Design and development of a portable electromagnetic coil accelerator for advanced defense applications

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ABSTRACT

In this work, a prototype of a six-stage coil gun was designed and developed to accelerate and propel a ferromagnetic projectile as an alternative technology to traditional firearms, which rely on explosive power for defense applications. The electromagnetic coils were arranged along the length of the barrel and were energized one at a time, sequentially, from one end of the barrel to the other to accelerate and propel the projectile forward. This paper presents the design, simulation, and optimization of the barrel and projectile, including details of the electromagnetic coils, triggering and switching circuits, and pulsed current sources. Simulations were conducted using COMSOL Multiphysics software with both single-coil and multiple-coil configurations. The prototype model incorporates a non-ferromagnetic barrel to minimize the retarding magnetic field and hysteresis, which could otherwise reduce the projectile's velocity. The barrel is equipped with IR sensors to detect the projectile's movement and activate or deactivate the corresponding electromagnetic coils, ensuring efficient forward propulsion. Utilizing a capacitor bank and rapid charging circuits, the developed prototype unit is capable of propelling the projectile at a velocity of 419 m/s measured at a 10-meter distance and could fire every 2 milliseconds successfully. The prototype unit developed is a handheld rifle using a polyvinyl chloride (PVC) barrel and uses a projectile with dimensions meeting the defense application.

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1. INTRODUCTION

The coil guns operate with electricity to propel bullets at high speeds, unlike traditional firearms [1]. Another method of transportation, military and space applications have been using electromagnetic launching as an alternative to chemical propulsion for over 150 years [2], [3]. Coil guns rely on induction, or reluctance, to accelerate the projectile armature and avoid contact, and thus wear and life cycle are minimized [4], [5]. Guns using induction coils use conductive, non-magnetic armatures, whereas those based on reluctance coils use ferromagnetic armatures. Such systems use low current and easy switching circuits, which improve efficiency and structural reliability. They are mostly found in defensive actuators and electromagnetic tools applications [6]. Conventional guns use the explosive nature of gunpowder to fire projectiles along the barrel to create noise and a by-product that needs to be cleaned. Conversely, when a high-speed-of-discharge store of energy is made to power an electromagnet that encircles the barrel to induce a high level of magnetic field, a substantial magnetic field is formed around the barrel. Electromagnetic coil guns apply Lorentz force to accelerate ferromagnetic projectiles and operate like linear motors, Maglev trains, and roller coasters. This removes the noise of gunpowder, residue of barrels, and maintenance. The latest research and developments in electronic warfare machinery indicate that there are chances that coil guns could supersede traditional and gunpowder-containing weapons in the future [7]. Innovations in science and engineering of materials have made it possible to develop hand-portable coil guns and long-range electromagnetic cannons to be used in next-generation warfare [8]. Newly invented coil guns are capable of shooting projectiles between 10 grams and even 5 kilograms at a speed to the tune of over 1 kilometer per second [9]. Coil guns have a number of challenges despite these advantages. Making the launch effective involves having the energy storage and conversion systems that are strong and efficient enough to produce large electric currents. There is also a need for a cooling mechanism to cover the coils and the projectile against overheating. Although the coil guns do not have the same mechanical wear as traditional firearms, the high-velocity friction may still wear away the barrel, and research is ongoing to develop wear-resistant materials. The paper discusses the design and prototype of an electromagnetic coil gun in six stages. This system comprises six electromagnetic coils, which are fitted around the length of a non-magnetic barrel, and cause acceleration of a ferromagnetic projectile to a speed of 400 m/s. The capacitor bank and rapid charging circuit fitted to the prototype model allow firing every 2 milliseconds. In the paper, the results of the simulation are presented in addition to the prototype model and its performance analysis.

2. WORKING PRINCIPLE

A coil gun is made of a field coil placed around a ceramic or plastic structure, which forms the barrel of the gun, and a ferromagnetic projectile, shot by a magnetic force. The resulting magnetic field (time-varying) exerted by the coil puts a force that accelerates the projectile towards the coil, as shown in Figure 1. The current into the coil is switched off as the projectile moves into the coil center, and due to the inertial momentum, the projectile proceeds to move forward. To reduce the deceleration due to the retarding force within the coil, the current is terminated at the proper time. After the projectile has left the barrel, the coil gets recharged again to make another launch.

