Nail Coil Gun

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Abstract

This paper covers the design of the Nail Coil Gun. The main purpose of the design is to fire a nail using stored energy from a capacitor released through coils in two stages. Charging and discharging was achieved during the design of the gun, and work is continuing so that a projectile can be fired.

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1. Introduction

1.1 Purpose

The Nail Coil Gun project attempts to fill a void in the nail gun market of coil gun based nail guns, while using the advantages of the coil gun to solve some problems associated with conventional nail guns. Traditional nail guns use compressed air, explosive gases or charge, or an electric motor. The disadvantage of the pneumatic nail gun is the hose and extra equipment, like a pump, that has to be on site at all times. The explosive gas nail gun gets rid of the need of the hose, but must be regularly cleaned and is very loud. The regular electric nail gun solves the problem of having to clean the gun, but is heavy due to the motor, and must be plugged in.

The gun consists of two stages, assuming 50% efficiency per stage, in order to launch the nail at 200m/s. To fire at this speed, each stage will have a 680uF, 350V capacitor. Each capacitor is charged by a boost circuit stepping up a 12V input into the desired voltage, and the MOSFET in the boost circuit will be controlled by a MOSFET driver which gets its signal from a 555 astable oscillator. The discharge of the energy from the capacitor to the coil is triggered by infrared sensors.

1.2 Benefits and Features

1.2.1 Benefits

- No moving parts, which increases the life of the gun
- No hose or extra equipment besides the batteries making it conveniently handheld
- No cleaning or maintenance required, making this gun easy to use.

1.2.2 Features

- Infrared LED switches to trigger coils, for simpler cheaper circuits

Safety feature in circuit to prevent charging capacitors past 350V

1.3 Block Diagram

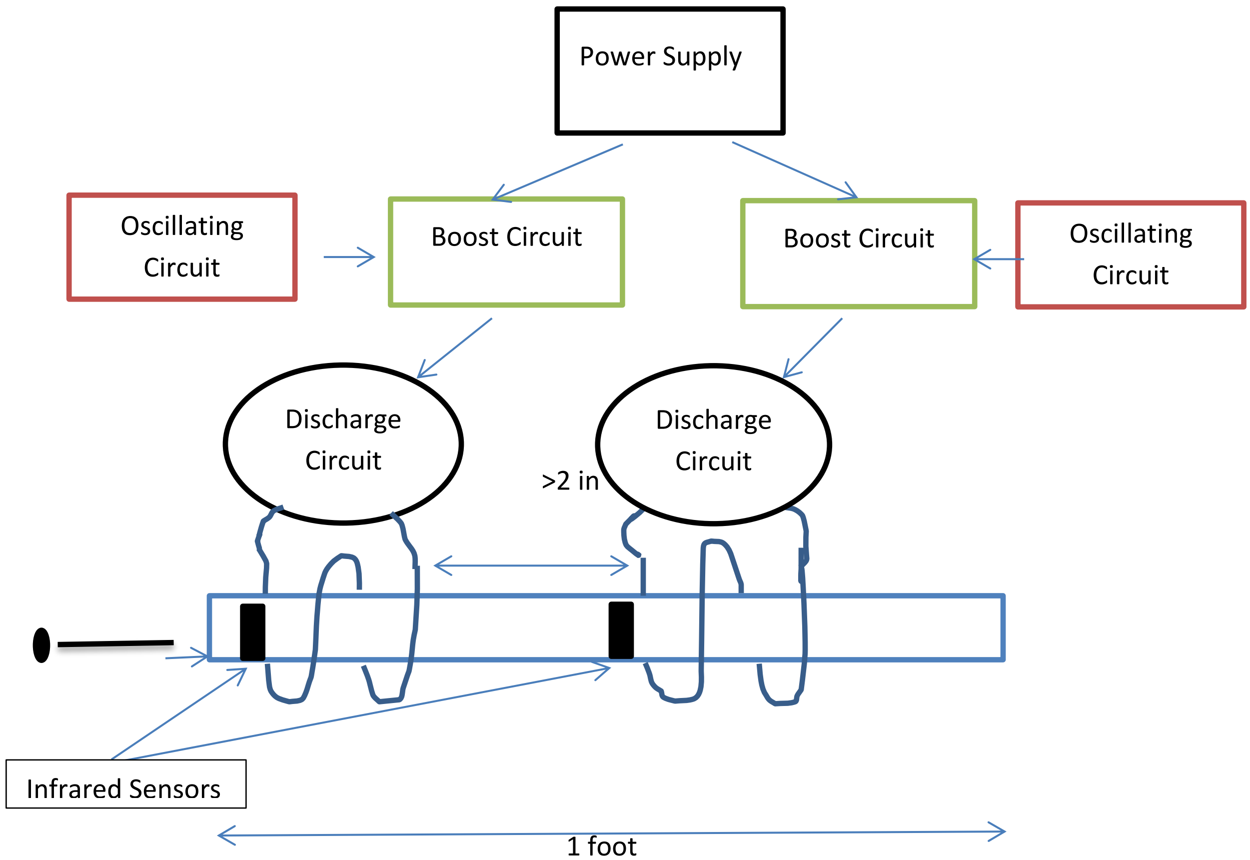

Figure 1. Nail Coil Gun: A connection not shown in this diagram is the SCR from the charging circuit to the inverted output of the infrared sensor.

