WORCESTER POLYTECHNIC INSTITUTE
A MAJOR QUALIFYING PROJECT

Stair-Capable Robot Vacuum

in partial fulfillment of the requirements for the Degree of Bachelor of Science by:

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Abstract

The commercial robotic vacuum is unable to bridge the coverage gaps associated with having multiple levels in a home. Staircases are insurmountable and uncleanable environments to these devices and divide a household into isolated regions. This project proposes a robotic vacuum platform that can unite these regions by traversing and cleaning stairs while maintaining a form factor practical for cleaning the rest of the home. The novel design features a three-stage platform interconnected with scissor lifts, which allows the robot to control its center of gravity and vertically extend to the heights required for stair climbing while retaining a retracted height less than that of a single stair. In tandem with the omnidirectional drive system, sensing capabilities, and wall-following control algorithm, this platform can traverse an entire multilevel home. Development of this platform included conceiving a stair climbing procedure, determining necessary sensors, calculating power requirements, CAD, tolerance analysis, manufacturing and assembly, electrical design, writing firmware, and tuning control algorithms. The resulting prototype stair-capable vacuum met our objectives and provided a proof-of-concept solution to the problem of robotic vacuums' inability to traverse stairs. The integration of this technology with the commercial robot vacuum would benefit consumers financially and disencumber them from the mundane and straining task of vacuuming stairs.

Contents

Introduction

The commercial robot vacuum is currently unequipped to clean an entire multilevel home. The standardized form factor associated with robotic vacuums is limited to single levels of a home, with the only marketed solutions for unified multilevel coverage being to manually manage the robot between the different floors of your household, or to buy multiple robot vacuums. No commercial robot vacuum has achieved traversing, let alone cleaning, any set of stairs, which means that stairwells are entirely dependent on manual labor for cleaning. Additionally, many of the solutions associated with cleaning stairs are inconvenient and cumbersome. Without a convenient solution for cleaning stairs, they are often skipped during standard cleaning routines, and can be one of the most debris ridden surfaces in a home. Stairwells divide households, and challenge both the homeowner and the consumer robot vacuum with the difficult task of cleaning them. A convenient solution to cleaning stairwells in a form factor applicable to the standard form factor of robot vacuums would benefit the homeowner and the robot vacuum market equally. The prospect of autonomous stairwell cleaning with the potential of entire household cleaning unites what would be a network of robots (individual robots for each staircase and home level) into one robot, saving the consumer from buying repetitive hardware, and opening an entirely untapped stair cleaning market to robot vacuum manufactures.

To summarize, the fundamental limitations of consumer robot vacuums are:

1. There exists no convenient, autonomous, or specialized robotic solution for cleaning stairs.
2. There exists no unified market solution to cleaning an entire multilevel home.

This project was inspired by the consideration of these limitations and strives to propose a platform capable of unified household cleaning that could be integrated with the standardized form factor of the commercial robot vacuum. Developing such a platform required competence in each of the fundamental pillars of robotics. Additionally, due to a limited budget and timeframe, it was critical to establish an engineering design process that was predictive of future phases of the project to not waste time or resources. With a small team and restricted manufacturing processes, design was held to the utmost importance, and much time was spent in the design phases to ensure the prototyping phases proceeded confidently. In this proposal, we outline the development and its many stages which took place to produce a functioning autonomous prototype from a series of concept sketches. What follows in this report is a presentation of these novel features, a breakdown of the engineering design process behind these features, and an evaluation of the robotic platform we developed and how it may apply to the standardized form factor of commercial robotic vacuums.

Preliminary Studies

Before any design work commenced, it was critical that we thoroughly investigated the problems that we faced and recognized how our idea would contribute to solving these problems. What follows is the central background research we did to prove that there existed a gap in the market, and that our idea (if development was successful) was approaching it in a novel way.

2.1 Solving the Engineering Problem of Climbing Stairs in a Novel Way

Stairs consistently act as an environmental constraint for the field of robotics and require ambitious and complex engineering design to overcome. For a mobile robot to traverse a staircase, it must be able to identify the stairwell in its environment, align itself with the first stair, shift its center of gravity across each stair without tumbling or becoming misaligned, and terminate its efforts once the entire stairwell is traversed. Generally, the problem of climbing stairs is approached with the simple solution of making a dimension of the robot significantly larger than the height of a riser (the vertical displacement of a single stair) or the length of the tread/run (the horizontal displacement of a single stair). A robot with a tank tread that spans the hypotenuse of the rise and run can engage with the stairs as it would an inclined plane, while a wheeled robot with a large enough wheel diameter can roll across the stairs if it can maintain traction, and a legged robot with an appropriate stepping height can approach stair climbing as it would other vertical obstacles if its center of gravity is considered. Each of these solutions approaches the problem in the same way: scaling a dimension until the granularity of the staircase relative to the size of the robot is reduced. Scaling up the size of a robotic solution cannot apply to many forms of mobile robotics that have constraints on certain dimensions, so the problem must be approached from a completely different direction. What if the platform needs to fit within the height of the riser and length of the tread? What mechanisms can be used to achieve stair climbing if their dimensions are constrained? How can a compact robot traverse stairs, and what applications lie within such a platform? These are the questions this report hopes to answer.

2.2 Limitations of the Current Robot Vacuum

Robotic vacuums, in their current state, are almost completely limited to two-dimensional motion. Yet very rarely are their environments entirely two-dimensional. Homes around the world are filled with vertical challenges, whether that be rugs, thresholds, platform floors, or staircases to entirely different levels of the home. The current market robot vacuum is extremely limited in its ability to move in the three-dimensional environments established by home layouts that extend upon a single floor, and generally cannot overcome obstacles that are more challenging than a thin carpet or a ramp. In a multi-level home, the only solutions for total floor coverage by a robotic vacuum is to manually relocate a single robot vacuum or buy more robot vacuums (that being one device per segmented level), and there exists no market solution for including stairwells in this coverage. This project was inspired by personal experience with this coverage gap. As the authors, each of our personal homes are cleaned by a network of robotic vacuums, yet the stairwells still require constant manual cleaning. Even non-robotic vacuums are not generally designed to clean stairs, whether that be their weight being too heavy to practically tote up and down the stairs, their power cords being too short to span between the transition of floors, or even the cleaning heads being too wide to maintain suction on the tread of a stair. Cleaning stairs is currently a difficult and mundane task for homeowners, and there exists no robotic solution to alleviate this frustration. But solving this solution by designing a device to exclusively maintain stairs is just as impractical as buying a new robotic vacuum for each level of your home. Stairs generally take up a small percentage of a home's total floor area, and most homes can expect to have numerous different stairwells in different locations throughout the home. Additionally, stairs are not entirely standardized, and building codes allow them to have a range of different dimensions. An ideal robotic solution for cleaning stairs must add stairwells to its coverage without retracting from any capability to clean and maintain the rest of the home. The mentality of having a single robotic assistant capable of cleaning an entire home, rather than having a network of specialized robots tasked with cleaning specific parts of the home can be expected to save the consumer on many fronts: not having to be tasked with maintaining a fleet of robots but rather maintaining one robot, not having to carefully position each robot throughout the home and instead establishing one location as a docking point, and reducing costs by combining a network of robots into one device. The theoretical market value of such a device would be monumental.

2.3 Integration with the Standard Form Factor

The uniformity experienced across the vast expanse of the commercial robotic vacuum market was important to recognize before approaching it with a new feature. Very rarely has any addition to this market strayed from the standard format established incredibly early on. Ever since the first commercially available robot vacuum, the Electrolux Trilobite, there has been insignificant deviation from the form factor they defined. The addition of new sensors, features, and power through the years has not significantly affected the shape, size, or cleaning philosophy of the new devices on the market. This is not because of a lack of design work, but because the earliest established form factor is very well-suited at tackling the engineering problem of cleaning a home (and continues to prove so). Because this form factor has been the foundation of household cleaning robotics for so long and is deeply rooted in the commercial market, diverging from it within the proposal of a new technology would take years of proving the capabilities of the new format for any chance of competition. Development of the commercial robot vacuum has meant adding new features and making additions to the standard form factor rather than starting from an entirely new format. So, it was important for our technology to demonstrate that it is a new feature, rather than a complete redesign. To ensure our design did not interfere with the fundamentals of the standard form factor, they first needed to be identified. What are the defining features that make this form factor so capable when cleaning floors? We answered this question by cross comparing many of the leading robot vacuums, and found that the fundamental features we needed to cooperate with to ensure a seamless integration of our technology with the standard form factor are:

1. Robot Size:
   (a) An average 12 × 12 inch footprint (12 in long & 12 in wide, or 12 in diameter);
   (b) A robot height that is a fraction of its length and width to ensure it can clean under couches, beds, etc.
2. One pair of driven wheels.
3. A centered debris collection vent.
4. Side spinning brushes to direct debris into the center vent.
5. Bumpers, and other sensors to interact with the environment.

A rudimentary model from these findings was then crafted which represents the most basic form of a commercial robot vacuum and contains the fundamental features this project needs to avoid interferences. This model can be seen below in Figure 2.3.1:

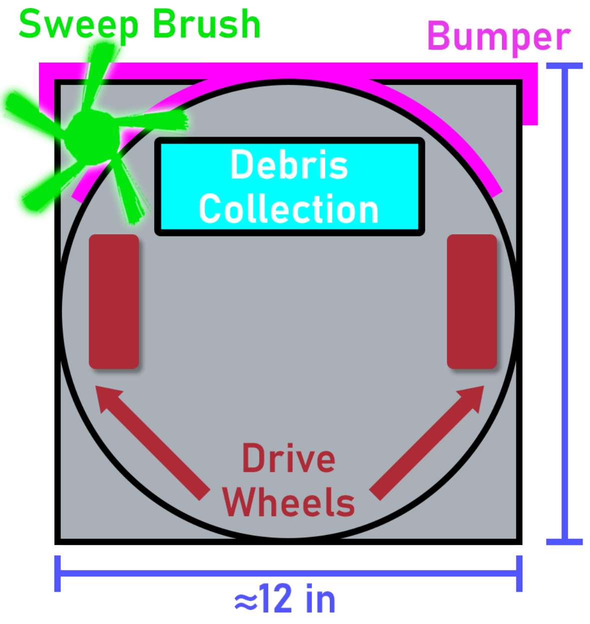


Figure 2.3.1: The Standardized Form Factor of the Commercial Robot Vacuum

Methodology

Within this section, we will shed light on the processes that took place to develop and idea from a series of concept sketches, to a fully functioning autonomous prototype. A crucial factor to our project's success was implementing a predictive engineering design process within each stage of our methodology. Initially planning a development sequence to identify each stage, and then carefully regarding the later stages of development while working through the sequence meant that there were minimal conflicts between the stages. Each stage had to come together to form one cohesive unit, and without this predictive design method, there would have been significant issues with compatibility between the stages of design. Effective communication between the small team made it easier to express the needs of later stages to ensure previously made design decisions did not interfere with the union of these phases. Figure 3.0.1 below represents the complexities and intertwined nature of our engineering design process, and what follows is a breakdown of each phase and how they contributed to the final product we delivered.

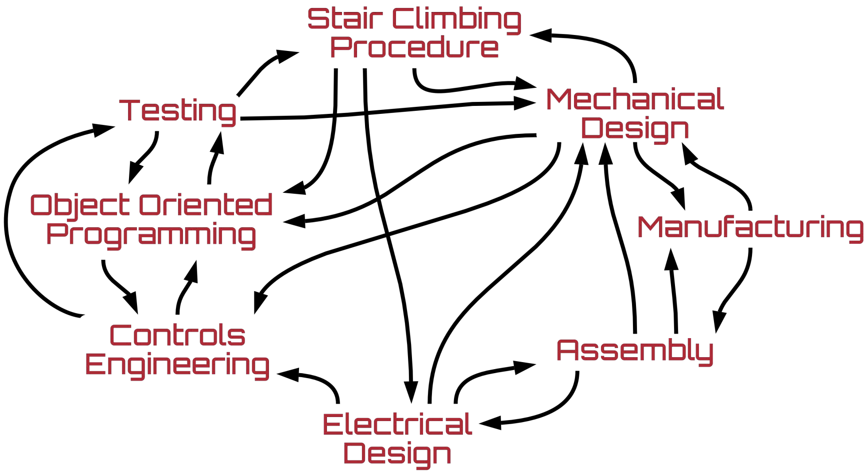


Figure 3.0.1: Engineering Design Process Flowchart

3.1 Project Objectives and Scope

The first step in producing a functioning prototype that proposes to solve the problems identified in our background research is establishing the goals of the project and constraining the scope of our design. This was necessary to ensure our engineering design was directed on materializing our novel solutions instead of wasting resources on developing systems that already exist. Without these constraints, time and money would have been exhausted on replicating engineering solutions that have already been standardized through extensive design work. This project is by no means reinventing the robot vacuum. Current robot vacuum technologies are rapidly accelerating towards more advanced solutions with many new capabilities and features each year. It was important for our technology to demonstrate that it proposes a new feature to the standard form factor rather than suggesting a complete redesign. This design focus allowed our team to target our efforts exclusively on the novel features we were designing, which invoked the production of the following project objectives and constraints.

This project aims to propose a robotic platform that is:

1. Capable of traversing stairs with the intention of cleaning those stairs:
    (a) Being able to ascend stairs;
    (b) Being able to move across the width of the stairs with respect to the debris collection layout.
2. Focused on unified home cleaning rather than specializing in stair cleaning:
    (a) Platform is equally capable of cleaning floors as it is stairs.
3. Applicable to the standardized form-factor of current robot vacuums without interferences or losing already associated cleaning capabilities (see Integration with the Standard Form Factor for definitions of the standard form factor):
    (a) Constraining platform dimensions;
    (b) Having familiar brush and debris intake layout;
    (c) Limiting the platform to a single pair of driven wheels;
    (d) Having a platform that can smoothly integrate with the current standard form factor.

The project scope constraints include:

1. Focusing design work on stair climbing with the intention of cleaning rather than producing a prototype capable of actual cleaning:
    (a) Allocating space for vacuum components, but hold on implementing them to focus on stair climbing;
    (b) Developing the stair climbing procedure to allow for autonomous stair cleaning.
2. Allow for prototype to be heavier and scaled larger than its ideal form to forgive the limitations within our manufacturing processes.
3. Allow for prototype to be slower than its ideal form to account for the extra weight and scale:
    (a) Focusing on developing stable logic behind stair traversal & cleaning rather than speed.

3.2 Concept

The concept of this platform was sparked from a dinner conversation on January 15th, 2021 in the Wofford household surrounding the pains of cleaning our stairwells. A series of concept sketches were made that night which inspired the development of the rest of this project. These sketches helped identify the engineering challenges we were to face with the development of this project.

