Wall-Climbing Robot Capstone

ME 495 M

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Group 4

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1. Summary

This report documents the design process of the Group 4 Wall Climbing Robot Capstone project. Throughout the report, the background, design, analysis, results, and overall cost can be found. The four main goals for this project were to attach/detach on the wall, counter gravity, move on the vertical wall, and carry a three-pound payload. These are the basic functions of the wall-climbing robot.

Going deeper into the main focus, the idea is to build a robot which can accomplish the basic functions of a robot which can perform maintenance on the inside of large containers and replace the work that humans do. Group 4, with the allocated timeline of the 2021 winter and spring quarters at the University of Washington, is to build a working prototype of a robot that can climb a wall.

This idea can be broken down into the 4 sub-functions: 1) attaching/detaching from a wall, this will allow the robot to change its contact points with the wall to avoid obstacles, 2) counter the force of gravity mimicking a vehicle on the ground, 3) climb the vertical surface to reach other areas, and 4) carry a three-pound payload which models any tools or equipment that need to be brought to a specific location.

The conceptual phase consists of the work done during the winter 2021 quarter. This includes all the preliminary research and design considerations. Research started off with looking at what others have done before with regards to wall climbing. That research revealed the four general methods of clinging to a wall; magnetism, vacuum, adhesive, or conservation of momentum (propeller manipulated air).

With the initial research out of the way, the team started brainstorming design concepts that attempt to achieve any or all the main goals. This still includes the goal of climbing over an obstacle, in which an I-beam was chosen. Several meetings went toward talking about each design and its pros and cons. The team considered each design's complexity, ability to achieve main goals, and the team's capabilities to pursue each design with the allotted time and resources.

At the beginning of spring quarter, the team chose the Leapfrog concept to pursue. The rest of the quarter would be dedicated to designing and fabricating this robot concept

to achieve all major goals. The Leapfrog concept relies on permanent magnets to cling to the wall, motor driven rubber wheels to climb the wall, and a chain enhanced parallel linkage arm and gripper (an alternative to a four-bar linkage) to climb over an I-beam.

One of the main reasons for choosing the Leapfrog design is its modularity and separation of important components. Every system could be proven individually without dependence on other mechanisms as opposed to a system with magnetic wheels that can climb over an I-beam. There would be too much dependence on magnetic wheels. This modularity would allow the completion of goals individually and allow flexibility to each mechanism.

With foresight of the quarter and the team's capabilities in the COVID-19 pandemic, a plan was made to first get the base chassis developed before moving on to building an arm. In the end the arm was never manufactured and tested, our final design was just a wall climbing robot.

The final test to prove the effectiveness of the wall climbing prototype was accomplished by demonstrating a sequence of attaching to the wall, driving up and down the wall, then detaching. A separate test would analyze the payload capacity of our robot. This was a demonstration with the robot climbing up the wall while pulling up on a load cell until it would stop ascending.

Table 1: *Results Summary*

Goal/Test	Satisfactory	Notes
Attaching/detaching from a wall	Yes	Linear actuator struggles switching on the magnets due to slider geometry
Counter the force of gravity	Yes	Robot can be held statically in place with no power supplied
Climb a vertical wall	Yes	Robot slowly ascends and descends on the wall, but there is no turning control.
Carry a 3 lb. payload	No	Robot starts slipping at a payload of 2.25 lbs.

Regarding the results above, we successfully demonstrated a concept and a prototype robot to climb a flat magnetic surface. Magnets can be driven to turn on and off to cling to the wall. The robot statically holds itself to the wall with no power necessary due to a high gear ratio. By driving the motors, the robot can be driven up or down the steel plate. Independent control of each drive motor has not been implemented leading to some slippage rotational misalignment while climbing. The payload is one area we were not successful in. We determined our magnetic force was not strong enough to meet the 3 lb. payload requirement. But the robot can lift its own weight at about 15 lbs.

2. Main Goals

Our main goals for this project are to design a wall-climbing robot for a ship hull tank inspection and maintenance. The system should be able to attach, detach from the wall, counter gravity, move vertically on the wall, transverse obstacles in a confined space and can carry a payload of at least 3lbs. However, due to the impact of the COVID-19 and the limitation of time, we want to at least achieve some of the basic functions of the wall-climbing robot. The deliverable goals are that the system should be able to attach, detach on the wall, counter gravity and move on the vertical wall before the end of this quarter, because these are the basic functions of the wall-climbing robot.

3. Background

3.1 Overview of Past Work

In the creation of this design, inspiration was taken from many existing robotic systems, which can be found in 13.1. There were certain design elements which we found particularly interesting, such as a hinged chassis and magnetic wheels. Several potential design approaches were brainstormed, a selection of which you can see below.

