Last Mile Drone Delivery

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2. Executive Summary

The Last Mile Drone Delivery Project is being conducted to develop a new and innovative way to increase the efficiency of modern-day package delivery, particularly in suburban/rural settings. The team envisions a modular system in which packages can be loaded into a drone from inside a delivery truck and the drone can then deliver packages from the courier to the customer semi-autonomously. The system in design currently includes three main subsystems, the package release mechanism and frame, the drone dock and alignment platform, and the docking platform elevator. The package release mechanism and frame are where the packages will remain until the drone reaches the desired drop-off destination where trap doors will open and release the package. The drone dock and alignment platform will allow the drone to land on the roof of the delivery truck and allow for an error in the drone's positioning system due to the platform's ability to center, secure, and align the drone in an appropriate position. This utilizes a set of motors and a microcontroller to align the drone and begin recharging the drone's batteries after being drained from a flight. Finally, the drone dock elevator system's purpose is to bring the drone from the roof of the delivery truck back into the cabin where packages can be reloaded into the drone. This system utilizes pulleys, linear slide rails, and a stepper motor to raise and lower the platform.

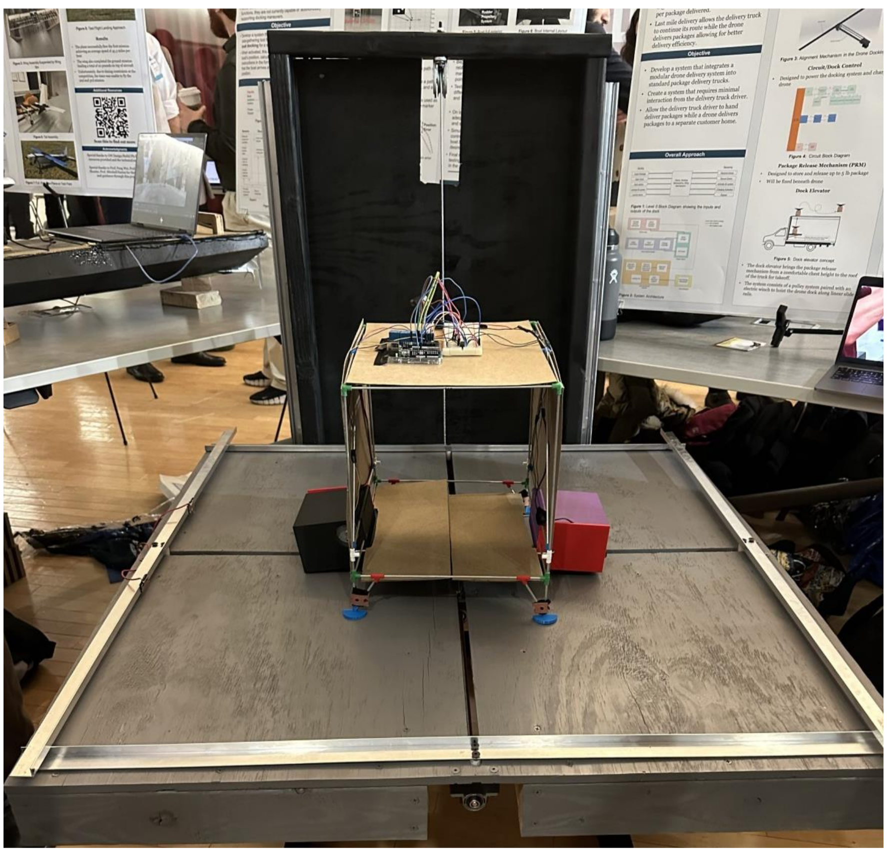

Figure 2.1 - Last Mile Delivery Final Product

3. Introduction

Last-mile delivery has multiple stakeholders. Consumers of e-commerce goods would benefit from drone delivery services as packages would be delivered faster and possibly at a lower cost. The second major stakeholder is the courier services that deliver packages to individuals. Drone delivery would increase the number of packages delivered in a given time frame by reducing the need for employees to drive or walk down potentially long rural driveways. Also, the drone could be delivering a package while the courier employee makes delivery by hand at a neighboring home, essentially doubling the rate of delivery. If delivery routes can be completed faster, the gasoline consumption per package will be greatly reduced, saving the company money as well as reducing excess greenhouse emissions produced by prolonged driving and idling trucks. However, the customer for this design project is The Mitre Corporation. Mitre Corporation is a federally funded research and development company, broadly focusing on projects that benefit the nation's safety, security, and prosperity. Our point of contact and mentor at Mitre, Dave Maroney, has been vital in our development of the project's functional requirements. Mr. Maroney has helped us define the scope of our project and professors Mitch Narins and Peng Wei have been essential in our concept ideation and prototype development so that we may successfully create a package delivery concept that furthers the field of delivery optimization.

4. Scope

Over the course of this project, we will design and construct a scaled-down modular delivery system easily integrated into delivery trucks. The system will be able to accommodate drone take-off, landing, and charging. It will also carry and deliver small-sized packages with minimal driver interaction. This system is being created to maximize delivery route efficiency in rural and suburban communities by decreasing the time and gas necessary to travel down potentially long private driveways.

5. Background

5.1. Last Mile Delivery

The last-mile delivery model broadly refers to the last leg in a global supply chain that commercial packages take from a business to a customer. This leg of the journey is by far the most inefficient. Costs associated with the last mile, based on a variety of factors, consist of 13% up to 75% of the total supply chain cost [1]. The most significant factors contributing to this high-cost relative to the entire supply chain are the necessity for individual residence and time window constraint deliveries.

5.2. Research

5.2.1. Delivery Route Algorithms

Last-mile delivery portion of a supply chain can be simplified into an algorithmic system. Consider the Flying Sidekick Traveling Salesman Problem (FSTSP) presented in [2]. It consists of a truck-drone pair delivering packages. The drone must visit its customer and return to the truck within its range – ie will not run out of battery. This problem can be optimized for delivery time and energy usage. Models from [3] using similar algorithms revealed key conclusions for the truck-drone system. Firstly, there is significant room for improvement in time and energy over traditional truck-only delivery. [4] recommends two or more drones are necessary to obtain a significant advantage over the truck-only delivery – assuming the drone carries only one package per trip to the customer and back to the truck. This is further limited by the drone speed relative to truck speed. It is noted in [3] major time savings are not achieved until the drone operates around twice the truck speed.

Algorithms are effective in recognizing the trend of a given factor. However, models begin to deviate from actual deliveries in reality. Factors not considered in the previously referenced models are the volume or charging requirements of such a drone system. A larger volume drone system reduces the space available for packages, which would result in fewer packages being delivered per truck. Similarly, as a driver progresses along a route, assuming intermittent charging, the drone battery will begin to drain thereby reducing range. These factors will need to be considered in our project, yet it is difficult to define the exact impact they will have on the overall gain in last-mile delivery efficiency.

5.2.2. Drone Docks and Autonomous Landing

Engineers are working to integrate autonomous drone operations seamlessly into everyday life. Autonomous drones need to be able to land in a precise location to succeed in its mission. Drones need to be in the predetermined spot of the dock or landing pad for consistent takeoff, landing, and charging operations. Typical GPS used to direct autonomous drones does not provide the degree of precision necessary to get centimeter-accurate positioning while landing. Current drone docks use a combination of sensors and mechanical controls to accomplish precision landings.

Autonomous drone missions primarily require an autopilot system that can be controlled by a mission planner. Ardupilot is the leading open-source autopilot system that allows for the easy development and integration of drone systems and accessories. The system is commonly used with APM Planner to plan and execute autonomous drone operations [4]. Using open-source software such as these, sensors can easily be integrated into the drone's operation, as well as execute fully autonomous takeoff and landing operations.

Several solutions exist on the market for precision autonomous drone dock landing. DJI, the largest consumer and industrial drone manufacturer in the world produces the DJI Dock. This model utilizes Real Time Kinematic Velocimetry (RTK) to have the drone land on the dock before an alignment system pushes it to the center and initiates charging [5]. RTK sensors offer centimeter-level positioning accuracy for drones in a small and light package. These systems are often built into the drone's global navigation satellite system (GNSS) and used in conjunction with a base station module. They rely on a fixed base station location to provide positioning data to the drone. There are a few RTK GNSS systems on the market, but the Hex Here+ RTK GNSS is the lightest, most energy efficient, and supported by Ardupilot right out of the box [6].

HEISHA is another manufacturer that produces drone docks with precision autonomous landing capabilities. Unlike DJI, HEISHA uses an IR system to accomplish autonomous landing, as well as a set of alignment bars to center the drone on the landing platform [7]. IR systems use a beacon to shoot IR light into the sky, so an IR camera attached to the drone can use it to land precisely over the beacon. The system can get accuracy to within several centimeters of the beacon [8]. Ardupilot allows for plug-and-play setup of IR systems, allowing for easy implementation into a drone. The only downfall of the system is that it is only accurate to the position of the camera on the drone [9]. The IR system can be used in conjunction with multiple beacons to easily facilitate landings at different locations along the drone's flight plan.

Sensors can only get the drone so close to the desired landing spot. Most drone docks use an alignment system to compensate for the several centimeters of error that sensors have, as well as charge the drone on the dock. For the DJI Dock, the drone is proprietary, so the alignment system interfaces directly with the body of the drone using small contact points [5]. HEISHA's alignment system is designed to accommodate multiple different drones. It utilizes two sets of beams that run the length and width of the landing pad. These bars push the drone from all four sides into the center of the landing pad [7]. HEISHA's system requires less precision from the autonomous landing sensors since the beams have more surface area to contact the drone, whereas the DJI system needs to interface with the drone in a specific spot on the drone's body. Both alignment systems integrate with the charging systems of the docks to supply the drone's power while they are not flying.

5.2.2.1. Charging Systems and Motor Control Technology

UAV engineers are constantly trying to find new, affordable ways to power their docks and supply charging to their drones. The drone dock will communicate with the UAV to send packages to the location it is given and back again to charge using the charging system.

5.2.2.2. Charging With Conduction VS. Induction

Drone charging systems are typically done either by conduction or induction. Conduction is the process by which negative or positive electrons are transferred from a charged body while in contact ("contact charging") while charging by induction transfers electrons without the particles touching ("wireless charging") [10]. Charging by induction is safer, more durable, reduces overheating in batteries, and can charge multiple drones. However, it is much slower than conductive charging.

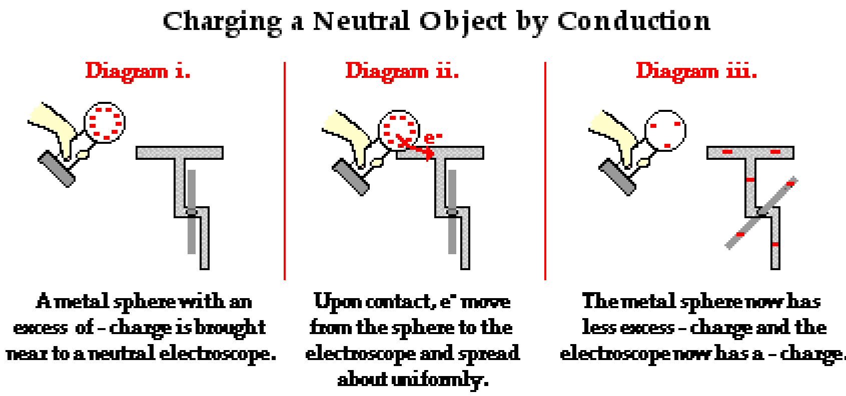

Figure 5.1 - Conduction and induction

5.2.2.3. Automated drone charging station

A possible solution for charging comes from a drone recharging patent [11]. The drone charging station includes at least one charging stack composed of multiple charging blocks. The charging block will have at least one conduction block that includes a first polarity for electrical engagement with the corresponding first electrode with one drone. Finally, it will have a guiding system to guide the drone into place for charging. This patent is used as a reference for the design of the charging system.

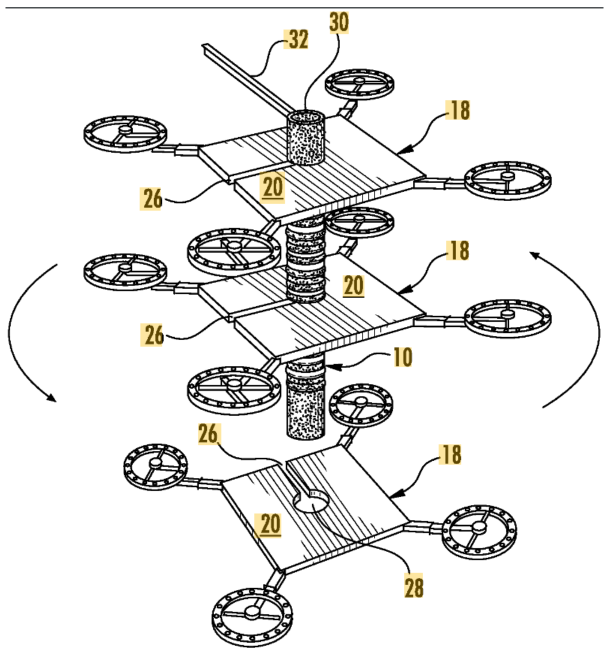

Figure 5.2 - Recharge Tower

5.2.2.4. Skycharge

The design of the docking system calls for a system that can quickly charge the drone battery while also making sure the battery does not overcharge. Using a smart contact charger like the Skycharge autonomous charger. The charger uses a system to efficiently charge a UAV system to the proper charge using a sink. The sink reads the battery and charges the system at the proper wattage. Once the system is charged to the given percentage, Skycharge will stop supplying charge to the system [12].

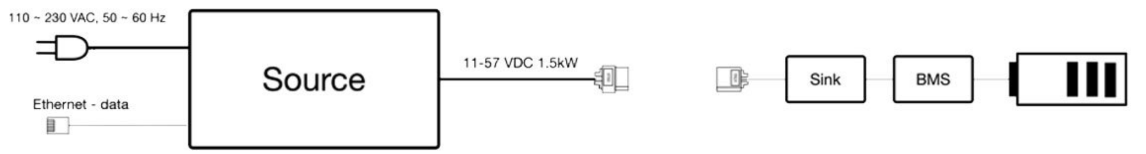

Figure 5.3 - Skycharge

5.2.2.5. Shunt Controller

A shunt charge controller is used so that the battery cannot be damaged by overcharging. This will allow the user to set the maximum battery the drone can charge to. When the battery is fully charged, the controller will stop supplying power to the battery, and instead, the power will be converted into heat, which is then dissipated through the onboard heat sinks [13].

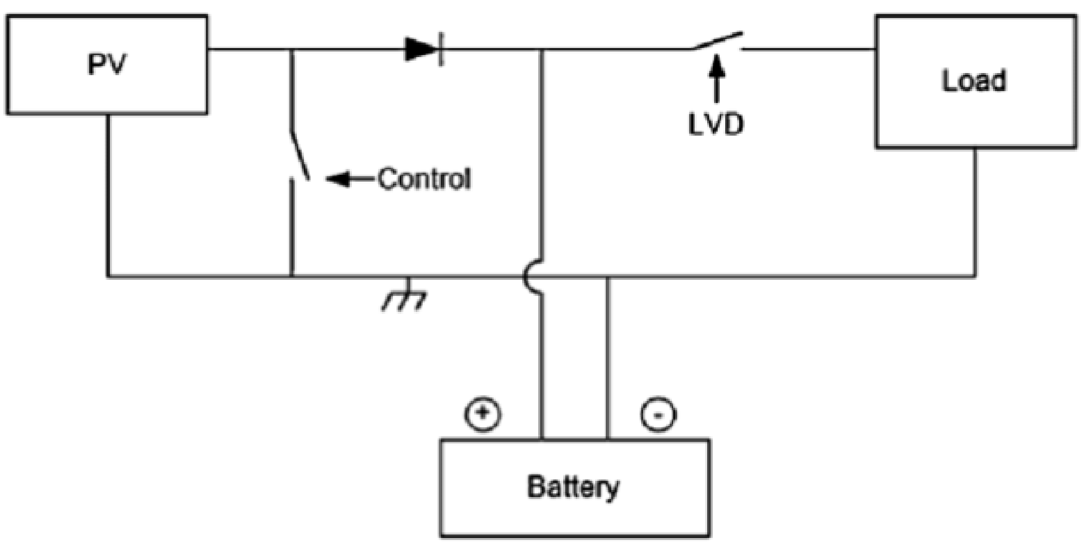

Figure 5.4 - Charge Controller Circuit

5.2.2.6. ADAfruit Motor Controllers

ADAfruit motor controllers operate by using an H-bridge. An H-bridge uses 4 switches to control a DC motor. By closing and opening different switches, the motor can be manipulated to spin faster, backward, etc. [14]. The ADAfruit controller sits on top of the raspberry pi’s GPIO pins and has built-in PWM speed control chips to add more options when controlling motors.

