

ELEC 3004/7312: Digital Linear Systems: Signals & Control!

Prac/Lab 3 LeviLab: Part I: System Modelling

May 1, 2019 by S. Singh, C. Reiger and I. Clough

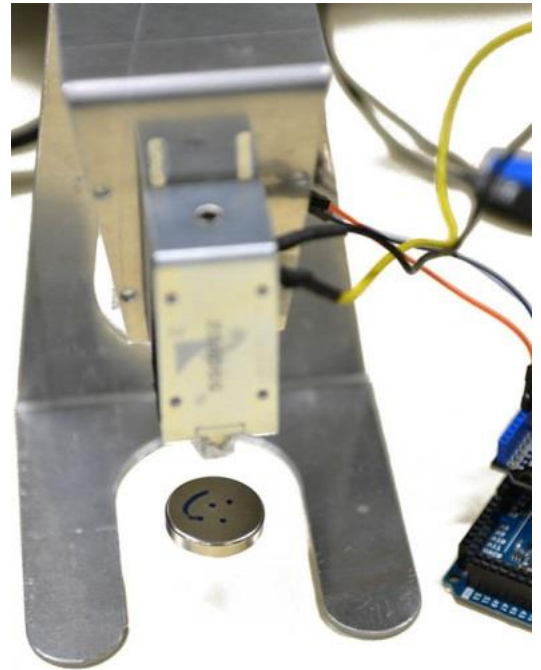
Pre-Lab

This laboratory considers system modelling and control as it applies to a levitating magnetic mass. Much like a magnetic bearing, this suspends ferromagnetic material (or a weight to which a magnet has been attached) by means of an electromagnet whose current is controlled by the position of the mass.

Laboratory Completion

Laboratory Completion:

Please work **together** on the lab in groups of 2-3.



Laboratory Safety

Please Handle Carefully!

This laboratory involves Neodymium rare earth magnets. These magnets are very strong (some of these magnets have surface fields of 7000 Gauss and holding forces of 30 kilograms). Please note that they are:

- **Not a toy**
- A choking hazard. Do not swallow.
- A suffocation hazard
- A pinch hazard. These magnets can snap together very quickly. Keep fingers clear.
- A nickel coated sintered ceramic. **They are very fragile.**
- Combustible. Do not grind or cut.
- Can erase credit cards and other magnetic storage media. Keep >20 cm away.
- Should not be heated above room temperature ($T \ll 80^\circ\text{C}$)
- **Not to be removed from the laboratory room**

This laboratory has a **strict safety policy**. Inappropriate handling is not only dangerous, but not fair.

Any violations (or perceived violations) of safety policy will result in **immediate dismissal from the lab**

LeviLab: An Introduction to System Modelling

Equipment:

1. Arduino Due 32-bit development board
(<http://arduino.cc/en/Main/ArduinoBoardDue>)
2. Motor Shield (Amplifier) – DFRobot DR1009
(http://www.dfrobot.com/wiki/index.php?title=Arduino_Motor_Shield)
3. Solenoid + Electromagnetic plunger -- Jaycar SS0902
4. Hall effect sensor – Allegro A1308 (The A1302 was discontinued in 2018, some kits still have these. They are functionally equivalent) (<https://www.allegromicro.com/en/Products/Magnetic-Linear-And-Angular-Position-Sensor-ICs/Linear-Position-Sensor-ICs/A1308-9.aspx>)
5. UQ LeviLab Frame (Aluminium)
6. UQ LeviLab Sensor Mount Circuit
7. UQ LeviLab Magnet Shield (Aluminium)

Leads:

8. USB Micro B Cable (PC ↔ Arduino)
9. BananaPlug Power Cable (Power Supply → Motor Shield)
[NOTE: Black tag on terminals indicates ground]
10. Solenoid drive leads (Motor Shield → Solenoid)
11. Hall effect signal leads (Sensor → Arduino)

Shared Tools:

