

Design and Control of a Translating Drum Spooling System for Gravity Batteries:
A Collaboration with Renewell



by

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ABSTRACT

Climate change and ensuring a clean, long term energy supply are two of the most pressing challenges faced by society. In order to shift to a sustainable energy supply, energy storage technologies must be prioritized and innovated. Renewell Energy proposes a solution of repurposing abandoned oil wells into gravity batteries, which serve as energy storage systems. Renewell operates by using excess clean energy to drive a motor that lifts a heavy weight. When there is energy demand that outpaces supply, Renewell returns energy to the electric grid by lowering the weight and converting the gravitational potential energy into electricity. Renewell's present winching system— responsible for spooling and unspooling cable to lift and lower the weight— incurs a lot of wear and cost to Renewell's technology. High costs and excessive cable wear prevent Renewell from becoming a viable long-term energy storage solution since energy storage requires longevity in order to become profitable. Our project reimagines cable spooling to reduce wear on the rope— thereby increasing its longevity— and reducing the infrastructure footprint and cost. In contrast to traditional industrial spooling which bends a rope onto a winding drum from a distance, we translate the drum itself in order to accomplish neat, controlled spooling. To test this system, we scoped the infrastructure for a loaded full-scale winch, we prototyped a scale model to test spooling across a translating drum, and we designed a feedback control system to meet the required precision for cable spooling. To quantify the performance of our winching system, we conducted spooling tests and used a number of measurements to verify our system's precision using image analysis, encoder readings, and spooling time. From our $\frac{1}{8}$ scale model we determined that we achieve the necessary precision for neat cable spooling, with even greater promise on a full scale system, since the acceptable margin of error grows with larger cable dimensions. The implications include an estimated \$70,000 in cost savings. In the future, this system would benefit from testing in a full scale or loaded configuration, to uncover any complicating dynamics of spooling large, tensioned cable. Further fine tuning of the controls during motor accelerations can help reduce the error in position to further reduce cable wear. In total, we successfully de-risked an innovative spooling method for Renewell's Gravity Wells, with significant improvements to the cost and efficiency of their system. This innovation is an important step in energy storage systems for a greener, climate-conscious future.

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1. Introduction

Halting climate change and mitigating the effects of global warming is one of society's most pressing challenges due to its widespread impact on the environment and habitability of our earth. The transition to renewable energy sources is paramount in combating climate change and reducing the emission of greenhouse gases into the atmosphere [1]. With the rise of intermittent renewable energy (wind, solar, etc), there is an increased demand for energy storage solutions. In order to compete with on-demand, pollutive fossil fuels, renewable energy sources need a means to store excess potential during windows of energy generation, and release energy from storage back to the electrical grid when electricity is not being generated.

Renewell Energy offers a creative solution to energy storage, by repurposing inactive, abandoned oil wells into novel gravity batteries. Gravity batteries store energy by converting electrical energy to gravitational potential energy by raising a heavy weight. It then releases energy back to the grid by lowering the weight. Renewell's technology uses the long vertical spaces in oil wells, which can help remediate and cap the estimated 2.6+ million orphaned oil wells in the US and Canada, which leak 11MT of CO₂e of methane into the atmosphere annually [2]. This approach provides purpose and value to abandoned well sites, and reduces environmental harm by cutting emissions from wells and promoting clean energy generation. In order to become a competitive energy storage solution, Renewell needs to significantly reduce their costs (Appendix 8.14) and ensure that their winching system is reliable over decades of cyclic operation.

The scope of our work is to extend the lifespan of the steel cable and reduce system costs by redesigning the spooling system. Given the slim profit margins found in energy storage, reducing costs is critical in order to ensure Gravity Well operation can pay back the initial investment costs. Additionally, over the course of operation, Renewell projects that over 50% of their operation and maintenance expenses will come from replacing and inspecting the cable [3]. The current winching solution does not minimize cable wear, and requires expensive infrastructures in order to spool cable neatly and consistently. The limitations of the current winching system on cable longevity are clear, as a cable broke within the first 3 months of operation. This failure destroyed the remediation of the well, and made the site inoperable. Therefore, the need for an inexpensive winch with minimal cable wear is necessary to improve the commercial viability of Renewell's Gravity Wells. Our proposed solution will eliminate the severe sites of cable wear in order to increase the cable lifespan and spool neatly.

2. Background

2.1. Problem Background

Renewell's Gravity Wells store gravitational potential energy by lifting a weight in a well and lowering it to release electricity to the grid during times of energy demand. The winching system is responsible for the spooling of cable as the weight raises and lowers. Shown below in Figure 1 is the winching system, which spools cable on a drum after pulling it over the fleet angle tower.

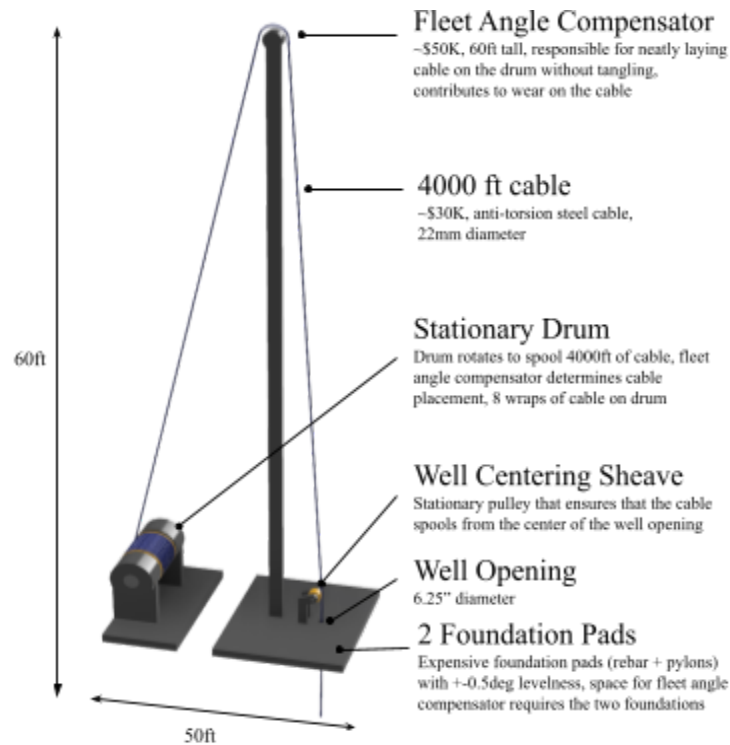


Figure 1. Schematic of Renewell's current system layout

Renewell's existing gravity battery has an inefficient use of land space and high installation costs. Further, there are multiple sources of wear to the cable that increase risk of failures and replacement costs. The inefficient use of space is due to the fleet angle (Appendix 8.11) requirement between the cable position and the centerline of the spooling drum. This angle must be $\leq 1.5^\circ$ in order to prevent tangling and chaotic spooling [4]. Therefore, in order to achieve neat spooling and accommodate 8 layers of cable while maintaining the fleet angle requirement, the drum must be located 80 feet away from the fleet angle compensator. This extends the required land area of the system, incurring cost. Additionally, the fleet angle compensator is expensive and bends the cable, increasing bending stress and wear volume. The fleet angle tower also necessitates a second concrete foundation pad, adding cost to the system.

Renewell uses a steel anti-torsion cable to lift and lower its weight. The cable is constructed by twisting together several strands of wire, which are then wrapped around a core to create the cable.

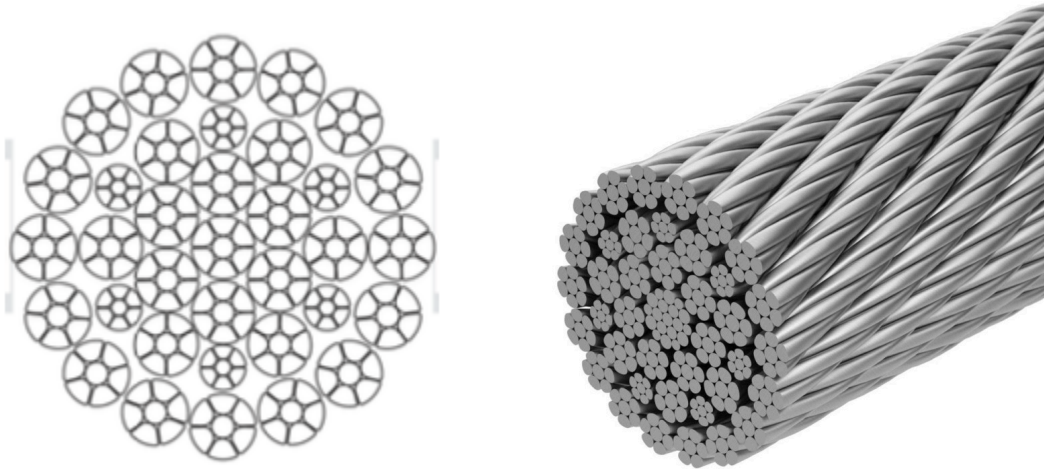


Figure 2. Cross section view (left) and perspective view (right) of the steel anti-torsion cable used in Renewell's Gravity Well.

As the cable is spooled in the winching system, two significant concerns are fretting and fatigue, both of which can result in failures by cable breaking. Fretting occurs when wire cables contact surfaces under load and rub together with friction. These forces create movements within the wire strands which can cause small, individual wires to break. These small breaks weaken the cable and can cause the cable to fail. Increased contact forces, high friction coefficients, and long distances of contact amplify fretting risk in the cable. These risks are present in the current system through bending around the fleet angle tower, over the control sheave, and against the floating sheave.

Additionally, the cable can fatigue over time with multiple cycles of lifting and lowering the weight. Repeated bending stress from routing around sheaves and the fleet angle tower introduce fatigue cracks, which can proliferate throughout the cable under cycles of wear and bending. In the current system, the most significant bend before spooling is around the fleet angle tower. This can significantly shorten the life expectancy of the cable and cause breaks.

An additional source of fretting and cable wear is the placement of cable on the drum. If the cable is not accurately spooled, the cable will rub together on the drum if it is placed too close together and overlap the previous cable. If the wraps are too far apart, this can create a groove that the subsequent cable layer will fall into, which will also incur wear by rubbing and create potential tangling problems when un-wincing.

2.2. User Research & Requirements

2.2.1 User Identification

The primary user of our project is Renewell, an early-stage startup based in Bakersfield, California. Renewell focuses on repurposing inactive oil wells by converting them into renewable energy storage systems using their patented Gravity Well technology. This system leverages existing well infrastructure—including the wellbore’s vertical drop, electrical components from pumpjacks, and established communication networks—to provide a low-cost energy storage solution. Renewell owns and operates these systems, handling both installation and annual maintenance.

Currently, Renewell's Gravity Well system operates on tight profit margins, generating approximately \$10.80 per day under an assumed 80% efficiency and an electricity sale price of \$0.30 per kilowatt-hour [5]. To become economically viable, Renewell must significantly reduce installation costs and minimize system failures, as any breakdowns result in expensive repairs and potential environmental hazards.

Through discussions with Aaron Munoz, Lead Mechatronics Engineer at Renewell Energy, we identified a key opportunity to lower costs: extending the lifespan of the steel cable that connects the 30,000-lb weight to the winch. The current cable has a diameter of 0.866 inches (2.2 cm) and costs \$30,470 for a 5,000-ft length. Cable failures—such as breakage—necessitate full well remediation and complete cable replacement, both of which impose significant financial burdens.

While Renewell has explored solutions like cable lubrication, the most cost-effective approach is to remove the fleet angle compensator. Eliminating this severe bend would reduce stress on the cable, prolong its lifespan, and decrease failure risks, ultimately improving the system’s overall cost-efficiency.

2.2.2 User and Engineering Requirements

Our user requirements align with Renewell’s key objectives: minimize cost and maximize energy efficiency. Since the cable is a significant cost, the new winch system should be designed to maximize the cable’s longevity in order to reduce risk of cables breaking or needing replacement.

Additionally, to function as a competitive gravity battery, the winch should spool within energy production times. Since periods of production are often based upon environmental conditions, we will ensure the winch spools during these periods to optimize energy storage. Similarly, our system should improve the efficiency of the winching motor such that charging the battery while spooling the cable does not incur significant energy losses.

We determined technical engineering requirements that would measure the success of meeting our defined user requirements. Here we discuss the high priority engineering requirements that we intend to fulfill with our prototype in ME170B. The full table of user and engineering requirements is included in the appendix.

The winch must be able to operate without incurring significant wear to the cable, since replacing the cable incurs absorbent expense, defined in UR1-1. To satisfy UR1-1, we defined three engineering requirements related to reducing bends, ensuring neat spooling, and reducing cable self-contact. To reduce bends that contribute to cable fatigue, we defined ER1-1a so that the maximum bending angle before spooling is $<10^\circ$. To ensure neat spooling, we defined ER1-1b, stating the fleet angle should be $<0.1^\circ$. The fleet angle exists when there is a discrepancy between where the cable is and should be placed on the drum, and thus is a measurement of how neatly spooled the cable is. To reduce cable wear on the drum, ER1-1c requires that the gap between cables placed on the drum should not exceed $1/10$ of the cable diameter. This consistent cable gap ensures neat spooling and reduces wear from cable rubbing on adjacent wraps.

UR2-1 addresses the viability of Renewell’s gravity battery in the context of energy production, stating that the drum should be able to spool and unspool in energy production windows. For this requirement, ER2-1 defines that spooling time should be ≤ 1 hour. The 1 hour spooling target matches Renewell’s current system that allows for flexible storage while renewable energy sources are producing in excess. This engineering requirement guides the drum dimensions of the final system.

Our final high priority user requirement is improving the efficiency of the winch motor (UR2-2). This can be accomplished by decreasing the torque from winding the drum. Currently, Renewell spools 8 layers of cable, with each layer adding 0.866 inches– the cable diameter– to the radius. Each additional wrap layer increases the effective drum diameter and consequently increases torque demands on the winch motor. Renewell has identified that reducing the number of wraps to 4 layers would provide an acceptable trade-off between the increased land area required by a longer drum and the decreased torque variability on the motor. Therefore ER2-2 specifies that our drum design should reduce the number of cable wraps from 8 to 4 while maintaining the capacity to spool 4,000 ft of cable.

Table 1 below summarizes the high priority engineering and user requirements that will guide the development of our solution.

Table 1. High Priority User and Engineering Requirements

User Requirements		Engineering Requirements	
UR1-1	Maximize cable longevity	ER1-1a	Prior to spooling, the maximum bending

			angle in the system layout is $<10^\circ$.
		ER1-1b	Our translating system should maintain a fleet angle of $<0.1^\circ$ between the drum and sheave.
		ER1-1c	A gap of a 1/10 the cable's diameter should be maintained between each cable line on the drum [6].
UR2-1	Spools during energy production window	ER2-1	Spooling time should be ≤ 1 hr
UR2-2	Improve efficiency of the winch motor	ER2-2	Reduce the number of cable wraps on the drum from 8 to 4 wraps (8.15)

2.3. Ethical Considerations

Renewell's ability to provide clean energy storage and well remediation hinges on the economic viability of their Gravity Well system. Without a cost-effective approach, this innovative solution cannot be successfully implemented at scale, limiting its potential impact in reducing reliance on fossil fuel-based energy storage and capping methane-emitting wells. As such, our project is not only an engineering challenge but also an opportunity to contribute to a sustainable energy future.

Our work aligns closely with the American Society of Mechanical Engineers (ASME) Code of Ethics, particularly the canon that engineers must consider environmental impact and sustainable development in their professional duties [7]. The Gravity Well system directly addresses environmental concerns by converting idle oil wells into carbon-free energy storage, reducing methane emissions from abandoned wells, and promoting the reutilization of existing infrastructure instead of building new facilities. However, for this environmental benefit to be realized, our engineering solutions must ensure that the system remains operational without causing additional environmental harm.

One of the greatest risks in the system is winch cable failure, which can lead to severe financial and environmental consequences. A snapped cable may damage well infrastructure, disrupt operations, and in extreme cases, result in debris contamination within the wellbore, necessitating costly remediation. Additionally, if the winch malfunctions due to cable failure, the entire energy storage mechanism is compromised, leading to potential energy losses and higher repair costs that reduce Renewell's economic feasibility. Thus, addressing the key failure mode

of the cable breaking is essential not just from a technical standpoint but also as a preventative measure against environmental damage.

Beyond environmental concerns, human safety is a paramount consideration in our design, aligning with ASME's first ethical canon: "Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties" [7]. The installation and maintenance of the Gravity Well system involve on-site work by engineers and technicians, making it critical to design a system that minimizes risk to human operators. Renewell currently applies a safety factor of 3 for components that interact with humans and 1.5 for non-human-interfacing components. However, during installation and maintenance, all components have the potential to come into contact with human workers, making it impractical to designate certain parts as entirely risk-free. To account for real-world uncertainties, we have chosen to implement a minimum safety factor of 3 across all components, ensuring higher reliability, structural integrity, and reduced risk of catastrophic failure.

