4-19-2022

Electromagnetically Propelled Garage Door

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April 12, 2022

Disclaimer

Acknowledgements

We would like to thank the following staff for their generous support toward the project. This design project was successful only because of their support:

Dr. Bade Shrestha – Senior Design Professor, Western Michigan University MAE Department

Dr. Jinseok Kim – Faculty Mentor, Western Michigan University MAE Department

Abstract

Garage door systems are loud and energy inefficient given their many contact points and need for continual maintenance. Most garage door systems use a loud, bulky electric motor to pull the garage door up and down using a chain. To reduce noise and energy loss due to friction from the electric motor and chain, electromagnetic forces used in Electromagnetic Suspension (EMS) trains were researched and adapted to a garage door system. The electromagnetically propelled garage door (EPGD) system was designed and validated using SOLIDWORKS and ANSYS simulation with significantly less contact points due to non-contact electromagnetic propulsion (EMP). The design is for a roll-up type garage door system that is used in most industrial settings and uses pre-designed garage door geometry while incorporating new propulsion through electromagnets. A prototype was built to show proof of the concept of the garage door system. The completed model provides further insight into EMP technology and its use in garage door systems. The electromagnetically propelled garage door system explores vertical application possibilities of EMS and EMP and will provide a quieter, more efficient garage door.

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Introduction

Background

Today, garage doors are found in most modern suburban and rural houses in America. Garages began appearing in the 1920s and became popular only one decade later after a need appeared to protect sizable household items and automobiles. Using a garage to store valuable items and vehicles has evolved since 1920 and has been a necessity for homeowners ever since. Not only are garage doors used in homes, but many garage doors are used in warehouses and other commercial settings.

As garages have become more widespread and with the invention of innovative technology, garage doors have become stronger, lighter, and have been designed to open and close without human effort. Currently, garage doors can open and shut using electric openers and remote controls, allowing owners to raise and lower their garage door with the press of a button. With this innovation, there are yet areas for improvement regarding noise and energy loss due to friction, which requires a solution to reduce this noise and friction within the garage door system.

Problem Posed and Need

In America, 63% of all housing units use either a garage or carport for vehicle protection or storage. With many garages in the United States, bringing about an innovative garage door product has large consumer potential and interest. Since garage doors are an essential necessity for every suburban and rural home, innovating garage opening and closing technology would benefit a significant portion of the population.

With every garage door opening and closing an average of 3-5 times a day, garage door opening and closing amounts to approximately 1500 times a year. With high usage, a design that is reliable and repeatable for these cycles will be ideal. Most garage door openers last for approximately 20 years, and the reason many fail is due to a lack of lubrication. The need for lubrication reveals that a leading contributor to the decline of garage door life is friction. This friction is due to contact from the garage door chain, pulleys, and rollers.

With a massive portion of the population using garage doors, there is a large market opportunity and need from consumers. With a lack of maintenance being the leading cause of garage door failure, decreasing the need for maintenance will increase garage door life and ultimately lower costs for the customer. An innovative, more reliable garage door would be a substantial improvement to the homeowner market.

Objective

The objective is to implement new propulsion technology through magnetic propulsion to open and close garage doors. The garage door would raise and lower with minimal contact on the tracks through electromagnetic propulsion. This would significantly decrease the friction points of the garage door system, leading to a decrease in the need for lubrication and maintenance. Since garage door maintenance is often overlooked by homeowners, decreasing maintenance required would increase the life of garage doors with electromagnetic propulsion technology.

Scope and Limitation of Work

This project is primarily focused on implementing innovative technology into garage doors to decrease energy losses. While there are ways to improve the structure of the garage door itself, most areas for improvement lie in enhancing efficiency and reducing noise through electromagnetic propulsion and suspension. For this reason, reinventing garage door structure and dimensions is omitted from the scope of this project.

Due to time constraints, safety features such as an auto-reverse function and mechanical release feature are omitted from the project scope. The auto-reverse function uses infrared photo eye sensors to sense if there is an object in the way of the garage door and keeps it from continuing to close once the eye sensors are obstructed by an object. The mechanical release feature allows users to manually raise and lower the garage door in the case of a power outage. In our case, a power outage would mean that the door cannot remain closed or open and will be able to be raised and lowered freely.

Specifications and Requirements

After extensive research on customer preference and market environment, design specifications and requirements were established for the garage door mechanism. According to the state of Michigan, a single residential garage door must not exceed 8 feet in height and 8 feet in width. As electromagnetic propulsion and suspension are the primary focus of this project, dimensions from a leading garage door manufacturer are used. The garage door component dimensions and requirements for the project are listed in *Table 1* below. In addition, *Figure 1* is provided for clarity and reference.

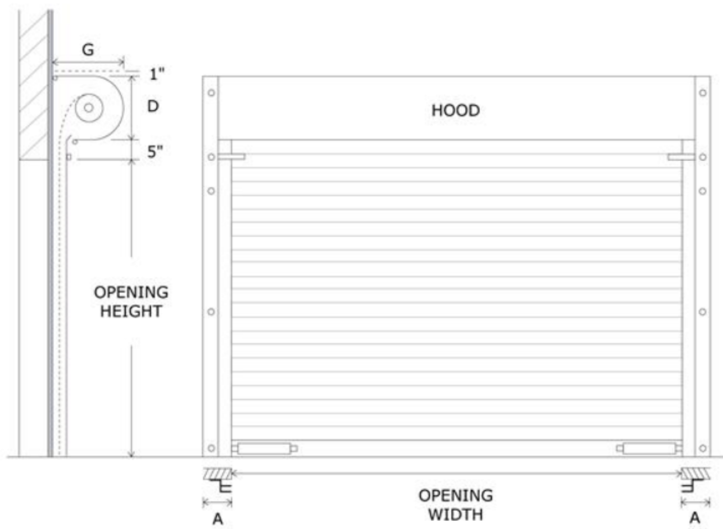

Figure 1: Diagram of Roll Up Door

Table 1: Component Dimension Constraints

Component	**Dimensions**
Opening Width	7.0 ft
Opening Height	8.0 ft
A	5.0 in
D	15.0 in
G	15.0 in
U-tube Guiderails	1 5/8 x 1 5/8 x 12 in
Torsion Spring	1 3/4 in diameter
	24 in length
	218 wire size
Permanent Magnets	1/2 x 1/2 x 1/2 in
Electromagnetic Coils	0.7 x 1 in diameter

Each physical component dimension constraint was researched and chosen regarding average customer requirements for residential garage doors. The garage door design is chosen as a roll-up garage door with an opening of 8ft wide by 7ft tall, as it is the most popular garage door opening size in America.

In addition to compact dimensions for the product, various performance specifications must be met as well. In order to be a competitive product that customers would prefer, specific specifications regarding opening/closing speed, noise, and durability must be met. In the list below, performance specifications are outlined and explained in further detail.

- <u>Speed:</u> The average garage door opens 7 inches per second. The specified speed for the electromagnetically operated garage door will be less than or equal to 7 inches per second (speed < 7in/sec).
- <u>Noise</u>: Noise occurring from operating a garage door ranges from 5dB to 20dB above background noise from the environment. The noise requirement for the

electromagnetically operated garage door will be less than or equal to 5dB above background noise (Noise < 5dB).

- Durability: The average life expectancy of a garage door is 20 years (10,000 cycles). The life expectancy requirement for the electromagnetically operated garage door will be greater than 25 years or 15,000 cycles (Cycles > 15,000)

Solution

Benchmarking

Currently, there is no electromagnetically propelled garage door system that exists on the market. Most garage doors use an electric motor that pulls a chain to raise and lower the garage door. The electromagnetically propelled garage door system will be the first garage door system to operate autonomously without a moving chain. Without this chain, there is significantly less noise and energy loss, making it advantageous for certain applications, allowing it to be slightly more expensive than the regular garage door system which is $2,000-$3,000. To remain competitive, the garage door system shall remain less than $3,000, although the electromagnetic garage door system has unique advantages that can justify being more expensive. Below is a benchmarking table over different types of garage door systems, with the magnetic levitation garage door on the right-hand side.

Features	Product			
	Sectional Garage Door	Roll Up Garage Door	Tilt Up/Hinge Garage Door	EMP Roll-Up Garage Door
Noise (1= Very quiet; 5= Very loud)	4	4	4	1
Maintenance (1= No Maintenance; 5= Lots of Maintenance)	2	2	3	1
Cost (1= Very inexpensive; 5= Very expensive)	4	4	4	4
Size (1= takes up minimal space; 5= takes up lots of space)	3	1	5	2
Total	13	11	16	8

Table 2: Benchmarking for Decision-Making Process

The EMP Roll-Up Garage Door scored the best (lowest) score of 8 compared to the other types of garage door systems. The main advantages of the EMP door system are the low noise level and smaller, more compact size. After using the benchmarking tool, the EMP Roll-Up Garage Door showed itself to be the most competitive garage door system and will be designed for the project.

Alternative Solutions

The EMP garage door system is designed to replace traditional electric motor garage doors. With multiple different ways to implement the new EMP technology, different propulsion strategies and door geometry types must be analyzed and compared using a decision matrix. This system has main factors that are placed at different priorities than others.

Decision Matrix

The decision matrix was used to help decide which kind of electromagnetic propulsion would be the best to use in the design. The EMS propulsion designs utilize programmed electromagnets that turn on and off to pull the door up and down the track. The EDS style propulsion designs utilize electromagnetic suspension through superconductors which provide levitation to the garage door between each vertical track while electromagnets turn on and off to pull the door up and down the track. The EDS style propulsion system would be an ideal system, except for the superconductors needed in the system. Superconductors must be cooled to extremely low temperatures to levitate in a magnetic field. Continuously super cooling superconductors for this application would add complexity and create new safety risks since liquid nitrogen is the main super cooler and is harmful to humans.

In the decision-making matrix below, propulsion strategies are compared with respect to safety, cost, efficiency, size, ease of construction, maintenance, and ease of design. Each strategy is given a score between 1-10 with 1 being the best score and 10 being the worst. Next to each criterion in the table, the weight of importance is given within the parenthesis. The weighted total is calculated by summing the weighted scores for each criterion in a propulsion strategy. The total is used to decide on the most ideal propulsion strategy, which is the EMS Roll Up design.

Decision-Making Matrix								
	Criteria							
Propulsion Strategies	**Safety (9)**	**Cost (6)**	**Efficiency (6)**	**Size (4)**	**Ease of Construction (6)**	**Maintenance (4)**	**Ease of Design (5)**	**Weighted Total**
EMS Roll Up	3	4	7	9	2	4	2	159
EMS Traditional	4	5	7	7	3	5	1	175
EDS Roll Up	8	5	7	9	6	6	4	244
EDS Traditional	8	6	8	7	4	7	3	239
Linear Motor (Railgun)	4	8	5	9	4	8	4	210

Table 3: Decision-Making Matrix

The goal of this project is to explore the application of electromagnetic propulsion in garage door systems. Since electromagnets have never been implemented into garage door systems, exploring the possible applications by creating a full SolidWorks model, ANSYS force simulation, and a working, scaled-down prototype of the garage door system is a satisfactory goal. After these requirements, programming the electromagnetic garage door prototype to raise and lower smoothly would exceed the reasonable expectations of the project.