The force exerted on the armature consistently propels it forward, allowing it to exit the barrel with minimal noise at subsonic velocity, leaving no residue that requires repeated cleaning. Advanced coil gun designs utilize multiple accelerator coils, which are activated sequentially as the projectile moves through the barrel. The primary challenge with electromagnetic weapons is the energy loss during the conversion of electrical energy into kinetic energy.

The electromagnetic coil flux linkage and the force exerted on the ferromagnetic projectile is given by the following expressions [4], [10]-[12]. The flux linkage of the coil is given by (1).

$$F = n\phi = nBA \tag{1}$$

The magnetic flux ϕ is given by:

$$\phi = BA \tag{2}$$

where B represents the flux density, and A represents area, and n is the number of turns in the coil [13].

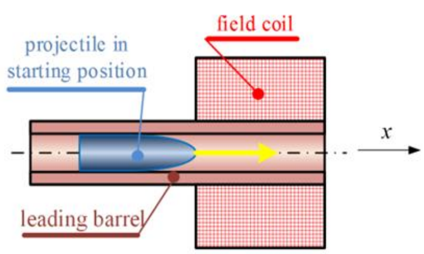


Figure 1. The working of a coil gun [13]

The flux density B has a large effect; the electromagnetic coil must be as powerful as possible to maximize the force of the projectile, and maximizing the area A and the number of turns n will increase flux linkage and the force on the projectile. The exact force F exerted on the ferromagnetic projectile is derived from Faraday's law as (3) [4].

$$F = a\,(4\pi * 10{-}7)\,(ni)\,/2(2g) \tag{3}$$

F = force, i = current, and g = length of the gap between the solenoid and a piece of metal, a = area, n = number of turns. 4π*10-7 is the magnetic constant in m.kg. s-2A-2. It is very important to minimize g since [4].

$$F \propto 1/\,(2g)2 \tag{4}$$

An excessive number of coils will reduce the current, as indicated by I = V/R with an increase in resistance. The variable a must also be maximized, and it is crucial to recognize that the wire's cross-sectional area is directly related to the current, since a larger area leads to lower resistance.

3. COMPONENTS OF A COIL GUN

3.1. Block diagram

Figure 2 shows the building blocks of a coil gun with IGBT-based switching current to the launch coil. The turn ON and turn OFF are controlled by a microcontroller with an input from an IR sensor. The microcontroller sequentially energizes the successive coils along the barrel, as shown in Figure 3, which illustrates the integration of multiple coils in a coil gun with individual switching circuits and microcontroller-based control.

