Hall-E Manual

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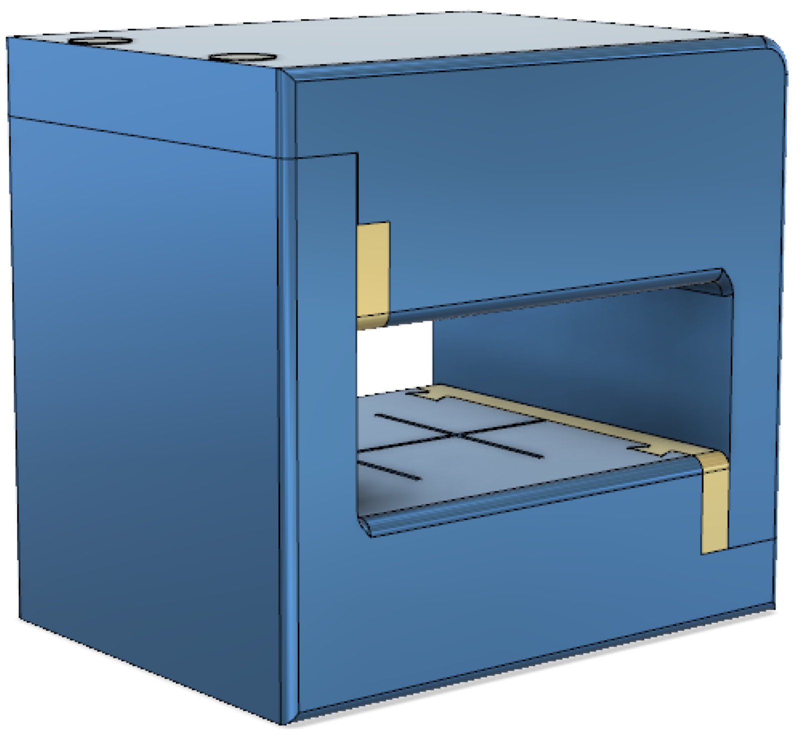

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1 Introduction

This document is designed to be used electronically as a PDF, although a paper copy can be used. There are hyperlinks in the document that take you to other parts of the document, and to external websites. The actual web addresses are provided in Links & References. We strongly advise that you use this manual with Adobe Acrobat Reader, or a similar program for reading PDFs that has a bookmark feature to aid in switching between sections. We hope that you find this document useful and enjoy working with our product as much as we have enjoyed making it.

The information detailed in this document is necessary to operate Hall-E. It was designed and constructed by the Alpha-Alpha Team for Physics Senior Design (PY495) during the Fall 2018 semester at NCSU. The Hall-E is, first and foremost, designed to assist in Hall effect measurements by using an AC magnetic field. However, it can be used for any application requiring an oscillating magnetic field that meets the uniformity and field constraints of the HG-1. ”AC” magnetic field and ”oscillating” magnetic field (OMF) will be used interchangeably throughout this document. You can control the frequency, duration, and amplitude of the magnetic field within specified ranges.

There are five main components for this device:

1. Base Board
2. Electrical Box
3. Belt-Driven System
4. Probe Stand
5. Magnet Container

In the following chapter, the main hardware and electrical components will be discussed. We will start from 1 (The Base) and end with 5 (Magnet Container). All blue and yellow parts are 3D-printed. They are made of Polylactic Acid (PLA). It is a biodegradable and recyclable thermoplastic.

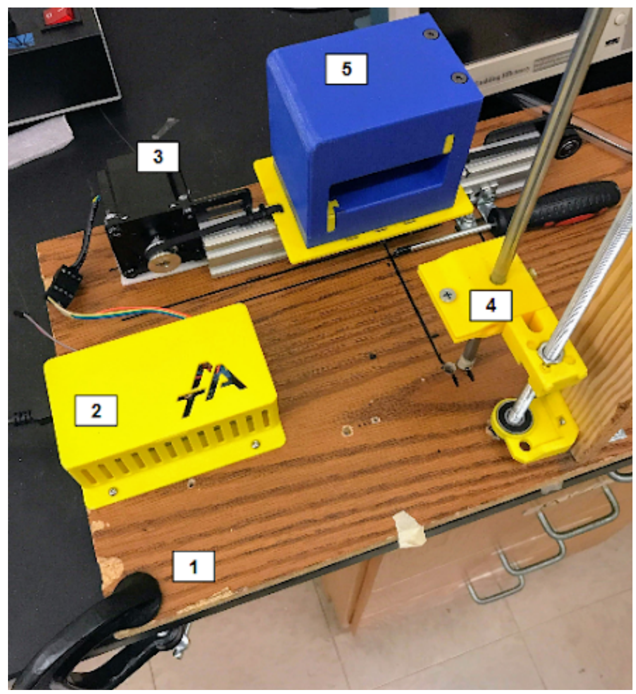


Figure 1: Basic Design Layout

1.1 Base Board

The base board is made of scrap wood that seems to be medium density fiberboard (MDF). It is decently strong but terrible at vibration absorption. All the important components are connected to the base in one form or another. Wood screws (Phillips and flat head) are used to screw down the belt-driven system and the probe stand to the base. Corner braces are used to join the vertical components to the base board. The electronics box has four M3 (3 mm diameter) screws that join it to the base.

The base should be placed on a table with edges that can be used by at least 2 medium to heavy-duty clamps. In Figure 1, you can see on the bottom left hand corner one of the clamps. This is used to reduce audible noise and some vibration. More clamps will likely reduce vibrations further.

1.2 Electrical Box

This yellow box houses two main circuit boards. The two boards have **different power sources and power requirements**. It has a lid that you can open to access the electronics. We don't recommend you do that unless you are diagnosing a specific issue. There are slits on the sides of the box that allow for adequate ventilation for the stepper driver. You can also see the lights on the Arduino through the slots when it is powered. Now we'll discuss the two circuits that are housed in the box:

- First is the Arduino Mega: the main device that handles all the Input/Output data to, and from, the user. For all intents and purposes, it is a "computer;" it is programmed using C++ and the Arduino library. You can read more about it here[1] for more details on how the board works, though it's not necessary for operation. A USB-A 2.0 to USB-B cable connects the Arduino to a laptop/desktop. This connection acts as a power source for the Arduino (not the motor). It also allows the user to set the frequency & duration of the oscillating field, and to see the output from the device.
- The second circuit board is a perf-board attached onto the corner of the Arduino. The A4988 Driver and several other components are soldered on this board. The driver takes small ($\sim$5 V) digital signals from the Arduino and turns them into higher voltage and current signals that power the motor. It has two sets of wires that lead to the outside of the box. More information on the A4988 driver can be found at How to Mechatronics[2].