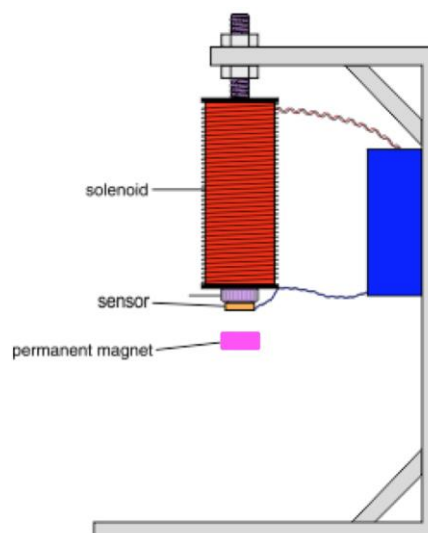
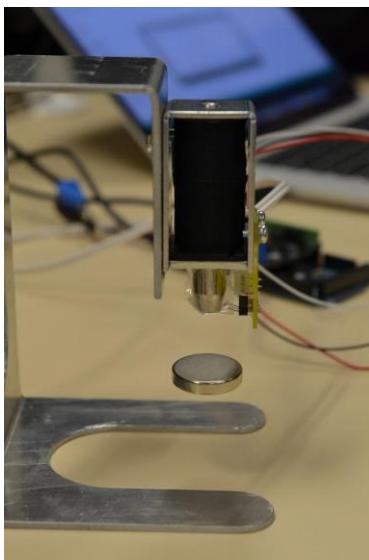
12. #1 Philips and 3.0mm Straight Screwdrivers
13. Masking/Office and Electrical Tapes
14. Dry-Erase and Permanent Marker Pens
15. An assortment of Neodymium Magnets (discs, spheres, and rods).

Goals of the Laboratory:

1. Construct the UQ LeviLab
2. Modelling and Simulation of the LeviLab
3. Start working on control code for the LeviLab

Scenario:

Labs 3 & 4 work towards building a magnetic levitation system using a digital PID controller under feedback control. The scenario is outlined below:



Overview:

The equation of motion is: $m \frac{d^2x}{dt^2} = mg + f(x, i)$

where the force on the ball due to the electromagnet is given by $f(x, i)$. At equilibrium the magnet force balances the gravitational force.

Let I_0 represent the current at equilibrium (where the magnetic force balances the gravity force), then we can linearize this system about $x = 0$ and $I = I_0$ to get: $m \frac{d^2x}{dt^2} = k_1x + k_2i$

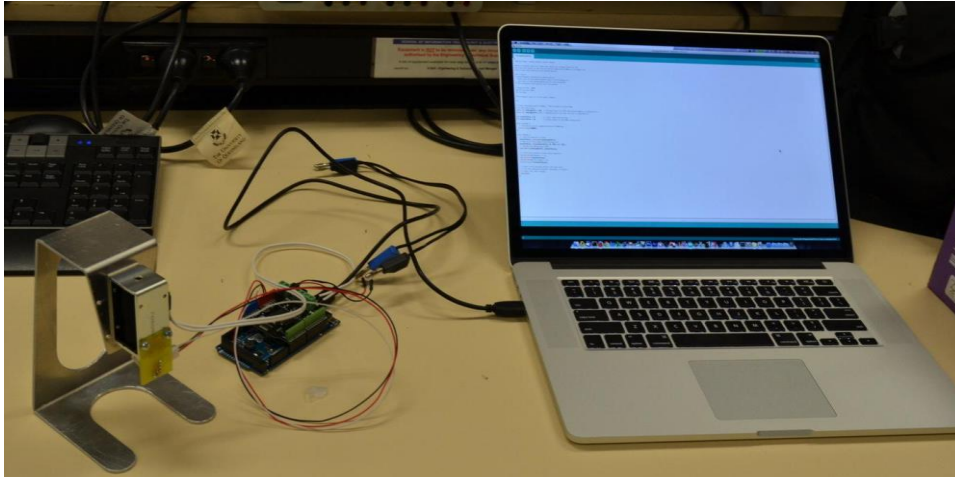
Modelling and Simulation Exercises (Start in Lab, Complete at Home):

1. Continuous transfer function.
Compute the transfer function from I to x (i.e., $G(s) = X(s)$).
2. Digital controller.
Design a digital control for the magnetic levitation device so that the closed-loop system has a rise time of less than 160 milliseconds ($t_r \leq 0.159s$), a settling time of less than 460 milliseconds ($t_s \leq 0.46s$), and overshoot ($M_p \leq 20\%$).
3. Step Response.
Plot the step response of your design to an initial (unit) disturbance. Show this for both the output response ($x(t)$) and the control effort ($i(t)$).

LeviLab: Construction Procedure

Lev Lab Construction In 10 Simple Steps!

The following setup is to be achieved. This guide will step you through the process of constructing the maglev system. Make sure you follow every step precisely to prevent later issues.