1.3.1 Individual Block Descriptions

- Power Supply – A 12V power supply was needed for the boost circuit. Originally we were going to use lead acid batteries but we drained too much of the power during testing. During the demo we used a power supply. The LM555, MOSFET driver, and the LM2904 op amp all needed 5V, so a 78L05, 5V regulator was used. The reference voltages for the op amp were 2V, so a LM317 variable voltage regulator.

- Oscillating Circuit – This is the signal that drives the MOSFET. The LM555 produces a 2kHz square wave. The 555 timer does not source enough current to drive the MOSFET alone so a MOSFET driver is used to amplify the signal. The output of this circuit is a 5V, 2kHz square wave.
- Boost Circuit – This circuit is a boost converter with a 12V input and 350V output. The output capacitor is a 400V, 680uF capacitor so it can store 40J of energy. The inductor used in this circuit is about 35mH. There is 500kΩ resistor in parallel with the capacitor so the capacitor can discharge in approximately 13 minutes when it's not in use. To prevent the capacitor from charging to above 350V the bleed resistors are also used as voltage divider for an input into the op amp.
- Discharge Circuit – When the sensor sees a nail the gate of the SCR is triggered which allows the energy from the capacitor to discharge into the coil. Then the nail should shoot.
    - Sensor – The original signal from the sensor goes from high to low when it's blocked. The op amp was used to invert this signal to trigger the SCR.
    - Coil –. The two coils are the main component of the gun, and are what supplies the magnetic field to pull/push the nail through the barrel. The inductance of the coils is 20uH each.

2. Design

2.1 Initial Calculations

2.1.1 Energy and Capacitance

The first task in creating the nail gun was finding the speed required of the nail. The speeds of nail guns range from 1400 m/s on the high end to 150 to 200 m/s on the low end. It was decided that to design the gun to shoot the nail at 200 m/s. A nail with a mass of 2 grams would need at least 40 joules according to the equation below.

$$KE = .5mv^2 = .5(.002)(200)^2 = 40joules \quad (1)$$

Using this energy, the corresponding capacitance can be found from the equation for the energy stored in a capacitor. Using the desired value of 350V, the capacitance is found in the following equation.

$$W = .5Cv^2 => {}^{2W}\!/_{V^2} = {}^{80}\!/_{350^2} = 653\mu F \quad (2)$$

The reason 350V was used, is because the voltage term in the equation is squared, requiring less capacitance for the same amount of energy. We want the capacitor to discharge as quickly as possible, so lowering the capacitance decreases the time constant τ=RC. This will also decrease the time needed for charging the capacitor. Due to availability we used a 680uF capacitor rated at 400V, which will store 41.65 joules.

2.1.2 Power

The power was the next important parameter that had to be considered. For the following calculations we will assume the initial speed of the nail going into stage one from the ignition coil is zero. This is because the initial speed of the nail will be so small it can be neglected. If we assume an effective length of acceleration as 3.5 inches, we can calculate the acceleration of the nail. This distance is chosen as an estimate of the distance that the nail will experience acceleration. If we estimate the length that the nail experiences a force as 3.5 inches for each stage, then we get a distance of 7 inches or 17.78cm. Using the using the following kinematic equations we get our values:

$$v_f^2 = v_i^2 + 2ad => (200)^2 = 0 + 2a(.111) => a = 112{,}500 m/s^2 \quad (3)$$

Using this acceleration, estimating to 112,500 m/s^2 for ease of calculations we find the following:

$$v_f = v_i + at => 200 = 0 + (112{,}500)t => t = .001778s \quad (4)$$

Therefore, our capacitors must discharge in half of the 1.778ms calculated above. This is equal to about 5 time constants of the RLC circuit. Since we assumed 50% efficiency the total discharge time is 3.556ms. Therefore using the equation for the time constant above, it can be seen that the equivalent resistance seen by the capacitor discharging into the coil will be about .5Ω. The resistance chosen for the output will be 1 ohm instead, which will help account for the inherent losses in the components and also keep the current from spiking to high. The power can now be found using the following equation:

$$Power = Fv = \frac{mad}{t} = \frac{(.002)(112{,}500)(.1778)}{.001778} = 22{,}500\ watts \quad (5)$$

2.2 Oscillating Circuit

We started designing the oscillating circuit by simulating different square waves with the boost circuit which is discussed in section 2.3. Amplitudes larger than 5V did not improve switching. The duty cycle was large was to allow the capacitor to absorb the maximum amount of energy in each cycle. However, at higher duty cycles the MOSFET did not behave properly. Therefore, at least a 5V peak to peak wave form at a 95% seemed to allow the best switching for the MOSFET. Switching a MOSFET at high frequencies could damage the part, so we kept the frequency at 2kHz and made up for it with the largest possible duty cycle [6].