In conclusion, our engineering decisions are guided by ethical principles that prioritize safety, sustainability, and economic viability. By ensuring cable durability, minimizing failure risks, and maintaining high safety standards, we are aligning with ASME's ethical guidelines while actively contributing to the success of renewable energy storage solutions.

2.4. Existing Solutions

Gravity batteries are an innovative storage solution that provides a sustainable option for energy storage. As we consider the limited supply of lithium for lithium ion batteries— the current technology in energy storage— innovation is necessary to meet the needs of renewable energy production. Other alternatives like hydroelectric flow batteries— which store energy by lifting water and then releasing it— take a toll on the natural environment and only have select suitable locations. In contrast, Renewell's wells improve the environment by eliminating methane-leaking dangers, and there is an abundant supply of millions of unused wells.

To solve Renewell's cable failures, a previous ME170 team designed a lubrication system for the cable. This reduces friction against surfaces while bending, which reduces wear and fatigue on the cable. However, this advancement skirts around the real problem: sharp cable bends. Our redesigned winch system can be used in parallel with a lubrication system in order to both reduce cable wear from bending, spool neatly, and reduce friction against contact surfaces— all of which will help increase cable lifespan.

3. Design

In order to eliminate the fleet angle tower and reduce bends to the rope, we propose to move the drum directly over the well opening, and translate it back and forth to control cable placement while spooling. The intent of a translating drum prototype is to remove large bends in order to improve costs of Renewell's system and reduce risk of cable breaks, and to reduce the infrastructure costs.

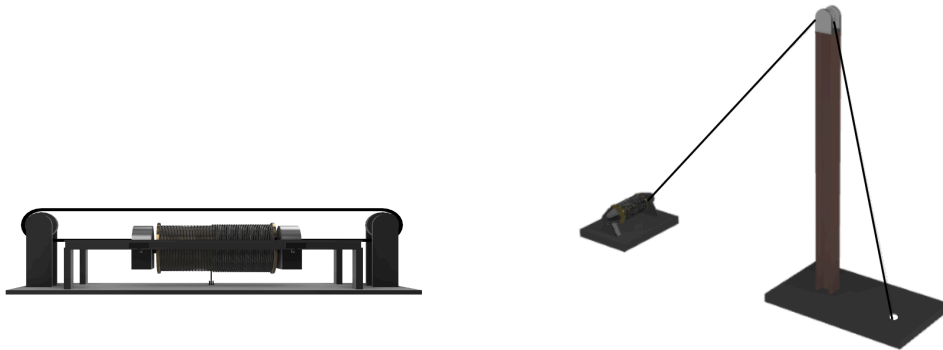


Figure 3. CAD representation of the proposed translating drum solution (left) and the current winching system (right), highlighting significant improvements in cable bending and land area.

To de-risk a translating drum solution for Renewell, we created an approximate $\frac{1}{8}$ scale prototype with the intent to investigate the feedback controls required for a translating drum. Our prototype is a partially unloaded system, with cable tensioned only to bend around the drum. This prototype coordinates the rotation of the drum to its position above the well so that the cable is spooled in a constant location. The drawing and CAD model below highlight the components of the build.

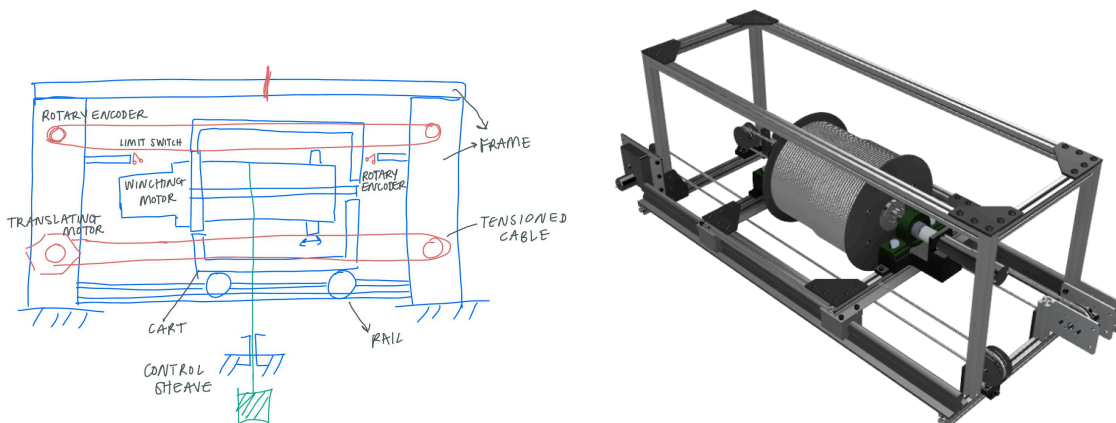


Figure 4. Drawing of parts in scale model, CAD representation

3.1 Mechanical System Design

Given our intent to prototype the control strategy of a translating drum, our system does not need to support the load from lifting a weight. Rather, the cable must simply be under enough tension to bend around the drum and not shift in position. As such, we designed an aluminum 8020 structure for the frame and cart in order to prioritize a rapid, modular, rigid design. All pieces of 8020 were machined on the mill to have flat ends and precise lengths. The cart is mounted upon bearings that translate along a set of linear rails.

3.1.1 Frame and Drum Assembly

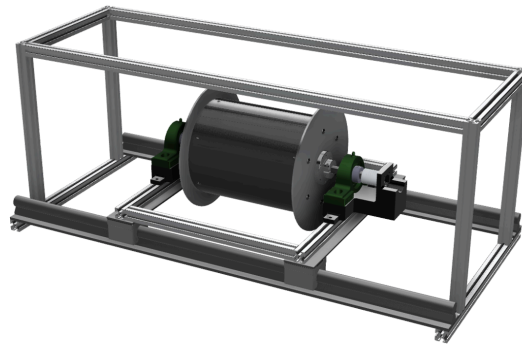


Figure 5. CAD model of Frame, Linear Rails, and Drum and Cart Assembly

Linear rails were selected for straight, low-friction translation of the cart. They were selected for the ability to rapidly prototype this solution for controls testing, yet are not the suggested solution for a final, loaded system (Appendix 8.15). The sides of the frame also support brackets that house pulleys, a motor, and an encoder. The motor drives the rotation of a pulley, which in turn pulls the cart. In a separate cable system, the pulley connected to the encoder rotates to record the cart position. Together, this system drives changes in cart position, and records the position given the pulses of the encoder in order to provide appropriate motor feedback. They are connected with cables seen below:

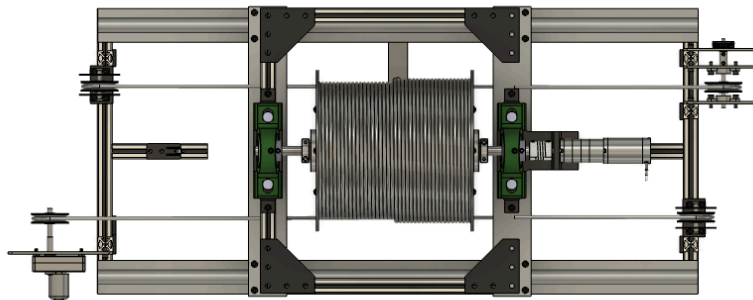


Figure 6. Top view of CAD model with cables

The drum was assembled from a hardened steel pipe and sheet metal in order to match the material properties of Renewell's full scale system. The steel pipe diameter was selected using the closest standard-size pipe to our desired $\frac{1}{8}$ scale. The drum has an outer diameter of 7" with a wall thickness of 0.25". 3D printed parts (Figure 7, dark blue) with heat set inserts were designed to fit inside the pipe and connect the sheet metal flanges to the drum.

The flanges protrude 1" past the edges of the drum to account for drum diameter growth after each layer of cable is laid. The flanges also contain adapter holes for $\frac{1}{4}$ " shaft collars, which rigidly connect the drum to the shaft driven by the winching motor. The drum tube was machined on the mill with the rotary table adapter to add the appropriate holes for the interface between the printed insert, drum tube, and flanges. The flanges were laser cut using $\frac{1}{4}$ " sheet metal. The final dimensions of the drum is 8.75in long and 7 in diameter.

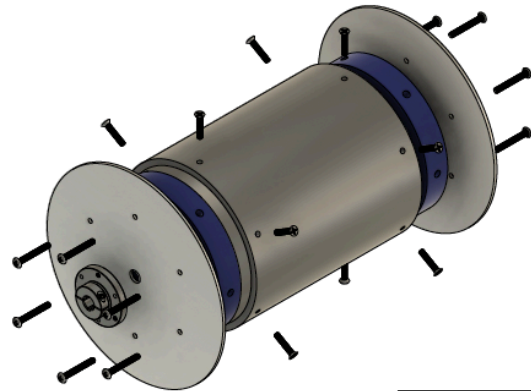


Figure 7. CAD model of drum assembly

The position of the drum is constrained with shaft collars between two pillow block bearings. The rotation of the drum is controlled by the winching motor, and monitored with the winching encoder.

3.1.2 Translating Motor and Encoder Assembly

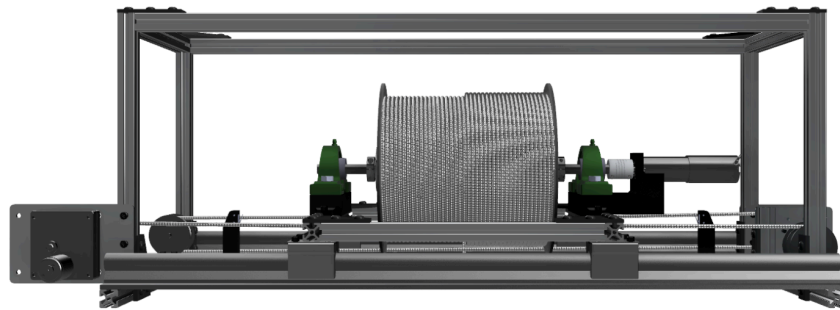


Figure 8. CAD model of assembly, including cables and motor/encoder mounts

The cart is pulled right and left using cables tensioned around pulleys. The two sets of cables are connected with eye bolts to the 8020 in the cart and respectively respond to the translating motor and encoder. We chose to lower the connection points to the cart base in order to reduce risk of binding from a moment being induced on the cart above the center of mass. We've included turnbuckle tensioners to both sets of cables in order to reduce lag in the response.

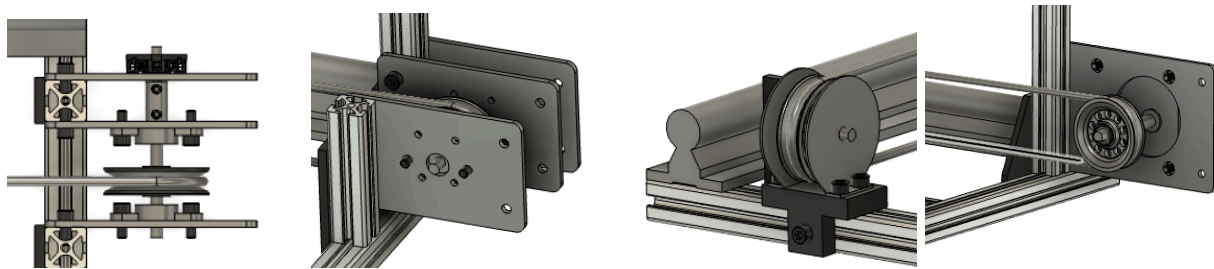


Figure 9. CAD model of assembly, including cables and motor/encoder mounts

The images above depict the motor, encoder, and pulley mounts that support the translational motion of the cart. The motor and encoder mounts are laser cut from $\frac{1}{4}$ " steel and the pulley mount is printed using PLA with 8020 T-slot adapters. We opted to use two sets of cables and separate the encoder from the motor in order to receive a more accurate position measurement. Separating the system using two cables ensures that we are understanding the true response of the cart to motor movement, and compensating for errors in measurement that could be caused by the cable slipping or elongating on the driving cable system.

3.1.3 Controls Design

The control system coordinates between the rotation of the drum to winch the cable, and the translational motor that determines the position of the cart on the track. An Arduino UNO was selected to control the logic of the system. From our Arduino, we used a serial connection to communicate with the Roboclaw Motor controller by Polulu using the Roboclaw Arduino library. The Roboclaw controller receives inputs from the winching motor, winching encoder, translating motor, and translating encoder and relays the encoder signal to the Arduino. The Arduino can control motor speed using PWM (pulse width modulation).

In addition, we connected two limit switches to the Arduino, which trigger when they hit the cart, signifying a direction change for a new layer of cable to be spooled. See on the next page a simplified electrical schematic:

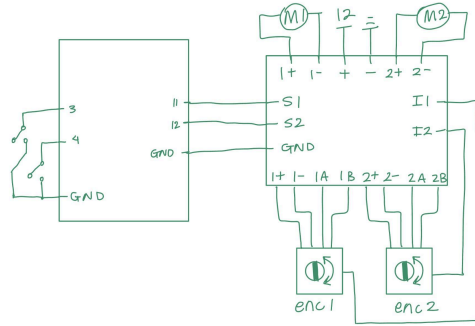


Figure 10. Electrical schematic of the motor controller, Arduino, motors, encoders, and limit switches

The logic which determines the PWM and direction of the motors is driven by the state machine and feedback control loop. In addition, we created manual states to drive the set-up and alignment while outside of the control loop.

Below are diagrams depicting the state machine and the control loop:

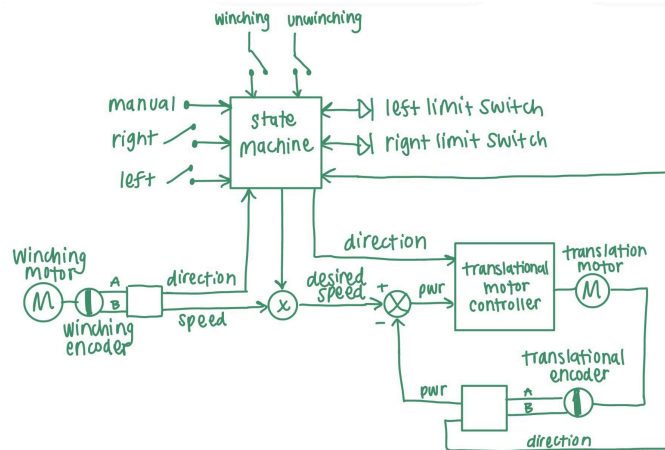


Figure 11. Feedback control block diagram

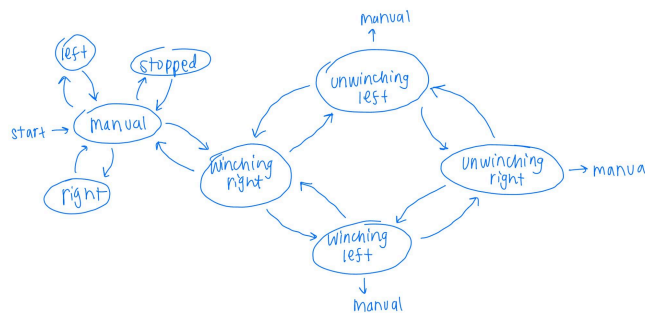


Figure 12. State machine diagram

Here, using the sensor input from the limit switches and encoders, we adjust the PWM of the translating motor in response to the error signal between where the translating encoder count should be (given the output of a transfer function on the winching encoder output) and where it actually is. We wrote the PID (proportional, integral, derivative) feedback control loop in Arduino and tuned it using the K_p , K_d , and K_i constants until an acceptable cable spacing was accomplished. Further tuning is recommended to achieve greater precision in cable placement and spacing.

Feedback is also provided for the winching motor to ensure that the angular velocity (5.5RPM) remains constant. This velocity control feedback is built into the roboclaw function, but disturbances to the drum (such as a changing torque load) necessitate the feedback based upon the winching encoder quadrature counts per second.

The Arduino code is provided in Appendix 8.10. The python script to capture the output of the Arduino serial monitor in a csv file is provided in Appendix 8.11. Important tracking information is calculated from the encoder inputs such as the position from the left, number of layers, number of wraps.

3.1.4 Scaling Prototype to Full Scale System

Our design is approximately $\frac{1}{5}$ scale of a full scale Renewell system. Because we are testing a partially unloaded system, we use linear rails and bearings to translate the drum cart, and we reduced the torque requirements of the motor. The control strategy matches a full-scale Renewell system, with an over-specified rotary encoder for cable placement since we are winching a smaller cable with greater precision. Here, we accomplish greater cable placement accuracy than a full scale would need. This design addresses our ERs by providing a platform for spooling with minimal cable bends and a control strategy to meet the required spooling neatness.