    1. The first pair of wires use a small 2-pin connector. Red (Live) and Gray (Ground) that power the A4988 chip and the motor. This device has only been successfully tested at **15 V and 0.5 Amp**. The electronics are rated to be functional at higher currents, but tests have been unsuccessful. Read the article linked above and proceed to change the power only if you know what youre doing. The current limiter will have to be set on the driver, and it is undetermined how it works and how to exactly set it so that it works at higher currents. **The driver may be permanently damaged at higher currents.** The good news is that the drivers are about $10 for a pack of five from Amazon, so you can experiment cheaply. You will have to re-solder a new chip on the perfboard if the current chip is ever damaged. See "Parts & Sources[4]" for links to the parts. See "**More Power**" in "Warnings" for further discussion on power limits and an alternative to the current brand of the chip.
    2. Second set of wires use a 4-pin connector that connects the A4988 chip to the motor. There are two coils in this motor that enable the stepping movement. The Red and Blue wires power one of the coils, and the Yellow and Green wires power the other. They should be taped & wired in this order: Red, Blue, Green, Yellow. The wires are connected using a pin connector with four small flat head screws. If you ever need to reconnect the motor power, remember "Red Down" which means the red wire will be at the lower end of the chip. "Down" is defined to be from the middle of the A4988 Driver towards the tiny screw that is located on the bottom edge of the chip. See the electronic schematic. Check it for yourself in the electrical box that it is "Red Down." If you flip this connection, the motor will run in the opposite direction from what is expected. So any "forward" movement will be backwards and vice versa.

1.3 Belt-Driven System

The belt-driven system uses a NEMA 23 bipolar stepper motor. This motor turns its axle in discrete steps (hence the name stepper motor). Each step is 1.8°, so 200 steps form a 360°rotation. The motor drives a belt that is connected to the gantry plate (yellow plate) to move the magnet container. The magnetic field peaks are $\sim$28mm apart. This is the distance the block will need to move to achieve complete field reversal. The motor cannot understand distances; it only understands steps. **92 steps produce the peak-to-peak**

distance for an OMF. The block will move back and forth $\sim$ 28mm during operation. Stepper Motor Motion shows the distance-to-steps calculation and provides more details on stepper motor programming.

1.4 Probe Stand

There are two uses for our probe stand: to securely hold the probe & adjust its height. See Calibrating the Hall Probe for more information on securing & adjusting the probe.

1. This probe stand is designed to hold the LakeShore HMNT-4E04-VR Hall Probe. It can be used with other Hall probes as long as the diameter of the probe body fits the probe holder. The probe body (the blue part of the probe with the "LakeShore" logo) is secured on the probe holder by a clamping mechanism. A Philips screw and nut are used to tighten the clamp around the probe body. Use a wrench to hold the nut while tightening or loosening the screw. You don't really need a wrench, holding the nut by hand should be enough since it doesn't need to be too tight to secure the probe. **Do not tighten the screw and bolt when the probe is not inside the probe holder, it can bend or shatter the PLA "clamp." Do not over-tighten the probe holder screw even when the Hall Probe is within the probe holder.**
2. The probe stand can also adjust the height of the probe. The probe holder is held at a certain height by two rods. A smooth rod and a threaded rod. The probe holder has a horizontal 5 mm screw that tightens against the smooth rod to hold in it place. The threaded rod has a traveling nut that is joined to the probe holder to adjust vertical position. **When adjusting the height, make sure the screw against smooth rod is loose.** If you try to change the height while this screw is locked to the smooth rod, it will break the piece that couples the traveling nut to the probe holder.

1.5 Magnet Container

This blue glorious plastic monstrosity contains magnets, which are configured in such a way as to produce a spatially oscillating magnetic field. The holders were 3D printed using polylactic acid (PLA), are L-shaped, and are held together by four M5 (5 mm) 25 mm long screws.

The container sits on a gantry plate that is attached to the belt-system. The space in the middle of the two holders is where the magnetic fields exist. Due to magnetic shielding, field values outside the magnet container are minimal. You can test this with a small piece of metal, like an Allen wrench, and run it along the outer surface of the container. Then do it in the magnetic space inside the container (be careful, it might scratch the PLA surface) to see the difference in field strength. The position of the block can be changed when there is no power supplied to the A4988 Driver (the Mega can still be plugged in the computer).

2 Warnings & Notes

2.1 Warnings

All the bold statements throughout the manual are to be taken as warnings. Additional warnings are listed below:

1. **Opening the Magnet Container:** It is generally safe to take the container apart, but we do not recommend that you remove the lids or magnets because there is a risk of displacing the magnets & altering the field.
2. **Out of bounds:** There are black aluminum plates on the ends of the sliver rail (V-Rail). These plates mount the motor and the smooth pulley. If at any point the gantry plate hits these mounts on the V-rail, turn the motor off IMMEDIATELY. There likely wont be any damage to the motor, but it could damage the gantry plate since it is made of PLA. This is one reason why it is recommended that the power supply have a switch. Another reason is so that you can adjust the starting position of the container by your hand when the A4988 chip is not powered. See Calibrating the Hall Probe.
3. **Re-uploading code:** DO NOT have the power ON to the stepper driver when re-uploading the code to the Arduino.
4. **Starting motion:** DO NOT turn the power ON to the A4988 chip UNLESS the Arduino is in the state of either 'Press 1 to begin oscillation or 2 to start begin again' or 'Input Frequency (Hz) and time (s)'. If you switch the power ON while the Arduino is executing its steps (i.e. it thinks it's moving the motor, but there is no power so it can't), it could result in unpredictable behavior. Press the reset button on the Arduino to restart the input process (open the yellow electronics box and press the button that is beside the USB-B port).
5. **More Power:** More power may be the solution to driving the motor such that $>$1.5 Hz OMFs can be produced. Supplying the A4988 Driver with a higher current than what is specified in the manual will have unpredictable results. At 2 A the stepper motor has inconsistent motion, not to mention the increase in noise. We have a strong suspicion that the chip's actual specification is at MAX 1 A/phase instead of the advertised 2 A/phase. We bought it from an off-brand seller on Amazon to save on costs, so perhaps the Pololu[3] brand might be better at higher currents. We recommend experimenting with the provided extra A4988 chip on a separate breadboard to adjust power delivery, or a new one from Pololu. Looking up the A4988 manual might also be a good idea before making changes to the circuit.
6. **Physical Frequency Limit:** Attempts to drive the Nema 23 motor at $>$1.5 Hz using Constant Step Delays (CSD) have been unsuccessful. Try Variable Step Delays (VSD) if higher frequency is pertinent. The drawback for this is the observable non-sinusoidal AC field.

2.2 Notes

- **Vibration:** There are two sources of vibration in this device: the stepper motor & the linear oscillatory motion. The former is the more significant source. If it becomes an issue when taking measurements, replacing the MDF base board with a vibration-absorbing material might be a good start; or situating more clamps.
- **Having a power source with a switch** is recommended for powering the A4988 chip. In the event that the gantry plate hits the black aluminum mounts during operation, you can easily turn off the switch to prevent damage to the gantry plate. Furthermore, when it is powered and not in motion,

there is a holding torque in the motor that makes it difficult to move the magnet container. So if you have a switch that you can turn off, it makes re-adjusting the magnet container's starting position quicker and easier.