Goal Checklist	
	Full SolidWorks Model
	ANSYS Force Simulation
	Autodesk Force Analysis
	Prototype

Table 4: Goal Checklist

Design

Explanation

The design of the garage door system was based on factors such as compactness, simplicity of design, noise reduction, and efficiency. With these factors in mind, a garage door was created using a "roll-up" design that used electromagnets to raise and lower the garage door upon request from the user.

When designing for compactness, the "roll-up" style garage door was chosen. Roll-up garage doors rotate about a spinning axle above the clearance of the garage door once fully open. This was chosen because it is a more compact design than a traditional overhead garage door system allowing for the overhead space to be used inside the garage. A schematic of a basic roll-up garage door is shown in the figure below.

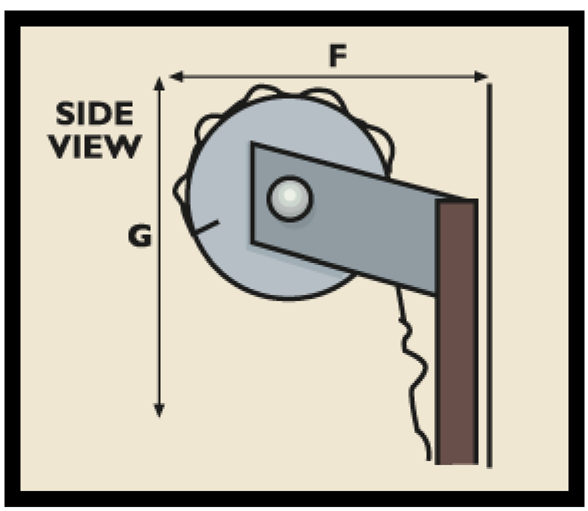

Figure 2: General Roll-Up Door Sideview

While designing for simplicity, the garage door track design will follow traditional door track designs in the industry while attaching electromagnets on the outside of the tracks periodically. Using a traditional door track design allows ease of manufacturing and installation.

If given more time, the design would be to implement electromagnetic propulsion technology into already used garage door systems to increase the marketability and sustainability of the product. A detailed schematic outlining the electromagnets along the track will be shown in the sections below.

Noise reduction and efficiency are considered in the design by designing the garage door system to operate without a chain and electric motor. The design uses electromagnets to raise and lower the garage door which requires no contact with the door system when raising or lowering. By significantly reducing the friction due to the contact points between the chain and the system and eliminating the motor, efficiency increases, and noise is reduced.

Electronics

The propulsion of the garage door is made possible through the electronic configuration used. Electronic devices such as metal-oxide-semiconductor field-effect transistors (MOSFET), Hall Effect Sensors, and Microcontrollers are used with electromagnets to enable the continuous propulsion of the garage door without any delay and to ensure easy movement.

The key propulsion of the garage door relies on the precise switching on and off the electromagnets along the vertical track. The electromagnets must switch on when the permanent magnet approaches the electromagnet and switch off immediately after passing the center of the electromagnet. This ensures the continuous movement of the permanent magnets (fastened to the moving door) by not allowing the permanent magnets to stick to the electromagnets. By continuously switching on and off the electromagnets, the door can raise and lower in continuous motion upon operation. As the permanent magnet approaches the electromagnet, the electromagnet is powered. As the permanent magnet passes the electromagnet, it turns off. A schematic featuring the operation of the electromagnet with a permanent magnet passing from left to right is shown in the figure below.

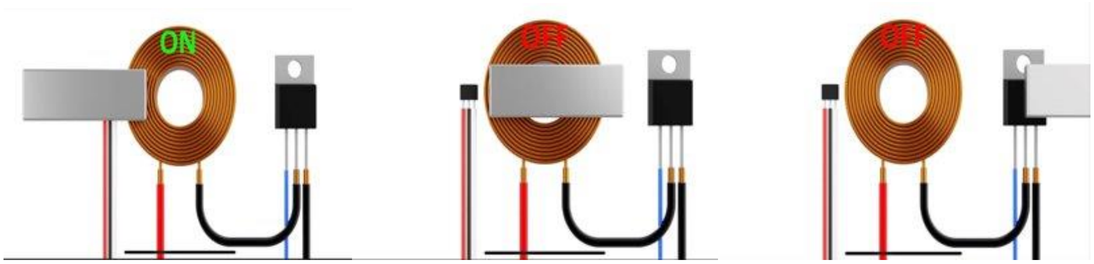

Figure 3: Electromagnet Operation Schematic

To further study the force field that the electromagnet emits, a simulation was created using a third-party software. This simulation was used to supplement the study in ANSYS and provide a clear visual of the magnetic behavior surrounding each electromagnet used in the design. The simulation results are shown in the figure below.

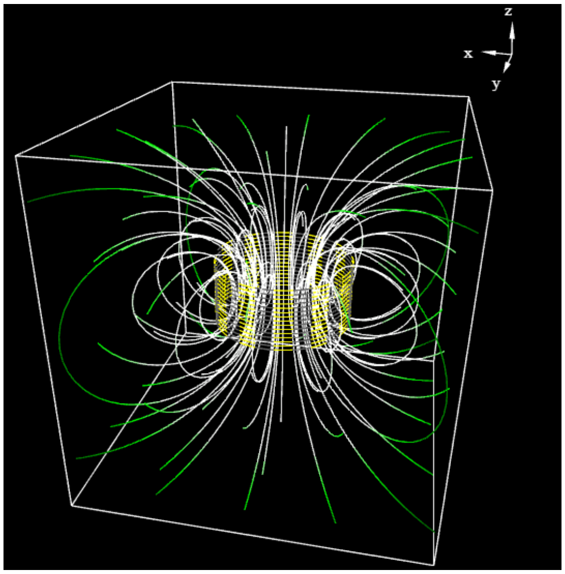

Figure 4: Electromagnetic Field Simulation

A transistor is essential in this process as the electromagnets need to be switched on and off depending on the position of the permanent magnet attached to the garage door. The transistor used is a MOSFET. The MOSFET is used instead of other types of transistors due to it requiring minimal power to its controlling terminal and for providing high switching frequency operation. The three pins of the MOSFET include the Gate, Drain, and Source. A schematic of the device is shown in the figure below. The source pin is connected to ground, the drain is connected to the load, or the electromagnet in this case, and the gate is connected to a GPIO pin in the microcontroller for input voltage.

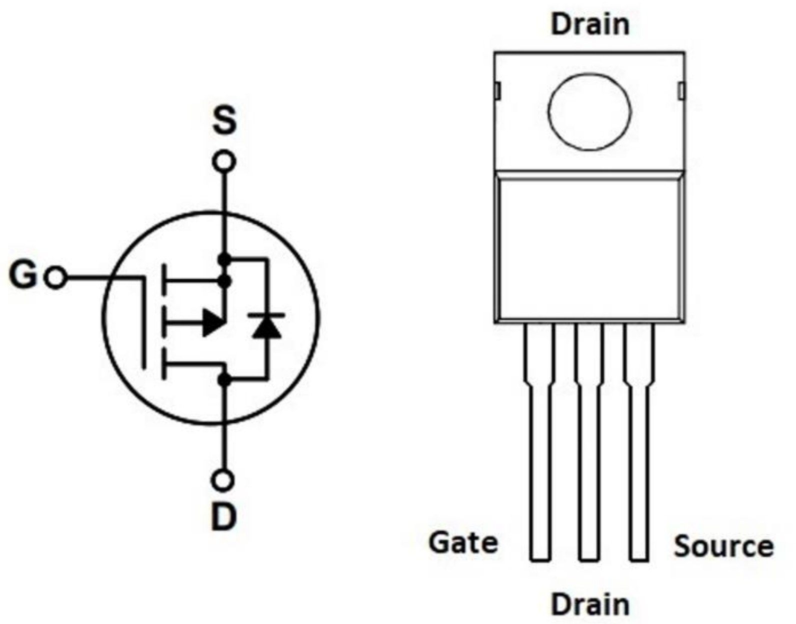

Figure 5: MOSFET Pin Configuration

The Hall Sensor shown below in Figure 6 is a type of sensor which detects magnetic presence and the magnitude of a magnetic field using the Hall effect. The Hall effect is the production of a voltage difference across an electrical conductor and to an applied magnetic field perpendicular to the current. The output voltage of the sensor is directly proportional to the magnitude of the magnetic field. In this application, the Hall Sensor is used to detect magnetic presence perpendicular to it and send a signal to the microcontroller.

The three pins of the sensor are for Input, Ground, and Digital Output connections. The input pin is connected to a voltage source to supply 5V, the Ground is connected in series with the ground for other devices, and the Digital Output is connected to the microcontroller to send the signal of any magnetic field detection.

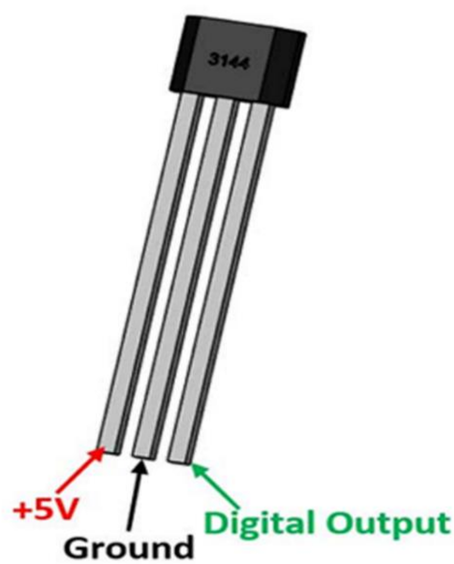

Figure 6: Pin Configuration of Hall Effect Sensor

The Microcontroller used in this system is chosen to be an Arduino UNO board. Arduino provides an open-source software to be easily programmable to fit this application. It essentially acts as the Brain in this system. It connects to the Hall Sensor, MOSFET, and the Electromagnet together. The Arduino is programmed to read the signal received from the Hall Sensor, and based on that, control the output of the transistor to control the power of the Electromagnet. A visual of the board used is shown below in Figure 7.

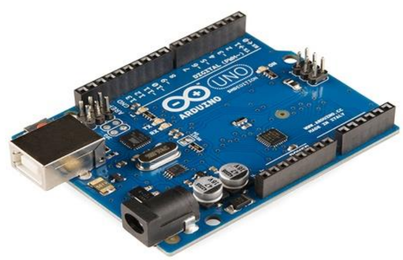

Figure 7: Arduino UNO Microcontroller Board

In Figure 8 below, the full electronic circuit is shown for a single sensor, MOSFET, and electromagnet. In the application, many of the electronic devices mentioned and electromagnets will be used. The connection of all devices unto the Arduino board can be implemented in two ways. First, the devices can all be connected in series and yield the same output. Or the devices can be connected to new pins on the Arduino board, then program the microcontroller accordingly. The first option will be chosen due to simplicity. Also, Figure 30 in appendices shows a simple form of the code written in Arduino to control the electronic devices.

