ELEC 3004/7312: Digital Linear Systems: Signals & Control!
Prac/Lab 3 LeviLab: Part I: System Modelling
May 21, 2014 (by C. Reiger & S. Singh)

Pre-Lab

This laboratory considers system modelling and control as it applies to a levitating magnetic mass. Much like a magnetic bearing in turbomachinery, 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.
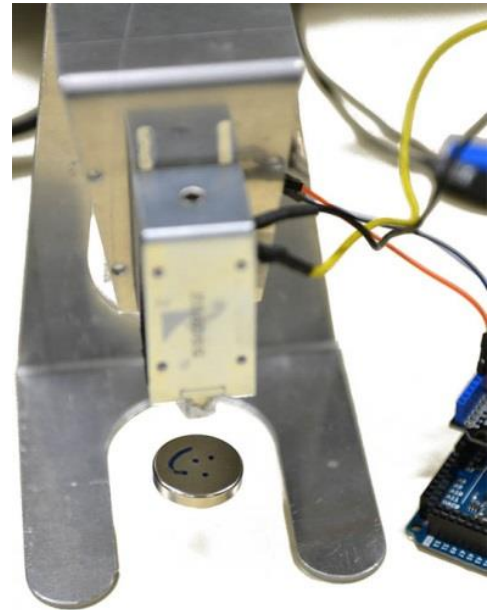
Laboratory Completion & Extra Credit Points

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

Extra credit points:
- +1 : Constructing the LeviLab
- +2 : Characterizing the LeviLab's open-loop operation
- +1 : For returning the parts back in the kit/box

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 >30 cm away.
- Should not be heated above room temperature ($T \ll 80°C$)
- **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 removal from the room**

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 A1302
   (http://www.allegromicro.com/en/Products/Magnetic-Linear-And-Angular-Position-Sensor-ICs/Linear-Position-Sensor-ICs/A1301-2.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:
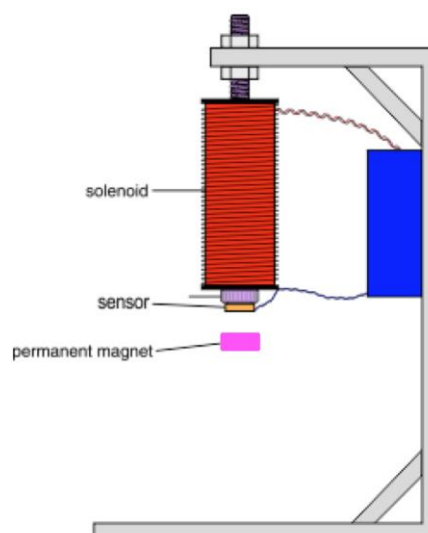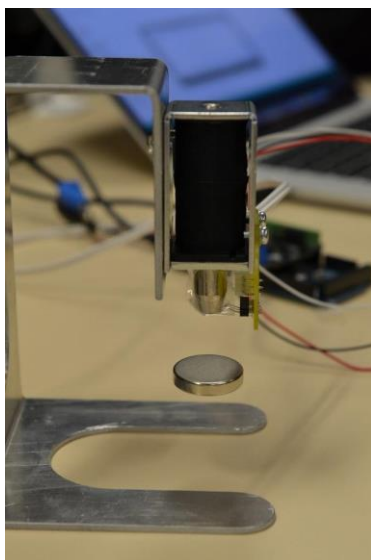
Overview:

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, 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.
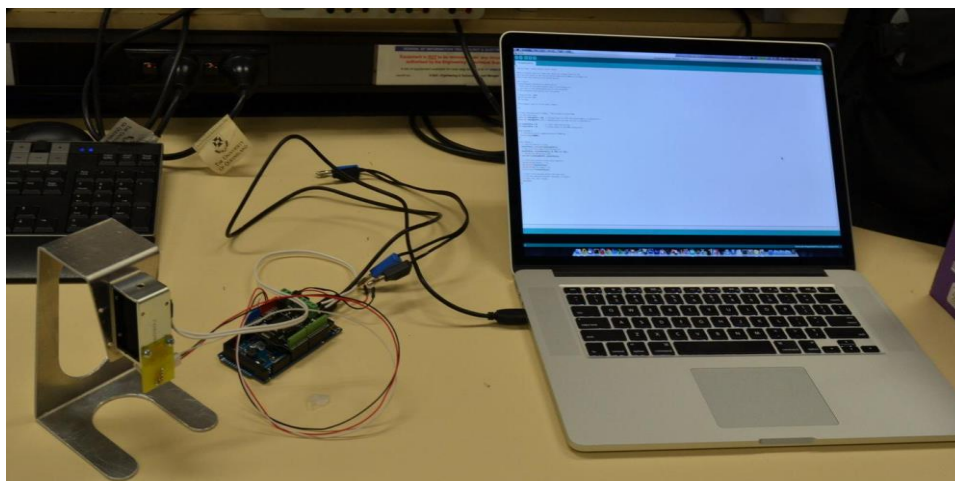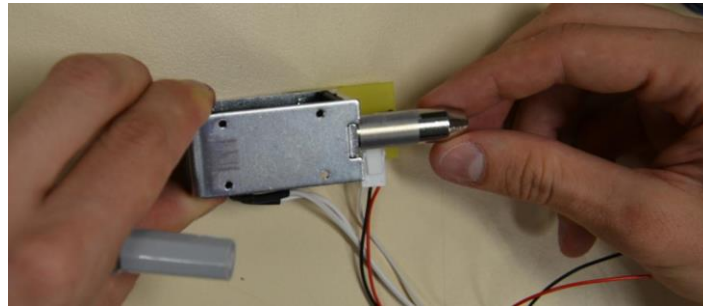

Step 1: Prepare Plunger

The electromagnet plunger requires wrapping of tape to stop it from slipping / falling from the electromagnet. Wrap *one turn* of tape around the plunger.
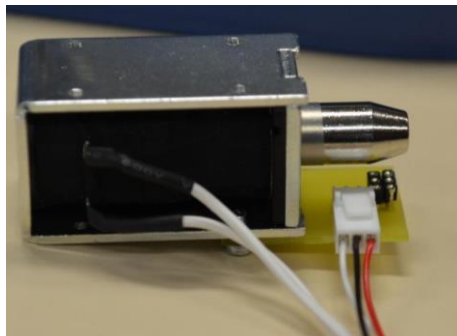
Step 2: Insert Plunger
Insert the plunger into the electromagnet. Note the direction of insertion. Make sure it is a snug fit such that it is difficult for the plunger to slip.