- **No response or error from Arduino:** This can be seen on the Arduino software if there is an interruption in the USB connection. Especially if the computer goes to sleep or is locked. If this happens, all you need to do is unplug and re-plug the USB cable to restart the process.

3 Safety & Care

3.1 Temperature

The Arduino Mega operation temperature range is from -40 to 85 °C. PLA melts around 170 °C and the magnets demagnetize at even higher temperatures.

3.2 Common Sense

Please use caution & care when working with the electronics and electronic equipment. Do not drop anything on the electronics, motor, or the magnet container. Keep food and water away from all the equipment. Clean any dust and other debris from the belt and the moving parts. Keep hair and other loose clothing away from the moving belt parts and objects at all times. Do not block or impede any movement while the system is in motion.

3.3 Power Supply and Wires

There are a handful of wires inside the electronics box that wire the equipment (see ”Electrical Box” for more details). **Do not remove or swap any wires unless you know what you're doing. Do not pull or yank the wires that are coming out of the electronics box (2-pin power wire and 4-pin motor wire). Do not touch these wires on their metal contacts without proper safety equipment while the system is powered.**

3.4 Magnetic Field

Even though there is a shielding effect (magnetic field inside the cavity is larger than it is outside), be careful when working with magnetic materials and metals. Especially small tools. Do not put small metal tools or objects inside the cavity. It can be difficult to get them out, and it can damage the PLA surface of the cavity.

4 Electronic Schematic

The purpose of the circuitry here is to drive the motor at specific speeds and distances to create the linear oscillatory motion for the OMF. The A4988 chip takes low-voltage pulses (~5V) from the Arduino and converts it to high-voltage and high-current pulses that power the motor. The Arduino is powered via a USB cable. The A4988 chip is powered via a separate source (not provided).

The picture below is the circuitry that is inside the yellow box. We used a 100 µF capacitor instead of the 47 µF that you see in the picture. The red chip is the A4988 driver chip. The blue box is the Arduino Mega.

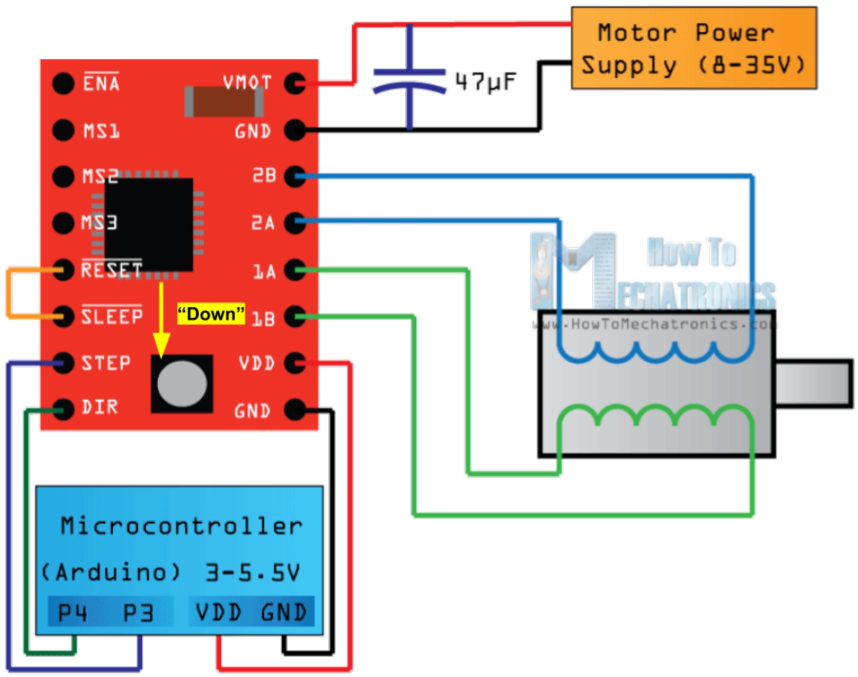


Figure 2: A4988 Wiring Diagram

5 Belt-Driven System for Linear Motion

The system uses a NEMA 23 bipolar stepper motor. Each step is a 1.8° turn. Thus, taking 200 steps makes a full revolution. The motor drives a belt that is connected to a gantry plate (yellow plate). The magnet container is attached to the gantry plate.

5.1 Stepper Motor Motion

Let's determine how much the belt will move horizontally per step:

- The motor axle is connected to the belt by a 20 tooth GT2-3M Timing pulley. The "3M" means a 3 mm pitch (the circumferential distance between each tooth). Therefore, the whole circumference is $3\,\text{mm}\times 20 = 60\,\text{mm}$.
- 200 steps form a full revolution of the axle because each step is a 1.8° turn. If we divide 60 mm by 200 steps, we get $0.3\,\text{mm/step} \Rightarrow 3.33\,\text{steps/mm}$. Prusa Printers [7] confirm this.

  On the Prusa Printers' calculator page, scroll down to the Belt-Driven section. Select the following:

  - Motor step angle: 1.8°
  - Driver microstepping: 1 - full step
  - Belt Pitch (mm): 3
  - Pulley tooth count: 20

  The result section should be: 3.33 steps/mm
- **Conclusion:** The magnetic field peak-to-peak distance is about 28 mm $\Rightarrow$ about 93 steps between the two peaks. The program uses 92 steps, which performed better during tests.

5.2 Modes

There are two modes of oscillation for the motor: Constant Step Delay (CSD) and Variable Step Delay (VSD). Before explaining what the differences are, we're going to look at how the motion is structured.

To form one oscillation, the magnet container will start out on the left side, move forward 92 steps and then move backwards 92 steps. The frequency of OMF (i.e. speed of motion) is controlled by a time delay (on the order of milliseconds) in between each step. Electronically, each step is formed when there is a "pulse" in the step pin on the Arduino. This is the signal that is converted by the A4988 chip to higher voltages to drive the motor. Every **[step]** is equivalent to:

1. Step Pin (HIGH) $\rightarrow$ *Pulsing the step pin up*
2. *Delay* (wait)
3. Step Pin (LOW) $\rightarrow$ *Pulsing the step pin down*
4. *Delay* (wait)

This would make the motor move one step (1.8°) in a specified direction.

Thus, motion for one entire oscillation looks like:

1. Move forward Y **[steps]**

2. Wait to change direction (necessary so acceleration is not infinite)
3. Move backward Y **[steps]**
4. Wait to change direction

The waiting time in-between direction changes is called the ”direction delay.”

How quickly the motor moves during a series of steps is controlled by the delay value. Smaller delay $\Rightarrow$ faster speed. Larger delay $\Rightarrow$ slower speed.