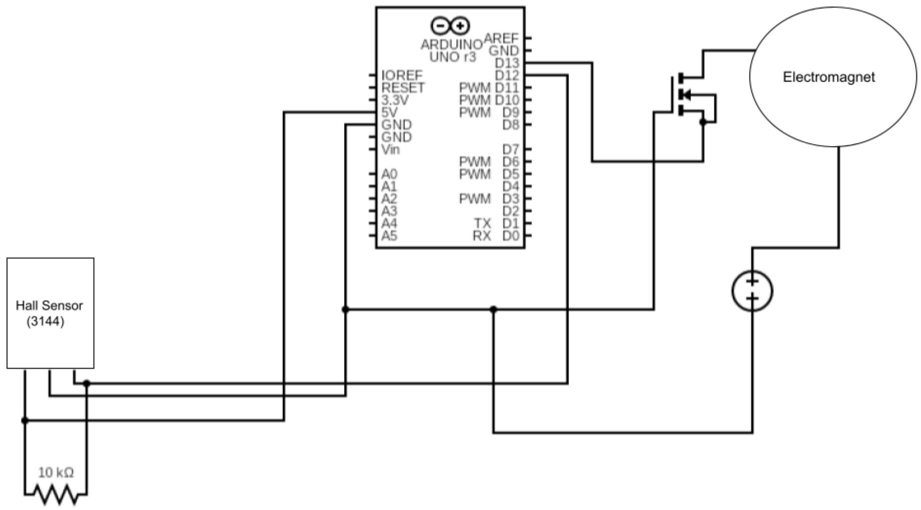

Figure 8: Full Electronic Circuit

To decide the amount of force needed from the electromagnet to pull the permanent magnets up and down the track, an expression is needed to model the relationship between them. The electromagnetic force relationship equation was researched online, and in Table 5, a list of the parameters and their assigned variables is shown.

Variable	**Description**
F [N]	The force of the electromagnet
N	Number of turns in the solenoid
x [m]	Distance between electromagnet and permanent magnet
I [A]	Current through electromagnet
A $[m^2]$	Area of electromagnet
μ_0 $[\frac{m*kg}{s^2*A^2}]$	Vacuum permeability

Table 4: Variable Description Table

The work of the electromagnet on the permanent magnet is expressed as,

$$F = (N * I)^2 * \mu_0 * \frac{A}{2 * x^2} \quad [N] \qquad \text{- (1)}$$

The force of the electromagnet in terms of mass can also be expressed as,

$$F = mg \quad [N] \qquad \text{- (2)}$$

Where g is the force of gravity. When the force needed depending on the mass of the door is calculated, the strength of the electromagnet can be determined by substituting equation (2) into (1), yielding,

$$mg = (N * I)^2 * \mu_0 * \frac{A}{2 * x^2} \quad \text{- (3)}$$

Given that the A, x, μ_0 and the current applied to the electromagnet are known after choosing an electromagnet, the amount of turns in the electromagnet can be determined by solving for N.

A few things to keep into consideration is that x, the gap between electromagnet and permanent magnet, in this application is changing with time, as the garage door is moving upwards/downwards. The gap is decreasing as the permanent magnet is perfectly perpendicular to it as shown in Figure 9. As the distance changes over the operation, the pull force acting upon the permanent magnet also changes. The relation to how this force affects the motion of the door is explained in further detail in the conclusion section of the report.

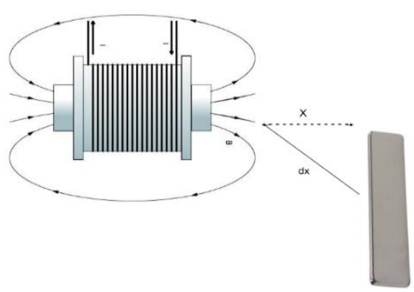

Figure 9: Distance Between Permanent and Electromagnet

SolidWorks Design

Figures of the full assembly are shown below. In Figure 10, an exploded view is shown to illustrate the torsional spring and the positions of the electromagnets along the rail. As shown, on each side, there are about eight electromagnets distributed throughout the rail to ensure continuous and smooth movement of the garage door. In Figure 11, a 3D view of the full garage door assembly is shown. The dimensions of the garage door include a height of 119" and a width of 17". For a view of the garage door with the dimensions, refer to Figure 28 in the appendices.

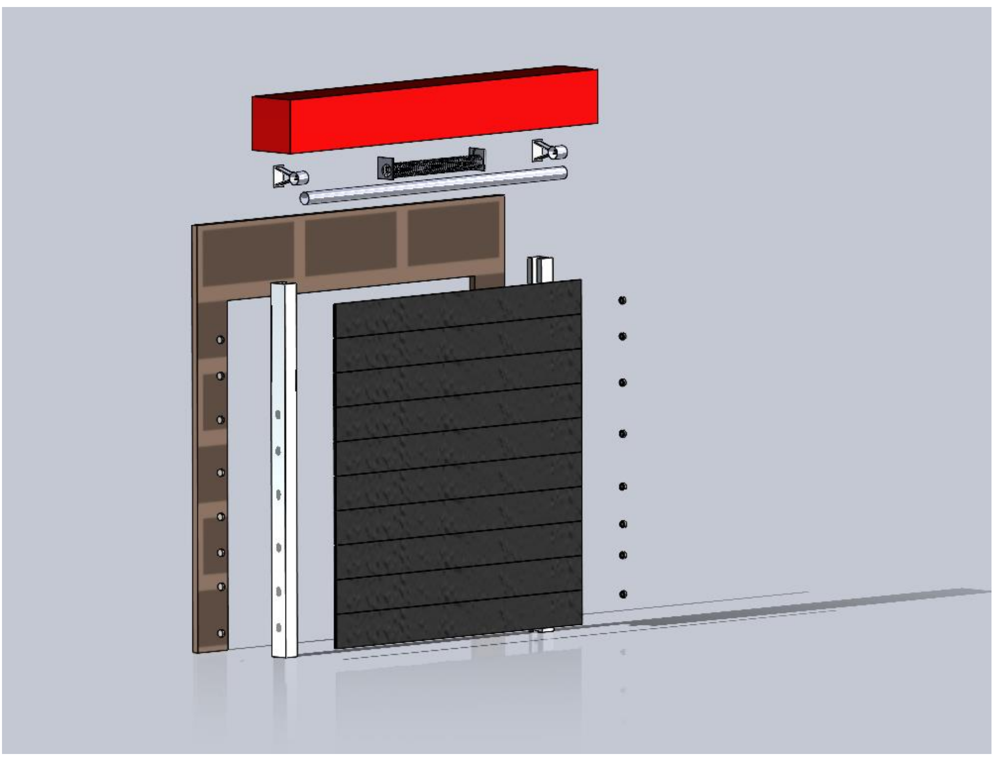

Figure 10: SolidWorks Exploded View of Assembly

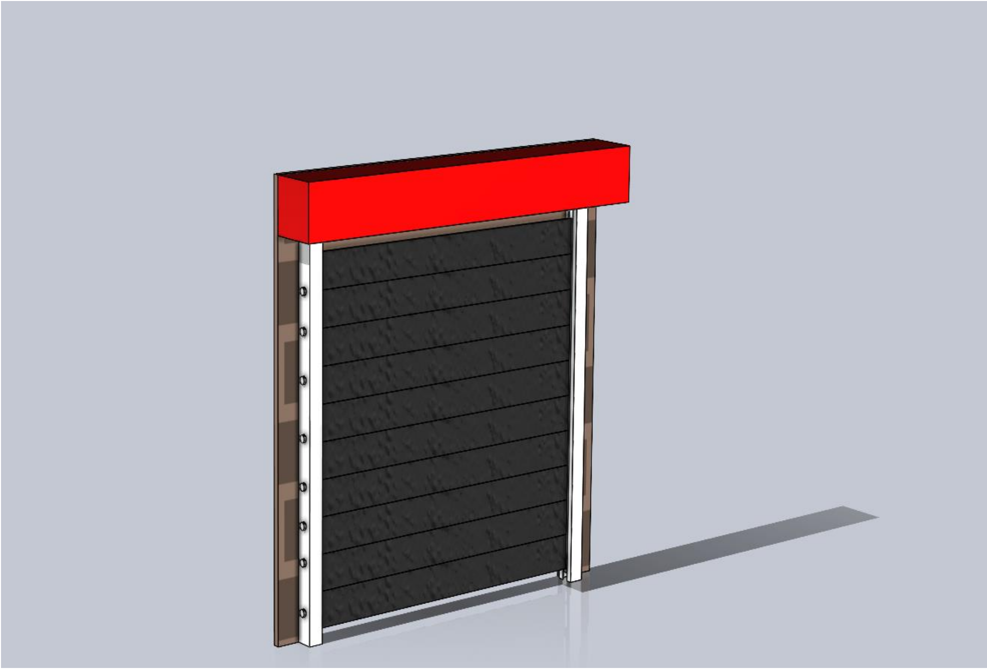

Figure 11: Full View of SolidWorks Model Assembly

ANSYS Simulation

In order to determine the force required for the magnets and to see how the garage door would behave under specific forces, a simple ANSYS simulation was done on a version of the garage door. An image of the model can be seen in Figure 12 below. Only a portion of the door is simulated because each electromagnet in the array will only have to pull its own region's weight even during opening and closing processes. When the door is fully closed and is called to open, all electromagnets switch on to pull up their respective regions of the door. While the door is open and is called to shut, all electromagnets turn on and begin pulling their respective regions downwards once the door approaches their respective region. The simulation is run for a single region that each electromagnet would see, and the setup is shown below.

