The Electromagnetic Levitator

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1 Abstract

The purpose of this project was to construct an electromagnetic levitator. This will be done with a closed loop feedback system controlling the current through a coil, which induces a variable field, which will then levitate small metallic objects beneath the coil, and keep the objects stable. The original design for the circuit was based off of an article in *Electronics Now*, but I have made several modifications specifically relating to the object position detection. Only after modifications to the *Electronics Now* design was I able to achieve stable levitation.

2 Introduction

Obviously, the most important part of this circuit is the feedback system, which will have to control the amount of current through the coil depending on where the object is instantaneously. This is done with input from an infrared beam, and control by a series of operational amplifiers and bipolar transistors, configured as a voltage level detector and limiter as well as a combination amplifier and differential amplifier. The theory behind the levitator is quite simple: from electromagnetism, we know that a finite coil will have a field inversely proportional to the separation outside and below the coil, and proportional to the current through the coil. Thus, by controlling the current through the coil it is possible to exactly cancel out the gravitational force on the object.

3 Theory

I will discuss the theory behind the circuit in three parts: the electromagnetics of the system, the electronic theory of a feedback system, and finally the specific circuit and how it works.

3.1 Electromagnetism

Assuming that the ferrous object to be levitated is on the axis of the solenoid, the calculations are much easier. We have the situation shown below:

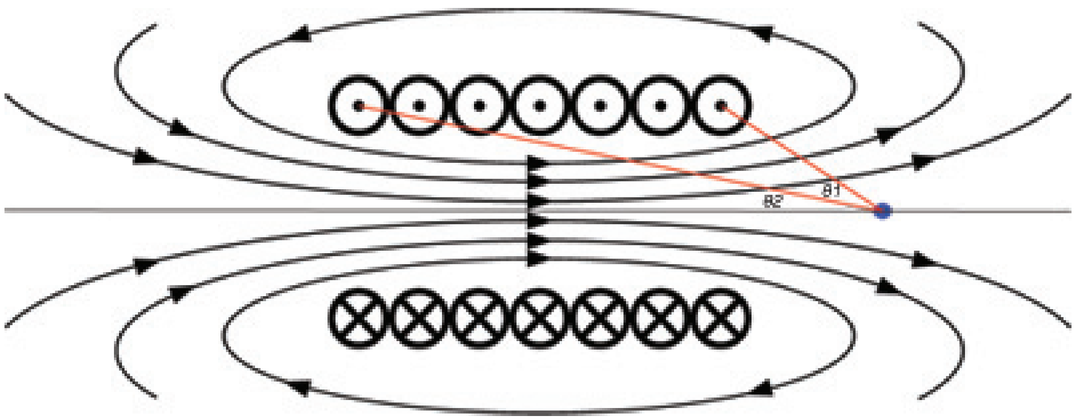

Figure 1

We can derive the field at the point shown:
We know that the strength of the field of a single loop of current at a distance z_0 will be [1]

$$B(z_0) = \frac{\mu_0 I}{2\pi} \frac{R^2}{(R^2 + z_0^2)^{\frac{3}{2}}} \tag{1}$$

R is the radius of the loop, I is the current through the loop. So, we can easily extend this to the solenoid, which is simply a series of loops. Thus,

$$B(z_0) = \frac{\mu_0 n I}{2\pi} \int \frac{R^2}{(R^2 + z^2)^{\frac{3}{2}}} dz \tag{2}$$

where n is the number of turns per unit length. Evaluating the integral yields, with L as the length of the solenoid and thus $-L/2$ and $L/2$ as our limits of integration,

$$B(z_0) = \frac{\mu_0 n I}{2} [\frac{1}{R^2} \frac{z - z_0}{\sqrt{(z - z_0)^2 + R^2}}]_{-L/2}^{L/2} \tag{3}$$

which we can simplify, with a trigonometric identity, to

$$B(z_0) = \frac{\mu_0 n I}{2} (\cos\theta_2 - \cos\theta_1) \tag{4}$$

where θ_1 is the angle between the axis of the solenoid and the closest loop of current, at the point in question, and θ_2 is the angle between the axis of the solenoid and the

[1] Griffiths, David J.; *Introduction to Electrodynamics*; Prentice Hall, 1999; pg. 218

furthest loop, at the point in question, which gives the general results that we anticipated: the field strength B decreases with increasing distance, and the field strength also increases with increasing current. Thus, with precise control of the current through the coil, we should be able to adjust the field strength at any distance to any value we with, with limitations on the maximum and minimum currents, obviously.