3.2.1 Tri-Stage Scissor Lift Concept

The basic idea was to approach stair climbing with a tri-stage design. Having three interconnected stages with independently operated actuation to control their height relative to the other stages means that raising or lowering an outer stage (with respect to momentum) will not tip over the robot because the other two stages are maintaining the center of gravity. If the mass of the entire platform is distributed equally across the three stages, then one of the outer stages can be actuated up or down freely because most of the mass is still planted with the two grounded stages. But, actuating these stages can be done in many different ways, most of which require the robot to have a homed height that is equal to or greater than the height it needs to achieve (such as using linear sliders or pulleys). To cooperate with the standard form factor, the robot needs to retain a small homed height (generally less than a single stair) while having the ability to extend to stair heights much greater than its homed vertical dimension. Applying scissor lifts to actuate the three stages allows for this to happen. The robot can have a homed height the fraction of its width, because the scissors are open. But, when they close, the scissor lifts can elevate the outer stages to heights appropriate for stair climbing. This is a novel idea when applied to robot vacuums and allows for a small form factor device to enlarge to dimensions required for stair climbing while maintaining the ability to fit under small areas (beds and couches) to vacuum when homed. The original concept sketches for this design can be seen below in Figure 3.2.1:

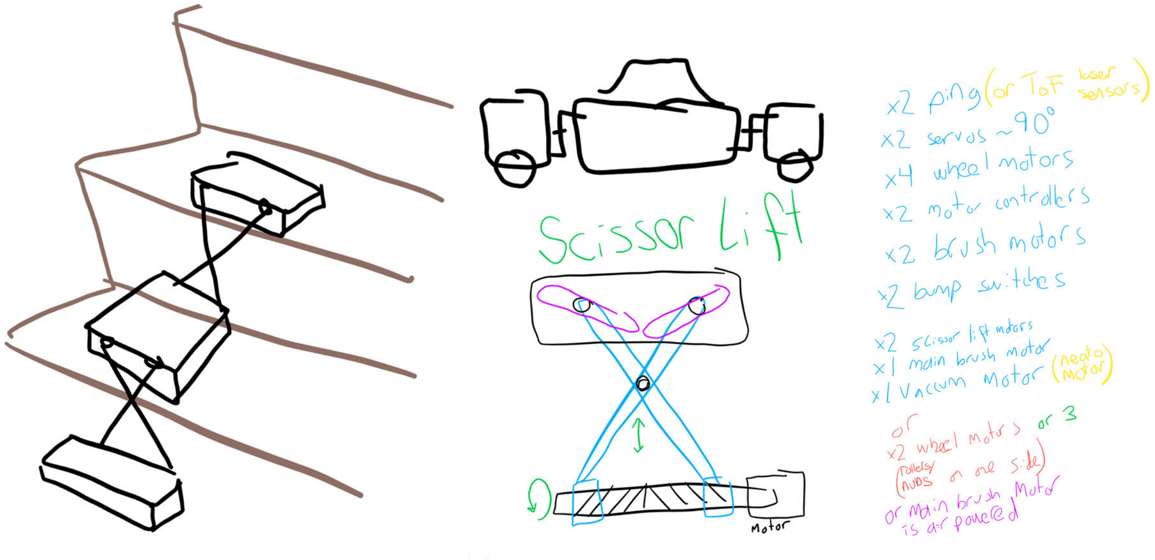


Figure 3.2.1: Original Platform Concept Sketches

3.2.2 Stair Climbing/Cleaning Concept

From this point, a stair climbing procedure concept was born. Essentially, the tri-stage scissor lift design allows for the robot to progress up the stairs by shifting its center of mass from one step to the next. Some original estimations were made for the type of sensors required to achieve this functionality. However, to meet our project objectives, the robot not only had to climb stairs, but also traverse the width of the stairs with the intention of cleaning them. The robot is also required to perform this task in cooperation with with the conventional cleaning layout. That is, for the robot to clean a stair, it needs to move a vacuum intake across the width of the stair in a way that covers the area of the step. If a conventional robot vacuum were to do this, the colinear axles of the two drive wheels would be normal to the stair riser, and it would be able to achieve cleaning one stair (assuming it doesn't fall off in the process). Additionally, the robot needed to proceed up the stairs in this orientation to optimize the navigation operations required for ascending and cleaning as opposed to cleaning the width of the stair and then turning 90 degrees to climb. The above logic helped define where the stages needed to be separated, which was parallel to the plane of the stair riser. When in terms of the standard form factor, one exterior stage would house the left drive wheel, the middle stage would possess the debris collection slot, and the other exterior stage would house the right drive wheel. However, for the robot to be able to drive across the width of a stair and then proceed up or down the stairs in an orthogonal direction without rotating the entire robot, it would need an omnidirectional driving solution. Figure 3.2.2 illustrates the concepts explained above for climbing and cleaning the stairs.

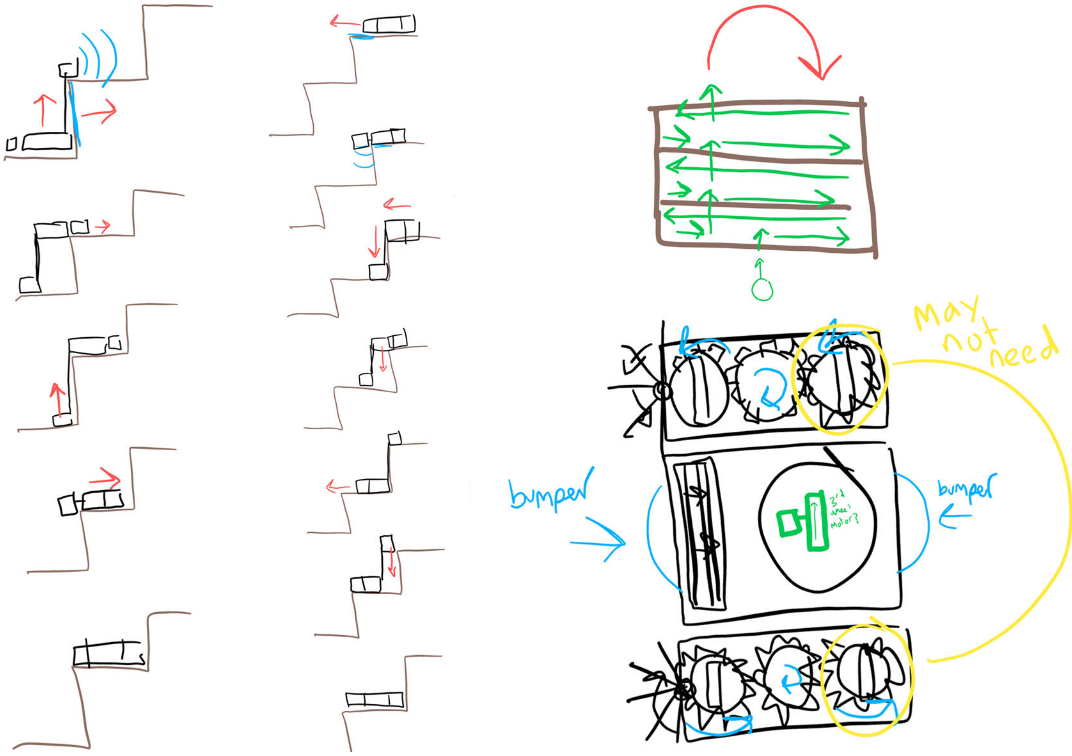


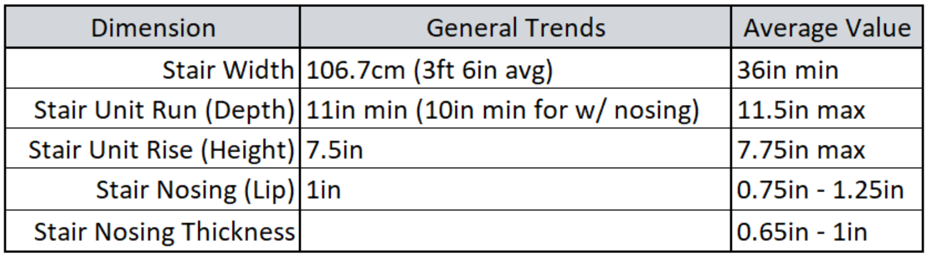
Figure 3.2.2: Original Stair Climbing/Cleaning Procedure Concept Sketches

3.3 Dimensioning

To turn a concept into a design, the concept needs to be given a sense of scale and needs to be imposed with a set of dimensional requirements to promote success in its environment. In this section, we establish the defining dimensions that our CAD model will have to meet later on.

3.3.1 Stair Dimension Research

This project is focused on climbing and cleaning stairs, which luckily have a strict set of rules to dictate their dimensions. Dimensioning our design to be able to handle most stairs first requires an understanding of what stair dimensions usually are. This was achieved by looking at general building codes and obtaining measurements from the wide variety of staircases in our personal lives. Figure 3.3.1 combines these measurements into a set of generalized stair dimensions.

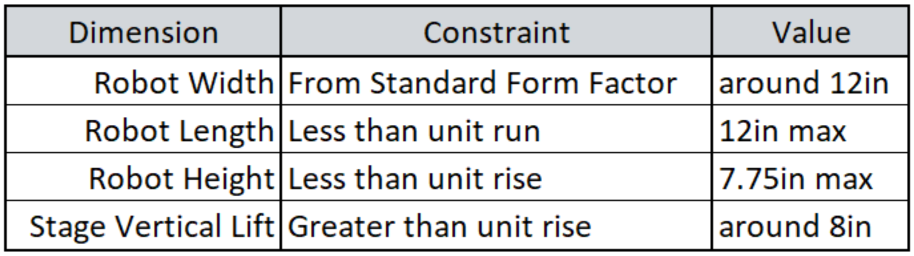


Dimension	General Trends	Average Value
Stair Width	106.7cm (3ft 6in avg)	36in min
Stair Unit Run (Depth)	11in min (10in min for w/ nosing)	11.5in max
Stair Unit Rise (Height)	7.5in	7.75in max
Stair Nosing (Lip)	1in	0.75in - 1.25in
Stair Nosing Thickness		0.65in - 1in

Figure 3.3.1: Stair Dimension Research

3.3.2 Dimension Constraints

The research discussed in our Stair Dimension Research enabled us to identify the critical dimensions of our platform along with the criteria required to meet for successful stair climbing. For the purpose of this project, the front of the robot is defined as the exterior stage which leads ascension up the staircase, while the back of the robot is defined as the exterior stage which follows the other two stages during ascension. The most important dimension is the length of the robot, which dictates the size of the stair it could climb. It is critical for this dimension to be less than the unit run of a staircase so it would fit within this depth. Notice that in the chart below (Figure 3.3.2), the robot length constraint is greater than the unit run established in Figure 3.3.1. This was done to account for the driven wheels' offsets into the length of the robot, that is, the realistic defining dimension is from the front edge of the robot to the rear driven wheel. The next most important dimension is robot height, which is defined to be less than that of a single stair. This decision meets our project objective of having a height a fraction of the length and width, while also demonstrating one of the defining novel features of our robot: a robot can exist in a form factor whose height is less than that of a single stair without losing the ability to ascend the staircase. The third defining dimension, and the least constrained one, is the width of the robot. The reason for this dimension being the least constrained is due to it being indirectly defined by the necessary displacement of the scissor lift, and therefore the length of the individual scissor arms. This dimension should aim to be as close to the standard form factor's width as possible, but is the only dimension available to enlarge if the scissor lift arms need to lengthen to meet their displacement requirements, that is, to be able to raise the stage to a height that exceeds and clears the unit rise of the stair. All of these constraints are listed below in Figure 3.3.2.



Dimension	Constraint	Value
Robot Width	From Standard Form Factor	around 12in
Robot Length	Less than unit run	12in max
Robot Height	Less than unit rise	7.75in max
Stage Vertical Lift	Greater than unit rise	around 8in

Figure 3.3.2: Platform Dimensional Constraints

3.4 Calculations

Before any decisions could be made regarding hardware choices or manufacturing processes, it was necessary to conduct some internal force calculations to determine the power requirements for this system. We needed to know:

1. The required output torque for each scissor lift motor.
2. The diameter, pitch, starts, and lead should be for the lead screw.
3. The ideal speed and torque of the drive module motors.

3.4.1 Drive Module Requirements

To remain consistent with our objective of creating a platform that can smoothly integrate with the standard robotic vacuum's form factor, the system is required to travel at similar speeds to those of existing platforms. We then had to choose a motor to allow the robot to drive at this speed, while accounting for the gear train and the wheel diameter of the drive module. This was done once the drive module was designed using the equation below:

$$RobotVelocity = GearRatio \times MotorVelocity \times WheelRadius$$

3.4.2 Internal Forces of Scissor Lift

The next power requirement to be determined was the minimum amount of force to be applied to the scissor lift to raise and lower the front and rear stages. The first step in this process was making a free body diagram of one of the scissor lift systems, as well as each individual scissor limb, as seen in Figure 3.4.1. The only force that required for further calculations was at the driven scissor limb's lower joint. This value would become the desired linear force in our lead screw calculations.

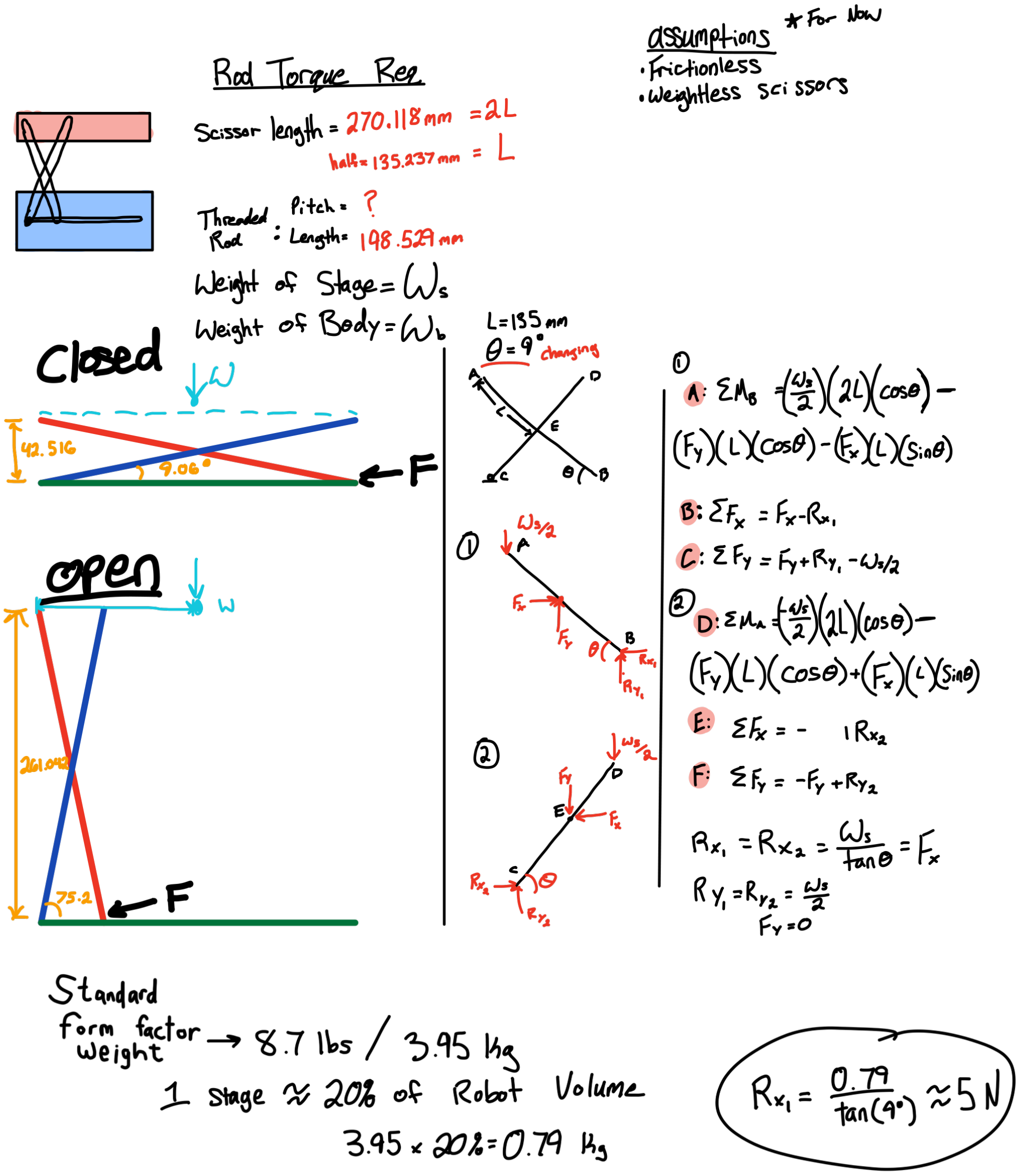
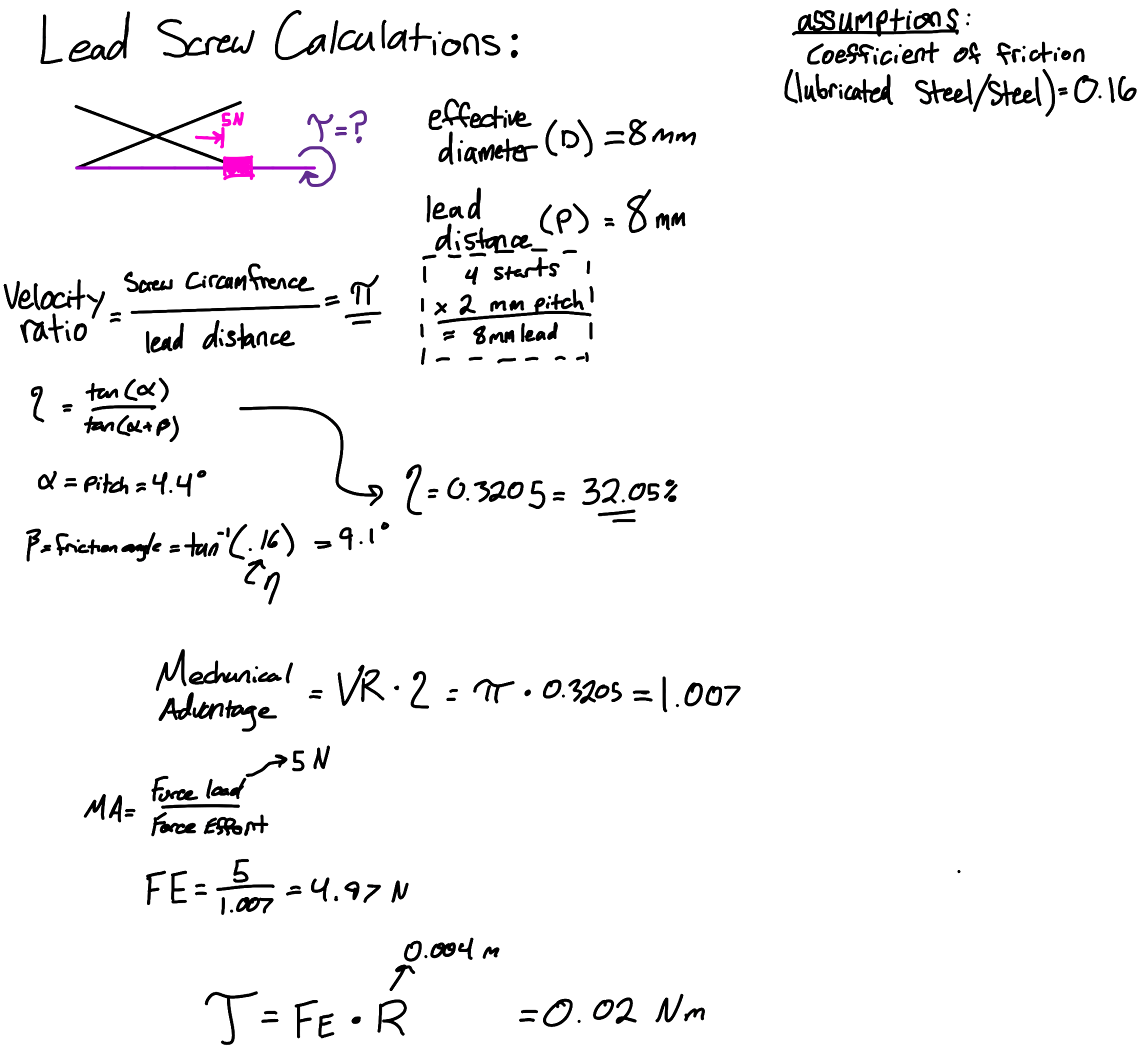


Figure 3.4.1: Free Body Diagram of a Scissor Lift

3.4.3 Scissor Lift Actuation

The next requirement to be determined was how powerful the motor driving the lead screw needed to be. The desired target force would be the result of the scissor lift calculation, which could be used to determine the torque needed to be applied to the lead screw to achieve the equivalent linear force. This can be done using the formula seen in Figure 3.4.2, which requires knowledge of the diameter, pitch, and lead of the screw. These lead screw characteristics were not determined through calculations, but rather availability and affordability of potential lead screws. The coefficient of steel was assumed to be equivalent to that of lubricated steel on steel, which is equal to 0.16.