Now that we've clarified the basics of the motion, let's look at the differences between the two modes of oscillation.

5.2.1 Constant Step Delays (CSD)

The speed of the container will be constant throughout the forward and backward motion. That means the *delay* between each **[step]** will be constant. The block will move at a constant speed for 92 steps, wait some time ($\sim$1 ms) to change direction, moves back 92 steps at the same speed.

The direction delay is constant at all frequencies (all frequencies that are capable with the current motor). The Arduino and A4988 chip setup has a minimum processing time for changing the direction. It depends on power and chip specifications. We have determined the minimum direction delay to be around 0.5 - 0.7 ms through trial-and-error methods. The actual direction delay that the program uses is 10 ms.

If the direction delay is too low, the motor won't have enough time to change its direction before the Arduino moves on to the next set of steps; resulting in more than the intended amount of steps to be taken before switching direction. This is known as ”skipping steps,” and it is not completely avoidable at higher frequencies. It currently works well at 0.5 to 1.0 Hz.

5.2.2 Variable Step Delays (VSD)

The speed of the block changes as it moves from one turning point to another. It will slow down (i.e. increase the delay) when it's getting close to the turning point. The delays here are estimated using a first order series approximation of a triangle wave. The position of the block was modeled as:

$$y(t) = A\sin(\omega t + \phi_1) - (A/3)\sin(3\omega t + \phi_2)$$

- f = frequency (Hz)
- A = An experimentally determined parameter ($\sim$12.7)
- ϕ_1 and ϕ_2 are wave offset parameters. These dont matter so much for determining the velocity, but the value of y(t = 0) matters for visualization purposes. The ϕ_1 and ϕ_2 are such that y(t = 0) = 0. This indicates that the block will more forward for the first half of the wave and then move backward for the second half. This is also represented by the starting position of the block. It starts at the left side (so that the probe experiences the negative field peak).

  ϕ_1 = offset for sin(x) term: (0.75*2π).

  ϕ_2 = offset for sin(3x) term: (0.75*3*2π)

Look at this Velocity and Position Graph[6] to get an idea of what's happening. The purple graph is the position with respect to time. The blue graph is the velocity with respect to time. The x-axis is time in seconds. The y-axis is in millimeters for the purple graph and for the blue graph the y-axis is mm/s.

Because it is an approximation, the actual frequency will be **less** than that which we approximate. The code will output the approximated frequency and the percent difference. Check with an oscilloscope to confirm this. See section 6.2.

Variable step delay is better for frequencies (>1.0 Hz). But be careful, further tests need to be conducted. See "Physical frequency limit" in Section 2.1, Warnings.

6 Setup

There are three major components of setting up this device. First is Calibrating the Hall Probe; second, How To Measure Magnetic Fields with an Oscilloscope (optional); and third, Motor Setup.

6.1 Calibrating the Hall Probe

Follow these steps for calibrating the Hall probe's position:

1. Adjust the probe holder height by rotating the threaded rod on the probe stand (clockwise to go up, counterclockwise to go down). Adjust the probe holder height until it is roughly midway between the top and bottom holder surfaces.
2. Turn on the Gaussmeter and insert the probe into its holder, with the "Lakeshore" side facing up, until you feel the probe (base of the probe's stem) barely touching your fingers (see figure below). Use a screwdriver to tighten the screw that clamps the probe, and make sure that the probe is not at an angle after tightening (should be perpendicular to the magnetic field).

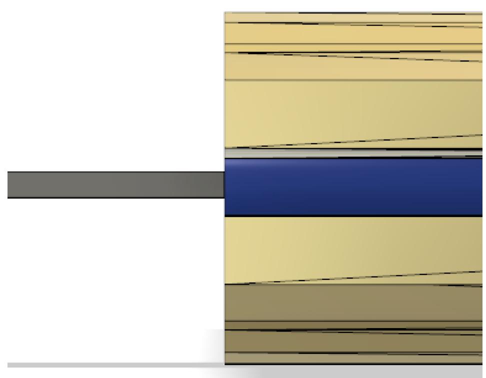


Figure 3: Align Surface with Stem Base

3. **Make sure that there is no power supplied to the motor.** The Arduino can be connected to a PC, but the red and gray pins that supply power to the A4988 chip should not be powered. Using your fingers, move the magnet holder assembly, attached to the gantry plate, back and forth until the Hall probe reads the maximum negative B_z value for the given height.

4. Adjust the probe's height by using the threaded rod until the desired field value is reached, based on the table of values below. Field measurements were taken from the base of the probe stand, up to the probe's stem. Since the field is symmetric about the mid-plane of the holder surfaces, you can obtain the same field values in both the lower & upper regions.

Average Field Strength (T)	Lower Region Height (cm)	Upper Region Height (cm)
-0.2	9.35	10.15
-0.25	9	10.45
-0.3	8.85	10.7
-0.35	8.65	10.85
-0.4	8.55	10.95

5. (Optional) It is recommended to use the upper region of the assembly for the sample, and the lower region for probe measurements. The difference between the lower region's positive and negative peak field values is roughly 2%. To combat this, since the Hall probe measurement area is very small, put the probe at the desired negative B_z in the lower region, and then move the magnet assembly to the left (thus offsetting the probe to the right) by 1 mm. This makes the peak-to-peak value closer to what the sample experiences in the upper region.

6.2 How To Measure Magnetic Fields with an Oscilloscope

Once the Hall probe is in place and calibrated, an Oscilloscope can be used to observe the field values with respect to time. We used a LakeShore Model 425 Gaussmeter. The auxiliary I/O port on the back of our Gaussmeter is a 25-pin D-sub socket. An analog representation of the field value detected by the Hall probe, displayed by the Gaussmeter's monitor, can be observed via this socket. Pin 1 provides this analog voltage ($\pm$3.5 V) that represents the magnetic field value in units of Gauss (1 T=10 000 G). The analog value will be proportional to the measured field on the selected range. Pins 14, 15, and 16 can be used as ground when using pin 1's output. See Model 425's User Manual, Section 3.7, for more information. A copy of Model 425's User Manual will be provided along with this document if it was originally emailed to you.

Two jumper wires were inserted in the auxiliary I/O. **One in pin 1 and another in pin 14.** Using a passive probe, we connected the output from the Gaussmeter to an Oscilloscope. Generally, this jumper wire connection was reliable in showing the field measurements during preliminary tests, but it is not a durable solution in the long term since it can easily disconnect with light touches or interference from other equipment. We recommend buying a connector for this 25-pin D-sub socket and splicing open the other end to get access to the specific pins (1 and 14) that can connect to the passive probe.

6.3 Motor Setup

The motor is setup to use Constant Step Delays (CSD). You will not be able to change that without changing and re-uploading the code to the Arduino Mega. The current version of the program does not allow for a change of modes without editing a variable in the code and re-uploading it.

In addition to the instructions below, please also read the Warnings section before implementing the setup.