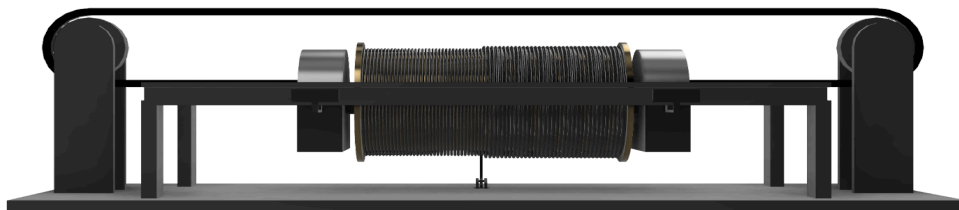


Figure 13. Proposed full scale model, with vertical control sheave, parallel I-beam tracks, pulleys with cables to control position

3.2 Engineering

3.2.1 Principles of Cable Wear

A main concern with Renewell’s current winching system is excessive cable wear, which is caused by multiple bends and movement of cable. Wire ropes subjected to a significant tension load tend to fail from fatigue from multiple bending cycles, excessive strain, or external wear of strands as they contact the sheaves, other cable, or drum itself [8].

During a spooling operation, the length of cable contributing to the tension load changes as the cable length shortens. The cable experiences its highest tension force of ~30,000lbs when the weight is lifted from its maximum depth of ~1000 meters. However, the total load from the weight and cable length are not available for us to change since the mass and length are selected to optimally operate a gravity battery storage system. Thus, the factors contributing to cable failure which we can mitigate in the winch design are reducing bending stress, and reducing wear from surface abrasion.

Relative motion between the strands of cable can be a cause for cable wear. If the cable is incorrectly placed such that it “slips” into position by moving across the drum or another strand of cable, that is a source of wear that can reduce the longevity of the cable. Therefore, we emphasize again that neat spooling and precise placement of cable within the control sequence is critical for minimizing cable wear. The following equation outlines some of the factors that contribute to cable wear:

Wear volume equation:

$$V = \frac{kFL}{H}$$

V = wear volume
 k = wear coefficient
 F = tension load
 L = length of motion
 H = surface hardness

Using a vertical sheave and eliminating the fleet angle tower reduces the length of motion of the cable, thus reducing risk of shear volume. Additionally, because the vertical sheave is simply for alignment, the normal force from the contact between the cable and the sheave only exists to compensate for misalignments. In contrast, the sheave from the fleet angle tower exerts a significant normal force as it counteracts the vertical component of the tension load in the cable.

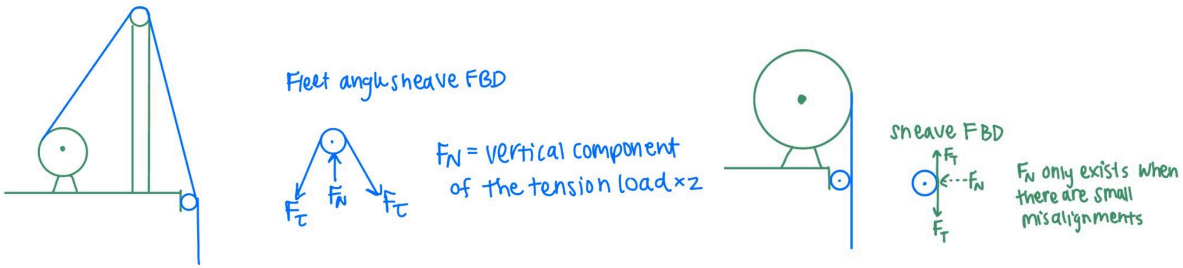


Figure 14. Cable contact force from fleet angle tower is a significant contributor to wear (left), contact force from vertical sheave contributes minimally to cable wear (right)

In addition, placing the drum directly over the sheave significantly reduces the number of bends the cable experiences prior to spooling. The intent to place a vertical sheave underneath the drum is to encourage minimal bending stress, calculated with the following equation:

Bending stress equation:

$$\sigma = \frac{Ey}{r}$$

- σ = bending stress
- E = Young's modulus
- y = cable radius
- r = bend radius

Our design improves the bend radius by eliminating the large bend around the fleet angle compensator tower. In a vertical sheave, the radius of the bend is around an infinitely large circle, so bending stress is minimal.

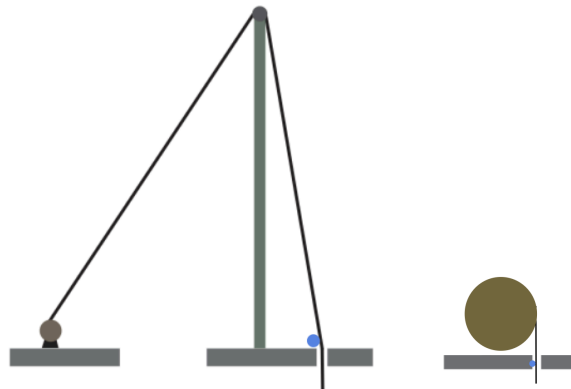


Figure 15. Previous cable bending around fleet angle compensator (right) and proposed bending in redesigned winch system (left)

3.2.3 Motor and Encoder Selection

Our prototype contains two motors and two encoders. The first motor and encoder pair is referred to as the “winching motor” and “winching encoder.” This motor drives the rotation of the drum that winches and unwinches the cable. The winching motor is selected so that it can lift an 8kg weight over 120 ft drop area.

Rated torque:

$$\text{Rated Torque} = (\text{Drum Radius}) \times (\text{Weight} + \text{Cable Weight})$$

Cable weight calculation:

$$\text{Cable Weight} = (0.065 \text{ lbs/ft}) \times (120 \text{ ft}) \approx 8 \text{ lbs}$$

Substituting values:

$$\text{Rated Torque} = (3.25'') \times (16 \text{ lbs} + 8 \text{ lbs}) \approx 80 \text{ in} \cdot \text{lbs}$$

We selected an 80 in*lbs rated DC gearmotor from Midwest Motion: MMP S14-247C-12V GP32-1140 (Appendix 8.12). It contains a gear ratio of 1:1140 and a built-in 400 PPR encoder, which correlates to pulses every 0.0007 degrees of rotation.

The second motor and encoder pair are referred to as the “translational motor” and “translational encoder”. This pair controls and provides feedback for the position of the cart, which determines the location of spooling on the drum. Given a winching speed of 5.5RPM, the corresponding translation speed is 1 cable diameter per revolution. Using a 20mm radius pulley, we can calculate the necessary average speed of the motor:

Drum translation speed:

$$\text{Drum Translation Speed} = (\text{Drum RPM}) \times \left(\frac{3''}{16} \right)$$

Translational motor RPM:

$$\text{Translational Motor RPM} = \frac{\text{Drum Translation Speed}}{\text{Pulley Circumference}} = 0.328 \text{ RPM}$$

Since this is a very low speed, we selected a DC gearmotor with a rated speed of 0.6 RPM and 1:7189 gear ratio. This allows for acceleration in the cases when the cart is lagging behind the desired position or changing directions.

The translational encoder is selected using our ER of 1/10 of a cable spacing between cables. An encoder with 512 PPR provides over 5 times the resolution for 1/10 of the cable spacing on a 50mm diameter driving pulley.

Position error precision:

$$\text{Position Error Precision} = \frac{0.1 \times \text{Cable Diameter}}{5}$$

Encoder angle at allowable error:

$$\text{Encoder Angle at Allowable Error} = \frac{360 \times \text{Allowable Error}}{\pi \times \text{Pulley Circumference}}$$

Encoder PPR:

$$\text{Encoder PPR} \approx 600$$

We selected an incremental 512 quadrature rotary encoder from Same Sky: AMT102-D0512-I5000-S (Appendix 8.12). It uses a 5V supply and records the rotation around a 5mm diameter shaft. This encoder has the necessary precision to meet ER1-1c using a rigid connection to a 50mm diameter pulley.

3.2.3 Improvements to Motor Efficiency by Reducing Variable Torque

The motivation behind reducing the number of cable wraps around the drum is to reduce the necessary torque on the winching motor. Renewell’s cable is around 1” in diameter. This means that with each layer of cable added to the drum, the radius of the drum grows by 1”. With Renewell’s current system, 8 layers of cable are added to the drum in order to use a drum size acceptable for the spooling range of the fleet angle compensator. Thus, the radius grows by 8” adding a larger lever arm to the load the drum experiences.

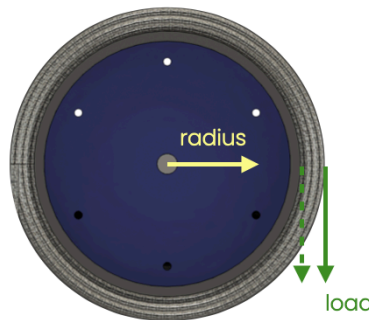


Figure 16. Comparing lever arm influencing torque in unspooled vs spooled conditions

In order to meet our ER 2-2, we are reducing the number of cable wraps from 8 to 4 wraps. This becomes possible with a translating drum because the length of the drum is no longer constrained by the range of the fleet angle compensator. We can approximate our improvements to the torque on the motor in the following calculations:

1. Initial Torque with 24-Inch Lever Arm:

$$\tau_1 = 40000 \times 24 = 960,000 \text{pound-inches}$$

2. Torque for 32-Inch Lever Arm (added 8 inches of spooled cable):

$$\tau_2 = 40000 \times 32 = 1,280,000 \text{pound-inches}$$

3. Percent Difference for 8 Layers:

$$\Delta\% = \left(\frac{1,280,000 - 960,000}{960,000} \right) \times 100 = 33.33\%$$

4. Torque for 28-Inch Lever Arm (4 layers):

$$\tau_3 = 40000 \times 28 = 1,120,000 \text{pound-inches}$$

5. Percent Difference for 4 Layers:

$$\Delta\% = \left(\frac{1,120,000 - 960,000}{960,000} \right) \times 100 = 16.67\%$$

Reducing the number of wraps from 8 to 4 greatly reduces the variable torque on the motor. This allows Renewell to reduce costs by purchasing a cheaper motor that will have higher spooling efficiency across the entire range of spooling.

3.2.4 PID Controller Design (Pseudocode)

The PID controller uses the input of the desired position, to correct for the actual position gathered from the translating encoder sensor. It controls this by changing the PWM of the translating motor.

```
positionError = (targetPosition - actualPosition) * Kp;
derivativeError = -1 * currentVelocity * Kd;
integralError = oldIntegralError + (positionError * Ki * -1);
oldIntegralError = integralError;
pwm = (positionError + velocityError + integralError);
```

Within the controller, we have the following transfer functions to convert the encoder outputs to the desired and actual positions of the drum.

```
targetPosition = ((drumEncoderCount/winchingMotorGearRatio) /
drumCPR) * cableDiameter * spacingTolerance
```

$$\text{actualPosition} = \frac{\text{translatingEncoderCount} * (\text{PI} * \text{pulleyDiameter})}{\text{cartEncoderCPR}}$$

By providing this feedback, we can minimize the error in position of the cart. The following graphs compare how the position is adjusted in the first 10 seconds of spooling as the control constants are tuned. Based upon qualitative testing, we set $K_p = 3.5$, $K_d = 2.0$, and $K_i = 0.2$. Further testing is necessary to further decrease the time to settle at an acceptable, minimum constant error, and further reduce this steady state position error.

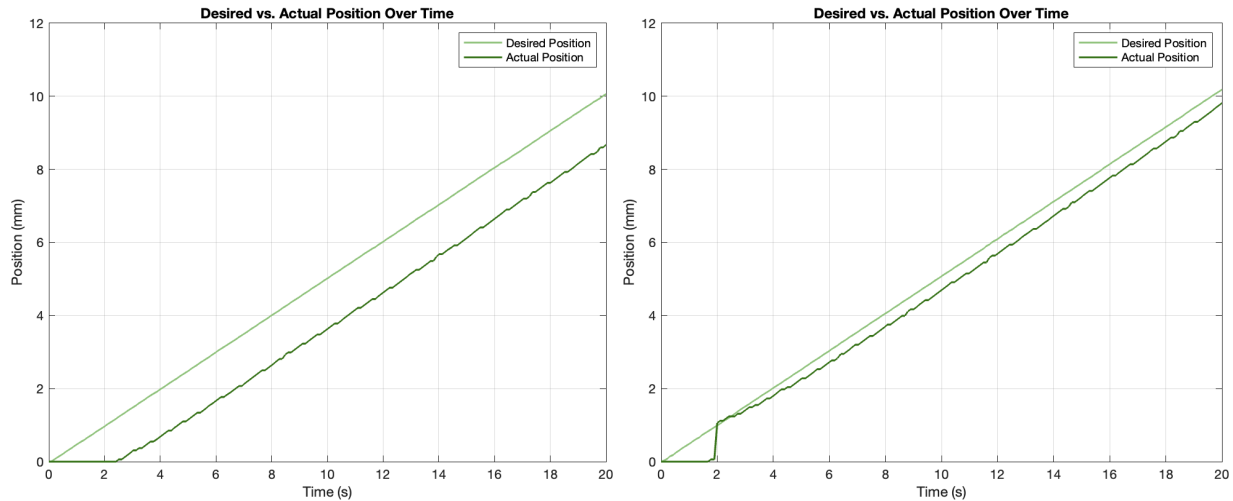


Figure 17. Position error in the first 20 seconds of winching. Untuned control constants settle at a large constant position error (left). The selected PID control constants reduce the position error in the system (right).

The feedback control allows for consistent, neat placement of cable on the drum. This is important for meeting our ER1-1b and ER1-1c.

3.3 FMEA Summary

Our team performed a Failure Mode and Effects Analysis (FMEA) on our testing setup, identifying high-risk failure modes related to load distribution within the mechanical system and the simulated heavy mass used to replicate the lifting and lowering process in Renewell’s energy storage system. We concluded that the most critical safety concern during testing would be the toppling of our drum, cart, and frame from the tall tower height. This could result in equipment damage, testing delays, and most importantly, personnel injury.

To mitigate these risks, we implemented two key changes: offsetting the drum and cart from the frame’s centerline, and orienting the guide sheave horizontally to offset the load to move our drum away from the drop area and anchor our frame to the ground.

3.3.1 Assembly FMEA

Potential high risk failure modes influenced the design of the frame of our system. The FMEA line item associated with the frame is in the table below.

Table 2. Assembly FMEA High Risk Items

FMEA line item	Potential Failure Mode (s)	Potential Effect (s) of Failure
d3	Tipping of entire system	25 lbs drum and frame free falling from 100 ft injuring people or equipment.

We identified that if the mass of the drum, cable and lift mass were not offset from the centerline, then a large moment from a significant lift mass could cause the entire system to tip. If tested from a high structure, the tipping of the assembly could cause injury to people in the general vicinity of the testing location. As a result, we made changes to the design of our system, ensuring that the drum would be offset in order to position the center of mass closer to the centerline.

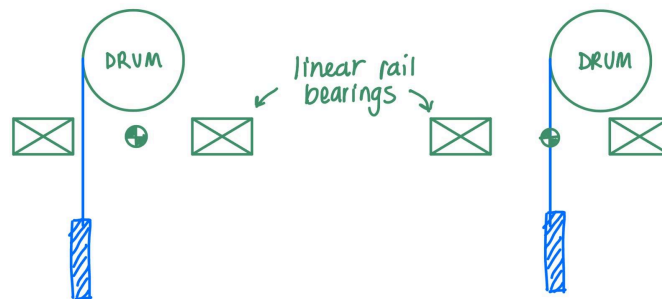


Figure 18. Moment from weight on drum can cause tipping (left) unless tensioned cable with weight goes through the center of mass (right)

3.3.2 Guide Sheave FMEA

Through an FMEA conducted on our testing set up, we identified a few high risk failure modes associated with constraints imposed by our testing location and the inability to safely place our tensioning weight directly under our system, which was important for verifying ER1-1a.

We conducted our initial tests on the second floor of building 520, which provided sufficient elevation to begin testing with an unloaded system. However, in attempting to orient the guide sheave (which directs the cable between the drum and hanging mass and constrains the mass

from swinging as the drum and cart assembly translates), we encountered significant safety concerns. Figure 19 below shows our initial setup.



Figure 19. Initial testing on the second floor of building 520

From these initial tests, we determined that centering the guide sheave vertically posed significant safety concerns. In order to achieve the necessary height, stacking tables created an unstable foundation, making the assembly more prone to falling. Additionally, positioning the guide sheave over empty vertical space required that the frame be only half supported. In the test shown above, we used heavy, 20 kg counterweights on the frame to prevent tipping from the moment caused by the tension in the cable. We also secured the frame using paracord to the ceiling beams and kept one hand on the assembly at all times.

After a risk assessment, we concluded this testing setup presented unacceptable safety hazards due to tipping in our 100ft tower, and subsequently modified our testing approach before testing. Table 3 below shows the FMEA line associated with the orientation of placement of the cable by manner of the guide sheave.

Table 3. Guide Sheave FMEA

FMEA line item	Potential Failure Mode (s)	Potential Effect (s) of Failure
d13	Tipping	System falling from high elevation, injury to personnel, destruction of property
d14	Bending	Hanging mass will hit stair rails

In order to mitigate the risks associated with the free falling weight for future tests we decided to orient our guide sheave perpendicular to the frame. This change to a horizontal guide sheave enabled us to place our system on an even foundation, which allowed us to run more full cycles without risks associated with the tipping of our system. Figure 20 shows our updated testing system layout.