Lead Screw Calculations:

assumptions:
Coefficient of friction (lubricated Steel/Steel) = 0.16

effective diameter (D) = 8 mm

lead distance (P) = 8 mm

4 starts
× 2 mm pitch
= 8mm lead

$$\text{Velocity ratio} = \frac{\text{Screw Circumfrence}}{\text{lead distance}} = \underline{\underline{\pi}}$$

$$\eta = \frac{\tan(\alpha)}{\tan(\alpha+\beta)} \longrightarrow \eta = 0.3205 = \underline{\underline{32.05\%}}$$

α = pitch = 4.4°

β = friction angle = $\tan^{-1}(.16)$ = 9.1°

μ

$$\text{Mechanical Advantage} = VR \cdot \eta = \pi \cdot 0.3205 = 1.007$$

$$MA = \frac{\text{Force load}}{\text{Force Effort}}$$

Force load → 5 N

$$FE = \frac{5}{1.007} = 4.97\ N$$

$$\tau = FE \cdot \overset{0.004\ m}{R} \qquad = 0.02\ Nm$$

Figure 3.4.2: Torque Requirements of a Lead Screw

Considering the efficiency of a ball screw compared to a lead screw, in the engineering design process it was proposed that a ball screw be used instead of a lead screw. This is shown below in Figure 3.4.3, where a much lower resultant torque is required to move the same amount of weight when compared to the lead screw.

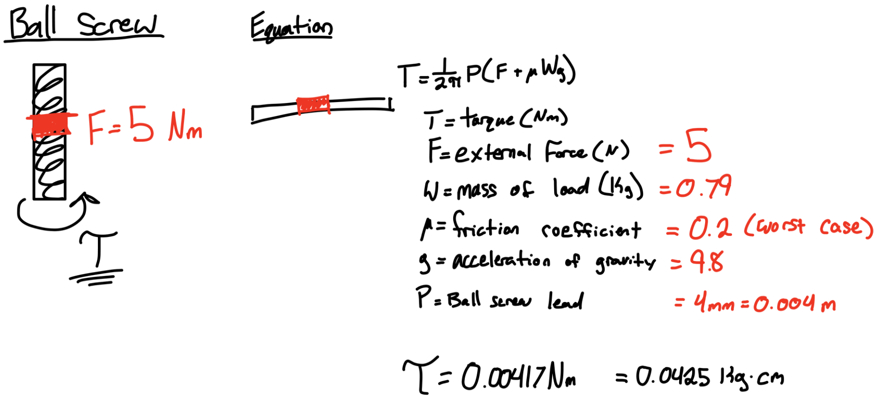


Figure 3.4.3: Torque Requirements of a Ball Screw

Ultimately, a lead screw was used in the final engineering design due to it not needing an external braking system, its affordability, and the greater variety of lead screws available at the time of prototyping.

3.5 Stair Climbing/Cleaning Procedure

Along with the dimension constraints and calculations, a robust stair climbing procedure needed to be defined to enhance the critical preliminary resources necessary for a thorough mechanical design. A general procedure was worked out within the concept stage, but it needed refining to ensure identification of the necessary sensors and vacuum component layout to support reliable climbing and cleaning. To refine this procedure, we first identified each phase of the ascent. Then each stage was individually evaluated to determine what sensors would be necessary to continue the sequence, that is, to move on to the next step in the procedure. In doing so, we produced a comprehensive model that:

1. Verified that two drive wheels (one on each exterior stage) was enough to move the platform up and down the stairs without needing a 3rd driven wheel on the middle stage;
2. Evaluated the location of each of our idler wheels, and confirmed that the robot always maintained at least three noncollinear points of contact with the ground to ensure balance;
3. Identified the locations and types of sensors necessary to progress through the sequence of stages, and the values that these sensors would read to influence conditions for the later implemented autonomous stair climbing state machine;
4. Confirmed the vacuum component layout, and ensured that the debris collection was well suited to clean stairs as well as general floors.

A comprehensive visualization of the stair climbing procedure can be seen below in Figure 3.5.1, while an animation of this visualization can be viewed HERE (or scan the QR code below in Figure 3.5.1).

Remark: The animations included in this section were made after the final model was developed, and provided here only to enrich the reader's understanding of the procedure. From the perspective of this point in our methodology during development, the stair climbing procedure was hand drawn with annotations on the stages because the refined model had not yet been crafted (much like originally observed with the concept sketches seen in Figure 3.2.2).

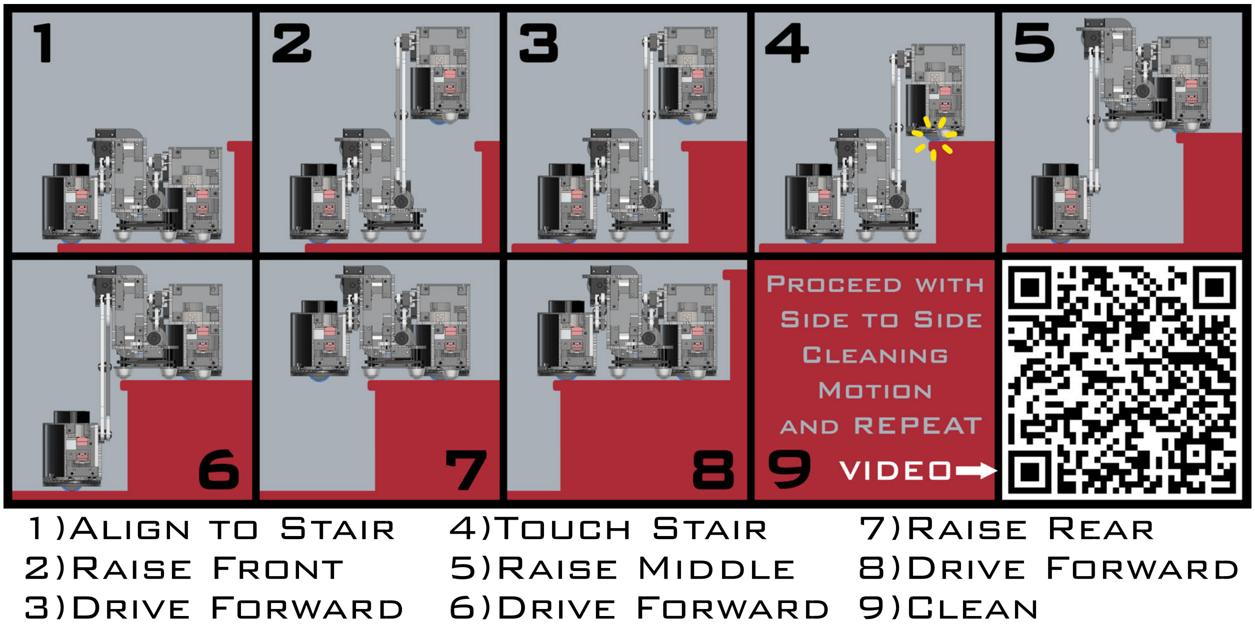


Figure 3.5.1: Final Stair Climbing Procedure: Click HERE for Video

3.6 Sensors

The Stair Climbing/Cleaning Procedure identified all of the sensors necessary for the platform to have sufficient responsiveness to itself and its environment. The sensors on the platform can be categorized into external and internal sensing. External sensing describes sensing of the robot's surroundings, such as touching a stair or measuring a distance, and is usually utilized in conditions that advance progress through a state machine. Internal sensing describes sensing that allows the robot to know states about itself, and is generally employed to ensure a robot knows its limitations and has feedback on its actuation. It was important for this project to prioritize low-cost sensors because the proposed platform targets the consumer market, where mass manufacturing and price optimization is employed. What follows is a list of the various external and internal sensing capabilities, followed by a visualization of our external sensor decisions and placement in Figure 3.6.1.

3.6.1 External Sensing

1. Two wheel touch sensors (one on each drive module) that sense the engagement of the wheel with the ground.
2. Two time-of-flight (ToF) sensors on the front side of the front stage to measure both distance and angle with respect to a surface.
3. Two bump sensors on the left and right sides of the middle stage to determine the bounds of a stair tread as the robot cleans and traverses its width.
4. An accelerometer and gyroscope module to determine the angle of the middle stage with respect to the ground plane (Information on this angle is necessary due to the non-linear translation of the scissor lift mechanisms, as will be discussed later in Controls)

3.6.2 Internal Sensing

1. Two homed position limit switches (one for each scissor lift) to sense when the scissors are open.
2. Two end position limit switches (one for each scissor lift) to sense when the scissors are closed.
3. Two encoders (one on each drive motor) to have feedback on driving behavior.

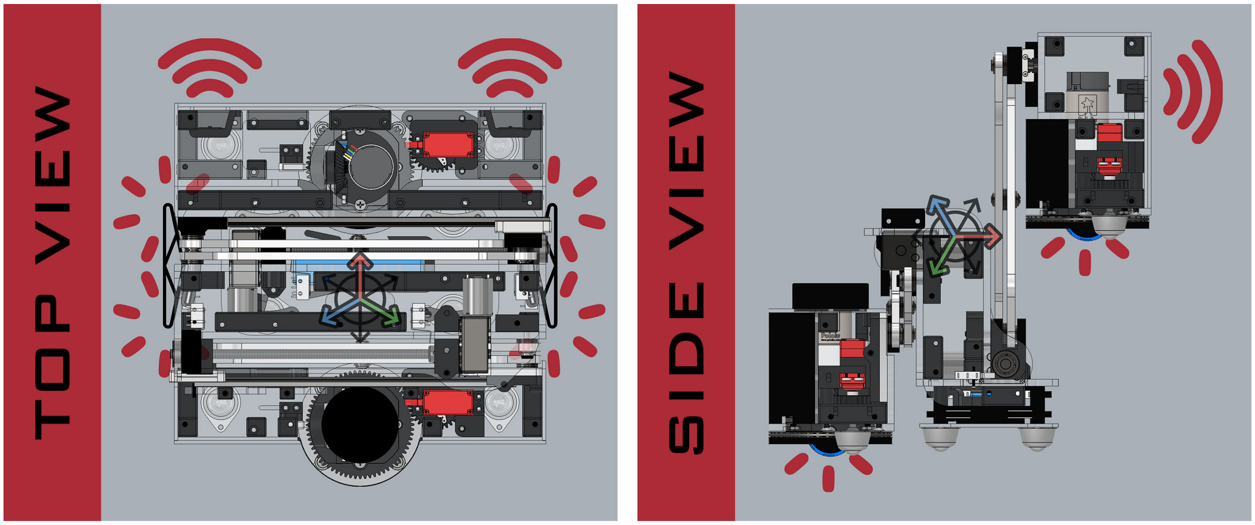


Figure 3.6.1: External Sensor Layout

3.7 Vacuum Component Layout

Because the scope of this project excludes physically implementing vacuum components into the design, it was crucial to account for their future implementation to prove the capability and value of our platform. The Stair Climbing/Cleaning Procedure defined that the vent needed to span the robot from front to back as much as possible, so that it is best suited to span the tread of the stair as it is moved across the stair's width. The length of this slot needs to be maximized, but the platform is divided into three stages which inhibits this because the stages are divided along the length that the vent spans (which would add the engineering challenge of maintaining suction throughout a segmented channel). Instead, side spinning brushes can be used to cover the areas where the vacuum slot cannot reach, and can even direct debris into the vent and scrape debris out of corners. This is a solution that is commonly seen in standard robotic vacuums, and is simpler than creating a system of interlocking airtight vents to maximize its width. Additionally, because the robot can only ascend the stairs in one direction due to the inability to toggle the scissor lifts, it was important to consider dead zones on the stairs that would not be within the vacuum's coverage. For example, if there is only one vent on the left side of the vacuum, there would be a robot-width-sized dead zone spanning the entirety of the right side of the staircase that is unreachable to the vacuum. This is not a very critical problem though, because most commercial robot vacuums suffer from significant dead-zones in their coverage (the recent adoption of the "D-Shaped" design has improved this). Nonetheless, we wanted to consider the optimal form factor of this design, which would be having vacuum vents and brushes on both the left and right sides of the robot to ensure minimal dead-zones. Additionally, the vacuum components are distributed amongst the three stages. The middle stage houses all of the debris collection components (vacuum), while the outer stages house the debris directing components (brushes). The design shown below in Figure 3.7.1 was critical in establishing the open development space required for our proposed platform.

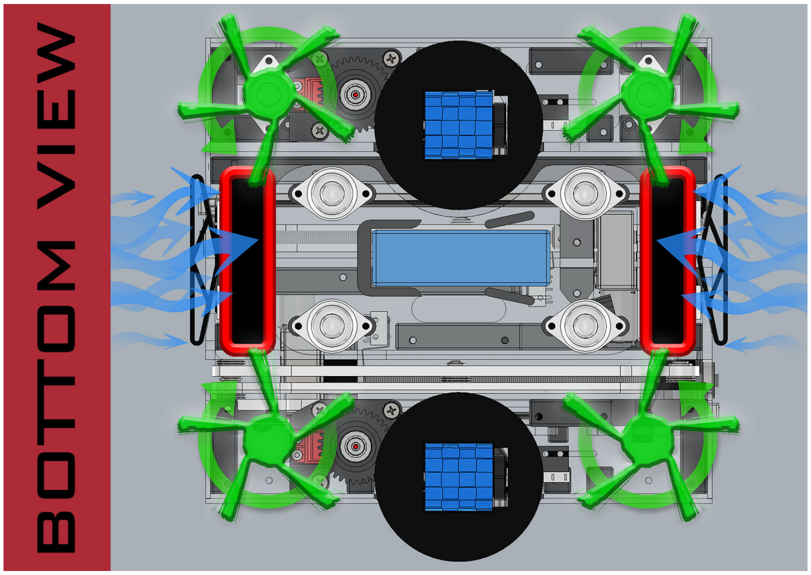


Figure 3.7.1: Vacuum Component Layout

3.8 Mechanical Design

Mechanical Design was one of the longest phases of this project due to several factors, including: the complexities that emerged once a CAD model started being developed, the intense spans of tolerance analysis, optimization problems, simulation, and analyzing mechanical assembly procedures. Up to this point, all of our design work had been more idea-based than math-based. No matter how good our visuospatial skills were, there were bound to be interferences our minds or sketches missed, and that CAD would be soon to unearth. The program of choice for this project was Autodesk Inventor, which was mainly chosen for its generally superior stability and better animation/rendering capabilities and environments when compared to its competitors. The team approached initiating the CAD model in an effective fashion, in that each member took a week to develop concept models of their own and reconvened to decide which one to continue developing. This promoted discussion and resulted in a lot of variation in the earliest models. However, the variation outlined in Figure 3.8.1 proved its superiority, and became the base of the final model. This figure is necessary to understand the basic components of our platform, and to understand the language used in the rest of the report. Additionally, all hardware for this project was sourced from McMaster-Carr's catalog, and occasionally supplemented with Amazon.com's counterparts when cheaper alternatives were found to reduce development costs.