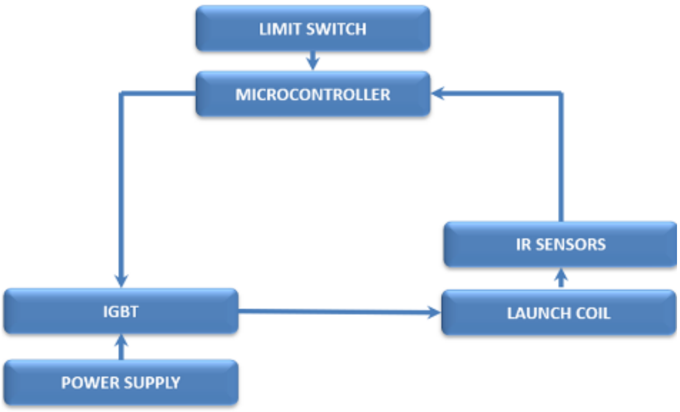


Figure 2. The building blocks of a coil gun

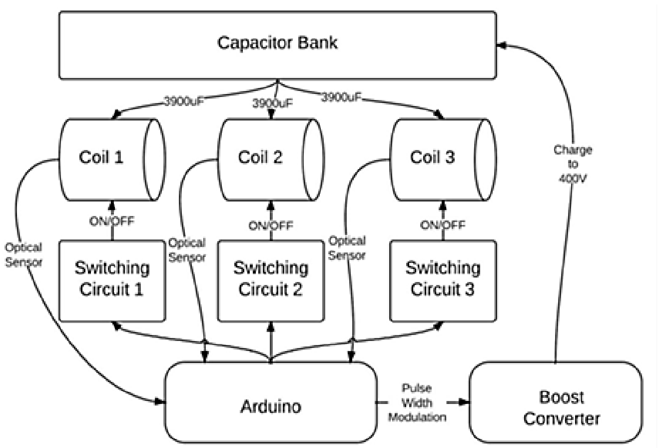


Figure 3. System block diagram

3.2. Projectile

The projectile is the ferromagnetic material that is under the influence of the magnetic field, accelerated and propelled through the barrel [13]. The length of the projectile is equal to the length of the coil, and the excess length outside the coil is not in the magnetic field and constitutes dead weight [14]. The central projectile is perfect since it will use the entire coil length until it is deactivated, as it will only be drawn to the coil's core. To optimize the magnetic flux acting on the bullet, its diameter should be roughly equal to the coil's inner diameter.

Figure 4 illustrates the projectile profile, showing its cylindrical body with a pointed tip and an outer casing, with labeled dimensions for length and diameter. Aerodynamics is a crucial factor to consider for every projectile. In case the projectile has an aerodynamic tip, the air gap in the design of the bullet will reduce its efficiency and the magnetic flux. The remedy must be either to use a paramagnetic tip on the bullet so that it will not interfere with the magnetic flux, and leave the metallic part in a flat and cylindrical form, or to be careful with the grinding operation so that the bullet will be merely slightly rounded. This efficiency is questionable, the pointed projectile having more magnetic flux and more dead weight than the rounded projectile, which has less magnetic flux and less mass.

The length-to-diameter ratio must exceed 3:1, as ballistics science demonstrates that this ratio ensures the projectile maintains a straight trajectory. The ratio must not exceed 5:1 while utilizing spin stabilization [15]. Positioning is important since the coil will run at maximum efficiency for a brief period of time when the capacitor discharges quickly. The projectile will not be attracted if it is placed far from the coil's entrance, which will result in less current by the time it gets there and enable the projectile to exit the barrel more slowly.

3.3. Ignite coil

Enameled copper wire is used for forming the electromagnetic coil with better insulation and provides a tightly wrapped coil for a concentrated magnetic field [7], [16]-[18]. The coil produces lots of heat when the capacitor bank discharges with a high current pulse, and to improve the heat dissipation, the conductor size was optimized [17], [18]. Figure 5 shows a holding resistor connected to the coil with a bypass switch using a transistor. During the charging process, the capacitor is connected to the voltage source through the holding resistor to limit the current flow, allowing a gradual charging of the capacitor till the capacitor voltage builds to the supply voltage [19], [20].

While the voltage source is disconnected, the capacitor discharges through the holding resistor. The discharge current flows in the opposite direction and reduces the voltage across the capacitor. The discharge time is given by the RC time constant, and with a large holding resistor, the discharge process slows down, while a small resistor provides a fast discharge [20], [21]. The holding resistor ensures controlled discharge of the stored energy in the capacitor and prevents sparks, shock, and component damage [22].

Stroke denotes the distance travelled by the projectile, and it is not minimized in the coil gun design [23]. The solenoid design must accommodate maximum force and could support high current levels. Timing circuits are used to minimize the duty cycle for better efficiency of the coil. Heat sink or other cooling systems are required to reduce the heating effect of the coil gun [24], [25].

3.4. Barrel

The barrel is engineered to accommodate the coils in six segments, with sensors integrated to automate the engagement and disengagement of the coils. Figure 6 shows the barrel design and the coil arrangement along the barrel. The barrel used for the prototype development is of PVC material to reduce magnetic hysteresis and retarding magnetic field developed in the barrel. But a barrel can be constructed from 316 L stainless steel, which is a robust structural material that improves the rigidity and sturdiness of the coil gun for field applications.

