Modeling, Constructing, and Testing an Electromagnetic Rail Gun with Python

Nicholas Swartz, Dr. Trey Holik| Department of Physics & Geosciences, Angelo State University

Abstract

A computational model was created to solve the coupled differential equations for projectile acceleration, current, and induced voltage of a rail gun. The final velocity is calculated based on projectile mass, capacitance, rail geometry, initial voltage, and resistance as input parameters. A small prototype rail and projectile was fabricated and characterized to verify the computer program and for use in physics outreach demonstrations.

Theory

- To find final velocity as a function of the design parameters, a combination of kinematics and electrodynamic laws must be applied.
- Rail guns convert electrical energy to kinetic energy using the Lorentz Force Law for a current-carrying wire:

$$\vec{F} = I\vec{l} \times (\vec{B}_L + \vec{B}_p)$$

Where:
F = Force on Wire
I = Current
l = Length of Wire
B_L = Induced Magnetic Field
B_p = Permanent Magnetic Field

- Induced Magnetic Field is given by the Biot-Savart Law of two semi-infinite parallel wires:

$$B_L = \frac{\mu_o}{2\pi} \ln\left(\frac{r+l}{r}\right)\frac{I}{l}$$

Where:
μ_o = Permeability Constant
r = Radius of Rails

- Kirchhoff's Law is used to find an equation for current, accounting for the capacitors, total resistance of the circuit, self inductance of the circuit, and back-EMF of the projectile's movement.

$$\frac{Q}{C} - IR - L\frac{dI}{dt} - B_p l v = 0$$

Where:
Q = Charge in Capacitors
C = Total Capacitance
R = Resistance of Circuit
L = Self-Inductance of Rails
v = Velocity of Projectile

- Self-Inductance of the circuit is given by Faraday's Law for two parallel wires:

$$L = \frac{\mu_o}{\pi} \ln\left(\frac{r+l}{r}\right) x$$

Where:
x = Position of Projectile

- Analytically solving these equations for functions of position and charge would be difficult if not impossible, so numerical solution methods were applied instead.

Computational Model

- To calculate muzzle velocity of a rail gun with known initial conditions, Python was used to apply Euler's method of numerical integration:

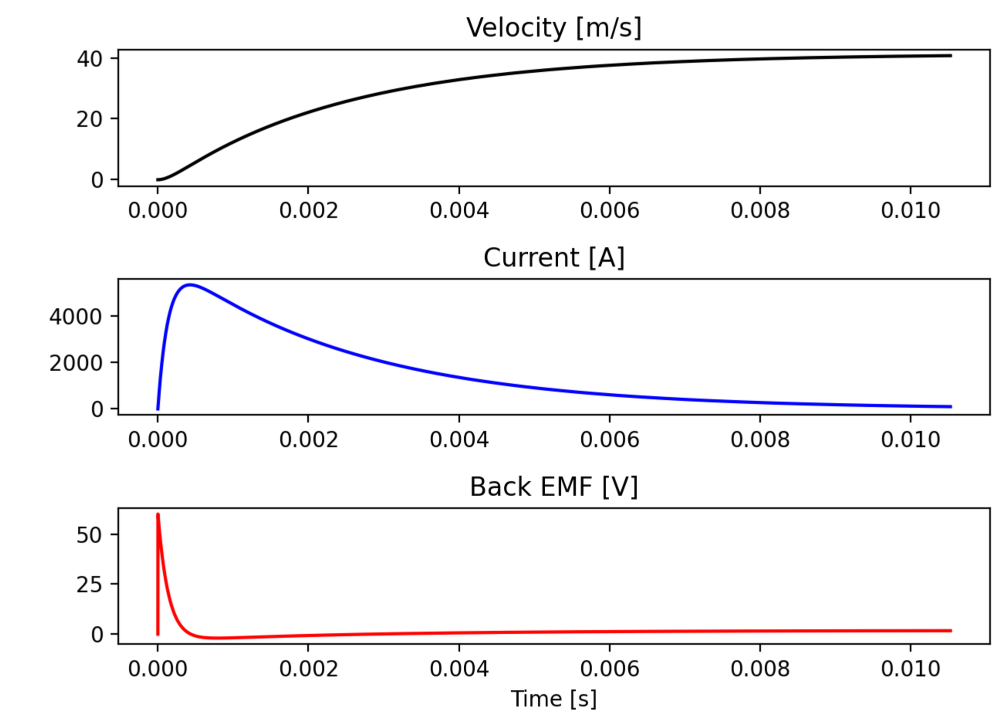
$$f(t + \Delta t) \approx f(t) + \Delta t \cdot \frac{df}{dt}$$

- The Lorentz force law and KVL can be solved to find dv/dt and dI/dt, respectively.