3.2 Electronic Feedback

This leads us into the theory of electronic feedback. It is not immediately obvious that this is a feedback system. However, we observe that the output of the circuitry here will control the current through the coil, which will control the strength of the magnetic field, which will control the position of the levitating object, which thus feeds back into the circuit as a voltage level from our phototransistor.

We know that there are two types of feedback available to us: positive and negative. If we have some position at which the voltage signal from the phototransistor results in enough current to counteract the gravitational force on the object, that will be our equilibrium. We also know that we want this to be a stable equilibrium, which means that any small perturbation should result in a restoring force to return the object to equilibrium. This is the definition of negative feedback, so that is what we want to implement.

We are planning on using a phototransistor for the controlling voltage signal, so this is perfect. The essence of phototransistor mechanics is a simple analog to a bipolar transistor. The phototransistor works exactly like a normal bipolar, except for the fact that the base current is replaced by a 'light current' - incident photons are turned into electrons in a semiconductor junction, essentially providing the base current. Thus, when no light of the right wavelength is incident on the phototransistor, there will be no current flowing through the phototransistor. When there is a large amount of incident light, the phototransistor will go into saturation. Thus, combined with a resistance, this will give us a voltage signal.

If we have the object hovering in the beam, we can see that this will result in negative feedback: if the object rises too high, the current will decrease, and the voltage level we observe will decrease, which we now know should decrease the current through the coil, which will cause the object to fall - thus, we have a restoring force. On the other hand, if the object falls too low, the current through the phototransistor will increase, and the voltage that we read across a resistance will increase, and thus the current through the coil can made to increase in our feedback system, picking the object up.

3.3 Circuit

Figures 3 and 6, which are attached, show the schematic supplied in *Electronics Now* [2] for this circuit. We can see that the circuit can be divided into several subsections. A block diagram for the circuit is shown below:

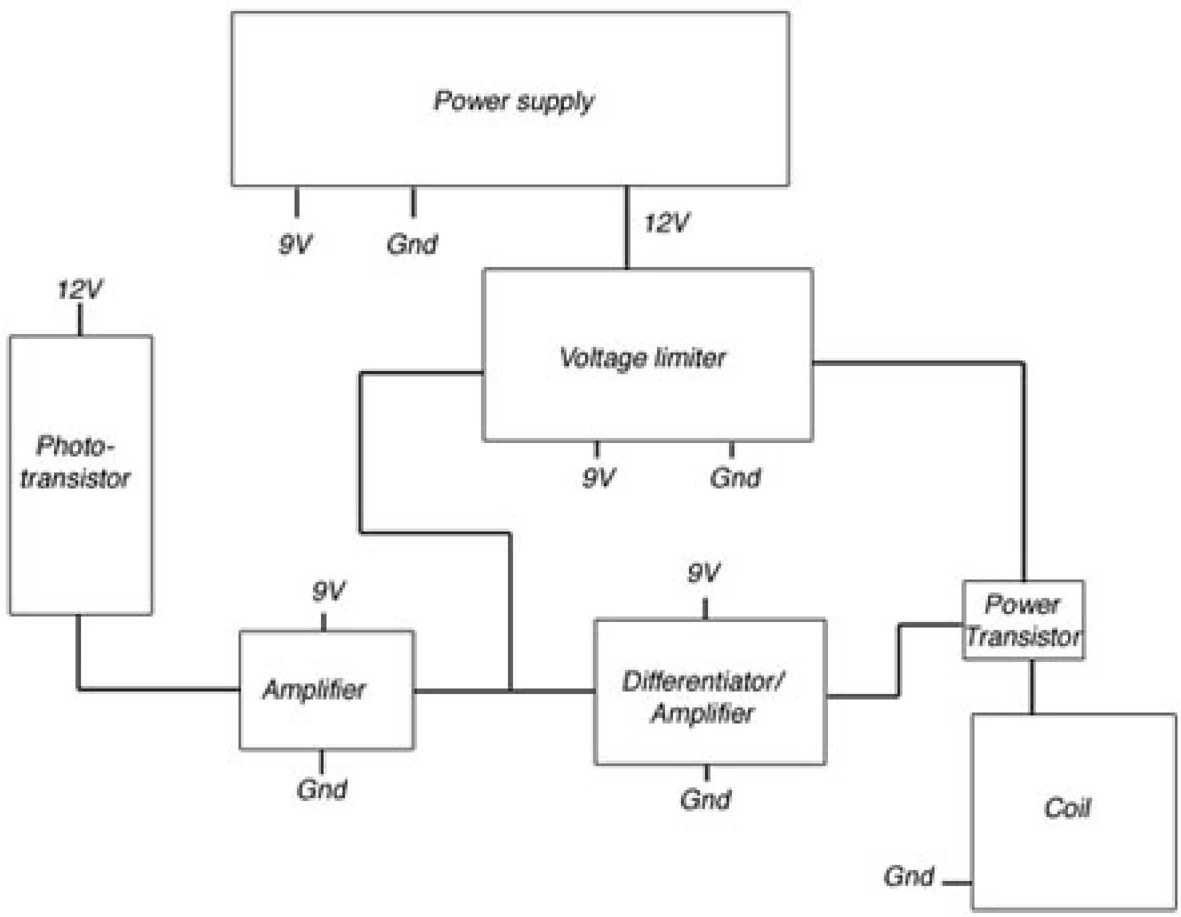

Figure 2

Now, looking at the circuit, we can tackle each block component one at a time. For instance, looking at our power supply, this block diagram block contains the transformer, which outputs a 12V line and a ground line. We use a large capacitor to filter AC signals out of this, by connecting it between the high line and ground. We also have a power

[2] Williams, David; *Electronics Now*; February 1996; pgs 33-4, 67-70

regulator, the LM78L09 integrated circuit, which takes in the high line (12V) and ground, and outputs 9V. We also filter the 9V output of the regulator by connecting a smaller capacitor between it and ground.

The block labeled as the phototransistor contains the phototransistor and LED pair, which also have associated connections to V_{cc} and ground, or a signal output. This component simply outputs a voltage from the phototransistor which increases as the amount of the beam from the infrared LED which is unobscured increases. The output of the phototransistor connects through a variable resistance to ground, which allows for calibration.

The first amplifier simply serves as a buffer and a non-inverting amplifier, with a gain of two.

The block labeled as a voltage limiter has two special properties. We want this subcircuit to detect the level of the output of the first operational amplifier, and only allow current to the power transistor for the coil should it fall within a certain range of values. This will have the desirable effect of turning off the coil should the object rise too high and completely block the beam to restore it to the feedback range, or turning off the coil if the object falls below the beam, at which point the magnet is probably not strong enough to recover the object, and will thus conserve power through the coil.
This accomplishes these goals with the use of several bipolar transistors. We can see that the PNP 2N3906 transistor (Q4) will conduct should the line coming from the first operational amplifier rise a diode drop above the voltage at the base. The base voltage is around 2.1V, which means that this transistor will go into conductance should the signal rise above 2.8V. This has the effect of driving a base current into the NPN transistor (Q3) with a base connected to the collector of this first PNP transistor (Q4), which means that the NPN (Q3) will go into conductance when the first transistor (Q4) goes into conductance, leading to the signal line being pulled to ground, which will ensure that the second NPN transistor (Q2) will not be in conductance.
If the signal line falls below 0.7V, a diode drop above ground, the NPN transistor (Q2) with that line feeding to it's base will not conduct. Thus, that transistor (Q2) will only conduct if the signal line is between 0.7V and 2.8V. When that transistor is in conductance, it will pull a base current through a resistor from the PNP transistor between the supply and the power transistor (Q1), in effect acting as a switch, connecting the supply voltage to the power transistor only if the signal voltage is between 0.7V and 2.8V.