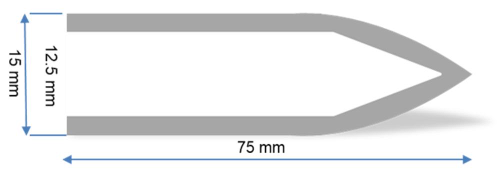


Figure 4. Projectile profile

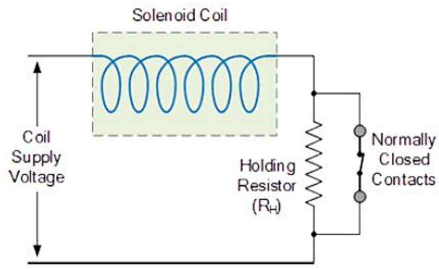


Figure 5. Configuration of a solenoid coil

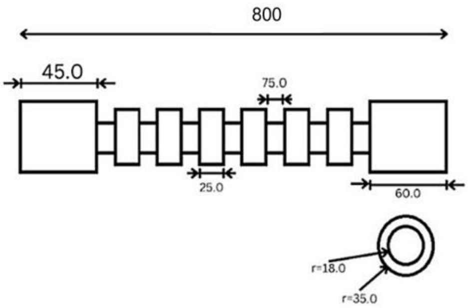


Figure 6. Coil gun barrel with coil arrangement

4. SIMULATION OF COIL GUN

The simulation model of the electromagnetic gun (EMG) was designed in COMSOL Multiphysics as shown in Figure 7.

Simulation parameters are as follows:
- Capacitor: 600 V, 1000 µF
- Voltage Source: DC
- Charging time for Capacitor: 10 ms
- Barrel length: 810 mm
- Material: Ferromagnetic material (silicon steel)

Number of coil stages: 1 to 6. The movement of the projectile in the barrel and the EMF around it was studied as shown in Figure 8. The simulation with a single coil could obtain a maximum EMF of 100.91N on the projectile, as shown in Figure 9. The maximum velocity obtained with a single coil is 45.12 m/s, as shown in Figure 10. Similarly, with a six-stage coil gun, the maximum EMF on the projectile is 151.25 N, and the maximum velocity achieved is 111.41 m/s, as shown in Figures 11 and 12, respectively [22].

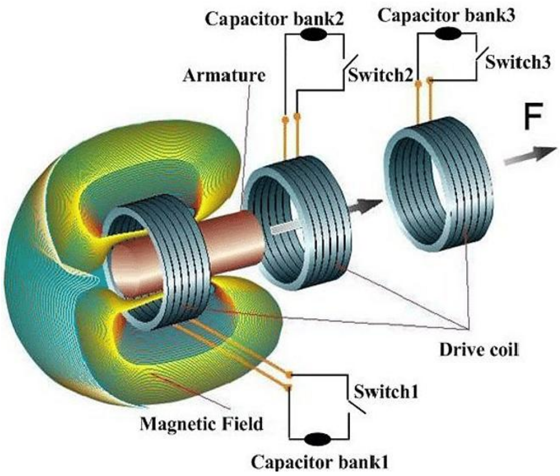


Figure 7. 3D simulation model of coil gun [16]