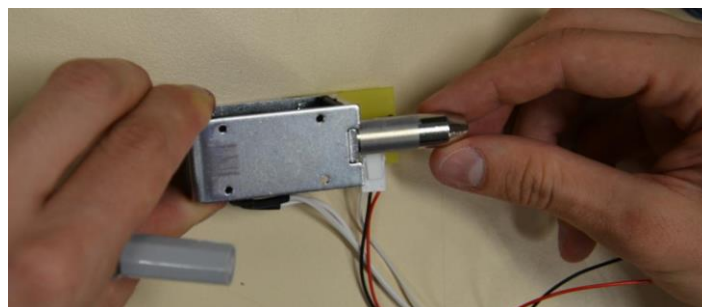
Step 1: Prepare Plunger

The electromagnet plunger requires wrapping of tape to stop it from slipping / falling from the electromagnet. Wrap *one turn* of tape around the plunger.

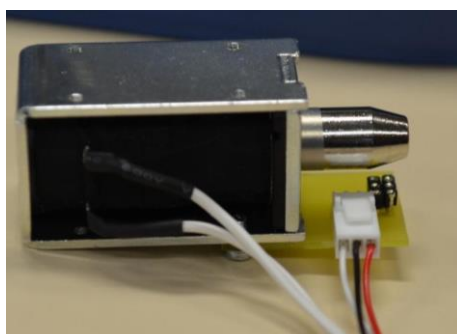


Step 2: Insert Plunger

Insert the plunger into the electromagnet. Note the direction of insertion. Make sure it is a snug fit such that it is difficult for the plunger to slip.

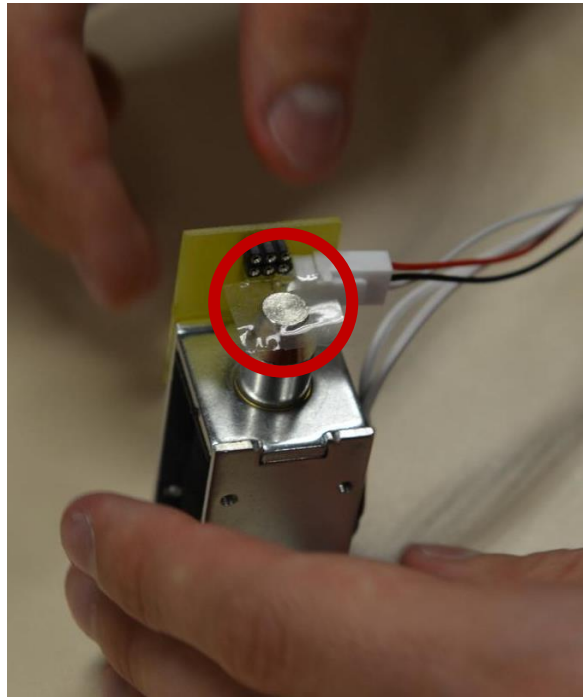


Your setup should now look similar to the following:

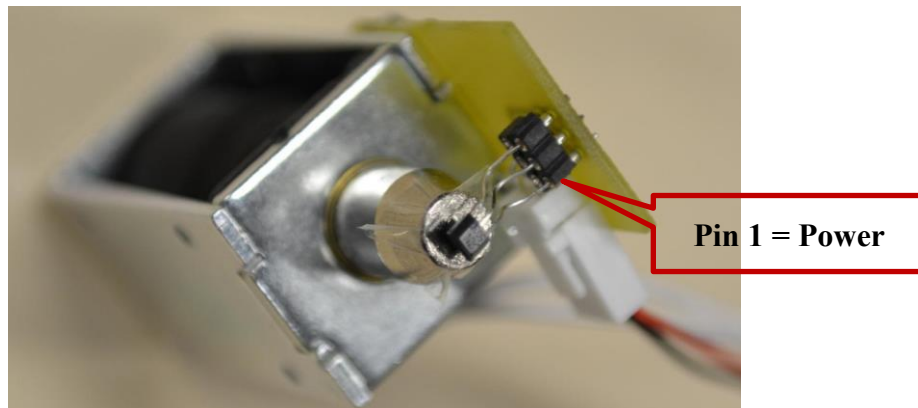


Step 3: Add (Electrical) Tape to Insulate the Hall-Effect Sensor from the Electromagnet

Put a piece of tape onto the top of the electromagnet as shown. This is an important step for later, as if the magnet accidentally collides with the sensor, the sensor leads will press against the plunger, causing a short circuit.