The software paired with the board allows for multiple to be stacked on top of each other (up to 68) [15].

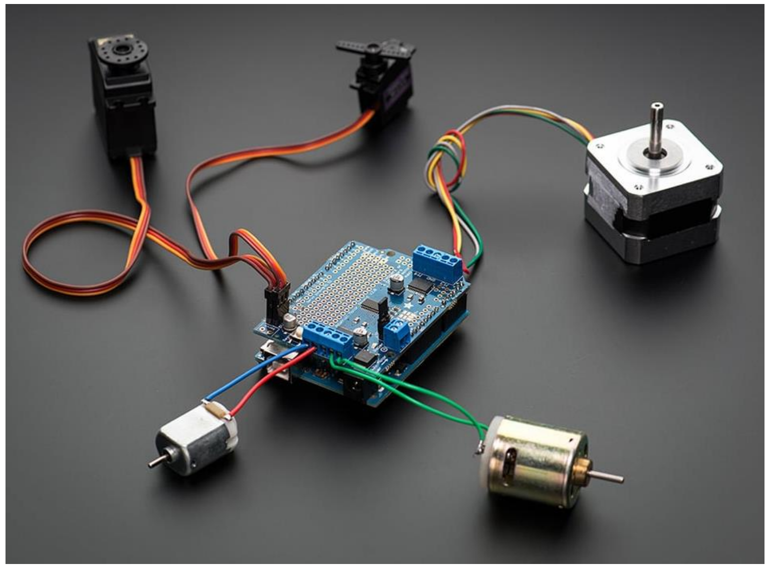

Figure 5.5 - Motor Controller

5.2.3. Drone Dock Elevator System

5.2.3.1. Introduction to Elevators

Mechanical engineering is the broadest and most versatile field of engineering. Mechanical engineers can find their place in most companies or industry sectors and perform engineering tasks for the benefit of their team. Mechanical engineers are often tasked with turning an energy source into movement. An elevator is a prime example of turning energy into movement and elevators can be presented in many forms. Elevators were once all pulley systems powered by steam engines, but today, an elevator could take the form of an electric scissor lift [16]. Just as elevator systems have advanced, delivery trucks are progressing as well and require an elevator to lower package delivery drones from the roof of the vehicle and down to a manageable height.

5.2.3.2. Exploration of Lever-Operated Lifting Mechanisms

The drone dock could be lifted utilizing the mechanical advantage provided by a lever arm. A lever increases mechanical advantage by providing an extended moment arm, allowing for greater torque from a given input force in a system. A lever can be used to rotate a pulley, applying a lifting force to the drone dock. Using a lever to rotate a pulley of arbitrary radius R, is an example of a second-class lever. A second-class lever is classified as a lever having an output force between the input force and the fulcrum of the lever [20]. Levers are typically utilized in scenarios where the angle of rotation range is at or below 180 degrees. Rotating a pulley within this range will not produce sufficient displacement of the drone docking platform. A large diameter pulley creates issues when cost and component size restrictions are present. To overcome the restrictions of such a system, a compound pulley system can be utilized to increase the displacement of the drone docking platform. Usually, compound pulleys are used to increase mechanical advantage at the expense of displacement speed [21]. A compound pulley can be used in the reverse and displacement is increased if mechanical advantage is reduced. A compound pulley can be utilized so that a relatively small rotation of a lever can lead to a comparatively large displacement in the drone docking platform. Using a compound pulley system in the inverse fashion requires an extended lever arm to overcome the increase in force required to lift the platform. In the interest of keeping as much space inside the truck free for package storage, a large lever arm is not suitable for this scenario. Finally, when the angle of rotation's range is over 360 degrees, such as in a hand crank mechanism, a lever could sufficiently displace the drone dock after multiple rotations. However, this is also not a suitable solution as it requires a substantial amount of effort and time from the courier employee.

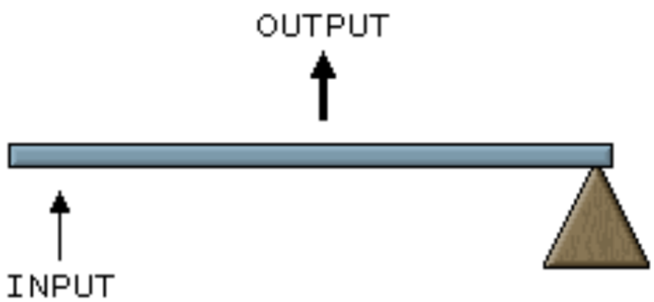

Figure 5.6 - Depiction of a second-class lever

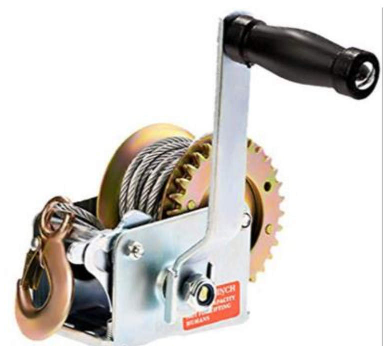

Figure 5.7 - Lever on a hand crank winch

5.2.3.3. Stepper Motor Operated Lifting System

The drone docking elevator has been designed so that the docking platform rides along vertically mounted linear slide rails with a pulley system that transfers force from an electric motor to the platform. A linear slide rail provides a low-friction rail surface for a bearing block to ride on and keeps motion controlled along a single axis [17]. The force applied to the pulley must come from a properly sized motor. An electric motor that is chosen inappropriately will either fail to lift the required load, overshoot, or be excessive in size and cost [18]. For a drone docking system weighing 40 lbs, using the load-torque calculation for a pulley drive of three inches in diameter, the required motor torque to lift the system is 960 oz-inch [19]. A motor of this torque rating is heavy, large, and costly. Also, the cost of electrical components required to operate stepper motors increases as the voltage and current demands grow. To combat the need for a more expensive motor, a compound pulley system can be used to increase the mechanical advantage of the motor. As previously discussed, a compound pulley system decreases the load required to lift the drone platform at the expense of displacement rate, however, this is not an issue as the electric motor has the capability to spin at an RPM that will lift the docking platform in a timely manner. More importantly, it can also operate semi-autonomously and allow for the courier employee to drive, take inventory, and complete other tasks of the job. Since stepper motors are also being utilized on the drone alignment platform, the elevator's stepper motor can be operated off of the same microcontroller and power supply, therefore simplifying the circuitry, increasing the cohesion of the system, and making motorized lifting the most suitable solution for this scenario.

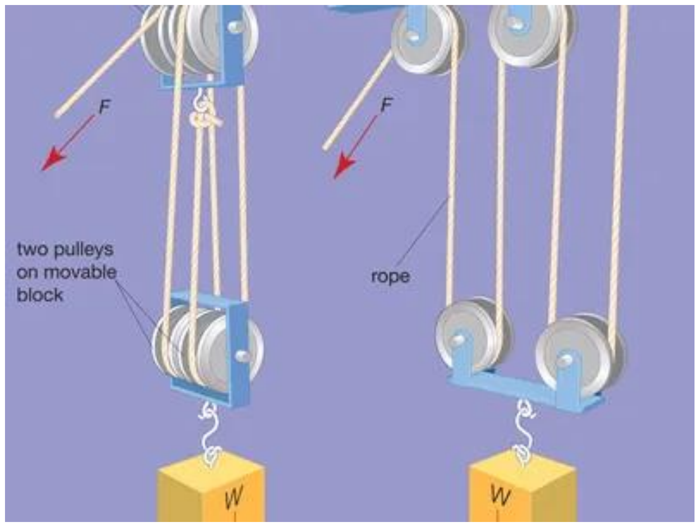

Figure 5.8 - Depiction of a compound pulley. A block and tackle, as pictured on the left, will be utilized in the design.

5.3. Customer and Functional Requirements, and System Architecture

The requirements for this project were obtained through a series of iterations. We first spoke with Dave Maroney of Mitre Corporation to outline the goals that were desired for this project. Using this input, background research was conducted on the various topics that were mentioned in the previous section. The information that was gathered was then further discussed with Mitre Corporation. This process was repeated several times until the team had a complete understanding of what was desired out of the project.

CR #	CR	Description
1	Drone Package Loading	- Driver can easily insert the package into mechanism
2	Drone launch	- Drone takes off from the roof of delivery truck - 40 in x 40 in landing pad
3	Drone Package Delivery at "Customer" Site	- Can release packages in under 15 seconds
4	Drone Return/Retrieval	- Drone can land within 10cm from the center of the landing pad - Alignment mechanism can push 20lbs
5	Drone Recharge	- Has the ability to charge the battery from 0% to 100% in 60 min - Drone returns with at least 20% charge - Cannot exceed 280 W

Table 5.1 - Customer Requirements

FR #	FR Description	Reasoning

1	Carries Up to 5 lb Packages	The FAA has a 55 lb limit on UAS (unmanned aerial systems) including any load. Large drones can weigh up to 25 lbs - 30 lbs, so the package can only weigh between 25 lbs - 30 lbs depending on the drone configuration. For a full-sized system with a max weight of 55 lbs, we chose 20 lbs to have some room with the weight. We decided to scale the system down further to half the size due to cost and resource concerns, leaving us with a weight of 10 lbs
2	Drone Dock can hold 55 lbs	The FAA has a 55 lb limit on UAS system including any load. The system must also be able to withstand a shock load of this weight dropping, but since the system will be a scaled-down version, this max shock load will not be reached
3	13" x 10’’ x 10’’ (LWH) Package Cage Volume	Found the average length width and height of all amazon package using excel and found that the aspect ratio of the length and width was 1.5. After measuring as many common smaller Amazon boxes as we could find, we decided on a 13 in x 10 in base. For the height, we round the average to the nearest 10
4	Charging Dock and Drone Operate on 12V	All microcontrollers, servo motors, and many other electrical components can operate under 12V
5	Release Package From Mechanism in Under 15 Seconds	Need a small power delivery device to release the package from the drone. This will be in the form of a servo motor or an electric linear actuator
6	Fully Charges Drone in 60 min	This is a reasonable amount of time because ideally, there will be a drone charging while another is delivering a package that we have set a max flight time of 20 minutes. Also, the drone will most likely return to the truck with battery life left so that it will not have to charge from 0%
7	Secure the Drone to the center of the Dock	To prevent the drone from shifting around in the truck while the truck is moving, as well as secure consistent charging connection
8	Dock cannot exceed over 50 celsius	After 50 celsius, electronics in the dock will begin to overheat. Because of this, the interior of the dock cannot exceed this.

Table 5.2 - Functional Requirements

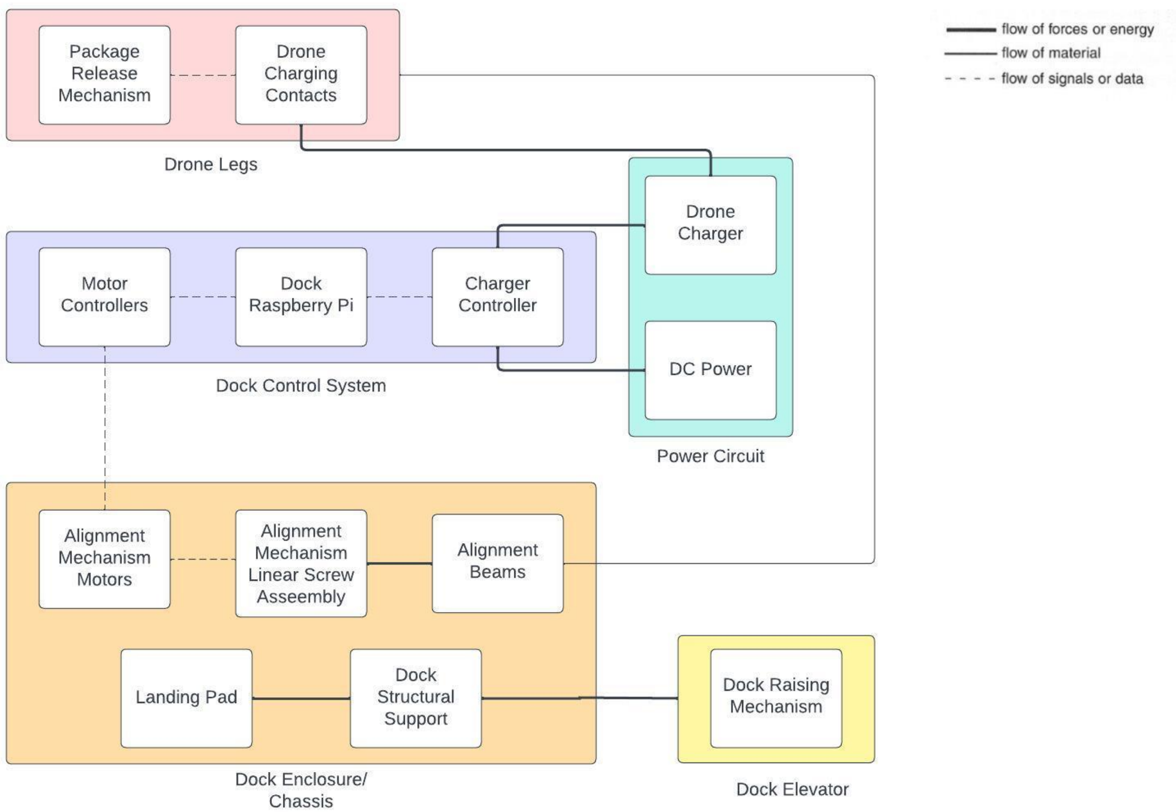

Figure 5.9 - System Architecture

6. Design Description

6.1. Overview

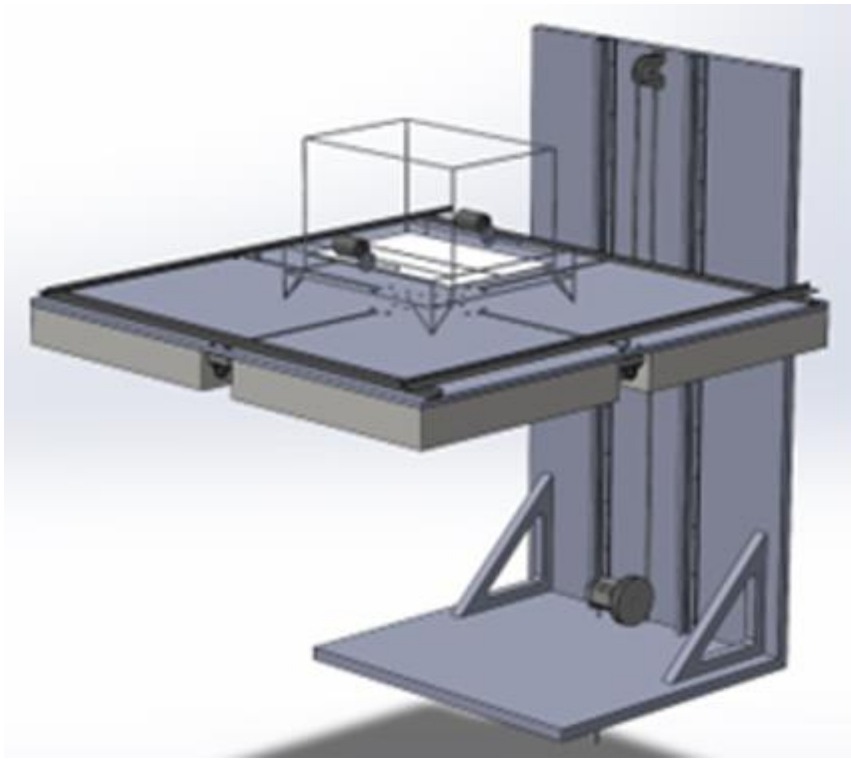

Figure 6.1 - Complete CAD Assembly

Figure 6.1 depicts the final Computer-Aided Design (CAD) model for a modular drone docking and release system, designed to efficiently transport packages to a customer with minimal driver involvement. This system is composed of four distinct subsystems - the package release mechanism (PRM), drone landing pad and alignment system, charging and drone circuit system, and dock elevator - each integrated to meet customer requirements and address fundamental system objectives. The PRM functions as the drone's legs and secures and releases the package upon command. The drone docking and alignment system ensures stable landing and charging of the drone and PRM in various road conditions. The circuit and charging system provides power to the subsystems and drives the motorized drone alignment system. The drone elevator is affixed to the delivery truck wall and facilitates the lifting of the dock to the roof. The integration of these subsystems represents a comprehensive and cohesive solution to the problem at hand.