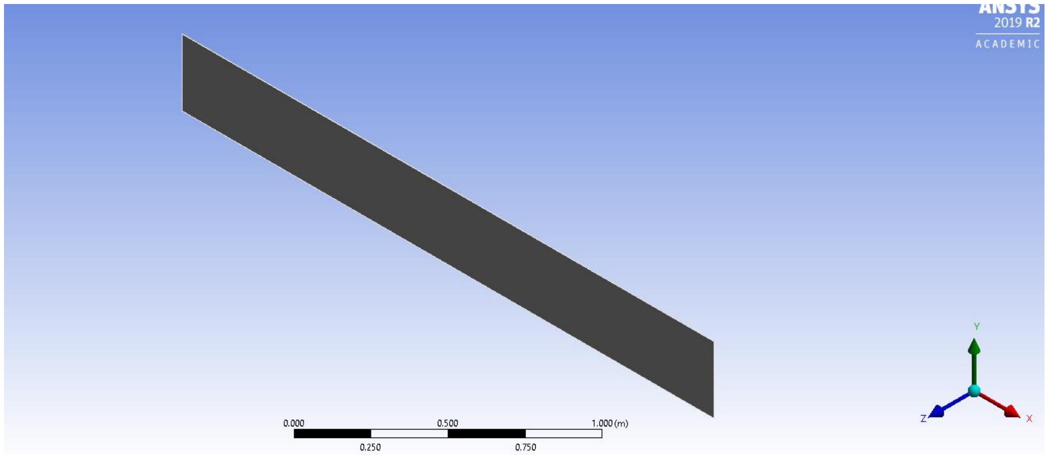

Figure 12: ANSYS Single Door Panel

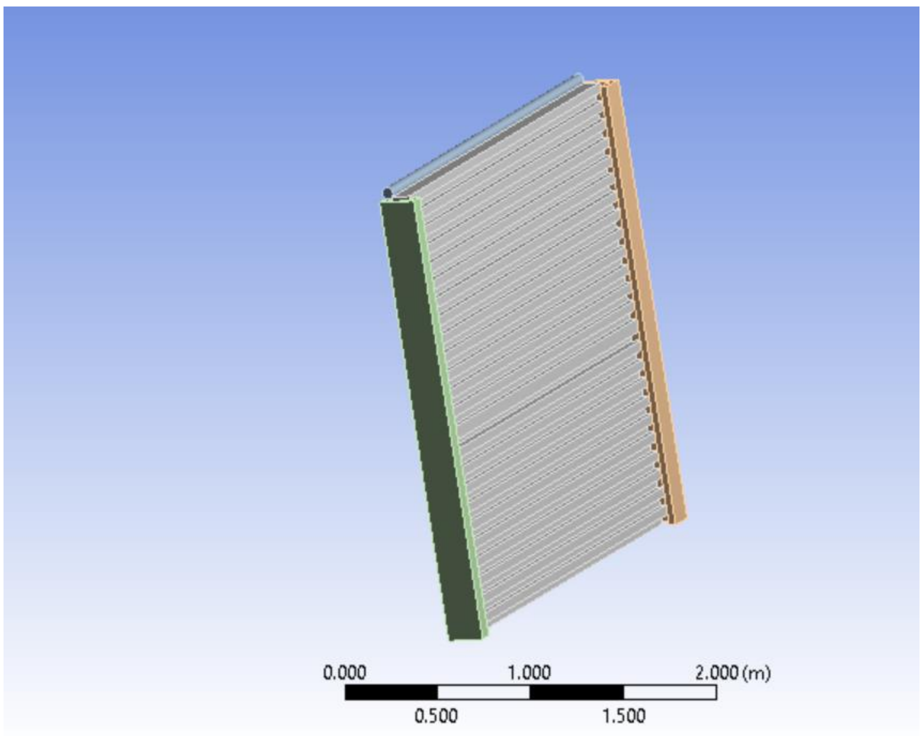

Figure 13: ANSYS Full Garage Door Simulation

After creating the panel, two forces were added to either side of the door to simulate the magnetic forces applied to the door. Although the magnetic force is not constant due to the distance between magnets changing, the average force of each magnet to electromagnet can be assumed to be 3N of force. Therefore, 3N of force is applied to each side of the panel in the simulation with a total of 6N of force acting on the entire garage. This simulation was done over a specific time interval and a velocity of 0.1778 m/s was given to the force which corresponds to the average speed of a garage door opening and closing. The results from the simulation can be seen in the figures below. After running the simulation with multiple size forces, the 6N forces moved the door enough to move the whole door. The deformation in the y direction can be seen in Figure 15 as 0.17887 m which is more than enough to move the small section the amount needed. A full-scale model of all the parts of the door was created and can be seen in Figure 13.

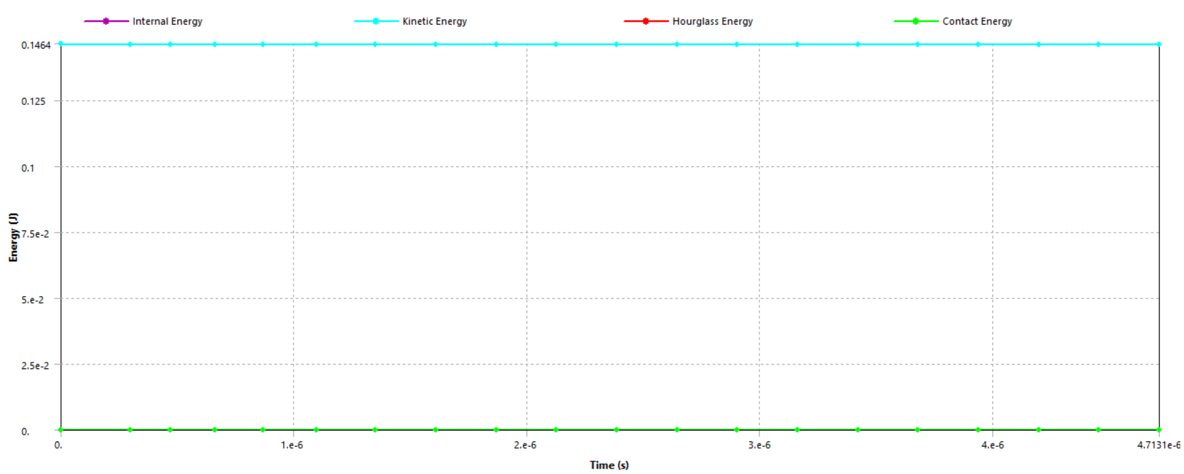

Figure 14: ANSYS Energy Summary

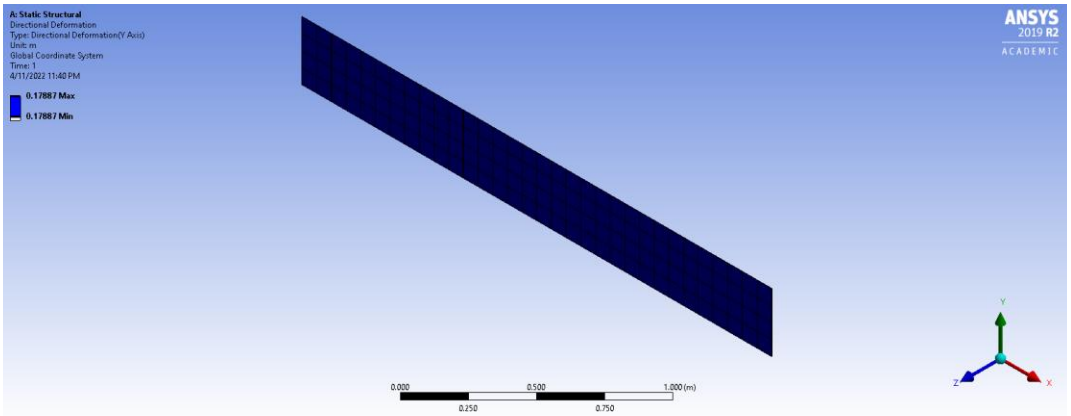

Figure 15:Deformation in the Y-Direction

Further simulation on the magnetic forces acting along each of the electromagnets was not able to be done because the software that is needed to simulate and solve the magnets requires a specific ANSYS package called 'ANSYS Electronics Premium MAXWELL' that Western Michigan University does not have. With this software, the specific magnetic force and pull could be analyzed for each individual magnet. This data could then be applied to the garage door simulation to get a more accurate representation of the impact the electromagnets have on raising and lowering the door.

/ ELECTRONICS	Electronics Premium MAXWELL	Electronics Premium HFSS	Electronics Premium SIWAVE	Electronics Premium Q3D EXTRACTOR	Electronics Premium ICEPAK	Motor-CAD	Electronics Pro 2D	Electronics Enterprise	EMA3D Cable
LOW FREQUENCY ELECTROMAGNETICS									
Electrostatics	•						• (2D Only)	•	
AC Conduction	•						• (2D Only)	•	
DC Conduction	•						• (2D Only)	•	
Magnetostatics	•						• (2D Only)	•	
Adaptive Field Mesh	•						• (2D Only)	•	
AC Harmonic Magnetic	•						• (2D Only)	•	
Electric Transient	•						• (2D Only)	•	
MAGNETIC TRANSIENT									
Translational Motion	•						• (2D Only)	•	
Fully Automatic Symmetrical Mesh Generation	•						• (2D Only)	•	
Rotational Motion	•						• (2D Only)	•	
Non-Cylindrical Motion	•						• (2D Only)	•	
Advanced Embedded Circuit Coupling	•						•	•	
Circuit Coupling with Adaptive Time Stepping	•						•	•	
Direct and Iterative Matrix Solvers	•						•	•	
ADVANCED MAGNETIC MODELING									
Vector Hysteresis Modeling	•						•	•	
Hysteresis Modeling for Anisotropic Material	•						•	•	
Frequency Dependent Reduced Order Models	•						•	•	

Figure 16:ANSYS Capabilities Chart

Force Analysis

For the force analysis, internal forces and external forces were computed for the system. The internal forces are of interest because they show how much stress each main component has, and the external force analysis is of interest because it shows how much force the full garage door system exerts on the wall it is installed on.

Autodesk Inventor 2022 was used to simulate and solve the internal forces numerically. Autodesk Inventor was chosen because it has an easy-to-use interface when designing, assembling, and simulating forces. When designing the assembly in Autodesk, only the main weight-bearing components were included and simulated for stress. These components were the two bearing side plates and the rotating rod in between them. The rod carries all the load from the garage door system and distributes it to the bearing plates on each side of the rod. The bearing plates are attached to the wall with four bolts. The force analysis was set to simulate the worst-case scenario, which is the garage door being completely rolled up around the rod without any support from the ground or sidetracks. The garage door tracks were omitted from the force analysis design because they do not exert any vertical forces on the system when in the worst-case scenario.

For the simulation, the material selected was stainless steel, since that is the industry standard for garage doors, the load used on the system was a 90lb distributed load downward to simulate the weight of an average steel door with the dimensions mentioned above, and an acceleration due to gravity of 386.4 in/sec^2 downward. With the 90lb load and gravity set, the system was set to have constraints on each of the eight bolts attached to the bearing side plates. These eight bolts fasten the bearing side plates to the wall and are the main constraints of the system. In the following figures, Von Mises stress, 1st principal stress, 3rd principal stress, contact pressure displacement, and safety factor are displayed.