**Step 4: Add Hall Effect Sensor (note the sensor direction and pin connection)**

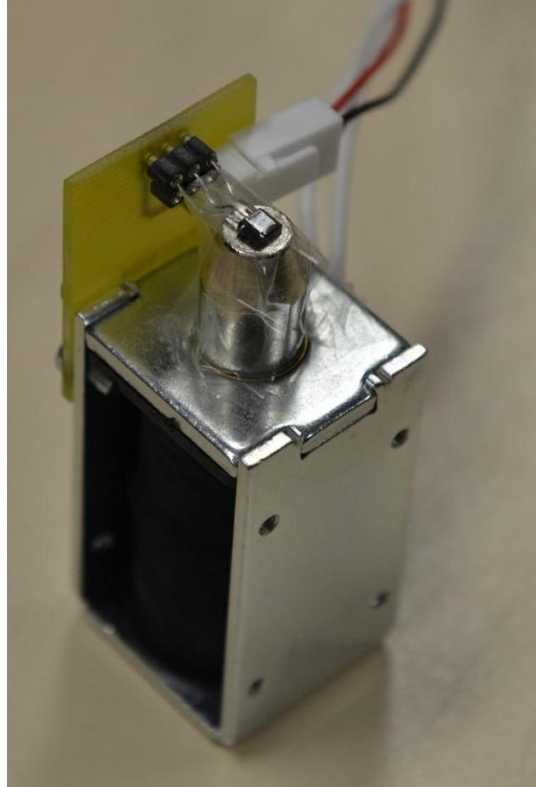
Insert the sensor, noting the direction (sensor edge + logo facing upwards). Inserting the sensor incorrectly may damage the sensor.



→ Remember to add tape to the top of the plunger before adding the sensor.

Step 5: Complete the solenoid sub-assembly

Place tape over the top of the sensor, holding it firmly against the electromagnet plunger as seen below.



→ It might help to wrap a piece of tape over the entire plunger and solenoid assembly

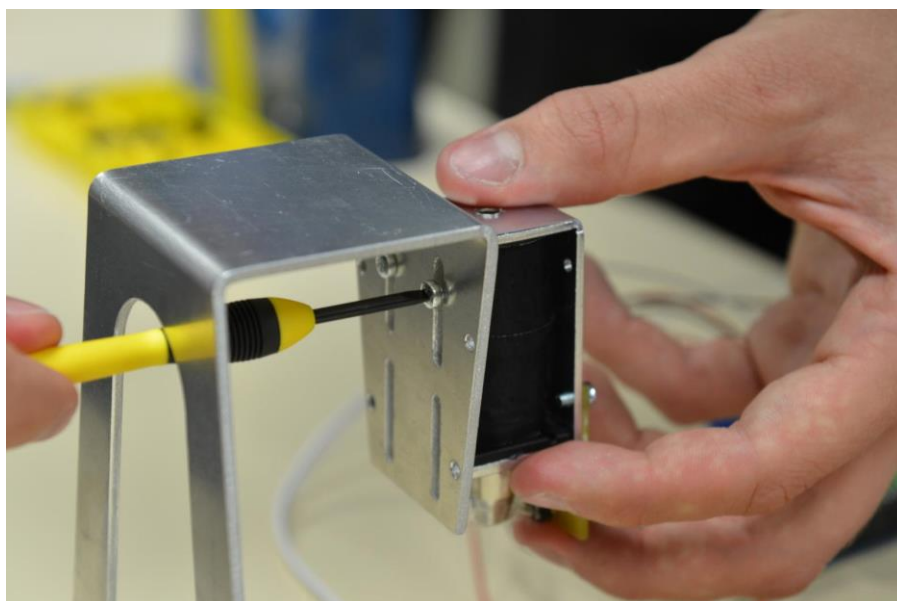
Step 6: Add LeviLab Magnet Shield and then Assemble the Parts

Find 4x washers and 4x bolts and place the washers on the bolts in your kit.

Then add the **LeviLab Magnet Shield** bracket to the side of the solenoid that is opposite to the side with the solenoid connection circuit.

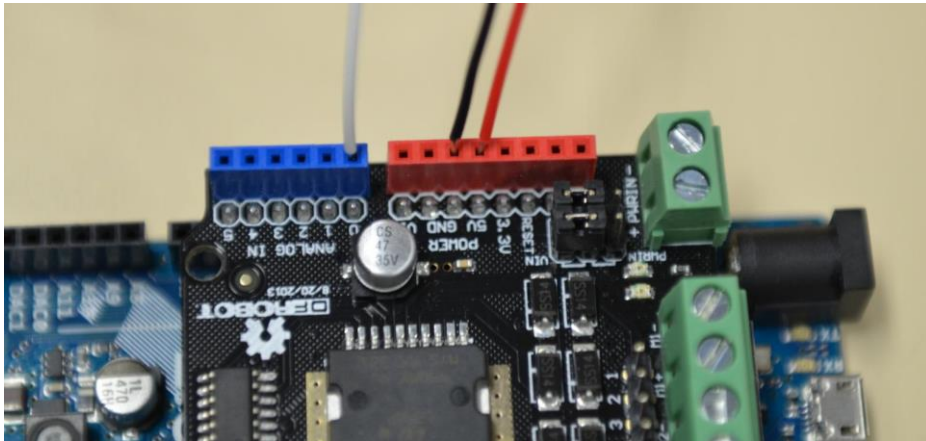
**Step 7: Mount the solenoid to the frame**