The combination differentiator and amplifier controls the current flowing through the power transistor. This is formed by taking the signal from the first amplifier and connecting it to the non-inverting input of an operational amplifier through a resistor and capacitor in parallel. The resistor will pass DC signals, whereas the capacitor will pass AC. We know that using a simple resistance here would lead to a simple amplifier, and using a simple capacitance would lead to a differential amplifier. Instead of diving into a complete mathematical derivation, it is simpler to just think of this combination as a combination of the known devices. We also can see that this operational amplifier will have a very large gain, from the resistances connected between the output and the inverting input, and then to ground. The output feeds through a small resistance into the base of the NPN power transistor, giving it a base current proportional to both the signal from the phototransistor and the derivative of the signal from the phototransistor.

It is desirable to have both direct feedback and differential feedback. This allows for a stronger restoring action if the object moves from equilibrium as we will have the negative feedback from the position change, and can have a very strongly negative feedback from the velocity. We don't have to worry about the differential feedback system throwing off levitation at equilibrium as it should be a roughly constant voltage signal.

Another important feature of this circuit is the two separate supplies. The large capacitor between the 12V line and ground has the additional benefit of providing line stabilization should the high current through the coil pull the supply low. The regulator also helps to isolate the circuit components, such as the operational amplifiers and transistors, from possible supply spikes.

4 Equipment

4.1 Integrated Circuits

- LM78L09 9V DC Regulator
- LM358N dual Op-Amp

4.2 Transistors

- 2N2907
- 2 × 2N3904
- 2N3906
- TIP41A
- IR phototransistor (Jameco #112176), nominally sensitive at 940nm

4.3 Resistors

- 82Ω
- 560Ω
- $4 \times 1k\Omega$
- $2k\Omega$
- $3.3k\Omega$
- $12k\Omega$
- $2 \times 100k\Omega$
- $150k\Omega$
- $360k\Omega$
- $470k\Omega$

4.4 Capacitors

- 0.1 μF, non-electrolytic
- 0.22 μF, non-electrolytic
- 330 μF, 25V, electrolytic

4.5 Miscellaneous Electronics

- 1N4001 Si diode
- IR LED, nominally with a peak at 940nm
- KUP11D15 6V relay
- AC-DC transformer: 120VAC to 12V DC, 500mA DC
- Miniature toggle switch
- Small heatsink
- 10K knob potentiometer
- Terminal strip
- Wiring

4.6 Mechanical parts

- Wood and wood screws for mounting structure
- Small steel sphere, approximately 0.75mm in diameter

4.7 Parts replacements for later modifications

- Additional 1KΩ resistor instead of the 560Ω
- 1 MΩ resistor instead of the 2.2KΩ
- 100 KΩ variable resistance instead of the 10KΩ
- Random LED

4.8 Tools needed

- Computer, with Eagle layout designer
- Circuit printing equipment
  - Unexposed boards
  - Light box or strong fluorescent lamp
  - Developer
  - Etchant
  - Jeweler's drill press with very small bits
- Soldering iron
- Wire cutters and strippers
- Woodworking tools
  - Band saw
  - Drill press
  - Screwdrivers
  - Clamps

5 Procedure

The procedure for the assembly of the electromagnetic levitator can be reduced into several subsections: the design, printing the circuit board, assembling the circuit, and constructing the mounting.

5.1 Circuit Design

As mentioned earlier, the basic design of the circuit was found in *Electronics Now* [3]. The original design was initially implemented. The computer program *Eagle* was used to represent the schematic and print the boards. The circuit design, board layout, and board traces printout are attached for each of the two boards to be printed as Figures 3-8.

5.2 Printing the circuit board

Two circuit boards were printed as shown in the attached figures using the photoengraving method of PCB construction. The trace layouts were printed onto transparencies, which were placed above a purchased board and exposed, which removed the positive photo resist in the regions not covered by ink on the transparency. Then the board was developed, etched, and drilled.