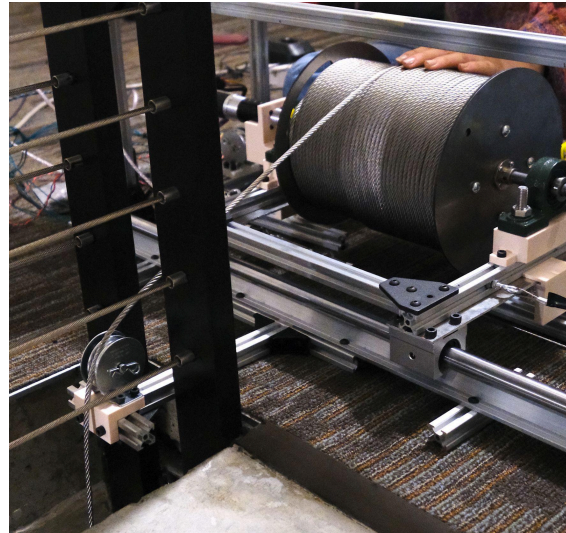


Figure 20. Redesigned test set up layout after risk assessment

In our revised testing configuration, we added an 8020 beam with a free spinning pulley as our guide sheave to offset the hanging mass from below the system. We relocated our full-scale tests to the EVGR stairwell, utilizing a tall, vertical, open space between the railings that would not interfere with pedestrians. Additionally, we ensured the weight of our hanging mass remained lighter than the system itself to prevent tipping that would occur if the center of mass shifted outside the frame’s base. These modifications were necessary to ensure safe operation. As a result, our guide sheave configuration introduced an approximate 45° bend, preventing us from experimentally verifying compliance with ER1-1a (maximum pre-spooling bend angle of less than 10°).

3.4. Experimental Plan

To achieve our engineering requirements, we targeted a number of high-priority requirements through the design of our system itself, which are listed in table 4 below.

Table 4. Engineering Requirements Addressed in Our Design

ER1-1a	Prior to spooling, the maximum bending angle in the system layout is <10°
ER2-1	Spooling time should be <= 1hr

ER2-2	Reduce the number of cable wraps on the drum from 8 to 4 wraps
-------	--

We validated ER2-1 and ER2-2 experimentally, measuring spooling time and cable layers. ER1-1a could not be tested safely due to the outcome of our FMEA.

While many engineering requirements were directly integrated into our system's design, others required experimentation to verify whether our prototype met our performance specifications. To ensure comprehensive evaluation, we conducted tests with our fully integrated system after tuning the controls. The specific engineering requirements addressed in our experiments are detailed in Table 5 below.

Table 5. High-Priority Engineering Requirements Targeted by Testing

ER1-1c	A gap of 1/10 the cable's diameter should be maintained between each cable line on the drum
ER1-1b	Our translating system should maintain a fleet angle of $<0.1^\circ$ between the drum and the sheave

Testing was conducted in the 9th-floor stairwell of EVGR, which provided an unobstructed 100-foot vertical drop. This location was chosen to ensure that our prototype experienced the tallest winching length possible on campus, allowing us to evaluate its performance under conditions similar to the full-scale implementation.

To replicate the long, narrow weight used in Renewell's actual system, we assembled a PVC pipe filled with 6lbs of sand. The shape of the pipe allowed the weight to ascend through the gaps in the stairwell.

To track the movement of the drum and cable, we set up multiple cameras. These cameras captured the translation of the cart, the cable spacing, and the lifting of the weight from multiple angles. We also used encoder readings to obtain a high-resolution numerical representation of the cart's position. By using visual and sensor-based data, we could review a rich set of data to evaluate the spooling behavior, system responsiveness, and potential sources of mechanical error.



Figure 21. Testing Setup in EVGR



Figure 22. Vertical Weight During Testing



Figure 23. PID Controller Setup



Figure 24. EVGR Building

3.4.1 Cable Spacing (ER 1-1c) Experimental Plan

To avoid cable wear, cables must be placed with a small gap between them to avoid rubbing. Our ER1-1c is to have this gap less than $1/10$ of the cable diameter. In our scale model prototype, the gap threshold is 0.5mm, or the size of a grain of sand.

The first layer of cable is most critical for this requirement, and the placement is replicated across all four layers of cable. To test that our integrated system is able to wind the steel cable so less than 1/10 of the cable diameter gap is between each cable line, we ran 5 trials of spooling on the first layer. Using a fixed tripod set-up, we took consistent photos of the spooled first layer. One of these images is provided below. As you can see in Figure 25, the contrast of the black steel drum allows for the cable gaps to be visible from the image.



Figure 25. Spooling image, trial 1

We used image processing software ImageJ to measure the distance between each cable revolution on the drum relative to the diameter of the cable. We then summarized the average gap size, the distribution, and the maximum gap in each layer.

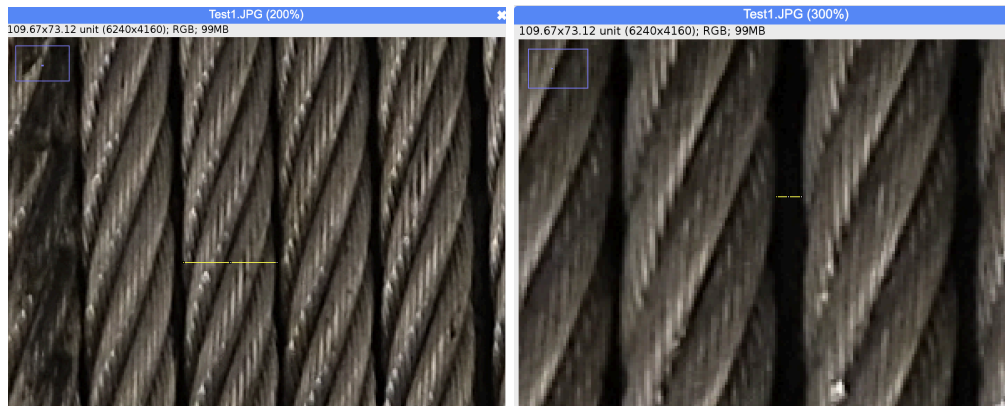


Figure 26. Cable diameter and spacing labels (faint yellow lines) in ImageJ. Repeated 215 times.

Since the initialization sequence does not guarantee perfect alignment with the control sheave, the first 3 cable wraps are not counted when determining average cable spacing.

3.4.2 Fleet Angle (ER1-1b) Experimental Plan

In Renewell's current system, the fleet angle compensator bends the cable back and forth across a span of $\pm 1.5^\circ$. Concerns with this movement are that the bending on the cable incurs fatigue, and wear against the moving guide sheave. The constraint on the angle of bending also necessitates a long distance between the guide sheave in order to span the entire length of the drum. The main innovation of a translating drum is eliminating the fleet angle tower and bending on the cable. Instead, we spool the cable directly above the well without bending the cable, and in turn move the drum. In a perfect system, fleet angle is approximately 0° since there is no cable movement or bending.

Fleet angle does arise when the drum is not in the correct position. This positional error creates a bend between the control sheave and the drum, as seen in Figure 27. Our ER1-1b of maintaining a fleet angle $< 0.1^\circ$ determines the accuracy and "neatness" of cable placement of the drum. It tests the ability of the control system to compensate for errors in position.

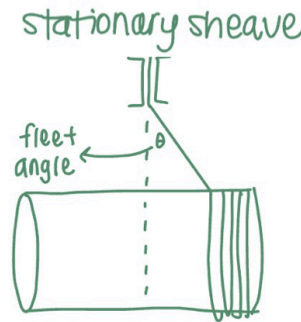


Figure 27. Inaccurate drum position creates a fleet angle between where the cable should be, and where it is actually laid.

By using the encoders on the winching motor and the translation pulley, we can note the positional error of the drum. From the positional error, we can determine absolute fleet angle using the trigonometric calculation below. This angle was then compared to the relative minimum or maximum fleet angle to adjust for the self-correcting nature of cable spooling:

$$\theta = \tan^{-1} \left(\frac{\text{position error}}{\text{control sheave distance}} \right)$$

$$\theta = \text{fleet angle}$$

To test this ER we ran four spooling cycles and exported the encoder errors to a .csv file. We then calculated the positional error and fleet angle using MATLAB.

3.4.3 Cable Pre-bending (ER1-1a) Experimental Plan

We integrated this ER into our design and used our CAD software to measure the bending angle onto the drum under two extreme conditions (fully spooled and fully unspooled). Initially, our plan was to test with this vertical sheave configuration. However, due to the safety risks outlined in the FMEA (Section 3.2.2), we offset the load and placed the guide sheave horizontal to the base of the frame.

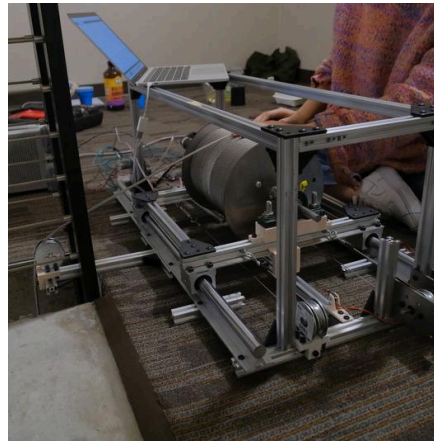


Figure 28. Sheave creates $\sim 45^\circ$ angle

3.4.4 Spool Time (ER2-1) Experimental Plan

To test for the one-hour spooling time, we ran the full spooling cycle (245 feet) and measured the displacement of the cable. From here we scaled this rate to the full-scale system by multiplying the rate by the drum diameter ratio (with the same rotational rate this would be achieved).

3.4.5 Cable Layers (ER2-2) Experimental Plan

To verify this ER we measured the displacement of the weight for a full layer of cable. We then used this information to determine the necessary drum dimensions for the full-scale system to meet the requirement by calculating a drum spooling efficiency (the percentage of the drum taken up by cable compared to the gap between cable) and using this value as a scale factor for the length of the drum.

3.4.6 Friction Testing Experimental Plan

The force required to pull the cart on the linear rails must be less than 115 N, based upon our motor specifications and the 0.052m diameter driving pulley. To ensure that our mechanical design would be able to support and translate our targeted loads with the motor we selected, we determined the maximum forces required to overcome static friction against the linear rails.

We decided our system at various levels of incline to account for the extreme cases of uneven foundation. We also tested with varying loads on the cart. We tested the force required using a handheld force gauge to pull the cart.



Figure 29. Incline friction testing set up

These tests can be used to determine the friction coefficient of following the equation derived from the following FBD: $F = f + mgsin(\theta) = mg(\mu\cos(\theta) + \sin(\theta))$

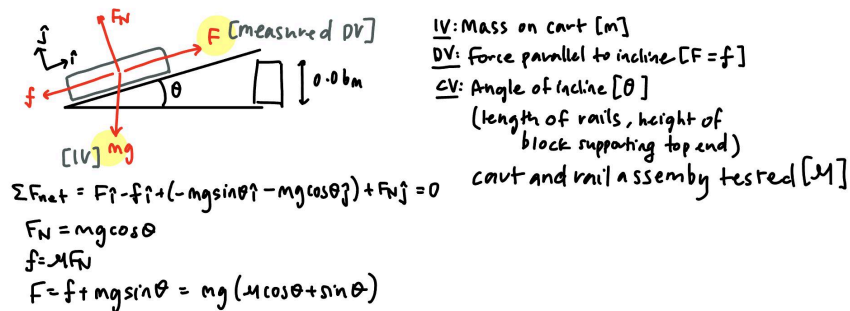


Figure 30. Free body diagram of the cart assembly on an inclined rail

We also repeated the test with a constant mass and varying incline levels. The purpose of determining the friction force between the bearings and rails is to evaluate that our motor is properly selected to meet the torque requirements for translating the cart.

4. Results and Discussion

From our experiments, we determined our prototype of a translating drum winch has promise for neatly spooling on a full scale system. In our scale model, we meet the precision requirements to neatly spool cable with minimal gaps in spacing, greatly reduce cable bending, and control the placement of cable with minimal error in position.

4.1.1 Cable Spacing (ER 1-1c) Results

The results from ImageJ cable spacing measurements are shown in the table below. In total, 215 gaps were hand labelled and measured.

Table 6. First layer cable spooling test results

Trial	mean (% cable diameter)	standard deviation	max (% cable diameter)
1	8.07	2.90	17.4
2	7.73	2.60	13.6
3	6.05	1.88	12.3
4	6.41	2.21	11.3
5	7.81	2.18	13.1

4.1.2 Cable Spacing (ER 1-1c) Interpretation

In our scale prototype, ER1-1c is conditionally met. All average cable spacings are below the necessary threshold, yet all trials contain cable gaps that exceed the 0.5mm threshold. In our software, there are a couple changes that could decrease the cable gap distance to meet ER1-1c. When establishing the desired distance translated per drum revolution, our software instructs the cart to translate $1.1 * \text{cableDiameter}$. This value was selected after multiple qualitative trials to eliminate risk of cables rubbing against each other or overlapping the previous cable while spooling. Reducing this value would reduce the space between cables, but it may risk rubbing or overlapping the previous cables. The second adjustment is further improving the controls feedback so that the desired position matches the actual position of the cart. Providing quick position adjustments would reduce risk of cables rubbing since the cart position would not lag behind or overshoot the desired cart position.

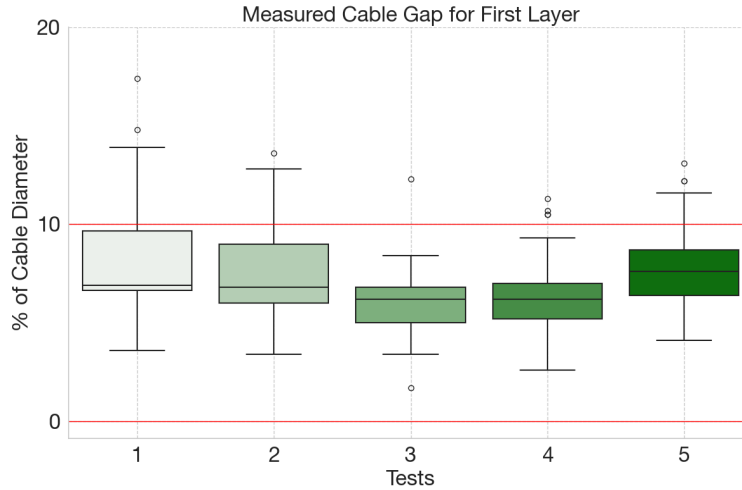


Figure 31. Distribution of cable gaps as a percentage of prototype cable diameter. Red lines indicate the thresholds for the prototype.

It is important to note that our fifth scale prototype requires more precision than a full scale system. Since the cable diameter is a fifth of the actual cable, the necessary granularity of our encoder is extremely small, and position tolerance is 0.5mm rather than 2.2mm. If we consider how our position control would fare under a full scale model, all of the cable spacings are significantly smaller than the allowable cable gap. Thus, in a full scale system, we can expect our controls design to meet the necessary precision and fulfill ER1-1c. Figure 33 below shows our results relative to Renewell’s scale.

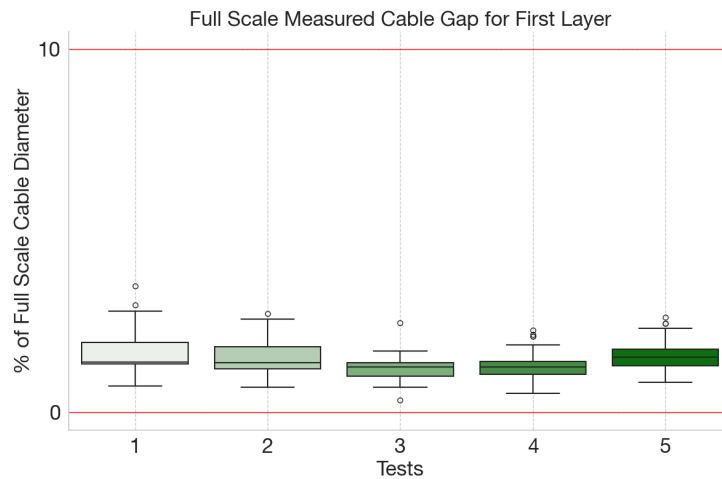


Figure 32. Distribution of cable gaps as a percentage of full scale cable diameter. Red lines indicate the threshold for the full scale system.

4.2.1 Fleet Angle (ER 1-1b) Results

The graphs of fleet angle over the course of spooling are similar across all four tests. There is an initial fleet angle error after each acceleration (stopped to moving, changing directions). The spikes in the following graph of trial 1 highlight the fleet angle after each change in direction. All fleet angle values are under the threshold of our engineering requirement of 0.1 degrees.