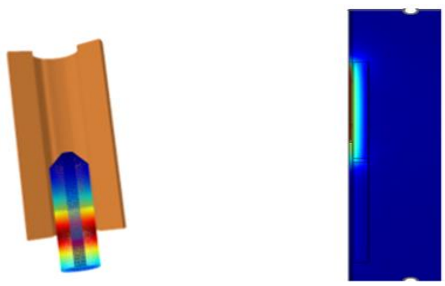


Figure 8. Simulated projectile trajectory within a barrel

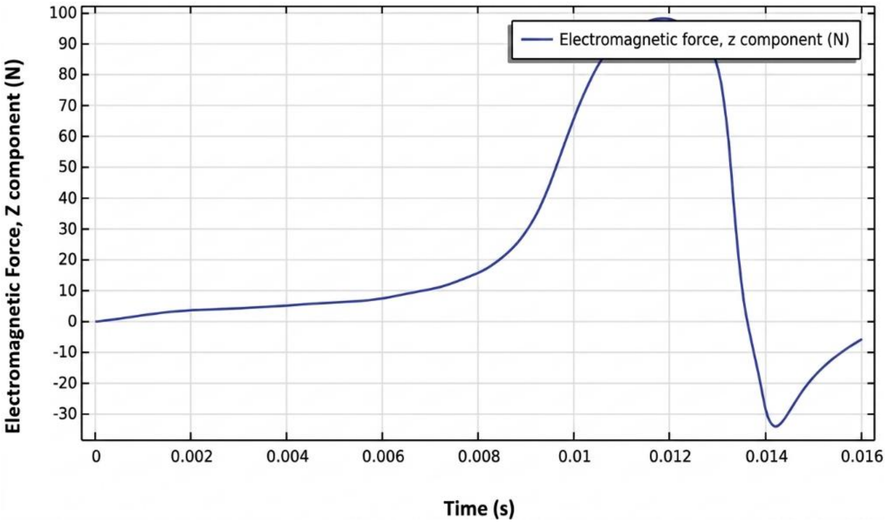


Figure 9. Maximum EMF of a single coil over time

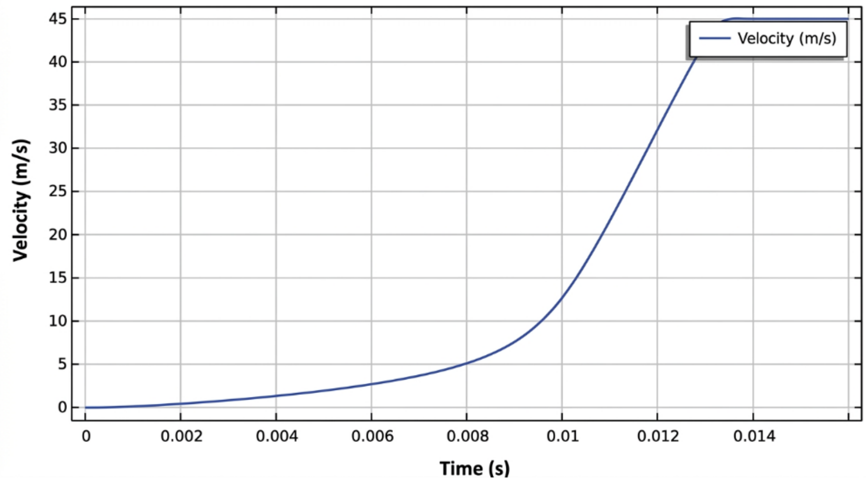


Figure 10. Maximum velocity of a single coil over time

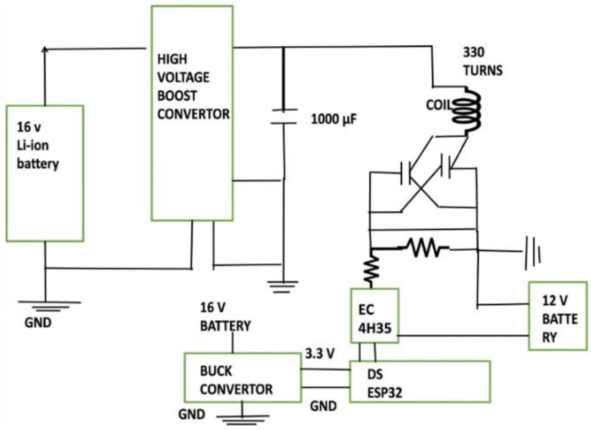
The EMF in a coil gun had increased from 100.91 N to 151.25 N when the number of coils was raised from one to six coils. The EMF is strong with the first coil and starts to reduce when the projectile moves from the first to the sixth coil, and the EMF does not increase 6 times in a single coil due to magnetic losses in the barrel. As a result, the velocity of the projectile did not increase proportionally with the increase in the number of coils.