5.3 Assembling the circuit

Components were soldered onto the boards as shown on the board layout diagram. Care was taken with the two 2N3904 transistors, as when constructing the layouts in Eagle, there was no library file for that particular NPN transistor, so a PNP transistor of the same package was used, which made the pinout reversed with respect to the collector and emitter.

5.4 Constructing the mounting

The mounting was constructed from scrap wood in the college wood shop in an afternoon, mainly without a specific design. The only real purpose that it need serve is to provide a stable mount for the coil, phototransistor board, and LED board, such that the beam between the phototransistor and LED is vertically below the coil, and that the coil is mounted vertically. My design, which can be seen in an attached photograph, has the additional benefit of providing a place to mount the terminal strip and the main board.

6 Analysis

When the board was first constructed, some design flaws were revealed. The voltage observed at the output from the phototransistor did not vary with varying incident IR light. Experimentation on a bread board with additional components revealed that the transistor was reaching it's saturation current even at background, which obviously led to no change in signal. I was unable to find a good data sheet for the transistor I was using, and thus approached the problem from an experimental angle. After trying differing

[3] Williams, David; *Electronics Now*; February 1996; pgs 33-4, 67-70

values of the resistance in line with the phototransistor, and different values for the variable resistance, I settled on a $1M\Omega$ resistance and a $100K\Omega$ variable resistance, which I thought provided the largest range.
This combination gave me a range in output voltage signals of approximately 0.3V. I was able to improve this by adding a series diode, and adjusting the level lower with the variable resistance. The diode that I used was a visible light, white, LED from a drawer in the college electronics lab. Nominally, this will have a diode drop of around a volt, but since there is not much current flowing through it the actual drop is closer to 0.2V, which is desirable. While this did not increase the range directly, this improved the levels that I was getting out of the amplifier, with adjustment of the calibration potentiometer. However, even thought this provided enough of an improvement to achieve stable levitation, the signal range should be greater than I was able to get out of this setup. I think that the model phototransistor which was used may be at fault, and perhaps one with a larger saturation current could fix this flaw.

I also observed that the value of the series resistance with the infrared LED was small enough that the model LED I had was burning out quickly due to too much current. I thus replaced the 560Ω resistor with a $1K\Omega$.

New schematics with my modifications are attached as Figures 9 and 10. The previous board layouts and trace routings are still valid for these if you are willing, as I was, to solder the lead from the phototransistor board to a lead of the diode.

Two pictures of the levitator with a small steel sphere in a stable equilibrium are attached, as well as a picture of the entire assembly.

7 Conclusion

With some impromptu modifications to the original design from *Electronics Now*, I was able to achieve levitation, using a small steel sphere as the object to be levitated. This can be seen in the attached photographs. The design for the levitator is simple enough that comprehension is accessible to people who are familiar with just bipolar transistors and operational amplifiers. The actual construction of the circuit is substantially more finicky - in particular the signal from the phototransistor and the voltage level detector and limiter gave me substantial trouble during my construction troubleshooting.

In particular, the PNP transistor used as a switch between the power transistor and the supply seems to have a tendency to break from unknown causes, although I speculate that a large V_{BE} caused by some human action during troubleshooting may have, at some point, reverse biased the base-collector junction. Also, the voltage signal from the power transistor did not have a large enough range to achieve stable levitation without substantial experimentation and tweaking.

I believe that this circuit has substantial applications as a very neat demonstration for an electronics, introductory mechanics or electromagnetism class, but actual construction from scratch should not be attempted by electronics students excepting the case where it is done as a substantial project, as here. I estimate that the entire project, even with the substantial guidance of the article in *Electronics Now*, took between thirty five and forty hours, including time spent on subtasks, such as learning to use Eagle to input the schematic and design a board layout. With the information contained in this paper and the board layouts I have constructed, especially the trace diagrams, this resulting setup could be reproduced in much less time, perhaps in ten to fifteen hours. With a provided printed and drilled circuit board and mount, I estimate that this circuit could be constructed and functioning within a long student lab session.