International Baccalaureate Diploma Program
Physics High-Level Extended Essay

Design of Single-Staged Coil Gun without Capacitors based on the Varying Voltages & Their Effect on the Travelling Distance of the Ferromagnetic Projectile and the Efficiency of the Coilgun

Research Question: What is the effect of the given voltages of 10V, 11V, 12V, 13V, 14V, and 15V on the traveling distance in meters of the projectile of a single-staged coil-gun without capacitors and the percentage efficiency of the coil-gun system?

Word Count: 3999

CONTENTS:

1. INTRODUCTION

Electromagnetic launching systems (EML), are the conversion of electrical energy into kinetic energy by attracting magnetizable (ferromagnetic) projectile through a magnetic field created around coil, timed to a thin-walled barrel. [2] Two types of EML are under construction: rail gun and coil gun. A rail gun, composed of a pair of parallel conducting rails, is theoretically more simple than a coil gun with a working principle of accelerating a sliding armature by means of electromagnetic effects of the current which flows through one rail into the armature and then back to the other rail. However, rail guns lack the proficiency to accelerate high-energy demanding objects due to greater mechanical friction between the projectile and the rail. [7] On the other hand, a coil gun is a projectile accelerator consisting of coils used as an electromagnet in a linear motor that accelerates a ferromagnetic projectile by giving a pulse of current through a solenoid.[3] Thus, coil guns are rather on the foreground as the coil gun can propel a projectile without any mechanical friction. [8]

EML systems have wide range of applications in aircraft launching. The complexity and costs of the space launch systems raised the main curiosity of this project and the question of finding the optimum parameters for the most efficient coil gun launching system for space applications is rised as coil guns considerably reduce the amount of fuels handling, man-power and minimises turn-around time between the launches [12]. As the main aim of the abstract, the effect of voltage on the traveling distance and energy output, efficiency of the system is investigated.

1.1. **Research Question:** What is the effect of the given voltages of 10V, 11V, 12V, 13V, 14V, and 15V on the traveling distance in meters of the projectile of a single-staged coil-gun without capacitors and the percentage efficiency of the coil-gun system?

1.2. Background Information

1.2.1. Design of An Electromagnetic Coilgun

a. Coil Gun Geometry

A coil gun is composed of a coil of wire, capacitor, switch, barrel and a movable core - ferromagnetic projectile which is a material (Fe) that can be easily magnetized by applying current. Coil is wounded around barrel in solenoid form and the ferromagnetic projectile is placed at one of its ends for the starting position [10], (**Figure 1**).

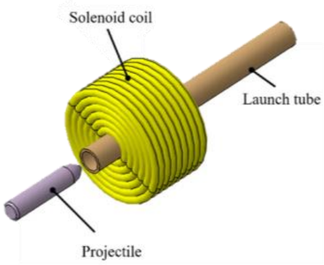

Figure 1[1]. The schematic diagram of coilgun launching tube systems

Projectile is placed at one of the ends of the coil and through magnetic induction, projectile is pulled to the coil's center. Ferromagnetic material is drawn to the center of the coil due to strong magnetic force formed by the current pulsed through the coil of wire. When projectile nears this point, electromagnet must be switched off in order to avoid projectile to arrest at the center and avoid coil from drawing projectile in opposite direction; a phenomenon known as the suck-back effect occurs due to induced current (**Figure 2**.) [5] Therefore, a microprocessor is used as current stopper. Sensor is placed in the circuit and coded to close the

[1] Seonmyeong, Kim, and Kim Jinho. "The Schematic Diagram of Coil Gun." *An Electromagnetic Circuit Design to Improve a Multi-Stage Coil-Gun's Energy Conversion Efficiency*, Applied Sciences, 6 Sept. 2022, file:///C:/Users/vural/Downloads/applsci-12-08942-v2.pdf. Accessed 10 Oct. 2022.

electrical system in 100 milliseconds. When current is cut out, projectile travels down barrel, exists gun with a velocity and moves towards intended target with its own momentum [3].

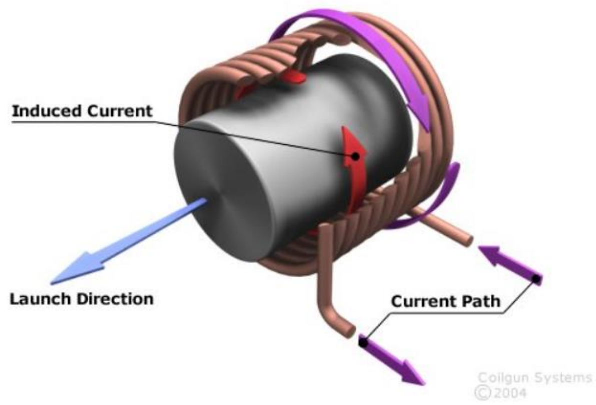

Figure 2*[2]*. *Demonstration of the induced current passing through the coil*

Coil gun has two main setups: single-staged coil gun and multi-staged coil gun. In a single-staged coil gun, the projectile is propelled with one electromagnet whereas in a multi-staged coil gun, several electromagnets in succession are used to increase the speed of the projectile [5]. In this experiment, a single-staged coil gun is constructed in order to be able to observe the effect of voltage on the travelling distance of the projectile.

b. Electrical Circuit Design

Power is supplied to the solenoid from a power supply, which can be a battery or high capacity high voltage capacitors for fast discharge. In this investigation, however, a power supply is used for energy generation and the coilgun is designed without capacitors. In order to create an automatic switching circuit an Ardunio UNO microprocessor which is a

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[2] "Tubular İnduction Launcher." *Coilgun Systems*, 2004, http://www.coilgun.eclipse.co.uk/coilgun_basics_3.html. Accessed 29 Dec. 2022.

Note: the contributor of the Figure 2 is unknown.

programmable circuit board and a software that works on the computer, used to uploud computer codes, is in the circuit for the closing of the current in 100 millieseconds. A relay board (**Figure 2)** is another significant component of the circuit as it acts as a switch component for high current and voltage devices. On the relay board 3 different connection exists [9]:

1. COM (Common): The "common entrence" and the voltage outlet is connected to this enterance.
2. NO (Normally Open) : The enterance which is in relation with the COM connection when there is no voltage and the curcuit is open. However, whent he voltage is given and relay board has a signal; the circuit is closed.
3. NC (Normally Closed): When there is the signal to open the relay board,it interacts with COM and the circuit is opened.

Relay board is connected to Ardunio UNO microproessor as the code in the processor closes the relay board, in addition to connection to the selonoid [9]. Lastly, the selonoid is connected to the power supply and the circuit is completed.