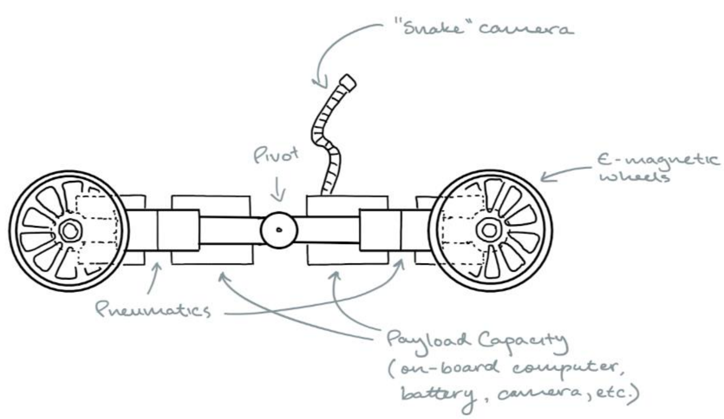

Figure 1: *Our 'Lego Car' design, based on the Lego Car (13.1 in the Appendix).*

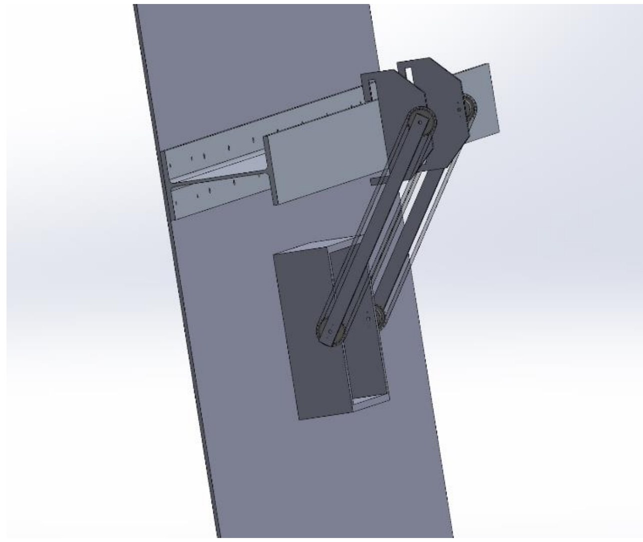

Figure 2: *Our 'Leapfrog' design.*

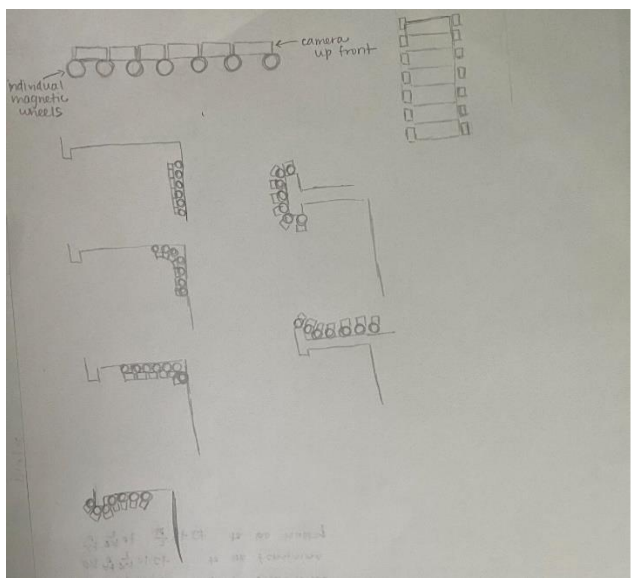

Figure 3: *Our 'Centipede' design.*

Due to the COVID pandemic, focus was placed on achieving some basic functions of the problem statement. The Leapfrog design was chosen due to its modular nature, which allowed for a gradual implementation of key design elements: attaching and detaching from a surface, movement along surface, and the obstacle-climbing mechanism.

3.2 Other Potential Applications

While the original motivation behind this project is the need for a mobile system for the inspection and possible maintenance of ship hull tanks, it has the potential to be applied in other environments and for other purposes.

This system is, in general, most suitable for confined space work in which it would have to move vertically along a magnetic surface. This kind of situation would take fuller advantage of the functionality of the system. That being said, work on horizontal or inclined non-magnetic surfaces would also fall within the scope of this system.

Possible situations for this kind of work include maintenance or inspection inside of other tank-like environments. This system could be implemented, for example, in the aerospace industry for the inspection of wing bays or other hollow aircraft components which may be hazardous for a human operator to enter.

3.3 Risk and Liability Issues

In its current application, this system poses very few liability concerns or costs. As it is meant to replace a human inside the ship tank, there is very little risk of human injury during operation, so we can narrow the analysis to the scope of the system itself and the tank.

The system is relatively inexpensive and made of robust components. In the event of a worst-case malfunction, which would result in the system falling a great distance, for example, the damage would still be largely to the electronics and chassis structure of the robot. With new chassis components and perhaps electronics (estimated to cost at most $200 total), it is likely the robot could be reassembled and regain original function. In the event of a catastrophic failure, in which the motors and magnets get destroyed (very unlikely), the cost of replacing the entire robot would still fall under $500 plus labor.

The other liability concerns in the event of a failure come from the potential damage to parts of the tank itself. Given the sensitivity of the information (the tanks being on US NAVY ships), we do not know what actually is inside, how prone it would be to damage, and the replacement or repair costs that must be considered.

That being said, we believe the benefit of removing the risk of human injury by implementing this system for inspection would greatly outweigh any potential risk of damage to components inside or to the structure of the tank.

3.4 Ethical Issues and Impact on Society

When proposing to replace a human worker with a robot in any situation, one must also consider the ethical issues and potential impact on society. The removal of a human worker implies the removal of the job for many people across the industry, so it must not be taken lightly.

We propose that any position that currently involves doing the manual inspection of these confined spaces be transitioned to a job that involves the operation of our inspection system. The robot is very intuitive to control, and with basic training, anyone could be taught to complete the necessary tasks of in-tank inspection, but without putting their health and safety at unnecessary risk.

3.5 Impact on Environment

The impact of this robotic system on the environment is minimal. Environmental costs in this situation come down to two major concerns: power and waste.

The system in its current form runs off of 12V battery power, which can be procured from any green method of choice – it does not require the burning or consumption of any fossil fuels, resulting in no damage to the environment by way of emissions or by-products of operation.

With regard to waste, this system is environmentally-conscious in a few key ways. First, the entire chassis is constructed of wood and aluminum – both are easy to recycle or reuse. The other major components have a high reliability and projected operating life due to their largely simple operation or passive nature – DC motors and magnetic bases. The batteries supplying power are rechargeable, greatly reducing the frequency of replacement, and thus, waste through disposal. Furthermore, the implementation of such a system could potentially identify structural issues which may otherwise go unnoticed and could lead to harmful spillage of waste into the environment from the area being inspected, if it carries such waste.

3.6 Cost and Engineering Economics

The projected costs of production and implementation of this robotic system:

Manufacturing:

- Parts - $420
- Labor – 2 hours of work at (for example) $20/hr - $40
- Machinery – hand tools, estimated at $200 (one-time cost)

Operation:

- Power – very little (negligible, comparable to charging a phone every so often)
- Training for operator – 2 hours of training – estimate: $200

4. Rationale for Design Choices

After deciding the deliverable goals, we choose leapfrog at last, since it is better to achieve the basic functions that we determine as we mentioned earlier. Lego car design is an integrated design that seems to have a better model to achieve the initial goals of this statement, especially climbing over obstacles and it can be applied to a wider range of applications. However, due to the pandemic, we narrow down the main goals. "Integrated" also becomes a problem and it is also the reason we didn't choose this design. We might not have enough time to test all the concepts in this design due to the limitation of time, so that we may not be able to finish our design at the end of the quarter. We didn't choose it not necessarily because it's worse, but because it is too "integrated". Considering we only aim to achieve some basic goals, leap-frog design is a better choice in this statement.