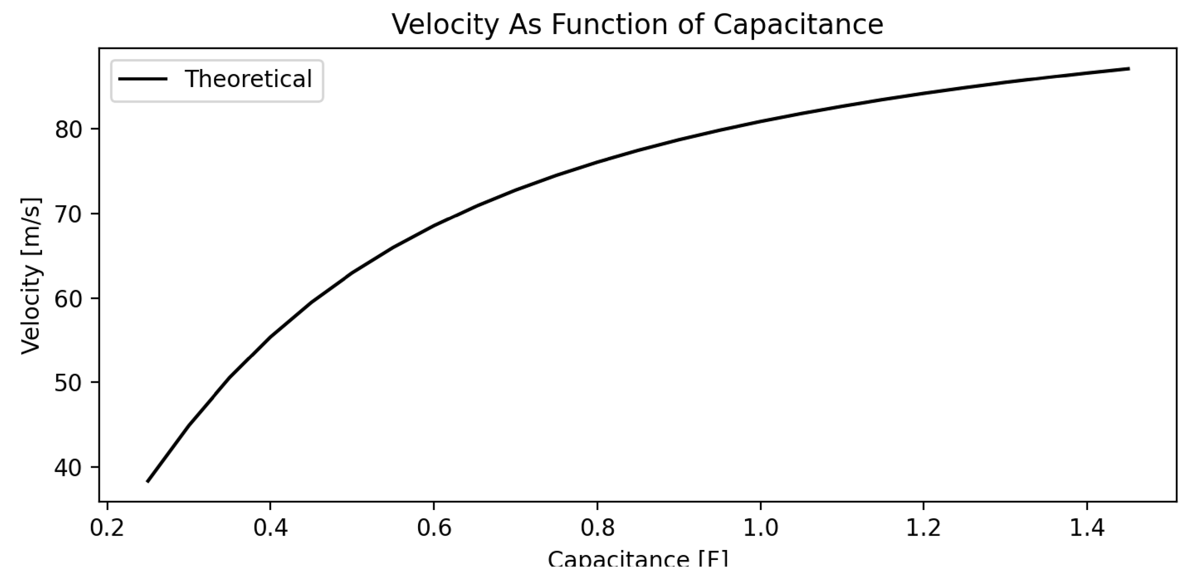
$$\frac{dv}{dt} = \frac{Il \cdot (B_L + B_p)}{m}$$

$$\frac{dI}{dt} = \frac{1}{L}\left(\frac{Q}{C} - IR - B_p l v\right)$$

- Using these equations and Euler's method, the values of velocity and current can be calculated in small steps. These calculations are continuously updated in a loop until the projectile reaches the end of the barrel and the muzzle velocity is output.

