Levitator

Coil

The coil is wound on a ¾inch bolt, with the coil length and outer diameter of 3.0 inches and 2.6 inches. The coil is wound overlapping the turns (not close fit, which is nearly impossible without a jig or a lot of time). The wire is #20.5 (where do you get that? On ebay of course!). It measures 11 ohms, so it must be about 1000 feet. It would work out to roughly 2000 turns if wound with the close fit method, and might have an outer diameter of about 2.2 or more inches. I did not count the turns, I did it with an electric drill.

The wire diameter is fairly critical for inductors, because the total resistance varies as a fourth power of the wire diameter. This can be seen by envisioning two cases. Take a cross section of the coil which includes just one wire, in coil A. Lets say its a square wire for simplicity. Now for coil B, lets divide that wire into four smaller squares. That is to say that the diameter of the wire is now half of coil A. The number of turns goes up by four (keeping the dimensions of the coil the same). Also, the resistance of each foot of wire goes up by four, because the resistance is inversely proportional to the area. So, the total resistance of coil B is 4 x 4 = 14 times as high as that of coil A.

It's nice to work with circuits like this in the general region of 1 to 2 amps, and 10 to 24 Volts or so. So, for a given coil dimension, pick a wire diameter that results in an appropriate resistance. It turns out that the power (in watts) delivered to a coil effects the magnetic pull in a way that is independent of the wire diameter. There are formulas for this at websites for coilguns, whose hobbyists have spent a lot of time optimizing coils. See the following links for information on coils:

http://www.oz.net/~coilgun/home.htm , Barry's coilgun site
http://mgc314.home.comcast.net/coilparameters.htm
Copper wire data can be found at http://mgc314.home.comcast.net/wirechart.htm.

I have done a spreadsheet which allows you to enter the inner and outer diameter of the coil, the length, the wire size, and shows the resistance, ohms/foot, length of wire and so forth. Email me at b.arntz@verizon.net if you would like it. I can't vouch for its accuracy, but it does correlate to some of the calculations on the coilgun sites, where I got the formulas. My spreadsheet is in inches whereas some of the other sources show dimensions in mm and cm.

Magnets.

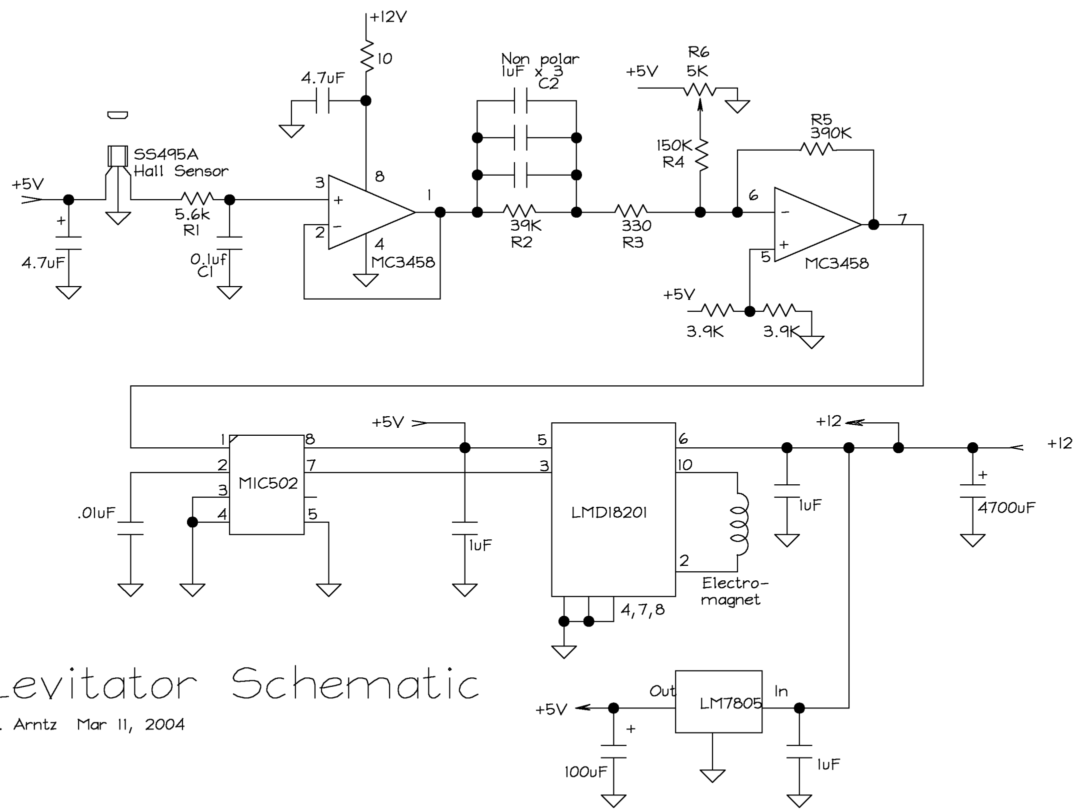
Three neodymium iron boron (NIB) magnets from Amazing Magnets.com, 0.75 x 0.25 inch, about $2.40 each. If you have never used NIB magnets you are in for a big surprize. They are the strongest things going and you can pinch your fingers like a pair of pliers would with the larger ones.