5. Modeling and Analysis of System

5.1 Modeling in CAD

Our climbing robot was modeled in CAD where the design continued to progress and improve throughout our timeline. The CAD is where we get our first physical model in terms of accurate dimensions which leads to planning ahead. The final CAD can be seen below in Figure 4:

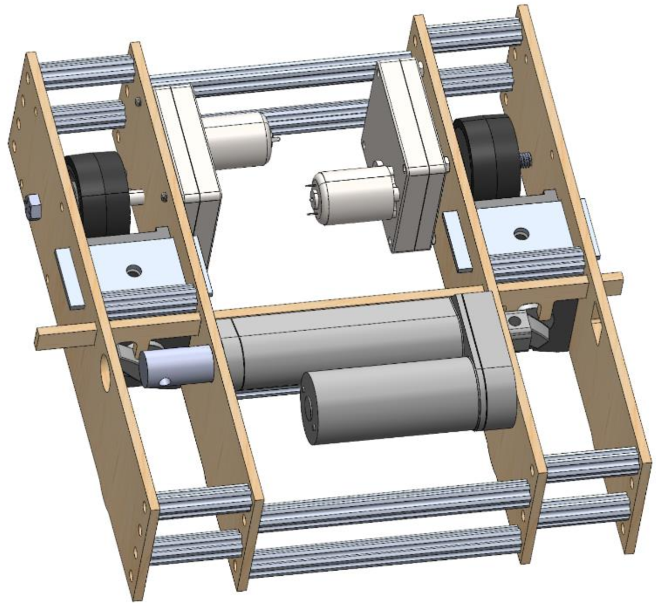

Figure 4: *Full prototype CAD*

5.2 Chassis

We started with a basic chassis which would support agile manufacturing where changes could be made to the design when necessary. It consists of laser cut pieces of wood and aluminum churro to construct a rectangular chassis (see Figure 5). This construction supports the direction of loading.

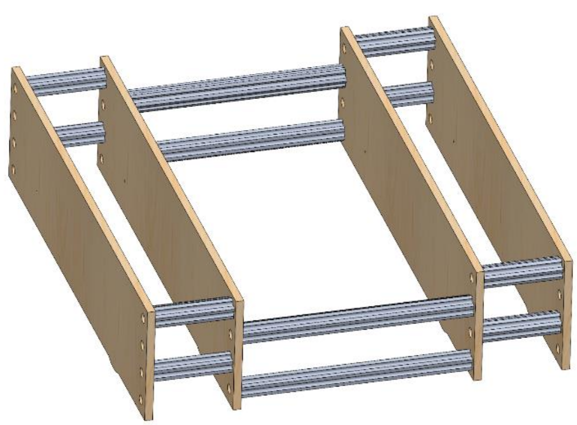

Figure 5: *Starting chassis model*

5.3 Wheels

The wheels are the critical point of the robot which both support the vertical (gravity) and horizontal (magnetic) forces acting on the robot. They need to be sturdy and have an excellent coefficient of friction. The wheels we chose were 2-inch stealth wheels with a hex shaft bore (see Figure 6).

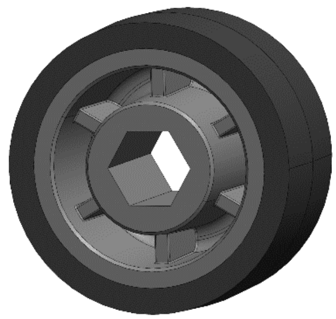

Figure 6: *Stealth wheel*

5.4 Motors

The motors are small 12-volt DC motors which come with an integrated gearbox allowing the ideal torque (40 in-lbf) for lifting the robot upward via driving the wheels. The gearbox has a face mounting design which assembles easily with the chassis. The motor mounted to the gearbox can be seen below in Figure 7:

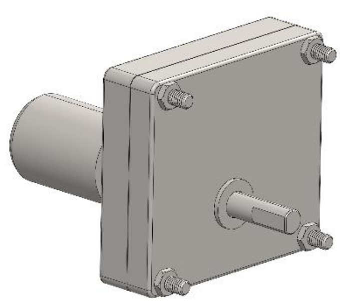

Figure 7: *Drive motor and gearbox*

5.5 Magnets

When considering magnets, the simplicity of a permanent magnet was advantageous to our short timeline. We repurposed the magnetic bases found in machine shops. They have switches which can orient the magnetic field to appear as on or off (see Figure 8). Their base force is 176 lbs. with no gap. However, a gap has been integrated to allow chassis movement, so the applicable force is less.

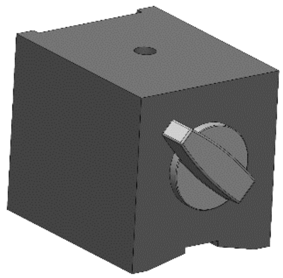

Figure 8: *Magnetic base*

5.6 Linear Actuator

The magnetic switches are normally operated by human hands. To automate this process, we have coupled together the two magnetic switches to a linear actuator, turning the linear motion into rotational motion. This linear actuator is a 12-volt motor and helical screw capable of pushing 35 lbf (see Figure 9).

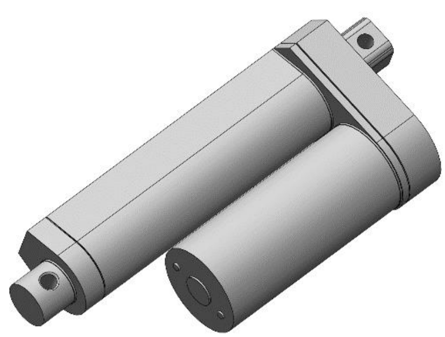

Figure 9: *Linear actuator*

5.7 Quantitative Results

To prove that the design works we performed analytical calculations based on a free body diagram (Figure 10) of the robot attached to the wall. Some key numerical results are the required magnetic force of 240 N (54 lbf) and the torque of 2.5 N-m (22 in-lbf). These numbers correlate to a predicted chassis mass of 10 kg (22 lbs.).