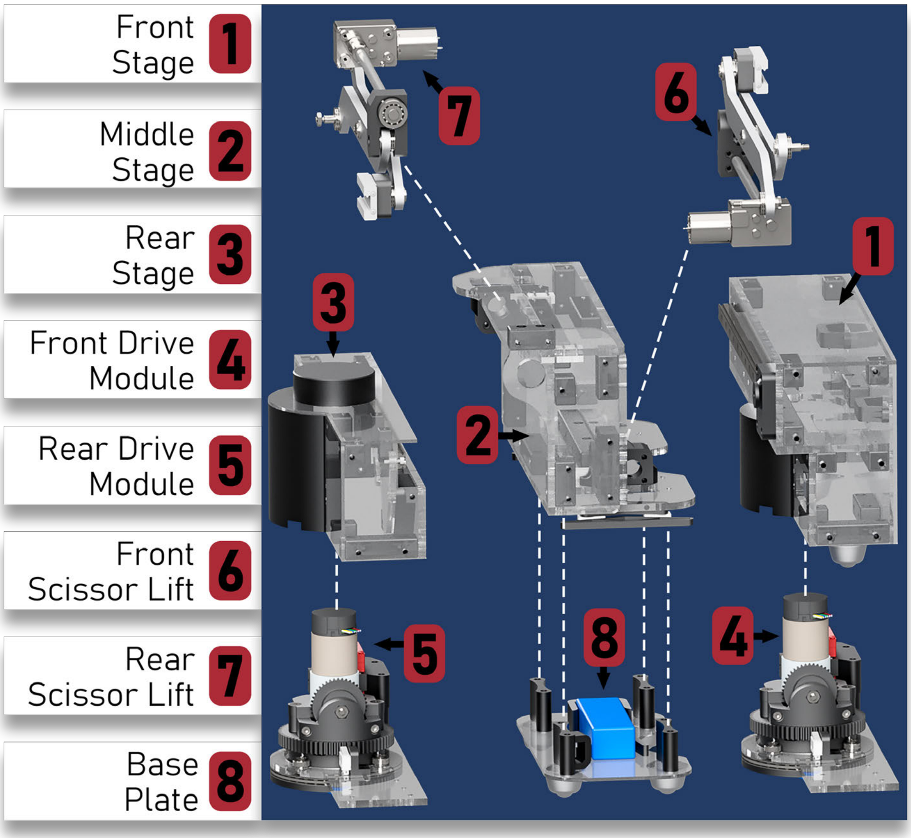


Figure 3.8.1: Platform Design Outline

3.8.1 Omnidirectional Drive Module

The first CAD problem we faced was developing the omnidirectional drive module. Early on, we deduced that simply using omnidirectional wheels would not be adequate, which was a result of a few considerations. First, we had limited our platform to having two drive wheels to comply with the standardized form factor found in our preliminary studies, and a single pair of omnidirectional wheels does not operate in constrained and expected ways. Additionally, we are focusing on a platform that can traverse an entire home, and because omnidirectional wheels are made up of a collection of smaller wheels, they do not perform well on rugged terrain such as carpet or rugs (that are commonly found throughout homes). If we wanted to propose a platform with enhanced mobility, then we would have to come up with a new solution. What was determined is that if we implemented a swerve drive system, we could maintain a thick and textured tire on the robot and being able to rotate the whole wheel on its steering axis to achieve an omnidirectional nature. The following is a list of requirements that this theoretical drive module needs to achieve:

1. Axially (vertically) optimized as much as possible to reduce the width of the outer stages.
2. Ability to rotate 120°:
   (a) 0° orientation for driving forward and backwards to climb stairs.
   (b) 90° orientation for driving across the width of the stair during cleaning, with ± 30° of steering to stay on the stair from this orientation.
3. Ability to sense when the wheel is engaged with the ground.

The requirements listed above guided the CAD development of the drive module. The first problem was creating a gear train that offset the motor from the wheel. Because the motor and encoder combination is generally large, it was important to orient this length to be vertical with respect to the robot so we could minimize the footprint of the drive module, and hence the width of the outer stages. Therefore, the motor needed to be offset above the wheel, on its steering axis (perpendicular to its axle). This was achieved using the combination of a pair of helical bevel gears and a belt system, with the bevel gears to account for the 90° axis rotation, and the belt system to account for the vertical offset. Because a belt and sprocket system was utilized, a belt tensioner was also required for reliable tooth engagement. Additionally, we were able to incorporate a removable tire design that was fitted on the wheel to allow for experimentation in the tread and material of the tire for enhanced traction. All of these design achievements can be seen below in Figure 3.8.2.

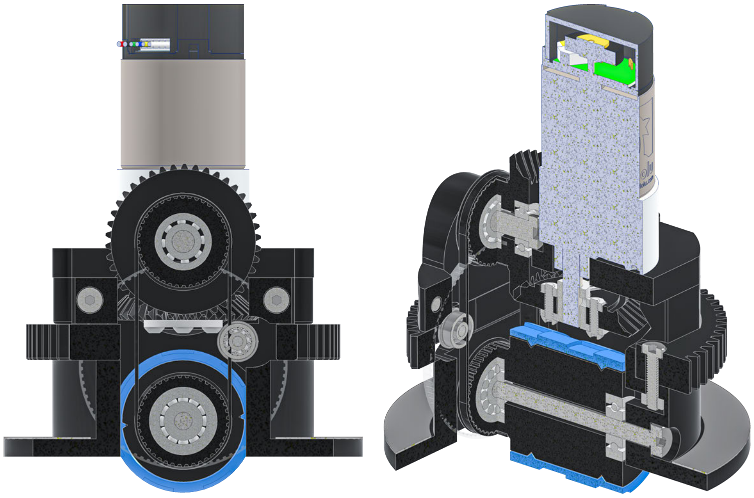


Figure 3.8.2: Gear Train Design for the Drive Module

Next, the drive module had to be given the abilities of omnidirectional driving and sensing. This was achieved by constraining the previously developed center assembly of the drive module (containing the gear train, motor, and wheel) as a cylindrical joint, which allowed it to rotate about its center axis and move up and down until it is further constrained. A servo with a large pair of spur gears was utilized to allow for vertical translation between the gears without losing engagement, whose gear ratio was determined by ensuring a 270° servo maintained at least 120° of rotation after range reductions. This center assembly was kept in place by a series of 4 roller bearings and was suspended over a limit switch that could be disengaged when the wheel was touched to the ground. When the drive module was lifted, gravity would force the center assembly down and click the switch. Finally, a large trust roller bearing was implemented on the upper cylindrical joint constraint to ensure smooth operation once this assembly was engaged with the ground and supporting the load of the robot. Figure 3.8.3 visualizes the complete omnidirectional drive module design.

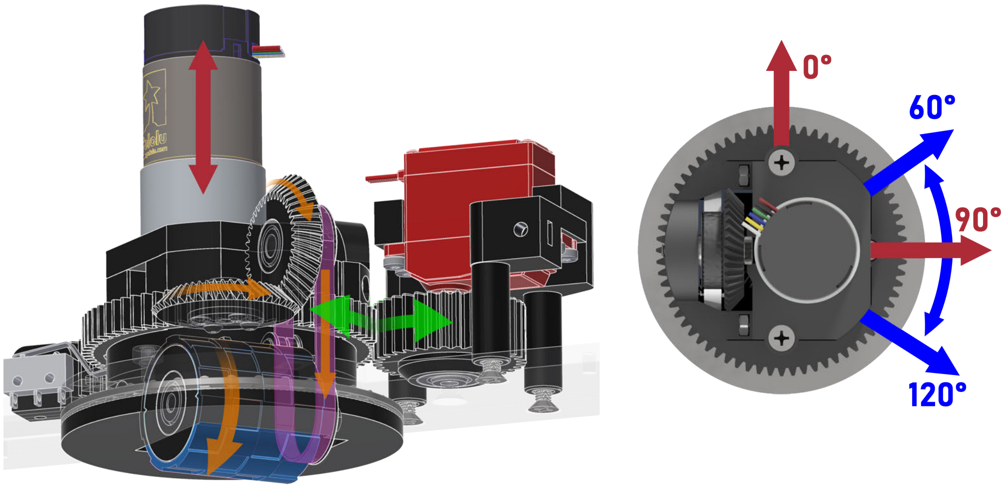


Figure 3.8.3: Omnidirectional Drive Module Full Design: Driving, Steering, & Sensing

3.8.2 Platform Structure

Designing the body of the platform, which entailed designing three independent stages connected by scissor lifts, was one of the most challenging aspects of this project. It was critical to address the manufacturing processes and tolerances to ensure a manufacturable design with our set of resources. First, a unified system for structure development had to be considered. A modular system was established early on, that connected 2D plate parts that would be produced by a laser cutter with 3D printed modular nut blocks. A parametric nut block model was created which resulted in the ability to quickly generate a nut block with any length, symmetry, and number of fastener holes (and embossed nut inserts) from a set of inputs. Once this model was robust, it could be used to populate a catalog of all the potential nut blocks we may have needed. Then, plates for the three stages were made using the robot dimensions established in our Dimension Constraints and were joined by specifically chosen modular nut blocks from our catalog. If a nut block did not exist, the parametric model made it very easy to generate one that exactly fit our needs.

3.8.3 Asymmetrical Stage Design

Another design focus was to optimize the width of the vacuum slot. A nonconventional and asymmetrical stage design was implemented to increase the span of the vacuum slot when compared to the width of the robot and reduce the width and weight of the outer stages. The benefits of this decision can be seen above in Figure 3.8.4.

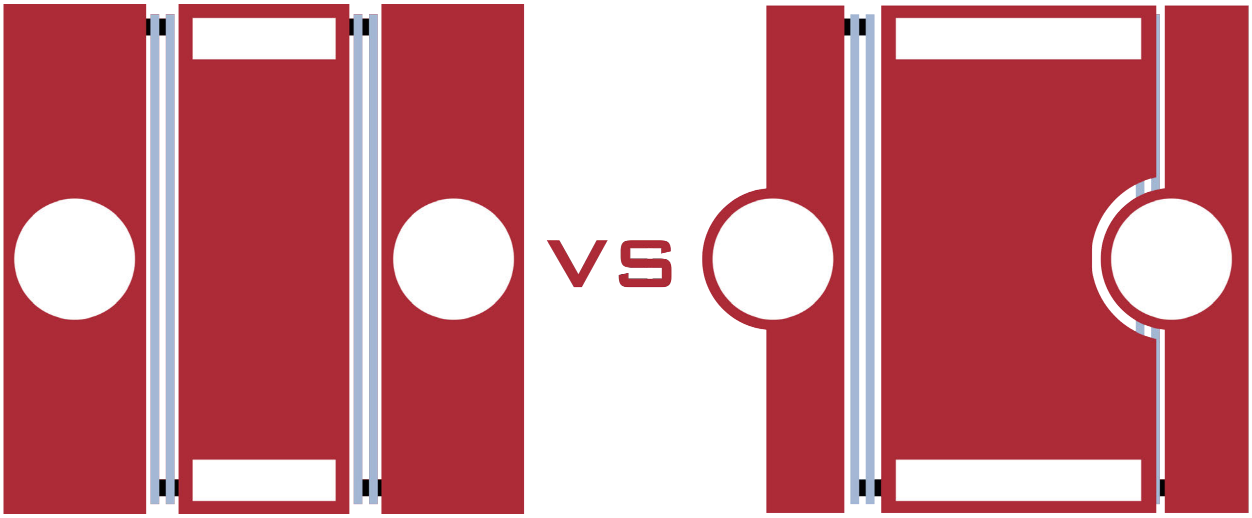


Figure 3.8.4: Asymmetrical Design: Optimizing Vacuum Coverage

To accommodate for this design, the scissor lift assemblies had to be offset within stages, so that the actuated mounting planes of the scissors were aligned as closely as possible to the edges of the middle stage. To avoid collisions between the stages, the front scissor lift was offset into the profile of the middle stage while the rear scissor lift was offset into the profile of the rear stage. This was done to optimize the distances between the stages, but an interference arose in the rear stage when the offset scissor assembly started to collide with the drive module. As a result, the rear stage gap could not be optimized as much as the front gap, which can also be observed above in Figure 3.8.4 below (it is apparent that the rear gap is larger than the front gap). Further optimization of the height of the drive modules (or choosing a smaller drive motor) would alleviate this interference and match the gap between the rear and middle stages to the optimal gap between the middle and front stages.

3.8.4 Constraining the Scissor Lifts

Having laid out the Asymmetrical Stage Design, it was time to interconnect them with scissor lifts. The rigidity of the scissor lifts was critical to ensure the stages did not sag, and that the joints could support the weight of the stages efficiently (without breaking or binding). Because these joints were experiencing particularly high transmission forces, they needed bearings to support each dimension of force transmission. This entailed combining a thrust roller bearing to allow tightening of the joints without binding to the mounting surface, and flanged ball bearings to be able to support this tightening process while supporting the reaction forces within the joint. This configuration can be seen below in Figure 3.8.5. The two pin joints in the front and rear scissor lift assemblies would be supported this way, while the remaining joints would be supported by linear slider joints.

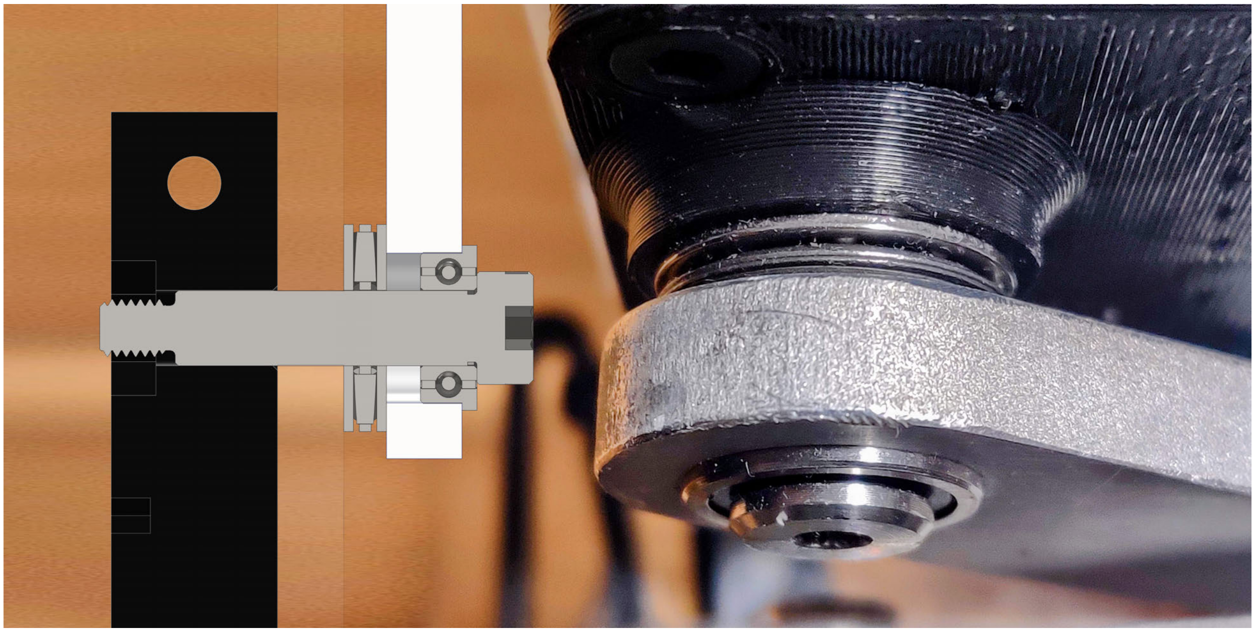


Figure 3.8.5: Scissor Lift Pin Joint: Cross Section View

3.8.5 Middle Stage Bumpers

A relatively easy mechanical problem when compared to the rest of the mechanical design was designing a reliable bumper switch for the robot's left and right sides to sense the walls of the stairwell. However, it was still important to develop a robust design to not reduce the quality of our final platform. As a result, a lightweight dual channel bumper switch was created that was configured to exist as an "OR" input, so the robot could sense if either channel was triggered. The dual channel design was to ensure that the bumper could be pressed from a wide variety of directions, and still be sensed. This design can be seen below in Figure 3.8.6.