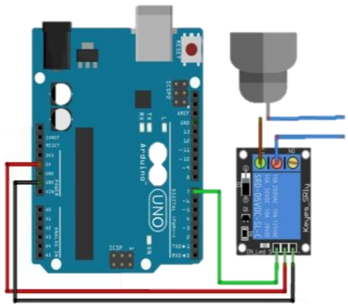


Figure 2.[3] Schematic model of the Ardunio- Relay Board connection

[3] Macit, Hüseyin Bilal. *Hüseyin Bilal Macit Phd Computer Engineer Asst Prof*, 9 Jan. 2020, https://www.hbmacit.com/2020/01/09/arduino-ile-role-kullanimi/. Accessed 13 Oct. 2022.

1.2.2. Parameters and Their Effect on the Performance of the Coilgun

a. Projectile Geometry

Projectile geometry holds a significant role in the performance of the coil. First, projectile must be a ferromagnetic material, thus it can be attracted and moved by the magnetic field. Iron has one of the strongest ferromagnet, therefore it is preferred in experiment. In order to reduce air friction which occurs due to air space and reduce the loss in energy, diameter of the projectile must be near to barrel diameter. [4].

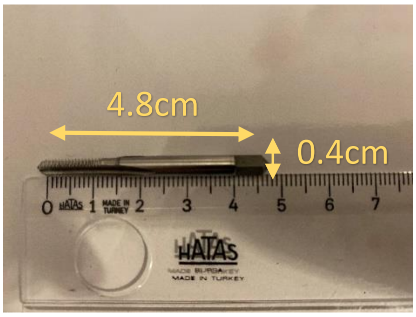


Figure 4. The projectile used in the experiment

b. Coil Design, Magnetic Field Force, Voltage and Current

The coil-gun design is another factor affecting the traveling distance, velocity and the efficiency of the projectile. The number of the turns of the coil has an increasing role on the the traveling distance of the projectile as it is directly proportional with the magnetig field force acting the coil-gun and causes an increase in the intial velocity. The length of the coil affect the resistivity therefore cause a change in current passing through the system as the induced magnetic field force is directly proportional to the current passing through the system. The range of the given voltages and passing current is based on the temperature rise on the coil as it can decrease the performance and efficiency of the coil and there is the possibility of coil damage.

Theory

In order to reach the efficiency of a coilgun, the initial velocity of the projectile at the time it leaves the barrel must be determined assuming that the projectile leaves the barrel with constant acceleration.

Derivation of the Velocity through the Horizontal Projectile Motion

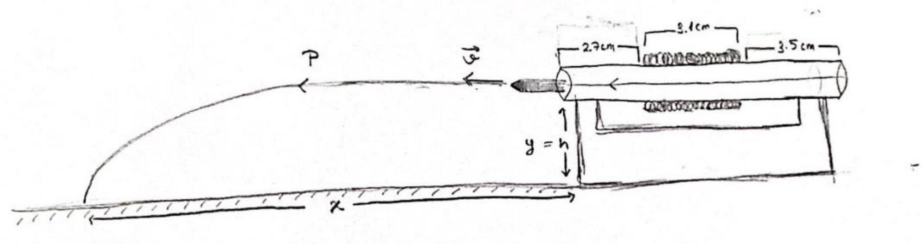


Figure 5. Demonstration of the horizontal projectile motion of the projectile after the release from the barrel

In horizontal projectile motion, in order to reach the velocity of the projectile; certain aspects of traveled distance (x) and the height of the projectile from the ground (h), (**Figure 5**), must be considered. Traveled distance (x) can be found through the equation below [11]:

$$x = v \times t \quad (1)$$

Therefore this equation can be transformed to,

$$v = \frac{x}{t} \quad (2)$$

x: traveled distance (m)

v: the velocity of the projectile (ms^{-1})

t: time of flight (s)

As the time (t) taken for the projectile to reach the ground is in milliseconds, in order to prevent massive errors, we can derive the t in the form of h and apply it to Equation 2 as h is a known variable. “h” can be determined through the following equation:

$$h = \frac{1}{2} \times g \times t^2 \quad (3)$$

Hence;

$$t = \sqrt{\frac{2h}{g}} \quad (4)$$

h: height of the object above the ground (m)

g: acceleration due to gravity (ms^{-2})

t: time of flight (s)

To finalize the derivation of the initial velocity of the projectile, *t* found in Equation (4) is put to its place in Equation (2) and the projectile velocity derivation is found, shown below:

$$v = \frac{x}{\sqrt{\frac{2h}{g}}} \quad (5)$$

Note: Acceleration due to gravity (g) *in the lab in which the experiment is carried out is known to be 9.79973* ms^{-2}.[4]

1. DESIGN

2.1. Hypothesis

Supported by Ohm's Law of $V = I \times R$, when the voltage increases, the current increases proportionally as there is no change in the resistance – the coil and the system is always kept constant throughout the experiment-. Therefore the magnitude of the force acting on the ferromagnetic projectile increases. However, high current outputs can result in damaging and risking the coil even though it is switched off during the launching process. Hence, I expect a certain range of voltage values that results in a longer traveling distance and the lower and higher values of 13V is expected to be result in minimal traveling distance. The velocities needed for the calculation of the efficiency is expected to be higher with the maximum value

[4] Adams, Brian. "Local Acceleration of Gravity." *Wolfram*, 6 Feb. 2014, https://www.wolframalpha.com/widgets/view.jsp?id=e856809e0d522d3153e2e7e8ec263bf2.

of traveled distance is directly proportional to velocity shown in equation (5)[5]. Therefore, with an increasing velocity, the efficiency is expected to show a linear trend as well.

2.2. Variables:.

2.2.1. Independent & Dependent Variables

Independent	*The voltages applied to single-staged coil gun system from the power supply* - voltages of 10V, 11V, 12V, 13V, 14V, and 15V is applied and voltages are calculated in V ± 0.01. **Method of measurement:** an adjustable power supply is used to arrange voltage values with an absolute error of ± 0.01 V and throughout the experiment, voltage values are controlled from the power supply.
Dependent	*The traveling distance of the ferromagnetic projectile-* the distance that the projectile from the instant it left the barrel is calculated using a ruler with an absolute uncertainty of ± 0.05 cm is used **Method of measurement:** The projectile performs a horizontal projectile motion on the determined ground and the place which the projectile hits th ground is marked. From the projectile leaving end of the barrel to the hitting point is calculated using a ruler.