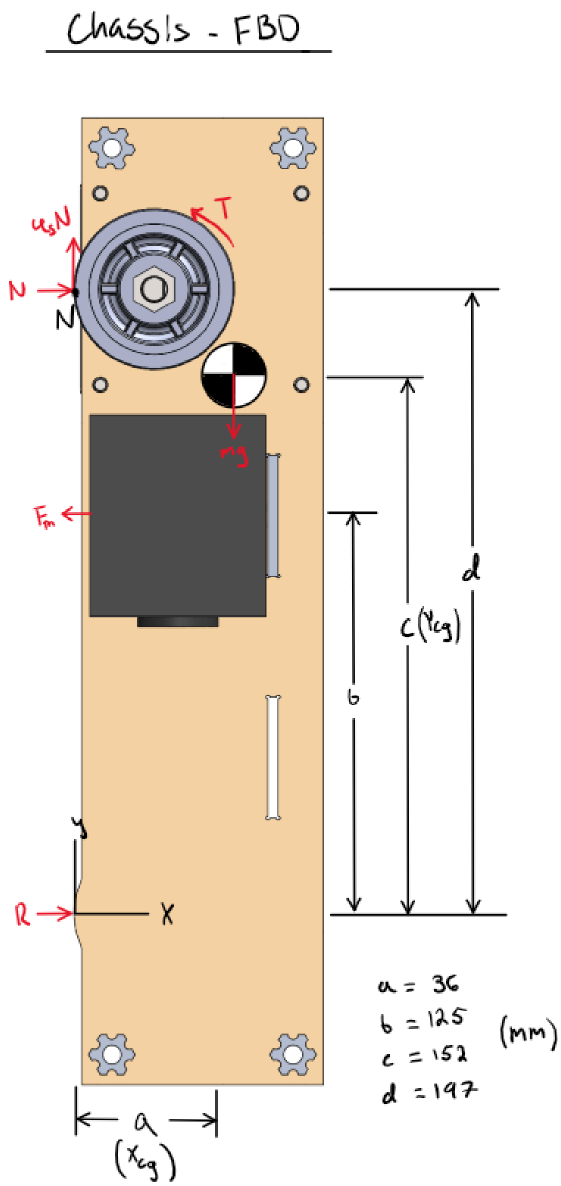

Figure 10: *Free body diagram*

After constructing the Free body diagram, the specific inputs and outputs need to be specified. These quantities can be found in Table 2. The important inputs are as follows: The predicted mass, *m* of the robot is a conservative 10 kg. The friction coefficient, μ is 0.64, predicted by the stainless steel-60A rubber coefficient documented by Engineers Edge [1]. Dimensions *a* through *d* are generated out of the CAD model. Specific outputs that are useful to know include the required magnetic force to stay statically attached to the wall, F_m (241.5 N), the normal force on the wheel, *N* (153.3 N), and the minimum required torque to climb the wall, *T* (2.49 N-m). The resulting calculations below can be referenced by the hand calculations in appendix 13.4.

The magnetic force F_m is calculated by the derived equation:

$$\mathrm{F_m} = \frac{\mathrm{m \cdot g \cdot d}}{\mu_s \cdot b} \qquad \text{Eqn. 1}$$

And the minimum torque *T* can be found by:

$$T > m \cdot g \cdot r \qquad \text{Eqn. 2}$$

Table 2: *Analytical calculation results*

Inputs	**Value**	**Units**
Mass *m*	10	kg
Gravity *g*	9.81	m/s^2
friction Coef. μ	0.64	
Distance *a* (X_{cg})	0.036	m
Distance *b*	0.125	m
Distance *c* (Y_{cg})	0.152	m
Distance *d*	0.197	m
Wheel radius *r*	0.0254	m
Outputs		
Magnetic force F_m	**54.3**	lbf
	241.5	N
Normal force *N*	**153.3**	N
Reaction force *R*	88.2	N
Min torque *T*	**2.5**	N-m
Motor specs (x2)		
Torque per motor	4.5	N-m
Max weight	18.1	Kg

6. Controller Design, Analysis, and Implementation

After we finish designing the chassis of our model, we immediately encounter another huge task, which is how to control our model. For controlling the model, we divide it into two parts. The first one is controlling the movement of the model in order to climb on the magnetic wall. The second one is controlling the switch of the magnetic base. In order to activate our model, we need a motor that can carry at least 3 pounds of payload capacity. Based on this requirement, we choose to use two CHM-1212-1M motors from Molon. It is a 12V DC motor which can provide 40 in-lb torque. On the other hand, we decide to use a linear actuator to control the switch of the magnetic base. In order to activate the DC motor and linear actuator, we use an Arduino board MEGA 2560 and a L298N motor driver for controlling.

Due to the current pandemic situation and limitation of time, we only consider the forward and backward motion of our model, which means we just need to adjust the rotation direction of the motor for clockwise or counterclockwise motion. For controlling the rotation direction of the motor, we need to change the direction of the current flow into the motor. One of the methods is using a H-bridge, which has four switching transistors with the motor at the center. By activating two switches at the same time, we can change the direction of the current flow. Meanwhile, the L298N is a dual H-bridge that can control the speed and the direction of the motor. That’s why we chose to use L298N for motor control. When we look at the L298N module from Figure 11, the module has three screw terminal blocks. One of the blocks is used for connecting the linear actuator, and another block is used for wiring two 12V DC motors. The last block is used for grounding and output of the battery. The battery we are using to power the motors and Arduino is 12 volts.

Figure 11: *L298N Motor Driver*

After we find out some basic knowledge of L298N, the next step is to decide how to control our model, either by wireless connection or jumping wire. It is easy to say using wireless connections such as Bluetooth or WIFI will be more convenient to control the model. However, we are afraid that using wireless connection will be unstable and also we don’t have that much time on designing the wireless connection. Therefore, we will be using a jumping wire with a joystick to control both the motors and the linear actuator.

The biggest problem of controller design is how to wire the L298N and the Arduino board. Since we are not learning Arduino through ME courses, all the knowledge we apply comes from the Internet. We put the sources under Appendix. Below is the wiring of the Arduino, L298N motor driver, and a joystick.

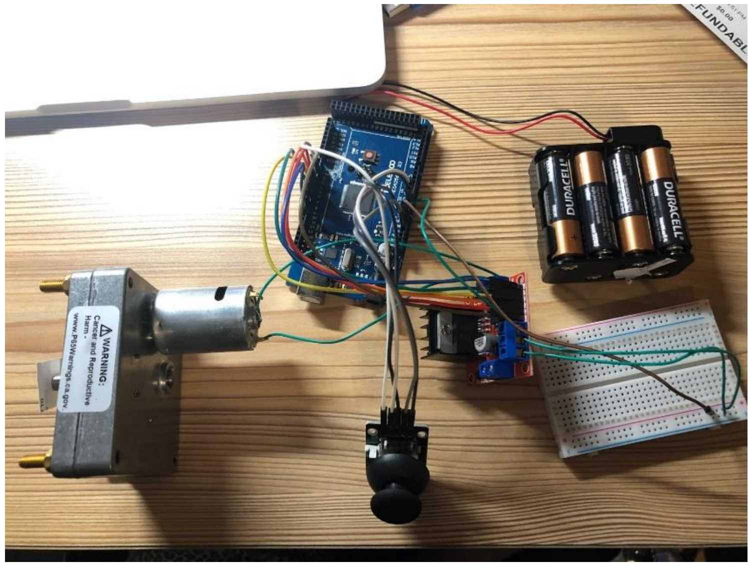

Figure 12: *Wired Connection*

For the Arduino coding, we first need to define the pin and some variables. In the loop section, we will read the value of X and Y-axis from the joystick. The joystick is made of two potentiometers which connect to the analog inputs of the Arduino. The value of the joystick goes from 0 to 1023. These values help to define the X and Y-axis of the joystick. At the center of the joystick, the value for both potentiometers is around 512. For considering the tolerance of the value, we will set the value from 470 to 550 as center. Therefore, if we move the Y-axis of the joystick backward and see the value goes below 470, we will set the two motors rotation direction to backward. The forward motion will have the same situation, but the value will be above 550. The completed Arduino code is shown in the appendix.