6.2. Package Release Mechanism

The package release mechanism functions to secure the package en route and autonomously deliver the package at the customer site. Overall weight is a significant constraint for this subsystem as it will be attached to the drone and will therefore directly affect the delivery range. The package with a volume of up to 13x10x10 inches will be inserted by the delivery driver into either side of the frame via manual latched doors. Upon delivery, the bay doors will open releasing the package from the bottom of this subsystem.

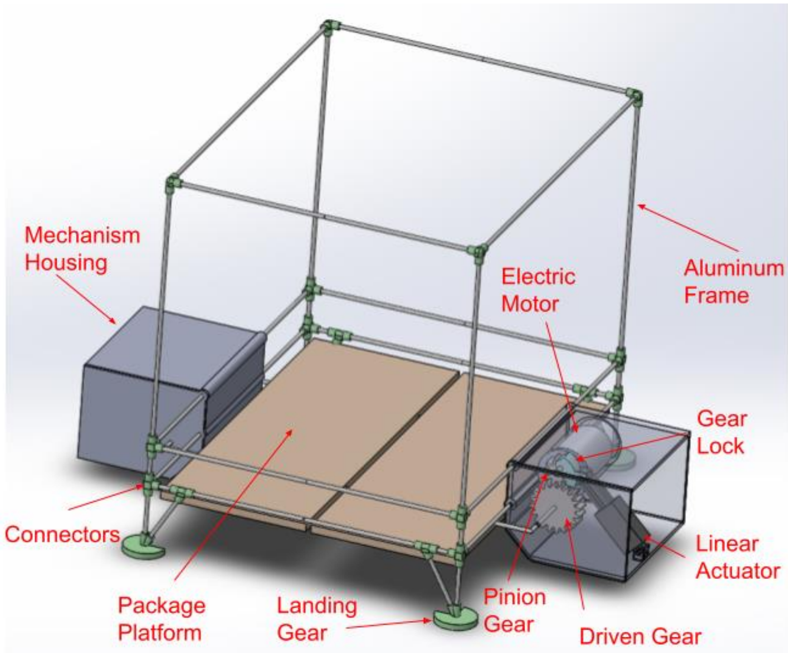

Figure 6.2 - Labeled Package Release Mechanism (PRM) in closed position

The PRM in Figure 6.2 consists of two main parts: the structural support frame, and dynamic bay doors. The former serves as the container the package will be inserted into as well as contains fixture points to the drone and the mechanism to open/close the bay door. The frame supports the drone/package weight and serves as landing gear. The latter is the mechanical system that will support the package's weight in transit and release it when desired. It is located within the housing case fixed to the frame and powers the opening, closing, and fixing of the bay doors.

6.2.1. Frame

The frame is constructed using 6061 ⅛’’ diameter aluminum rods and ABS-printed connection points. Through Solidworks simulation, the frame is capable of supporting up to 17 lb with minimal deflection. Additionally, this configuration allows for relative flexibility and ease of manufacturing. Aluminum rods are cut from stock to specification, and fixed into place using epoxy at each of the connection points. When configured for customer use the frame will be cased in lightweight cardboard paper to aid in package securement and aesthetics.

The mechanism housing in Figure 5.2, printed from ABS plastic secures the door mechanism in place. It contains fixtures for the motor, linear actuator, and gears. It is intentionally left open to allow for ease of testing and manufacturing. Upon completion, it will be sealed with ABS plastic sheeting.

6.2.2. Bay Door

Each bay door is powered by a 12V DC geared electric motor, 0.4’’ stroke linear actuator, and gear system. The electric motor has a torque of 84 lb*in. operating at 10 RPM and the linear actuators have a max load of 20 N. The motors are fixed with a pinion that drives a spur gear attached to the base of the door. The gears are 3D Printed ABS plastic and have a ratio of 2:1. The driven gear is secured to the package platform frame using epoxy.

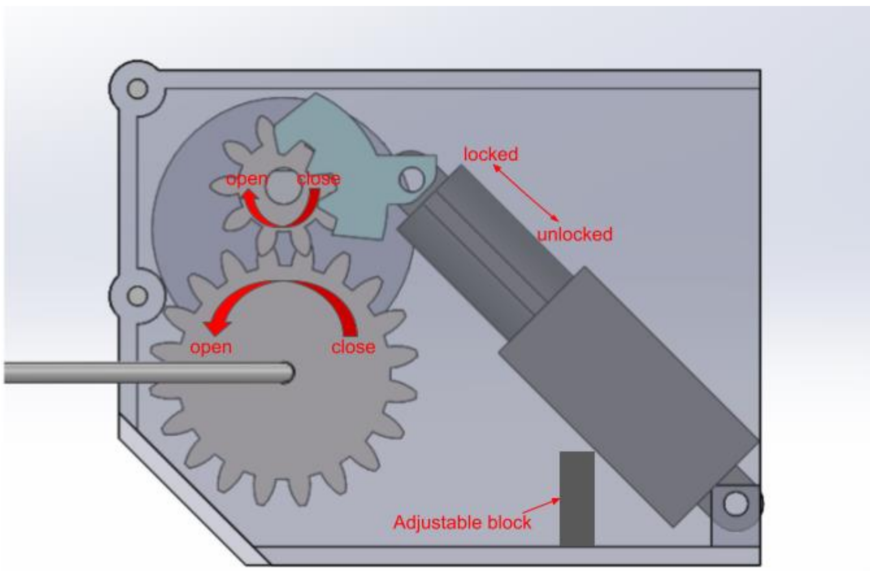

Figure 6.3 - Bay door mechanism in up and locked position

Figure 6.3 displayed the linear actuators fully extended 0.4’’. In this position, a gear lock is inserted on the pinion thereby fixing the platform doors in the up position. This is advantageous because the motors will only need to raise the weight of the door itself. Therefore, less powerful and expensive motors are used. Additionally, an adjustable block is used to support the actuator and allow for design flexibility.

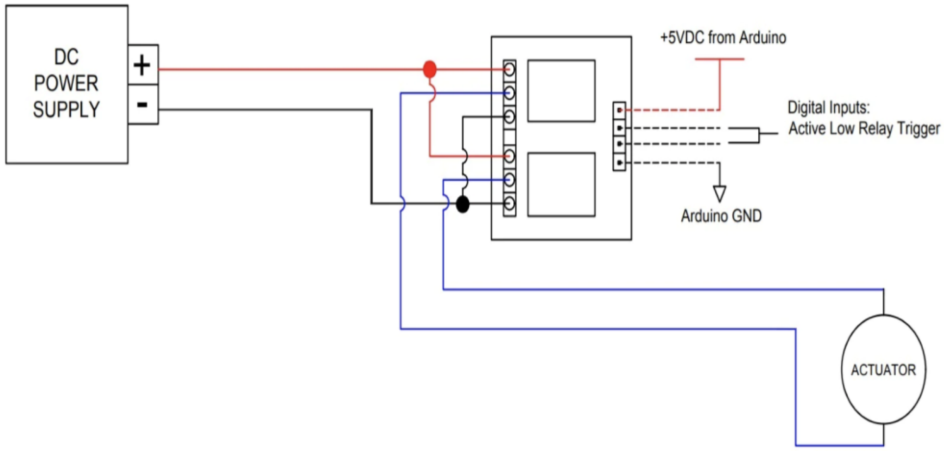

Figure 6.4 - Linear Actuator control schematic

Figure 6.4 depicts the electrical circuit used to control the two linear actuators used to lock the bay door in flight. It is controlled by an Arduino and is to be powered by the drone's batteries. For testing purposes, a variable power supply was used. The circuit consists of a 2-channel relay, power supply, actuators, and Arduino.

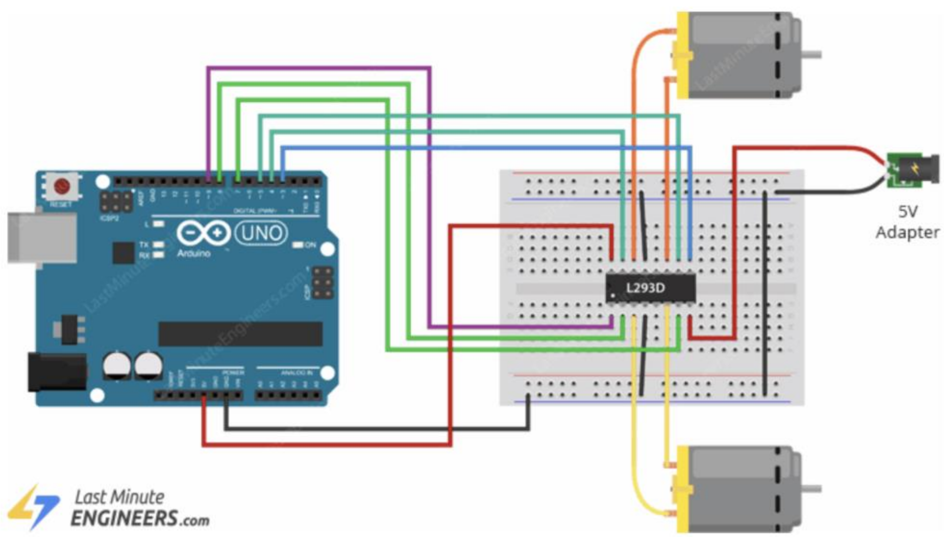

Figure 6.5 - Geared DC Electric Motor Control Schematic

Figure 6.5 depicts the motor control circuit used to open the bay doors. In this circuit, an L293D chip functions as an H-bridge which allows the Arduino to change the direction and stop the motor as desired.

Item	Component	Fabricated or Purchased	Status

1	Aluminum Support Rods(10 lengths)	Purchased	complete
2	Package Insertion Door Frame	Fabricated	complete
3	Package Door latch	Fabricated	complete
4	Landing Gear (Left and Right)	Fabricated	complete
5	Linear Actuators	Purchased	complete
6	Gear Stopper	Fabricated	complete
7	Pinion Gear	Fabricated	complete
8	Spur Gear	Fabricated	complete
9	Junctions (3 types)	Fabricated	complete
10	Package Platform/Frame case	Purchased	complete
11	Geared Electric Motor	Purchased	complete
12	Motor Housing (Base, Top, and Cap)	Fabricated	complete
13	Arduino	Purchased	complete
14	Motor Controller (L293D)	Purchased	complete
15	4 Channel Relay	Purchased	complete

Table 6.1 - PRM Component Status List

6.3. Drone Dock

The drone dock design had many design considerations. The landing pad had to be large enough to accommodate the footprint of the package release mechanism (15 in x 14 in) as well as the overall diameter of the drone attached to it. For this system, the landing pad was chosen to be 40 in x 40 in to accommodate a variety of drones that can be used with the package release mechanism. The landing pad needed to be made of durable but inexpensive material. The surface of the landing pad also needed to be smooth for the drone to be able to easily slide along the surface for alignment. It was decided that a half-inch thick piece of plywood would be sufficient for the project’s needs. Figure 6.6 provides a view of the drone dock from the top, where the plywood landing pad can be seen.

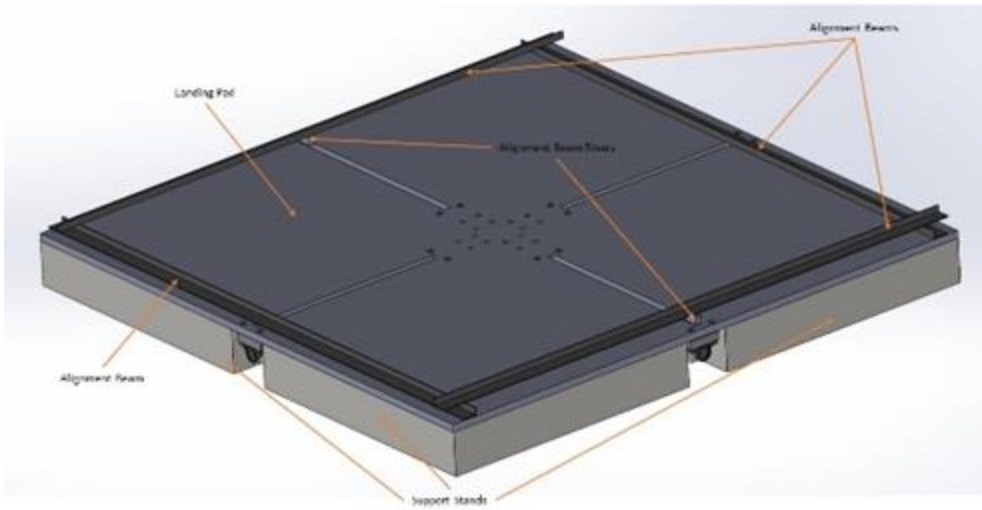

Figure 6.6 – Drone Dock (Top View)

In order to make room for the alignment mechanism on the bottom of the landing pad, stands were needed to keep the four assemblies from touching the ground. Four 18 in x 18 in square frames made from 2x4in wood beams were designed and placed in each of the quadrants of the landing pad as can be seen in Figure 6.7.

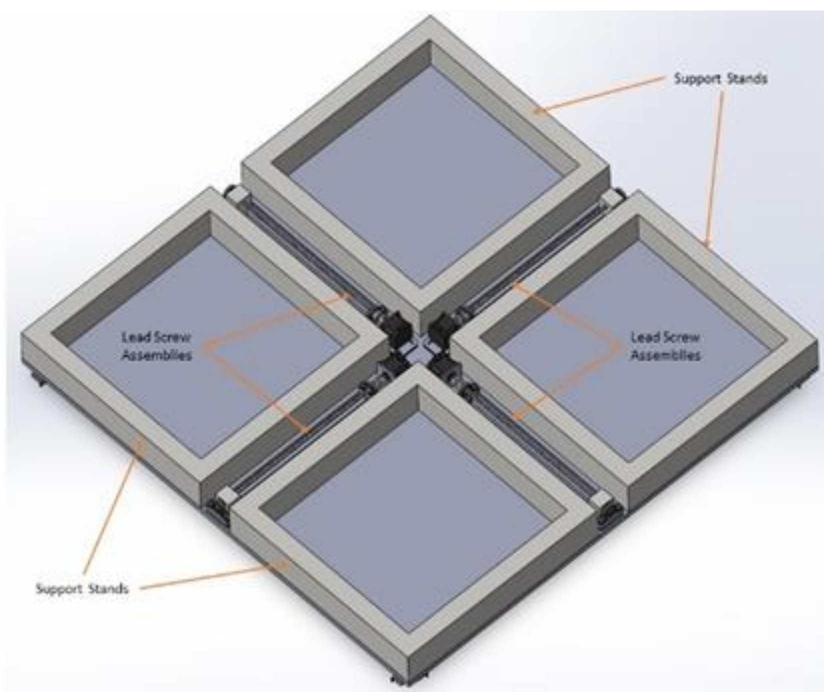

Figure 6.7 – Drone Dock (Bottom View)

A mechanism was needed to align the drone in the center of the dock. Linear movement screws are an ideal solution for this. Several configurations were designed using a T8 lead screw and nut. The design with the least amount of motors was chosen to minimize the cost and complexity of the mechanism. A NEMA 17 motor rotates the T8 lead screw to move the T8 nut as shown in Figure 6.8. This mechanism sits on a base plate with appropriate risers and mounts for the motors and bearings. The nut housing is kept aligned using two 4mm rods that run the length of the lead screw. Four of these assemblies are needed for the alignment of the drone, two for each axis in each direction. This configuration can also be seen in Figure 1. These assemblies are mounted to the bottom of the landing also seen in Figure 6.7.