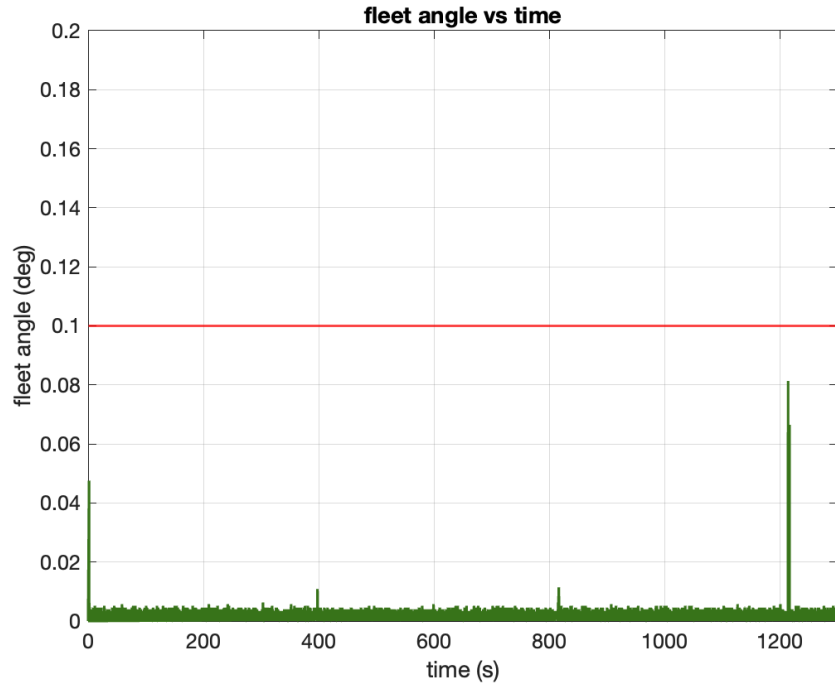


Figure 33. Fleet angle over the course of spooling.

The following table displays the maximum fleet angle in each trial, as well as the average fleet angle. Since maximum fleet angles appear sharply and settle quickly, average fleet angle is a conservative approximation for the steady state error, when the motor is not undergoing significant accelerations.

Table 7. Summary of fleet angle across 4 trials.

trial	Max fleet angle (degrees)	Average fleet angle (degrees)
1	0.0814	0.0018
2	0.0544	0.0022
3	0.0773	0.0018
4	0.0476	0.0017

4.2.2 Fleet Angle (ER 1-1b) Interpretation

To visualize initial growth in fleet angle, we can observe the following graphs of the first 20 seconds of winching:

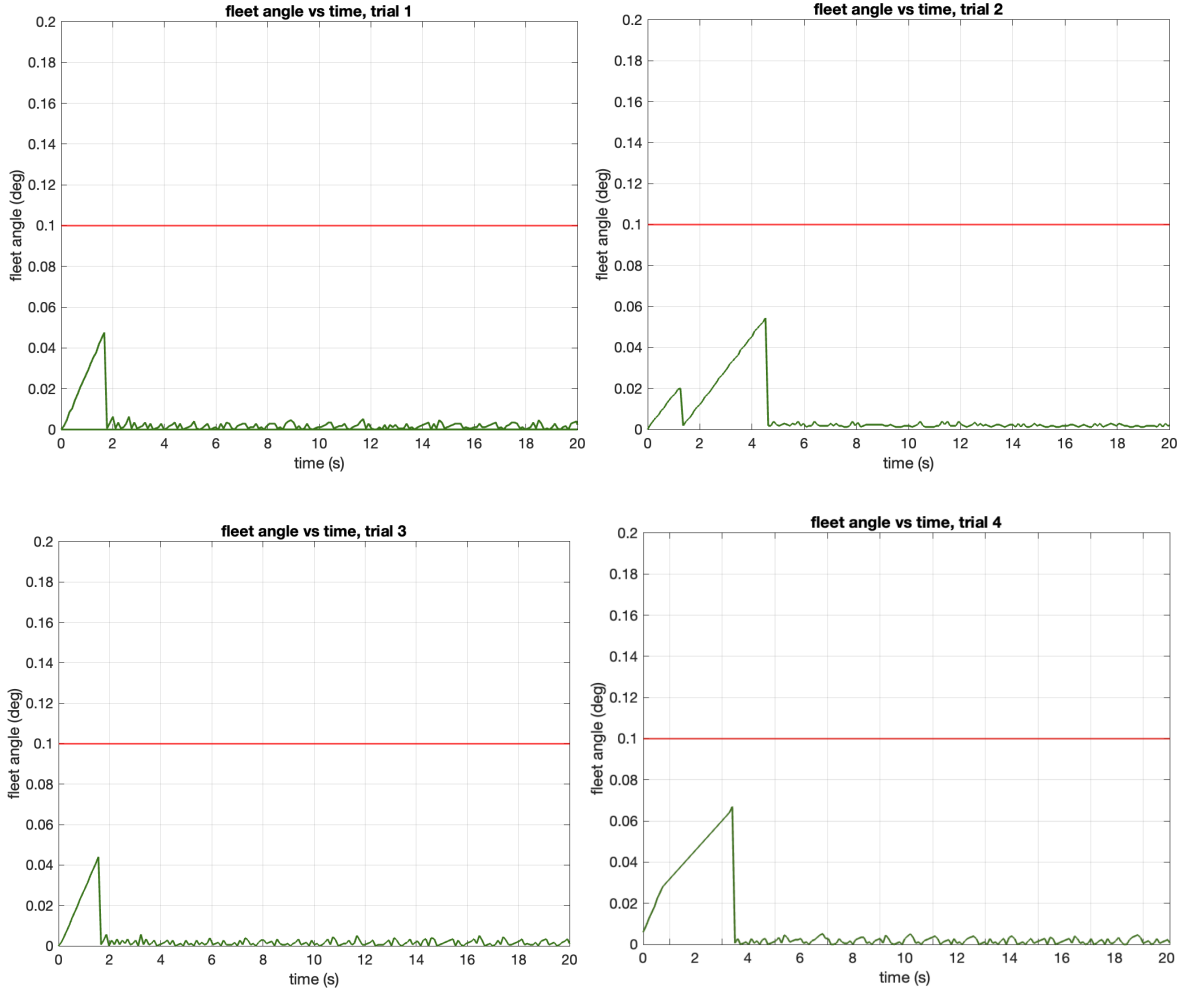


Figure 34. Fleet angle over first 20 seconds of spooling for trials 1-4.

From these graphs, we note a rapid growth in fleet angle, which corresponds to the cart position lagging behind its desired position. After around 2 seconds, the cart begins moving at a constant speed and fleet angle is minimized. Mechanically, this likely reflects that the motor has overcome its initial friction torque that opposes rotational acceleration. In total, we note all trials meeting our required engineering requirement of < 0.1 deg fleet angle. We also conclude that the lag in motor response creates an accumulation of error during accelerations, which can be minimized with improvements to the controls program.

4.3 Cable Pre-bending (ER 1-1a) Results and Interpretation

From our design, we see that a vertical sheave meets the pre-bending requirements of being less than 10 degrees.

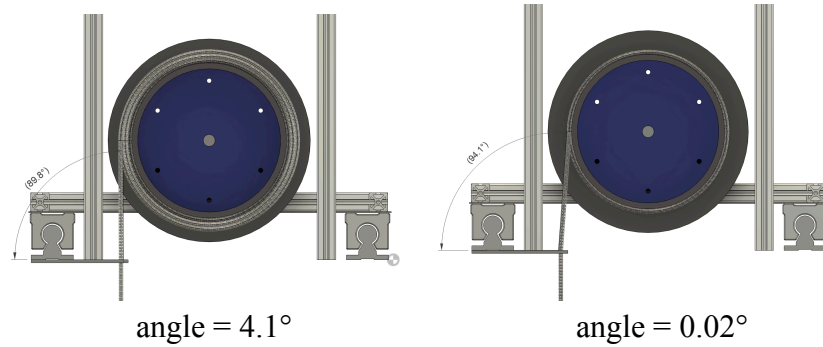


Figure 35. Bending angle when fully spooled (left) and unspooled (right)

However, due to DFMEA considerations, we were unable to fully meet this ER in testing due to safety risks. Consequently, our testing setup introduced more than 10 degrees of bending into the system. Thus, we can consider ER1-1a fulfilled in design but not experimentally validated.

4.4.1 Spool Time (ER 2-1) Results

Table 8. Spooling time scales to under 1 hour.

	Time(min)	Spool Distance(feet)	Prototype drum diameter (in)	Actual drum diameter (in)	Prototype Rate(ft/min)	Extrapolated Rate (ft/min)	Time to spool(min)
Results	21.7	245	7.08	42	11.3	67.1	59.63

4.4.2 Spool Time (ER 2-1) Interpretation

This test involved measuring the time to full spool and unspool the drum. Once we had a measurement of the model's timing, we were able to estimate with expected timing to fully spool and unspool the full scale system. While our prototype could complete this process in 21 minutes, we estimate that the full model will take 59.6 minutes. This just meets our requirements, which validates that our motor specifications are accurate in that they are tuned to the minimum required for this test.

4.5.1 Cable Layers (ER 2-2) Results

By comparing the circumference of our drum to the full scale system we can determine the necessary drum length to achieve 4 wraps of cable.

Table 9. Drum length scales to reasonable length for 4 cable wraps.

Number of wraps	Cable displacement (ft)	Cable D (in)	FS Cable D (in)	Drum length (in)	Drum Diameter (in)	FS Drum Diameter (in)	Length efficiency	FS displacement per wrap (ft)	# wraps required	Calculated required length (ft)
41	76	0.188	0.85	8.4	7.0	42	0.914	11.0	364	7.052

4.5.2 Cable Layers (ER 2-2) Interpretation

This test validates if the controls system can lay cable efficiently to fit a drum that meets certain specifications. We found the “length efficiency” which is the amount of drum being used to store cable, and were able to then solve for the minimum length of drum for the full size. Our drum needed to be shorter than 8 feet to meet the user requirements, so our estimate of 7.05 feet falls well within our range.

4.6 Friction Testing Results and Interpretation

To ensure that pulling the cart along the linear rails is within the torque range of the translating motor, we conducted two tests to determine the force required to overcome static friction on a cart with mass. Since static friction is the greatest force the cart experiences opposing its motion, we tested our motor to ensure it can overcome the static friction of the cart under various loads and inclines. The incline values encompass Renewell’s foundation tolerance of 5 degrees.

Table 10. Force required to overcome static friction with varying loads and incline

Weight on cart (lbs)	Force (N)	Angle (degrees)	Force (N)
25	12.74	1.5	7.84
50	23.52	3	15.68
75	29.4	4.5	23.52
100	39.2	6	29.4
125	47.04	7.5	39.2

From solving the free body diagrams of the cart on an incline, we predict that the force needed to overcome the static friction between the rails and the cart would be governed by $F = mg(\mu\cos(\theta) + \sin(\theta))$, which is linear with respect to an increased mass on the cart. A

graph demonstrating the relationship between the mass on the cart and the force measured is shown below.

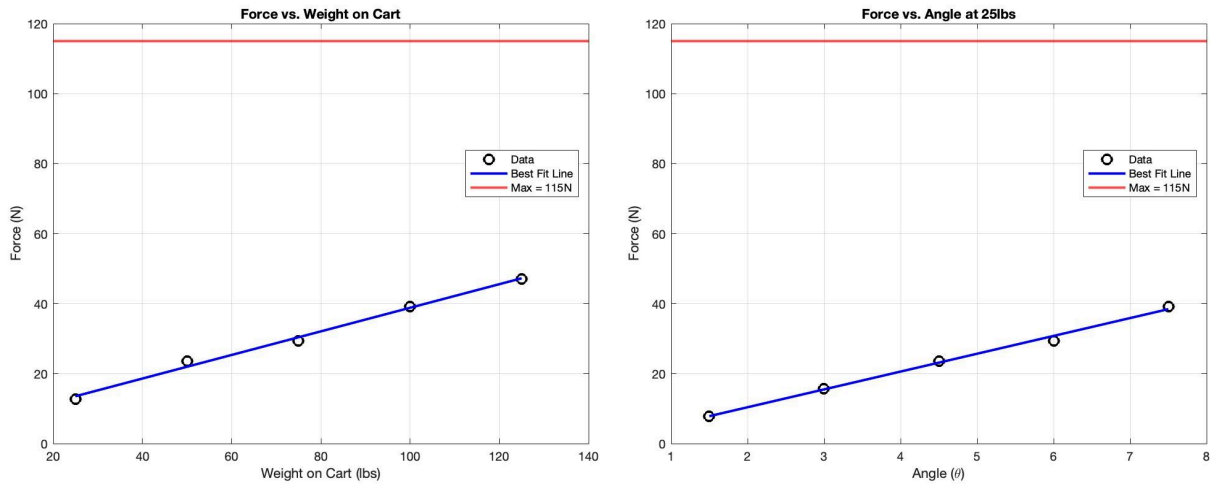


Figure 36. The force to translate the cart is within motor specifications for varied angles of incline and cart masses.

We can conclude from our testing that the motor selected can sufficiently overcome the torque required to pull the cart along the linear rails. This gives us confidence in the ability for the cart to accelerate in motion and translate back and forth to neatly spool the cable.

4.7 Discussion

The results of testing indicate great promise for an effective translating drum winch at full scale. Our control system achieved the small, precise gaps in cable spacing at a fifth scale, and minimized position error to reduce bending of cable. Additionally, placing the drum directly above the well reduces the number of bends endured by the cable. When scaled to a full system, we can achieve the spooling of 4000 ft of cable on a reasonably sized drum (42 in diameter, 7 ft length). Additionally, we can improve the motor efficiency– or cut costs by selecting a different motor– by reducing the torque requirements due to the decreased radial growth of the drum. The benefits of this design at scale correlate to over \$70,000 in savings for Renewell (Appendix 8.13).

A summary of the engineering requirements we tested and incorporated into the design is displayed in table 11 on the following page:

Table 11. Summary of Tested and Designed Engineering Requirements

	ER1-1a	ER1-1b	ER1-1c	ER2-1 & ER2-2
Prototype	Designed but untested	Maximum: 17.5% cable gap Average: 7.2% cable gap	Fleet angle <0.1 degrees	11.1 ft/min 8.5in long drum
Full scale	Met at full scale	Precision grows at full scale	Met at full scale precision	59.6 spool time 7ft long drum
Benefits/Savings	Reduces cable wear	Neat spooling, Reduces cable wear	Neat spooling, reduces cable wear	Spool in energy production window Spool 4 layers

5. Conclusion

In order to make Renewell a competitive energy storage option, we were tasked with reducing the cost of the winching system and improving its efficiency by minimizing cable wear during spooling. Our prototype reimagines spooling by translating a drum above the well opening in order to neatly spool cable with minimum wear and fatigue. Our prototype scales directly to a full sized system, immensely reducing system complexity, cable wear, and cost. Our innovation provides Renewell with two critical contributions.

First, our prototype provides proof of concept that a translating drum can be used to control cable spooling placement, thus providing a simple cable management solution to systems requiring high tensioned loads over a long lifespan. Our results confirm that a translating drum can streamline spooling with reliability and efficiency, reducing wear and improving long-term performance. By derisking the dynamics of cable moving across the drum, we provide Renewell with a clear path forward to a full scale mechanical system.

Secondly, our prototype provides the framework for a high-precision control feedback system. By selecting the necessary hardware and integrating with control software, we have the ability to precisely control the position of the drum, ensuring smooth and consistent cable winching within necessary spacing tolerances.

Through rigorous testing, we verified that a translating drum winch meets key performance thresholds for speed, efficiency, and cable bending. We observed significant reductions in fleet angle, cable rubbing, and bending during spooling, factors that will extend the cable's lifespan and enhance long-term system reliability.

Beyond technical performance, our design has major financial implications for Renewell. By eliminating the need for a tall spooling tower and foundation pad, the translating drum winch saves the company over \$70,000, making it not only a practical solution but also a cost-effective one.

For Renewell's Gravity Well to become a truly viable energy storage solution, a fundamental redesign of their winch system is essential. Their current model suffers from excessive cable bends, inefficient use of space, and unnecessary complexity. Our prototype de-risked fundamental aspects of simplifying their spooling, providing a clear path forward and bringing Renewell significantly closer to a scalable and commercially viable renewable energy storage solution.

6. Future Work

We recommend improving the experimental setup to allow for full-cycle winching of the entire steel cable length with the tensioning mass attached. One of the primary challenges we faced was testing our system against engineering requirements due to constraints in our available testing locations. Both the second floor of Building 520 and the ninth-floor stairwell of EVGR had insufficient height and limited space, which impacted our testing approach in two key ways.

1) Inconsistent Cable Tensioning:

The cable length required for testing exceeded the available height in both locations, preventing us from maintaining consistent tension with a properly suspended mass. As a result, testing in 520 relied on manual tensioning, introducing potential human error; and testing in EVGR required reattaching the mass midway through the lift, disrupting continuity.

2) Unintended Cable Bending and Safety Concerns:

Due to space constraints and human risk, we were forced to use a horizontally oriented guide sheave, which introduced a 45° pre-spooling bend—significantly higher than our design's intended <10° bend. This prevented us from verifying Engineering Requirement ER1-1a. Retesting with a vertical sheave.

To address these challenges, Renewell should explore securing a taller testing location, such as conducting tests at actual well sites, or designing a specialized test rig that maintains consistent cable tension without requiring full well depth.