For controlling motors, we came up with the easiest method to control the linear actuator and DC motors at the same time. We use one joystick x-axis to control the linear actuator and the other joystick y-axis to control DC motors. In order to achieve this controlling set up, we gave up the option of left and right movement for our model. Therefore, our model can only move forward and backward based on the current setting.

7. Design and Testing of Prototype

7.1 Design of Prototype

Using our CAD model as reference, we began manufacturing the parts for our prototype. For our chassis walls, we used ¼" thick laser cut wood. Our initial chassis wall design is shown in Figure 13 below:

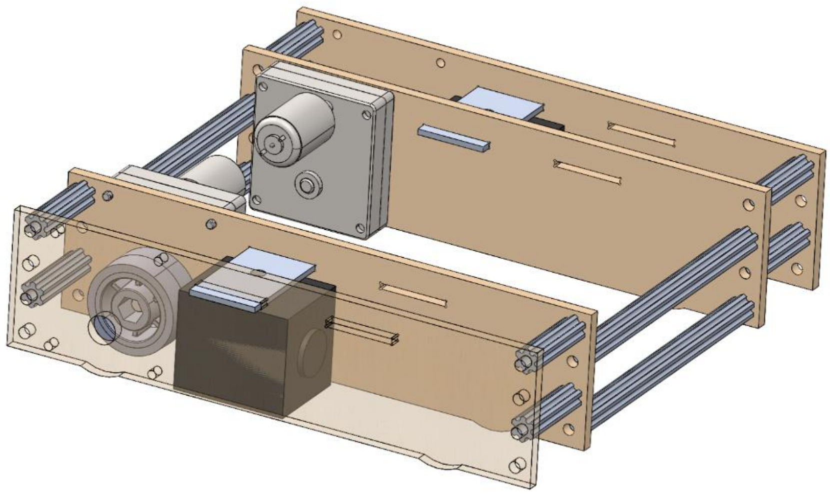

Figure 13: *Initial chassis wall design*

This chassis was manufactured as a quick prototype to do brief tests with the magnets and determine how well they clung onto the steel plate. Later, a linear actuator was added to the robot design, so a new chassis wall was made to be able to hold the linear actuator. The second chassis wall design was used for more in-depth tests and full assembly of the robot. The updated chassis wall designs are shown in the figures below.

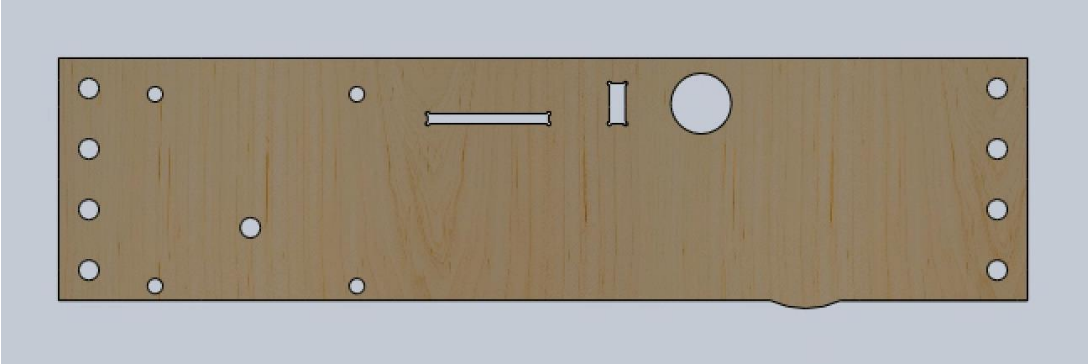

Figure 14: *Updated chassis wall design for left side wall showing additional holes for linear actuator and slider*

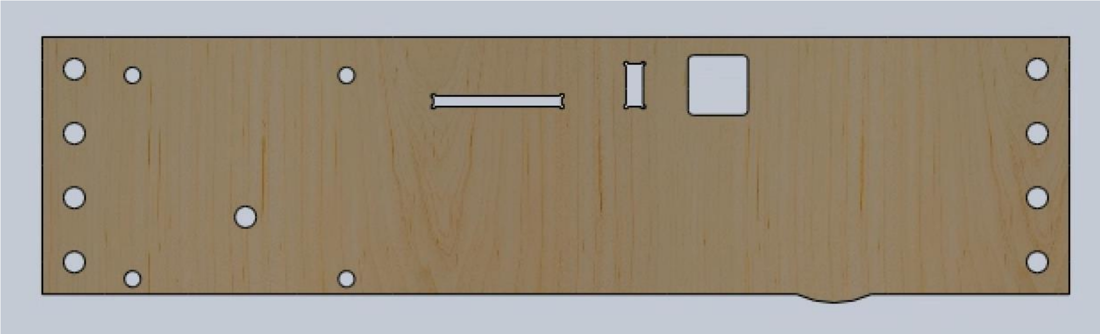

Figure 15: *Updated chassis wall design for right side wall showing additional holes for linear actuator and slider*

This second chassis wall has sufficient holes to hold the two motors, the magnets, and the linear actuators. It also has holes for a slider which will turn the magnetic switches on and off using the linear actuator. We manufactured different iterations of the slider to determine the most suitable geometry of the slider. The figure below shows the three different slider geometries. After testing the different sliders with the linear actuator, slider E was the best choice.

Figure 16: *Different slider geometries where top slider is slider D, middle slider is slider E, and bottom slider is slider F*

The full assembly of the chassis, without the linear actuator, is shown in the figure below.

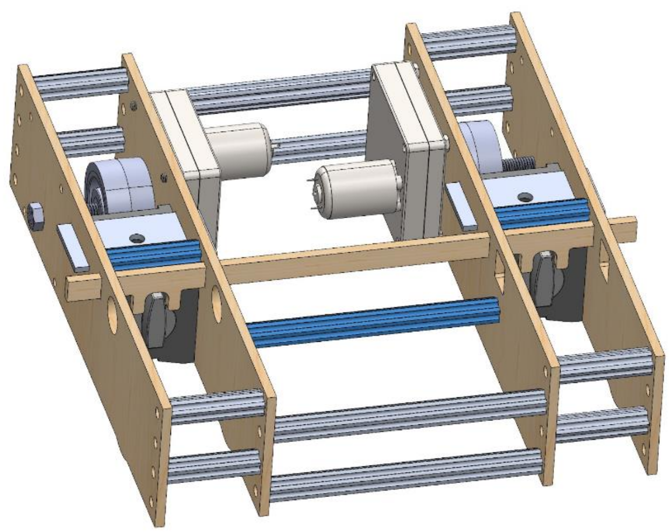

Figure 17: *Assembled chassis*

7.2 Testing of Prototype

One of the first tests we did was testing the magnets and how well they clung onto the wall. The figure below shows our testing setup.