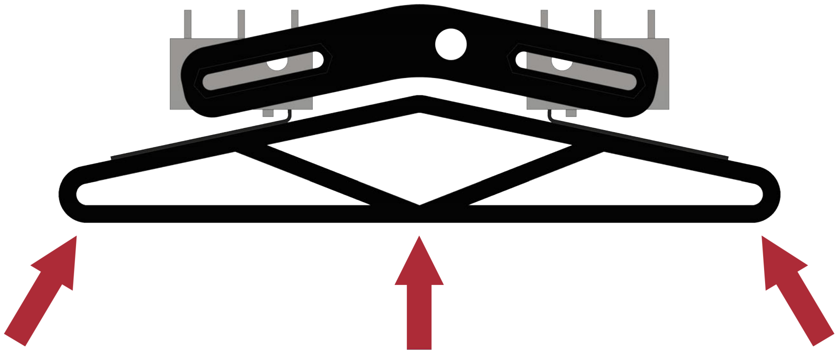


Figure 3.8.6: Middle Stage Bumpers: Dual Channel "OR" Switch

3.8.6 Idler Wheels

The idler wheel type and placement was critical for balancing the robot during its various positions within the stair climbing/cleaning sequence. The middle stage idlers are only contacting the ground if one of the two drive wheels is not engaged with the ground, meaning that for most of the sequence, these idlers are floating. Originally, we expected to have a total of 8 idler wheels, that being a pair on each outer stage, and four on the middle stage. Additionally, we had originally expected all of the idler wheels to be spherical Mokell Ball Transfer Units to allow for free rolling planar motion. Further investigation and experimentation proved that some of this was unnecessary, so the design was adapted. If each outer stage was equipped with two idler wheels, when combined with the driven wheels, there is the potential for 6 points of contact with the ground (which was excessive). Therefore, the two idler wheels from the rear stage were removed, and the robot would still be able to balance with at least three points of ground contact when the middle stage was lifted. Additionally, we determined that because the idler wheels on the middle stage would only be engaged with the ground when the robot is driving forward into the staircase, the wheels didn't need to support planar motion and could rather support linear motion. Two of the four of these idlers were replaced with regular one-axis rollers later on in our methodology to avoid the "caster wheel effect" (when the platform can drift off axis during the initial push in a specific direction, commonly experienced with grocery carts). A final configuration of all the wheels can be seen below in Figure 3.8.7.

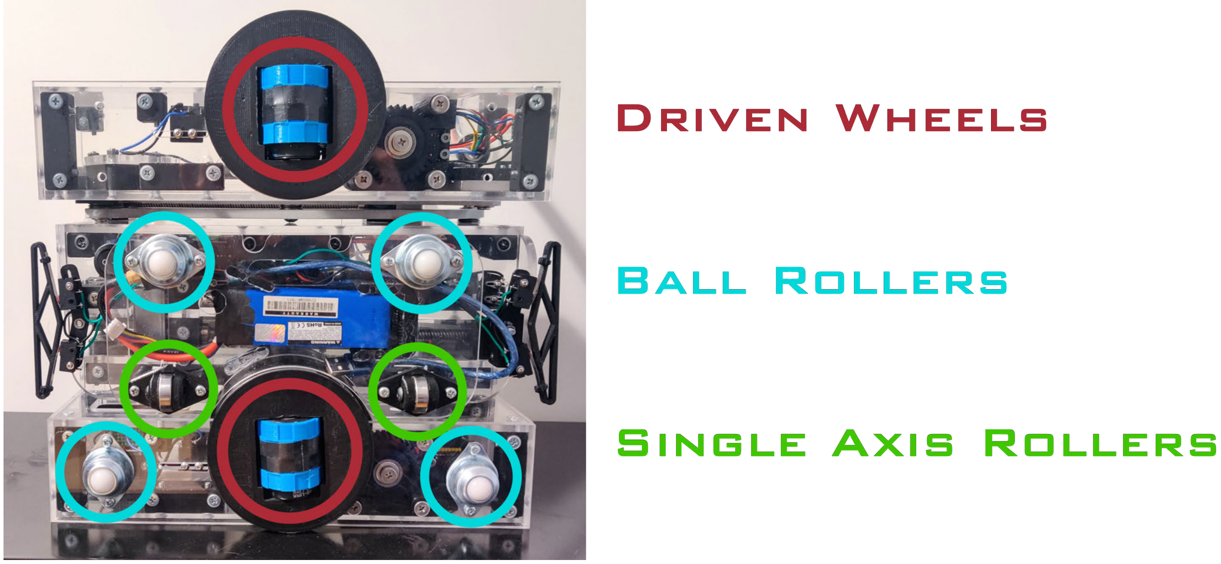


Figure 3.8.7: Platform Wheel Layout

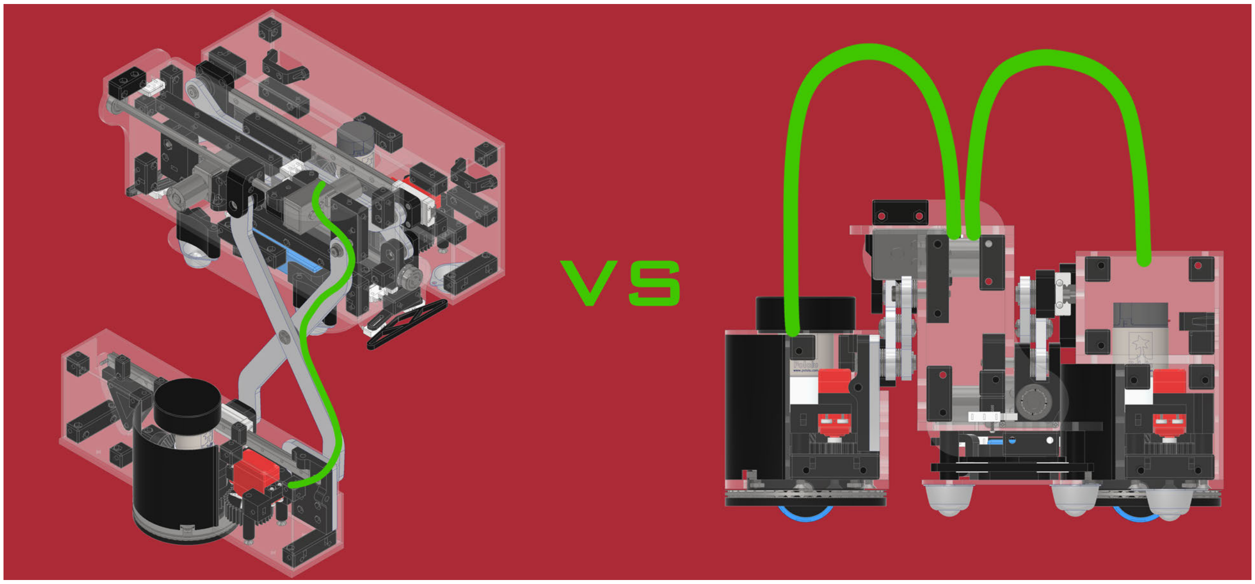


Figure 3.8.8: Wiring Channel Comparison: Ideal VS Real

3.8.7 Electrical Pathways Between Stages

Because our design was divided into three independent stages, it was important to consider the implementation of future electrical systems. Without this consideration, there would have been no way to achieve an elegant electrical system within the final prototype. Distributing power and communicating between independently moving stages mean that channels would need to be developed to feed the wires from one stage to another. Originally and ideally, it was theorized that the wires would be weaved with the scissor limbs themselves to not have them clearly identifiable from an external view, but we realized we did not have manufacturing processes available to us to make this possible. To address this issue, an alternative solution was adopted of having the wires extend over the stages in arcs that were large enough to account for the displacement of the stages relative to each other. Clear flexible tubing was used for these channels, and we experimented with certain materials and tube wall thicknesses to achieve a desired rigidity and bend radius. These ideas are visualized above in Figure 3.8.8.

3.8.8 Split-Apart Design

When developing a platform that exists to promote further development, it is crucial for that platform to have easy access into its structure to add components/sensors, adjust wiring, etc. The proposed platform has three stages that each needed a non-restrictive way to be opened. This was a rudimentary task for the outer two stages because of easily removable plates that housed no components, but was a difficult challenge for the middle stage because there was scissor lift hardware mounted to all six of its structure plates. Our solution for this was establishing a set of fasteners that could be removed to split the stage in half and allow full access to the interior of the stage. The line at which the middle stage splits can be seen below in Figure 3.8.9, and this concept is further developed in our Electrical Wiring.

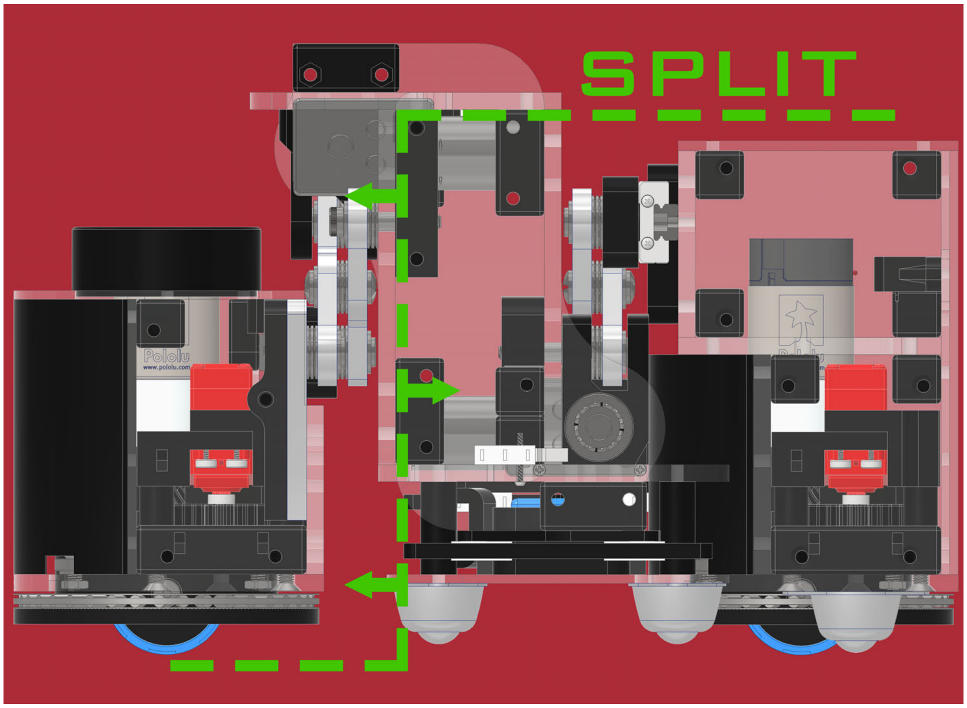


Figure 3.8.9: Split Apart Design of the Middle Stage

3.8.9 Simulation

Now that a robust and detailed model of our platform had been developed, it was critical to evaluate its performance before moving on to the following manufacturing phase. If we were to start prototyping before confirming our design is reliable, there is an increased chance that time and resources would be wasted on building something with some major interference or flaw that would be exposed in the subsequent stages of development. Due to the strict budget and schedule, it was valuable for us to catch these potential flaws before manufacturing commenced. To do this, the robot was tasked to ascend a modeled staircase by proceeding through its stair climbing/cleaning sequence using Autodesk Inventor Studio to animate individual joint ranges over the course of time. This verified that our design was dimensionally and mechanically prepared to handle stair climbing and cleaning. A preview of this simulation can be seen below in Figure 3.8.10, and video of this simulation can be found HERE. During this virtual procedure, the center of gravity was also simulated based on the assembly's input material properties to ensure the robot would never tip.

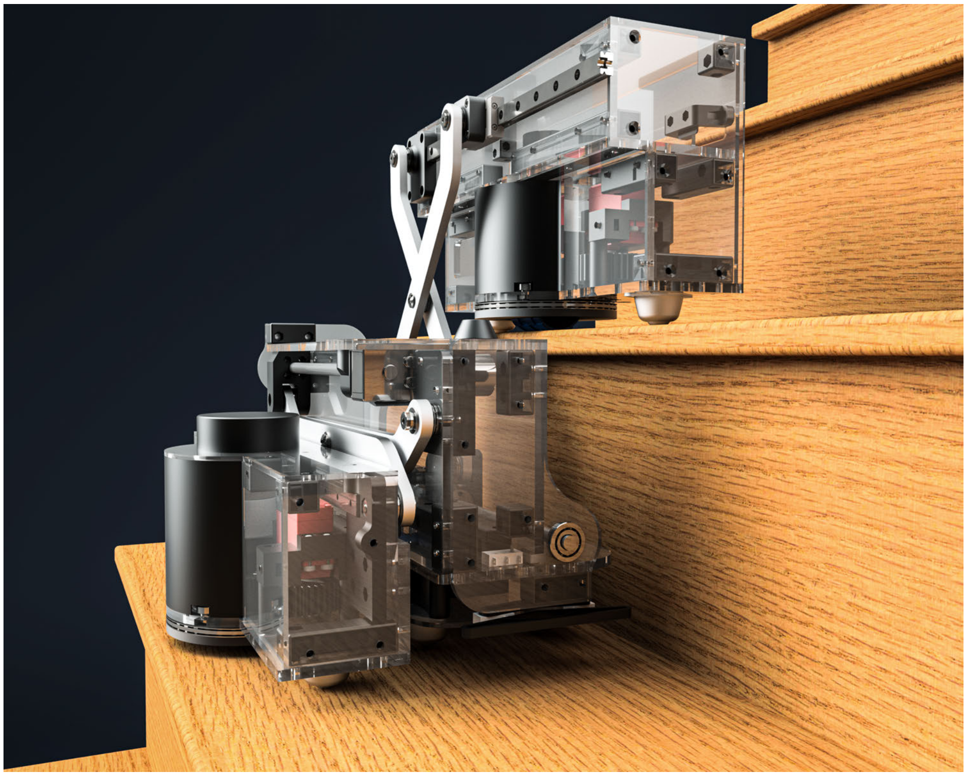


Figure 3.8.10: Stair Climbing Procedure Simulation: Click HERE for Video

3.8.10 Assembly Analysis

The final step before moving on to the manufacturing phase of this project was to perform thorough analyses on each of the sub-assemblies. The steps that were taken to ensure that every assembly was verifiably capable of being produced in the physical world from its CAD model were:

1. Using Inventor's interference checker to ensure no parts had been modeled to collide with other parts.
2. Carefully looking at each of the interfaces between parts, and ensuring that extra space is allocated to forgive a part's scaling when manufactured (for example, 3D printing generally produces parts that are slightly bigger than when they were modeled due to plastic expansion).
3. Disassembling and reassembling each assembly using Inventor's free move tools to ensure that no fasteners are inhibited from being installed/tightened and becoming familiarized with the sequence of assembly.

Once these steps were complete, our CAD model had been finished, and the next phases of the project could be continued. The final CAD model is shown below in Figure 3.8.11.

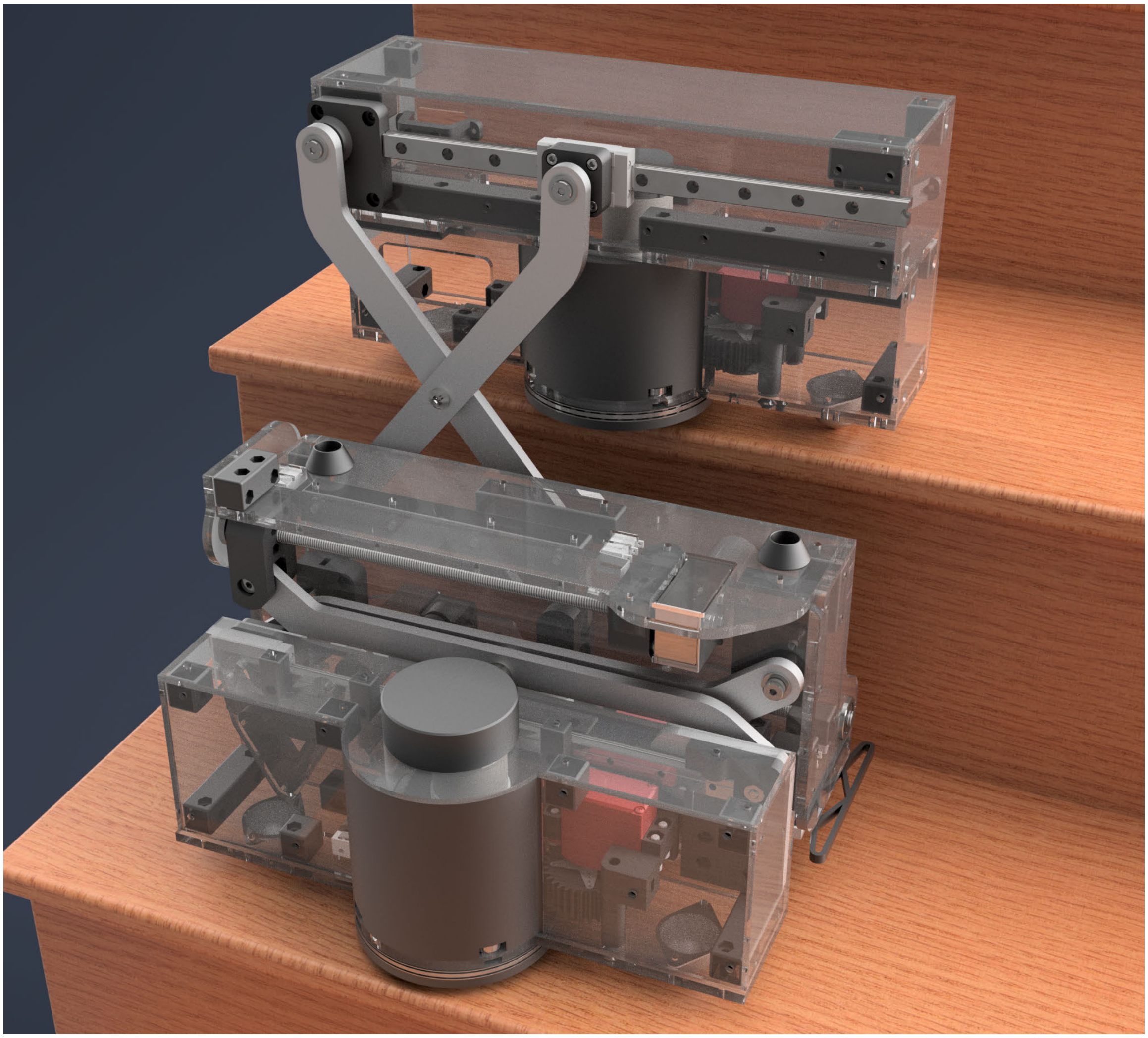


Figure 3.8.11: Finalized CAD Model

3.9 Manufacturing

This section outlines the manufacturing processes and sequence that took place to develop the proposed platform. By the end of this step in the methodology, all of the individual parts from the final CAD model will have been brought into their final form and will be prepared for assembly.