1. Install Arduino software[8] (`https://www.arduino.cc/en/Main/Software`) with default settings.
2. Start the Arduino program.
3. Go to "Tools" > "Board" > **"Arduino/Genuino Mega or Mega 2560"**.

4. Plug the Arduino to a computer via the provided USB cable. Make sure you can see lights on the Arduino, either through the slits of the electronics box or after opening the lid.
5. Go to ”Tools” > ”Serial Monitor”. When doing this, note the shortcut for opening the serial monitor. On Windows it is **(Ctrl + Shift + M)** and on Mac it is **(Command + Shift + M)**.
6. The serial monitor should say:

   `Enter frequency (Hz) and operation time. (ex: 1.0 60)`

   Example explanation: Entering `1.0 60` means the OMF will be at 1 Hz for 60 s.
7. Now you can type something like `1.0 20` in the input box and hit ”Enter” or click Send.
8. The serial monitor will output the approximated frequency based on its calculations.
9. Now you want to adjust the negative field peak values according to the subsection 6.1 before continuing. Calibrating the Hall Probe .
10. Plug the Red (live) and Gray (ground) pins to a 0.5 A power supply at 15 V. Preferably something with a switch that can turn the power ON and OFF, so that the motor is not getting power when making modifications. In Stepper motors there is a holding torque, so when the motor is powered it will be much harder to move it. We recommend that you dont attempt to move it while it is powered.
11. Follow the instructions on the serial monitor. It should say:

    `Type 1 to begin oscillation, 2 to start again`

Notes on motor setup:

- For a diagram of how the Arduino program works, please see User Interface.
- We recommend that you set the time for movement to be low at first to test it. Then progressively go for longer times while taking field measurements as detailed in ”How To Measure Magnetic Fields with an Oscilloscope” to get an accurate frequency.

7 User Interface

The device uses a serial/text-based user interface that allows control of the frequency and duration of oscillation. There are 2 main types of inputs that can be valid. First is for frequency and duration. Second is for starting the oscillation, or restarting the process of frequency/duration input. Below is the state diagram for the system. **Note:** Code for the program will be available on GitHub upon request. Please contact Sayam for any questions.

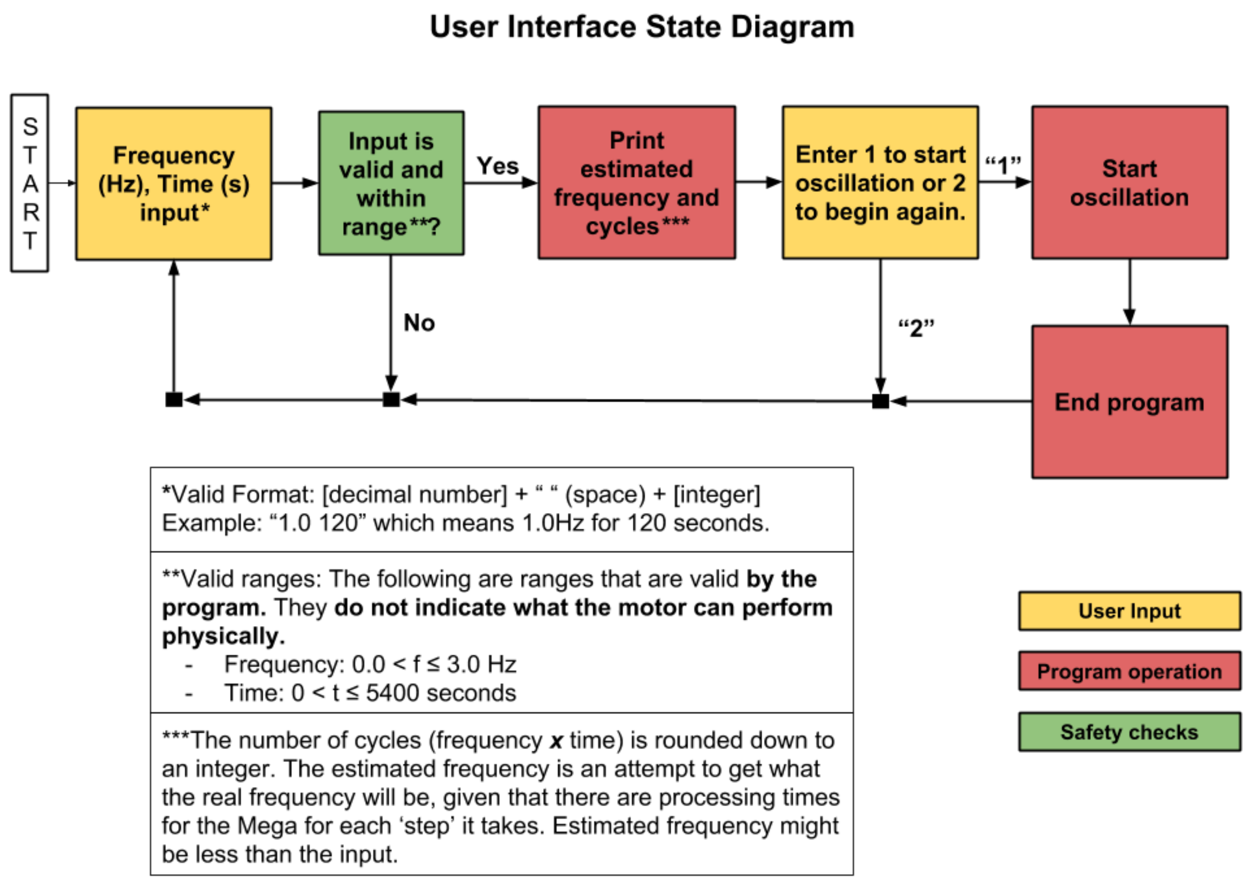
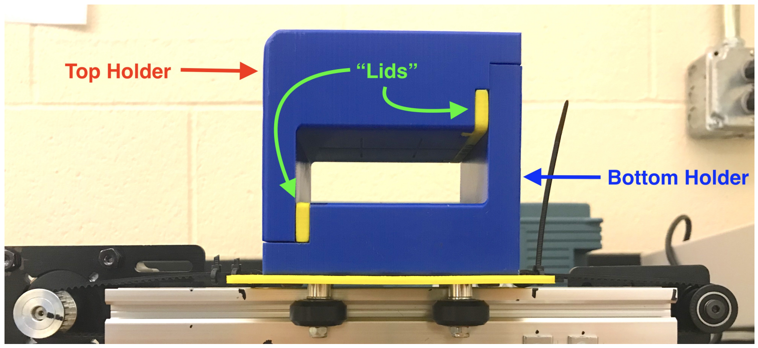