[5] *The efficiency calculation method is demonstrated in the Calculations section.*

2.2.2. Controlled Variables

Controlled	Method of Control	Possible effects on results
The axial turns of the coil (N)	Winding of the wire is carried out with exactly 200 turns. Throughout the experiment same coil is used.	Axial turn has direct effect on magnetic field force acting on the projectile and the current passing through. Therefore an increase in turns would result in a longer travelling distance, explained in *Background* section.
Barrel Length and Diameter (±0.05 cm)	Throughout the experiment same barrel and pen with the parameters of 9.2 length-0.5 diameters is used	The pen is chosen deliberately in order to minimize the air gap between the projectile and the barrel. Otherwise, increased air-gap would increase the friction, leading to loss of energy and lowering the traveling distance and efficiency. The length is kept constant for the placement of the coil.
The place of the coil on the barrel (±0.05 cm)	Using a ruler, the coil is winded 3.4cm away from the starting and 2.7cm away from the leaving end.	Different parameters can result in an increase in reverse magnetic force, therefore leading a suck- back effect in given voltages.
The place of the projectile from the starting end	Projectile is placed at the starting end of the barrel, 0.8 cm of its length outside with the pointed part forwarded.	The wrong placements of the projectile would lead to errors in the experiment as the time it faces the current will shift if it is further inside the barrel. Pointed part must be the forward part otherwise the projectile cannot pierce the air.
The time current is applied (100 ± 0.01ms)	The time needed to open and close the switch is controlled through coding the time length to Ardunio microprocessor.	The longer current applying periods and late closure of the system would lead to suck-back effect. Lower application would lack the sufficient current to mobilize the projectile.

1.3. Safety Requirements

- Never touch the electrical components during an electrical incident. First, disconnect the power supply.

- Control for damage in the cord-and-plug connected equipment, power supply, extensions, cables etc before use and replace the damaged equipment.
- Make sure you are using the right cables, which are resistive to the amperage and voltage you are applying.
- Make sure the electrical equipment is not near a wet or damped area as the chance of facing an electric shock is greater in these areas.
- Label all the cables, circuit breakers, plug-ins and make sure they are rightly placed according to their application.

1.4. Preliminary Testing

During first trails, a projectile with parameters 4.80 cm length -0.01cm diameter was used and voltages of 4 to 8V is tried to launch the projectile with the coil 1.0cm away from the starting end fully inside the barrel. However, when the system is started, the projectile is either lack a movement, left the barrel without any considerable acceleration or result in the suck-back and withdrawl. The data were inconsistent (Appendix A). Therefore, the projectile is moved 0.8 cm away from the inside, the coil is placed 3.4 cm away from the starting point and voltage increased up to 10V and 15V, which diminished the suck-back effect and created the optimum range of activeness for the projectile used throughout the experiment.

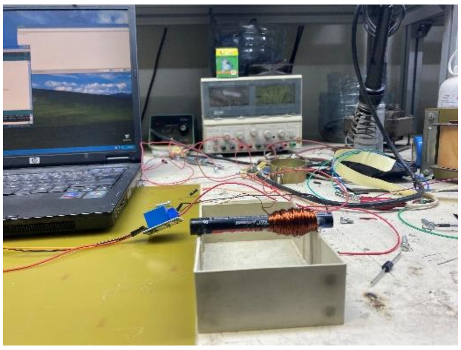


Figure 6. The very first demonstration of the single-staged coilgun

1.5. Materials

- ❖ A pen- [9.2 cm length & 0.5 cm diameter (± 0.05 cm)]
- ❖ A caliper
- ❖ A ruler (± 0.05cm)
- ❖ 5m of copper wire with the dimeter 0.2mm (±0.1mm)
- ❖ A box -[6.0cm width, 10.0 cm length, 5.0 cm height (± 0.05cm)]
- ❖ A computer with the programme Ardunio 1.8.7
- ❖ An Arduino UNO microprocessor and the second cable *
- ❖ 5 × 80.0 cm Rainbow Ribbon cables in 5 different colours (±0.05cm)**
- ❖ A 5V 2 channel relay board***
- ❖ A Phillips screwdriver
- ❖ An empty data set and pens
- ❖ A pliers
- ❖ A power supply
- ❖ An iron nail for ferromagnetic (Fe) projectile[length of 4.8 cm & diameter 0.4 cm (±0.05cm)]

Figure 7.* An Ardunio UNO microprocessor[6]

Figure 8.** Rainbow Ribbon Cable[7]

[6] Ada, Lady. *Adafruit*, 2013, https://learn.adafruit.com/arduino-tips-tricks-and-techniques/upgrade. Accessed 18 Nov. 2022.

[7] "Uxcell IDC Rainbow Wire Flat Ribbon Cable 30 Pins 128cm Length 2.54mm Pitch Type-C." *Amazon*, https://www.amazon.com/uxcell-Rainbow-Ribbon-Cable-2-54mm/dp/B07JPLNW5B. Accessed 18 Nov. 2022.

*The author and the publishing date is unknown as the image is taken from an online shopping website

Figure 9.*** An 5V 2 channel relay board[8]

1.6. Method

Design of the launching tube

1. Arrange your camera in slow motion mode and put it in front of setup in order to record the point the projectile hits the ground.
2. Take a plastic pen with the diameter of 0.2cm ± 0.1 and cut the back-front curved parts using a caliper in order the create the launching tube of the system with a flat inner surface. (After the cutting process the length of the pen is decreased to 9.2cm ± 0.1)
3. Leave a piece of 8 cm wire sagging of the pen at the beginning. Start winding the 0.2 ± 0.1mm wire around the pen, 3.4 cm away from the side you will place the projectile. The wire should be winded in a selonoid-like form, one complete winding around the radius of the pen counting as one turn, the other turn is made right after it without leaving a space.
4. Continue the winding until the length of the coil reaches 3.1 cm horizontally leaving 2.7cm at the end of the pen.
5. Keep winding the wire from the top of the winding you have made until reaching 200 turns in total, finishing the creation of the coil. Leave 8 cm long wire sagging from the coil in order to be used in the electric circuit.

[8] "Arduino 5V 2 Kanal Röle Kartı (5V 2 Channel Relay Module)." *n11*, https://www.n11.com/urun/arduino-5v-2-kanal-role-karti-5v-2-channel-relay-module-14739004. Accessed 18 Nov. 2022.

*The author and the publishing date is unknown as the image is taken from an online shopping website

6. Place the prepared launching tube horizontally at the top of a box with 6.0cm width, 10.0 cm length, 5.0 cm height. Fix the tube to the box at the ends with a glue gun to prevent it from moving, the exact position (**Figure 10**).