5. PROTOTYPE DEVELOPMENT

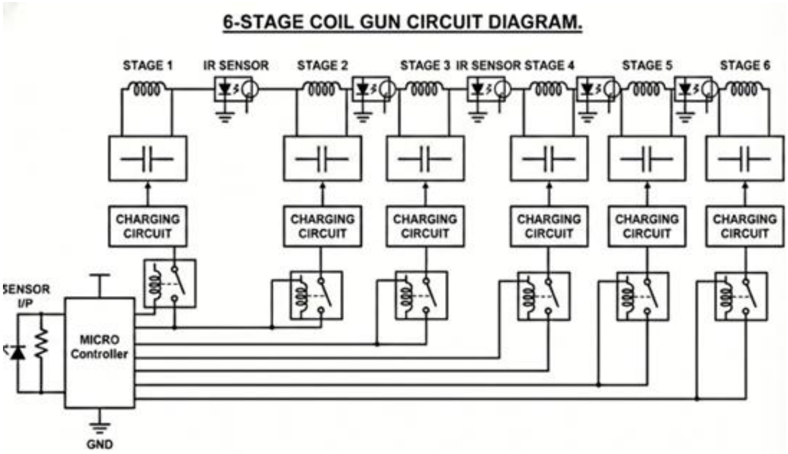
The Prototype system is built with the following components for a defense application. Figure 13(a) shows the overall schematic circuit diagram of the developed prototype unit, Figure 13(b) shows the detailed working block diagram, and Figure 13(c) shows the charging and discharging circuit block diagram. The various components are:

i) Microcontroller: The microcontroller used in the prototype is ATmega328 by Atmel. It is used to display the voltage from the capacitors with fast ADC input lines, detect the velocity with digital inputs, and output to an LCD display.
ii) Power supply: The power supply uses a 12 V, 40,000 mAh lead acid battery pack. This battery was chosen for its ability to handle heat with a higher operating temperature and quick recharge. The battery provides a constant voltage to the charging circuit to charge the capacitor bank.

(a)



(b)



(c)

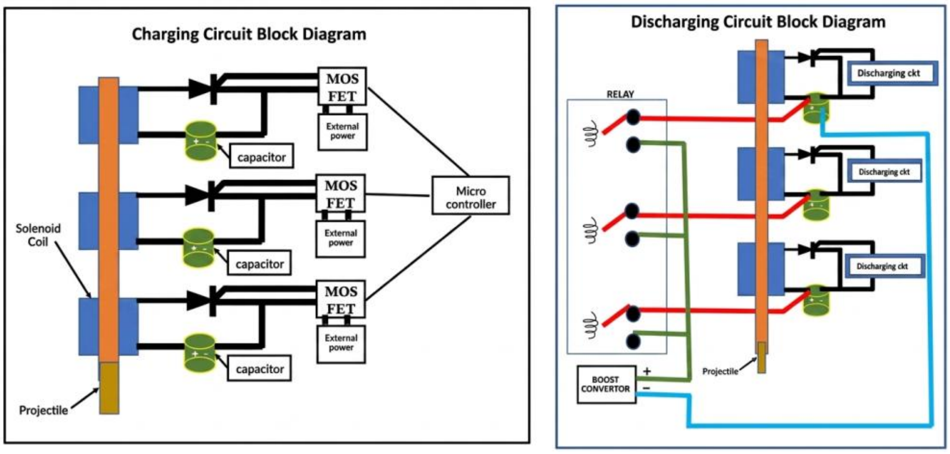


Figure 13. Components of Prototype design: (a) schematic circuit diagram, (b) working block diagram, and (c) charging and discharging circuit

iii) Regulated power supply: The regulated power supply is provided for electronic devices using 78XX family linear voltage regulators for a 5 V DC output.

iv) Infra-red sensor: This is an infrared emitter/receiver circuit implemented at the end of the coil. Its function is to turn the coil off as the end of the projectile comes out of the coil. The total time from the first coil to the sixth coil is 2 ms, and the IR sensor detects the projectile and energizes the subsequent coil upon its arrival. This circuit vastly increases the efficiency of the coil gun by ensuring that no work is done against the direction in which the projectile is being accelerated.

