Lab 4: Magnetic Levitation

I. Objective

The goal of this project is to design an analog controller for the system shown in Figure 1. **We want to design an analog compensator such that the DC gain is 1 A/1 mm and the phase margin is 60 degrees.**

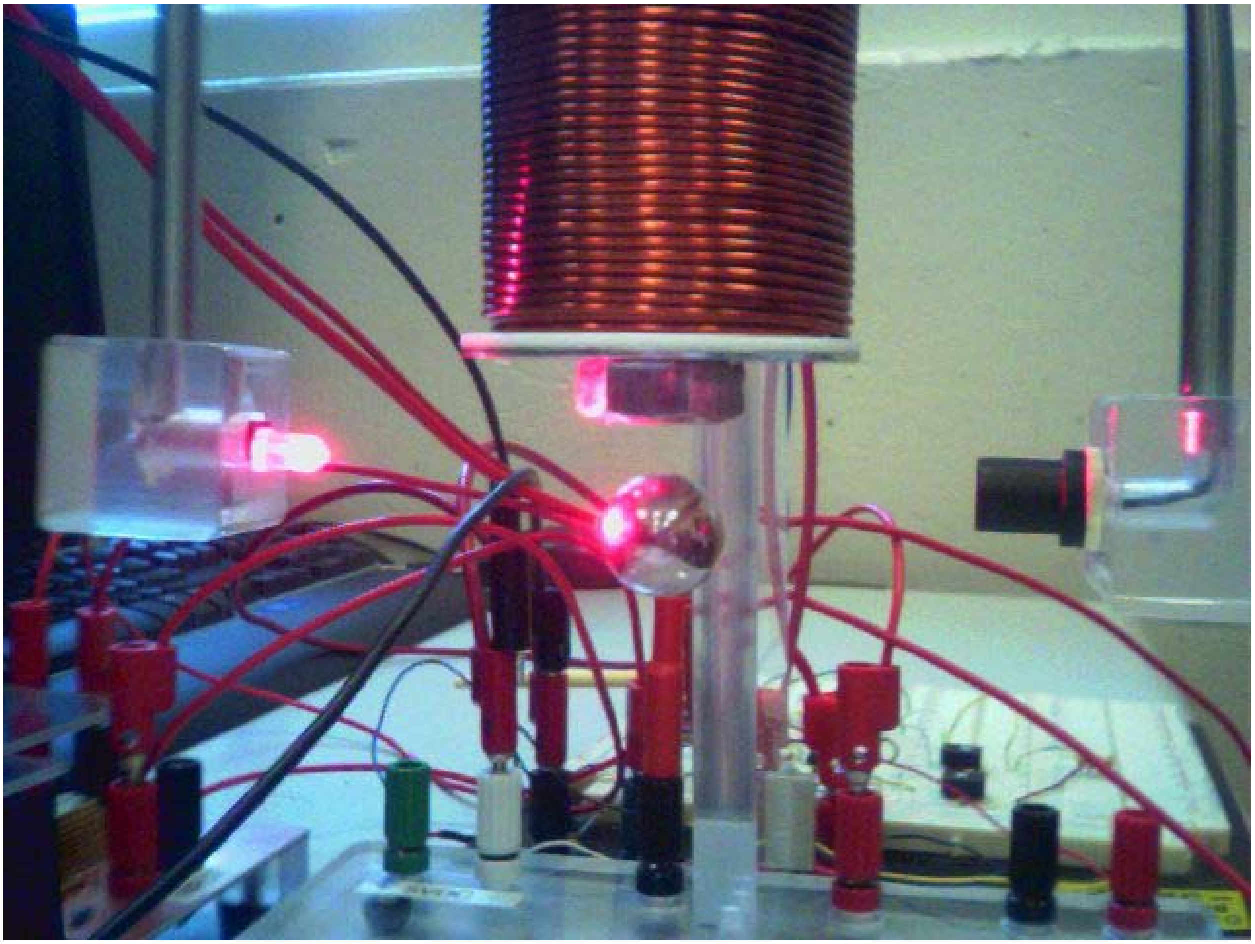

Figure 1: Working magnetic levitation system in action.