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.
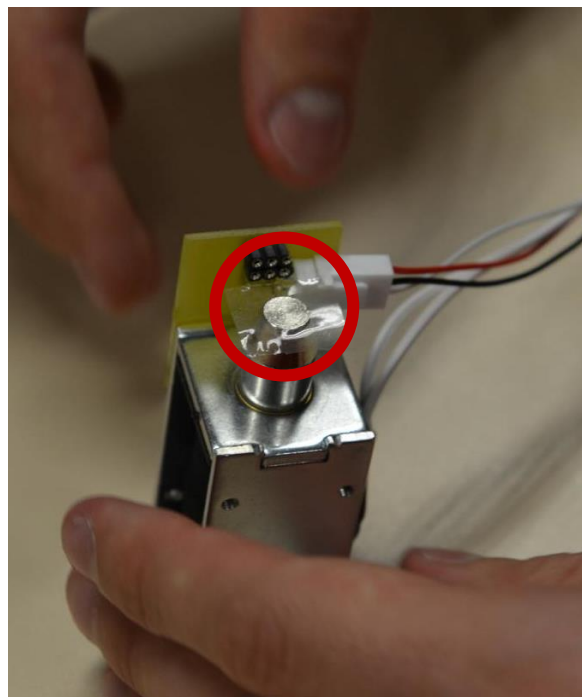
Step 4: Add Hall Effect Sensor (note the sensor direction and pin connection)
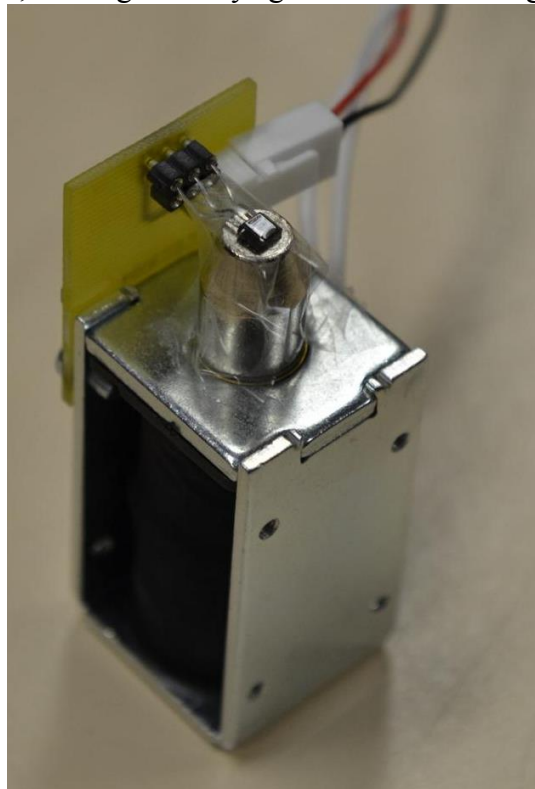Insert the sensor, noting the direction (sensor edge + logo facing upwards). Inserting the sensor incorrectly may damage the sensor.
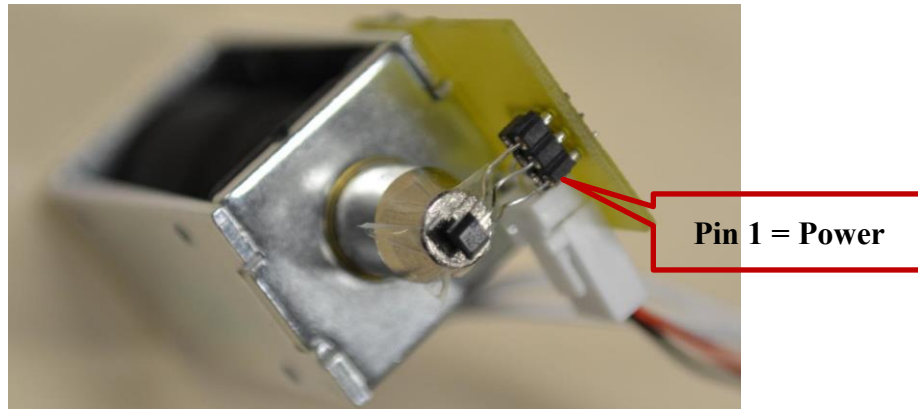
➔ Remember to add tape to the top of the plunger before adding the sensor.

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

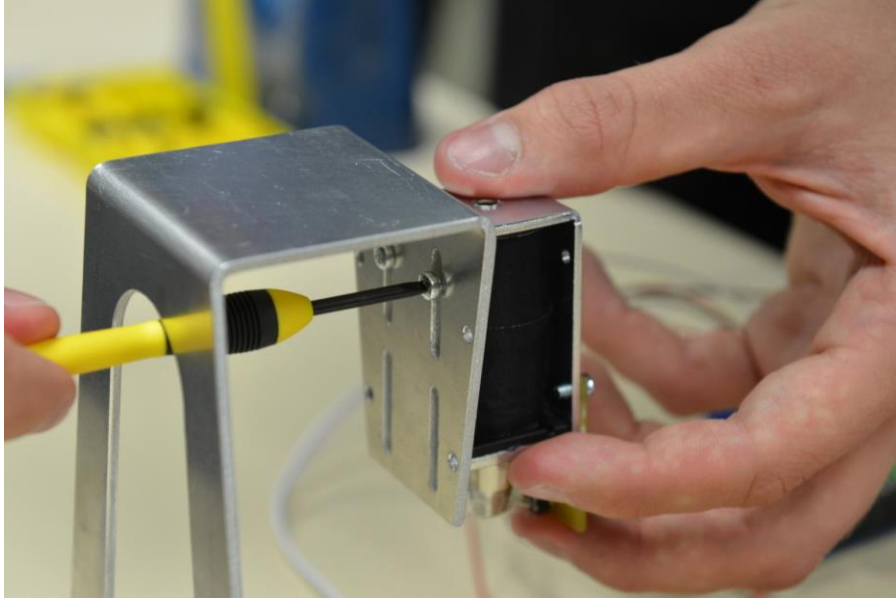**Step 6: Add LeviLab Magnet Shield and then Assemble the Parts**
Find 4x washers and 4x bolts and place the washers on the bolts in your kit.