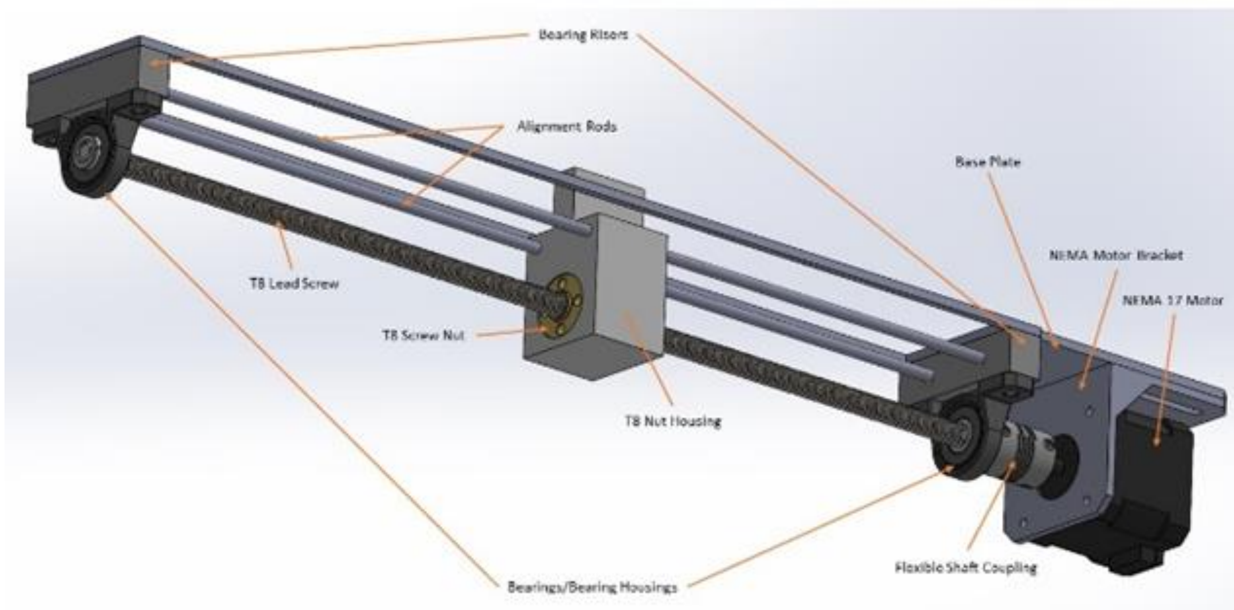

Figure 6.8 – Lead Screw Assembly

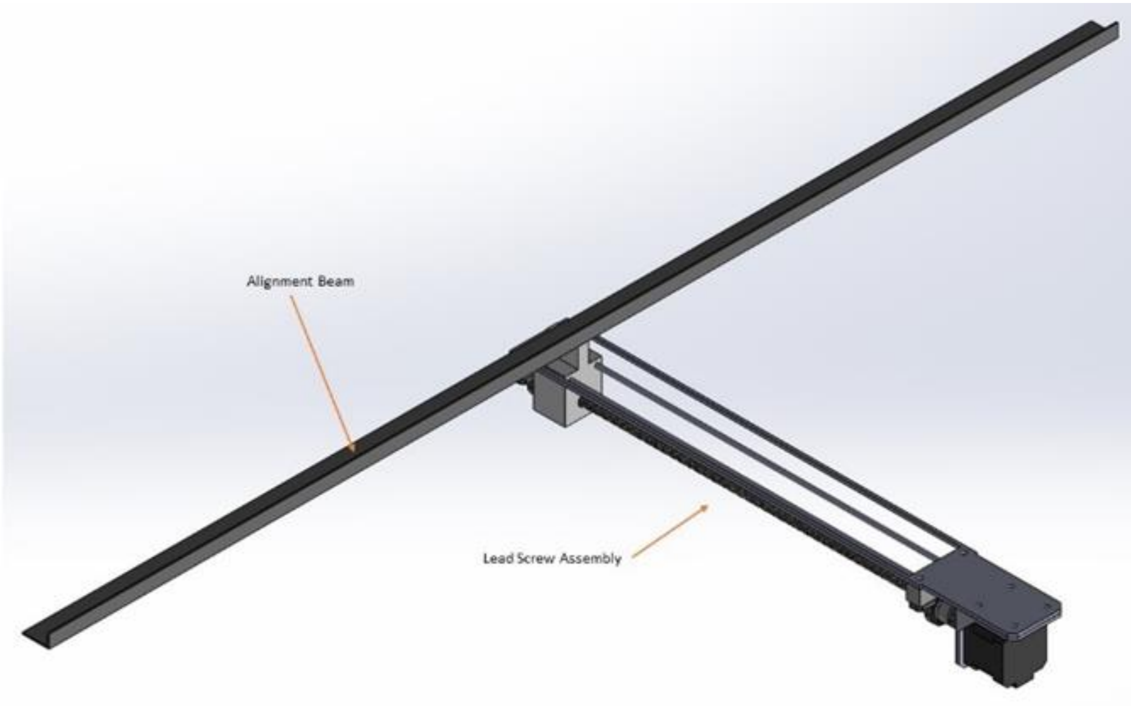

Figure 6.9 – Alignment Mechanism (Lead Screw Assembly + Alignment Beam)

The nut housing sticks up through the landing pad and attaches to an alignment beam as shown in Figure 6.9. The alignment beam pushes the drone from each side toward the center of the landing pad as the NEMA motors move the T8 nut. The alignment mechanism will align along one axis before the other in order to ensure consistency when centering the drone without jamming the system.

Item	Component	Fabricated or Purchased	Status
1	Landing Pad	Fabricated	Complete
2	Structural Support	Fabricated	Complete
3	Alignment Mechanism	Fabricated/Purchased	Complete

Table 6.2 - Drone Dock Component Status List

6.4. Drone Dock Circuit

6.4.1. Dock Circuit Design Overview

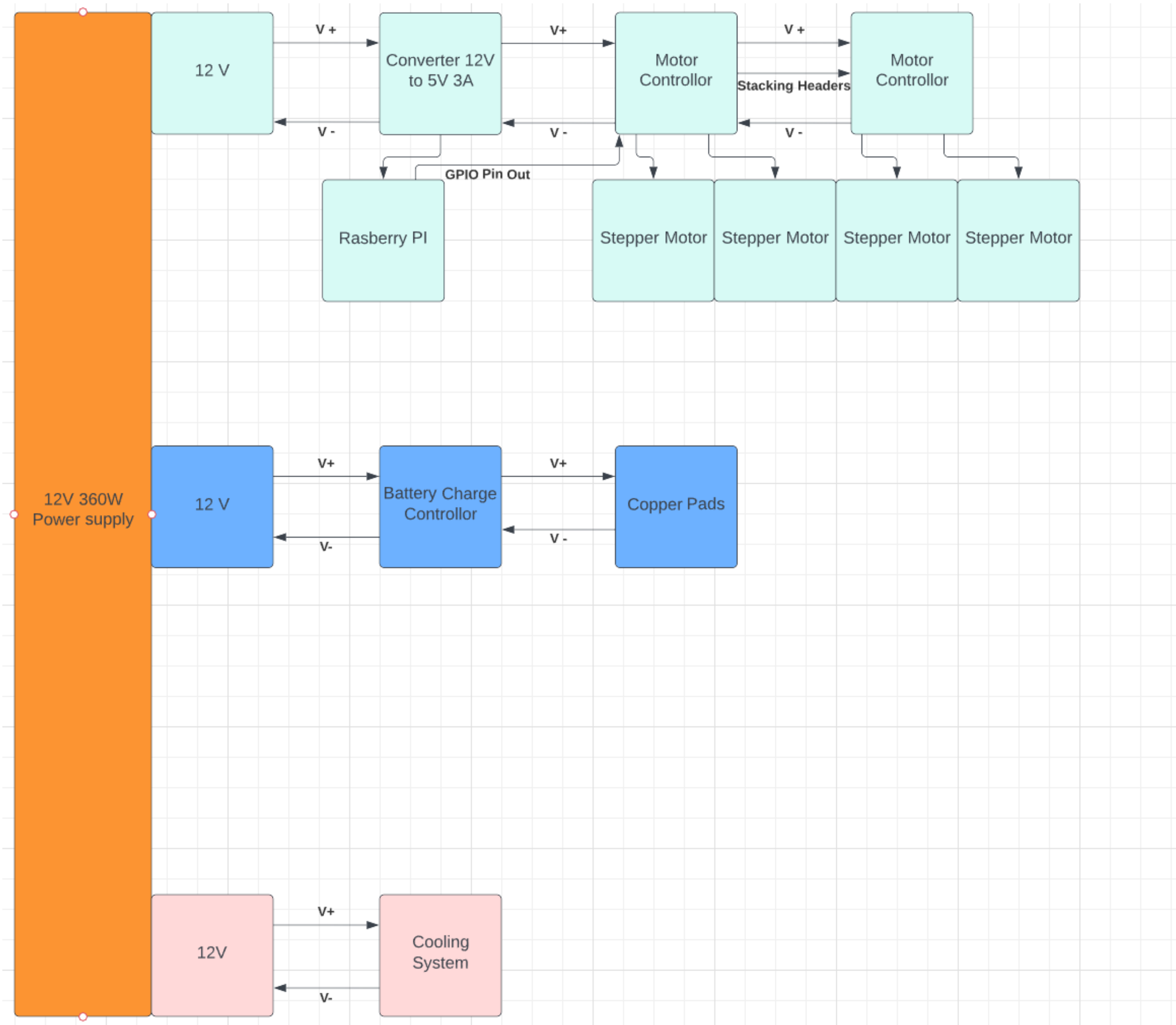

Figure 6.10 - Block diagram of circuit

Figure 6.10 demonstrates the power supply used in the dock system. A 360W 12V power supply with three outputs will be used to power the system. Each output is designated for a specific subsystem. These subsystems include the Raspberry PI and motor controller, charging system, and cooling/communications system. Each separate sub-system will be wired in parallel. When components are wired in parallel, the voltage across each component will remain the same while the amperage between the components will decrease. This allows for multiple components to be wired together while still getting enough power.

The Raspberry PI and motor controller subsystem uses a transformer, two motor controllers, 4 motors, and a Raspberry PI. The Raspberry PI will be powered through the transformer at 3A 5V, the motors will be powered at 12V and 2A each. The Raspberry PI serves as the controller for the motors which are used to drive the system. The motor controllers and motors are the most important components of the system. The main purpose of the motor controllers and motors is to secure the drone so that the charging system can charge the drone.

The charging system is the second input, which will be connected via charging contacts to the drone’s battery. The charge controller is configured to supply the battery with a charge of up to 80% before stopping. The charger will consume 5A and 12V of the power supply. The battery is a critical component of the system. The overall drone docking station will not be viable if the drone battery is overcharged or damaged. The charging system ensures that it is maintained at the proper charge level, maximizing the battery's performance and life.

The final section of the power supply is allocated to the cooling system. The cooling system employs a CPU cooler, which is rated at 12V and 3A. The cooling system is critical for maintaining the system's temperature, which is essential for maximizing the system's performance and lifespan. The CPU cooler is an efficient and effective cooling solution that ensures the system is running at a cooler temperature.

The communication and LCD screen are designated for future iterations of the design. It is essential to note that the communication system and LCD screen can consume significant power, and they must be incorporated into the power budget. The power budget will be a crucial component of any future design iterations. In future iterations, the system's total power consumption will need to be re-evaluated based on the inclusion of additional features. The system's total power usage can be calculated using the power equation:

$$P=IV \tag{1}$$

where I represents the current in Amps and V the voltage in volts. The total power usage for the system is 255W. This is based on the current design and does not include the communication system or LCD screen. The available power for future iterations or additions to the system is 105W, which provides lots of room for potential additions to the system.

6.4.2.1. Power Supply

Figure 6.11 - 12V 360W Power Supply

Figure 6.11 shows the power supply that will power the circuit. It uses a 360W 12V supply that has 3 different outputs. The supply will be powered by a 110V outlet using a three-prong plug in a wall outlet. The components are split up into three groups; charging, raspberry PI system, and cooling/communications. Each group will have its own output in the power supply and will be wired in parallel in order to allow for multiple components to get the same voltage and their given amperage.

6.4.2.2. 18 Gauge Wire

18 gauge wire will be used in the system because of its low resistance and its use in common computers. The components in the circuit have a wire rating of 18-26AWG, 18 will be used because of the lower resistance.

6.4.2.3. Raspberry PI

Figure 6.12 - Raspberry Pi

The Raspberry PI 3B is shown in Figure 6.12. The Raspberry Pi system will be used to control the motors on the alignment mechanism and to control the APM planar software. The

Raspberry PI will control the alignment mechanism by using a motor controller hat on its GPIO pins.

6.4.2.4 Motor Controller

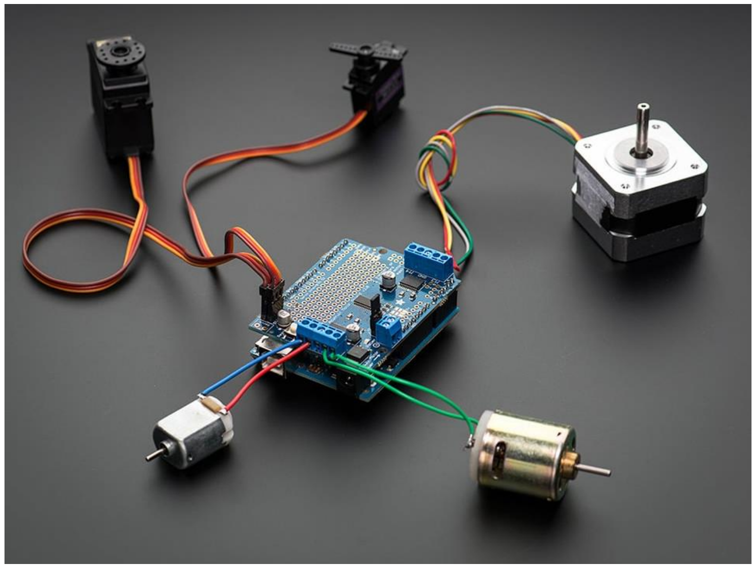

Figure 6.13 - Motor Controller

The motor controller (shown in figure 6.13) for the stepper motors will be the ADAfruit motor controller for Raspberry PI. The controller uses TB6612 Mosfet drivers to hold the 12V from the power source until the Raspberry PI turns the mosfet on. When on, through Python the amount the stepper motor can spin is controlled. However, the motor controller cannot control how many amps the motor will draw, thus an amperage chopper will be used to control the amperage of the motors. This system will control the alignment mechanism.

6.4.2.5 Shunt charge controller and charging

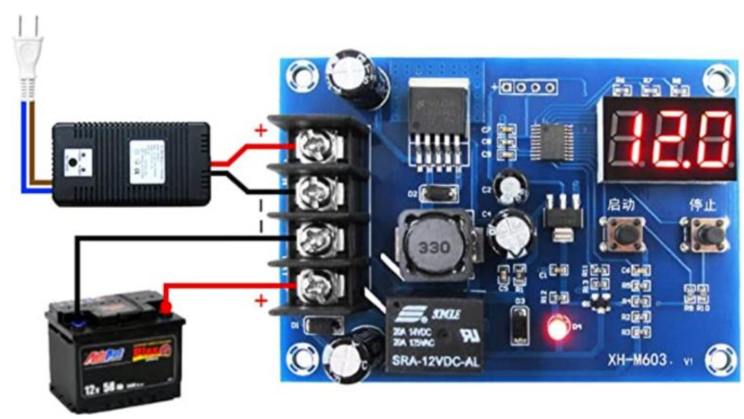

Figure 6.14 - Shunt Charge Controller

In the docking station design, a shunt charge controller is attached so that the battery cannot be damaged by a power surge or overcharging. The shunt charge controller circuitry will allow the user to set the maximum battery the drone is able to charge at. When the battery is fully charged, the controller will stop supplying power to the battery and instead, the power will be converted into heat, which is then dissipated through the onboard heat sinks [4]. Using this technology, the drone battery will have a longer life by optimizing the amount of battery the drone will have (25-85%) and decreasing the amount of heat the drone battery will produce.