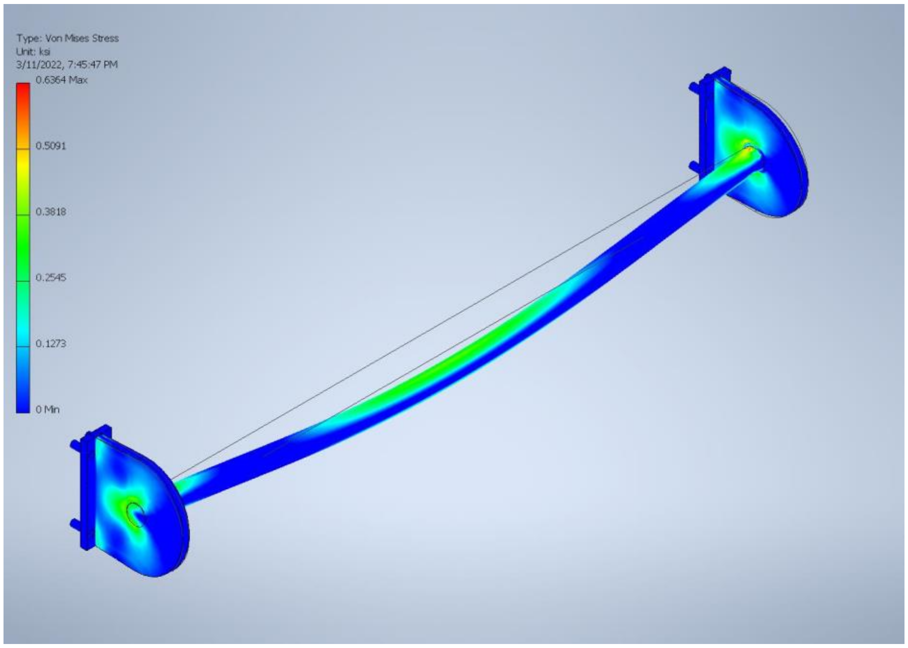

Figure 17: Von Mises Stress

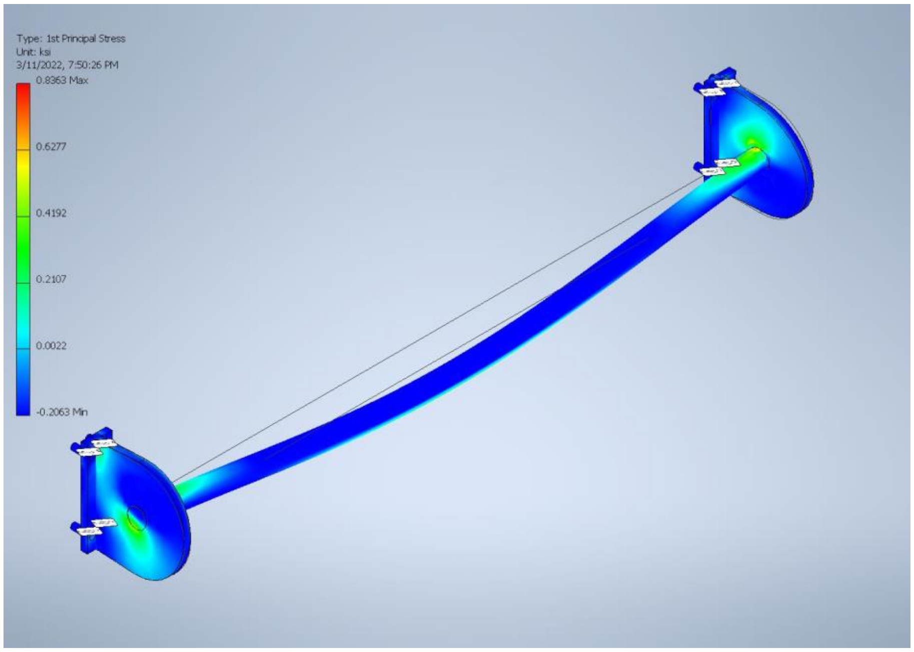

Figure 18: First Principal Stress

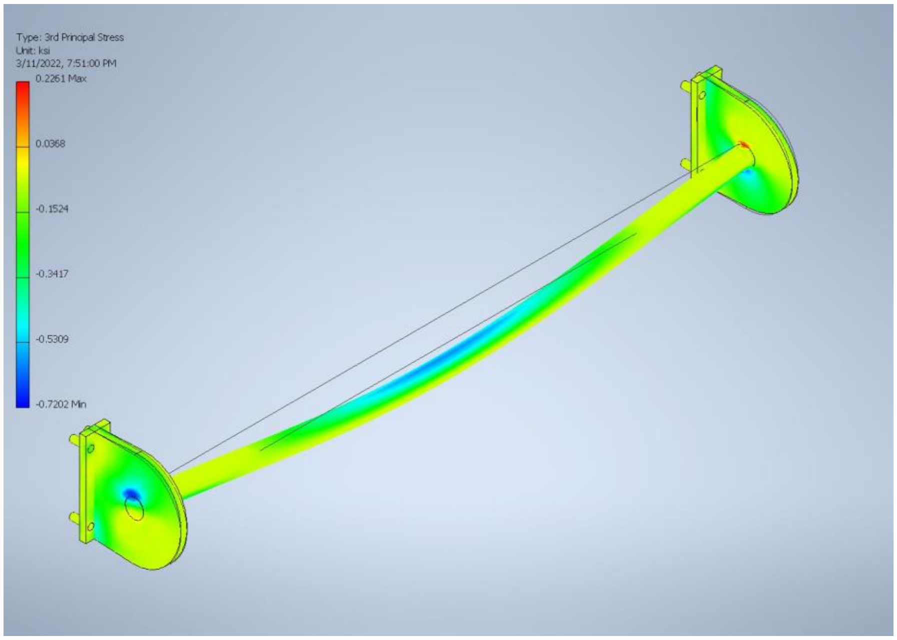

Figure 19: Third Principal Stress

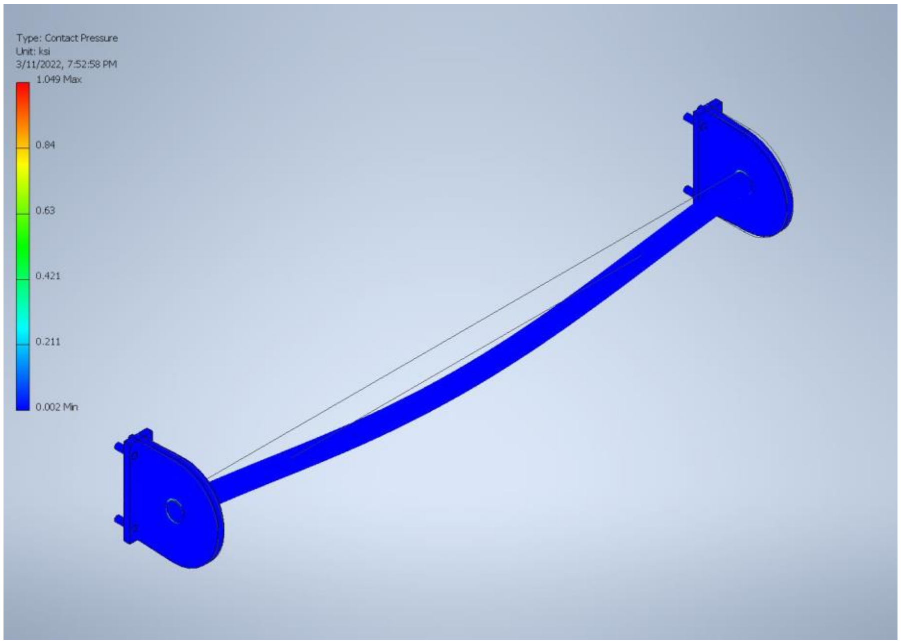

Figure 20: Contact Pressure

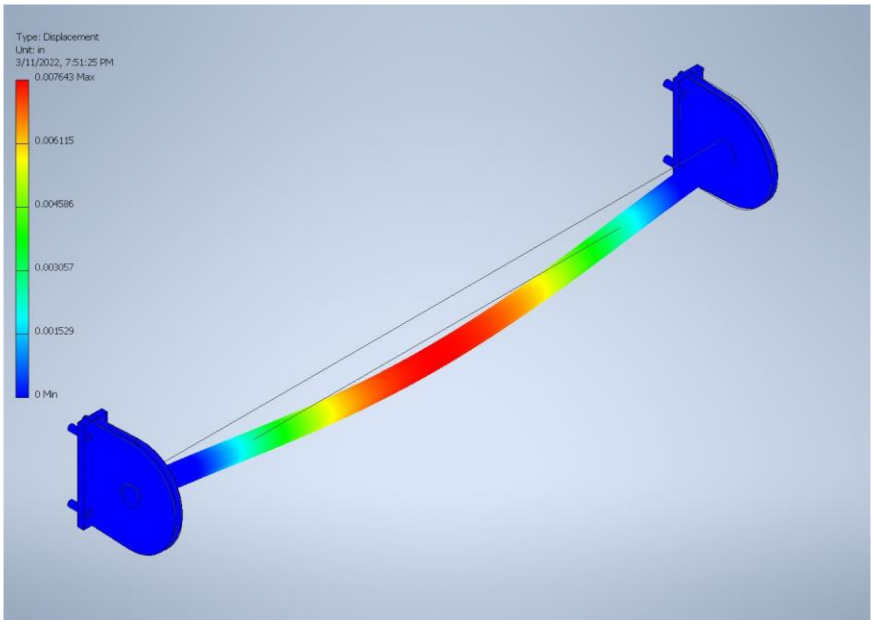

Figure 21: Displacement

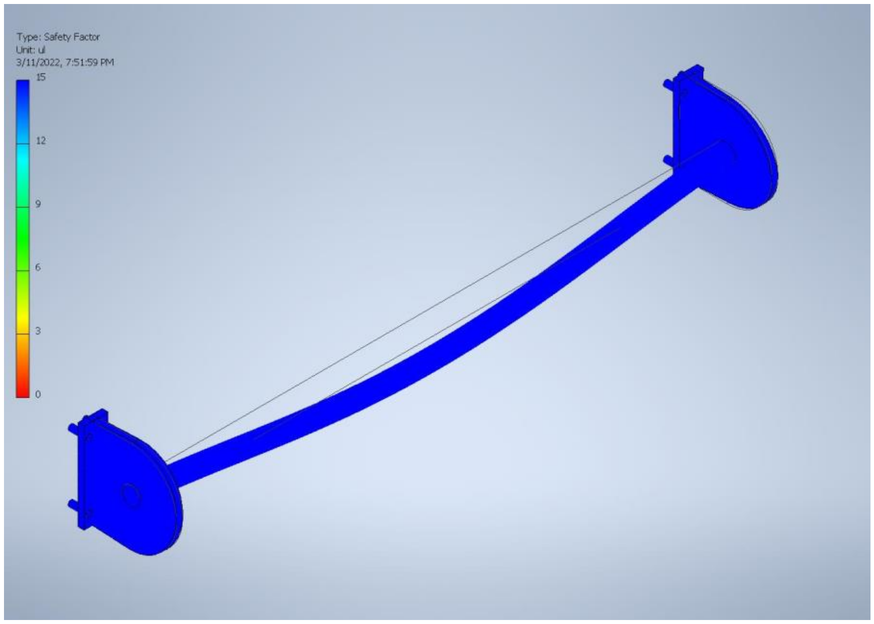

Figure 22: Safety Factor

The table displayed below will show the values of interest found in the simulation and analysis in Autodesk Inventor above. In the table, the maximum stress value is 0.8363 ksi and only appears on a small portion of the rod. It is also shown that the maximum displacement is 0.007643 [in] which is an exceedingly small displacement. Finally, the safety factor for the stress in stainless steel is solved and it never dips below 15, meaning that the internal loads are very safe for the life of the steel and users of the garage door.