Mount the electromagnet onto the holder as follows:

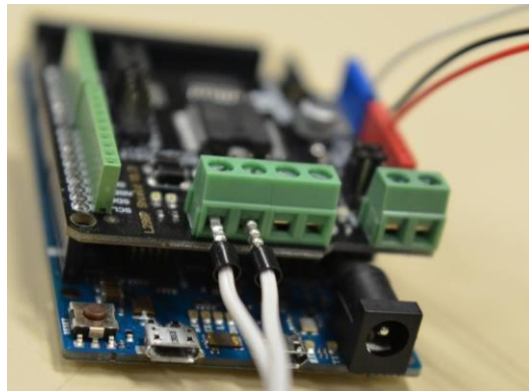


Step 8: Connect the Hall-Effect Sensor to the Arduino

Plug the three wires coming from the hall-effect sensor into the Arduino Motor Shield as seen below. The sensor requires +5v (RED), GND (BLACK), and the analog sensor output (WHITE).

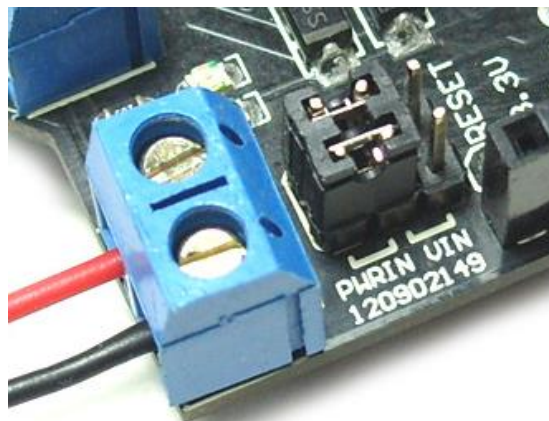
**Step 9: Connect the Solenoid Actuator to the Arduino**

Insert the white cables leading from the solenoid (electromagnet) into the motor shield motor terminal 2 as indicated below.

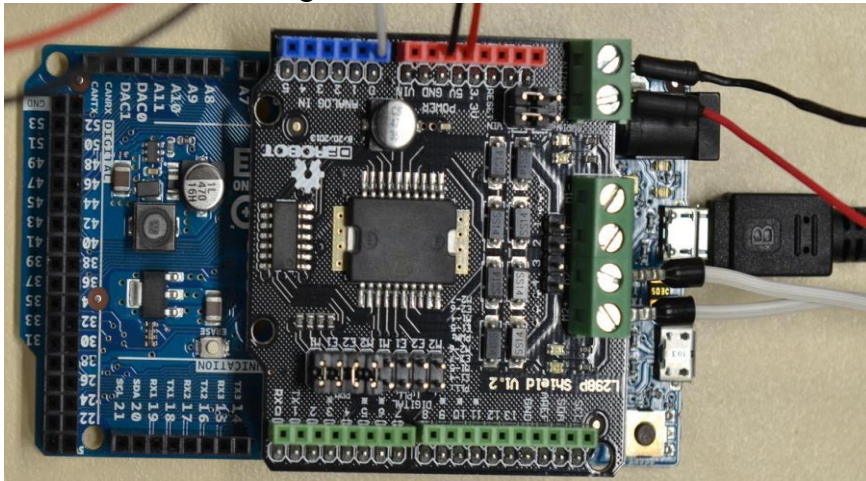


➔ Note that the solenoid is (by default) connected to the top or left pair. If you connect it to the right, you'll have to update the software in several places.

Then connect the external power supply to the board and **remember** to set the power source selection jumpers (PWRIN) to the left (or the side using PWRIN).