II. Equipment

1. Magnetic levitation system – magnetic coil, LED, and photoresistor
2. DC power supply
3. Current amplifier
4. Scale and ruler
5. Cables and wires
6. Various circuit elements (op amps, potentiometers, resistors, *ceramic* capacitors)
7. Multimeter and oscilloscope

III. Theory

1. System setup and block diagram

A high-level block diagram of the system is shown in Figure 2:

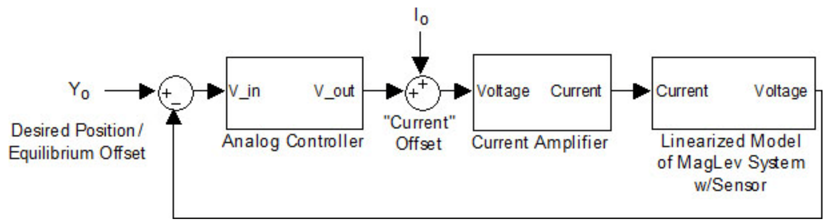

Figure 2: High-level block diagram of our system with all details hidden.

Figure 3 shows the block diagram with circuit level details:

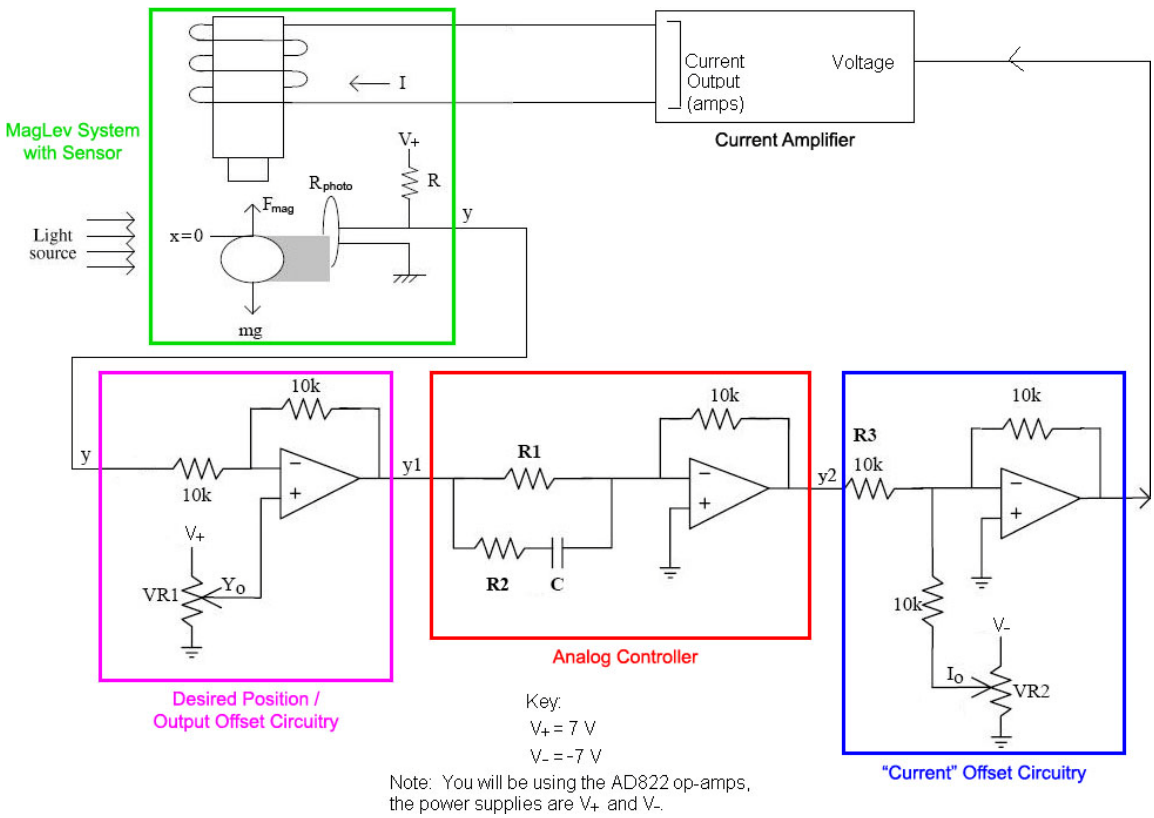

Figure 3: Circuit diagram of entire system. You will be picking values for R1, R2, and C to stabilize an equilibrium point.