Then add **the LeviLab Magnet Shield** bracket to the side of the solenoid that is opposite to the side with the solenoid connection circuit.
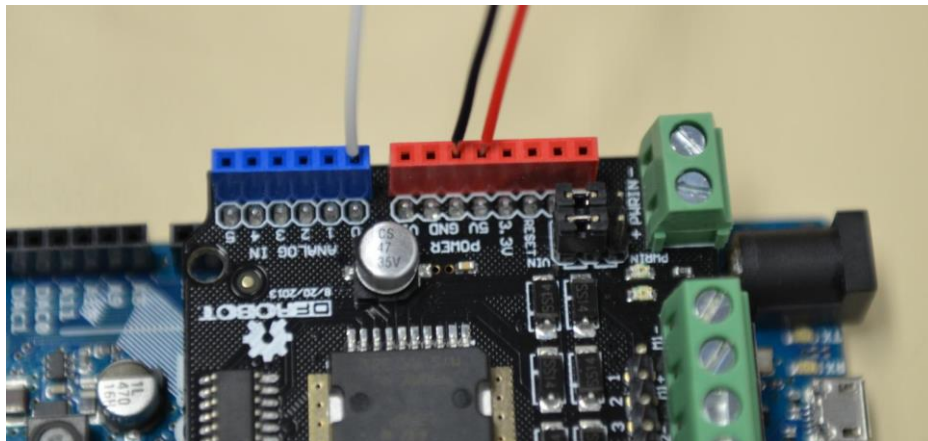
Step 7: Mount the solenoid to the frame
Mount the electromagnet onto the holder as follows:

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.
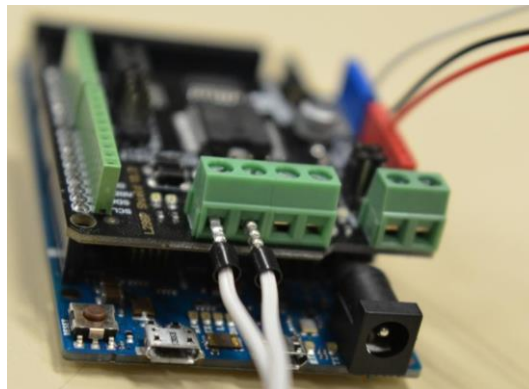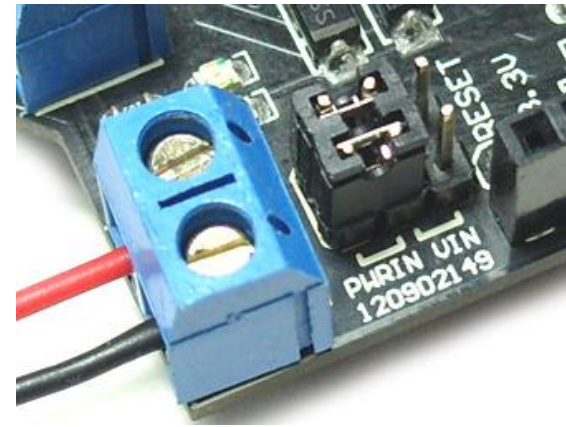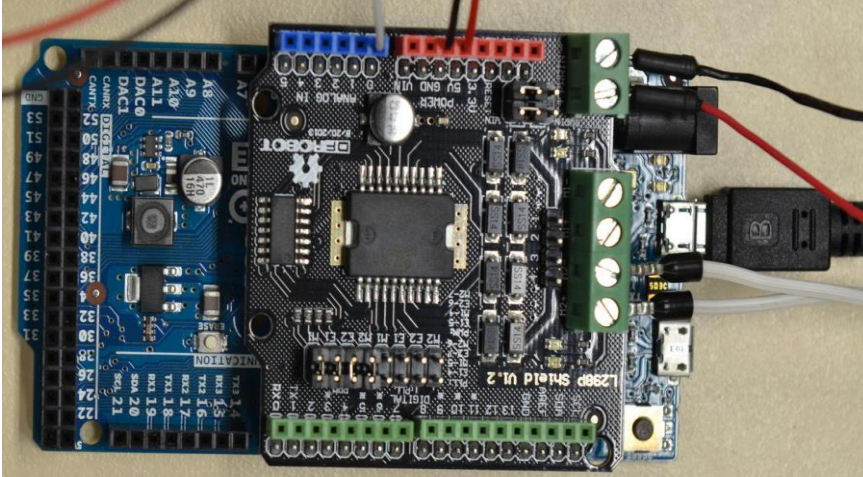