To create this square wave we considered different oscillators such as the AD2S99 programmable oscillator, but these parts were not readily available. The LM555 timer was a familiar analog wave form generator that could be found in the ECE Electronics Service Shop. The amplitude, duty cycle, and frequency were easily controlled with the LM555. If we needed to the any of those factors it was done easily.

The design was based off of the NE555 [2] design specifications for astable operation. The calculations are done below.

$$\frac{t_H}{t_H+t_L} = .95 \tag{6}$$

This value was chosen so that $t_H \gg t_L$.

$$.95 = 1 - \frac{Rb}{Ra+2Rb} \tag{7}$$

$$Ra + 2Rb = 1\text{k}\Omega \tag{8}$$

$$Ra = 900\Omega \quad Rb = 50\Omega \tag{9}$$

One kilo-ohm was chosen so that the frequency could lie anywhere between 10Hz – 100kHz. To get to the frequency to 2kHz the capacitance for C2 = .67uF. The output of this circuit is than amplified by the MOSFET driver. Figure 3 in section 2.6 shows the oscillating circuit.

For the actual circuit 909Ω and 56Ω are used instead 900Ω and 50Ω respectively. Figure 4 is the output of the oscillating circuit. The top (yellow) wave form is the 555 output. The bottom (green) wave form is the MOSFET driver output.

Figure 4 above shows that the output of the MOSFET driver is 8.3V. On the actual PCB with larger components drawing more current, the MOSFET driver output was actually 5.3V which was the needed peak to peak voltage to drive the boost circuit.

2.3 Boost Circuit

For the boost circuit we needed to charge a fairly large capacitor to high voltage in a reasonable amount (less than 2 minutes). We started with a transformer design. To get the voltage on the capacitor up to 350V we needed an input voltage of 20V and a transformer ratio of 10uH to 10000uH. Transformers of this size were physically large and expensive and winding our own transformer would have been tedious and time consuming. Even though the charging time with the transformer was faster, a boost converter in CCM mode was chosen. This way the capacitor could charge up to 350V at lower input voltage (12V-15V) [11].

In the boost circuit the capacitor is charged to 350V. A 600V rectifier diode, 600V Vds NPN MOSFET, and a 400V capacitor are used in the actual circuit. The oscillating circuit output is connected to the gate of the MOSFET and this drives the boost circuit. When the MOSFET is an open the charge stored in the inductor is dumped into the capacitor. A simulation of the charging curve is in Figure 7.

2.3.1 Bleed Resistors

The resistors in parallel with the capacitor serve two purposes. The first is they are bleed resistors. With 500kΩ resistor the capacitor would discharge to 35V in 13 minutes when it's not in use. Also, since 500kΩ is a high resistance, the capacitor wouldn't charge too slowly.

$$35 = 350e^{-t/_{RC}} = 350e^{t/_{(.00068*500000)}} \tag{10}$$

$$t = 782.88s = 13.05\ minutes \tag{11}$$

Second, we used the resistors as voltage divider. The output of the voltage divider was the input of the LM2904 op amp. For the second resistor we used a variable resistor to tune exactly when we wanted the capacitor to stop charging. When the capacitor reached the desired voltage the 555 was shut off and the capacitor slowly began to discharge. When is discharged past the reference voltage of 2V the capacitor charged back up to the desired voltage.

2.3.2 Inductor

Our initial design called for a 21uH inductor. During breadboard tests it was discovered that this inductance was too small to charge the capacitor up in a reasonable amount of time. After trial and error we found that the optimal inductance was 35mH. We found that any inductance above this caused the cores to saturate.

2.3.3 Charging Time

The charging time depended heavily on the frequency and the inductor. We chose a 2 kHz signal for our circuit, a higher frequency would have imposed higher switching losses. Through some trial it was found that a 35mH inductor allowed the charging time to be on the order of 1 minute. The actual charging time can be found as follows:

$$W = \frac{1}{2} * \frac{V_{bat}^2}{L} D^2 * T^2 = \frac{1}{2} * \frac{12^2}{35mH} * .95^2 * \frac{1}{2000} = .928 joules \quad (12)$$

$$Charge\ Time = \frac{41.65 Joules/Capacitor}{.928 joules} = 44.9\ seconds \quad (13)$$

There is an error of 26.67% between the measured time of one minute and the calculated time of 44.9 ms, but this error is most likely due to resistances in the windings and the circuit.

2.4 Discharge Circuit

The design for the discharge circuit varied very little from the beginning of the semester. Using a sensor to trigger the SCR was the simplest way to integrate the sensor into the discharge circuit. The only addition was the op amp used to invert the sensor signal.

When the sensor sees the nail the gate of the SCR is triggered from 3.6V output of the op amp and the energy from the capacitor is discharged into the coil which induces a current in the nail. This current forces the nail forward. Figure 8 is the simulation for the discharge circuit.

2.4.1Coil

The inductance of the coil was found using the simulator on Barry's Coilgun Design site using our values of current, voltage, resistance, and capacitance [9]. The inductance of the coil was 20uH based on 680uF capacitor and 350V max voltage. The circuit is shown in Figure 6.