v) Charging circuit: A DC-DC booster converts 12 V DC to 100 V DC. The DC input current from the supply will store energy in the magnetic field of the inductor and will be unable to pass it. When the switch is closed, the inductor will begin to oppose the change in input flow of current since the circuit resistance and voltage drop begin to realign. The terminal of the inductor connected to the battery will become negative with respect to the terminal connected to the diode, effectively locking the two in series as a much larger voltage, which will proceed to dump their combined energy into the capacitor as a transient waveform. The diode will block the capacitor from discharging itself through the inductor, thus absorbing all the energy and allowing its voltage to steadily climb. Figure 14 shows the charging circuit diagram. The built prototype model of the coil gun is assembled on a table for testing its performance, as shown in Figure 15 for a six-stage coil gun unit. The velocity of the six-stage coil gun was measured using a velocity meter constructed with the prototype unit, as illustrated in Figure 16. A projectile was discharged towards a wooden board positioned 10 meters away, resulting in a penetration depth of 1 cm upon impact with the board.

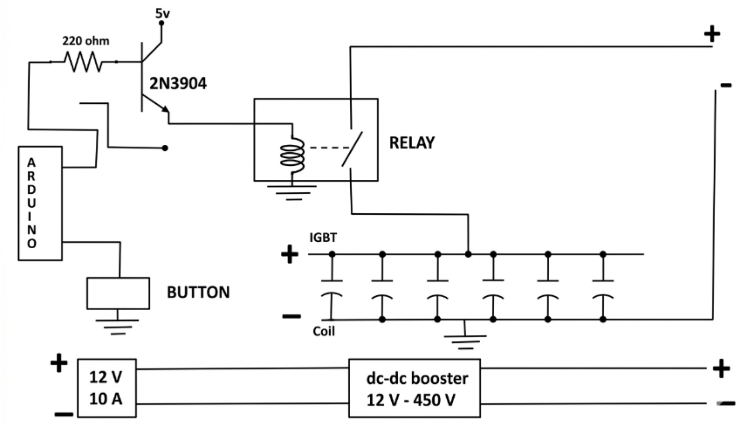


Figure 14. Charging circuit schematic

Figure 15. Prototype model of a 6-stage coil gun

Figure 16. Bullet velocity measured in a 6-stage coil gun

6. THEORITICAL ANALYSIS

The theoretical analysis of the 6-stage coil gun with the design values is done for estimating the force on the projectile as in (5), mass of the projectile as in (6), length to diameter of the projectile, Muzzle velocity as in (7), and the losses in the unit as in (8) and (9).

$$F = \frac{a(4\pi * 10^{-7})ni^2}{(2g)^2} \tag{5}$$

Where F = force, i = current, g = gap between the barrel and projectile, a = area of projectile, and n = number of turns. Substituting value: $a = \pi r^2 = 3.14\times(5\times10^{-3})^2 = 7.85\times10^{-5}\ m^2$, n = 140. i = 100 amp, and g = 1.5 mm.

i) Mass of projectile (m) = volume × density

$$= \pi r^2 h \times \text{density of iron} = (3.14\times25\times10^{-6}\times50\times10^{-3})\times7850 = 0.0308 \text{ kgs} \tag{6}$$

ii) Length to diameter ratio (L/D)

= Length/diameter = 50 mm/10 mm = 5 mm

iii) Force on the projectile $= \frac{\pi \times (7.85\times10^{-5})^2 (\pi\times4\times10^{-7})(100\times140)^2}{(2\times1.5\times10^{-3})^2} = 2147.2$ N

iv) For 6 slots, force on the projectile = 2147.2×6=12883.2 N

v) Muzzle velocity = √ (2F/(mass of projectile))

$$= \sqrt{(2\text{x}12883.2 / 0.0308)} = 914.6 \text{ m/sec} \tag{7}$$

vi) Copper losses

- R = ρl / A

$$= \frac{10\times1.68\times10^{-8}\times140\times2\times\pi\times6.5\times10^{-6}}{0.25\times10^{-6}\times\pi} = 3.84\times10^{-3} \text{ Ohms} \tag{8}$$

- Total losses = i^2R

$$= 1002 \times 3.84 \times 10^{-3} = 38.4 \text{ watts} \tag{9}$$

vii) Efficiency of a single-stage coil gun

The efficiency of the coil gun is calculated as a ratio of the kinetic energy (KE) as in (10) imparted on the projectile to the electrical energy (EE) as in (11) supplied. The calculation is simplified by estimating the kinetic energy and electrical energy supplied to find the efficiency as in (12) without considering ohmic losses, magnetic losses, and air friction losses, which require intense simulation and experimental analysis.