Floating Object

The floating object is a stripped down VCR head and spindle, with two NIB magnets on the ends. The lower magnet is for the Hall sensor. I had serious stability problems when putting the Hall sensor under the electromagnet, so I decided to separate the position measurement function from the lifting function. The distance between the two lifting magnets is about 1.4 inches, and the distance of the lower magnet to the Hall sensor is about 0.95 inches. There is a cork under the top magnet to keep from breaking them (really) when they slap together.

Circuit.

See the schematic. The fan controller IC and bridge switching IC form the heart of the controller, and is an elegant design by Guy Marsden, who inspired my project. The fan controller acts as a pulse width modulator, which is a much more sophisticated method than using a fat Class A transistor for the output. The bridge IC operates in push pull mode so the electromagnet can push and pull. At rest, the NIB magnets hold the weight. The electromagnet only applies correction. When adjusted and at rest, there is a square wave across the coil. Because of the inductance, the AC part of the signal does not actually make its way into the coil. The only part that does is the DC part, when there is an offset and the wave is now rectangular.



This way it remains cool, drawing maybe 0.25 amps or so DC, typically. It can sit there all day like that. The bridge IC has internal diodes for shorting out the otherwise destructive spikes from the electromagnet during the 1 kHz switchover.

The first op amp is a buffer, because if you look at the hall sensor specs, the output impedance and drive capability are not well defined. R1 and C1 keep spikes out of the op amp. Even though the hall sensor is several inches from the electromagnet, some switching spikes reach it, because of the large coil dimension.

The coil inductance was measured at 84 mH (.084 H) at 1 kHz. This inductance along with the 11 ohm resistance would yield a frequency pole of 20 Hz. However, tests of the loop showed a pole at 4 Hz, going out at least past 100 Hz and I'm sure it's from the electromagnet (the tests were of just the fan IC, bridge, electromagnet, and the Hall sensor, with the loop open). I suspect that the winding capacitance of the 1 kHz inductance measurement affected it, and that the true inductance is really much higher than 84 mH.

So, given a pole at 4 Hz, and two integrators from the basic mechanics of "position is the second derivative of force", there is definitely a need for damping and/or a lead network. This is formed by R2-C2. C2 is actually three caps in parallel because they have to be non polar, and 1 uF is as large as I had. I did a lot of experimenting with these, as well as overall gain selection by R5. The gain and damping are very dependent on the distance to the Hall sensor. I would have liked the distance to the sensor be larger, for visual reasons. I think by increasing R5 (or decreasing all the elements that feed pin 6 of the second op amp), the electronic gain could be increased and the distance could likewise be increased.

The second op amp sums the phase-leaded position with an offset pot R4, which is set so that the average DC voltage across the coil is near zero. This can be used to change the height of the floating object over a range, but the current will go up.

The vertical damping is very nice. When you pull down on the weight you can feel a velocity dependent force in the opposite direction (that is, a squishy feeling). The effect is the strongest when the gain is high. The vertical damping is overdamped and takes several seconds for final settling.

There is a lot of bypassing, which may be overkill, but I was having spikes and funny oscillations, so I put lots of caps in, and a big 4700 uF on the +12V. There is a heat sink on the bridge IC, but it does not get warm at all.

Damping.

A peculiar aspect of this arrangement is that there was torsional instability. That is, the upper magnet on the floating object would move left and the lower magnet would move right and v.v. This happens at 5 to 10 Hz, for reasons not known, but seem to have to do with the way the magnets pull harder when offset. If you were to start off by steadying the object by hand, small oscillations would develop and within a minute, the object would fly off the stand. The solution to that was a ½thick piece of copper (onlinemetals.com) under the lower magnet. Being nonmagnetic, it does not affect the static magnetism for the sensor. I don't think (but I am not sure) that it affects changes in the field due to vertical magnet movement, only horizontal. It works really well. Its rock solid and settles in a second or so to external disturbances. By the way, if you drag a NIB magnet across a thick piece of copper you can feel the eddy current drag quite nicely. Or, try dropping one of the little coin cell size NIB magnets down a piece of ½ inch copper tubing. It drops real slow.

The “pull zone” or sweet spot of the system is maybe a half inch, depending on the position of pot R4. You can lay pieces of wood on it, and it gets lopsided, but its still very stable. You can spin it and it just goes forever. I have had more fun with this thing than anything I ever built.