2.4.2 Sensor

The original signal from the sensor went from high to low when the led was blocked. To invert the signal we used the LM2904 op amp. The delays associated with the sensor and the op amp were tested and the results are shown in Figure 9. The sensor worst case delay was 440us which compared to the discharge time of 4ms is negligible.

The reference voltage (in the non-inverting input) for the op amp was 2V. So we used a AAA battery on the output of the sensor. The negative terminal of the battery was the inverting input of the op amp. A diagram of the hook up is shown Figure 10.

2.5 Modularity

There are two stages that will each have their own PCB with the components described above, and one power source consisting of two sealed lead acid batteries will power the whole device, with one AAA for the sensor. Also the main coils and the sensors will be on the tube, and will be soldered into the PCB boards. This allows for simpler troubleshooting, and allowing smaller cheaper components to be used instead of needing to withstand much higher currents and voltages. Also the nail can only withstand so much magnetic flux before it is saturated, so separating the stages allows the this to be split up between the stages, and prevents extremely high accelerations, which would occur with one stage.

2.6 Figures

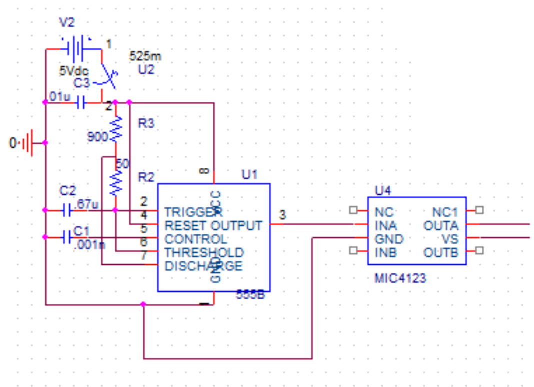

Figure 3. The Oscillating Circuit

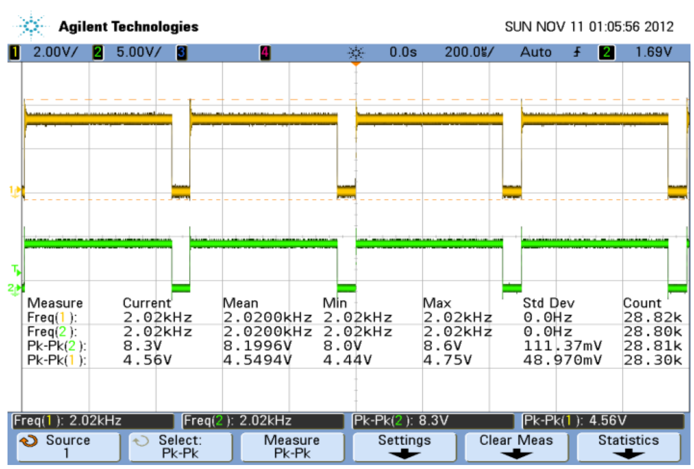