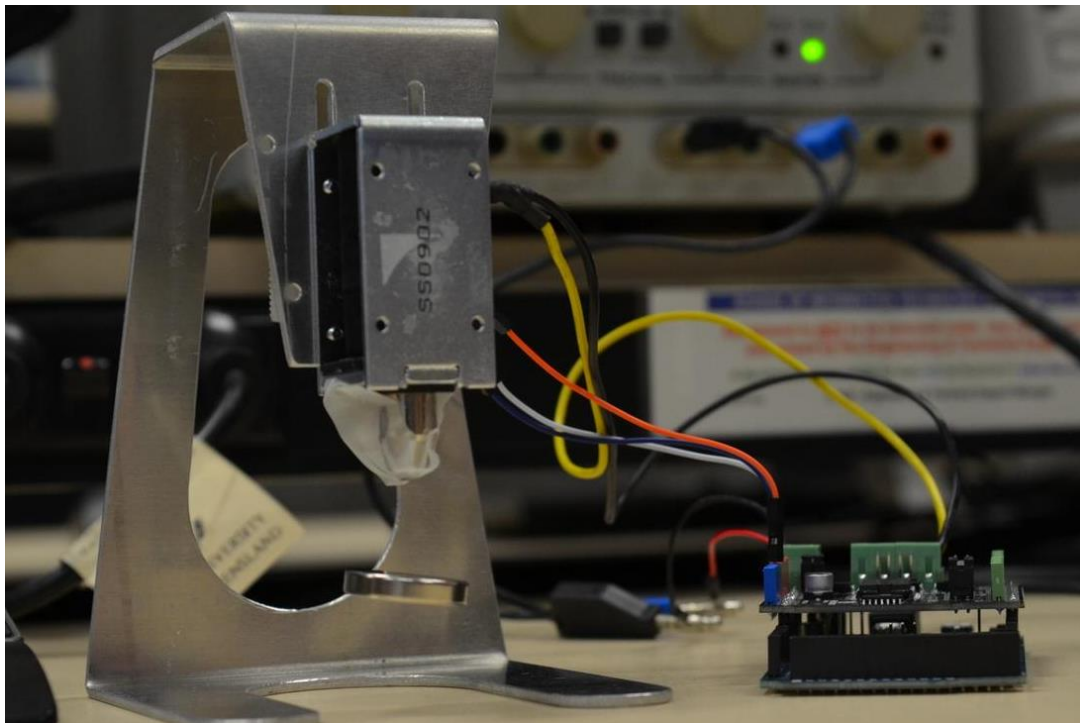


Your setup should now look like the following:



Step 10: Let's Connect to PC and Let's Start Exploring!

Begin coding and exploring ... by the end of Lab 4 (Week 11) we should start levitating things!

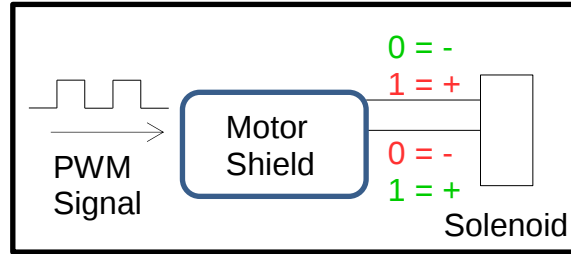
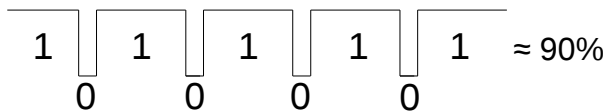
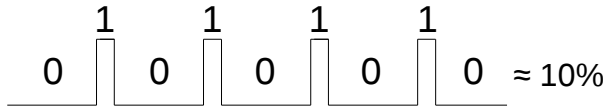
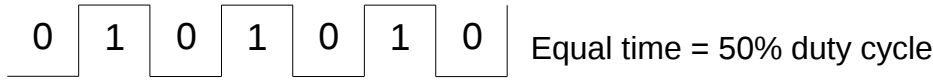


Powering The LeviLab

- Set the laboratory power supply to **12 V** and power the motor shield.
- Plug the hall effect sensor into the **A0** port of the arduino.
- Plug the solenoid into the motor1 port of the shield.