Figure 4: User Interface State Diagram

8 Magnet Container

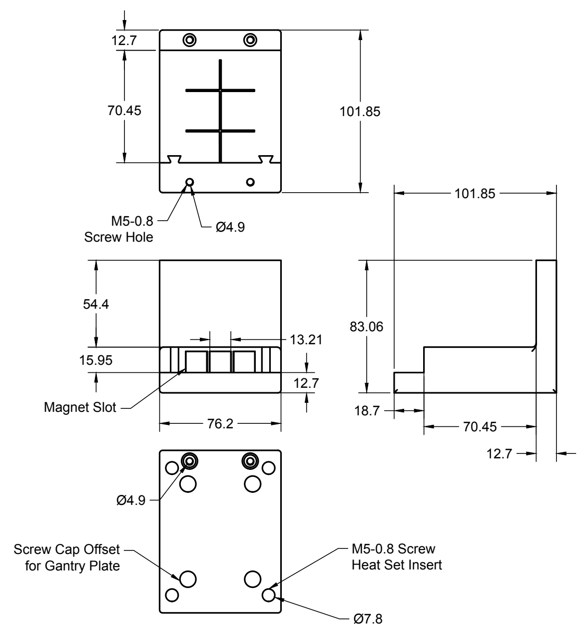
In this section we'll go over the dimensions & features of the container (in millimeters), along with the process we used for inserting & removing the magnets inside the holder. The holder is made up of four pieces: the Top holder, Bottom holder, and two "lids" that keep the magnets secured. Below is a diagram that is, hopefully, labeled clearly to see the different pieces.



The bottom & top holders are L-shaped pieces that are somewhat symmetric, but there are differences that will be explained in the next two subsections. The lids are also nearly symmetric. They also required some sanding to get a smooth & close fit around the interlocking dovetails on each of the holders.

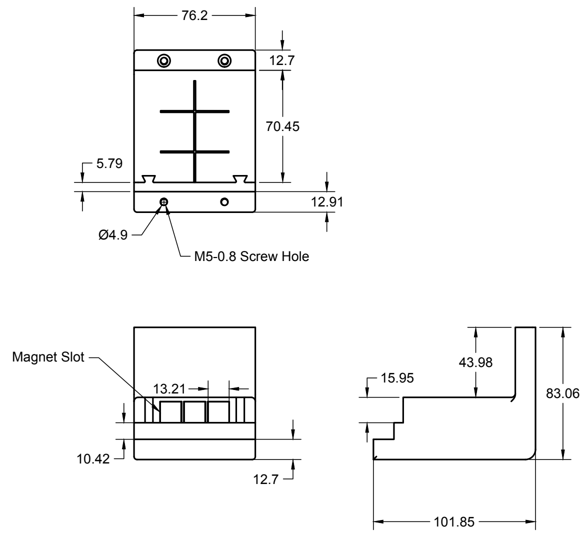
8.1 Bottom Holder

The bottom holder is the more complicated of the two holders, so we'll be explaining its features first. Both holders are about four inches (101.85 mm) long, three inches (76.2 mm) wide, and $3\frac{1}{4}$ inches (83.06 mm) tall. As can be seen in the upper schematic, we've created a small groove on the surface to assist with aligning the probe near the peak values. This is useful for approximately calibrating, but you should still follow the steps in "Calibrating the Hall Probe" in order to properly calibrate the Hall probe. There are four M5 screw holes in each holder for securing the two together. We initially made larger diameter openings to the holes so that heat set inserts could be used, but the 25 mm long M5 screws alone were more than enough to secure the holders together so we forewent the heat set inserts. At the user's own risk, you can insert the corresponding heat sets; but make sure to carefully insert them such that they align or else you may no longer be able to secure the holders together. On the bottom of the bottom holder there are four holes for heat set inserts that are used to secure the holder to the gantry plate. Since the gantry plate has wheels screwed onto it, the screw heads needed clearance space (labeled in the schematic) to allow the bottom holder & gantry plate to press against one another. Many of the edges have been beveled for safety (printed edges can be sharp) and aesthetic reasons.



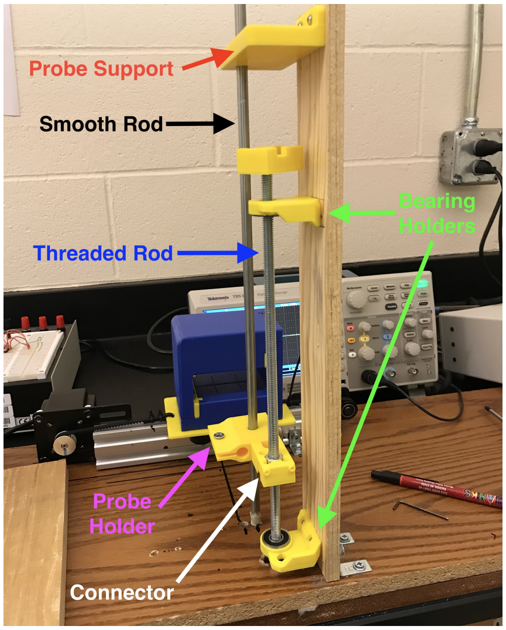
8.2 Top Holder

The top holder shares most of the same features as the bottom holder except for two differences. The most noticeable one is that the top holder does not use any of the holes for the heat set inserts since it isn't attached to the gantry plate. The second difference is that the top holder has an offset raising the "Magnet Slots." This was done towards the end of the design process to increase the field strength & improve uniformity by bringing the magnets closer together. This offset allows a "lip," or edge, of sorts (seen in the bottom right, side-face, schematic) just before the Magnet Slots' entrance so the top lid could still comfortably & securely contain the magnets. Since each holder takes about 17 hours to print, and the bottom holder needs heat set inserts, we only altered the top holder. However, it is possible to make the container more symmetric if you are willing to print new top & bottom holders and insert the heat sets.



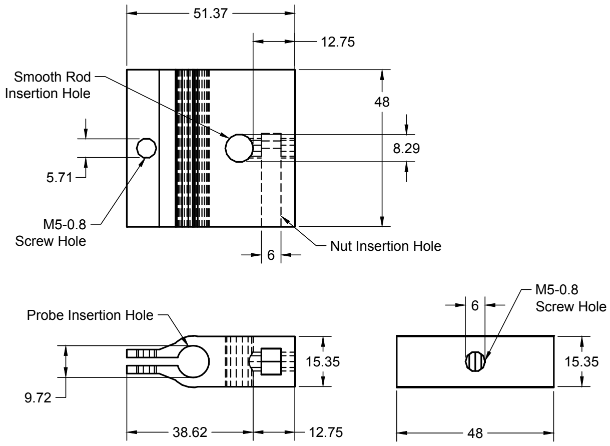
9 Hall Probe Holder

This section begins with design measurements (in millimeters) and explains some features of the holding stand that is used to adjust the Hall probe's height. The assembly is designed for use with LakeShore HMNT-4E04-VR Hall Probe, although other transverse probes can be used as long as their body can fit in the probe holder. The holder consists of two 8 mm rods, one smooth and the other threaded, held together by several 3D printed parts. The probe itself is held by a single piece that slides along the smooth rod, and is kept in place by tightening a 5 mm horizontal screw until it presses against the rod. Below is a diagram of the entire probe support stand with labels that are hopefully clear to see.