Figure 4. Oscillating Circuit Output

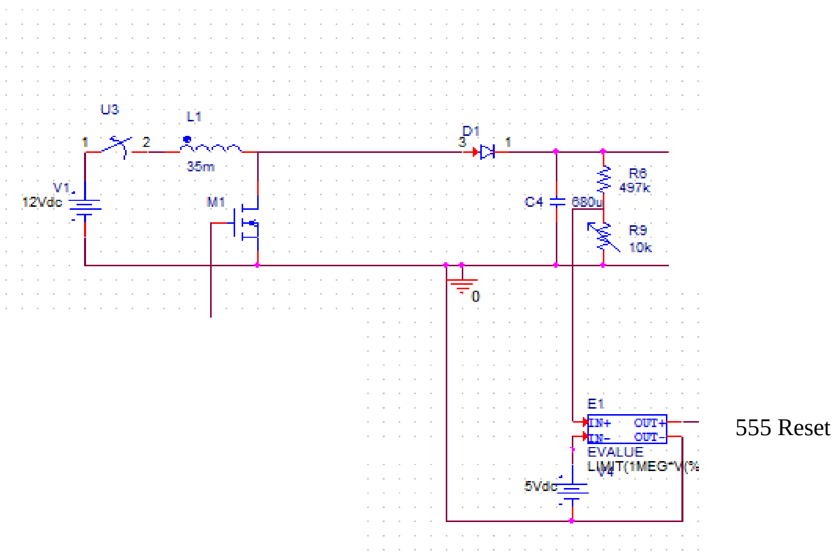

Figure 5. Boost Circuit

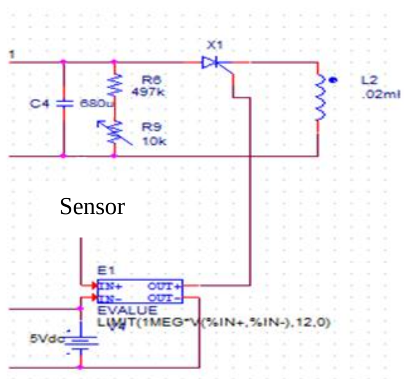

Figure 6. Discharge Circuit

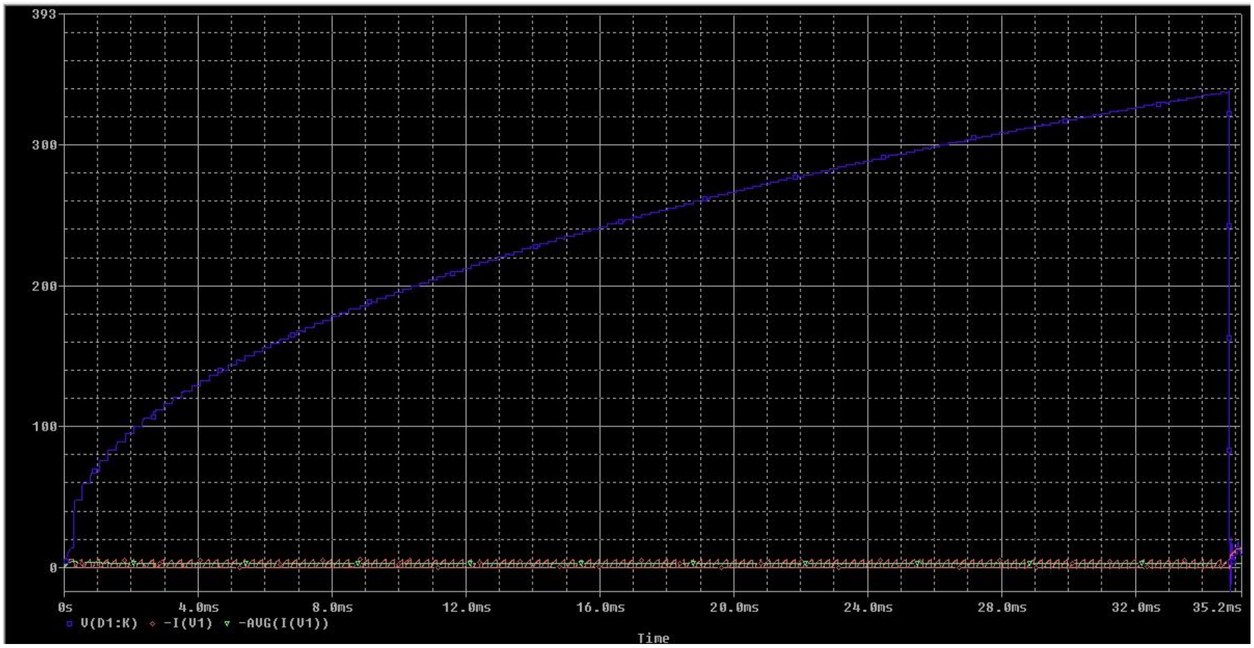

Figure 7. Charging Curve

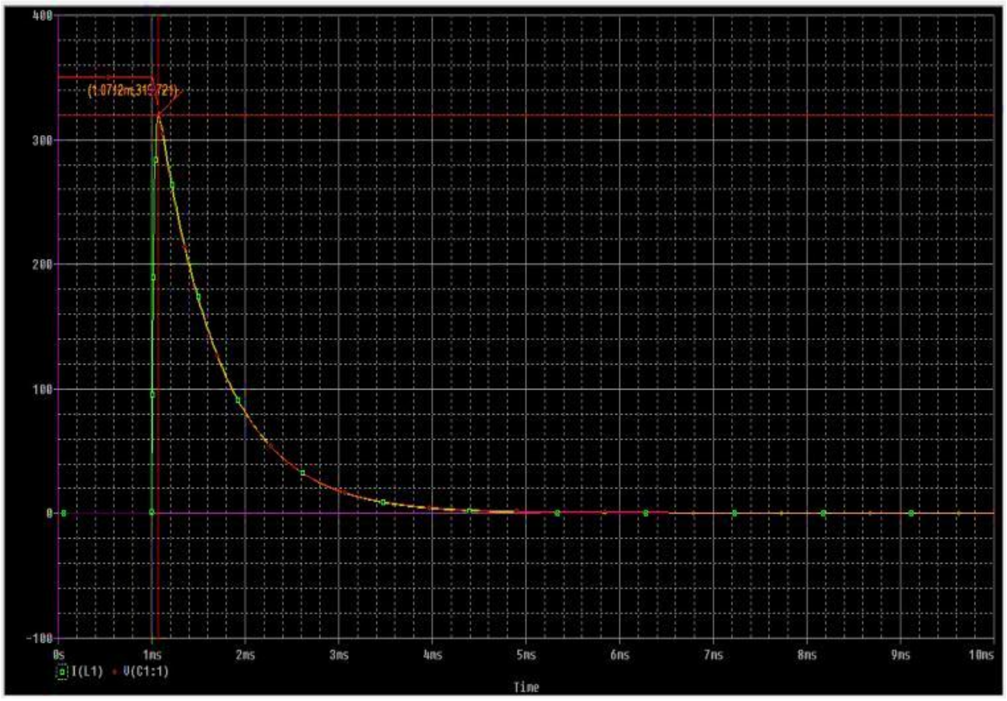

Figure 8. Discharge Curve: The peak current in the coil is 320A

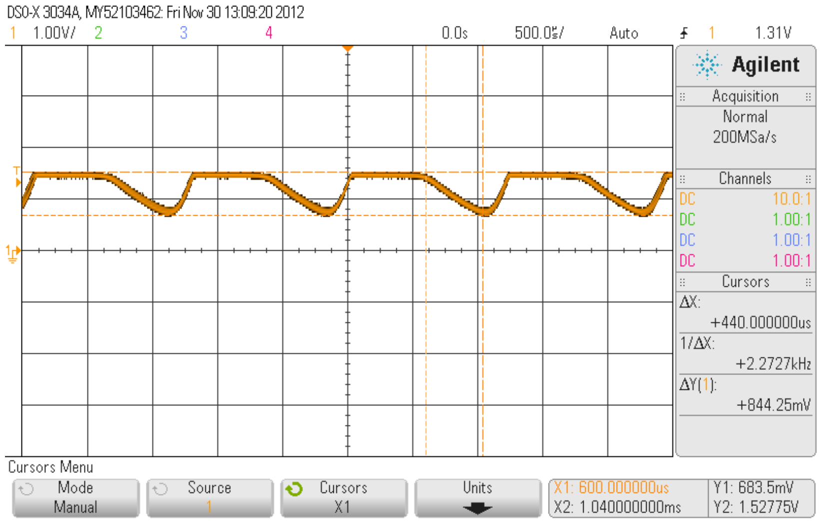

Figure 9. Sensor delays

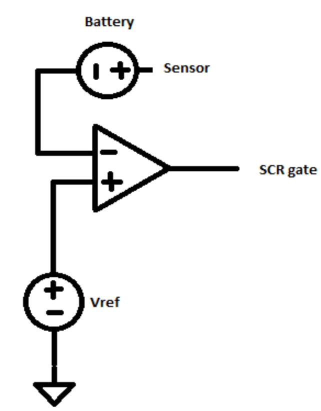

Figure 10. Inverting the sensor output

3. Verification

Our requirement and verification table details the process for complete testing of the circuit, and is located in Appendix A.

3.1 Power Supply

To test the power supply, we probed the voltage output of the 5V regulator and the 2V regulator and made sure these voltages were seen by the logic circuits. Also 12V had to be supplied to the boost circuit.

3.2 Oscillating Circuit

The 555 timer had to output a 2 kHz square wave at 5V peak to peak. This signal then had to be amplified to 5 to 8V by the MOSFET driver. A probe on pin seven of the MOSFET driver will show full functionality of oscillating circuit.

3.3 Boost Circuit

To test the boost circuit we used two 12V lead acid batteries in parallel to source enough current. This way the capacitor charged faster. We probed the cathode of the diode to ground with a high impedance probe for the oscilloscope. We did each stage separately at first then we connected the two stages together.

