	Enjoy Thanksgiving Break	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao
11/28	1. Final round of test and verification 2. Demonstrations	Hanyao Zhang Ting-Wei Hsu

		Zhiyuan Yao
12/5	Final Presentation	Hanyao Zhang Ting-Wei Hsu Zhiyuan Yao

8. Discussion of Ethics and Safety

Safety is the one of the most important concerns in creating our project; while what we hope to achieve with this project is more or less aesthetics, it goes without saying that we must also consider possible safety hazards in the design process.

First, the material we use needs to fulfill safety standards. We will use only a safe ferrofluid (that is, we will avoid using highly toxic, industrial grade products). Meanwhile, the fluid filled into the container along with the ferrofluid will not contain any hazardous materials. The seal of each container will be rigorously tested to ensure user safety and product usability. This last bit is particularly important due to the inherent volatility present when a fluid and electronics are in close proximity to each other.

Second, we considered the operation conditions and environment of the clock. Since the size of the clock will allow for desk use, we will use something like plexiglass for the outer shell to shatterproof the product to some degree. In addition, when the electromagnet arrays are in operation, current goes through the body of the clock and causes heat to be produced. In order to not burn the user, we considered either adding buffer material to the outer shell of the frame or to try to limit the maximum temperature the clock can reasonably reach. Note that the danger heat poses in our design is very low (that is, the display is *highly* unlikely to reach unsafe temperatures). Nonethless, precautions must be made.

9. References and Citations:

[1] “74HC154; 74HCT154 4-to-16 line decoder/demultiplexer.” *NXP*, 29 Feb. 2016, http://www.nxp.com/documents/data_sheet/74HC_HCT154.pdf

[2] “L298N Motor Driver Board.” *TinySine*, http://www.tinyosshop.com/index.php?route=product/product&product_id=228

[3] “CSD13306W 12 V N Channel NexFET™ Power MOSFET.” *Texas Instruments*, Mar. 2015, http://www.ti.com/lit/ds/symlink/csd13306w.pdf

[4] Luke A. Wendt. “Another Alternative.” 2016