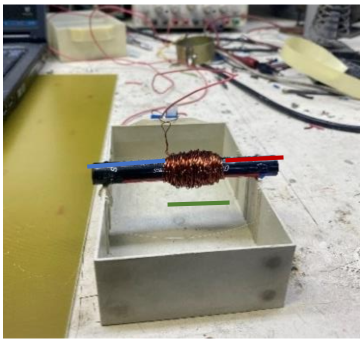


Figure 10. Demonstration of the launching tube with given parameters

Set up of the Electrical Circuit

a. **Preparation and coding of Ardunio UNO microchip**

1. Download the Ardunio 1.8.7 programme on your desktop and open the programme.
2. Plug the Ardunio UNO microprocessor into your desktop using a secondary cable.
3. Go to the device manager on your desktop, and choose the section "USO SERIAL CH340 (COM7)" under the title of "Ports (COM & LPT)", and wait for the appearance of red LEDs on the cart.
4. In the programme Ardunio 1.8.7, write the codes in **Figure 11** to create an algorithm which will function as the switching component in the circuit. According to code; when the signal of typing something is taken – just pressing the enter in this code is enough – the relay board lets the passage of the current for 100 millieseconds.

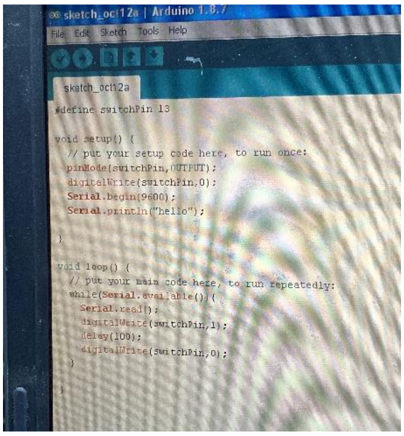


Figure 11. Demonstration of the example code for the Ardunio system

5. Press the right arrow in the left top side of the programme in order to upload your directives to the microprocessor.

b. Complete circuit design

1. Take 2 cables, connect one to the negative (-) pole of the power supply and fix the other side of this cable to COM channel of the relay board using a Phillips Screwdriver.
2. Peel off the 2.5 cm of the insulating top layer of the released ends of the coil with the help of pliers.
3. Take the second cable, connect it to the positive (+) pole of the power supply and thrust the other side of this cable to one of the peeled parts of the released end of the coil.
4. Connect the second released end of the coil to the NC channel of the relay board with the aid of a Phillips Screwdriver.
5. Take 3 cables of 80.0 cm ± 0.1 in the color red, black and orange for the connection of the Ardunio UNO microprocessor to relay board.
6. Connect one side of the orange cable to entrance of the 13 th I / O pin of the Ardunio UNO microprocessor while connecting the other side to signal entrance of the relay board (**Figure 6,7,8**).

7. Connect the one side of the black cable to GND pin of Ardunio UNO microprocessor while connecting the other side to negative (-) module of the relay board, shown in (**Figure 6,7,8**).
8. Connect the one side of the red cable to 5V pin of the Ardunio UNO microprocessor while connecting the other side to positive (+) module of the 5V powered relay board, (**Figure 6,7,8**).

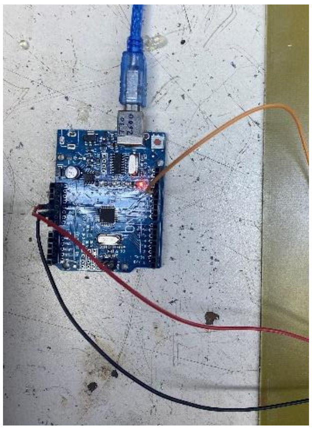


Figure 12. Ardunio microprocessor

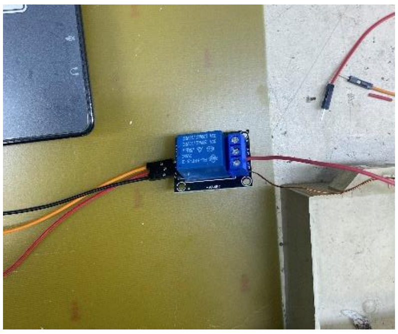


Figure 13. Relay board

Launching of the Projectile

1. Place nail with the length of 4.8 cm ± 0.1 cm and diameter 0.4 cm at the 3.4 cm away end from the coil. Make sure the nail is also 0.8 cm out of the tube to avoid suck-back effect.
2. Adjust the voltage to 10V from the power supply.
3. Press the enter button on the desktop, power the system and observe the launching of the projectile.
4. Measure the distance from the point the projectile hits the ground to the launch mechanism recorded by the camera and record it in the data table.
5. Repeat steps 1 to 4 for other voltage values of 11V, 12V, 13V, 14V, 15V.

The Complete Set-Up of the System:

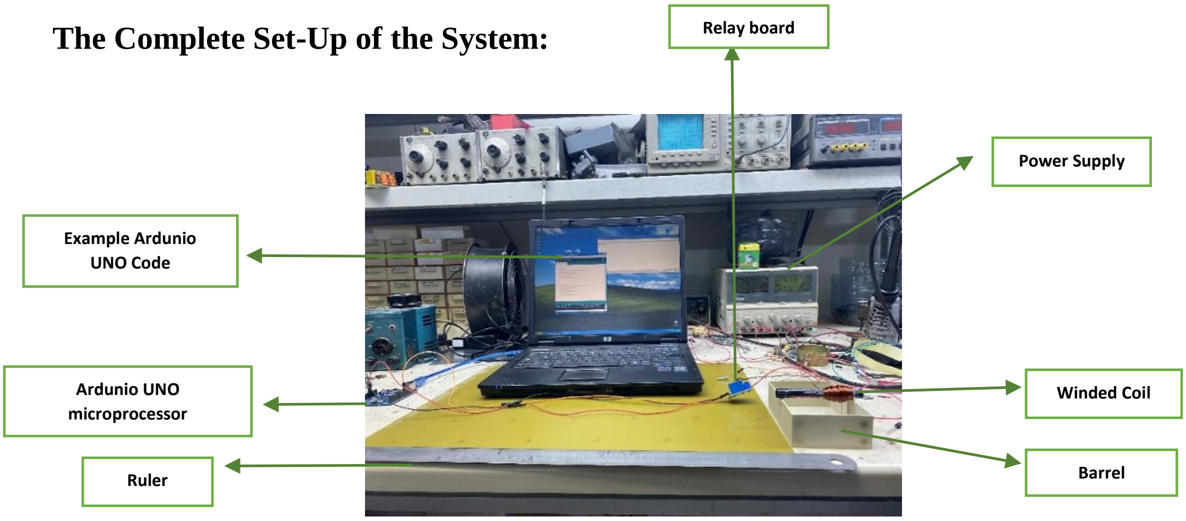


Figure 14. The demonstration of the complete experiment setup

2. ANALYSIS

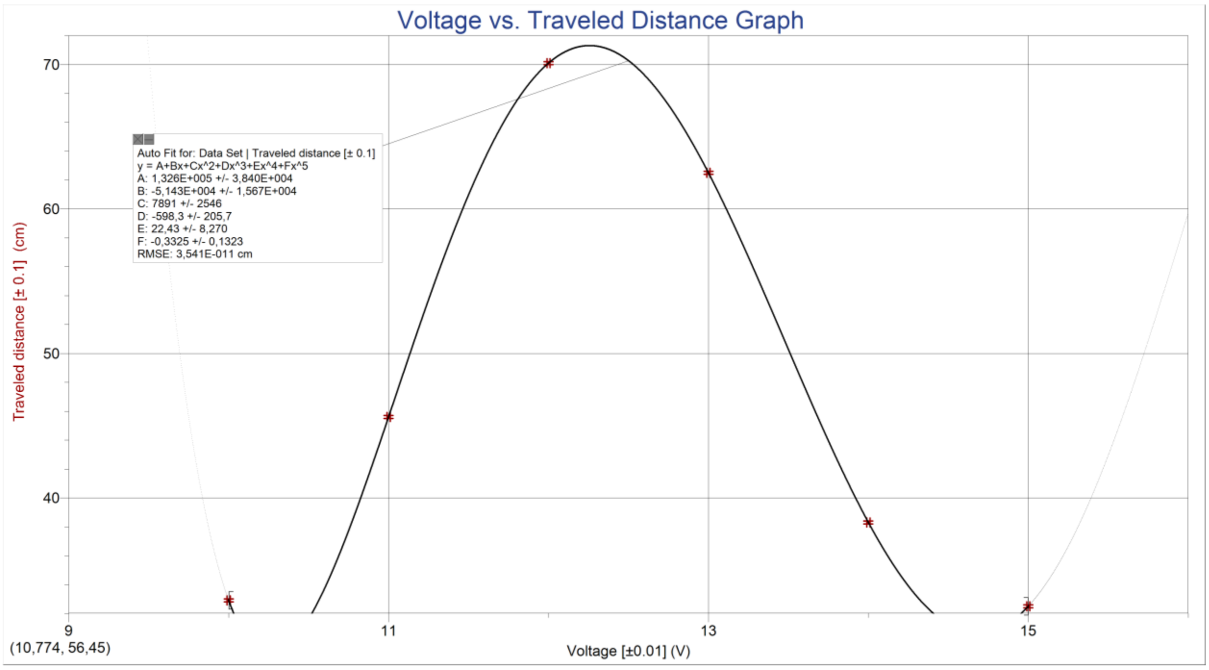
2.3. <u>Raw Data</u>

3 data for each voltage value are collected. (*Calculations are exampled in Appendix A Part 2*) The average of these data is taken and the uncertainty in the traveled distance (*Appendix B: Part 1*) is calculated in Table 1. (*The error of the data,*Δ***d,*** *is examlified in Appendix B: Part 2*).

Trials	Voltage (V) [±0.01V]	Axial Turns (N)	Current (A) [+ 0.01A]	Travelled Distance (cm) [±0.05]	Average Travelled Distance (cm)	Δd (cm)
1	10.00V	200	8.50	32.50	32.90	0.30
2		200	8.50	33.10		
3		200	8.50	33.10		
1	11.00V	200	9.00	45.80	45.60	0.25
2		200	9.00	45.30		
3		200	9.00	45.70		
1	12.00V	200	9.50	70.00	70.10	0.70
2		200	9.50	69.80		
3		200	9.50	70.50		
1	13.00V	200	10.00	61.70	62.50	0.85
2		200	10.00	62.40		
3		200	10.00	63.40		
1	14.00V	200	10.50	38.10	38.30	0.60
2		200	10.50	39.00		
3		200	10.50	37.80		
1	15.00V	200	11.00	32.00	32.5	0.35
2		200	11.00	32.80		
3		200	11.00	32.70		

Table 1. Quantitative data showing the effect of voltage on the travelled distance of the ferromagnetic material

Mass of the projectile used at each trial: 0.5g



Graph 1. Graph representing the voltage against traveled distance with percentage errors and the line of the curve fit.

Note: As the error bars are relatively small, bars cannot be observed clearly.

A curvative relationship between the change in voltage and the travelling distance of the projectile is present. Around the range of the voltages 10 to 12 there is an increase in the travelling distance of the projectile. 12V resultes in the furthest distance and supportes the notion of projectile working best in a certain range, which is claimed in the hypothesis.

2.4. Processed Data

2.4.1. Velocity Calculations using Horizontal Projectile Motion

The velocity determination of the projectile holds significance in the calculation of the efficiency of the coilgun.

Example calculation of the velocity of the 10V projectile

The traveling distance of the projectile launched with a voltage of 10V is determined to be 32.90 cm which corresponds to 0.329m as 1m= 100cm. The height of the barrel above the ground is known to be 5cm = 0.050m and gravitational acceleration is 9.79973 ms^{-2}. Therefore, when these values are fit into the equation, the velocity of the 10V given projectile is determined to be:

$$v = \frac{x}{\sqrt{\frac{2h}{g}}} = \frac{0.329 \pm 0.0005}{\sqrt{\frac{2\times(0.050\pm0.0005)}{9.798}}}$$

$$\approx 3.26 \pm 1.15\% \, ms^{-1}$$

Note: The uncertainty of the gravitational acceleration is not taken into account as it is relatively low (10^{-8} ms^{-2}).

Voltage (V) [±0.01V]	Average Travelled Distance (m) [±0.0005]	Average Velocity of the Projectile (ms^{-1}) [±0.0005]	Percentage uncertainty (3sf)
10.00	0.329	3.26	1.15 %
11.00	0.456	4.51	1.11%
12.00	0.701	6.94	2.07%
13.00	0.625	6.19	1.08%
14.00	0.383	3.79	1.13%
15.00	0.325	3.22	1.15%

Table 2. Processed quantitative data showing the correlation between the voltage, average travelled distance and the average velocity of the projectile with percentage uncertainties

The theoretical calculations of the velocity showed a corresponding value with the traveled distance, 12V representing the highest velocity (**Table 2**).