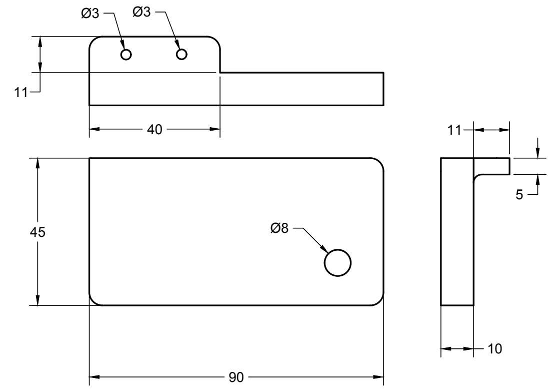


9.1 Probe Holder

To the right is a schematic for the probe holder piece. This can be found in the probe stand diagram (9) near the bottom with a pink label. There are two large holes in the holder: one for the probe, and the other for the smooth rod. And two smaller holes for screws: one for securing the probe in the holder, the other for securing the holder along the rod. The "Probe Insertion Hole" is labeled in the diagram and it is, hopefully, clear how a M5 (5 mm) screw & nut could be used to clamp the probe in place. The holder is secured by sliding a M5 nut into the labeled "Nut Insertion Hole" and then screwing in a corresponding M5 screw until it presses against the smooth rod.

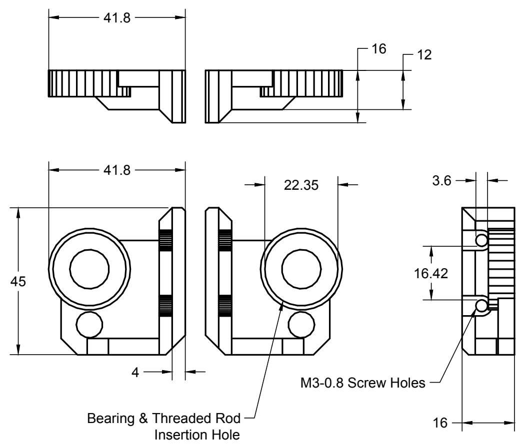


9.2 Probe Holder Support



This diagram shows the various dimensions of the Probe Holder Support piece. You'll find this at the top of the probe stand diagram (9) with a red label. This is used to help keep the smooth and threaded rods parallel so that the height adjustment is easier. It has two holes for M3 (3 mm) screws and a larger 8 mm hole for the smooth rod. This hole was smoothed out similarly to that in the "Probe Holder" subsection; using a drill bit to expand it slightly due to defects inherent to the 3D printing process.

9.3 Bearing & Threaded Rod Holders

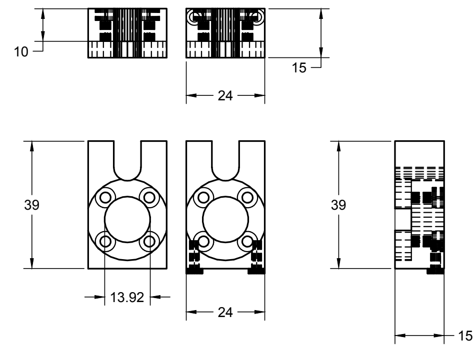


You'll find these pieces at the bottom & middle of the probe stand diagram (9) marked with a green label. These two pieces are symmetric and are used to allow the threaded rod to spin, causing the connector & probe holder pieces to move up or down. As labeled on the schematic, the larger 22.35 mm hole is where we super-glued (along the outer circumference) the bearing.[1]

The two holes for screwing the piece to the board are M3 (3 mm) sized. At the bottom of the probe stand diagram (9) you may be able to see a slight gap between the bearing holder and the MDF, this is where a 5/16"-18 Nylon Hex Nut is placed so that the threaded rod isn't able to move up or down. This was an initial problem when trying to move the probe down, since instead the rod would move up. There is another nylon hex nut of the same size at the top of the threaded rod. We have put a connector piece on it to help turn the threaded rod by hand during height adjustment.

[1] This bearing has an outer diameter of 7/8" (∼22.23 mm) and an inner diameter of 3/8" (9.525 mm). If you have to replace those bearings, please buy 608 (metric) Bearings. Easily available online or a hardware store.

9.4 Connector for Probe Holder



This piece can be found in the probe stand diagram (9) near the probe holder, since it connects the holder to the threaded rod, and has a white label. The connector piece's hole is large enough to fit two corresponding sized hex nuts for the 5/16"-18 threaded rod. We used two nuts to help smooth out the movement when adjusting the probe's height. The connector is super-glued to the probe holder. The second connector piece can be seen at the top of the threaded rod in the probe stand diagram (9), it is used to help with turning the threaded rod, but it is not necessary for it. The connector has previously come undone from the probe holder in two instances. The first time was when the probe holder stand (9) was disassembled and the probe holder was accidentally struck. The other time was when the probe holder was secured to the smooth rod by the fastening screw and we started adjusting the height; however it was only a problem because we thought it was just sticking and tried to force it up. Because of this, be sure to check if the fastening screw is securing the probe holder before adjusting the height.

10 Tools & Repair

10.1 Tools you will need:

1. A Phillips head screwdriver for the smooth rod and probe holder screws, needed for regular operation.
2. A flat head screwdriver for bolts into the base board, only needed for repairs or alterations.
3. A small flat head screwdriver for electronics.
4. M3 (probe stand base) and M5 Allen wrenches (belt system).
5. See "How To Measure Magnetic Fields with an Oscilloscope" for additional equipment you may need to accurately measure the OMF using an Oscilloscope.

10.2 Disassembly Information

- Four 8 mm M5 hex screws join the magnet container to the gantry plate via heat set inserts in the magnet container.
- The top & bottom halves of the magnet container are joined together by four 25 mm M5 screws, as can be seen in the Bottom Holder & Top Holder subsections.
- **Decoupling the Belt:** There are two pulleys that the belt goes around: The timing pulley (attached to the motor) and the smooth pulley. The motor is attached to the V-Slot aluminum rail via a motor mount (a black aluminum plate). The smooth pulley is attached via a smooth pulley mount (smaller black aluminum plate). To decouple the belt and the motor, all you need to do is loosen the two M5 screws that are on the smooth pulley mount. The mount will go inward slightly as the tension is released. The belt will loosen from the timing pulley and can be easily decoupled. Note, however, that the belt will not have much room to move unless it is removed from the gantry plate as well.
- **Re-coupling the Belt:** Put the belt around the timing pulley teeth on one side and around the smooth pulley on the other side. Then pull the smooth pulley mount back along the V-Slot and hold it so that the belt is taunt under tension. Screw in one of the M5 screws on the smooth pulley mount tightly in this extended position so that the belt stays tight. You can let go of the smooth pulley mount at this point and tighten the other screw. The belt needs to have some tension to properly couple with the motor. You can test this by pushing down on the belt, it should come back into position as soon as you let go. As long as this happens, it should be properly coupled. **Do not over extend the belt or try for the highest tension possible.** Take a look at this video[5] for more on how the belt system is kept at tension. Particularly at time stamps: 15:40 & 16:20