Figure 3.9.1: Manufacturing Processes

3.9.1 3D Printing

3D printing was one of the main forms of manufacturing for this project and was carried out on two personal printers owned by the team members. This project would not have been possible without these printers, because they allowed us to produce complex parts such as those seen within the drive modules and allowed for the rapid production of our increasingly large part count associated with the many nut blocks that made up the structure of the platform. PLA and TPU filaments were used, and slicer settings that modified strengths, resolutions, and weights were specifically chosen for each part. Our 3D printing strategies focus on rapid prototyping and iteration to improve the tolerances and features of the parts we were making. A preview of what this looked like can be found above in Figure 3.9.1.

3.9.2 Laser Cutting

Laser cutting was utilized in this project to manufacture the structural plates that made up the body of our platform. Plexiglass was used, which not only made the platform have a unique transparent look, but also greatly assisted in electrical wiring and debugging because we could see if connections were misplaced or unplugged. Plates were categorized into two thicknesses of plexiglass, 1/4in and 1/8in. The refined CAD model determined the material thickness to cut a plate out of to ensure the stages were balanced. Additionally, laser cutting was used to produce cutting templates that contained different sized holes to perfect the tolerances of our press fit hardware. Our laser cutting phase is also shown in Figure 3.9.1.

3.9.3 Water Jet Cutting

When developing the scissor lift arms, our CAD model demonstrated the intense loads that these members would have to support. And after cutting them out of plexiglass to test our scissor lift joints, it was immediately apparent that they would not be able to support the loads of the stages without severe deformation. Without the ability to get thicker plexiglass, the next solution was to upgrade the members to a stronger material. This was achieved by waterjet cutting 6061 aluminum sheet, which was used to make all four scissor lift arms, as well as making the mounting point plate of the rear stage to the scissor lift. This was done to preventatively strengthen a part that was vexing during the CAD process, and was predicted to be a potential platform weakness if manufactured out of plexiglass. An inside look of this process can be seen above in Figure 3.9.1, as well as a comparison of the plexiglass and aluminum scissors seen below in Figure 3.9.2.

3.9.4 Manual Machining

Most of the parts on this platform required some form of manual manufacturing to remove defects, or to add features that exceeded the capabilities of the automated manufacturing processes we had available to us. This mostly entailed filing off “elephant foot” on the edges and boring out plastic globules in the through holes of each 3D printed part, adding countersinks and machining slots in the laser cut plates, and deburring, drilling, and counterboring the waterjet aluminum parts. This phase was laborious but critical in guaranteeing a sturdy assembly. Parts of this phase can be seen above in Figure 3.9.1.

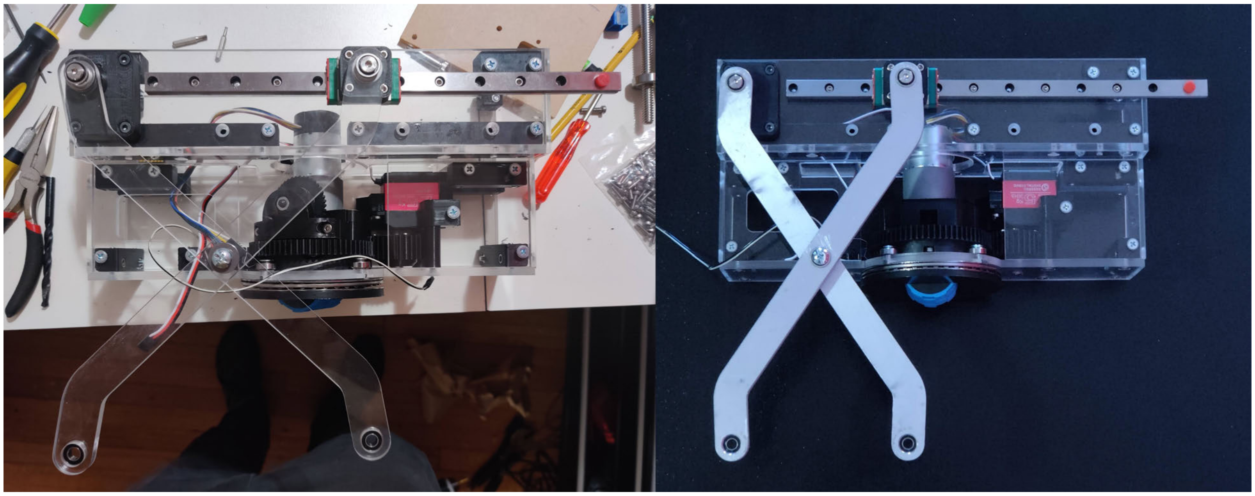


Figure 3.9.2: Plexiglass Prototype vs Aluminium Final Part

3.10 Assembly

Assembly of this platform turned out to be one of the most seamless phases of the entire project and presented only a few unexpected challenges that disrupted assembly no more than drilling a screw access hole or sanding the corner off of a part. This was due to the thorough execution of our design and manufacturing phases. By the time assembly began, we were already familiar with the sequence and techniques required to build everything. This platform contained high number of fasteners, which meant organization was key to an easy assembly. Luckily our use of McMaster-Carr made this simple, and fasteners were pre-organized into bags that made assembly as easy as looking at the CAD model and finding the corresponding fastener storage bag. A preview of what the assembly looked like can be seen below in Figure 3.10.1, and a time-lapse of a section of this assembly can be viewed HERE.

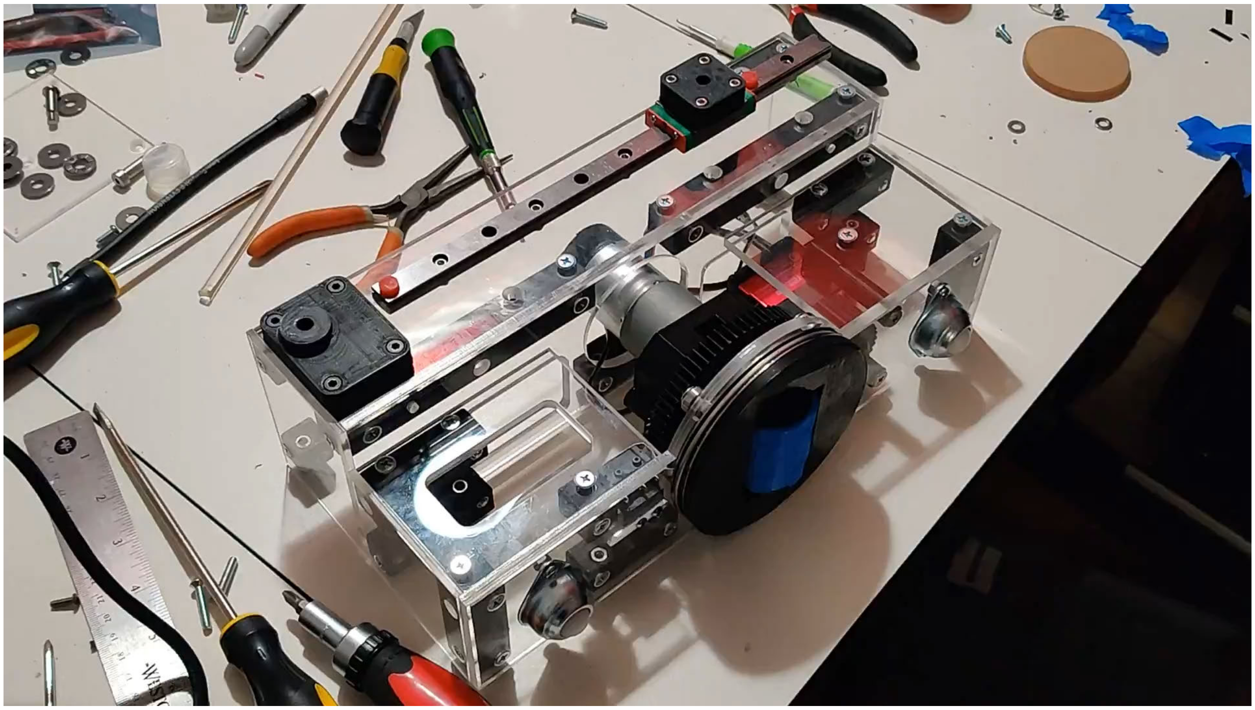


Figure 3.10.1: Assembly Preview: Click HERE for an Assembly Timelapse

3.10.1 Mechanical Tuning

Tuning and calibrating the robot was the most rigorous aspect of the assembly process. The belts needed to be tensioned, the lead screws lubricated, and the structures squared. Final assembly of the robot meant building the robot in a thoughtful way that took note of datum features and prioritized critical features in the assembly order. The homed and end-stop limit switches needed fine calibration to achieve the exact homed heights, which took extensive trial and error to achieve. By design, these switches were mounted to the platform on sliders, so adjusting them only required a screwdriver.

3.11 Electrical Design

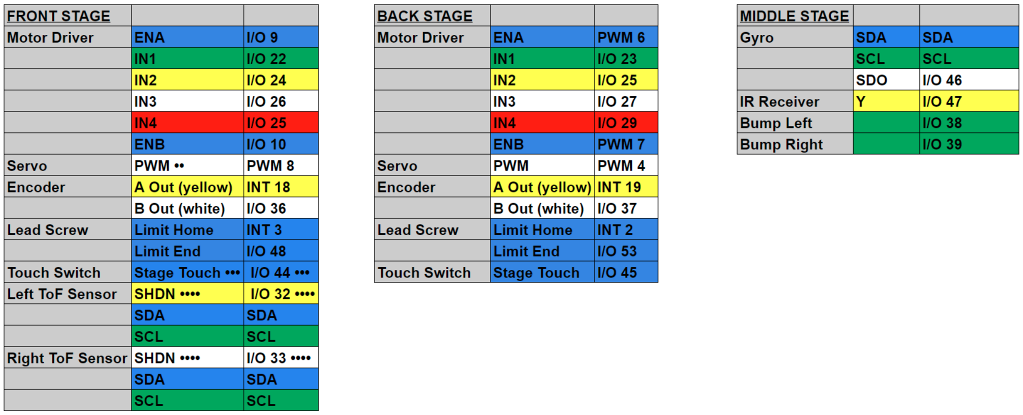
The electrical design phase of this project entailed choosing electronics and sensors, designing a power distribution system, and routing communication between components. Choosing our electronic hardware was simple, because it was well defined from our stair climbing procedure and CAD models. Amazon and Pololu were used as vendors, and a list of the final hardware is provided below:

3.11.1 Electrical Components

1. 65RPM DC Turbo Worm Gear motors for the scissor lift mechanisms:
    (a) Worm Gear motors feature self-locking in their unpowered state to keep stages in their positions without drawing current, which provides extra strength redundancies when paired with the self-locking of the lead screw.
    (b) DC motors with different RPMs were tested, and 65RPM met the torque requirements of our lead screw calculations while also offering the most speed we could get from the motor size.
2. 50:1 Metal-Geared DC motor for the drive modules:
    (a) Equipped with 64 CPR Encoders.
    (b) 200 RPM speed was selected based on the final wheel diameter, and the equation seen in our robot velocity calculations.
3. 25KG-CM Servos:
    (a) 270° of servo range after the gear reduction of our drive module provided the 120° of wheel steering we needed for ideal omnidirectional movement.
4. Dual Channel H-Bridge Modules:
    (a) The L298N module was an affordable and compatible solution to driving the necessary DC motors.
5. DC-DC Adjustable Buck Converter:
    (a) Converts the 12V battery power to 5V with minimal noise for powering peripherals.
6. Arduino Mega R3:
    (a) The Atmel ATmega 2560 microcontroller has sufficient general-purpose inputs and outputs to accommodate our system with widely available resources and documentation.
7. 12V 3-Cell 2200mAh LiPo battery:
    (a) Readily available power source capable of powering the motors and peripherals.
8. The Sensors defined by the Stair Climbing/Cleaning Procedure

3.11.2 I/O Assignments

One of the more tedious tasks during electrical design was assigning GPIO's on the Arduino Mega to different functionalities. There were limited quantities of pins capable of generating PWM signals and triggering interrupts. Moreover, some of the pins capable of generating PWM interfered with the hardware timers used by the microcontroller for conducting system critical processes. With thorough examination of documentation and datasheet, we generated a pinout table (shown in Figure 3.11.1) and were able access all necessary inputs and outputs with minimal compromises. Once the pinout table was made, an in-depth electrical power and logic diagram was made, as demonstrated in Figure 3.11.2, that guided the wiring of the system.



FRONT STAGE		
Motor Driver	ENA	I/O 9
	IN1	I/O 22
	IN2	I/O 24
	IN3	I/O 26
	IN4	I/O 25
	ENB	I/O 10
Servo	PWM ••	PWM 8
Encoder	A Out (yellow)	INT 18
	B Out (white)	I/O 36
Lead Screw	Limit Home	INT 3
	Limit End	I/O 48
Touch Switch	Stage Touch •••	I/O 44 •••
Left ToF Sensor	SHDN ••••	I/O 32 ••••
	SDA	SDA
	SCL	SCL
Right ToF Sensor	SHDN ••••	I/O 33 ••••
	SDA	SDA
	SCL	SCL

BACK STAGE		
Motor Driver	ENA	PWM 6
	IN1	I/O 23
	IN2	I/O 25
	IN3	I/O 27
	IN4	I/O 29
	ENB	PWM 7
Servo	PWM	PWM 4
Encoder	A Out (yellow)	INT 19
	B Out (white)	I/O 37
Lead Screw	Limit Home	INT 2
	Limit End	I/O 53
Touch Switch	Stage Touch	I/O 45

MIDDLE STAGE		
Gyro	SDA	SDA
	SCL	SCL
	SDO	I/O 46
IR Receiver	Y	I/O 47
Bump Left		I/O 38
Bump Right		I/O 39

Figure 3.11.1: Electrical Pinout Tables

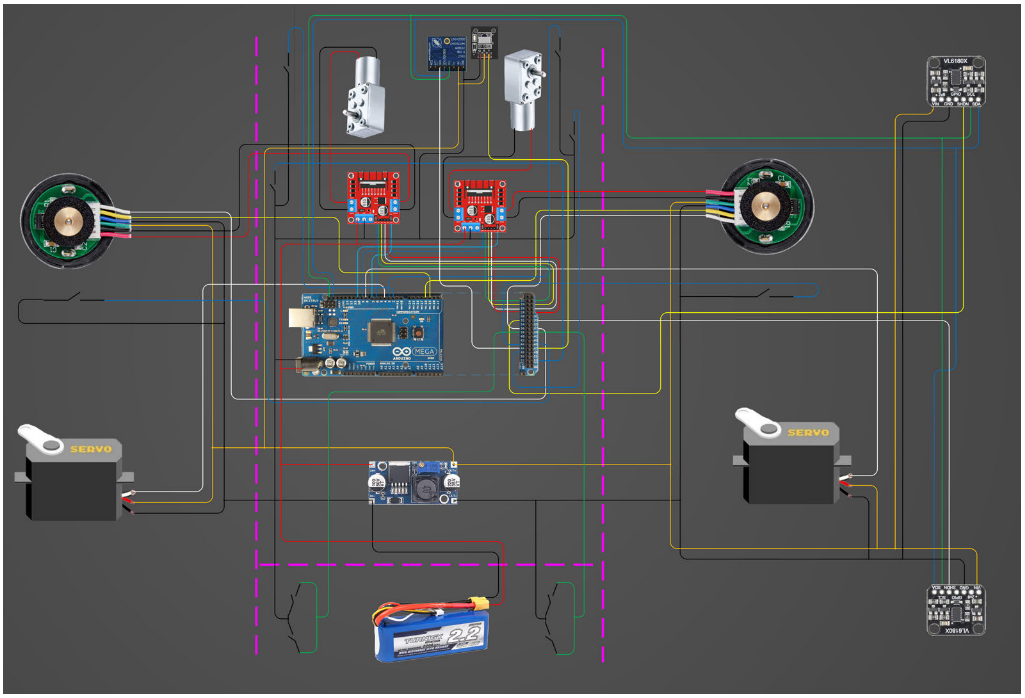


Figure 3.11.2: Complete Electrical Wiring Diagram

3.11.3 Electrical Wiring

Before wiring commenced, specifically chosen wire was shipped in based on the expected power requirements. 18 AWG wire was used for the 12V lines and worm gear motors, while 22 AWG wire was utilized for the 5V lines, drive module motors, and unified ground wires to the exterior stages, and 24 AWG wire was used for sensor logic and communication lines. Wiring the three stages entailed hard wiring the power system first with soldering, and then creating custom DuPont connectors for all of the logic. The most challenging part of electrical wiring was routing wires through the wire channels between the stages and working with the split apart design to ensure the middle stage could be split into two parts without breaking and connections. This was achieved by dedicating one half of the middle stage to the power system, and the other half of the middle stage to logic and computing. Then, connectors were utilized to bridge the gaps in the circuitry broken by this split apart design, and were chosen in a way that only allowed for correct reassembly. To tat end, different connector types and genders were used, and wire color coding was established between these connections. The final product is a platform that can split entirely in half, giving the developer easy access to the inside of the middle stage. This process is demonstrated in Figure 3.11.3.