2.4.2. Efficiency Determination of the Coilguns with Varying Voltages

The works on coilgun systems are mainly based on increasing the efficiency of the system through the optimization of the parameters and determining the optimum values to reach the desired values of traveling distance or speed in the most efficient way. Efficiency is the ratio of output energy to input energy in the system. In the experimental set up of the system, the input energy is generated by the power supply. The energy provided by the supply is converted into the kinetic energy by the linear motion of the projectile in the barrel and the horizontal motion of the projectile after leaving the barrel. Therefore, the efficiency of the coilgun can be calculated through the following equation [11]:

$$Efficiency = \frac{Energy_{output}}{Energy_{input}} \times 100\%$$

Where;

$$Energy_{input} = \ P \ \times t$$

P: power generated by the power supply in watts (W)
t: the time power supply is active in seconds (s)

The power generated by the power supply to the circuit can be calculated with the following formula[11]:

$$P = I \ \times V$$

Where,
P: power generated by the power supply in watts (W)
I: current passing through the system in ampere (A)
V: voltage given to the system in volts (V)

Therefore, the input energy can be writtten as;

$$Energy_{input} = \ I \times V \times t$$

The output energy of the system is equal to the kinetic energy of the projectile *(the energy is assummed to be conserved throughout the motion of the projectile, ignoring the heat loss and friction)*. Hence, the output energy can be formulated through the following equation:

$$Energy_{output} = Kinetic\ Energy\ (KE)$$
$$= \frac{1}{2} \times m \times v^2$$

Where,

m: mass of the projectile in kilogram (kg)

v: velocity of the projectile (ms^{-1})

When the derivations are regulated, the efficiency of a single staged coilgun is found to be;

$$Efficiency = \frac{mv^2}{2IVt} \times 100\%$$

- <u>Example calculation of the efficiency of the 10V projectile</u>

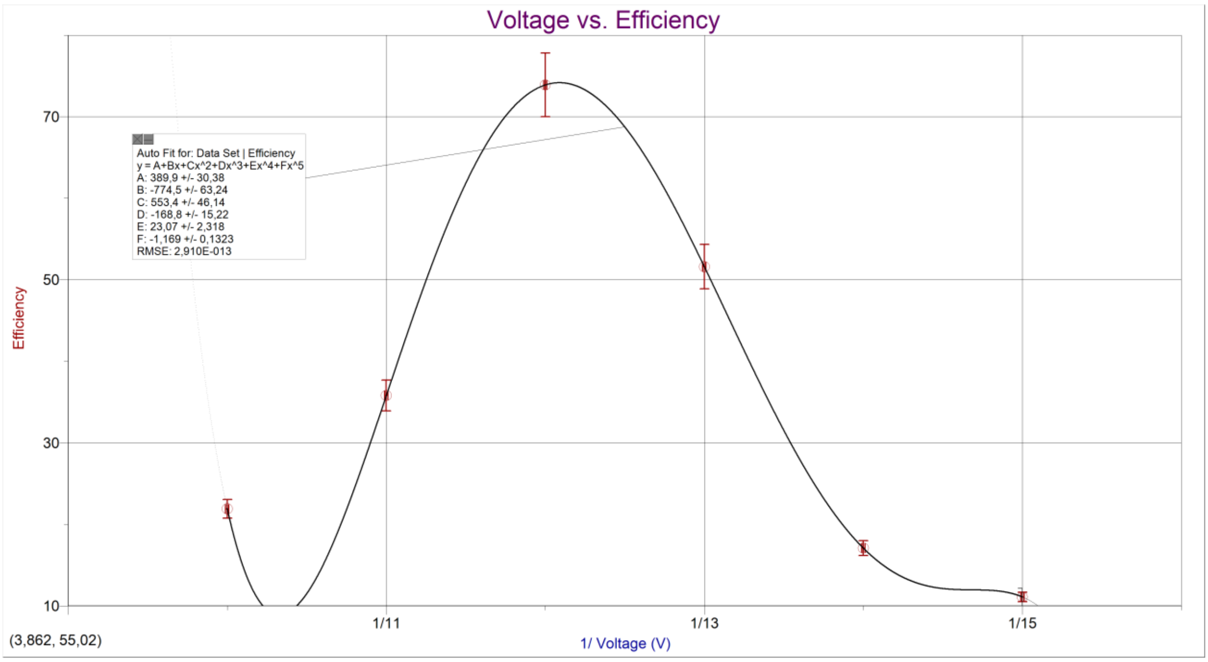
  The velocity of the projectile launched with a voltage of 10V is determined to be 3.26 ms^{-1}. The mass of the projectile is determined to be 3.5 g which corresponds to 0.0035 kg as 1g = 10^{-3} kg. The current passing through the system for 100 milliseconds which is 0.001 sec is determined to be 5.40 A. Therefore, when these values are fit into the equation below, the efficiency of the 10V given projectile is determined to be:

$$Efficiency = \frac{0.0035 \times (3.26)^2}{2 \times 8.50 \times 10 \times 0.001} \times 100\%$$

$$\approx 21.9\ \%$$

Voltage (V) [±0.01V]	**Average Velocity of the Projectile (ms^{-1}) [±0.0005]**	**Current (A) [+ 0.01A]**	**Time (sec) [± 0.0005sec]**	**Efficiency**	**Percentage uncertainties (%)[3sf]**
10.00	3.26	8.50	0.001	21.9%	3.38
11.00	4.51	9.00	0.001	35.8%	5.28
12.00	6.94	9.50	0.001	73.9%	7.19
13.00	6.19	10.00	0.001	51.6%	5.20
14.00	3.79	10.50	0.001	17.1%	5.29
15.00	3.22	11.00	0.001	11.1%	5.32

Table 3. Processed quantitative data showing the correlation between the voltage, the average velocity of the projectile, and the efficiency of the single staged coil gun with current and time values in addition to percentage uncertainty of efficiency.



Graph 2. Graph representing the inverse voltage against efficiency with percentage errors and a curve fit .

Note: The inverse of the voltage is used according to the equation.

There is an increase in the efficiency of the single staged coil gun with respect to increase in the voltage of the projectile until the 12V (**Table 2, Graph 2**). Between comparisons of the voltage to efficiency, it cannot be commented that the voltage and efficiency is directly proportional as the maximum velocity values do not belong to the highest voltage value. There is the data with the velocity of 3.71 ms^{-1} and voltage of 14, claming an outlier and distrupting the linear relationship between velocity and efficiency. This is a convincing evidence supporting the hypothesis, which claims that there is a certain voltage range where the coil gun reaches the most efficient parameters which is found to be 12V according to experimental results of this investigation.

3. CONCLUSION AND EVALUATION

This investigation of a single-staged coil-gun and the effect of voltage on the traveling distance of the coil-gun projectile has led to several unexpected conclusions with the calculation of initial velocities, hence the efficiency of the coil-gun.

It is observed that, with the given parameters of the experimental set-up, a range of voltage values work for the forward motion of the projectile. Through the preliminary experiments, the voltage range that works for this coilgun system is determined. Due to the suckback effect, in values lower than 10V, the system did not work, the projectile fled back, or the distance resulted relatively low, stating a value of 0 for the velocity among the voltages 0 to 10V. In this investigation after the 13V, the data depict a decreasing relationship rather than an increasing trend.