6.4.2.6 Cooling system

Figure 6.15 - Motor Controller and Fans

The cooling system will use a CPU cooling controller and fans shown in Figure 6.15 to cool off the electric components. The system will use three 120mm fans, one fan will pull air out while two will pull air in. Heat sinks will be added to components where needed.

6.2.2.7 Motors

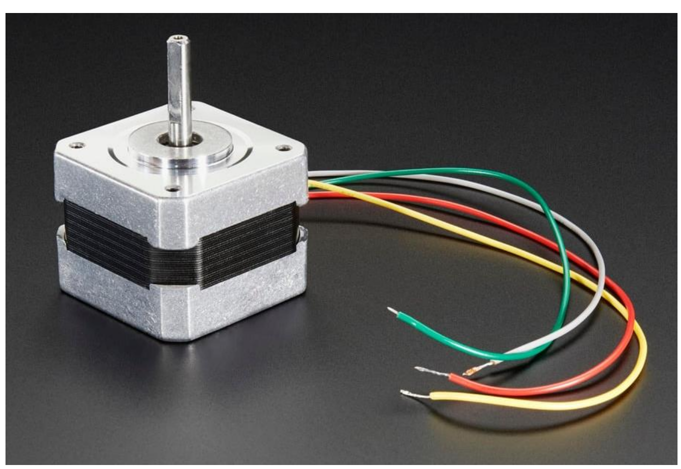

Figure 6.16 - Stepper Motors

The motors that will be used are ADA fruit stepper motors shown in figure 5.16. These motors will be used for the alignment mechanism and will be controlled by the raspberry PI through the motor controllers. These motors will be housed inside of the dock away from the rest of the electronic components.

6.4.3. Complete Dock Circuit Design Overview

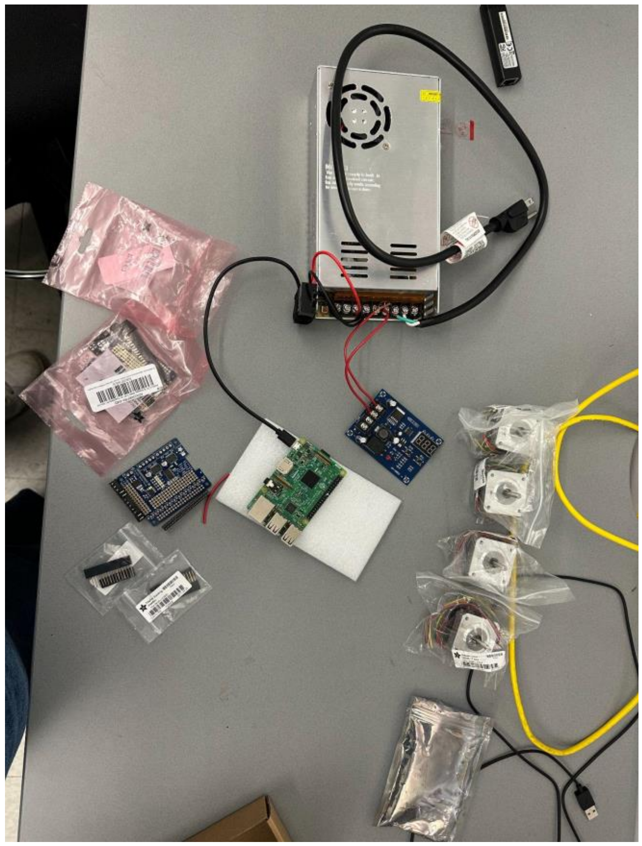

Figure 6.17 - Circuit components laid out to be put together

In Figure 6.17, all the components are laid out to show how they will all fit together. The Raspberry PI and the motor controllers (shown on the left) will be put on top of one another to power the alignment mechanism shown in Chapter 6.3. The shunt charger and CPU cooler (displayed on the right side of the image) will be separated in the final design.

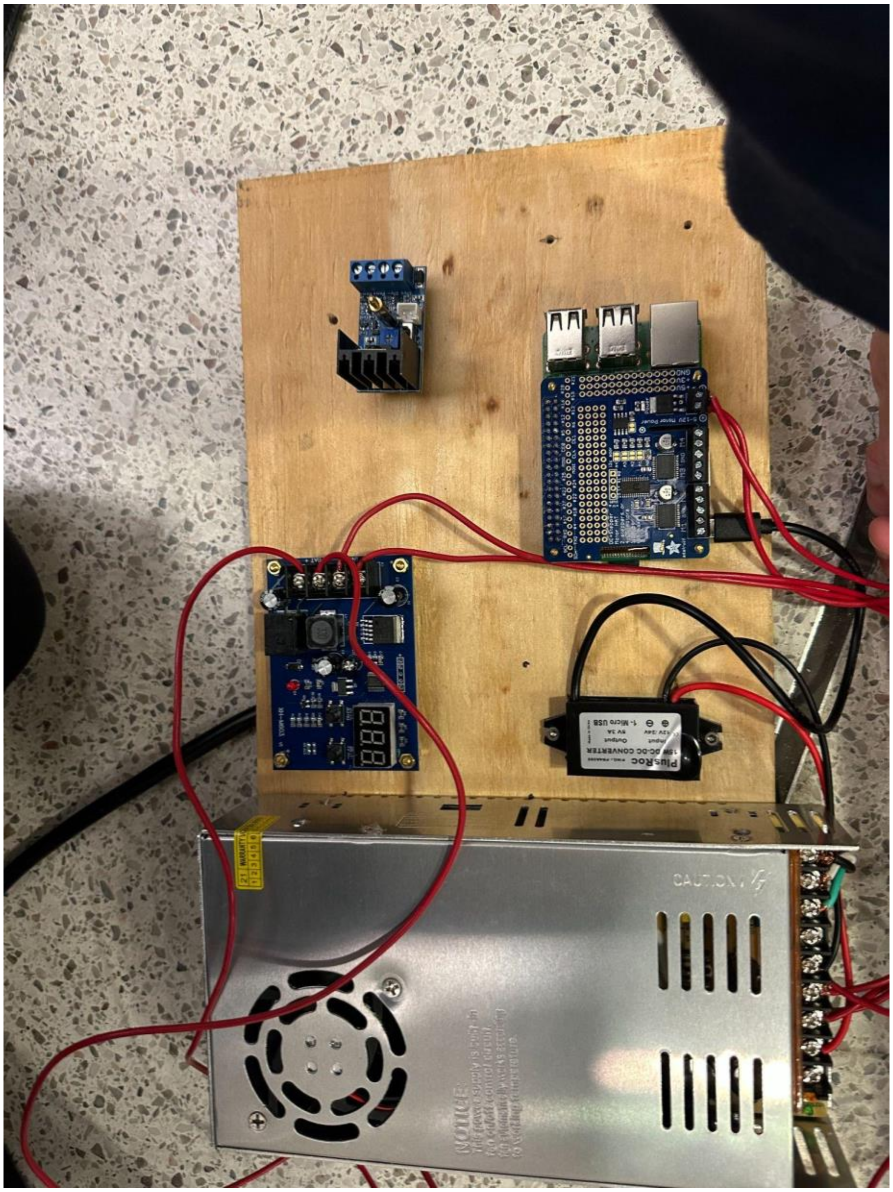

Figure 6.18 - Final circuit board

The final circuit board is shown in Figure 6.18. The Raspberry Pi and motor controllers are shown in the top right while the other components are spread out across the board. Each component is off of the board using metal standoffs. This board was inserted into the dock by using two slide rails. The slide rails were inserted into one of the square frames of the dock leaving one of the sides exposed. The circuit wooden board is then slid in upside down to the dock and plugged into an external screen, mouse, and keyboard.

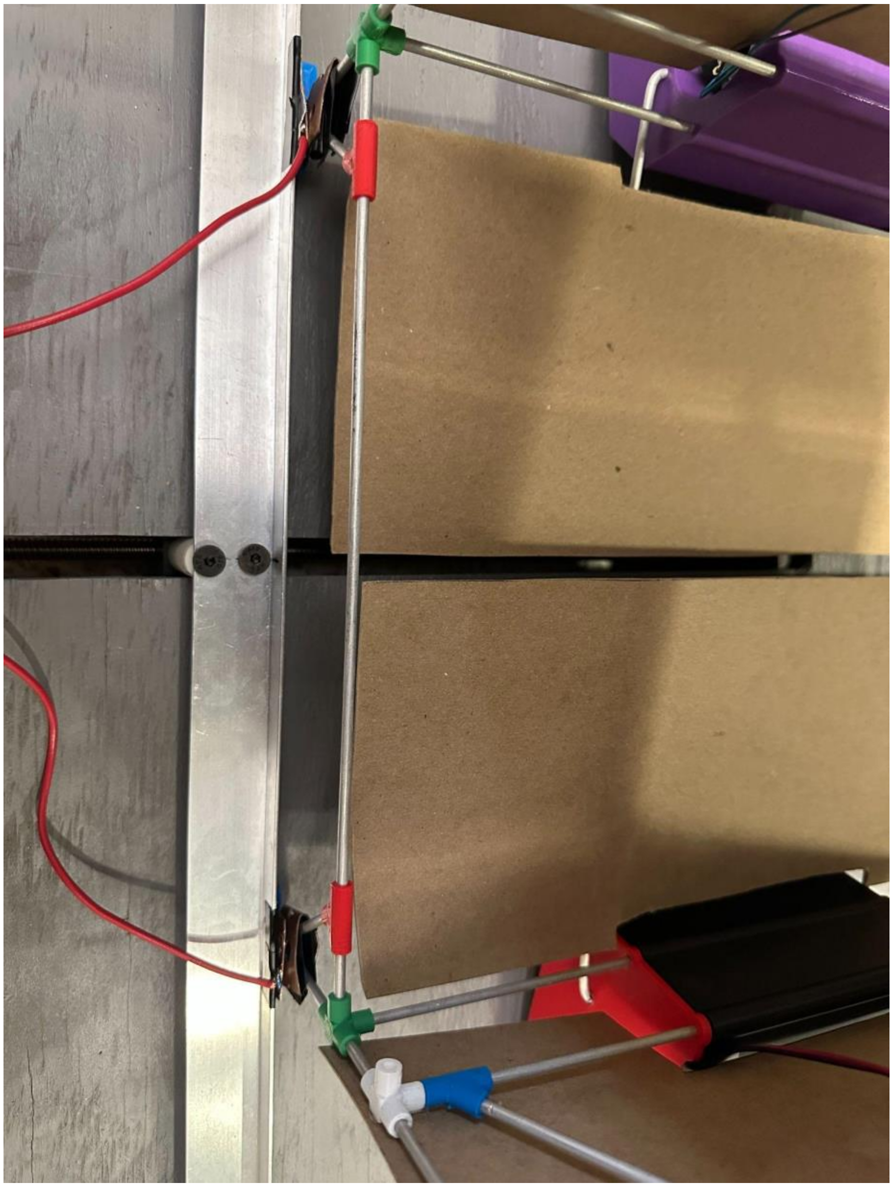

Figure 6.19 - Drone charging contacts

In Figure 6.19, the drone charging contacts are shown. Metal sheets that were soldered to the wire from the motor controller were then connected to the charging contacts on the PRM. There is an insulator on each so that there will not be a short circuit across any of the bars. The contacts on the PRM are pressed onto an insulator which would be soldered to the positive and negative wires of the drone battery. These contacts are on either side of the PRM so no matter which side it’s facing, the drone will be able to charge from the contacts.

Item	Component	Fabricated or Purchased	Status
1	Raspberry PI	Purchased	Completed
2	Charge Controller	Purchased	Completed
3	Motors	Purchased	Completed
4	Solder	Purchased	Completed
5	Fans	Purchased	Completed
6	Motor Controllers	Purchased	Completed
7	Stacking Headers	Purchased	Completed
8	Standoffs	Purchased	Completed
9	Power Supply and Cord	Purchased	Completed
10	Wood Plate	Fabricated	Completed
11	Cooling Controller	Purchased	Completed

Table 6.3 - Drone Dock Circuit Component Status List

6.5. Drone and Drone Dock Elevator

The drone and drone dock elevator are essential components to having a practical drone delivery module inside the cabin of a truck. The elevator functions to bring packages and the drone from within the truck up to the vehicle's roof, a suitable location for takeoff. Without this apparatus, courier employees would have to physically reach up to the roof of the truck in order to load packages into the drone's package compartment. This is not only inconvenient but may also be impossible depending on the height of the operator. With the elevator system, packages and the drone are raised to their appropriate launch location with the touch of a button. The system includes linear slide rails, block bearings for the slide rail, a pulley system, and an electric motor.

The drone docking platform is connected to the linear slide rails via supports underneath. The supports mount to the sliding carriages on the linear slide rails and are made of plywood. Plywood is a cheap and easily manufacturable material with suitable strength characteristics for this application as confirmed by finite element analysis. FEA has shown that the material and geometry of the design is sufficient to support the load of the docking platform with minimal deflection.

Figure 6.20 - Dock Elevator Frame

Linear slide rails consist of two components, the rail, and the sliding carriage. The rail is a rigid length of metal and the sliding carriage is what attaches to the load and allows for low friction movement along the rail. The linear slide rails ensure that our drone dock travels securely and in a controlled manner, reducing the risk of jostling the package as well as any sensitive electronics in the drone.

Figure 6.21 - Linear Slide Rails

With an estimated load of 40 lbs on the elevator, the required motor torque to support this weight is 960 Oz-inches. A stepper motor to satisfy the torque requirement requires a large power source, external controllers, and drivers, and is also very expensive. To reduce the complexity and cost of the electric lifting system, a winch was substituted for the stepper motor in the original design. The chosen winch has the ability to lift ten times the estimated drone dock weight, is equipped with a remote control, and reduces the complexity of the design, all while remaining a budget-friendly component.

Figure 6.22 - Electric winch attached to the elevator frame

The frame experienced a higher moment force than anticipated which resulted in deflection during testing. To compensate for the increased moment, tension straps were connected from the top of the frame to the base to create a moment in the opposite direction as the moment created by the weight of the drone dock. The tension straps negated any deflection in the frame as the sum of the moments in the system was equal to zero.

Item	Component	Fabricated or Purchased	Status
1	Elevator Frame	Fabricated	Completed
2	Steel Pulley	Purchased	Completed
3	Dock Support Brackets	Fabricated	Completed
4	Electric Winch	Purchased	Completed
5	Linear Slide Rails	Purchased	Completed
6	Ratcheting Tension Straps	Purchased	Completed

Table 6.4 - Dock Elevator Component Status List

6.6. Method of Operations

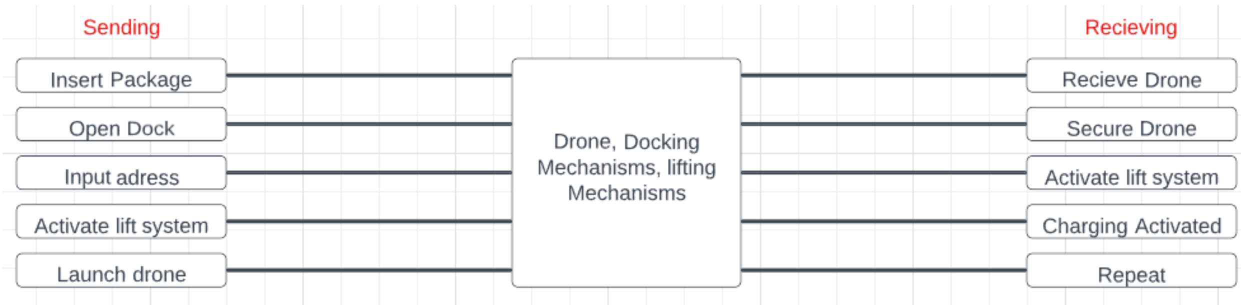

Figure 6.23 - Operations Block Diagram

The operation of the components together is shown in Figure 6.23. The driver will first stop the truck and go to the back where the system will be sitting. The driver will then grab a package and insert it into the PRM. The driver will then activate the release mechanism by running the opening Python code, and while it's opening the driver will type into the autonomous drone software where the drone needs to drop off the package. After this, the driver will raise the package using the dock elevator winch and bring it to the roof where it will take off. The drone will then come back and the reverse will happen. The drone elevator will be activated to come down, the alignment mechanism will be activated to secure the drone with the Python code, and then another package will be able to get released.