When the batteries discharged we had to use the power supply, which sourced too much current and damaged the MOSFETs. So when using the power supply we started the input voltage at 6V and slowly raised the voltage to 12V so that the current never exceeded 100mA. With a 35mH inductor we were able to charge the capacitors to within 10% 350V in about 1 minute.

3.4 Discharge Circuit

To test the discharge circuit we put a small resistance on the output of the capacitor. Then we blocked the sensor with the nail and using the voltmeters we saw the capacitor discharge immediately.

3.5 Failed Verification

Verification 7 failed and so the gun did not shoot. We do not know the exact cause. Possible causes are discussed in section 5.2.2. To complete this verification, we have made new PCBs. We are currently testing these boards.

4. Cost

4.1 Labor

Team Member	Hourly Wage	Total Hours*	Total Cost	Total × 2.5
Andria Young	$35	180	$6300	$15750
Seth Hartman	$35	180	$6300	$15750
			Total	$31500

*Total hours include 12 weeks of work at 15 hours/week.

4.2 Parts

Parts	Cost	Multiplier	Total
680uF @ 350V Capacitor	$6.54	3	$19.62
NPN MOSFET	$2.33	5	$11.65
NPN MOSFET**	$2.33	5	$11.65
Tubing	$0	2	$0
SCR 600V	$1.54	5	$7.70
SCR 800V**	$3.74	5	$18.70
Diode	$0.17	5	$0.85
Voltmeter	$5.00	2	$10.00
Op Amp LM2904**	.352	10	$3.52
		Total	$81.83

*Except for the PCBs, if the part is not listed above it was free.