The traveling distance is observed as it is the main aim of several industries, such as aerospace, as the velocity of the rocket and the distance it travels are important for determining the amount of energy it needs to reach an orbit. Using the traveling distance, we deduced the velocity, which is later used in the calculation of the efficiency of the coilgun. The initial velocity of the projectile was determined through the mechanical derivations, which is horizontal motion, as the acceleration of the projectile leaving the barrel is assumed to be constant.

The current flowing in a magnetic field faces an action force. In the launching process, the induced current in the projectile opposes the current passing through the coil. The applied current to the coil creates an alternating magnetic flux, which induces an alternating current from the main current, resulting in a force with a repulsiveness of half a period. If the magnitudes of the repulsive and attractive forces were to be the same, the projectile would remain motionless or would oscillate; however, this is not possible in this case. The repulsive forces outdid the attractive forces, dominating the system. Therefore, a constant acceleration is reached for the projectile where the electromagnetic force experienced by the projectile is equal to the mass per change in velocity in the coil divided by the change in time, proving the constant acceleration [3]. However, calculating the velocity through mechanics rather than the equations based on electromagnetics presents a limitation. The electromagnetic equations were meant to be the derivations of the velocity in this experiment in the first place, but due to the lack of a constant induced current and magnetic force, which cannot be calculated through equations and simulations are needed, the electromagnetic derivation is not preferred.

Traveling distance and the initial velocity values of the data resulted similarly, showing a quartic relationship, with the 12V resulting both with the longest travelling distance in addition to the highest velocity (**Graph 1, Table 2**). The similarities between the trends prove that long travel distances can be achieved through high velocities. Hence, it is determined that the coilgun reached the highest velocity with a relatively high voltage but low current, regarding the experimental ranges of voltage and current. Higher voltage results in higher current passing through the coil and an increase in the delivered energy; however, the thickness of the coil is a substantial parameter (as it is the main resistance of the system) in the limitation of the current, with further voltages and higher currents ensuing the possibility of coil damage and a lack of carrying capacity for the current.

Finally, the efficiency calculation of the coilgun **(Table 2)** suggests that the voltage of 12V results with the highest value with showing 73.9% efficiency. In literature, the efficiency of a coil gun is determined to be able to reach up to 74%. However, this value can be reached through approximately 466 coils and energy must be recovered, in the single staged coilguns the efficiency is relatively low; only reaching 1%-2% [6]. Therefore, the theoretical efficiency values are way higher than literature values, which can be explained as the result of disregarding the friction and energy loss to heat in the velocity calculations and in the power calculation for the efficiency derivation. Also, in the literature value; the data with the maximum voltage did not found to be the most efficient one shown (**Figure 15** [9]), corresponding the conclusion derived from the investigation. **Graph 2** shows the quantic relationship between the inverse voltage and efficiency similar to voltage vs. velocity. **Table 2** depicts a direct relationship between the efficiency values and the velocities parallel to expectation, stated in the hypothesis and supporting the trend in **Graph 2**. However, the data contains several outliers indicating the error due to derivation of the values trough several calculations and random error occurred during the collection of the data.

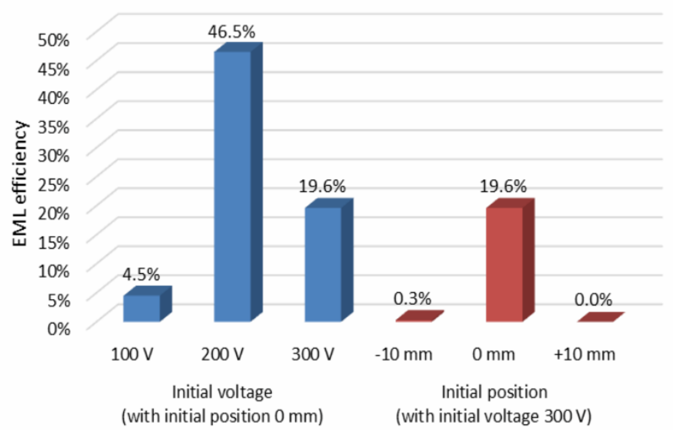


Figure 15. *Literary eficicency values for varying voltages*

Overall, the most efficient single-staged coil gun with 200 axil turns, a diameter of 0.2 mm, and a projectile of mass 3.5g with a length of 4.8 cm and a diameter of 0.4 cm launched from a barrel with 9.2 cm length and 0.5 cm diameter is determined to be 12 V.

Most of the uncertainties arise from the limitation of the set up. Due to the smoothness of the surface where the projectile hits the ground, projectile makes a bouncing motion right after it hits the ground. The first place projectile hits ground was taken into

[9] Klimas, Maciej, Dariusz Grabowski, and Anna Piaskowy. "Efficiency Analysis of an electromagnetic launcher." *Elektryka, Silesian University of Technology Publishing, Poland* (2016).

account. Even though a camera is used to determine the position of the projectile the results are still opened to random error. This error can be minimized by using a surface, such as a sandy one, in which the projectile can rake when it hits the ground. However, this error is rather small and results in acceptable data (**Graph 1**). Another issue and error source is the turns of the coil. Even though, I tried to turn the wire properly by not leaving a space between the turns; it is still a major random error. Therefore, an already existing coil can be used instead of creating one. Another problem with coil was that with every new trail, the coil became hotter and hotter due to current passing, causing the energy to transform to heat; therefore the magnetism of the coil was affected, resulting in a systematical error. This prolongs the data collection process and reduced the number of trials. Different coils with same number of turns and wires can be used to avoid this limitation. Also, in a coilgun set up without a capacitor, using Ardunio UNO programming for the closing of the switch circuit instead of a button, reduces the random error caused by the reaction time greatly.

Another major limitation is that there was not any direct formulation for the velocity calculation for distance and efficiency calculation from velocity. Therefore, indirect verifications were use to reach the values involving lenght and time calculations which increase the uncertainties further (**Table 2, Table 3***)*. To avoid one step of the derivation, Logger Pro can be plugged to draw the velocity graph in order to determine the exit velocity of the projectile. Hence, the velocity values would result with lower errors.

This experiment can be extended to various parameters such as coil number, projectile mass, barrel length, and the optimization of a multi-stage coil gun. I would love to see research and calculations based on electromagnetic derivations, which are above my level of understanding. I believe further experiments could lead to new applications of the EML systems and improvements in aerospace and industrial research.