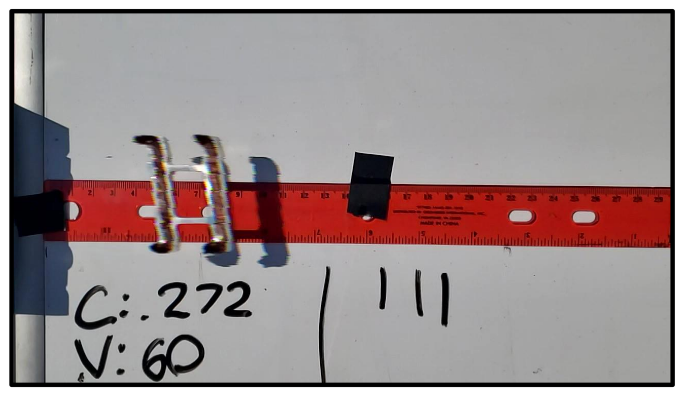


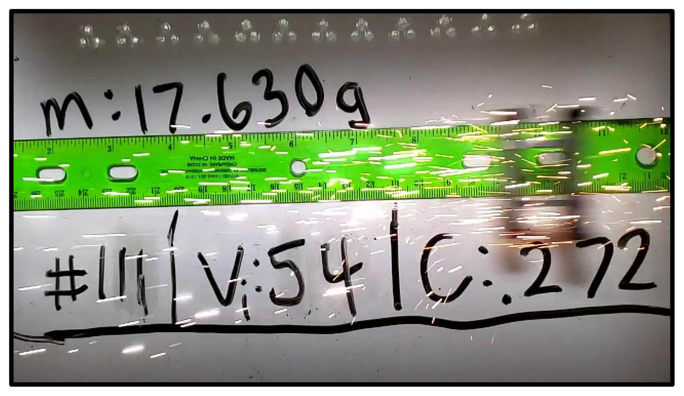
- By placing this Euler's Method loop into another loop that will increment a design parameter, I can see how changing that parameter changes muzzle velocity.