Once the testing conditions are improved, we recommend running multiple spooling cycles with a weight attached, and using the gathered data to further refine the control system's precision and consistency. During our tests at EVGR, the full spooling cycle was time-consuming, limiting the number of trials we could conduct due to setup logistics, transportation, scheduling conflicts, and authorization requirements. Although we collected sufficient data to verify our engineering requirements, additional testing would further optimize control parameters and troubleshoot sources of error affecting cable spooling.

Since our prototype successfully demonstrated a control loop capable of neat cable spooling, the next step is refining the mechanical design and testing under full-scale loading conditions. While our prototype was tested with a relatively small 6 lb weight, Renewell's system operates at a much larger scale, lifting and lowering a 30,000 lb mass. To validate the feasibility of our translating model under substantial loads, future teams should focus on designing a system capable of sustaining these forces.

In our prototype, linear rails were sufficient for translating the drum and cart assembly under light loads, but at higher loads, bending and frictional forces within the linear rail could become

a significant issue. To address this, we recommend transitioning to a trolley and I-beam system instead of linear rails, as this would better accommodate the increased load.

Additionally, introducing a secondary translation mechanism to move the system away from the well opening could help further reduce the 4 degree bending around the control sheave. Here, the drum would translate away from the well opening as the radius grows with each subsequent cable layer. A cost-benefit analysis should be conducted before pursuing this design in order to evaluate if adding a third motor and additional axis of translation would be a worthwhile investment.

7. References

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8. Appendices

8.1 Team Members, Roles, and Responsibilities

Kai Rayle: Company Liaison

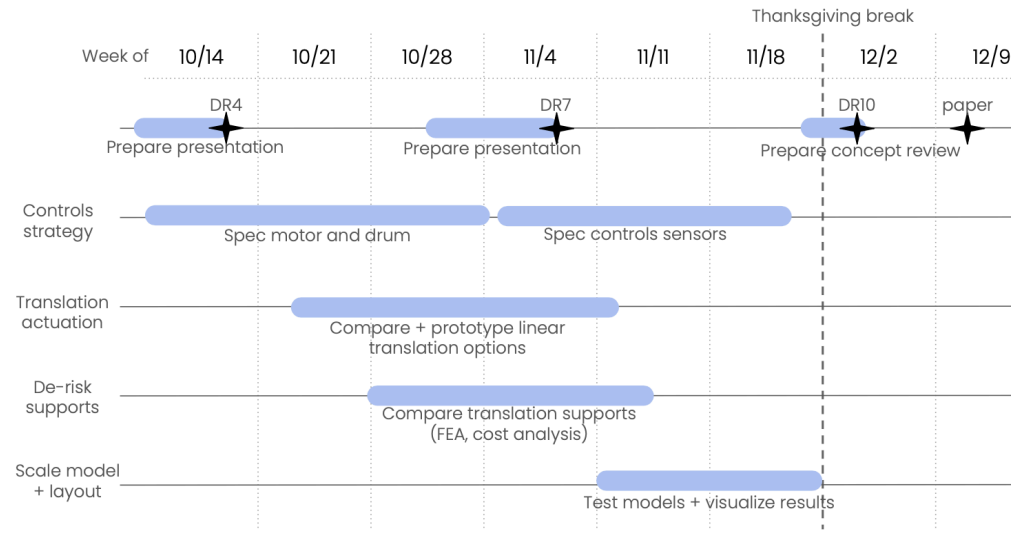
Melanie Quan: Project Manager, Document Focal Point

Nolan Topper: Engineering Requirements Manager

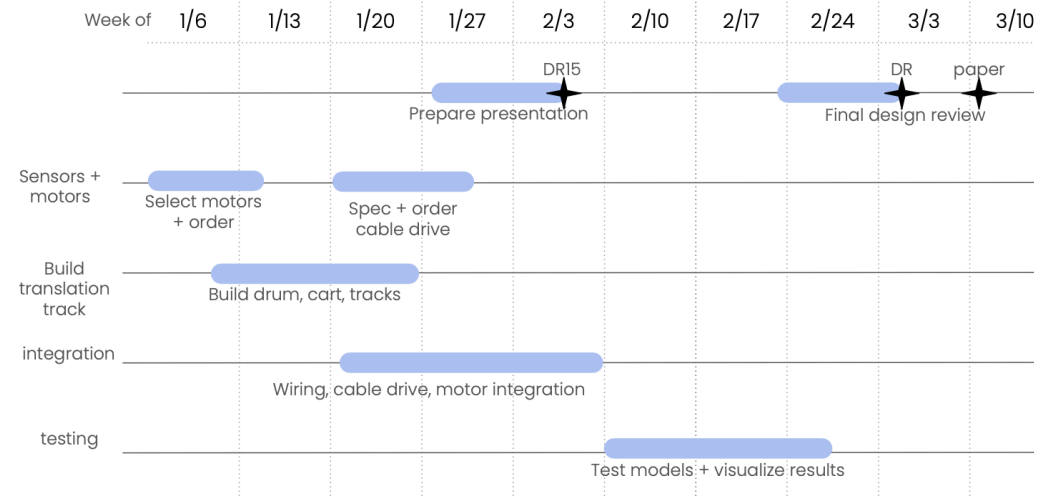
Sarah Hwang: Materials Manager, Document Focal Point

8.2 Gantt Chart

Quarter 1:



Quarter 2:



8.3 User and Engineering Requirements

Req.	Priority	User(s)	User Requirements	Justification	Source
Performance / Features					
UR1-1	HIGH	RENEWELL	Winch system should maximize cable longevity (>15 years)	Due to the high cost of wire rope, to minimize the overall cost of the system and operations, the winch system should be designed to preserve the condition of the rope.	Liaison meeting
UR1-2	HIGH	RENEWELL	Winch system must spool wire rope so each cable line is positioned side by side rather than overlapping	Wire must be placed onto spool so that each cable line is lined up in order to maximize length of rope stored on drum, which is around 4000 ft for their working system.	Liaison meeting, project debrief
UR1-3	HIGH	RENEWELL	The drum should be able to support the full length of cable needed in the system	Ability to spool amount of rope on the drum for the full depth of well is important for the value of the battery.	Liaison meeting
Environment / Operating Conditions					
UR2-1	HIGH	RENEWELL/ Operators	Winch prototype must withstand California climate conditions	The system should be able to withstand environmental conditions of where it is intended to be used in order to be a viable solution. For the scope of the project, RENEWELL has defined that at minimum the system must be able to withstand California's climate	Liaison meeting
UR2-2	MEDIUM	RENEWELL/ Operators	Winch should withstand all continental US climate.	To be an implementable solution for RENEWELL's oil wells around the US, the winch system should be able to operate in more extreme climates such as precipitation, freezing, and humidity.	Liaison meeting
Reliability					
UR3-1	MEDIUM	RENEWELL/ Operators	Winch system should be able to consistently endure repeated cycles without fail	The expected maintenance inspection is once a year, encompassing a visual inspection of wire rope, grease and oil cleaning.	Liaison meeting
Conformance					
No identified conformance requirements for this system					10/9/24 Liaison Meeting

Req.	Engineering Requirements	Measurement Method	Justification
Performance / Features			
ER1-1a	Target 4 layers and must be less than 8 layers.	Counting	As a high number of bends in the rope decrease the life of the rope, the number of wraps should be kept to a minimum. Based on Renwell's analysis of their system, they stated that 8 layers should be the maximum.
ER1-1b	Neat spooling	Qualitative inspection, measure outer radius after each layer of rope is added to make sure they are not overlapping in one area	Having the wires lie in a fishing-line like manner reduces friction that could come from ropes in the same layer that may intersect and overlap is minimized.
ER1-2a	Maximum gap between adjacent wraps of 1/10 diameter	Spool full length and measure displacement	Extra gap between adjacent wraps requires more spooling and extra friction.
ER1-2b	Fleet angle of <1.5 degrees must be maintained	CAD Assembly	The fleet angle of <1.5 must be adhered to for system's drum to be able to spool wire rope.
ER1-3	Drum length and radius can hold wire with a length of 4000 ft and a diameter of 2.2cm while having less than 8 layers.	Spool full length or equivalent for scale model	The drum needs support enough cable to travel the full depth of the well to maximize energy storage for Renwell's system. x x
Environment / Operating Conditions			
ER2-1	Winch subsystem should be able to function in a 60-70 degree, dry, sunny climate.	Test prototype in different conditions, using thermometer/weather app.	The average California climate is around 60-70 degrees F.
ER2-2a	Winch subsystem should be able to function in -30 -150 F	Test prototype in different conditions, using thermometer/weather app.	Temperatures across the US can range from -30 to 150 degrees F.
ER2-2b	Winch system should be able to operate in slightly damp conditions	Add moisture to system then check functionality.	The RENEWELL system will be exposed to wet conditions that the drum, needs to withstand.
Reliability			
ER3-1a	Low efficiency losses from friction or improper loading after 1000 cycles.	Cycle system 1000 times, then measure output and input from a few cycles	Ensure that the system is designed to endure repeated cycles with minimal loss to efficiencies so that it is not a liability to the operator.
ER3-1b	Low wear to rope after 1000 cycles	Qualitative observation of the rope's condition	To ensure the reliability, after testing the system for at least 1000 cycles, the condition of the rope can be qualitatively observed to ensure that the designed system does not cause noticeable damage to the rope.
Conformance			

8.4 FMEA

dFMEA Item	Functions		Potential Failure Mode(s)			Potential Causes					Recommended Action(s)		Action Results								
	Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S e v e r i t y	Potential Cause(s)/ Mechanism(s) of Failure	O c c u r r e n c e	Current Design Controls	D e t e c t	R e p a r t	C o n t r o l	Recommended Action(s)	Responsibility	Target Completion Date	Actions Taken	New Sev	New Occ	New Det	New RPN	New CRI	
d1	Frame	Provides structure for rails and cable	Buckling	10-15lbs drum free falls from tower	16	Downwards forces of gravity and tension result in buckling on the frames	4	Truss system with supporting columns and cross beams	4	160	40	Kai	1/24/2025						4	0	
d2	Rail	Supports cart	Bending then breaking	Drum-cart+weight assembly falls through	8	Weight of drum-cart assembly causes rails to bend	4	Selecting rail with appropriate safety factor	3	96	32	Nolan	1/24/2025							0	0
c	Drum + Cart Assembly	Rolls along the rails to translate back and forth	Tipping	10-15lbs drum free falls from tower	10	Connected weight swinging knocks cart wheels off rail	6	Control sheave to prevent cable from swinging while rotating	4	240	60	Nolan	1/24/2025	Moved drum off well hole.		5	3	4	60	15	
d4	Guide rails + cart wheels	Translates	Binding on track	Excessive tension to failure in driving cable system causing it to snap and whip testers	6	Guide rail uneven causing binding, force on drum damaging wheels, repeated testing stresses wheel system	4	Testing wheel system, ensuring rail is straight and functional	3	96	32	Kai	2/14/2025							0	0
d5	Winching motor	Winds the tensioned cable around the drum to raise the weight	Motor stalls	System cannot lift mass, system stops lifting mass mid-way	6	Uneven foundation, inefficient motor losses, DC motor loses power	3	Selecting the appropriate DC motor to withstand the torque, testing an unloaded system.	5	75	15	Melanie	1/31/2025							0	0
d6	Winching motor	Controls drum rotation	Loose connection to rotational motor (connecting gear/side snaps) or power lost to motor	Weight freefalls to ground	10	Increased load on system stresses motor connection, wire connecting motor pulled out, power loss	5	FEA on gears and motor connection ensuring strength and reliability	5	250	50	Nolan	1/31/2025	Safety system to catch weight		3	5	5	75	15	
d7	Winching Cable	Wound on drum, attached to and used for lifting the mass	Breaking	Whipping up and hitting testers, dropping weight	4	Cable wear from high friction or repeated bending	3	Selecting cable with appropriate material properties, minimize bending and loading in the cable	4	60	15	Sarah	1/31/2025							0	0
d8	Driving cable	Attached to the drum-cart assembly, driving its linear translation with the pulley-motor system	Slipping or slack in the cable	Linear translation not consistent	4	Elasticity of cable, weight of the drum and cart assembly	8	Designing system with appropriate tensioners, selecting the driving cable for purchase	3	96	32	Sarah	1/31/2025							0	0
d9	Control system	Controls translational motion	Failure to neatly spool	Tangling of cable, damage to frame/motors/drum, stalling of motor, not neatly spooling cable	4	Slipping or binding on the pulley with a rotary encoder or interference with the limit switch could send false inputs to the controls system and cause premature or delayed switching of translation direction.	4	Tension the cable to prevent slipping and consider notching the driving pulley. Use a counter for total rotations to get the length of cable spooled	4	0	0	Melanie	2/14/2025							0	0
d10	Passive cable drive	Determines position of drum by rotating a rotary encoder	Cable length change	Inaccurate position error feedback	4	change in tension, elongation of cable from tension or wear	4	Calibration sequence before entering the controls loop to ensure that drum is centered above the lead sheave	4			Melanie	2/14/2025								
d11	Sheave	Positions cable above well	Bending/snapping	Weight moves and is unstable	4	Fleet angle between the cord coming off the drum and the sheave too large.	4	FEA on sheave system to ensure strength	4	80	20									0	0

8.6 Project Summary

Goal of Project: We improved the winch system of Renewell's gravity batteries by designing a new method of spooling that minimizes cable wear and maximizes efficiency while also reducing costs.

Background: Renewell's Gravity Wells store energy by lifting and lowering a heavy weight within the vertical space of abandoned oil wells. Their current winch is expensive and incurs a lot of cable wear, which has led to cable failures. The infrastructure to neatly spool the cable that lifts and lowers the weight in the well requires a tall tower that bends the cable into place while spooling.

Project Motivation: We are reimagining spooling by redesigning the winch for Renewell's Gravity Wells. Instead of moving the cable back and forth across the drum, we are translating the drum itself back and forth across the well opening. We prototyped a fifth scale model and the controls software to de-risk this new, innovative winching method.

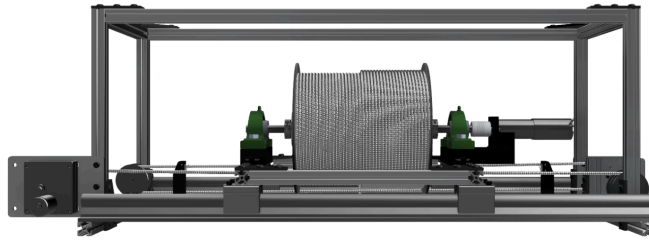
High Priority Requirements:

- Prior to spooling, the maximum bending angle in the system layout should be $<10^\circ$.
- Our translating system should maintain a fleet angle of $<0.1^\circ$ between the drum and sheave.
- A gap of $1/10$ the cable's diameter should be maintained between each cable line on the drum.
- Spooling time for the entire length of cable should be ≤ 1 hr.
- The number of cable wrap layers on the drum should be reduced from 8 to 4 layers.

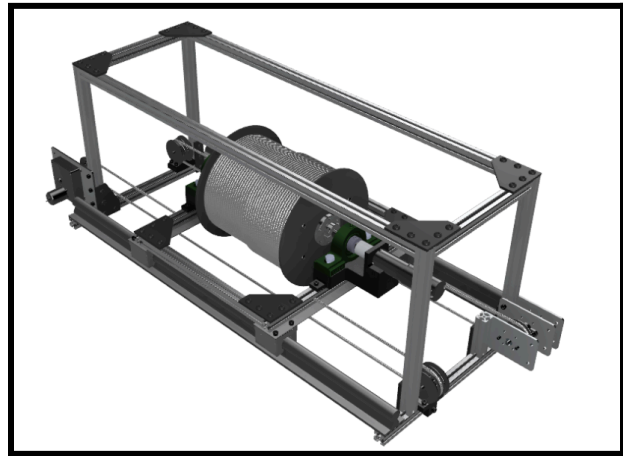
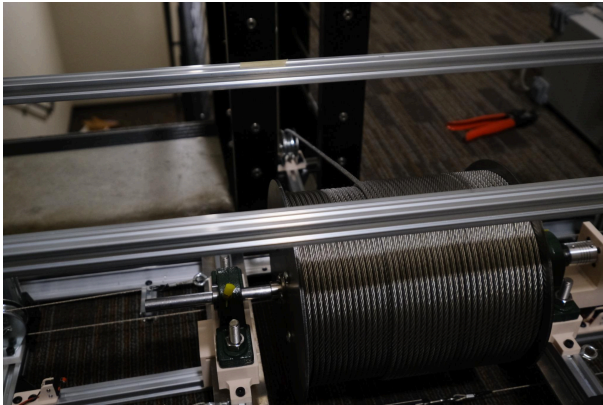
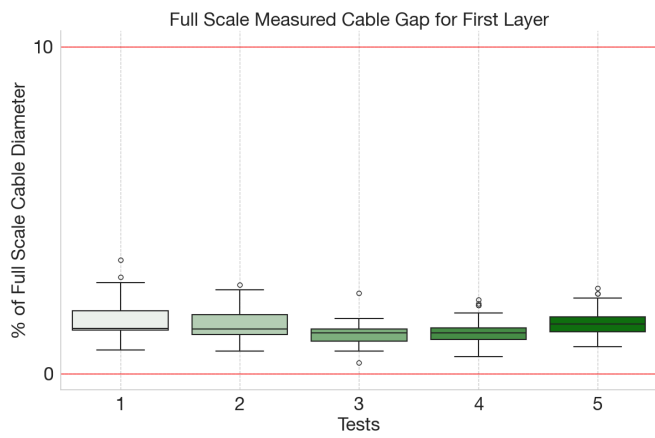
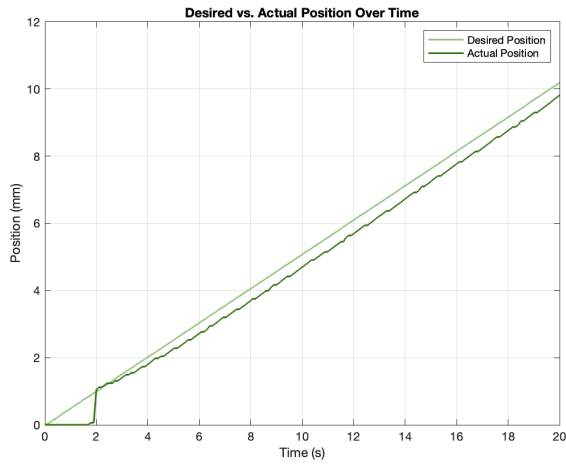
Ethical Considerations: In order to promote sustainable, renewable energy generation, Renewell provides gravity batteries and oil well remediation. The values of sustainable development and minimal environmental impact align with ensuring a long-lasting, reliable system. We also prioritized safety by applying a safety factor of 3 throughout Renewell's system, exceeding their recommendations to account for real-world uncertainties.