2. System modeling

The equations of motion of the ball are:

$$\sum F_{vert} = m\frac{d^2x}{dt^2} = f(I, x) - mg$$
$$y = h(x)$$

Where:
- $\boldsymbol{x}$ – ball vertical position (m)
- $\boldsymbol{m}$ – mass of ball (kg)
- $\boldsymbol{I}$ – current (A)
- $\boldsymbol{g}$ – gravitational constant (m/s^2)
- $\boldsymbol{f(I, x)}$ – magnetic force (N) as a nonlinear function of x and I
- $\boldsymbol{h(x)}$ – output voltage (V) as a nonlinear function of x

You will need to do a system identification process in order to determine a linearized system model. This is unlike your previous labs where you were given the system parameters.

You will notice that the most difficult part of the project is the system identification. But the point of the project is to expose you to control systems design in the real-world, so the effort is worth it!

IV. Pre-lab

1. Week 1 (Familiarization)

1. Look over Figures 2 and 3 above and the system modeling equations.
2. Brush up on linearization, op-amp, and impedance theory.

2. Week 2 (Controller Design *Group* Check-off)

1. Present your data from Week 1: R, K_x, K_i, a, and K_c. Justify their signs ($+/-$).
2. Derive a linearized system representation (TF/SS) of your system symbolically. Then plug in your data from Week 1, being *extra careful* that all of the units match.
3. Plot the open-loop root locus and frequency response of your system and explain what you see.
4. Based on these plots, decide if you need a lead or a lag compensator and describe its purpose.
5. Design a controller to meet the specifications from the objective (use MATLAB's `margin` and `sisotool`). You are solving for a controller of the form $C(s) = K_c\left(\frac{1+s/z}{1+s/p}\right)$. Explain your process and reasoning.
6. Derive the relationships (or transfer functions) between the input and output of the following subsystems in Figure 3: Desired Position / Output Offset Circuitry, Analog Controller, Current Offset Circuitry.
7. From your controller design, calculate the values of R_1, R_2, and C to use in your circuit.

V. Lab

1. Week 1 (System Identification)

In lab, you will identify parameters to model the magnetic levitation system. Remember to have proper SI units for all of these measurements and calculations and keep track of what you are measuring (i.e. force is in Newtons, not grams).

1. Decide on an equilibrium height of the ball. The $x = 0$ position should be set at about 15 mm (for your reference, not exact for every setup) from the bottom of the electromagnet so that about half of the light going to the photo-resistor is covered.
2. Measure and report the range of variation of the resistance of the photo-resistor as the ball's shadow covers from none to the entire resistor surface. Using this data, determine a suitable resistor value R to use in series with the photo-resistor (see green System box in Figure 3) given that $V_+ = 7V$ and we want to make it as a voltage divider to determine our output. The value of R you picked should make that the values of y seen for values of x around the equilibrium point would be comfortably within the $0 - 7V$ range. (Note: the photo-resistor will break if it ever exceeds 250mW power dissipation although this limit would probably not be reached in practice.)

3. To linearize $h(x)$: Move the ball over small perturbations (e.g., 1~2 mm) about your equilibrium position. Record the output voltage y versus ball position x. Plot the data and find the slope of the curve at $x = 0$. This linearized approximation (slope) for $h(x)$ we will denote a.