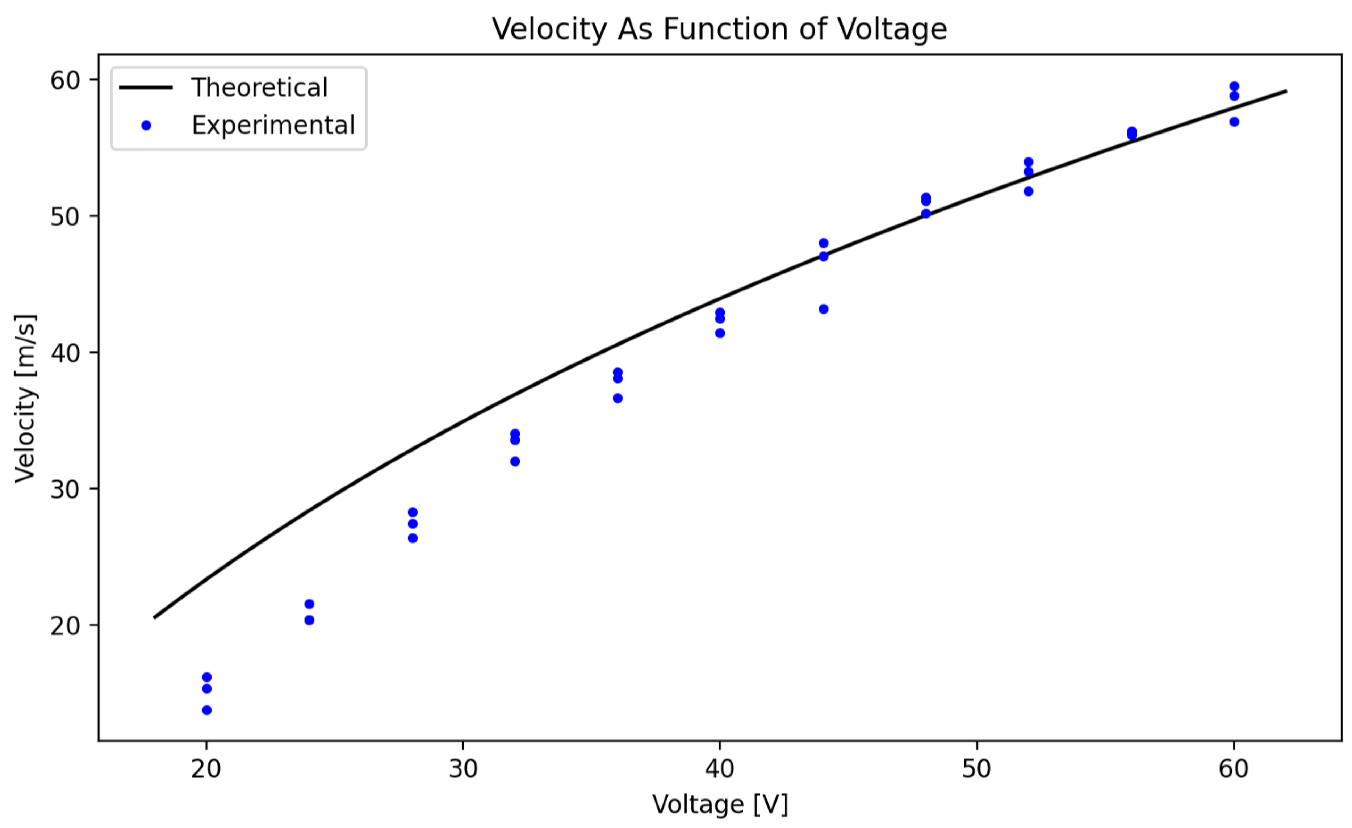
Experiment & Data Analysis

- To verify the computational model is correct, it is input the design parameters of the constructed rail gun and compared against experimental data.
- Muzzle velocity was measured by placing a ruler at the end of the barrel and recording the movement of the projectile using a 960fps camera.





- Initial voltage was controlled in steps of 6V with a power supply, with three firings recorded at each voltage step.
- To account for velocity variation as wear on the rails and projectile progressed, data was taken in three consecutive sets of one firing per voltage value.

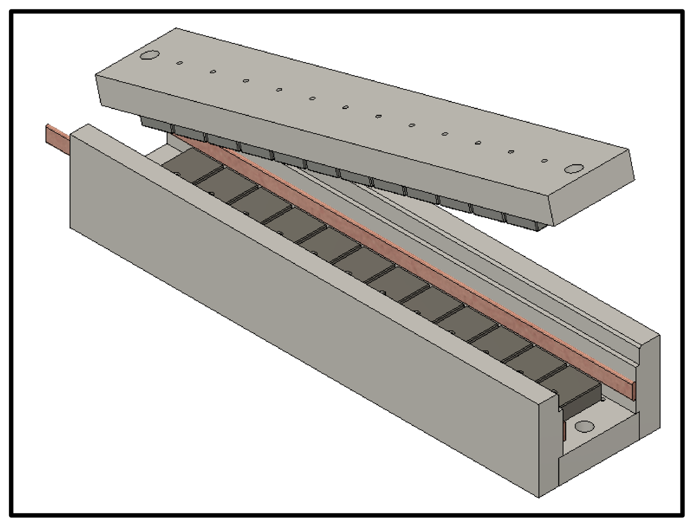


Conclusion

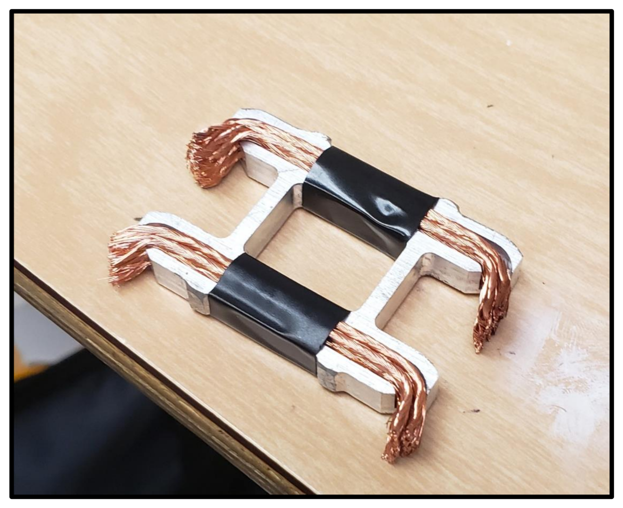
- The computational model appears to accurately model muzzle velocity as a function of initial voltage, with some deviation at lower voltages that could be due to friction being more prevalent or due to how the projectile holds contact with the rails.
- Future work will be to experimentally measure velocity as a function of capacitance by removing capacitors between firings, or measure as a function of barrel length by loading the projectile further inside the barrel.

Rail Gun Fabrication

- The barrel of the rail gun is composed of neodymium magnets above and below the projectile slot, with graphite-coated copper rails on either side.
- ¾ inch thick steel surrounds the magnets and rails to provide rigidity and paths to focus magnetic flux.



- The projectile is made from two strands of braided copper cable held within an aluminum frame.
- The copper wire acts as an electrical brush to hold electrical contact with the rails with minimal friction and can be easily replaced as the contact surfaces vaporize.



- Electrical current is provided by a bank of aluminum electrolytic capacitors connected in parallel.
- The capacitor bank is charged from 9-volt batteries and then discharged across the rails.
- Charging and discharging is safely controlled using two high power relays.