7. Standards Implementation

All the testing is in accordance with FAA Part 107 in order to avoid breaking any regulations. Part 107 defines a small unmanned aircraft as an aircraft that weighs less than 55 lbs. on takeoff with all the elements attached to it. We will design our drone to weigh less than this, including the weight of the package to meet FAA standards for UAS. In order to operate a drone weighing more than 249 grams, but less than 55 lbs, the pilot must acquire a small UAS rating remote pilot certification. The person with this certification is allowed to let other people fly under their supervision. Part 107 also discusses the operation of a drone from a moving vehicle, which can only be done in sparsely populated areas. There are many more regulations in Part 107, mostly regarding the safe operation of a drone, and operations that are not allowed, which the group will take careful measures to follow as well.

ASTM B 221- 08 is used to find the correct aluminum thickness for the designed leg and package delivery system. The standard will give the tensile strength as well as other values to easily look at and decide what material and what diameter is needed.

The FMSCA requires that cargo in certain-sized motor carriers must be able to withstand certain levels of deceleration in each direction. (0.8g in the forward direction, and .5g in the rearward and lateral directions). In order to meet this standard, the design of the dock will interface with the feet of the drone such that it is firmly held in place. Then testing can be done to ensure that the drone can withstand the forces the FMSCA outlines.

The NEMA 17 standard is only applicable to the motors chosen. The group will design our dock around standard NEMA 17-sized motors. The NEMA standard allows us to choose a motor of a certain size and gives us a variety of torque options to choose from.

The IEEE Standard Interface Requirements and Performance Characteristics of Payload Devices in Drones are used to design the payload carrier. The standard document dictates rules when implementing a payload system when delivering with a UAV system. The standards go through many different rules relating to drone flight and payload securing. For example, the payload must be secured on both sides.

All of the design work is in accordance with ASME Y14.5, the dimensioning and tolerancing standards list. This will ensure that communication with the machine shop is clear, which will lower the possibility of mistakes and fitment issues while reducing costs by limiting the number of components that may possibly need to be remade. ASME PTB-8 standards regard the metallic material selection and proper procurement methods. This is important to the design choices as the standards go over what materials should be used in each situation and how to order the materials needed. Proper material selection is necessary for components that are under load as the material selection changes materials' properties which include hardness, ductility, and strength limitations.

8. Analysis, Testing, and Evaluation

8.1. Analysis

8.1.1. Calculations

8.1.1.1. Subsystem 1: Package Release Mechanism

The calculations for this subsystem aimed at finding the range of motors that should be used, the maximum package weight under the worst-case scenario, as well as the time to deliver the package. The system is characterized in Figure 6.1 below.

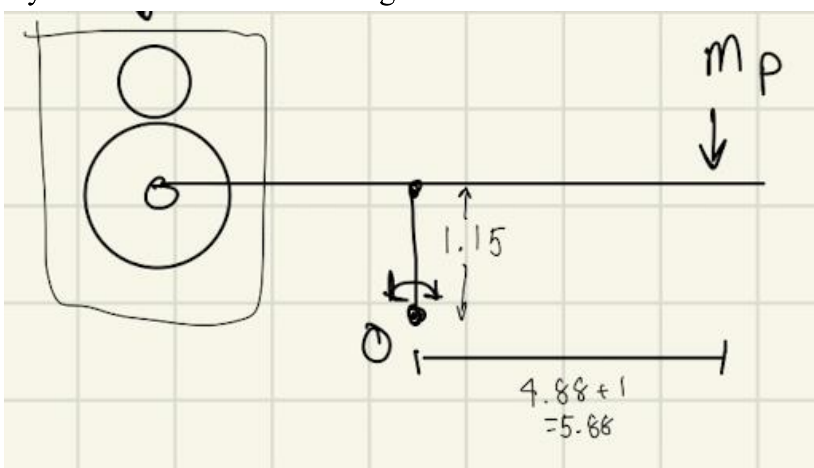

Figure 6.1 - PRM Torque system

Seen in the rectangle is the pinion on top driving the gear below which is on the same axis as the spool. The following equation is used to classify the gears in the box above:

$$GR = \frac{T_2}{T_1} = \frac{d_2}{d_1} = \frac{n_1}{n_2} = \frac{Output\ Torque}{Input\ Torque} \ (2)$$

Where T1 and T2 are 12 and 36 respectively, the GR = 3. Next to find the range of motor torque required, the sum of moments about point O was calculated, with mp = 5 lb (from our FRs).

$$\Sigma M_O = 0 = 1.15 * F_{cable} - 5.88 * m_p \ (3)$$

For the force in the cable produced by the motor and GR, the required force to suspend a 5 lb package is at least 25 lb. Using this value a motor with a torque of 84 lb/in was found to be sufficient. Using the same equations above, but now solving for mp, the max package weight is determined to be 6.6 lb. Next, the time to release the package is determined. The speed ratio between the spool and moment arm is 4.6 determined by the equation. A known spool speed of 3.3 rpm results at the moment arm turning at .724 rpm. In order to fully open the moment arm must rotate ¼ of a rotation. Unit conversion results in the arm rotating at 82 seconds/rotation, resulting in a time to open of 20.7 seconds.

8.1.1.2. Subsystem 2: Drone Dock

To calculate the torque required to push the drone using the alignment system, equation 10.4a for the torque required to move a load using a power screw was used. The load was the force of friction between a smooth sheet of plywood and the plastic feet that will be on the legs. The coefficient of friction between these surfaces is 0.4 [22]. Assuming that the drone weighs twenty pounds, the force of friction was calculated.

$$N = W = mg \rightarrow N = (20lbs \cdot \frac{1kg}{2.204lbs})(9.81\frac{m}{s})(\frac{1N}{1\frac{kg \cdot m}{s^2}}) \rightarrow N = 88.97N \quad (4)$$

$$F_f = \mu N \rightarrow F_f = (.4)(88.9N) \rightarrow F_f = 35.56N \quad (5)$$

Then equation 10.4a was applied. The friction and collar friction of the screw are equal and between steel and brass, $f = f_c = .015$ [23]. A lead screw assembly of the desired size that could be purchased was found and the dimensions of it were used for the mean diameter ($d_m = 22.5mm$), lead ($L = 8mm$), and collar diameter ($d_c = 22.5mm$). For ACME and metric precision lead screws, the lead angle (α_n) is roughly equal to zero. Plugging all these values into equation 10.4a:

$$T = \frac{Wd_m}{2}\frac{f\pi d_m + L\cos\alpha_n}{\pi d_m \cos\alpha_n - fL} + \frac{Wf_c d_c}{2} \quad [24]\ (6)$$

$$T = \frac{(35.56N)(8mm)}{2}\frac{(.015)(\pi)(8mm)cos(0) + (8mm)}{(\pi)(8mm)cos(0) - (.015)(8mm)} + \frac{(35.56N)(.015)(22.5mm)}{2}$$

$$T = 53.6Nmm$$

These calculations show that the required torque needed to overcome the force of friction between the drone and landing pad through the alignment mechanism is 53.6N*mm. The motors selected for the alignment mechanism must have a minimum torque greater than this value.

8.1.1.3. Subsystem 3: Charging Systems and Power Circuit

To calculate the capacity of the drone capacity, The single formula we use is:

$$time = capacity\ X\ discharge/AAD \quad [25]\ (7)$$

Time - Flight time of drone expressed in hours. We will use 5 min because the average drone flies at 45 mi/hr and the maximum length of flight is 2 mi.

Capacity – Capacity of your battery, expressed in milliamp hours (mAh) or amp hours (Ah). You can find this value printed on your LiPo battery. The higher the capacity, the more energy is stored in the battery

Discharge – Battery discharge that you allow during the flight. As LiPo batteries can be damaged if fully discharged, it's common practice never to discharge them by more than 80%.

AAD – Average amp draw of your drone, calculated in amperes. This can be calculated given the equation:

$$AAD = AUW \times \frac{P}{V} \quad (8)$$

AAD – Average amp draw, expressed in amperes.
AUW – All-up weight of the drone. Estimated to be 7 lbs.

P – Power required to lift one kilogram of equipment, expressed in watts per kilogram. Assume a conservative estimate of 170 W/kg. Some more efficient systems can take less, for example, 120 W/kg.

V – Battery voltage expressed in volts
This gives us:

$$AAD = 7lbs \times \frac{374.786lbs/W}{12V} = 249.86A$$

Rearranging and plugging into other equation:

$$Capacity = time \times \frac{AAD}{discharge}$$

$$Capacity = 5min \times \frac{249.86A}{60\%} = 4889\,mAh$$

A 5000mAh battery will be used to fly the drone.

8.1.2 Finite Element Analysis

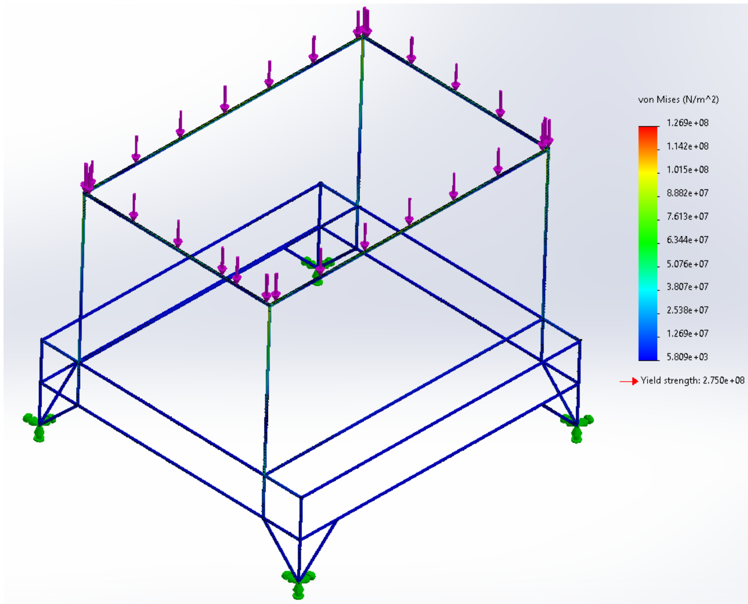

Figure 7.1 - FEA of PRM Frame

Figure 7.1 is based on an assumed drone load of 15 lbs. Additionally, this load is distributed equally across the top mounting location. Fixed geometry is used for the legs that make contact with the landing pad. This is based on the assumption that while secured, negligible slipping will occur at the base.

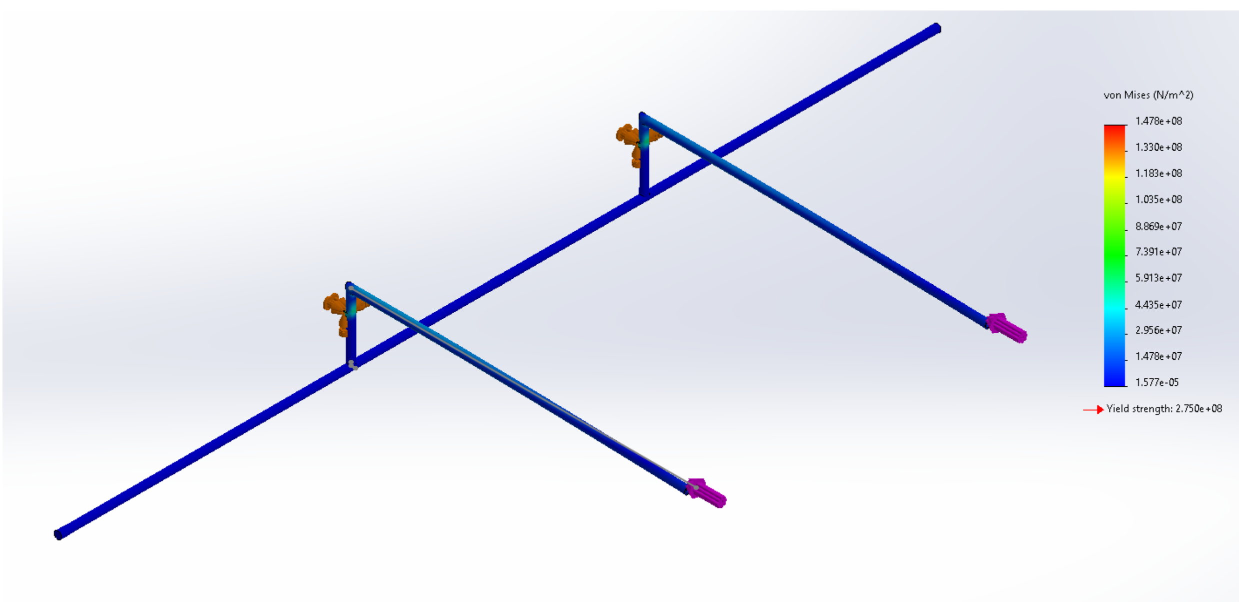

Figure 7.2 - Bay Door Frame/Hinge

This part was tested to ensure the frame which keeps the bay doors in the up, the closed position is capable of withstanding the forces needed to hold the package. The tension in the cable determined in section 7.1.1.1

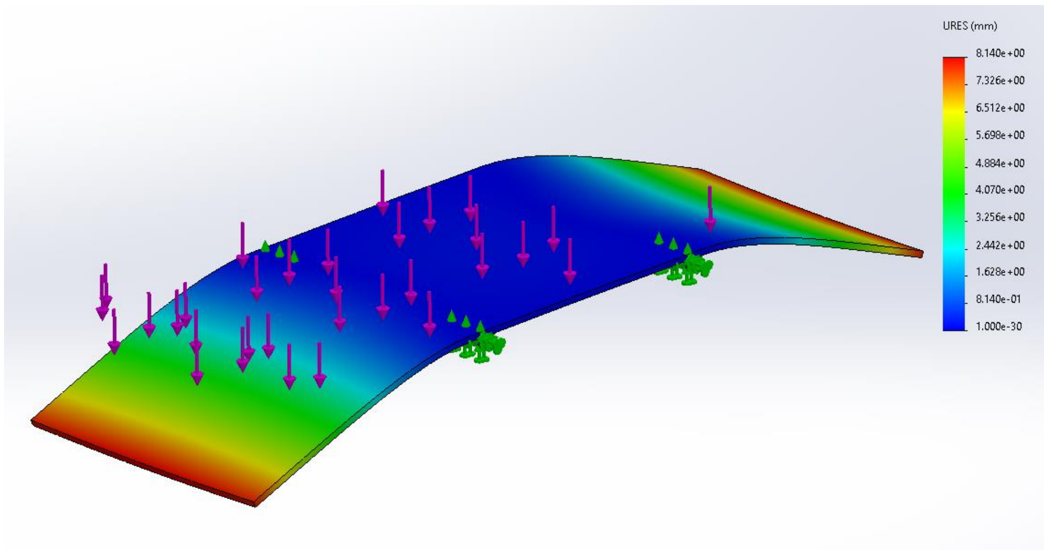

Figure 7.3 - Initial Package Platform Design

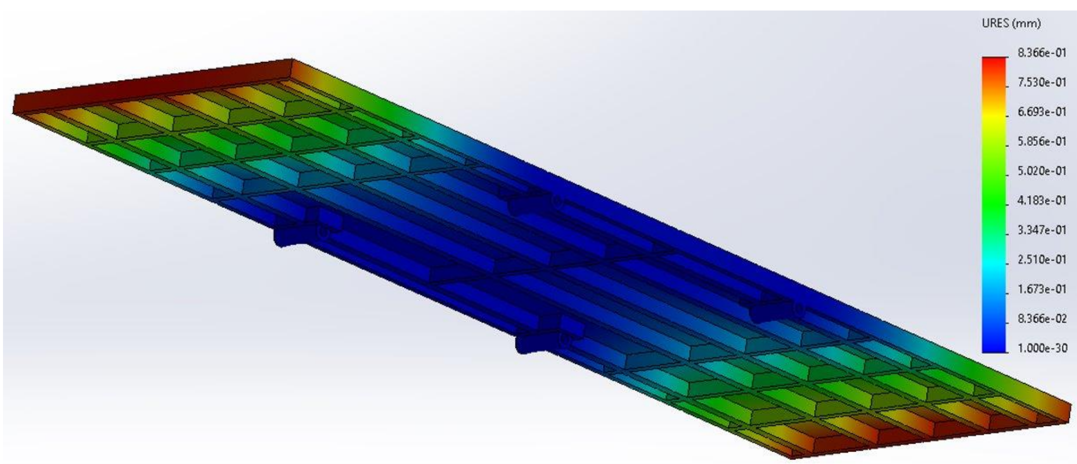

Figure 7.4 - Revised Package Platform

Unlike the frame and hinge from figures xx and xx, the initial package platform revealed issues. The initial platform thickness was too thin and resulted in an almost 1 cm deflection at the edges. Adding ribs beneath significantly reduced the max deflection to less than 1 mm while only adding 0.05 lb of material.