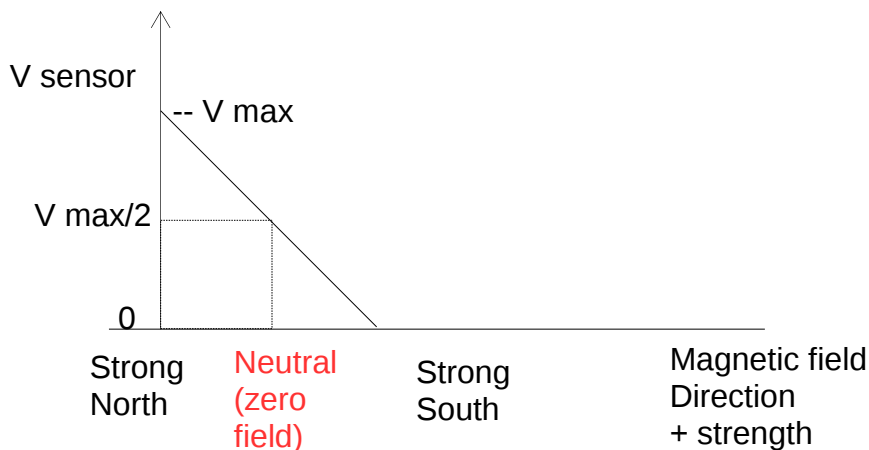
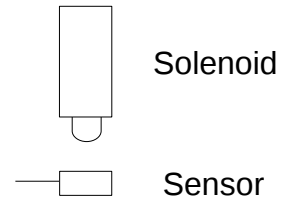
PWM System Calibration

This is a system calibration. We want to know the magnetic field strength of the solenoid for various PWM values. The PWM signal is either 1 or 0, but the amount of time that it is 1 varies from 1% to 99%, and the 0 time is 100% - '1' time.

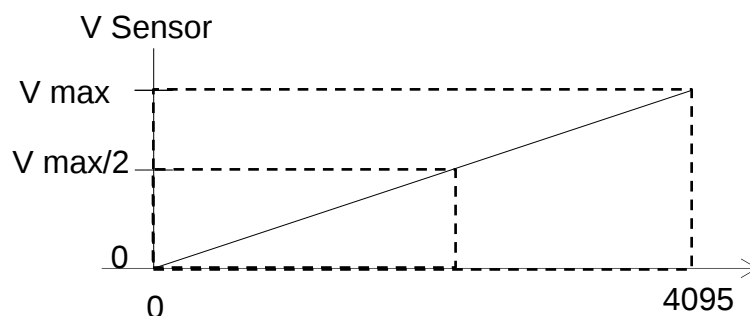


The PWM signal controls the polarity of the solenoid's magnetic field – i.e. 1 = north, 0 = south.

- At 50% duty cycle the average magnetic field appears to be zero, because it is rapidly switching from north to south.
- At 90% duty cycle, the magnetic field is mostly north.
- At 10% duty cycle, the magnetic field is mostly south.
- The sensor voltage depends on the strength and polarity of the average magnetic field across it from **both** the permanent magnet and the solenoid
- If you apply PWM of 50%, the sensor should measure in the middle of its range. See the data sheet for details.
- The PWM value is controlled by the digital value written to it. For 12 bits this is values 0 to 4095, representing 0% to 100%, which then maps to full south at 0% to full north at 100%.

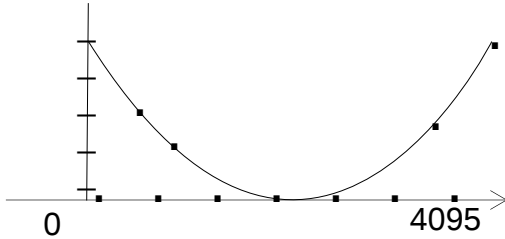


- you can measure the solenoid field strength by applying a known PWM value, then measuring the sensor voltage. Repeat this for all values up to 4095. This will give you this relationship between PWM and sensor voltage. (Something like the case below, but it may not map to these values)



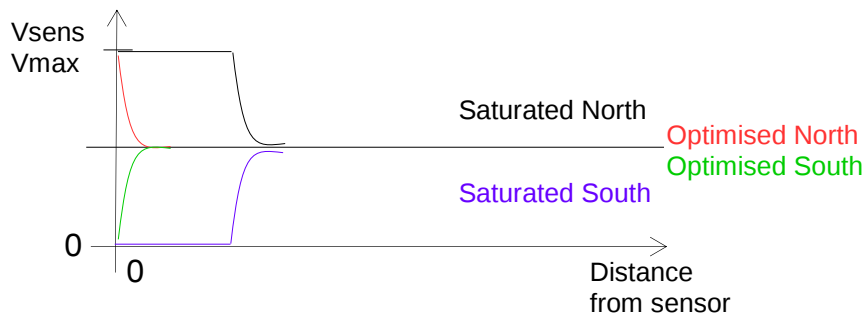
- Now we can repeat for current to the solenoid vs PWM, but we have to measure current manually. Pick about 10 PWM values from 0 to 4095 and measure the current at each one. Set only 1 discrete value at a time. Don't use a loop unless you have a very large time delay between value changes.