Value Type	Von Mises Stress	1st Principal Stress	3rd Principal Stress	Contact Pressure	Displacement	Safety Factor
Maximum Value	0.6364 ksi	0.8363 ksi	0.2261 ksi	1.049 ksi	0.007643 in	15

Table 5: Internal Force Values

To solve for external forces, the force diagram is solved using only one bearing side plate due to the symmetry of the system. Due to symmetry, each bearing plate carries half of the load of the door. Also, the bearing plate itself is symmetrical, meaning that the two bolts on top and two bolts on the bottom will carry the same loads. A free body diagram of the bearing side plate is shown in the figure below.

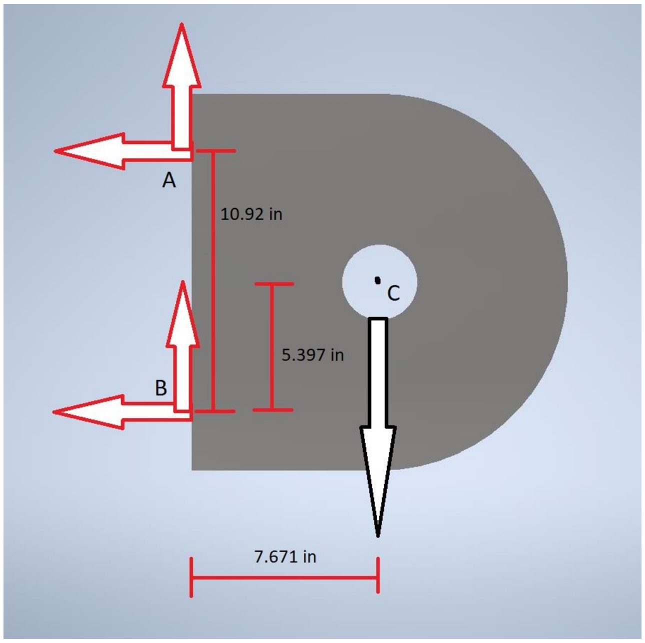

Figure 23: Bearing Plate Free Body Diagram

In the free body diagram, the forces in the x and y direction are used for the bolts and the internal force at C is in the negative y direction. Autodesk Inventor 2022 is used for the reaction force analysis for all eight bolts and is shown below.

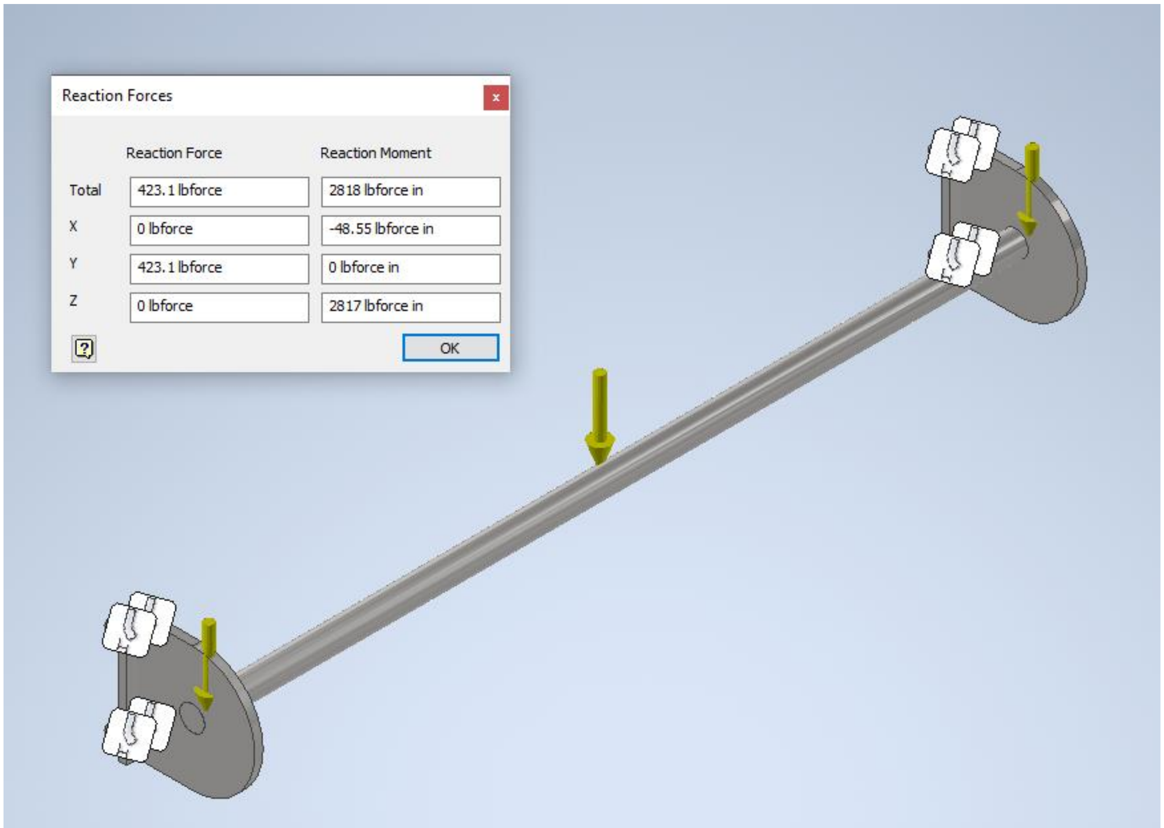

Figure 24: Forces Acting on System

After running the simulation in Autodesk Inventor, the total reaction force supported by all eight bolts is 423.1lbs. Knowing that the total reaction force in the Y direction is distributed to all eight bolts, the force acting on each bolt and reaction force for the wall are assumed safe for supporting the garage door system in its worst-case scenario.

Prototype

To make the concept a reality, a small-scale prototype was built to simulate a real garage door. The prototype model is intended to be 1/3 the size of the regular garage door dimension modeled in the project, but for ease of construction using pre-made components, the dimensions of the garage door are 32 inches in width and 37 inches in height. The garage door frame was built with wood used to build the frame of the door and two metal U-channel bars were used as the garage door track. Electromagnets were added to the outside of the tracks and permanent magnets were attached periodically to each side of the garage door panels.

The garage door panel was created using plastic panels from a package of window blinds fastened to a canvas cloth. To create a door mechanism that raises and lowers accurately and consistently, a few factors must be considered. First, the door must open and close without shifting to one side, so uniform plastic panels were bought and fastened to the cloth using strong glue and tile spacers for precision. Second, the cloth used to connect all the individual panels must not stretch to ensure reliable, lasting operation. Lastly, the door must open and close without falling to one side of the track. To avoid the door slanting, the door was fastened to the rotating axle while using a level, ensuring that the panels were completely horizontal. An image of the prototype that has been built so far can be seen in Figure 25.

Figure 25: Prototype Progress

Electromagnetic Propulsion Testing

In order to prove that the electromagnetic propulsion theory works, a permanent magnet was fastened to a ferrous metal bolt that was fitted to slide across a track. The circuit explained above was created along with ample Arduino code and Hall Effect sensors which were fastened along the track. Multiple transistors were used with each transistor is being set up as an output in the Arduino, and the hall effect sensors are all connected in a series connection and set up as one input. The sensors were placed periodically alongside electromagnets and positioned precisely to ensure a propulsion force. When power is supplied to the circuit, the permanent magnet is immediately propelled and accelerated across the three electromagnets. This concept can be applied vertically on the side rail of a typical garage door to create smooth movement. The electronic circuit and the code are provided in Figure 26 and 27, respectively.

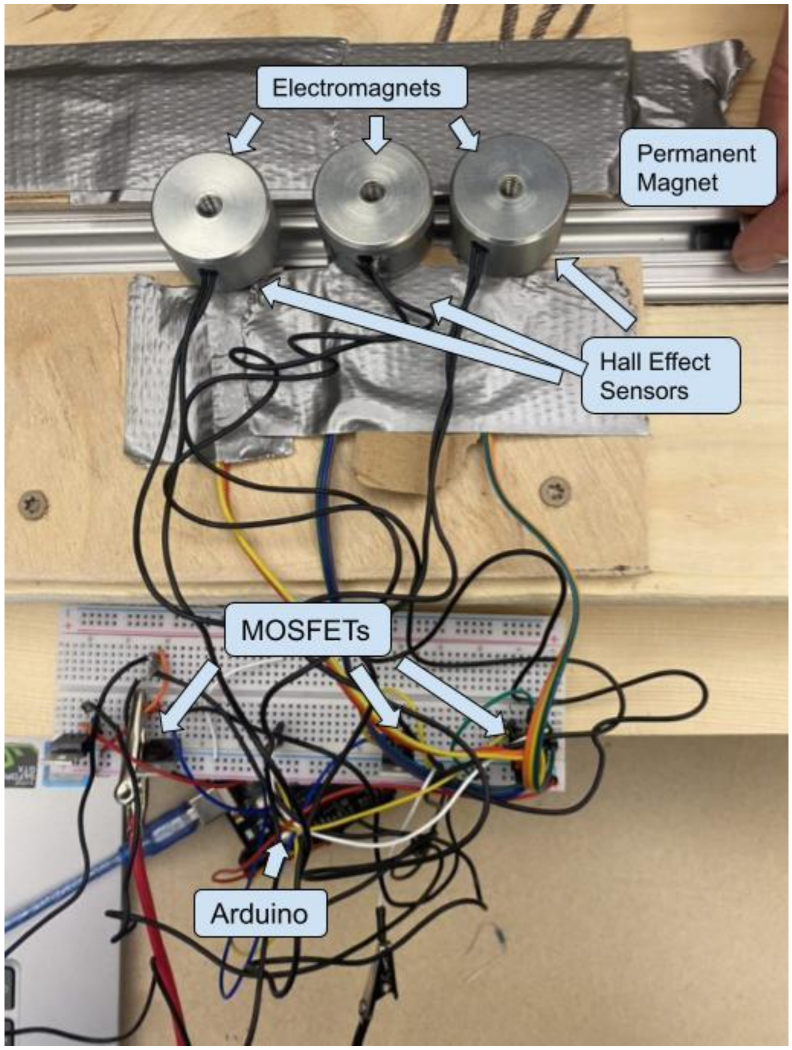

Figure 26: Electronic Circuit

sketch_apr02a §

```
int he_sensor = 12;
int mosfet = 13;
int mosfet1 = 11;
 int mosfet2 = 8;

int heState = 0;

void setup(){
  pinMode(mosfet, OUTPUT);
  pinMode(mosfet1, OUTPUT);
  pinMode(mosfet2, OUTPUT);
  pinMode(he_sensor, INPUT);
  //pinMode(he_sensor1, INPUT);
}


void loop(){
  heState = digitalRead(he_sensor);

  if (heState == LOW){

    digitalWrite (mosfet,HIGH );
    digitalWrite (mosfet1,HIGH);
    digitalWrite (mosfet2, HIGH);
  }

  else {
    digitalWrite (mosfet, LOW);
    digitalWrite (mosfet1, LOW);
    digitalWrite (mosfet2, LOW);
  }
}
```

Figure 27: Arduino Code for Prototype

Conclusions

After completing the project, important knowledge and understanding was gained. Electromagnetically propelled garage doors prove to be a very effective potential new idea that can be implemented given more research. The study of general performance of electromagnets and their feasibility of implementation to more widespread use has been an important pillar of this project. The project is deemed a success due to the educational gain along with a deeper understanding of using electromagnets for propulsion.