March 11, 2004
B. Arntz

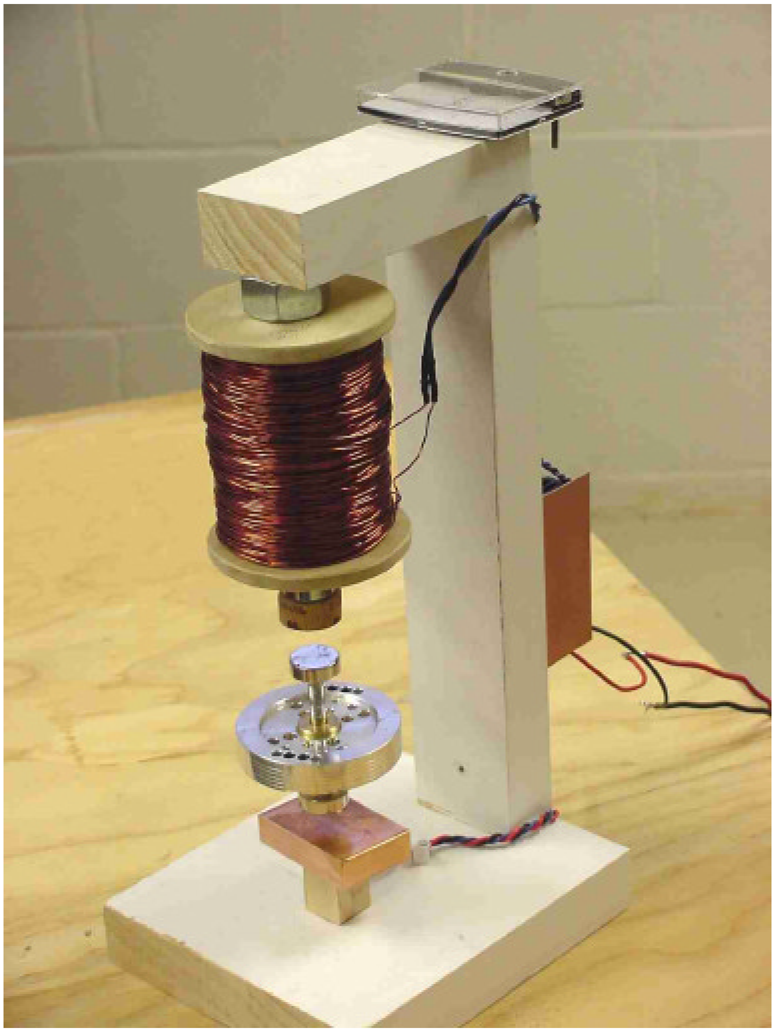


Figure 1. The meter on top is connected across the coil, to center the amount of lift.

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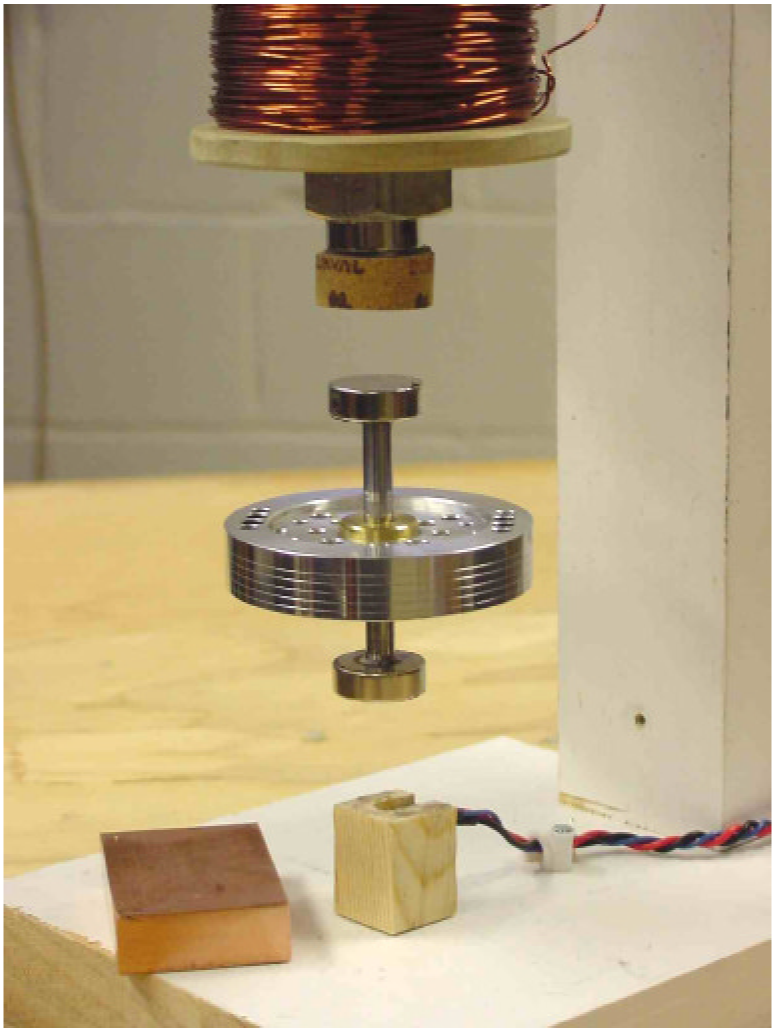

Figure 2. Copper damper removed.