4. To linearize $f(I, x)$: Find the value of I that renders the ball weightless at the position $x = 0$. Denote this equilibrium point as (x_0, I_0). Then, take force readings over small range around this equilibrium point. That is, find K_x and K_i using similar method in Part 3 for the equation:

$$m\frac{d^2x}{dt^2} = f(I, x) - mg = f(I_0, x_0) + K_i i + K_x x - mg = K_i i + K_x x$$

Thus, the linearized model of your system is:

$$\frac{d^2x}{dt^2} = \frac{K_x}{m}x + \frac{K_i}{m}i$$
$$y = ax$$

Note: the scale would be your device to take force readings in terms of mass. And use multimeter to measure voltage input to current amplifier instead of measuring current output of current amplifier. Trust the gain $K_a = 1\ A/V$ in the Part 5. Be careful of the units for your measurements.

5. Let's analyze the DC gain of your system. The ball's position is first sensed, then passed through your controller, and then converted to a current that is sent to the electromagnet. So the DC gain is the sensor gain multiplied by the gain of your controller (K_c) multiplied by the gain of the current amplifier (K_a).

In variables: $DC\ gain = a * K_c * K_a$

Now, we want the DC gain of our circuit to be 1 A/mm. Assume $K_a = 1\ A/V$ and then use this along with a from part 3 to calculate K_c.

2. Week 2 (Controller Implementation)

Implement the controller and offset circuitry. One possible procedure to balance the ball:

1. Place the ball at the zero position. Adjust the potentiometer in the "Desired Position / Output Offset Circuitry" in Figure 3 such that $y_1 = 0$.
2. Now remove $R_3 = 10k$. Adjust the pot in the current offset amplifier such that the ball is just balanced by the electromagnet. Now, re-install R_3 and slowly remove the support.
3. If it is not working, use general circuit debugging techniques. Easiest check is to make sure that your controller output changes significantly when you wave your hand across the light sensor.

Alternatively, you can get a feel (literally) by holding the ball at the equilibrium and qualitatively trying to understand how the controller is reacting. Is it pulling too hard/not enough? Is it too jittery or is the controller output not making large enough corrections? Try to relate the behavior back to general system concepts such as gain and stability as well as your offset values.

3. Extra Credit (3 pt)

Using your tuned Maglev system, generate a plot of a disturbance response by reading the sensor output and controller input with an oscilloscope. First, stabilize the ball at the equilibrium point. Next, set up the oscilloscope to measure the data (see Maglev Tips document). Finally, disturb the ball by either tapping it hard enough to produce a visible response but have it still return to equilibrium or by introducing a disturbance signal in your circuit. Include these plots into your lab report, explain what kind of disturbance you gave to your system, and analyze the output.

VI. Special Lab Report Instructions

- Objective – same as usual
- Experimental System – describe the entire maglev system and feedback loop with controller
- Procedure – VERY brief overview of what you did (NO data)
- Analysis – break into the following sections and present in this order:
  - System Identification – linearization and system model
  - Controller Design – make sure everything from your week 2 prelab check-off is included here or in system identification
  - Physical Implementation – What numbers did you actually use? What was your general procedure for getting the ball to levitate?
  - Extra Credit – Include it here if you have any results.
- Conclusions - same as usual

Throughout, please describe what steps you took and where you had difficulty. You should explain your reasoning for each step. The controller design should be the bulk of the report. Make sure you explain each portion of the overall circuit as well somewhere in your report.

VII. Revision History

Semester and Revision	Author(s)	Comments
Fall 2010 Rev 1.4	Wenjie Chen, Jansen Sheng	Updated lab for Fall 2010. Added Extra Credit part. Modified some prelab and lab wording.
Fall 2009 Rev. 1.3	Justin Hsia	Post-lab changes from EE128 Fall 2009. Updated the block and circuit diagrams.
Winter 2008 Rev. 1.2	Justin Hsia	Post-lab corrections and clarifications from EE128 Fall 2008
Summer 2008 Rev. 1.0	Bharathwaj Muthuswamy	1. Formatted write-up into different sections 2. Typed up solutions
Fall 2005 Rev. 0.0	Ping Hsu	Initial write-up