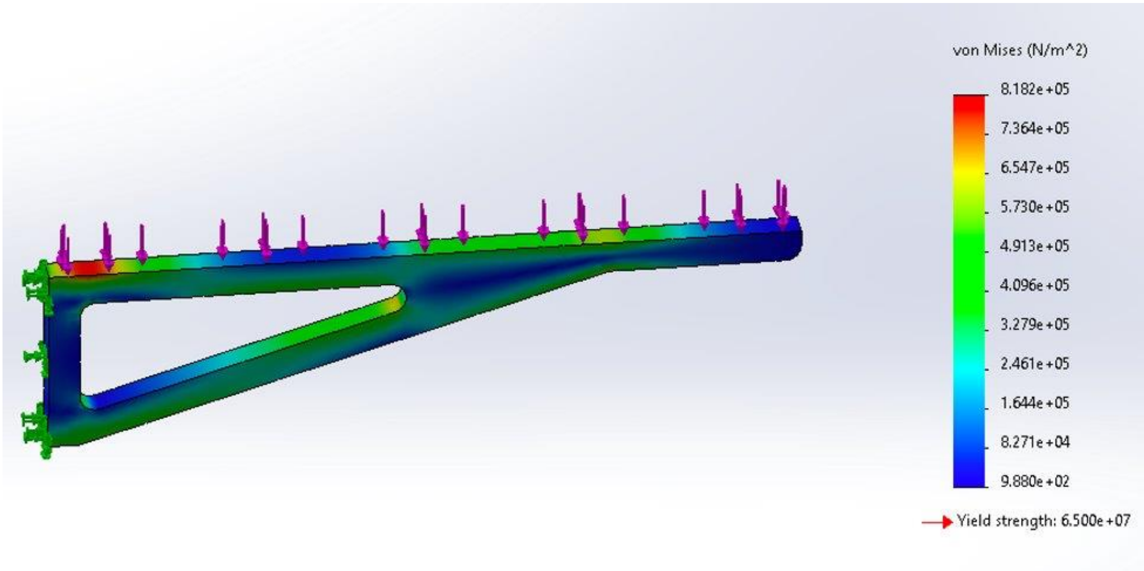

Figure 7.5 - Drone dock support bracket for implementation of the elevator system

The support bracket for integration of the drone platform into the elevator system was subject to FEA and it was found that the yield strength for the given geometry and material selection was well above the maximum von Mises stress value.

8.2. Testing Overview

Test	Subsystem	FR	Test Methodology	Status/Outcome
1	Drone Dock Structural Support	FR 2 — Drone Dock can hold 55 lbs	Add up to 55 lbs to dock Drop 55 lbs onto the dock	Success
2	Drone Dock Alignment Mechanism	FR 7 — Secure the Drone at the center of Dock	Place PRM on the center of the dock at varying angles, and check if the system is aligned Verify that the alignment mechanism prevents PRM from moving	Partial Success, Incomplete — broken electronics
3	Battery Charge and power supply Test	FR 6 -Can charge the drone at 60W FR 6 - Control the charge of the drone so it does not exceed 80%	Use a DMM to test if it charges and if the power supply is at correct voltage Plug in a battery to see if it stops at 80%	Success
4	CPU Cooling Test	FR 8 - Cannot exceed interior temperature of 50 Celsius	Put in warm area and see if it starts up	Success
5	Package Insertion	FR 1	13x10x10 in. box will be put into PRM to test for ease of fit	Success
6	Stress Tests A) Total Weight B) Under Load	FR 2, 6	A) PRM is weighed B) Weight is added incrementally up to 15 lbs. to top of PRM to simulate package and drone weight and evaluated for deformations	A)Success B)First test unsuccessful, after redesign – success
7	Package Platform Door Stress Eval	FR 3, 4	Weight is added incrementally up to 5lb to package platform to test gear lock	Unsuccessful - only able to hold 4 lb.
8	Motor Performance	FR 4	Motor will be evaluated in lifting package platform.	Success
9	Dock Elevator	FR 1 - Can support a load of 40lbs	Weigh the drone and drone dock platform before placing onto the elevator. Add weight	Success

			until the total load is 40 lbs.	
10	Dock Elevator	FR 2 - Elevator Can Lift 36 Inches	Measure the total displacement of the drone dock from the bottom to the top of the elevator.	Unsuccessful - Only able to lift 32 inches
11	Dock Elevator	FR 3 - Can Lift the Drone Dock in 10 Seconds or Less	Using a stopwatch, time how long the elevator takes to travel from bottom to top.	Success

Table 8.2 - Overview of Testing and Evaluation Table

8.3. Dock Structural Support Test

The drone dock needed to be able to hold 55 lbs of weight to fulfill the second functional requirement. Not only must it be able to withstand a normal load, but a shock load of this weight as well in the event of a bad drone landing. This required two tests to verify the strength of the dock itself.

The first test was a normal load of 55 lbs on the dock. With the dock on the floor, weight was placed in increments of 10 lbs onto the dock until 50 lbs was reached, and then a final weight of 5 lbs was added. The dock held this weight with no issue. The team was confident at this point that one of the group members could stand on the dock with no issue due to it being constructed out of wood. One of the group members weighing roughly 200 lbs stood on the dock with no issue. The dock greatly surpassed the required weight it needed to hold.

The second test was a shock load of 55 lbs. In order to test for this, 55 lbs of weight would be dropped onto the dock from 6 in off the surface of the landing pad. A height of 6 in was chosen since this is likely the worst landing scenario for a drone. With the dock placid on the floor, the weight was raised to roughly 6 in using a ruler and dropped. The dock showed no signs of damage after this test was repeated five times, allowing us to conclude this test as a success.

8.4. Dock Alignment Test

The alignment mechanism needed to be able to align and secure the PRM at the center of the dock. Unfortunately, issues with the electronics circuit have left the testing for this portion incomplete. Due to the unexpected short circuit of a component during assembly, the alignment system was not able to be tested with the PRM. Before shorting the electronics, the alignment mechanism did work as intended, the alignment bars did move as desired.

Despite the issues with the electronics, the system was able to be controlled manually by twisting the lead screws of each of the alignment mechanisms. This allowed the team to test the securement aspect of the system. The PRM was placed in the center of the dock, and the alignment mechanism was manually closed around it. The feet of the PRM align under two of the alignment bars, preventing it from being lifted. The alignment bars constrain the movement of the PRM around the landing pad. The PRM was unable to be lifted or moved around when the alignment mechanism was closed, so we determined this part of the test to be a success.

8.5. Battery Charge and Power Supply Test

To test the power supply and the charge controller, a DMM was used to measure the voltage across the positive and negative terminals of the power supply and the charge controller. Using the resistance, the total power used was found to be about 60W using Ohm's Law and the power law. It was determined that the power supply was going to work and supply enough power to the circuit.

To test if it will stop at 80%, the transformer to step down the 12V to 5V 3A was plugged directly into the charge controller and was then plugged into a computer to see if the charger will stop when it hits the set amount (80%). The charge controller was able to stop charging the computer at 80%.

The power supply was plugged into all of the components and was turned on with no issues. However, after two weeks of using it to code the Raspberry PI and controller, it shorted. The reason has been identified. On the charge controller, there is a chip numbered TB6612FNG which is fried. The chip uses voltage from both the raspberry pi and the power supply to power the motors. When testing the Raspberry PI, the motor controllers, and the power supply the only damage that was done was to this singular chip. There could be only two possible shorts in this case, the motor controller or the Raspberry PI. Because the Raspberry PI did not show any damage and worked fine when connected to a power source, it was wrongly determined that the motor controller was the shorted component. It was later determined that the Raspberry PI was drawing too much power leading to the chip and the transformer burning up.

8.6. CPU Cooling Test

The CPU cooler was attached to the power supply on a black table in the sun with a fan. The cooler was left for a few minutes alone in the sun to heat up and then was plugged in. The cooler came on immediately and started the fan to spin at a high speed. The cooling controller was then set on a desk with a large fan blowing on it to make it as cool as possible. It was once again turned on and did not start spinning the fan because it was too cold. The test was a success.

8.7. Package Release Mechanism Test

The stress tests revealed mixed results. After the first round of testing, the frame was only able to hold 7 lb until deflection began. As a result, additional support struts were included on two sides of the frame. This modification allowed the frame to easily support 15 lb.

With regard to the evaluation of the bay doors, only 4 lb could be reliably supported. This test failed due to the fixture point between the main driven gear and the bay door support frame.

8.8. Dock Elevator Test

The dock elevator succeeded in satisfying two of its three functional requirements. The elevator was able to hold the weight of the drone dock and the package release mechanism. The functional requirement is satisfied if the elevator can support 40 lbs which it surpassed and the test was concluded at a load of 50 lbs, 10 pounds over the requirement. The combined weight of the drone dock and PRM came to be 35 lbs and 15 pounds of metal were added onto the center of the drone dock to bring the testing total to 50 lbs.

The second functional requirement was unsuccessful as the drone dock could only lift the drone dock 32 inches instead of the desired 36 inches. The linear slide rails are 39 inches long, long enough to satisfy the requirement, however, the space occupied by the drone dock support brackets was not accounted for during the initial design which occupies 7 inches of the linear slide rails. If the drone dock support bracket's edges were shortened to a length of 3 inches, the elevator would be able to travel the full 36 inches, however, the impingement and moment forces between the support brackets and the linear slide rails would be too great, resulting in material fracture.

9. Budget

This project included $250 per group member for the year – $1000 for the entire project. The majority of parts were purchased at the end of the fall semester. The total spent in Appendix D amounted to $828.28. However, this did not include shipping costs.

10. Summary and Recommendations

Overall, the Last Mile Package Delivery prototype was a success. There were a few shortcomings, as some of the functional requirements were not met and electrical components burned out, however, the main functions of each subsystem were successfully operational or at one point operational. The prototype was a culmination of all we have learned over our collegiate career as it combined aspects of mechanical, electrical, and computer engineering. The project was an excellent learning experience and, in the end, our mentor and sponsor from MITRE was very pleased by what we had accomplished over the past year.

Our recommendations for future engineers who decide to add to our project or create something similar is to generate designs early, consult with experts within the GWU engineering department, and order multiples of components you believe are in danger of breaking and burning out. In terms of recommendations for advancing the project, automation is needed to refine the system. Ideally, each subsystem would be actuated via a single input signal, minimizing the driver interaction and increasing the efficiency of the system. Also, fabricating the drone and drone navigation system is essential for the Last Mile Package Delivery prototype to be in use making the drone another great next step for the project.

11. Acknowledgments

The team would like to thank Dave Maroney and Mitre Corporation for their sponsorship and guidance on this project, as well as a special thank you to Professor Mitch Narins and Professor Peng Wei of The George Washington University SEAS Mechanical and Aerospace Engineering department for their assistance throughout the project. We would also like to extend gratitude to Professor Steven Shooter, Duncan Frazier, and the rest of the capstone class professors and teaching assistants. The team would also like to acknowledge the GW SEAS Machine Shop for all the help in manufacturing the project, it could not have been done without them.

12. Appendices

12.1. Appendices A: Standards Table

Table 11.1: Applicable Standards	
Standard	Rationale
[1] FAA Part 107 – Small Unmanned Aircraft Systems https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107	Outlines regulations for small unmanned aircraft system within visual line of sight. Our system will eventually fly beyond the line of sight, but our testing will be done within the line of sight, so we must follow the regulations of part 107 during our testing. The most notable system parameter to come out of this regulation is that our UAS must weigh less than 55 pounds on takeoff, so we must design our drone with this in mind. Package delivery under part 107 may be permitted in special cases by the FAA, but beyond line-of-sight package delivery operations are largely certified through part 135.
[2] ASTM B221-21: Standard specification for aluminum and aluminum-alloy bars, rods, wire, profiles, and tubes. https://tajhizkala.ir/doc/ASTM/B221.pdf	This standard covers all specifications for aluminum and aluminum-alloys such as tensile and yield strength. In order to design a product that will be durable we need to determine if it will break. Since we plan to use aluminum for the metal components of the system, we need to know the material characteristics of these metals.
[3] Federal Motor Carrier Safety Administration (FMCSA): https://www.fmcsa.dot.gov/regulations/cargo-securement/cargo-securement-rules	This standard may apply to our drone alignment, charging, and elevator system. While charging, the drone must be held securely in place under these loads. This regulation is applicable to commercial motor vehicles (as defined in 49 CFR 390.5) weighing more than 10,000 lbs. A typical step van exceeds this limit.
[4] National Electrical Manufacturers Association (NEMA) MG 1-2021: NEMA 17 Stepper Motors https://www.nema.org/standards/view/motors-and-generators	NEMA 17 motors have a 1.7in x 1.7in face plate and have a 1.8-degree step angle (200 steps/revolution). These motors give us a great amount of precision when it comes to aligning our drone on our dock. Compared to other NEMA motors, these ones are small which gives us more flexibility in our design. NEMA 17 motors are relatively inexpensive and can be purchased in different torque variations, as well as different wiring connections. These attributes make these motors a suitable choice for our design
[5] Institute of Electrical and Electronics Engineers (IEEE) Payload Devises in Drones: https://drive.google.com/file/d/1YYadlP7vmjwcewB99Yg31ivFopdx5RJZ/view?usp=sharing	This goes over the standards for having a payload attached to a UAV system. It goes over the types of different payloads and goes through the requirements for each type of payload. For our purposes, we will look at section 6.1: General Requirements, section 6.2: Mechanical Interface, and section 6.3: electrical interfaces
[6] ASME PTB-8: Procurement Guidelines for Metallic Materials https://www.asme.org/codes-standards/find-codes-standards/ptb-8-procurement-guidelines-metallic-materials/2014/drm-enabled-pdf	This goes over the processes for evaluating material specifications for metals. It discusses challenges certain materials may encounter and also how to procure the materials. This is important for our design because aluminum will be integral to the structure of our prototype. Aluminum type and how its material specifications differ will be important for the stress analysis of our systems.
[7] ASME Y14.5: Dimensioning and Tolerancing https://www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing/2018/print-book	ASME has devised standards regarding GD&T. Dimensioning and tolerancing is important for our design as it ensures clear communication between the project group and the machine shop.

	This will reduce errors in manufacturing and decrease lead time.

Table 11.2: Non-Applicable Standards	
Standard	Rationale
[8] FAA Part 135 – Commuter and on-Demand Operations https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-135	This is the certification process that allows drones to deliver small packages beyond visual sight. It is a 5-phase certification process and has 4 types of certifications. Part 135 is a difficult process and was awarded for the first time in April 2019 to Wing Aviation, LLC for delivering medical supplies. In order to implement our system commercially, our UAS will have to be certified with this process.
[9] U.S. General Services Administration (GSA) SIN 492110: Domestic delivery services for express small package and heavyweight shipments to assist the Government in meeting its delivery needs.	This regulation provides standards on delivery services. However, it will only be relevant to our project as a contractor to the federal government.
[10] ISO/DIS 5110 Test method for flight stability of multi-copter UAS under wind and rain conditions https://www.iso.org/standard/80802.html?browse=tc	This regulation provides standards for testing the flight of a UAV in bad weather conditions. We will not be using this standard because flying outside of near perfect conditions is outside of our scope.