Upon the completion of research and the prototype, important knowledge was gained concerning the practical use and performance of vertical electromagnetic propulsion in garage doors and other possible applications. Building a prototype from scratch proved to be a difficult and ambitious task. The group learned the importance of using pre-made assemblies due to their precision and elimination of human error. The high strength, high precision and accuracy, and cost are also notable lessons gained from the project and will be described in more detail below.

Magnetic Strength

Typical garage doors weigh 125-200 pounds, meaning the electromagnets used must be strong while remaining compact for special considerations on the door. Fortunately, well-studied torsion springs are used to act as a counterweight to the door. The electromagnets are tremendously helped by the force of the torsion springs used in garage door systems. However, force is large force is required for the initial motion of opening and closing the door. The force is mostly to bring the door up to a specified speed using impulse forces to bring the door to a desired momentum. The equations of interest are shown below.

$$p = m \times v$$

$$F \times \Delta t = m \times \Delta v$$

$$F = \frac{m \times \Delta v}{\Delta t}$$

Figure 28: Momentum Equation

In the above equations, momentum is *p*, mass is *m*, velocity is *v*, force is *F*, and time is *t*. After using the impulse equation, we can rearrange to find force *F*. In our project, this force is of great importance to see the amount of force required to raise and lower the garage door at the desired speed of 0.2286 m/s. In this application, the force between the electromagnets and permanent magnets continuously changes as a result of the changing distance, the mass changes as a result of the door being rolled up and down, and the time of contact continuously changes as electromagnets turn on and off. With all these changes in the variables, the equation becomes complex very quickly, making it hard to simulate with adequate accuracy, even with some of the most advanced programs in the industry, such as ANSYS.

Precision and Accuracy

In the construction of the garage door system, accuracy and precision with the placement of electromagnets is paramount. Since the force of the electromagnets are greatly reliant upon proximity to permanent magnets on the door, distances must be precise with a very small amount of error on vertical placement. Also, a large goal of this project is to minimize friction, which means that the garage door has a gap between the door and siderails when in operation. To maintain this gap when using electromagnets on either side of the door, the corresponding electromagnets must be almost perfectly horizontal to eliminate the door pulling from on side to another as it slides up and down the track.

With respect to the prototype used, the electromagnet pairs were placed by hand and were very challenging to align completely horizontally, but with advanced machinery and assembly processes used in modern manufacturing, this goal can be achieved.

Cost

After completing the full model design, the rough total cost can be estimated. It is important to note that if electromagnetic propulsion technology is implemented into pre-existing garage door systems, the cost of implementation will greatly decrease. In the table below, the estimated cost analysis is displayed.

Items	Quantity	Unit Price	Total Price
Roll Up Door Assembly	1	$553.00	$553.00
5.2-Watt Electromagnet	8	$66.34	$530.72
NDR-120-12 Mean Well Power Supply	1	$33.19	$33.19
Hall Effect Sensors	2	$8.28	$16.56
MOSFET Switches	2	$9.99	$19.98
16 Gauge Wire	1	$46.50	$46.50
Neodymium Magnets	3	$13.99	$41.97
Adhesive	1	$61.00	$61.00
Construction Costs	1	$200.00	$200.00
Total Cost			**$1,502.92**

Table 5: Cost of Electromagnetically Propelled Garage Door

The estimated cost of a single garage door system comes to be about $1,500. With the average cost of a garage door ranging from $850 to $3,000, the electromagnetically propelled garage door is well within the average cost of a roll-up garage door. With the added benefits of noise reduction and reduced friction explained in the introduction, electromagnetically propelled garage doors are highly marketable to homeowners and industrial suppliers.

Future Plans

If given more time, the goals of the project would be to fully implement this concept into already existing garage doors and find the most efficient way to install the system into garage doors that already exist. The other main ideas would be to implement a locking system for the garage door. A locking feature would ensure that the door would stay closed or open when it's not running is an important security feature ensuring the safety of customers' homes and factories.

Another feature that would be added and researched would be an emergency brake system. In most modern garage door systems, a safety beam is used to arrest the movement of the door once the beam senses an object in its path. A safety beam system to stop the door while its running would prevent users from getting injured and prevent damage to objects that may be in the path of the closing door. The sensor would be added if given more time which would be able to automatically sense if there was someone or something in the way of the door and prevent the door from beginning a path up or down. The electromagnetically propelled garage door design would be further enhanced by the implementation of installation to pre-existing garage doors for cost and marketability, locking features for security, and safety beam sensors for safety.

Appendices

A1. Extra Figures

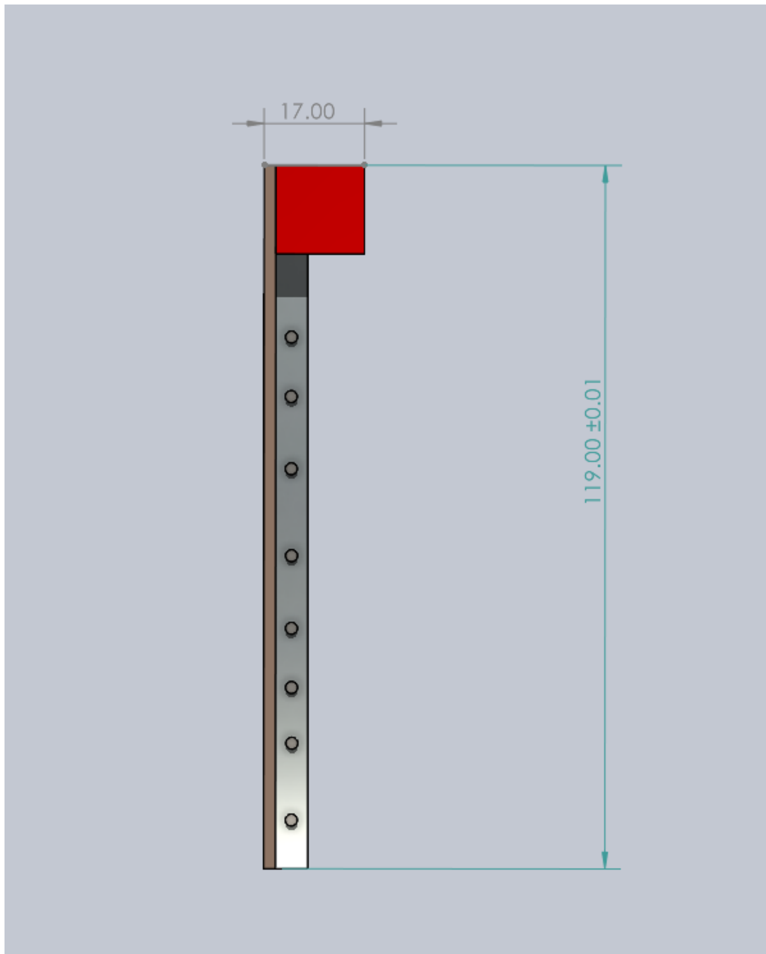

Figure 29: SolidWorks Side View

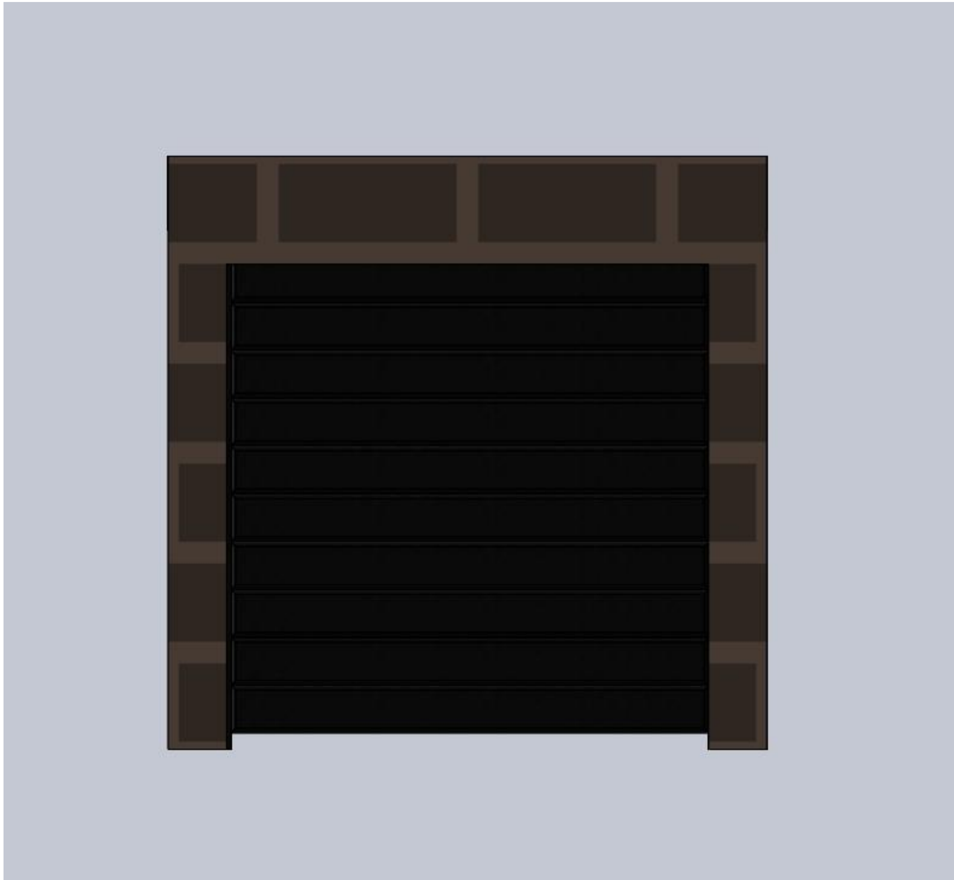

Figure 30: SolidWorks Front View

```
int he_sensor = 12;
int mosfet = 13;


int heState = 0;

void setup(){
  pinMode(mosfet, OUTPUT);
  pinMode(he_sensor, INPUT);
}


void loop(){
  heState = digitalRead(he_sensor);

  if (heState == LOW){

    digitalWrite (mosfet,HIGH );
  }

  else {
    digitalWrite (mosfet, LOW);
  }


}
```