Figure 18: *Testing setup for magnets*

We found that we could have a gap between the magnets and the steel plate and still have the magnets cling to the plate. With a gap of approximately 0.0625”, the magnets were still strong.

For our electronics test, we wanted to test that our two motors and linear actuator could be controlled independently from each other with the joystick. From an earlier test, the two motors are easily controlled with the joystick, moving clockwise and counterclockwise. During a recent test, we had issues with controlling both the motors and the linear actuator. When the joystick was moved in one direction, both the motors and the actuator moved. Ideally, we want to program the electronics so that moving the joystick “up and down” controls the direction of the motors and moving the joystick “left and right” controls the movement of the actuator. By the end of our project, we were able to have one axis of the joystick control the linear actuator and the other axis control the motors.

After complete assembly, our testing revolved around the robot's motion. Once attached to the steel plate, we tested how well the robot could move up and down the plate. We found that the robot itself could move well up and down the plate. However, after adding a payload of about five pounds, the robot would not go up the plate. Then when we removed the payload, after a few more test runs, we began to encounter slipping with just the weight of the robot. We cleaned the wheels and the plate to help but even after, we still encountered slipping. We realized that there is a magnet gap “sweet spot” that allows the robot to go up the plate the best. Our most recent test allowed the robot to have a payload of approximately two pounds and was still able to move up the wall. However, like before, we kept encountering slipping after a few more test runs.

8. Results

The key results of the whole project are an analysis of the final products performance related to the project goals: 1) attaching/detaching from a wall, this will allow the robot to change its contact points with the wall to avoid obstacles, 2) counter the force of gravity mimicking a vehicle on the ground, 3) climb the vertical surface to reach other areas, and 4) carry a three-pound payload which models any tools or equipment that need to be brought to a specific location. Weather each goal was met by the prototype can be referenced by Table 3.

Table 3: *Results*

Goal/Test	Satisfactory	Notes
Attaching/detaching from a wall	Yes	Linear actuator struggles switching on the magnets due to slider geometry
Counter the force of gravity	Yes	Robot can be held statically in place with no power supplied
Climb a vertical wall	Yes	Robot slowly ascends and descends on the wall, but there is no turning control.
Carry a 3 lb. payload	No	Robot starts slipping at a payload of 2.25 lbs.

Goal number 1 (Attaching/detaching from a wall) depends on the magnets, slider, linear actuator, and our ability to control the linkage. There are two states where the robot is either attached or detached. Both states are fully satisfactory. Detached has no requirements besides being disconnected form the plate. In the attached case, the magnets solidly connect the robot to the steel plate. No expected interactions would cause the robot to unintentionally detach. The action of switching between states is an ideal function the robot should be able to accomplish, but there are some minor issues of the transition involving the movement of the slider. The slider linkage is pushed by the linear actuator, but the geometry of the linkage tends to bind where the actuator can not continue pushing and there in a potential for the slider to snap. This can be fixed in a future iteration with different slider geometry. The whole goal is considered satisfactory since the transition sometimes works smoothly.

Goal number 2 (Counter the force of gravity) depends on the magnets, wheels, drive motors and gearbox. This goal is considered satisfactory if the robot can be statically joined to the wall. The magnets provide enough normal force on the wheels such that the friction force of the wheels on the plate is equal to the force of gravity (this can be seen in the free body diagram in figure 10 and the hand calculations in appendix 13.4). The motors and their gearboxes have a high enough gear ratio and internal friction to hold the wheels still. No power in the motors is necessary resulting in fully satisfactory goal met.

Goal number 3 (Climb a vertical wall) depends on the wheels and the motors. To be satisfactory the wheels must turn and lift the robot up and allow it to drop down. Referencing goal number 2, the robot already statically holds itself to the wall with no supplied power. Applying power should allow the robot to move up if the wheels do not slip due to a greater torque than wheel friction can counter. By applying power to the motors, the robot does ascend the wall, and a power reversal allow the robot to lower done, resulting in a fully satisfactory goal.

Goal number 4 (Carry a 3 lb. payload) is satisfactory if the robot can carry a 3 lb. payload while still maintaining the 3 previous goals. This tests the limits of the robot and its ability to carry other tools. In our testing with a load cell, the final prototype starts slipping at 2.25 lbs. deeming this goal unsatisfactory. This occurred because the wheels did not have enough friction force to counter the weight of gravity. This is contrary to our analytical calculations in table 2.

9. Budget

Initially, our estimated budget is too rough compared to the actual budget. The actual design model is much more complicated than we thought. We divide the system into four subsystems initially. They are chassis ($200), magnet ($50), arm ($150), electronics ($100). However, in the actual case, it became quite different as we moved through the process. We decided t delete the arm part due to the pandemic and time constraints. And Chassis uses less than we expected, since we take advantage of one of our team members Yesenia working in the mill. Besides, for testing, we need to purchase a metal plate that we didn't think of initially. Fortunately, we bought the metal plate together with the other group that has the same project to cut down the cost. Also, to control the magnet switch, the linear actuator comes to our list. The actual budget is shown below in the bill of materials.

Bill of Materials (BOM):

Total:

- Chassis:
    - Churro stock - $ 36.00
- Magnet:
    - Magnetic base - $ 31.92
- Controls and power:
    - Motor - $ 125.48
    - Batteries - $ 6.99
    - Motor controller board - $ 6.89
    - Breadboard jumper wires and joystick - $ 11.99
    - Battery holder case box - $ 8.00
    - ELEGOO MEGA 2560 R3 board - $ 15.99
    - Linear actuator - $ 109.99
- Others:
    - Metal plate (for testing shared with another group) - $ 224.95

10. Scheduling of Tasks

Overall, we almost followed the estimated scheduling of tasks. Due to the well-organized schedule and the good communication, the process of the design and manufacturing of the prototype flows fluently. Except some minor shift in time and the deleting of the arm design in our robot. Also, the control system is more challenging and takes more time than we thought. The deletion of the arm design provides us more time to tackle that. The major dates of estimated schedule and actual schedule are shown below.

The major dates of estimated scheduling of tasks are shown below.