12.2. Appendix B: Equations

#	Description	Equations	Variables
1	Ohm's Law	P = IV	P = Power I = Inductance (A) V = Voltage (V)
2	Gear Ratio	$GR = \frac{T_2}{T_1} = \frac{d_2}{d_1} = \frac{n_1}{n_2} = \frac{Output\ Torque}{Input\ Torque}$	T = # of Gear teeth d = diameter n = rpm 1,2 = input, output
3	Sum of Moments	$\Sigma M_O = 0 = 1.15 * F_{cable} - 5.88 * m_p$	F = force m = mass
4	Force eq.	$N = W = mg \rightarrow N$	N = newtons W = Weight m = mass g = gravity
5	Friction Force	$F_f = \mu N \rightarrow F_f$	μ = coefficient of friction N = normal force
6	Lead Screw Torque	$T = \frac{Wd_m}{2} \frac{f\pi d_m + L\cos\alpha_n}{\pi d_m \cos\alpha_n - fL} + \frac{Wf_c d_c}{2}$	W = weight d = diameter f = friction force L = lead screw length α = lead angle
7	Batter flight time	$time = capacity\ X\ discharge/AAD$	Capacity = battery cap. (mAh) Discharge = total discharge of flight AAD = average amp draw
8	AAD	$AAD = AUW \times \frac{P}{V}$	AUW = All Up weight P = power V = voltage
9	Torque	$\tau = F \times R$	F = Force R = radius

12.3. Appendix C: CAD Drawings

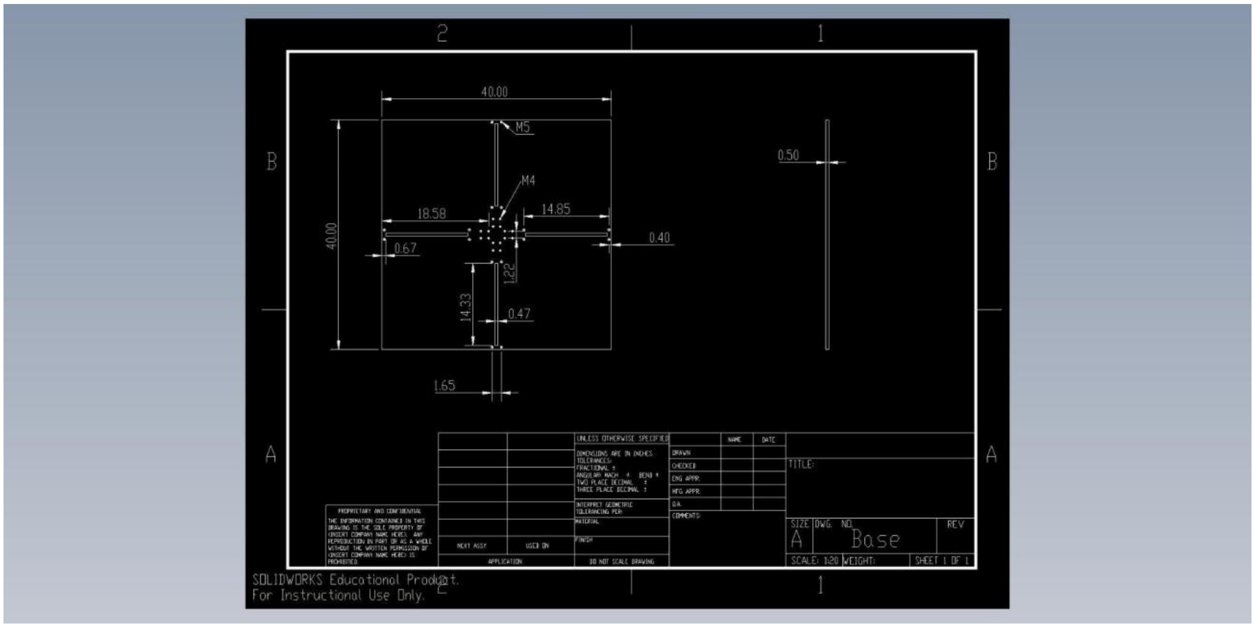

Figure C.1 - Landing Pad Drawing

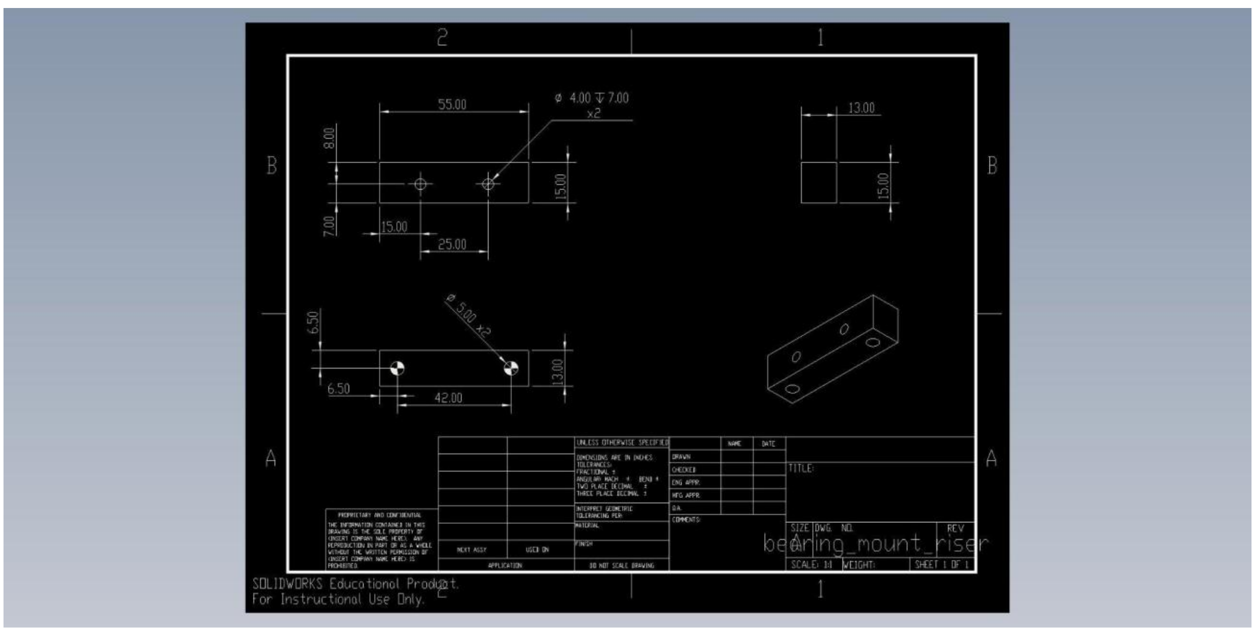

Figure C.2 - Bearing Riser

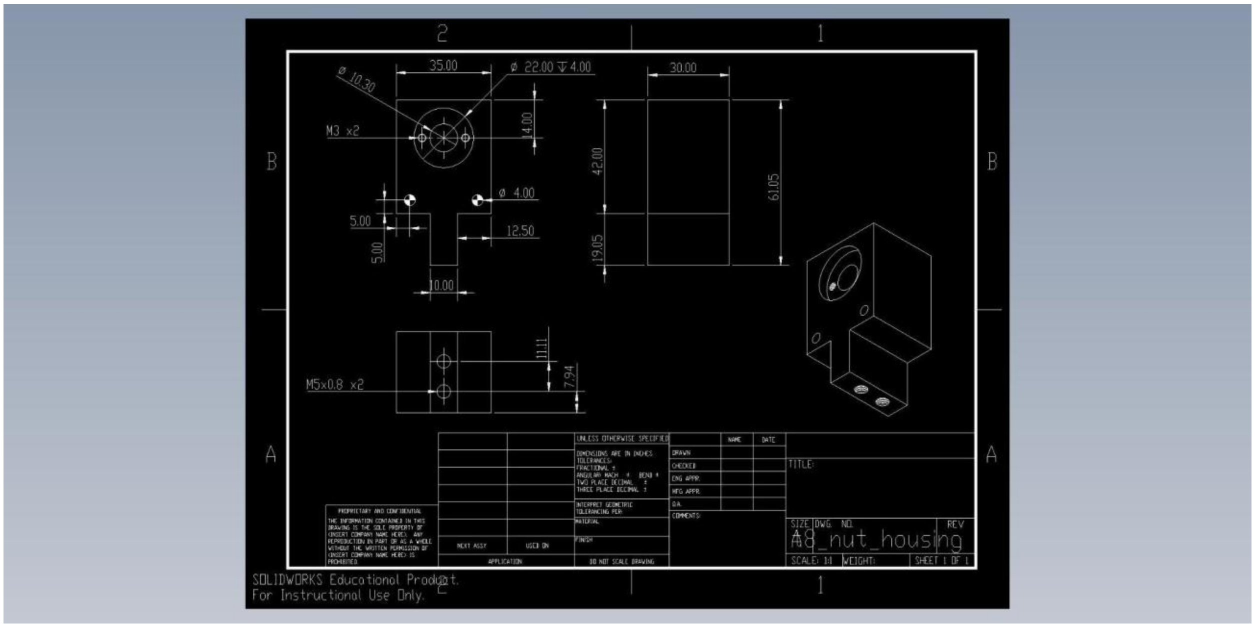

Figure C.3 - Nut Screw Housing

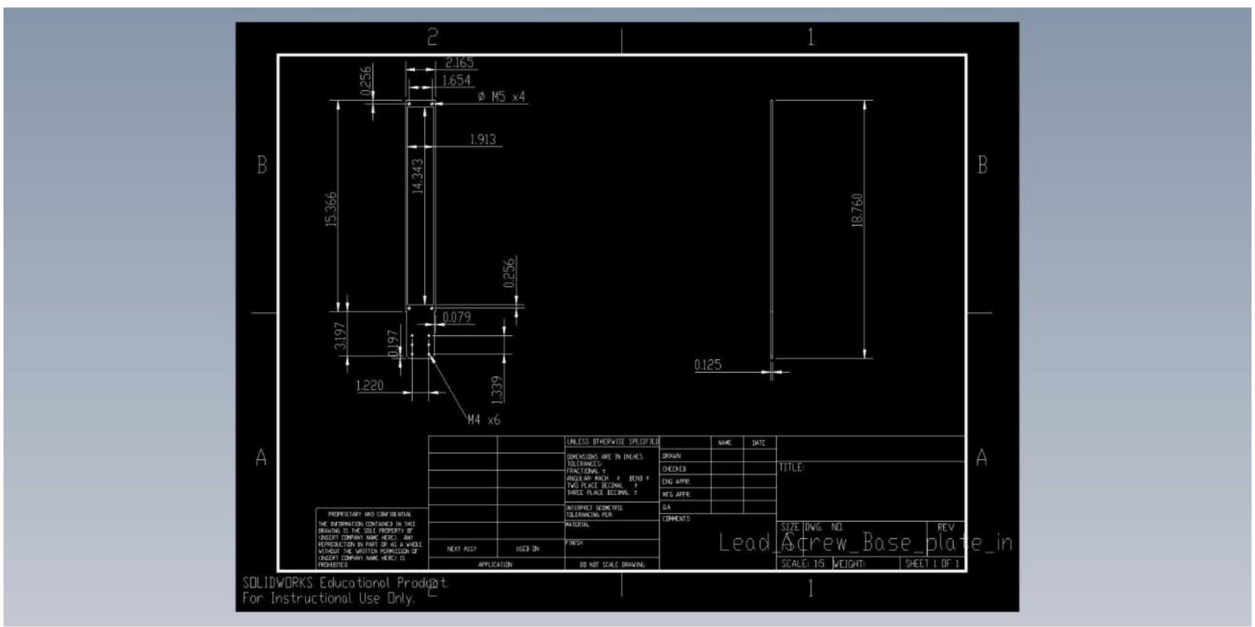

Figure C.4 - Lead Screw Base Plate

12.4. Appendix D: Budget Spreadsheet

Part Name	Part #	Supplier	Link	Quantity	Cost Per Piece	Total Cost	Notes
Drone Dock							
18-Gauge Wire	1	Amazon	https	1	9.16	$ 9.16	
Motor Controllor	2	ADAfruit	https	0	22.5	$ -	Hold Off
Stacking headers	3	ADAfruit	https	2	1.25	$ 2.50	
Transformer	4	Amazon	https	1	11.99	$ 11.99	
Power Supply	5	Amazon	https	1	21.91	$ 21.91	
Plug	6	Amazon	https	1	2.83	$ 2.83	
Battery Charge Controllor	7	Amazon	https	1	18.99	$ 18.99	
Cooling controllor	8	Amazon	https	1	11.58	$ 11.58	
Fans	9	Amazon	https	1	10.99	$ 10.99	
Nema 17 Motor Mount (6 pack)	10	Amazon	https	1	16.99	$ 16.99	
Nema 17 Motors (5 pack)	11	Amazon	https	1	55	$ 55.00	
Lead Screw Assembly	12	Amazon	https	4	12.99	$ 51.96	
4mm x 400mm Shafts (10 pack)	13	Amazon	https	1	13.99	$ 13.99	
M5 Flat Head Screw (50 pack)	14	McMaste	https	1	14.4	$ 14.40	
M5 Hex Nut (100 pack)	15	McMaste	https	1	4.05	$ 4.05	
M4 Flat Head Screw (100 pack)	16	McMaste	https	1	10.91	$ 10.91	
M4 Hex Nut (100 pack)	17	McMaste	https	1	3.33	$ 3.33	
48in x 48in x1/2in Plywood Sheet	18	McMaste	https	1	30.75	$ 30.75	
Aluminum 90 Degree Angle	20	McMaste	https	2	12	$ 24.00	
T8 Nut Block	21	Machine Shop		4	0	$ -	speak to machine shop
Bearing Risers	22	Machine Shop		8	0	$ -	speak to machine shop
Lead Screw Assembly Mounting Plate	23	Machine Shop		4	0	$ -	speak to machine shop
Alignment Bar Riser	24	Machine Shop		2	0	$ -	speak to machine shop
Stepper Motor drivers	25	Pololu	https	5	12.95	$ -	Hold Off
Release Mechanism:					Total	$ 315.33	
Frame -	26	McMaste	https	5	4.09	$ 20.45	(1/8" diameter - 6 ft length) part ID: 8974K19
Motors	27	Amazon	https	2	14.99	$ 29.98	
Cable	28	Amazon	https	1	8.49	$ 8.49	
Plastic sheeting	29	3D-print		1	0	$ -	
Gear and Pinion	30	3D-print		1	0	$ -	
Spool + caps	31	3D-print		1	0	$ -	
Package door	32	3D-print		2	0	$ -	
Frame fixtures	33	3D-print		x		$ -	CAD
Bay door plate	34	3D-print		2	0	$ -	
Landing caps	35	3D-print		4	0	$ -	CAD
Dock Elevator					Total	$ 58.92	
Linear Slide Rails	31	Amazon	https	1	46	$ 46.00	
Winch	32	Toolshou	https	1	56.7	$ 56.70	
Pulley	33	Amazon	https	1	15.95	$ 15.95	
Plywood	34	McMaste	https	1	44.8	$ 44.80	
					Total	$ 163.45	
Spring Orders:							
Chipwood sheets	35		https	1	$5.00	$5.00	
Arduino Uno Rev3	36		https	1	$27.60	$27.60	
USB 2.0 Cable Type A/B	37		https	1	$7.60	$7.60	
Linear actuators	38		https	2	$28.99	$57.98	
L293D Motor Controller	39		https	1	8.99	$8.99	
Motor Controllor	40		https	3	26.09	$52.18	
Motors	41		https	4	$14.00	$56.00	
2x4 Wood	42		home depot				
					Total	$ 215.35	
					Overall total	$ 753.05	
					10% tax	$ 828.36	

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