I solenoid



PWM Val	Manually Measure Current
0	
500	
1000	
...	
4090	
4095	

- You now have V_{sensor} vs PWM and I_{solenoid} vs PWM. From this you can plot V_{sensor} vs I_{solenoid} . Using the data sheet, find the mV/G value to calculate the field strength from V_{sensor} vs PWM.
- Now run some code in a loop to continually read V_{sensor} , but with either the solenoid unpowered, or PWM = 2047. Use your supplied magnet and place it under the sensor about 5cm away, then lift it towards the sensor. You should see the values change. When the magnet is right on the sensor you will measure its magnetic strength.
- If the magnet is too strong, V_{sensor} will reach one of its limits (zero or V_{max}) before the magnet touches the sensor.



- From this graph you can see the relationship between distance and field strength (plus polarity) Use the data sheet to find magnet strength.
- Compare this to V_{sensor} vs PWM and you can see the relationship between strength of the solenoid field at a given distance, versus the magnet's field at a given distance.
- Can you calculate where they might balance to compensate for gravity's effect on the magnet?

Basic Control Code Template

```
// ELEC3004 Levitation Lab
// Template

// PWM frequency
#define PWM_FREQ 25000
// Serial On?
#define _SERIAL
// Debug On?
#define _DEBUG

// On the Due, pins 6,7,8,9 are hardware PWM pins.
int pwmPin = 7; // PWM the DIR pin on the H-Bridge
int enablePin = 6; // Enable the PWM pin on the H-Bridge
int sensorPin = 0; // For Analog Data IN
int sensorValue;
int i=0, j=0;

// Setup
void setup() {
  #ifdef _SERIAL
    Serial.begin(115200);
  #endif
  #ifdef _DEBUG
    pinMode(2, OUTPUT);
  #endif

  // Ensure 12 bit Read / Write
  analogReadResolution(12);
  analogWriteResolution(12);

  // Setup PWM output
  pinMode(enablePin, OUTPUT);
  digitalWrite(enablePin, HIGH);
  pinMode(pwmPin, OUTPUT);
  analogWrite(pwmPin, 2048); // 50% duty Cycle
  PWMC_ConfigureClocks(PWM_FREQ * PWM_MAX_DUTY_CYCLE , 0, VARIANT_MCK);
}

// PID Function
int Calculate_PID()
{
  // Write your function here... :-
}

// Main Loop
void loop() {
  sensorValue = analogRead(sensorPin);

  analogWrite(pwmPin, sensorValue);

  delayMicroseconds( 500 ); // 0.5ms

  #ifdef _SERIAL
    Serial.println( sensorValue );
  #endif
  #ifdef _DEBUG
    // Allows us to know the PID loop speed through external pin.
    i = ~i;
    digitalWrite(2, i);
  #endif
  //while (0); // Halt
}
```

As an additional exercise you may write an interrupt routine to achieve an accurate equal time delay in the controller without adjusting the loop delay manually. (See: <http://playground.arduino.cc/Code/Timer>)

Lab Activities

Activity 0:

Draw a Free Body Diagram and experimentally test/describe the open loop operation of the system. What will be needed to get the magnet to balance at a lower height?

Will it be easier to balance nearer the solenoid or nearer the base?

Will it be more stable nearer the solenoid or nearer the base?

Activity 1:

Using the hall effect sensor and solenoid, measure and plot the relationship between 'average input current' $i(x,t)$ and the sensor voltage $y(x,t)$. Is this a linear relationship? Where are the saturation limits of hall effect sensor?

Activity 2:

Perform a frequency sweep on the coil and plot its frequency response.

Use this to find the coil model parameters.

Appendix I: Specifications

1. Solenoid + Electromagnetic plunger

Jaycar SS0902

Voltage: 12VDC, Current: 0.5A, DC Resistance: 24ohms, Rated Power: 6W,

Pulling force: 110g-1.78Kg (continuous), total weight: 205g, Plunger weight: 39g.

2. Hall Effect Sensor A1302 or A1308 – See manual**3. Arduino Motor Shield (L298N) (SKU_DRI0009) – See manual****4. Neodymium Magnets – See manual**

END OF LAB 3

Experiment III:**LeviLab: Part I: System Modelling**

Name: _____

Student ID: _____

Date: _____

Lab Kit Number: _____

Group Name/Members: _____

Part Completed**Laboratory Part 1: Assembly**

Discuss the easiest and hardest part of the assembly process

Laboratory Part 2: Lab Activities**Laboratory Part 3:***Has the unit been fully and properly disassembled and returned to its kit box please?*