**Parts purchased for the redo of project

Cost of Gun With Bulk Order*				
Parts	**Bulk**	**Cost**	**Multiplier**	**Total**
680uF @ 350V Capacitor	5000	$3.60577	2	$7.21
MOSFET	10000	$0.9375	2	$1.88
4mm OD Glass Tubing	2080 ft	$0.053/ft	2	$0.10
SCR	5000	$1.70	2	$3.40
Diode	5500	$0.0492	2	$0.10
Op Amp LM2904	5000	$0.10695	2	$0.21
Copper	-	$3.61/lb	.2	$0.72
555 timer	500	$0.10385	2	$0.21
5V Regulator	5000	0.62909	2	$1.23
LM 317	5000	$0.09114	2	$0.19
Sensor	1000	$1.32	2	$2.64
Inductor	10000	$0.5694	2	$1.14
PCB[12]	10000	$4.05	2	$8.10
A123 Lithium Ion Phosphate	-	$3.25	6	$19.50
Other Capcitors and Resistors**	-	~0.02	40	$0.80
			Total Per Unit	$47.43

*Doesn't include housing of gun
**Assuming Conservatively Max Cost is 2 cents per unit

4.3 Total Cost

$$\text{Parts} + \text{Labor} = \$49.82 + \$31{,}500 = \$31{,}549.82 \tag{14}$$

5. Conclusion

5.1 Accomplishments

The circuit was fully functional, except for test firing the nail, the night before the demo. The setup for firing the nail matched our expectations, because we found a tube very close to the diameter of the nail, while still allowing the sensors to sense the nail. We were able to get the boost circuit to charge the capacitors to 350V as specified. This meant full functionality of the 555 timer circuit and MOSFET driver, supplying the 2 kHz signal to the gate of the MOSFET. Although we had troubles later on with the PCB, we were able to charge the capacitor to 350V using just the sealed lead acid batteries. The comparator recognized the 350V and prevented further charging as per design. Also we were also able to discharge the capacitor after by tripping the sensor and using a resistor as the output load. We are currently in the process of rebuilding the circuits, and have ordered new PCB's and parts. Our hopes are to achieve full functionality before the end of the semester.

5.2 Uncertainties

5.2.1 MOSFET

A problem we encountered when testing was that we found that we were blowing out the MOSFETs. When beginning to charge the capacitor, there is a current spike because the inductor starts out as a short. We believe this the reason our MOSFETs stopped working. To solve this we start charging at 6V and raise the voltage slowly so that the current wouldn't go above 100mA. We never tested out limiting this current spike and using a constant 12V source.

5.2.2 Discharge Circuit

Another problem we encountered was that our discharge circuit stopped working. We believe it was because during the demo we hooked up the AAA battery incorrectly. We removed the sensors and tested them with the op amp on the breadboard and the sensor wasn't damaged, but it no longer worked on the PCB. All other functions of the circuit were working and MOSFET and SCR were behaving properly. We tested each stage separately with the same results. Because we couldn't solve problem we decided to get all new PCBs and parts.

The desired discharge time was less than half of the actual discharge time. To compensate for this we moved the coils closer together to about 2 inches. Having not been able to shoot the gun we are unsure if this change in design will allow for the gun to shoot past the first stage.

5.2.3 Sensor Hook Up

When using the AAA battery for the sensor output we thought since the voltage of the battery is 1.5V that the reference voltage would be equal to that. However the sensor/op amp hook up did not work until the reference voltage was set to 2V. We don't know why this is, but the only thing we needed to change because of this was the voltage divider output for the bleed resistors. We adjusted with the variable resistor.

5.3 Future Work / Alternatives

While working on the project several mistakes in the initial design, or more advanced ideas came up as future design options. The capacitors take over a minute to charge, so speeding up the charge time would be important for the design to be made more practical for regular use. In order to do this, the frequency could be increased, which would also make the circuit small because the inductor size would decrease. The boost circuit would be run on the edge of the discontinuous conduction mode so that all of the energy stored in the inductor is transferred to the capacitor in one cycle. A bank of capacitors could also be added so that after one capacitor discharged it would immediately start recharging, and the next capacitor could be used to fire the next nail. This would increase the size of the circuit slightly but would allow for rapid succession firing of the nails.

Another improvement would be to create a portable housing that is nonconductive and able to withstand appropriate forces of the gun, and the coils, and also able to supply a continuous stream of nails to the firing tube. In order to make it portable lithium ion phosphate batteries would be the best option for they provide a large energy density, and would lighten the load. An A123 Lithium Ion Phosphate Batteries supplies the following amount of energy using the energy density of 108.10 Watt-Hours per kilogram [10]:

$$Energy = 108.10\frac{WHrs}{kg} * (.074kg) * \left(\frac{3600s}{1Hr}\right) = 28798\, joules \qquad (15)$$

$$Number\ of\ nails \approx \frac{28797\ joules}{41.65\ joules} \approx 345\ nails \qquad (16)$$

This assumes no losses, but does present a significant number of nails that can be fired on a single charge of the rechargeable battery back, and switching out battery packs would allow for immediate continued use. Solar panels could be added for longer use, which would be beneficial since nail guns are often used outside, on roofs for example.

5.4 Ethical Considerations

Our project may encounter ethical issues since we are dealing with very high voltages. We will disclose any new findings in data and calculations they may change the course of our project. We will also make sure to be truthful in our labeling of high voltage components. This follows this ethic from 7.8 of the IEEE code of ethics:

"1.) To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment"

We will also, and have already taken into account the possibility of injuries involved, and have equipped the gun with appropriate safety measures. The voltage is prevented from going above the specified 350V limit using the comparator. Also we had a Plexiglas shield put in front of the gun, and the demo will be done behind another shield, in order to protect observers from projectiles. Full implementation of the design for customer use would undergo rigorous testing and extra safety precautions. This follows the ethic from 7.8 of the IEEE code of ethics:

9.) “to avoid injuring others, their property, reputation, or employment by false or malicious action”

6. References

[1] *LM2904*, datasheet, Texas Instruments, 2010. Available at: http://www.ti.com/lit/ds/symlink/lm358.pdf

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[12] *PCB Design*, webpage, Available at: http://www.ladyada.net/library/pcb/costcalc.html. Accessed December 2012.