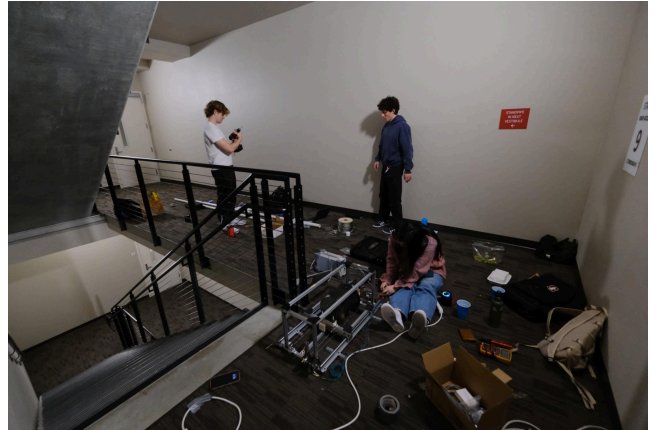
Solution:

In order to neatly spool, we prototyped a drum that moves back and forth above the well opening to neatly spool cable. In order to gain precise positional control of the drum, we incorporated a PID controller to minimize position error. Our testing provides significant promise that a translating drum winch will significantly reduce cable wear and costs, while also neatly spooling cable.



Images:





8.7 Detailed Test Plans and Results

Experimental Goal:

In order to linearly translate the drum and cart assembly (to enable neat spooling with a minimal fleet angle), the force used to pull the cart on the rails must be less than 115 N, which is the calculated maximum force that our motor can pull based on its rated torque and the 0.052 m pulley it will drive. To validate that in our mechanical setup the drum and cart would be able to be translated by the driven cable and inform the control parameters for the output of the motor, we wanted to determine the force needed to overcome static friction from the linear rails of our system and verify that the static friction was the primary force that needed to be accounted for. The decision to test the cart at an incline was to account for an extreme case of an unlevel foundation that could arise in our build and ensure that even so, our rails would be able to translate the cart and drum assembly.

Hypothesis:

If the mass on the cart were increased then the force used to overcome static friction would increase approximately linearly because the primary force acting on the cart and rails should be the friction in the cart bearings governed by $F = f + mgsin(\theta) = mg(\mu\cos(\theta) + \sin(\theta))$ with low frictional forces from the linear bearings.

Variables:

- **Independent Variable:** Mass on the cart, measured in kg [m]
 - **Dependent Variable:** Force required to overcome static friction, measured in N [F]
 - **Controlled Variables:** Incline of the rails, measured in degrees [θ];
Cart assembly tested [μ]; Initial position of the cart [0 meters from bottom end of incline].
-

Experimental Control:

The experimental control used for the experiment was pulling the cart with a 11.33 kg mass at an incline angle of 5 degrees. This weight was used to minimally load the cart so that there was a measurable value of the frictional force of the rail. This control had repeatable results, demonstrating that the set up was valid and would yield reliable results for other levels of the IV.

Materials:

- Cart + Rail Assembly
 - Aluminum Plate
 - 0.06 m blocks
 - Inclinometer (Phone)
 - Hanging Scale (660 lbs/300 kg; Brand: Modern Step)
-

Procedure:

1. Place the cart and rail assembly on a level surface and place an aluminum plate on top to hold the mass on the cart.
2. Place two 0.06 m blocks under the same end of each rail to create an incline angle of 5 degrees and verify the angle by placing an inclinometer on the aluminum plate and measuring.

3. Start the cart on the bottom end of the rail.
4. Place a 11.33 kg mass (25 lbs) on top of the aluminum plate resting on the cart.
5. Hook the force gauge to the cross beam of the cart facing the top end of the rail.
6. Pull the force gauge until the cart begins to move, recording the force at which the cart overcomes static friction.
7. Reset position of car at bottom of incline. Increase mass on cart by 11.33 kg (25 lbs).
8. Repeat steps 5-7 until a mass of 56.70 kg (125lbs) has been tested.

8.8 Bill of Materials

Encoder for Translation	\$32
Motor for Translation	\$82
Motor for Rotation with Encoder	\$603
Motor Controller	\$135
Linear Rail	\$37
80/20	\$76
Hardware for Frame Connections	\$100
Pulleys (x 4)	\$30
1/16" Steel Cable	\$10
Steel Pipe for Drum	\$40
3/16 Steel Cable - 250 ft length	\$63
Mass Assembly	\$30
Miscellaneous connection hardware	\$150
Total	~ \$1388

8.9 Fleet Angle Compensator

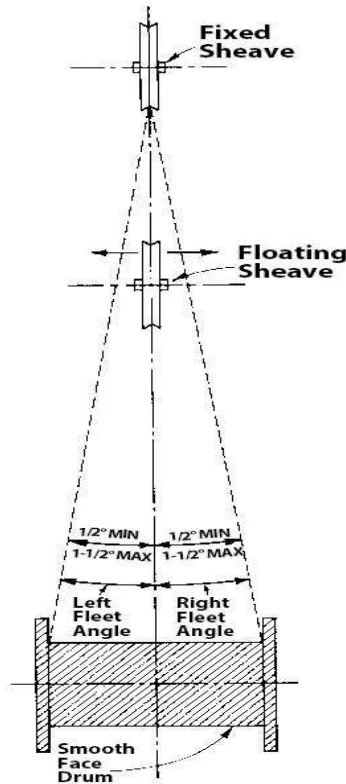


Figure 7: Fleet angle compensator diagram

The fleet angle compensator controls the placement of the cable onto the drum. It does this by shearing a sheave against the cable to direct it at an angle from the centerline of the drum. This fleet angle cannot exceed 1.5° or else it enters a chaotic regime where the cable can be easily tangled. Because of the limit on the fleet angle, the fleet angle compensator must be very tall to spool onto a drum from a distance; a longer drum needs a taller fleet angle compensator. Because of this, Renewell's existing design is constrained by height of the fleet angle compensator, so their drum is shorter than what we propose (needing 8 wraps of cable). Additionally, there is concern with cable wear as the cable bends against the floating sheave.

8.10 Arduino Controls Code

```
#include <SoftwareSerial.h>
#include <Metro.h>
#include <math.h>
#include <RoboClaw.h>

// constants
#define address 0x80
#define FULLSPEED 125
#define NOSPEED 0
#define DRUM_DIAM_BASE_MM 165.1
#define DRUM_RPM 5.5
#define DRUM_ENC_CPR 100.0 * 4.0
#define CART_ENC_CPR 512 * 4 // cpr = ppr * 4
#define PULLEY_DIAM_MM 39.78
#define LAYER_LIMIT 4
#define WRAP_LIMIT 38.9
#define CART_RPM 0.338
#define M2_GEARBOX_RATIO 1140
#define M1_GEARBOX_RATIO 7189
#define CABLE_SPACING_TOL 1.1
#define CABLE_DIAM_MM 4.8 * CABLE_SPACING_TOL
// #define CABLE_DIAM_MM 5.8 * CABLE_SPACING_TOL
#define DIST_PER_REV_MM M_PI * PULLEY_DIAM_MM
#define DIST_PER_COUNT_MM DIST_PER_REV_MM / (CART_ENC_CPR)
#define CART_SPEED_MM_PER_MIN CABLE_SPACING_TOL * DRUM_RPM * CABLE_DIAM_MM
#define LENGTH_MM 203
#define CART_RPM_MAX 0.7
#define DRUM_RPM_MAX 6667 / M2_GEARBOX_RATIO
#define QPPS_cart ((CART_ENC_CPR / 4) * CART_RPM) / 60
// #define CART_SPEED ((CART_ENC_CPR / 4) * CART_RPM) / 60
// #define QPPS_DRUM ((DRUM_ENC_CPR / 4) * M2_GEARBOX_RATIO * DRUM_RPM_MAX) / 60
#define DRUM_SPEED ((DRUM_ENC_CPR) * M2_GEARBOX_RATIO * DRUM_RPM) / 60
#define DRUM_SPEED_UNWINCHING -41800
// #define QPPS_cart 40000
#define CART_SPEED 10000
#define QPPS_DRUM 41800
#define QPPS_DRUM_UNWINCHING -41800
// #define DRUM_SPEED 10000

// Arduino digital pins
#define SERIAL_1 10
#define SERIAL_2 11
#define LIMIT_LEFT 3
#define LIMIT_RIGHT 4

// Arduino SoftwareSerial
SoftwareSerial serial(SERIAL_1, SERIAL_2);
RoboClaw roboclaw(&serial, 10000);

// states
typedef enum {
    WINCHING, UNWINCHING, WINCHING_RIGHT, WINCHING_LEFT,
    UNWINCHING_RIGHT, UNWINCHING_LEFT, LEFT, RIGHT, MANUAL_MOVE
} States_t;
States_t state = MANUAL_MOVE;

// timers
static Metro printStateTimer = Metro(3000);
```

```

static Metro printPositionTimer = Metro(1000);
static Metro printTimeFromStart = Metro(100);

bool printState = false;

// position tracking
long cartEncoderCount = 0;
long drumEncoderCount = 0;
long drumEncoderCountBaseline = 0;
long drumEncoderCountcartient = 0;
float desiredDrumPosition = 0;
float wraps = 0;
long layers = 0;
long drumDiameter = DRUM_DIAM_BASE_MM;
bool rightLimit = false, leftLimit = false;
float endPosition = LENGTH_MM;
bool isWinching = false, isUnwinching = false;
bool encodersCalibrated = false;
float startTime;
float cartPositionMM = 0;
float desiredCartPositionMM;
long desiredcartEncoder;
long Kp = 3.5, Kd = 1.0, Ki = 0.2;

bool setPIDVelocity = false;

long position_error;
long velocity_error;

long proportionalControlError;
long differentialControlError;
long integralControlError;
long errorSignal;
long pwm;

int rightSwitchHit = 0;
int leftSwitchHit = 0;

void setup() {
  Serial.begin(57600);
  roboclaw.begin(38400);
  // Serial.println("Starting");
  setInitialValues();
  // Serial.println("Manual set-up");
  state = MANUAL_MOVE;
}

void setInitialValues(){
  //roboclaw.ForwardM1(address, NOSPEED);
  //roboclaw.ForwardM2(address, NOSPEED);
  roboclaw.SetM2VelocityPID(address,1,0,0,QPPS_DRUM);
  roboclaw.ResetEncoders(address);
  // arduino pins
  pinMode(LIMIT_RIGHT, INPUT_PULLUP);
  pinMode(LIMIT_LEFT, INPUT_PULLUP);

  startTime = millis();
  roboclaw.ResetEncoders(address);
}

void loop() {

```

```

    checkLimitSwitches();
    checkEncoders();
    checkInputs();
    handleStateMachine();
    // printToCSV();
}

void printCurrentState() {
    printPosition();
    if (printStateTimer.check()) {
        if (state != MANUAL_MOVE) {
            Serial.print("Current state: ");
            Serial.println(stateToString(state));
            printStateTimer.reset();
        }
    }
}

void handleStateMachine() {
    switch (state) {
        case MANUAL_MOVE:
            manualMove();
            break;
        case LEFT:
            left();
            break;
        case RIGHT:
            right();
            break;
        case WINCHING:
            winching();
            break;
        case UNWINCHING:
            unwinching();
            break;
        case WINCHING_RIGHT:
            winching_right();
            break;
        case WINCHING_LEFT:
            winching_left();
            break;
        case UNWINCHING_RIGHT:
            unwinching_right();
            break;
        case UNWINCHING_LEFT:
            unwinching_left();
    }
}

void checkInputs() {
    if (Serial.available()) { // Read from Python script
        char command = Serial.read();
        switch (command) {
            case 'l': state = LEFT; break;
            case 'r': state = RIGHT; break;
            case 'w': state = WINCHING; break;
            case 'u': state = UNWINCHING; break;
            case 'x': state = WINCHING_RIGHT; break;
            case 'y': state = UNWINCHING_RIGHT; break;
            case 'm': state = MANUAL_MOVE; break;
        }
    }
}
}

```

```

void manualMove() {
    roboclaw.ForwardM1(address, 0);
    roboclaw.ForwardM2(address, 0);
}
/* Function that makes the drum go all the way to the left until it hits the limit
switch.
* The output is the drum aligned left and in the manual state.
*/
void left() {
    roboclaw.BackwardM1(address, FULLSPEED);
    if (leftLimit == true) {
        state = MANUAL_MOVE;
        roboclaw.SetEncM1(address, 0);
        cartEncoderCount = 0;
    }
}
/* Function that makes the drum go all the way to the right until it hits the limit
switch, and then stops.
* The output is the drum aligned right and in the manual state.
*/
void right() {
    roboclaw.ForwardM1(address, FULLSPEED);
    if (rightLimit == true) {
        state = MANUAL_MOVE;
        roboclaw.SetEncM1(address, 0);
        cartEncoderCount = 0;
    }
}
void winching() {
    // winching motor only
    if (!isWinching) {
        desiredDrumPosition = drumEncoderCount + 400;
        isWinching = true;
    }
    roboclaw.ForwardM1(address, NOSPEED);
    roboclaw.ForwardM2(address, FULLSPEED);
}
void unwinching() {
    // winching motor only
    if (!isUnwinching) {
        desiredDrumPosition = drumEncoderCount - 400;
        isUnwinching = true;
    }
    roboclaw.ForwardM1(address, NOSPEED);
    roboclaw.BackwardM2(address, FULLSPEED);
}
void winching_right() {
    // determine state based upon position
    if (!encodersCalibrated) {
        roboclaw.ResetEncoders(address);
        encodersCalibrated = true;
        checkEncoders();
    }

    // set the speed of the winching motor
    roboclaw.SpeedM2(address, DRUM_SPEED);

    // set speed of translating motor
    cartMotorFeedbackPWM();

    if (rightLimit || cartPositionMM > LENGTH_MM) {

```

```

    endPosition = cartPositionMM;
    drumEncoderCountBaseline = drumEncoderCount;
    wraps = 0;
    if (layers > 3) {
        state = UNWINCHING_LEFT;
        layers--;
    } else {
        state = WINCHING_LEFT;
        layers++;
    }
}
}

void winching_left() {
    roboclaw.SpeedM2(address, DRUM_SPEED);
    cartMotorFeedbackPWM();

    // determine state based upon position
    if (!encodersCalibrated) {
        roboclaw.ResetEncoders(address);
        encodersCalibrated = true;
        checkEncoders();
    }
    if (leftLimit || cartPositionMM <= -20.0 * CABLE_DIAM_MM) {
        drumEncoderCountBaseline = drumEncoderCount;
        if (layers >= 3) {
            state = UNWINCHING_RIGHT;
            layers--;
        } else {
            state = WINCHING_RIGHT;
            layers++;
        }
        wraps = 0;
    }
}

void unwinching_right() {

    // determine state based upon position
    if (!encodersCalibrated) {
        roboclaw.ResetEncoders(address);
        encodersCalibrated = true;
        checkEncoders();
    }

    if (!setPIDVelocity) {
        roboclaw.SetM2VelocityPID(address,1,0,0,-41800);
        setPIDVelocity = true;
    }

    // set winching speed
    roboclaw.SpeedM2(address, DRUM_SPEED_UNWINCHING);

    // set translating speed
    cartMotorFeedbackPWM();

    if (rightLimit || cartPositionMM > LENGTH_MM) {
        drumEncoderCountBaseline = drumEncoderCount;
        endPosition = cartPositionMM;
        wraps = 0;
        layers--;
    }
}