➔ Note that the solenoid is (by default) connected to the top or left pair. If you connect it to the righ, you'll have to update the software in several places.

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 start levitating things!
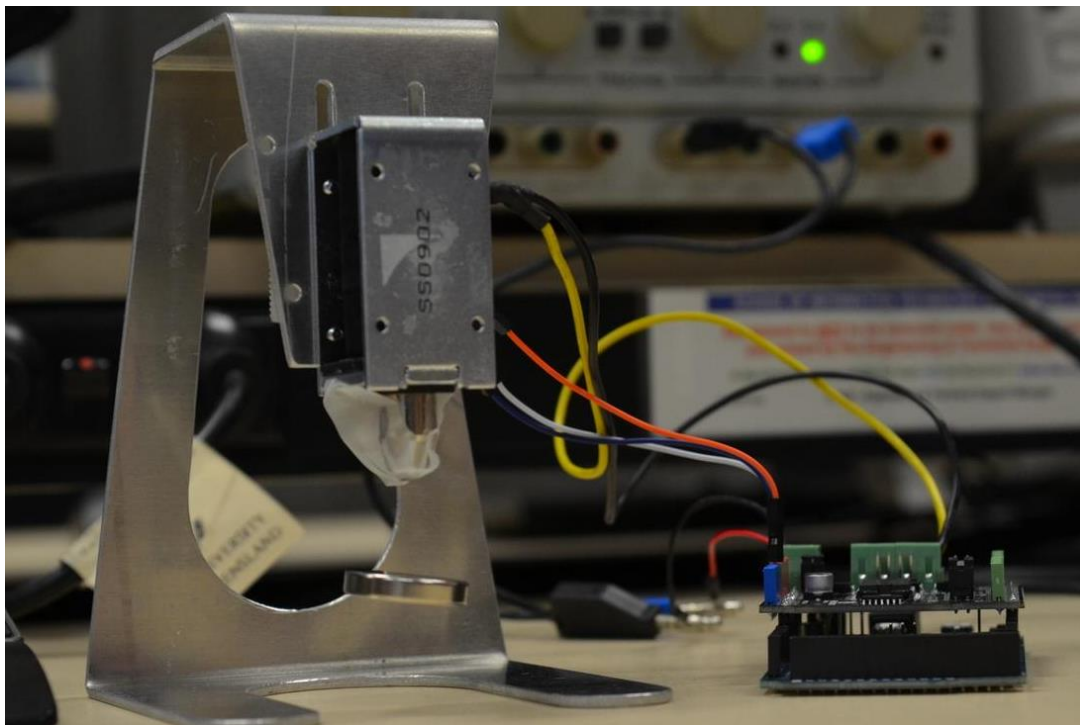
Powering The LeviLab

- 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.

Basic Control Code Template

```cpp
// 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.

Activity 3:
Write code for the following function:

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

Remember the PID definition (Further reading: http://en.wikipedia.org/wiki/PID_controller)

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

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 – See manual**

3. **Arduino Motor Shield (L298N) (SKU_DRI0009) – See manual**

4. **Neodymium Magnets – See manual**

END OF LAB 3

Experiment III: *Hand-In Sheet*
LeviLab: Part I: System Modelling

Name:
Student ID:
Date:

Group Name/Members:

Part Completed	✔ (Tutor)
Laboratory Part 1: Assembly (+1 point) Discuss the easiest and hardest part of the assembly process	

Laboratory Part 2: Lab Activities 0, 1, 2, and 3 (+2 points):
Laboratory Part 3 (+1 point): Has the unit been fully and properly disassembled and returned to its kit box

Total Extra Credit Awarded: _____

Tutor Sign-Off: _____