Appendix A: Requirements and Verifications Table

Requirements	Verifications
1. The 78L05 regulator supplies 5V to the 555 timer, MOSFET driver, and op amp.	1. Probe the power pins of the 555 timer, the op amp, and the MOSFET driver. Results: The output of the voltage regulator was 4.9775V.
2. The LM317 regulator supplies 2V to the op amp and the sensor.	2. Verify that the voltage regulator supplies 2V by probing pin 5 of the op amp. Results: The output of the LM317 was 2.02V.
3. The 555 should output a 2kHz square wave.	3. Switch on 5V power and verify that a 2kHz square wave is coming out of pin 3 of the 555. Results: Square wave seen in Figure 3 is seen on the oscilloscope.
4. The MOS driver should output a 5V-8V peak to peak 2kHz square wave.	4. Verify that a 2kHz, 5V-8V peak to peak square wave is coming out of pin 7 of the MOS driver with the oscilloscope. Results: Square wave seen in Figure 3 is seen on the oscilloscope.

5. The capacitors should charge to within 10% of 350V, so that for safety reasons, the output voltage is known, and the capacitors are not stressed beyond their rating.	5. Show that the voltages of both capacitors are charging to within 10% of 350V on the gun's voltmeters. Results: The capacitor charges to within 10% of 350V.
6. The bleed resistors should a) Provide a voltage divider from the capacitor as an input and make the op amp output go low when 350V is reached. b) Stop the 555 circuit when the capacitor is fully charged. c) And have the capacitor discharge in about 13 minutes when it's not in use.	6. When the voltmeters read 350V the capacitor should begin to discharge which means the 555 stopped. When power is turned off, after 13 minutes the voltage on the capacitor should be approximately 0V. Results: The capacitors do not charge beyond 350V. Also the capacitors discharge to about 30V in 13 minutes.
7. When the sensor sees a nail the energy from the capacitor should discharge into the nail. The nail should shoot.	7. Make sure the capacitors have stopped charging Push the nail into the gun past the sensor of the 1st stage. Verify that the capacitor discharged into the coils by reading the voltmeters. The voltage should be about 0V. The gun should fire the nail.

	Results: The capacitor energy does not discharge in the coil. The gun did not shoot.

Appendix B: The Final Circuit

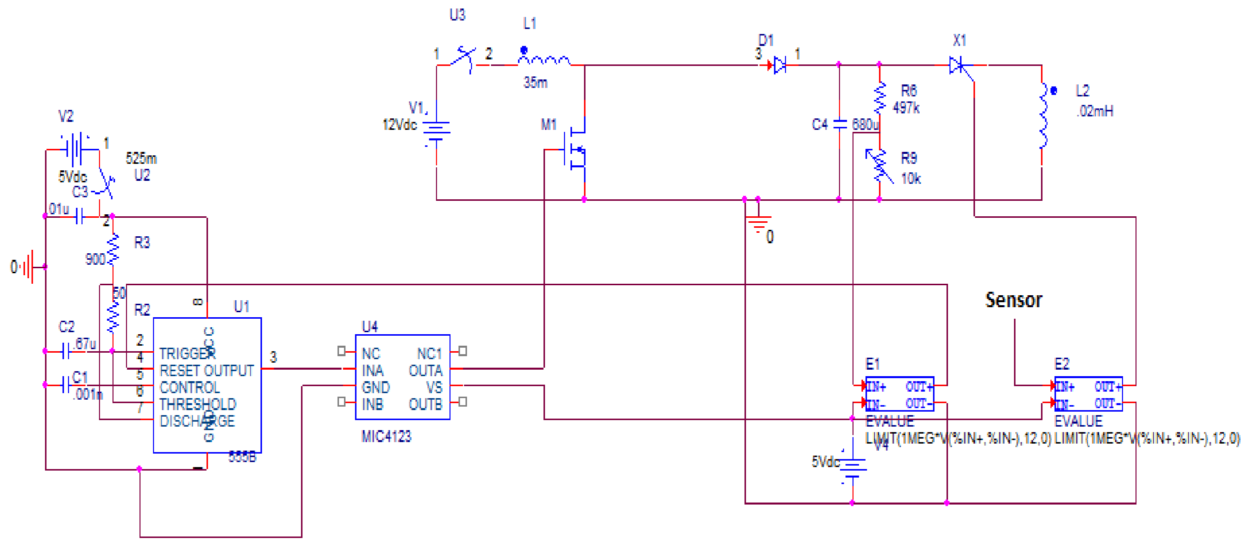

Figure 2. The Final Circuit