Figure 31: Arduino Code

Figure 32: Prototype Sideview of Spring Configuration

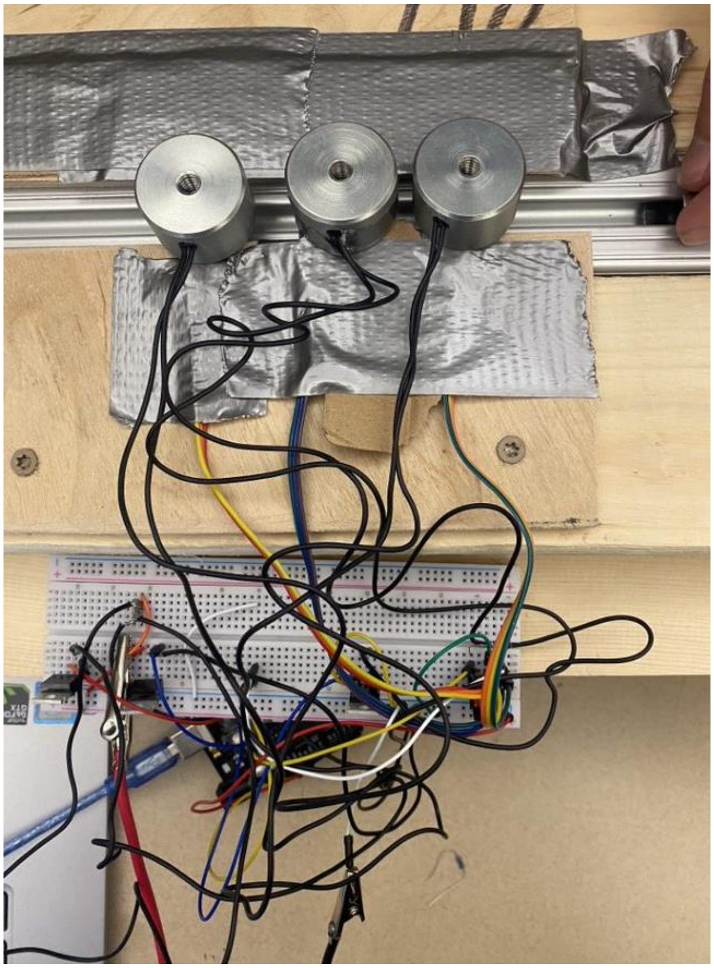

Figure 33:Circuit Setup

A2. References

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A3. ABET Questionnaire

ABET Program Evaluation Questionnaire
Mechanical and Aerospace Engineering Project (ME/AE 4800) Program Outcomes' Indicators Assessment Worksheet
Mechanical and Aerospace Engineering Programs

Semester: Spring
Project Group Number: 04-22-20
Project Title: Electromagnetically Propelled Garage Door
Student Team Members: David Boktor, Rachel Cavan, Connor Seifert
Faculty Team Members: Dr. Jinseok Kim

Please respond to all of the following questionnaires as best you can.

Outcome (2) An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns and consider the effects of the relevant design factors.

Performance Indicator 1

Describe the engineering needs for this project:
Most garage door openers last for approximately 20 years, and the reason many fail is due to a lack of lubrication. The need for lubrication reveals that a leading contributor to the decline of garage door life is friction. This friction is due to contact from the garage door chain, pulleys, and rollers. (Page 8) Implementing electromagnetic propulsion would greatly reduce friction along with noise for the garage door system. Reducing friction would prolong life of the door and reducing noise is desirable for consumers.

List the project goals along with performance criteria:
The goal of the project is to implement electromagnetic technology into the propulsion of the garage door to decrease friction between the door and tracks. This would make the garage door last much longer than the ones out today and decrease the noise involved in the door operation.

List the project constraints:
The major constraints of the project are sizing and dimensions. The door designed should reflect an average-sized garage door and be designed using as little extra space as possible.

List the methods/procedures that were implemented to ensure that the customer expectations were addressed:
Benchmarking was done to compare the differences between various other garage door types in order to find the best and most efficient door. Research was done on the noise generated from the door, maintenance, and other factors that affect the customer experience

Performance Indicator 2
Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

Public health: N/A

Public safety:
The safety of the public could be in danger when the door is opening and closing if people are in the way they could get hurt or stuck in the door. If there was more time our group would implement a locking and emergency braking system to prevent this from happening.

Public welfare: N/A

Performance Indicator 3
List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.

Global factors: N/A

Cultural factors: N/A

Social factors: N/A

Environmental factors: N/A

Economic factors: Purchasing a lot of magnets can get very expensive very quickly, so building a prototype to test the performance of the technology was needed in order to ensure that there is a market for the product.

Performance Indicator 4
(To be addressed by the faculty adviser).

Outcome (5) An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet objectives

Performance Indicators:

1. Student's ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks
6. Group meets objectives.

Performance Indicator 1
(Project's adviser will determine whether the listed tasks were completed).

Performance Indicators 2 & 5

List all tasks required to accomplish the goals of this project, and name the group member responsible for the completion of each task.

Internal/Dynamic Force Simulation – Rachel Cavan
Administration – Connor Seifert
Computer Model – David Boktor
Prototype – Connor Seifert, David Boktor, Rachel Cavan
External Force Analysis – Connor Seifert
Electronics – David Boktor

Student 1: Connor Seifert
For project tasks in which I was not the leader, I provided the following inputs towards their completion: I assisted in providing direction for what to simulate for regarding the internal/dynamic force simulation. I also provided input and dimensions through research to use to the computer model. Along with providing direction and input, I assisted in answering questions regarding the electronic circuit configuration for the electromagnets. In addition to these, I headed the creation of the final report document for the project.

Student 2: Rachel Cavan
For project tasks in which I was not the leader, I provided the following inputs towards their completion: I assisted in organizing and lead in the housing of the materials for the prototype. I also lead the creation of the presentation for the proposal, ethics presentation, along with the final project presentation.

Student 3: David Boktor
For project tasks in which I was not the leader, I provided the following inputs towards their completion: I assisted in answering questions regarding force analysis along the door and the electromagnets, CAD modeling and formatting the reports/presentations. Also, I helped in deciding which materials or devices to use in the prototype and the theoretical assembly. Lastly, I assisted in providing research in modeling the force of the electromagnets.

<u>Performance Indicator 3</u>

For project tasks in which you **were** the leader, describe the input other group members provided towards the successful completion of these tasks.

Student 1: Connor Seifert
With the tasks noted above for which I was the leader, David Boktor helped provide input and guidance regarding the electronic implementation and relationships needed to be implemented with the rest of the system. Rachel Cavan assisted with reminding me of what to include regarding safety sensors for the future planning section of the paper.

Student 2: Rachel Cavan
With the tasks above that I was the leader, Connor Siefert helped in understanding and input regarding what forces to simulate in ANSYS. David Boktor helped in providing SolidWorks files to import into the ANSYS simulation for the forces.

Student 3: David Boktor
With the tasks for which I lead, Rachel Cavan and Connor Seifert help gave input on how to improve the SolidWorks model. Rachel Cavan assisted in providing info regarding the electronics details. Connor Seifert assisted in answering questions on the flow of the garage door prototype.

Performance Indicator 4
List all goals this project had to satisfy to be considered successfully completed.

1. Full-Sized Computer Model
2. External Force Analysis
3. Electronic Configuration Schematic Design
4. Internal Dynamic Electromagnetic Force Analysis
5. Construction of Prototype
6. Adequate Conclusion for Future Project Team Opportunity

Performance Indicator 6
(To be addressed by the faculty adviser)
.

Outcome (7) An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.
Performance Indicators:

1. *Student's ability to find information relevant to problem solution without guidance.*
2. *Student's ability to identify the additional knowledge needed to complete project.*
3. *Student's ability to acquire and apply the additional knowledge needed to complete project.*

Performance Indicator 1
Describe what information you found in order to successfully complete the tasks you were assigned in the project.

Student 1: Connor Seifert
I researched many things with respect to the real-world problem/application opportunity. I was able to confirm the need for a product like this and perform extensive research on garage door dimensions, prices, leading problems, etc. I also researched prices for many components needed for the full-size and prototype model. This allowed us to begin creating a prototype as well as accurately assess the cost of a full-sized system.
I also performed technical research regarding garage door design and weight bearing materials and mechanisms. For my force analysis, I researched how to use a new software to me called Autodesk Inventor. This research allowed for an accurate external force analysis along with good direction to the other team members with their tasks.

Student 2: Rachel Cavan
I researched many things regarding ANSYS simulations along with magnetic forces being applied with dynamic forces. Due to the fact that ANSYS was a software I was not familiar with, a lot of research was done to understand how to simulate magnetic and non-magnetic forces and apply those forces to the garage geometry. Research was done as to how magnetic forces behave vertically with a torsional spring.

Student 3: David Boktor
I conducted a lot of research on the technology needed to make this project possible. I analyzed all the different electronic devices such as sensors, transistors, and which electromagnets to use, compared them and decided which models would be the most appropriate for our application. Along with electronics, I did a lot of research on how roll-up garages work in order to model our door correctly on SolidWorks with the implementation of our technology.

What sources did you use to find this information?

Student 1: Connor Seifert
A few of the sources I used were national consumer databases, leading garage door suppliers, CAD sharing platforms, online Autodesk Inventor forums, and YouTube videos showing electromagnet projects.

Student 2: Rachel Cavan
Most of the sources that I used were from the ANSYS website, ANSYS forums, question and answer websites, along with YouTube videos and textbooks.

Student 3: David Boktor
Arduino forums/projects helped substantially in guiding me through the electronic configuration, Coding, and circuit wiring. I also used Youtube, SolidWorks forums, and a book called "Magnetic Levitation. Magnetic Technology and Applications" by Hyung-Suk Han and Dong-Sung Kim

Performance Indicator 2
Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

Student 1: Connor Seifert
To successfully complete the force analysis task, I had to learn a new software from scratch as mentioned in the above question. In order to create the prototype, I had to learn material properties, new tools, find new industrial suppliers, and create accurate records. To lead the administrative tasks, I had to develop more soft skills, communication techniques, and leadership and decision-making skills in order to keep the team on track.

Student 2: Rachel Cavan
As mentioned in the previous questions, I had to learn new software's from scratch. In order to properly simulate the garage and the forces applied to the entire system.

Student 3: David Boktor
Understanding Arduino or the configuration of electronic devices to any microcontrollers would be beneficial, along with learning the code for how to control the flow. Also, understanding a CAD software or MATLAB that can implement the use of magnetism/electromagnets and model it dynamically.

Performance Indicator 3
Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

Student 1: Connor Seifert
To acquire and improve my knowledge and skills during the project, I used techniques shared in class about future planning, timelines, ethics, etc. to approach the tasks for the project. I also used team coordination principals to try to maintain accountability and coordination within the team in the project.

Student 2: Rachel Cavan
To acquire and improve the knowledge and skills needed, I used knowledge of physics and applied forces from my previous class. I had to do research regarding how to use the software's properly and how to simulate both magnetic and non-magnetic forces at the same time.

Student 3: David Boktor

To acquire the skills mentioned, a lot of research was done along with going through old notes from the Electronics lectures. Also, to better understand modeling the force of the electromagnets, research was done through physics books to understand the expression of magnetic lifting forces.