- April 20 - Finalize base model
- May 7 - Test base prototype
- May 14 - Fabricate arm
- May 18 - Test full prototype
- May 23 - Polish and Finalize
- May 28 - Final test/Done

The major dates of the actual scheduling of tasks are shown below.

- April 8 - Finalize base model
- April 15 - Chassis design/magnet testing / Arduino research
- April 29 - Chassis testing with magnet / Control system setup
- May 13 - Code for two motors and testing
- May 18 - Linear actuator assemble / First prototype testing
- May 25 - Electronics testing for three motors / Second prototype testing
- May 27 - Final testing and filming demo

11. List of Parts

Table 4: *List of Parts*

Parts	Quantity	Scoured
Chassis wall (left)	2	Wood scrap from the Mill
Chassis wall (right)	2	Wood scrap from the Mill
Shortest churro (1in)	2	https://www.andymark.com/products/1-2-in-churro-different-length
Short churro (2in)	10	https://www.andymark.com/products/1-2-in-churro-different-length
Long churro (6in)	5	https://www.andymark.com/products/1-2-in-churro-different-length
Stealth wheel	2	https://www.andymark.com/products/stealth-wheels-options
8mm to hex adapter	2	Hyperloop surplus
hex spacers	12	Wood scrap from the Mill
2mm machine key	2	https://www.mcmaster.com/92288A710/
Drive motor	2	https://www.mcmaster.com/6409K15/
Magnetic base	2	https://www.mcmaster.com/1878A22/
Magnet mount	2	Hyperloop surplus
Magnet coupler slider	1	Wood scrap from the Mill
Linear actuator	1	https://www.firgelliauto.com/products/linear-actuators
Electronics		
Battery pack	1	Amazon
Arduino board	1	Amazon
Bread board	1	Amazon
Motor controller	1	Amazon
Joystick	1	Amazon
Fasteners		
1/4-20, 0.625 length	33	Hyperloop surplus
M8 bolts	2	Hyperloop surplus
Washers	8	Hyperloop surplus

12. References

12.1 Previous Work Explored

1. Lego Car : found on YouTube: https://www.youtube.com/watch?v=MwHHErfX9hI&t=1s&ab_channel=BrickExperimentChannel
2. Magnet Crawler : found on YouTube: https://www.youtube.com/watch?v=8y-099GUak0&t=2s&ab_channel=Mashable
3. Pneumatic Wall Climber : found on YouTube: https://www.youtube.com/watch?v=ytaJsYjpb9o&t=1s&ab_channel=NevonProjects
4. Wall-climbing Robot (suction) : found on YouTube: https://www.youtube.com/watch?v=RwMJLKSZjpE&t=1s&ab_channel=RIGNITC
5. (Waygate Technologies Robotics) : found on YouTube: https://www.youtube.com/watch?v=_kNlT_s9zNQ&ab_channel=WaygateTechnologiesRobotics
6. China's wall-climbing robot to remove ship rust : found on YouTube: https://www.youtube.com/watch?v=gGsCPO1KPeQ&ab_channel=NewChinaTV
7. Stanford's 'Stickybot' : found on YouTube: https://www.youtube.com/watch?v=o5lMJtQOKSY&ab_channel=Stanford
8. Scorpio: bio-inspired wall-climbing robot : found on YouTube: https://www.youtube.com/watch?v=uDoummhJTlo&ab_channel=ROARLab

12.2 Works Cited

1. Engineers Edge, L.L.C. "Coefficient of Friction Equation and Table Chart - Engineers Edge," *Engineersedge.com*. [Online]. Available: https://www.engineersedge.com/coeffients_of_friction.htm.