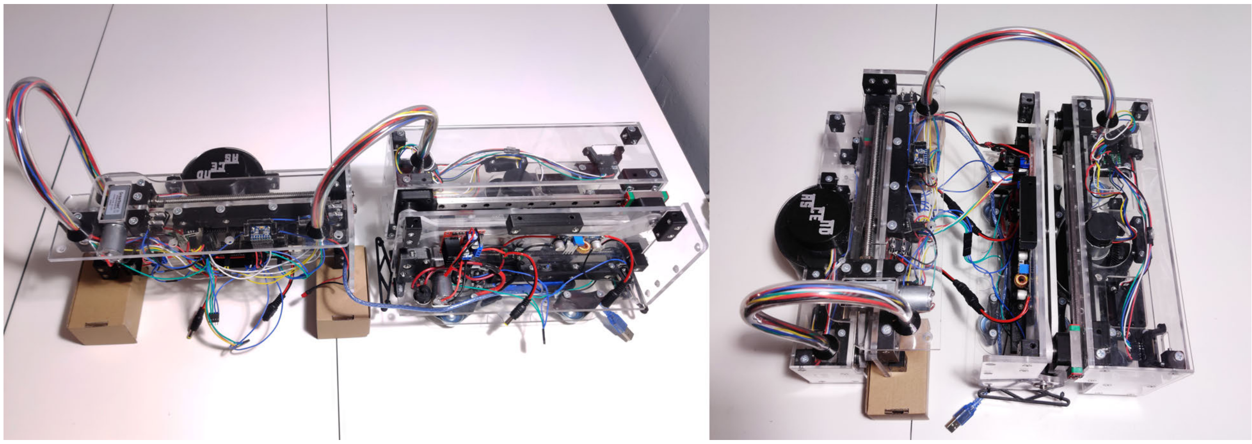


Figure 3.11.3: Split-Apart Electrical Design

3.12 Code Structure and Philosophy

Firmware for this project was developed entirely in object-oriented C++. From the start of development, the goal was to keep the code as organized, readable, and as modular as possible, so that future development of the robot could be done with ease. To achieve modularity, the firmware was written using object-oriented techniques and principles, with unique classes developed for the scissor lifts, drive modules, sensors, encoders, PID controllers, and the robot itself to encapsulate all these classes. A general outline of these classes is represented in the UML diagram shown below in Figure 3.12.1. The UML diagram was initially drafted to guide the coding process. Each class strategically utilized public methods and private fields to make debugging the robot more streamlined.

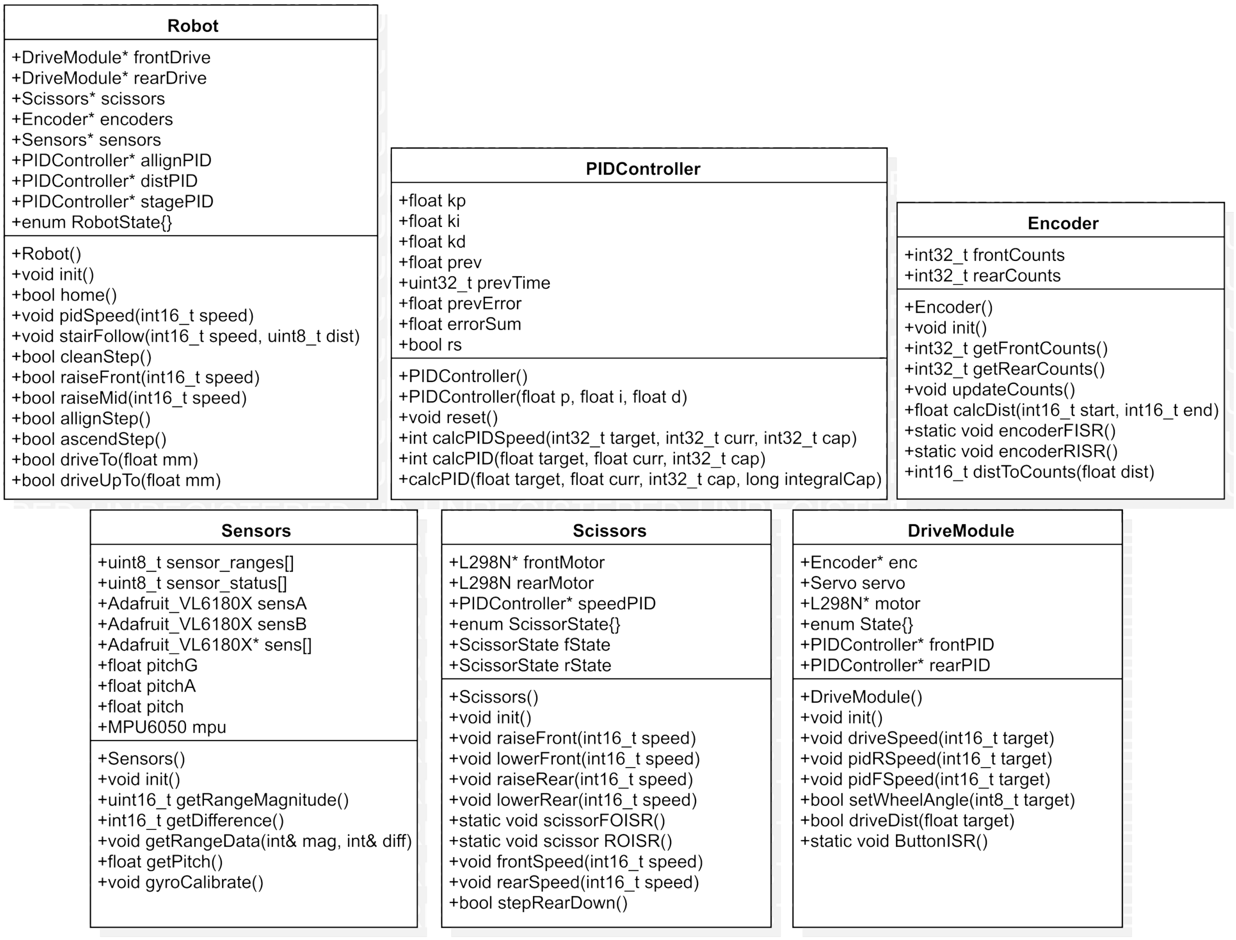


Figure 3.12.1: UML Diagram

3.12.1 Practices and Etiquette

During development, a conscious effort was also made to minimize the use of void type methods in favor of bool type methods. Void type methods, although sometimes convenient, do not return any useful information. With bool type methods, we can indicate to higher level classes that the method encountered no issues in running or completely finished its procedure, which makes it easier for state machines to detect state changing events. Every method utilized in the robot is also non-blocking, except for some initialization procedures which only run once after powering on. This is good practice, but also quite necessary, as the robot uses interrupts and hardware timers to dictate the occurrence of critical events, such as stopping scissor lifts at their endpoints, and collecting encoder data at a constant rate to determine wheel speed.

3.12.2 Autonomous Stair Climbing and Cleaning

The autonomous stair climbing routine that exists as a public method in the Robot class operates using standard state machine practices. This method is also what was used for the final demonstration of our prototype. As seen in Figure 3.12.2, the state machine is modular and repeatable, which is crucial for a staircase with an undetermined number of steps. To advance the robot state, the robot uses the returned Boolean values from lower-level component methods, and depending on the current robot state will either change state for the next system cycle or use the non-blocking waiting state to add a pause between state changes. This process concludes once the robot has ascended and cleaned a step. As such, this process can be repeated while waiting for an event where the robot no longer sees a step ahead of it, indicating it has ascended and cleaned an entire staircase.

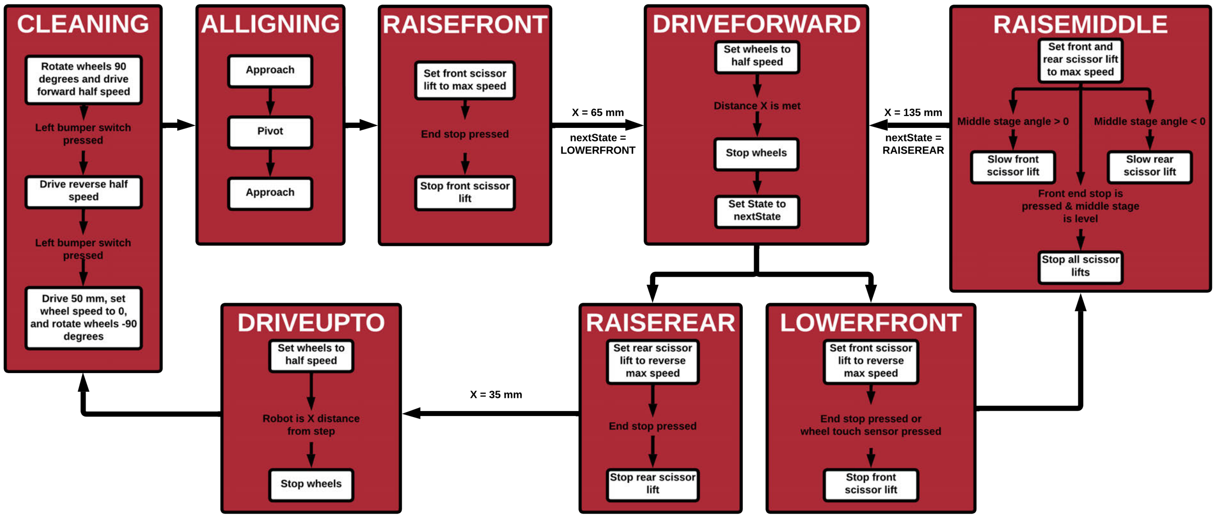


Figure 3.12.2: Autonomous Stair Climbing State Machine Diagram

3.12.3 Communication Protocols and Libraries

The MPU6050 gyroscope and accelerometer module, along with both VL6180X time-of-flight distance sensors, communicated with our microcontroller using I2C serial communication protocols. Using I2C as opposed to other forms of serial communication such as SPI allowed us to use less wires between the sensors and microcontroller which helped during the complex wiring process of the three stages. To communicate with the ToF distance sensors, we used a third-party library made by Adafruit. For the accelerometer and gyroscope module, we used the MPU6050 library by jarzebski. Lastly, we used the L298N Arduino library by Andrea Lombardo to communicate with our drive module drivers. Beyond these three libraries, we utilized only the standard Arduino libraries for code development. Minor changes were made to the Adafruit VL6180X library and the standard Servo library due to conflicts between the utilization of hardware timers, them being initialized but not used, and because some internal methods used blocking code that needed to be removed.

3.13 Controls

Robust control algorithms were necessary to achieve successful stair climbing autonomy, and to ensure that the robot could align to and traverse across steps without tumbling down the stairs. A PID controller class was developed to maintain the many different moving systems that required smooth and precise motion. Each necessary section of the robot initialized its own PID controller object and underwent their own tuning processes to find the best P, I, and D values for their purposes. Specifically, the drive module utilized specialized PID controllers to achieve and maintain a target wheel speed as well as to travel a target distance. The scissor lifts utilized a PID controller to raise the middle stage of the robot at a constant speed while keeping the stage level relative to the ground. This controller needed to operate using angle as an input variable as opposed to scissor lift speed because the rate of the ascension of one scissor lift is not linear relative to the horizontal displacement at the limb of a scissor lift. For example, if a scissor begins to open and close at a constant rate, the ascension of this scissor has a higher velocity at the start of the motion and slows down at the latter half of the motion. Since the scissors of the rear and front stage start in different states as the middle stage is raised or lowered, it is difficult to predict the speed at which the scissors should operate to keep the stage level with the ground. This problem was solved by running the scissors at full speed by default and subtracting the output of the PID controller from either the front or rear scissor lift speed depending on if the angle error of the middle stage is positive or negative. Another beneficial outcome of this method is that at any point, at least one scissor lift will be running at maximum speed, which as a result minimizes the overall time to ascend stairs.

3.13.1 Omnidirectional Wall Following Controller

Another unique use of the PID controllers in this project was their application to the wall following process. Due to minimal space on the step that the robot has to correct errors as it cleans laterally, a precise wall following routine needed to be developed. The general approach to wall following is to exclusively skid steer, because the standardized form factor does not utilize omnidirectional wheels. If our platform were to depend exclusively on skid steering to stay on the stair, there may be instances where the robot gets misaligned from the step during climbing, and the resultant path to a steady state distance from the riser would result in the robot steering of the stair. We were able to give our platform a more precise wall following controller by utilizing the omnidirectional drive modules to change the distance from the face of the step, and skid steering to vary the angle of the robot relative to the face of the step. As the robot drifts further or closer from the step due to error, the omnidirectional drive modules will turn the wheels toward or away from the wall at a degree dependent on the output of its PID controller, shifting the whole robot closer to its target distance. As the robot becomes askew relative to the riser, a PID controller varies the speeds of the left and right wheels to change this angle, trying to keep parallel with the riser. Tuning was conducted for each of the individual systems in this process, as two different PID controllers were being combined into one unified driving behavior. Ultimately, this process allowed for a much more robust and precise wall following controller when compared to that seen in the standardized form factor of robot vacuums. This controller is visualized below in Figure 3.13.1.

Input Parameters:
θ_M is the angle from the surface derived from the two measurements made by the ToF sensors.
d is the average distance of two measurements made by the ToF sensors.

Output Parameters:
$_F$ is the front stage's drive wheel velocity.
$_R$ is the rear stage's drive wheel velocity.
θ_W denotes the drive modules' steering angle.