$$\text{Kinetic energy (KE)} = \tfrac{1}{2} mv^2 \tag{10}$$

Where m = mass of the projectile and v = velocity of the projectile for a single stage.

$$\text{Electrical energy (EE)} = \tfrac{1}{2} CV^2 \tag{11}$$

Where C = total capacitance for a single stage and V = Voltage across the capacitor bank.

$$\text{Efficiency } \eta = \frac{Kinetic\ Energy}{\text{Electrical Energy}} * 100 \tag{12}$$

Given m = 0.0308 kg, v = 45 m/s (simulated for single stage), C = 8000 μF, V = 100 volts, KE = ½ × 0.0308 × 45^2 = 31.185 J and EE = ½ × 8000 × 10^{-6} × 100^2 = 40 J.

viii) Efficiency (η) for single stage = 77.96 %

The efficiency is improved with a multistage design, advanced switching with MOSFET, a projectile design, and using low resistance and fast switching capacitors.

7. RESULT

The six-stage prototype electromagnetic coil gun achieved a velocity of 419 m/s compared to the theoretical value of 914.6 m/s. Figure 16 shows the measured velocity attained with the electromagnetic coil gun. The reduction in velocity is due to the use of a non-ferromagnetic barrel, which has lower permeability compared to a ferromagnetic material. Table 1 shows the comparison with other electromagnetic coil gun designs.

Table 1. Comparison with other similar electromagnetic coil gun designs

Reference	Velocity m/s	Firing cycle ms	No coil stages	Turns per coil stages	Summary
[26]	424	14	5	-	Only a simulation, not a portable model
[12]	100	-	3	18	Only simulation
[27]	8	-	4	21	Working model, single stage with multi-layer coil (Sandwich coil)
[12]	13.34	5.45	1	140	Working model single stage
[28]	107	-	9	26	Working model
Our design	419 at 10 m distance	2	6	140	Working model and portable unit

8. FUTURE SCOPE

There is further scope for improvement in the prototype of the electromagnetic gun, as outlined below: At the muzzle, the velocity can be accelerated by increasing the current, the coils in each section, and the number of turns per section. Reducing firing can be accomplished with one or more capacitor banks; this would reduce weight and cost, but would result in a higher firing rate. The application of supercapacitors should be pursued. The circuit current may be adjusted by a potentiometer in order to provide a variable-range gun option. Portability is also an issue and has to be checked with the performance characteristics. The greater the specifications, the more coils, turns, and capacitor banks, which causes the system to be heavier. An interface fitted on the weapon may help in tracking the remaining power, weapon programming, malfunctions, and other relevant details.

9. CONCLUSION

It is novel in the sense that it is compact, a portable handheld gadget, which creates a velocity of 419 m/s when loaded with a ferromagnetic projectile of 30.8 grammes and has a barrel made of PVC, with a distance of 10 meters. The speed of the prototype is much higher than that of the simulated six-stage coil gun, which achieved a speed of 111.41 m/s with silicon steel. The simulation suggested that the magnetic losses of the ferromagnetic barrel are substantial and fail to give the expected rise in EMF. These losses, in turn, result in a decrease in velocity as compared to the PVC barrel with the prototype unit. The developed multi-stage coil gun has a higher velocity as compared to the single-stage coil gun, with the velocity directly proportional to the number of solenoids in the multi-coil setup. The first was the design that used high-power capacitors with 100 V and 100 Amps, featuring a PVC barrel, and could show high muzzle velocity. The EMG operates at a frequency of 2 ms and is combined with IR sensors to correctly trigger the next coil according to the forward movement of the projectile.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors affirm that they have no competing interests or conflicts of interest, whether financial, professional, or personal, that could have influenced the work reported in this manuscript.

DATA AVAILABILITY

All the data used in this study were acquired through a special experimental design and prototype model, which was founded on the systematic testing of the six-stage electromagnetic coil gun under controlled conditions and was applied to the analysis, validation, and comparative evaluation.

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