13. Appendix

13.1 Catalog of Previous Work Explored:

1. Lego Car:

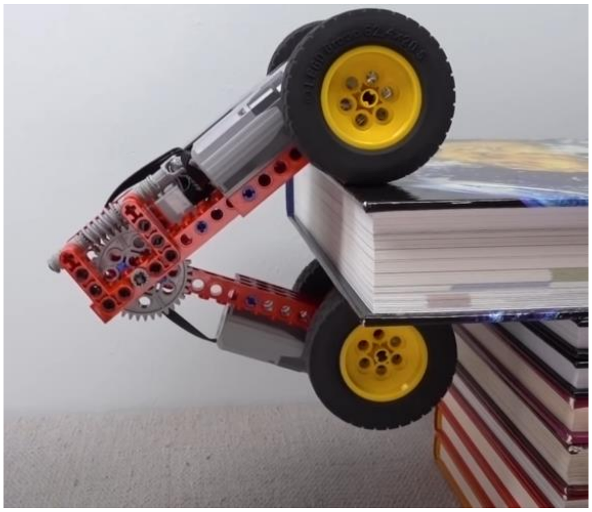

Figure 19: *screenshot from source video*

2. Magnet Crawler:

Figure 20: *screenshot from source video*

3. Pneumatic Wall Climber:

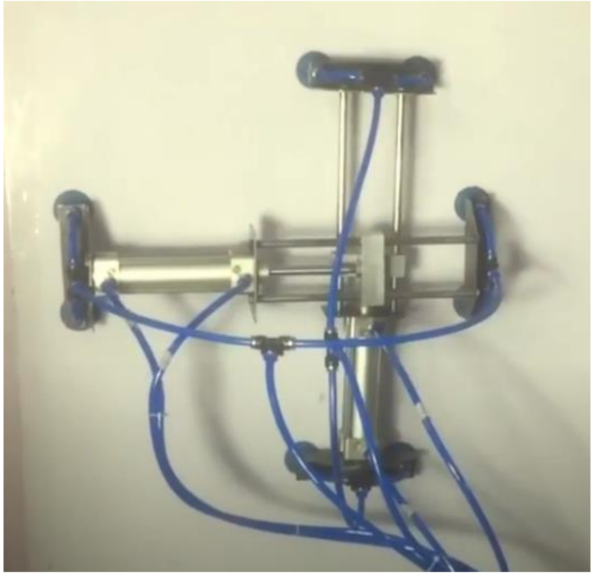

Figure 21: *screenshot from source video*

4. Wall-climbing Robot (suction):

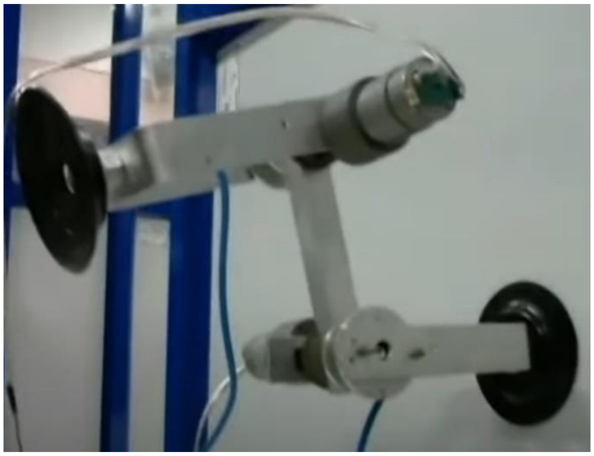

Figure 22: *screenshot from source video*

5. BIKE (Waygate Technologies Robotics):

Figure 23: *screenshot from source video*

6. China’s wall-climbing robot to remove ship rust:

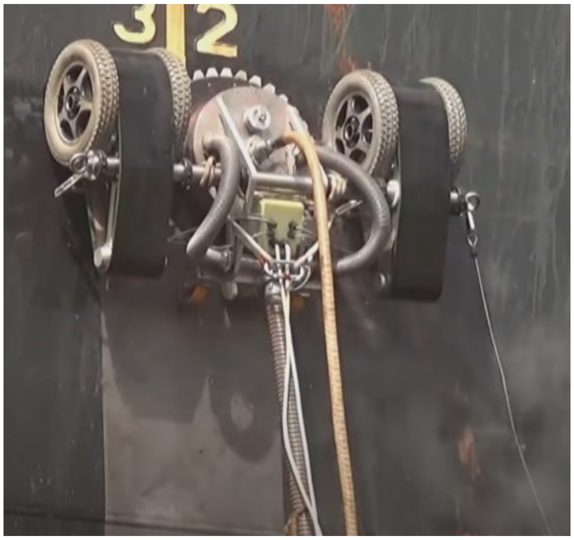

Figure 24: *screenshot from source video*

7. Stanford's 'Stickybot':

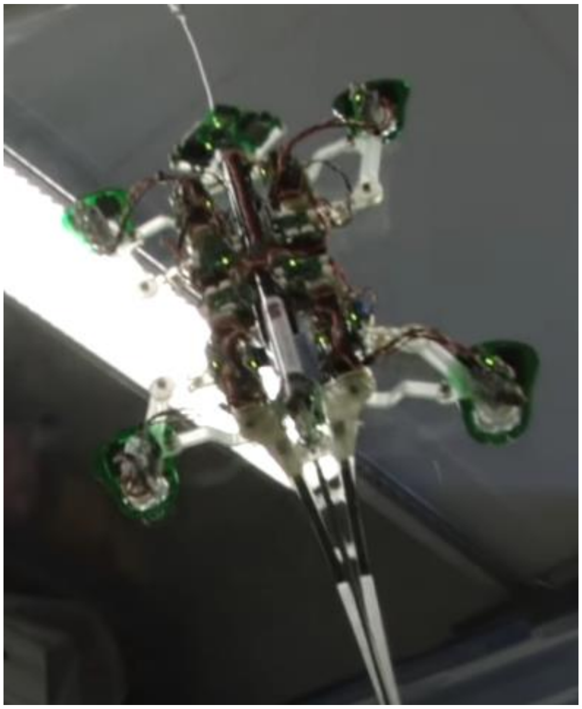

Figure 25: *screenshot from source video*

8. Scorpio: bio-inspired wall-climbing robot

Figure 26: *screenshot from source video*

13.2 Arduino source

Dejan, et al. "L298N Motor Driver - Arduino Interface, How It Works, Codes, Schematics." *HowToMechatronics*, 11 May 2021, howtomechatronics.com/tutorials/arduino/arduino-dc-motor-control-tutorial-l298n-pwm-h-bridge/.

13.3 Arduino Code

motor_control_2

```
#define enA 9
#define in1 4
#define in2 5
#define enB 10
#define in3 6
#define in4 7
int motorSpeedA = 0;
int motorSpeedB = 0;
void setup() {
  pinMode(enA, OUTPUT);
  pinMode(enB, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
  pinMode(in3, OUTPUT);
  pinMode(in4, OUTPUT);
}
void loop() {
  int xAxis = analogRead(A0); // Read Joysticks X-axis
  int yAxis = analogRead(A1); // Read Joysticks Y-axis
  // Y-axis used for forward and backward control
  if (yAxis < 250) {
    // Set Motor A backward
    digitalWrite(in1, HIGH);
    digitalWrite(in2, LOW);
    motorSpeedA = 1023;
  }
  else if (yAxis > 750) {
    // Set Motor A forward
    digitalWrite(in1, LOW);
    digitalWrite(in2, HIGH);
    motorSpeedA = 1023;
```

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motor_control_2

```
    digitalWrite(in2, HIGH);
    motorSpeedA = 1023;

  }
  // If joystick stays in middle the motors are not moving
  else {
    motorSpeedA = 0;
    //motorSpeedB = 0;
  }
//  New X axis
  if (xAxis < 250) {
    // Set Motor B backward
    digitalWrite(in3, LOW);
    digitalWrite(in4, HIGH);
    motorSpeedB = 1023;
  }
  else if (xAxis > 750) {
    // Set Motor B forward
    digitalWrite(in3, HIGH);
    digitalWrite(in4, LOW);
    motorSpeedB = 1023;
  }
  // If joystick stays in middle the motors are not moving
  else {
    //motorSpeedA = 0;
    motorSpeedB = 0;
  }

  analogWrite(enA, motorSpeedA); // Send PWM signal to motor A
  analogWrite(enB, motorSpeedB); // Send PWM signal to motor B
}
```

13.4 Analytical Hand Calculations

Hand calculations (Static, @N)

① $\sum F_x: \quad N + R - F_m = 0$

② $\sum F_y: \quad \mu_s N - mg = 0$

③ $\sum \overset{\circlearrowleft}{M_N}: \quad R(d) - F_m(d-b) = 0$

Solve for F_m

① $F_m(d-b) = R(d)$

③ $N = \dfrac{mg}{\mu_s}$

② $R = F_m - N = F_m - \dfrac{mg}{\mu_s}$

$$\hookrightarrow F_m(d-b) = \left(F_m - \frac{mg}{\mu_s}\right)d$$

$$F_m(\cancel{d} - b) = F_m\cancel{d} - mg\frac{d}{\mu_s}$$

$$F_m(-b) = -mg\left(\frac{d}{\mu_s}\right)$$

$$F_m = \frac{mgd}{b\mu_s}$$

For Climbing

$mgr < T$

$$m_{max} = \frac{T}{rg}$$

13.5 Schedule

[Full schedule here](https://drive.google.com/file/d/1nSB71BhGgR_u9w5ycdTzdaofm_2YrUEe/view?usp=sharing)

https://drive.google.com/file/d/1nSB71BhGgR_u9w5ycdTzdaofm_2YrUEe/view?usp=sharing