10.3 Parts & Sources[4]

11 Links & References

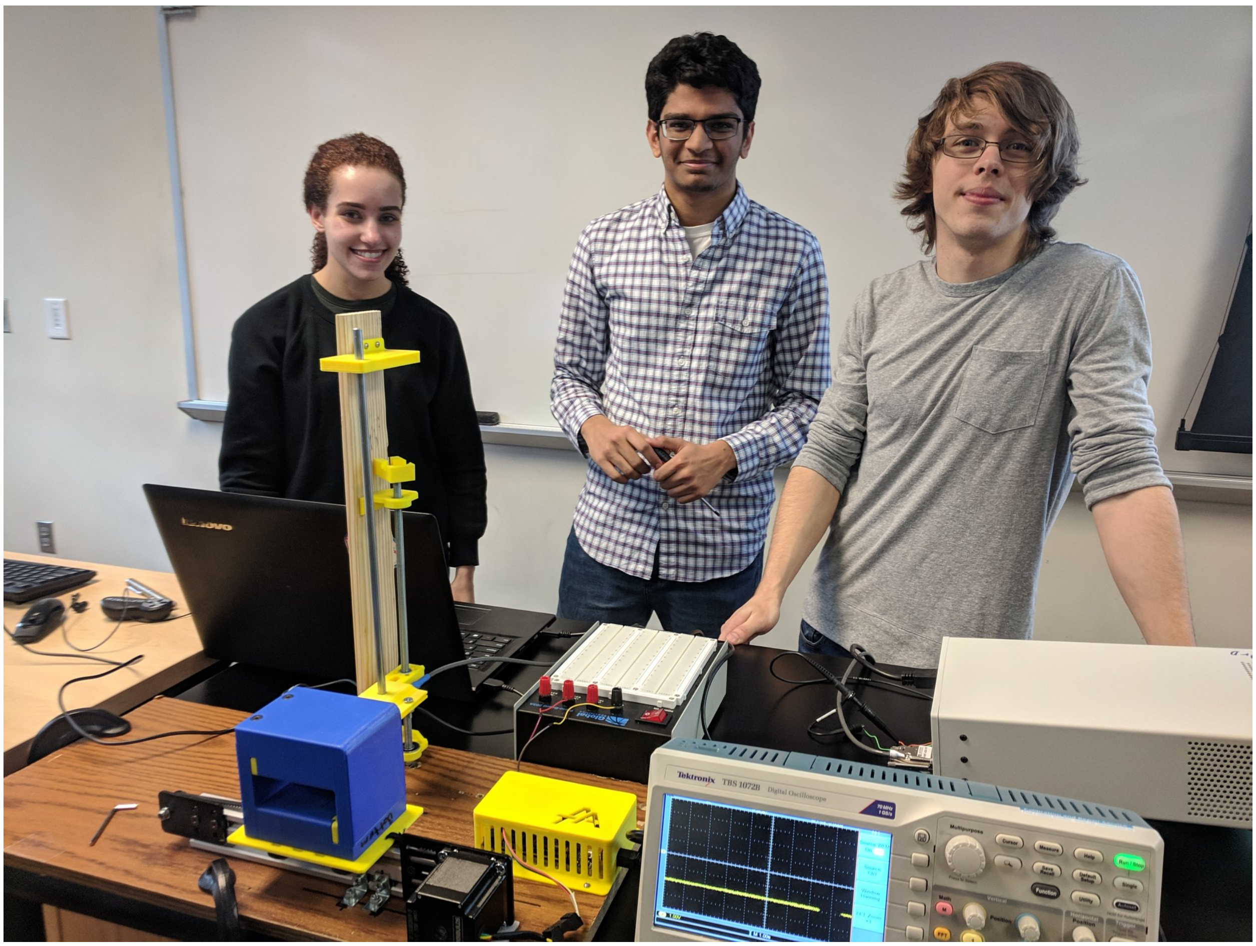
Below are the links & references used throughout the manual. Each link has a superscript that takes you to the section in the manual where the link is used. If you are unable to use any of these links or have questions, you can contact Conner Dearing (cpdearin@ncsu.edu).

1. Ardruino Mega Reference[1] (https://www.arduino.cc/en/Guide/ArduinoMega2560)
2. Using the A4988 chip with Arduino Mega (How to Mechatronics)[2] (https://howtomechatronics.com/tutorials/arduino/how-to-control-stepper-motor-with-a4988-driver-and-arduino/)
3. Pololu A4988 Chip that might be better[3] (https://www.pololu.com/product/1182)
4. Parts List[4] (https://drive.google.com/open?id=1UsQPWfIyrtplQSk1uIpFM64nuq_r7yhW) If this link doesn't work, backup of this file should've been provided in the email containing this manual.
5. Linear System Assembly Video (Openbuilds)[5] (https://drive.google.com/file/d/1nO6K3vUy6zmlSjKBvlx1pIFj1C 1I/view?usp=sharing) If this link doesn't work, a backup of this file should've been provided in the email containing this manual.
6. Desmos Variable Step position and velocity graph[6] (https://www.desmos.com/calculator/vhtbojdtb4)
7. Prusa Printers[7] (https://www.prusaprinters.org/calculator/)
8. Arduino Software[8] (https://www.arduino.cc/en/Main/Software)
9. TheN tHEIR was linear motion [9]

12 Acknowledgements

We would like to thank all the friends and NC State Physics Department faculty and staff for their assistance and advice; Dr. Daniel Dougherty, for his sponsorship, advice, and for his encouragement that we try a novel approach for this device; Dr. Divine Kumah and Dr. Dali Sun for taking the time to answer all the questions on Hall effect experiments; Ashley Dyer for her assistance in acquiring our materials and personally returning our wrongly ordered items; Beau Brakman, for his advice on electronics and his humor. We would specially like to thank the instructors of the course, Dr. Laura Clarke, Dr. Brand Fortner, and Dr. Robert Riehn, for their invaluable advice and patience throughout the semester.

13 Alpha Alpha Team



- *Left* Monique Martone: Magnet and Simulation Specialist (mmarton@ncsu.edu)
- *Middle* Sayam Patel: Calibration and Electronics Specialist (sdpate11@ncsu.edu)
- *Right* Conner Dearing: 3D Design and Hardware Specialist (cpdearin@ncsu.edu)
- *Photo Credit* Dr. Karen Daniels (kdaniel@ncsu.edu)