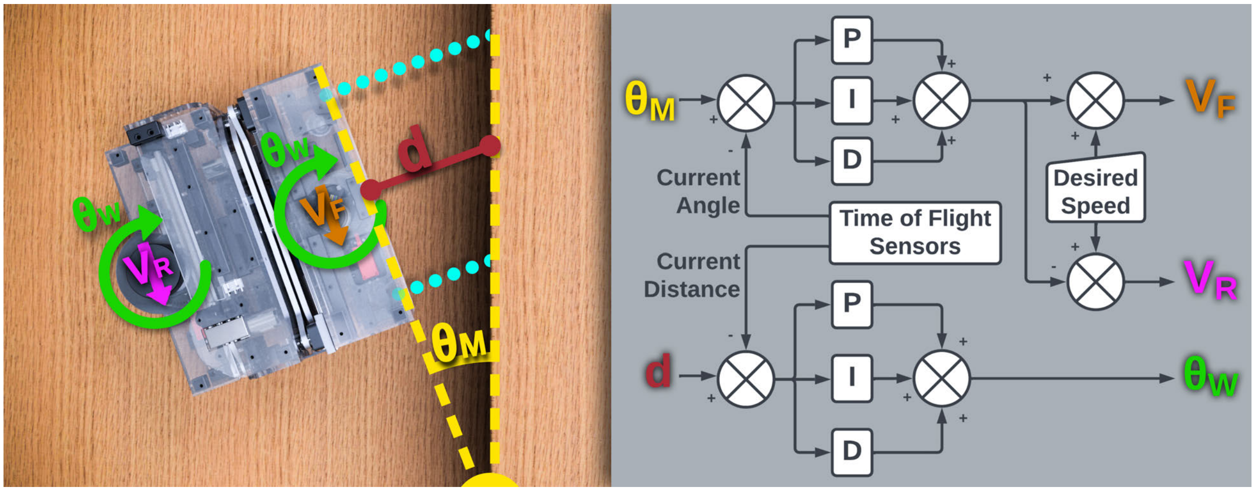


Figure 3.13.1: Omnidirectional Wall Following Controller

Results

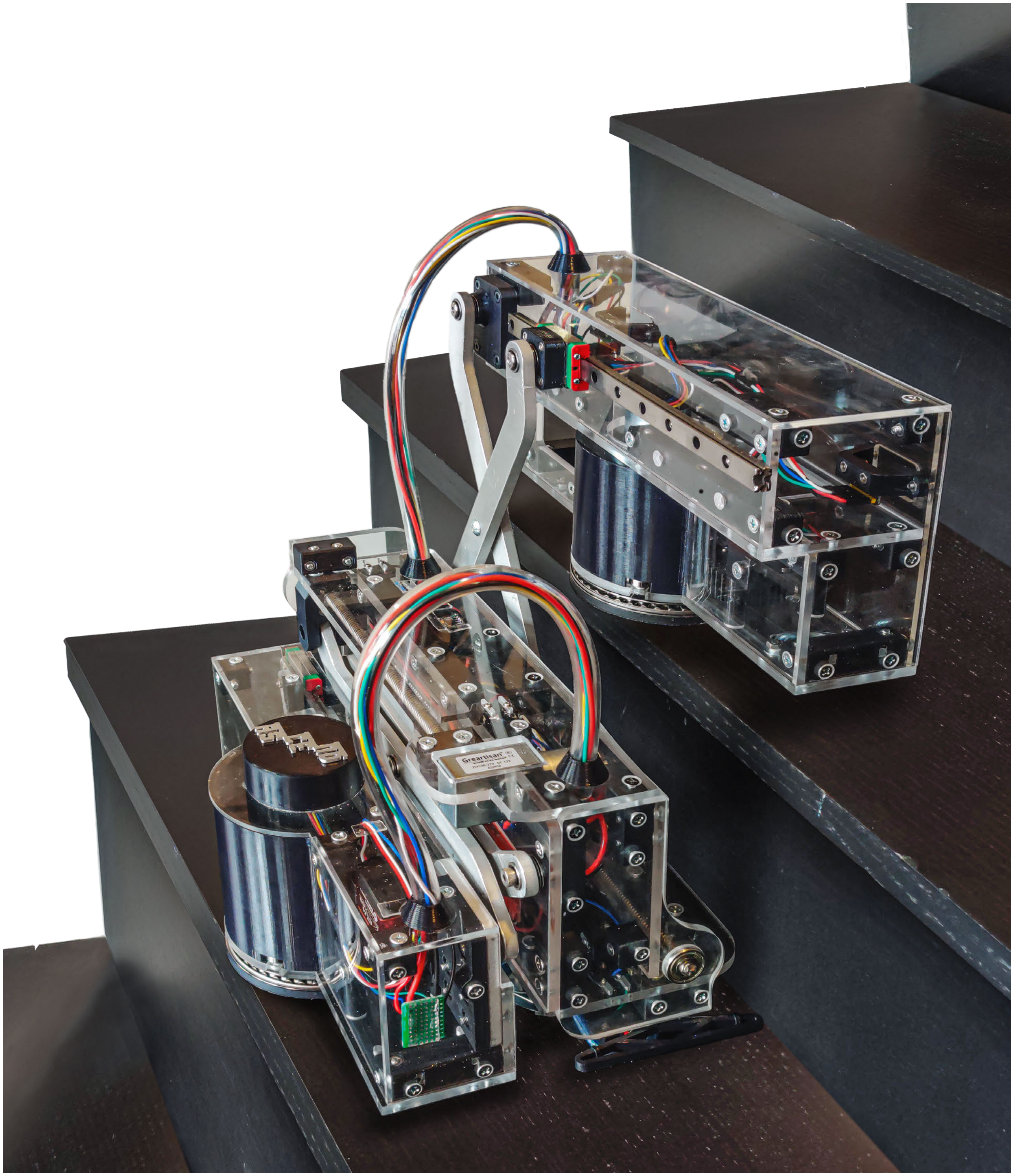


Figure 4.0.1: Robot Cover Photo

4.1 Final Prototype

Ultimately, this project was successful in creating an autonomous prototype entirely from scratch over the course on an academic year. Our final prototype was a tri-stage and compact robotic platform that utilized two scissor lifts to raise and lower the front and rear stages. Each sub-system was developed with immense focus on the engineering design process and subsequent phases of the project in a predictive manner, which resulted in a cohesive final product. The mechanical assembly was developed to be exceptionally robust, and the careful use of bearings and fastener hardware promoted a rigid platform with predictable degrees of freedom. Additionally, the incorporation of a completely transparent design further highlights the platform and its novel features. The final physical form of the prototype is displayed above in Figure 4.0.1 with views of other angles in Figure 4.1.1.

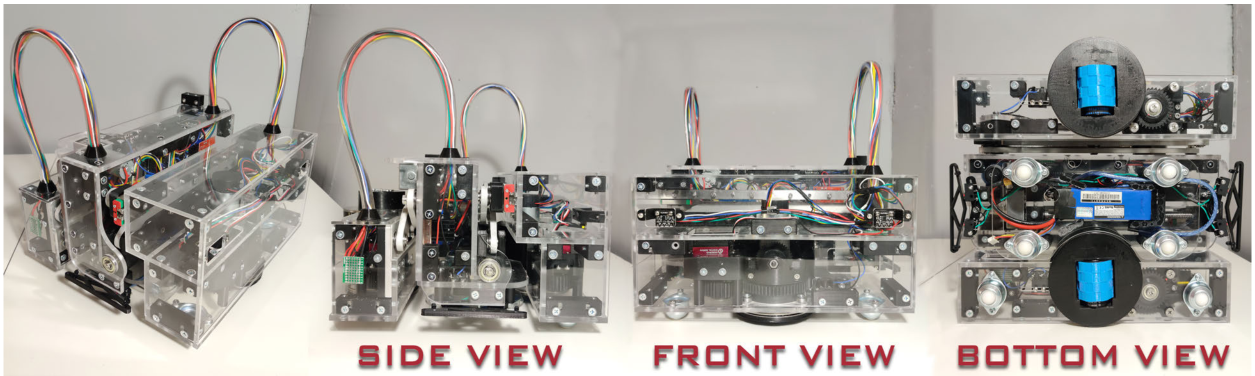


Figure 4.1.1: Prototype Overview

4.2 Autonomous Stair Climbing Performance

Using specially designed PID control algorithms, our platform was successful in efficiently and effectively ascending steps, and was able to use the novel omnidirectional drive modules and controllers to laterally traverse each stair, therefore proving the robot's capability to both ascend and clean stairs. We were able to prove the robustness of our final prototype's ability to do this during WPI's Project Presentation Day, where we had a live demo running intermittently over the course of a 10-hour period without any battery charging or maintenance (the live demonstration space can be seen in Figure 4.2.1). Our demo successfully ascended the demo stair every time it attempted it over the course of the day (which was over 25 times with a 100% success rate of ascension), with only 2 times where a software bug in the wall following controller froze the state machine. The level of robustness achieved greatly exceeded our expectations and confirmed the significance of our engineering design process. Additionally, our demonstration correlated very closely with our original simulation, which can be previewed below in Figure 4.2.2 and shown in our demonstration video HERE.

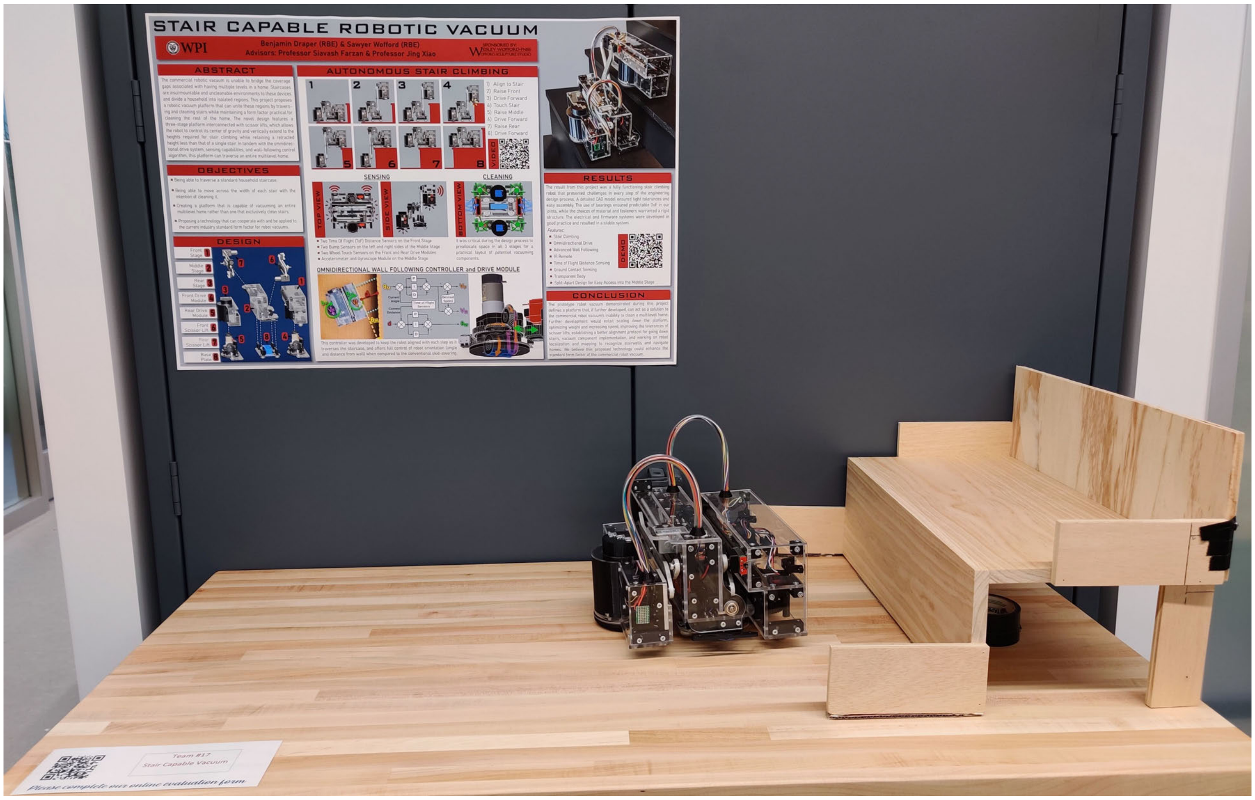


Figure 4.2.1: Project Presentation Day Setup: Click for POSTER and for PRESENTATION

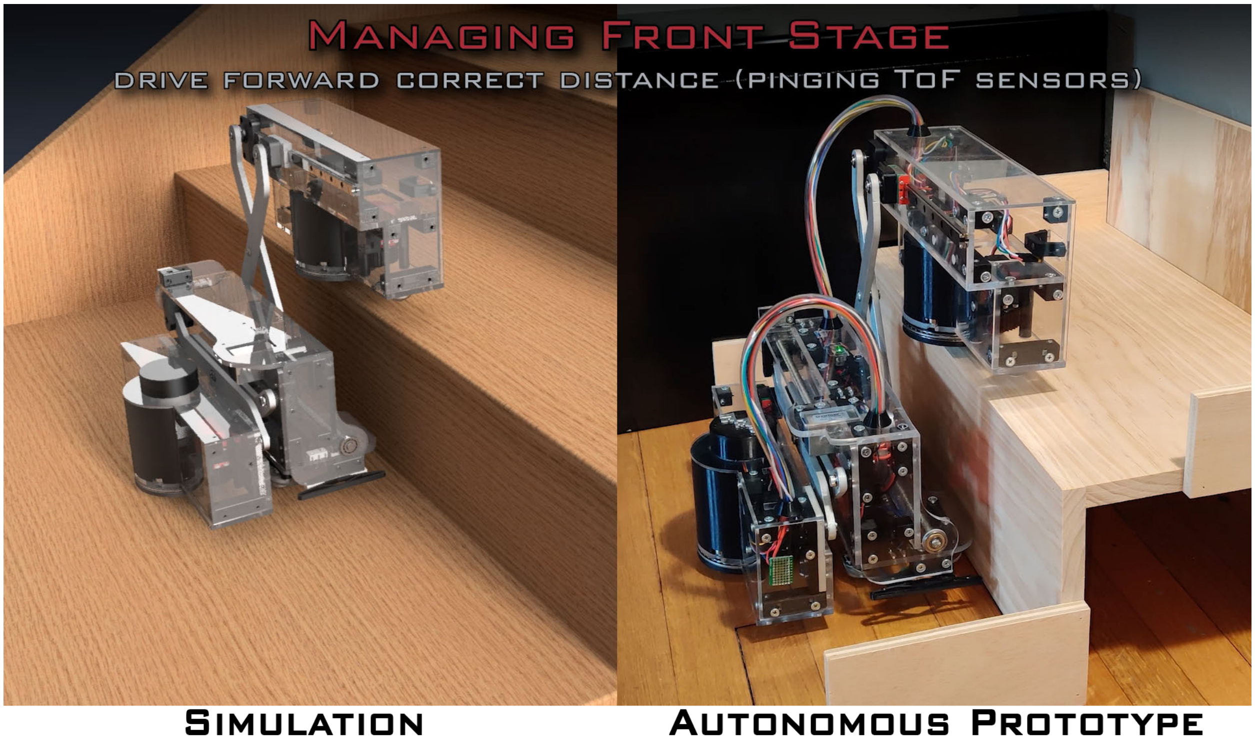


Figure 4.2.2: Final Demonstration: Click HERE to View the Full Demo

Conclusion

In conclusion, this report details the development of a platform that proposes a new addition to the standard form factor or the commercial robot vacuum to expand its cleaning coverage from what is currently limited to a single floor, to be all encompassing and unified household cleaning coverage. Ultimately, the project was successful in creating an autonomous prototype entirely from scratch over the course of an academic year. The proposed prototype is capable of ascending and moving across stairs all while having cooperated with the standard form factor. When our platform's stages are homed and its wheels are rotated to their 90° position, its form matches that of a generic robot vacuum, with a layout and dimensions that coexist with what is currently on the market. We have met our project objectives and developed a platform that is capable of climbing and cleaning stairs without deviating from the standardized form factor of commercial robot vacuums. These capabilities, when considered together, are equipped to tackle the problem of unified home cleaning. Adopting this technology to the standardized form factor could promote innovation throughout the entire robot vacuum market and could redefine what owning a robotic cleaning assistant means. There is significant value to proposing a technology focused on unifying specialized robotics, and the platform's capabilities can only grow brighter as it evolves and advances from future development.

5.1 Future Work

Even with the objectives of this project met, there is still much improvement to be made and future work to be done to prepare this platform for coexisting with the inhabitants of a household. One alteration that can be made to the design in future work is to scale the robot down and reduce/optimize the overall weight so that the robot can operate faster, and on a greater variety of staircases. Additional work could be done to improve the internal scissor lift slider joints tolerances. Due to the resources available at the time of prototyping, the scissor lift actuation slider had to be 3D printed, which resulted in some interferences between the slider and slider wall and reduced the efficiency of the slider joint. A higher tolerance lead screw nut could be implemented to reduce the slack of the exterior stages in their homed positions, and the actuation of the scissor lift could be redesigned to include a linear rail parallel to the lead screw to better constrain the degrees of freedom. Furthermore, additional sensors should be added to the underside of the rear stage so the vacuum can more accurately align itself with the top stair before descent. Along with this, sensors to incorporate localization and mapping would also benefit the system, as the robot would be able to identify staircases from thresholds, couches, etc. And lastly, the incorporation of specially designed vacuum components into the robot would complete the process in developing an ideal, stair-capable and unified household robotic vacuum.

List of Figures

Bill of Materials

1. Electronics:
    - ELEGOO MEGA R3 Board ATmega 2560
    - BETU 2Pack 25KG High Torque RC Servo
    - Qunqi 2Packs L298N Motor Drive Controller Board Module Dual H Bridge
    - Greartisan DC 12V 65RPM Turbo Worm Geared Motor
2. Sensors:
    - Twidec 10Pcs Mini Micro Limit Switch 5A 125 250V
    - HiLetgo 2pcs VL6180 VL6180X Range Finder Optical Ranging Light Sensor
    - HiLetgo GY-521 MPU-6050 MPU6050 Accelerometer/Gyroscope Module
3. Hardware:
    - uxcell F623ZZ Flanged Ball Bearing 3x10x4mm
    - Donepart Small Bearings 5mm ID 13mm OD 4mm Width 695ZZ
    - Rannb 635ZZ Ball Bearings Double Shielded Steel Bearings 5mm x 19mm x 6mm
    - Donepart R4-2RS Ball Bearings 1/4 x 5/8 x 0.196 inch
    - uxcell AXK75100 Needle Roller Thrust Bearings
    - uxcell 6mm Inner Dia H12*D10 Rigid Flange Coupling
    - uxcell FR188-2RS Flanged Ball Bearings 1/4" x 1/2" x 3/16"
    - Iverntech MGN12 300mm Linear Rail Guide with MGN12H Carriage Block
    - uxcell TC411 Thrust Needle Roller Bearings 1/4" Bore 11/16" OD 5/64" Width
    - Donepart Skateboard Bearings 608ZZ ABEC3 High Speed 8x22x7mm
    - 300mm T8 Tr8x8 Lead Screw and Brass Nut (Acme Thread, 2mm Pitch, 4 Starts, 8mm Lead)
    - uxcell 6mm to 8mm Bore Rigid Coupling Set Screw L22XD14
    - Donepart Skateboard Bearings 608ZZ ABEC3 High Speed 8x22x7mm
    - RMP 6061-T651 Aluminum Sheet, 12 Inch x 12 Inch x 1/4 Inch Thickness
    - Mokell Ball Transfer Units CY-15A Flange Mounted 5/8-inch