4. APPENDIX

Appendix A: Data Collection

Part 1. Preliminary Testing Results

	Travelled Distance ± 0.05 cm				
Trials	Voltage:5.00± 0.01V	Voltage:6.00± 0.01V	Voltage:7.00± 0.01V	Voltage:8.00± 0.01V	Voltage:9.00± 0.01V
1	1.00	-	1.50	-	1.50
2	0.50	2.00	-	-	2.00
3	-	-	0.50	-	1.50

Part 2. Raw Data Table

$$\textit{Average value} = \frac{\textit{Sum of all observations}}{\textit{Total number of observations}}$$

(Datas from 10V is used as an example)

$$\textit{Average value} = \frac{32.5+33.1+33.1}{3} = 32.90 \text{ cm}$$

Appendix B: Processed Data Calculations

- Travelled distance is converted into meters by dividing the values by 10^2.

  (Datas from 10V is used as an example)

  Distance = $32.90/10^2 = 0.329$m

- Time that is taken to close the circuit is converted into seconds by dividing the value by 10^6.

  Time= 100 milliseconds= $100/10^6 = 0.001$ sec

- Mass of the projectile is converted to the kilograms by dividing the value with 10^3.

  Mass= $3.5 / 10^3 = 0.0035$ kg

Appendix C:

Part 1. Uncertainty Calculations

- **Velocity Calculations using Horizontal Projectile Motion**

When distance is converted to meters, values and uncertainty is both divided by 10^2, which results in the uncertainty of the value of height 5± 0.05cm becoming 0.0005. The uncertainty of the travelled distance corresponds to uncertainty value of 0.0005 as the same apparatus is used for both calculations. Percentage uncertainty in the velocity is determined for the example of 10V:

$$\Delta(v)\% = (x \div h) \pm (\Delta x\% + \Delta h\%)$$

Travelled distance(x) = 0.329 ± 0.0005 m

Height(h) = 0.050 ± 0.0005 m

$$\boldsymbol{\Delta(v)}\% = \pm(\frac{0.0005}{0.329} \times 100 + \frac{0.0005}{0.050} \times 100)$$

$$\approx \pm\mathbf{1.15}\%\ \boldsymbol{ms^{-1}}$$

Note: As the uncertainty of the constant "2" is 0 and the uncertainty of the gravitational acceleration is ignored, therefore the uncertainty is solely affected by the uncertainty of distance and height.

- **Efficiency Determination of the Coilguns with Varying Voltages**

When mass is converted to kilograms, values and uncertainty is both divided by 10^3, which results in uncertainty being 0.0001. Therefore, the uncertainty of the efficiency of the coilgun can be found by;

$$\Delta(Eff)\% = \left(\frac{m \times v^2}{I \times V}\right) \pm (\Delta m\% + 2 \times \Delta v\% + \Delta I\% + \Delta V\%)$$

(10V is used as example)

$$\Delta(Eff)\% = \pm(\frac{0.0001}{0.0035} \times 100 + 2 \times \frac{0.0005}{0.329} \times 100 + \frac{0.01}{8.50} \times 100 + \frac{0.01}{10.00} \times 100)$$

$$\approx \pm(2.86\% + 0.30\% + 0.118\% + 0.1\%)$$

$$\approx \pm\mathbf{3.38}\%$$

Note: As the uncertainty of the constant "2" is 0 and the uncertainty of the time is ignored as it is deduced by the written code, therefore the uncertainty is affected by the uncertainty of mass, velocity and voltage.

Part 2. Error Calculations

The error of the collected data is calculated through extracting the minimum value from maximum value and divided by the 2.

(Datas from 10V is used as an example)

Data Collection Error = $\frac{maximum\ value - minimum\ value}{2} = \frac{33.1-32.5}{2} = 0.30cm$

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5. BIBLIOGRAPHY

1. Abdo, Tamer M., et al. "Performance analysis of coil-gun electromagnetic launcher using a finite element coupled model." *2016 Eighteenth International Middle East Power Systems Conference (MEPCON)*. IEEE, 2016.
2. Andras, M. (2018, December). *The demonstration model of an electromagnetic accelerator gun*. Research Gate . Retrieved September 22, 2022, from https://www.researchgate.net/publication/330426363_The_Demonstration_Model_of_an_Electromagnetic_Accelerator_Gun
3. Chaithanya, S., & Kumar, V. (2021, April 22). *Ijert-a review on technological advancement in Electromagnetic Coil Gun System*. International Journal of Engineering Research and Technology (IJERT). Retrieved April 23, 2022, from https://www.academia.edu/47428417/IJERT_A_Review_on_Technological_Advancement_in_Electromagnetic_Coil_Gun_System
4. Holzgrafe, Jeff, et al. "Effect of projectile design on coil gun performance." *Franklin W. Olin College of Engineering, December* 14 (2012).
5. Khandekar, Sucheta. “Single-Stage Reluctance Type Coilgun - Paperpublications.org.” *Paper Publications*, International Journal of Recent Research in Electrical and Electronics Engineering (IJRREEE), 2016, https://www.paperpublications.org/upload/book/Single-Stage%20Reluctance%20Type%20Coilgun-794.pdf.
6. Klimas, Maciej, Dariusz Grabowski, and Anna Piaskowy. "Efficiency Analysis of an electromagnetic launcher." *Elektryka, Silesian University of Technology Publishing, Poland* (2016).
7. Lee, Su-Jeong, et al. “Coil Gun Electromagnetic Launcher (EML) System with Multi-Stage Electromagnetic Coils.” *Journal of Magnetics*, vol. 18, no. 4, The Korean Magnetics Society, 31 Dec. 2013, pp. 481–486. *Crossref*, doi:10.4283/jmag.2013.18.4.481.
8. Lee, Su-Jeong, Jin Ho Kim, and Soo-Hyun Kim. "Design and experiments of multi-stage coil gun system." *Journal of Vibroengineering* 18.4 (2016): 2053-2060.
9. Macit, Hüseyin Bilal. “Arduino Ile Röle Kullanımı.” *HÜSEYİN BİLAL MACİT*, 4 June 2020, https://www.hbmacit.com/2020/01/09/arduino-ile-role-kullanimi/.
10. Skala, B., Kindl, V. (2014). Electromagnetic Coil Gun – Construction and Basic Simulation. In: Březina, T., Jabloński, R. (eds) Mechatronics 2013. Springer, Cham. https://doi.org/10.1007/978-3-319-02294-9_12. Accessed 10 Oct. 2022.
11. Tsokos, K., 2014. *Physics for the IB diploma*. 1st ed. Cambridge: Cambridge University Press.
12. Turman, B. N., and R. J. Lipinski. "Electromagnetic coilgun launcher for space applications." *AIP conference proceedings*. Vol. 361. No. 1. American Institute of Physics, 1996.