```

```

    state = UNWINCHING_LEFT;
}
}
void unwinching_left() {
    // determine state based upon position
    if (!encodersCalibrated) {
        roboclaw.ResetEncoders(address);
        encodersCalibrated = true;
        checkEncoders();
    }

    if (!setPIDVelocity) {
        roboclaw.SetM2VelocityPID(address,1,0,0,-41800);
        setPIDVelocity = true;
    }

    // set winching speed
    roboclaw.SpeedM2(address, DRUM_SPEED_UNWINCHING);

    // set translating speed
    cartMotorFeedbackPWM();

    if (leftLimit || cartPositionMM <= -20.0 * CABLE_DIAM_MM) {
        drumEncoderCountBaseline = drumEncoderCount;
        wraps = 0;
        layers--;
        state = UNWINCHING_RIGHT;
    }
}

void cartMotorFeedbackPWM() {
    if (state == WINCHING_RIGHT) {
        desiredCartPositionMM = wraps * CABLE_DIAM_MM;
    } else if (state == WINCHING_LEFT) {
        desiredCartPositionMM = endPosition - (wraps * CABLE_DIAM_MM);
    } else if (state == UNWINCHING_RIGHT) {
        desiredCartPositionMM = -wraps * CABLE_DIAM_MM;
    } else if (state == UNWINCHING_LEFT) {
        desiredCartPositionMM = endPosition + (wraps * CABLE_DIAM_MM);
    }
    desiredcartEncoder = (desiredCartPositionMM / (PI * PULLEY_DIAM_MM)) * CART_ENC_CPR;

    //pid
    position_error = desiredcartEncoder - cartEncoderCount;
    velocity_error = roboclaw.ReadSpeedM1(address) - QPPS_cart;

    proportionalControlError = position_error * Kp;
    differentialControlError = -1 * roboclaw.ReadSpeedM1(address) * Kd;
    integralControlError = (integralControlError + position_error) * Ki;

    errorSignal = proportionalControlError + differentialControlError +
integralControlError;

    pwm = errorSignal;

    if (pwm > 126) {
        pwm = 126;
        roboclaw.ForwardM1(address, pwm);
    } else if (pwm < -126) {
        pwm = 126;

```

```

        roboclaw.BackwardM1(address, pwm);
    } else if (pwm > 0) {
        roboclaw.ForwardM1(address, pwm);
    } else if (pwm < 0) {
        pwm = abs(pwm);
        roboclaw.BackwardM1(address, pwm);
    }
}

void checkLimitSwitches() {
    if (digitalRead(LIMIT_RIGHT) == LOW) {
        rightSwitchHit++;
        Serial.println("Right switch triggered");
    } else {
        rightLimit = false;
    }
    if (digitalRead(LIMIT_LEFT) == LOW) {
        leftSwitchHit++;
        Serial.println("Left switch triggered");
    } else {
        leftLimit = false;
    }

    if (rightSwitchHit > 3) {
        rightLimit = true;
        rightSwitchHit = 0;
        Serial.println("DIRECTION CHANGE R -> L");
    } else {
        rightLimit = false;
    }

    if (leftSwitchHit > 3) {
        leftLimit = true;
        leftSwitchHit = 0;
        Serial.println("DIRECTION CHANGE L -> R");
    } else {
        leftLimit = false;
    }
}

void checkEncoders() {
    cartEncoderCount = (long) roboclaw.ReadEncM1(address);
    drumEncoderCount = roboclaw.ReadEncM2(address) / (M2_GEARBOX_RATIO);

    drumEncoderCountcartient = (long) drumEncoderCount - drumEncoderCountBaseline;
    cartPositionMM = cartEncoderCount * DIST_PER_COUNT_MM;

    wraps = (float) drumEncoderCountcartient / (DRUM_ENC_CPR);

    if (leftLimit) {
        cartPositionMM = 0;
        roboclaw.SetEncM1(address, 0);
    }

    if (wraps > 500) {
        wraps = wraps - 9418.72;
    }
}

void printPosition() {

```

```

if (printPositionTimer.check()) {
  if (state != MANUAL_MOVE) {
    Serial.print("Position in mm from left: ");
    Serial.println(cartPositionMM);
    Serial.print("Cart Encoder Count: ");
    Serial.println(cartEncoderCount);
    Serial.print("Desired cart position in mm from left: ");
    Serial.println(desiredCartPositionMM);
    Serial.print("Wraps: ");
    Serial.println(wraps);
    Serial.print("PWM: ");
    Serial.println(pwm);
    printPositionTimer.reset();
  }
}

void printToCSV() {
  if (printTimeFromStart.check()) {
    if (state != MANUAL_MOVE) {
      Serial.print(millis() - startTime);
      Serial.print(",");
      Serial.print(position_error);
      Serial.print(",");
      Serial.print(desiredCartPositionMM);
      Serial.print(",");
      Serial.print(cartPositionMM);
      Serial.print(",");
      Serial.println(pwm);
      printTimeFromStart.reset();
    }
  }
}

const char* stateToString(States_t state) {
  switch (state) {
    case WINCHING: return "WINCHING";
    case UNWINCHING: return "UNWINCHING";
    case WINCHING_RIGHT: return "WINCHING_RIGHT";
    case WINCHING_LEFT: return "WINCHING_LEFT";
    case UNWINCHING_RIGHT: return "UNWINCHING_RIGHT";
    case UNWINCHING_LEFT: return "UNWINCHING_LEFT";
    case LEFT: return "LEFT";
    case RIGHT: return "RIGHT";
    case MANUAL_MOVE: return "MANUAL_MOVE";
    default: return "UNKNOWN";
  }
}

void updateDrumDiameter() {
  drumDiameter = DRUM_DIAM_BASE_MM + layers * CABLE_DIAM_MM * 2;
}

```

8.11 Python Script

```
import serial
import csv
import time
import threading

# connects to the Arduino's port
SERIAL_PORT = "/dev/tty.usbmodem101"
BAUD_RATE = 57600


# name of the output .csv file
CSV_FILENAME = "arduino_log14.csv"

# opens serial connection
ser = serial.Serial(SERIAL_PORT, BAUD_RATE, timeout=1)
time.sleep(2) # Allow time for connection
ser.flush() # Clear any existing data in the buffer
file = open(CSV_FILENAME, mode="w", newline="")
writer = csv.writer(file)
writer.writerow(["Time (s)", "Message"])
start_time = time.time()

# continuously reads and logs serial data
def read_serial():
    while True:
        line = ser.readline().decode('utf-8').strip()
        if line:
            elapsed_time = round(time.time() - start_time, 2)
            print(f"[{elapsed_time}s] {line}")
            writer.writerow([elapsed_time, line])
            file.flush()

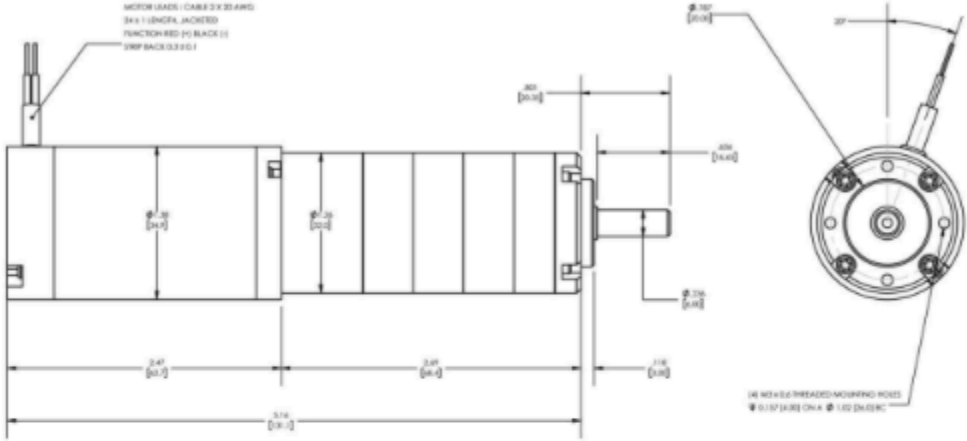
# start the serial reading in a separate thread
thread = threading.Thread(target=read_serial, daemon=True)
thread.start()
print("Logging data... Type commands to send, or press Ctrl+C to stop.")
try:
    while True:
        command = input("Enter command: ").strip()
        if command:
            ser.write((command + "\n").encode('utf-8'))
except KeyboardInterrupt:
    print("\nStopping logging...")
finally:
    ser.close()
    file.close()
```

8.12 Motors, Encoders, and Motor Controller Spec Sheets



REVERSIBLE DC GEARMOTOR

Model Number:
MMP S14-247C-12V GP32-1140



DIMENSIONS ARE INCHES UNLESS OTHERWISE STATED

PLANETARY GEARMOTOR OUTPUT PARAMETERS:	VALUE	UNITS	TOLERANCE
Gearhead Ratio (exact)	1139.73 : 1		
Gearhead Shaft Output Speed (at full-load)	4.9	RPM	MAX
Gearmotor Rated Continuous Torque	79	In-Lbs	MAX
Gearmotor Rated Peak Torque	80++	In-Lbs	----
Gearhead Standard Backlash	99	Arc Minutes	MAX
Gearhead Efficiency	65%	----	----
Output Shaft Radial Load Capacity	30	Lbs	MAX
Output Shaft Axial Load Capacity	9	Lbs	MAX
Gearmotor Total Weight	1.3	Lbs	MAX

++ All Peak Torque values are dependent upon duty. Contact our sales office for details.

DC MOTOR PERFORMANCE PARAMETERS:	VALUE	UNITS	TOLERANCE
Rated DC Voltage	12	DC VOLTS	----
Rated Continuous Current	1.59	AMPERES	----
No-Load Speed	6667	RPM	MAX
Rated Speed	5620	RPM	+/- 15%
Rated Continuous Power Out	7	WATTS	+/- 15%
Rated Continuous Torque	1.7	OZ-IN	----
Peak Torque (motor only)	16	OZ-IN	----
No-Load Current	0.88	AMPERES	MAX
Back EMF Constant (K _e)	1.8	V/KRPM	+/- 10%
Torque Constant (K _t)	2.4	OZ-IN/AMP	+/- 10%
DC Armature Resistance	1.19	OHMS	+/- 15%
Armature Inductance	0.10	mH	+/- 15%
Armature temperature	155	DEG. C	MAX

NOTES:

- ENCODER & BRAKE OPTIONS AVAILABLE - [FOLLOW THIS LINK FOR DETAILS](#)
- NEMA MOUNTING FLANGE OPTION AVAILABLE - [FOLLOW THIS LINK FOR DETAILS](#)

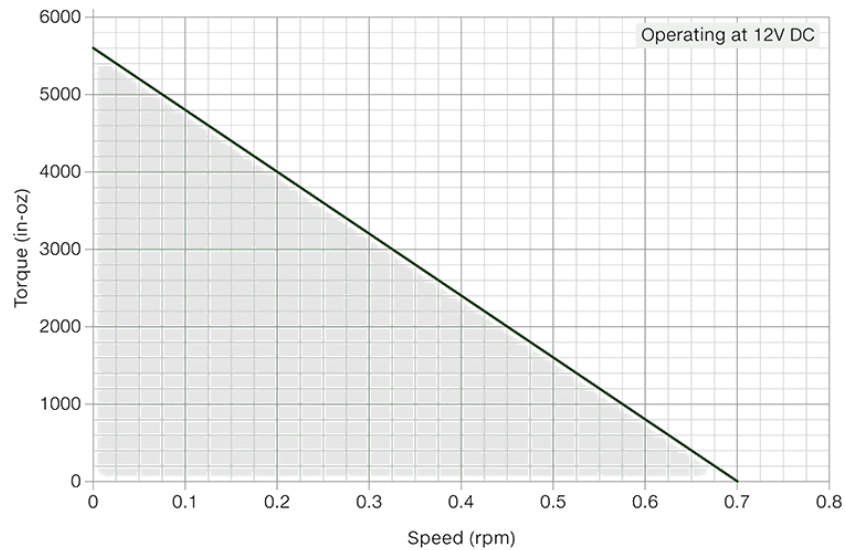
MIDWEST MOTION PRODUCTS

DESIGN, MANUFACTURING & DISTRIBUTION - MOTION CONTROL EQUIPMENT

www.midwestmotion.com email: sales@midwestmotion.com

Torque-Speed Chart

for Gearmotor (6409K11)



McMASTER-CARR.

Power Source	Electric
Mounting Style	Face
Face Shape	Square
Voltage	12V DC
Maximum Speed	0.6 rpm
Speed @ Continuous Operating Torque	0.6 rpm @ 800 in.-oz.
Starting Torque	800 in.-oz.
Radial Load Capacity	Not Rated
Motor Enclosure Type	Open
Power	0.0003 hp
Full Load Current	0.1 A
Electrical Connection Type	Hardwire
Wire Connection Type	Tab Terminals
Duty Cycle	Continuous
Motor Type	Brushed, Permanent Magnet
Service Factor	1
Efficiency	85%
Overall	
Length	3 1/4"
Width	2 3/4"
Height	3"
Mounting Orientation	Any Angle, Horizontal, Vertical
Enclosure Material	Cast Zinc
Gear	
Type	Spur
Material	Acetal Plastic and Metal
Bearing Type	Plain
Plain Bearing Type	Sleeve
Shaft	
Diameter	5/16"
Length	1"
Center to Base	1.43"
Orientation	Parallel
Type	D-Profile
Direction of Operation	Clockwise or Counterclockwise
Insulation	
Class	B
Maximum Temperature	266° F
Mounting Thread Size	10-32
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	Not Compliant
DFARS	Specialty Metals COTS-Exempt
Country of Origin	United States
USMCA Qualifying	No
Schedule B	850110.4040
ECCN	EAR99

SERIES: AMT10 | DESCRIPTION: MODULAR INCREMENTAL ENCODER

FEATURES

- patented capacitive ASIC technology
- low power consumption
- CMOS outputs
- 16 DIP switch selectable resolutions
- index pulse
- modular package design
- straight (radial) and right-angle (axial) versions
- 9 mounting hole options for radial version
- 8 mounting hole options for axial version
- -40-100°C operating temperature



ELECTRICAL

parameter	conditions/description	min	typ	max	units
power supply	VDD	3.6	5	5.5	V
current consumption	with unloaded output		8		mA
output high level		VDD-0.8			V
output low level				0.4	V
output current	CMOS sink/source per channel			2	mA
rise/fall time			30		ns

INCREMENTAL CHARACTERISTICS

parameter	conditions/description	min	typ	max	units
channels	quadrature A, B, and X index				
waveform	CMOS voltage square wave				
phase difference	A leads B for CCW rotation (viewed from front)		90		degrees
quadrature resolutions ¹	48, 96, 100, 125, 192, 200, 250, 256, 384, 400, 500, 512, 800, 1000, 1024, 2048				PPR
index ²	one pulse per 360 degree rotation				
accuracy			0.25		degrees
quadrature duty cycle (at each resolution)	256, 512, 1024, 2048	49	50	51	%
	48, 96, 100, 125, 192, 200, 250, 384, 400, 500	47	50	53	%
	800, 1000	43	50	56	%

Notes: 1. Resolution selected via adjustable DIP switch, pre-set to 2048 PPR. All resolutions are listed as pre-quadrature, meaning the final number of counts is PPR x 4.
2. Some stepper motors may leak a magnetic field causing the AMT index pulse to not function properly (non-magnetic version available with 8 pulses per revolution).

MECHANICAL

parameter	conditions/description	min	typ	max	units
motor shaft length		9			mm
motor shaft tolerance			NOM +0/-0.015		mm
weight	AMT102		20.5		g
	AMT103		14.0		g
axial play				±0.3	mm
rotational speed (at each resolution)	192, 384, 400, 500, 800, 1000, 1024, 2048			7500	RPM
	48, 96, 100, 125, 200, 250, 256, 512			15000	RPM

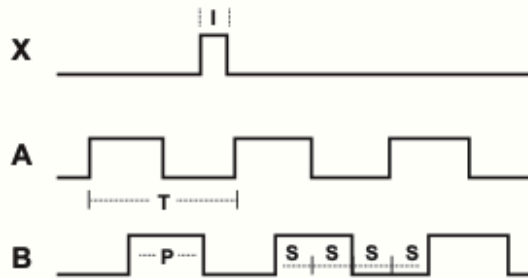
ENVIRONMENTAL

parameter	conditions/description	min	typ	max	units
operating temperature ¹		-40		100	°C
humidity	non-condensing			95	%
vibration	20-500 Hz, 1 hour on each XYZ			10	G
shock	11 ms, ±XYZ direction			50	G
RoHS	yes				

Note: 1. Encoders with operating temperature of -40-125°C are available as a custom order

WAVEFORMS

Figure 1
Quadrature signals with index showing counter-clockwise rotation



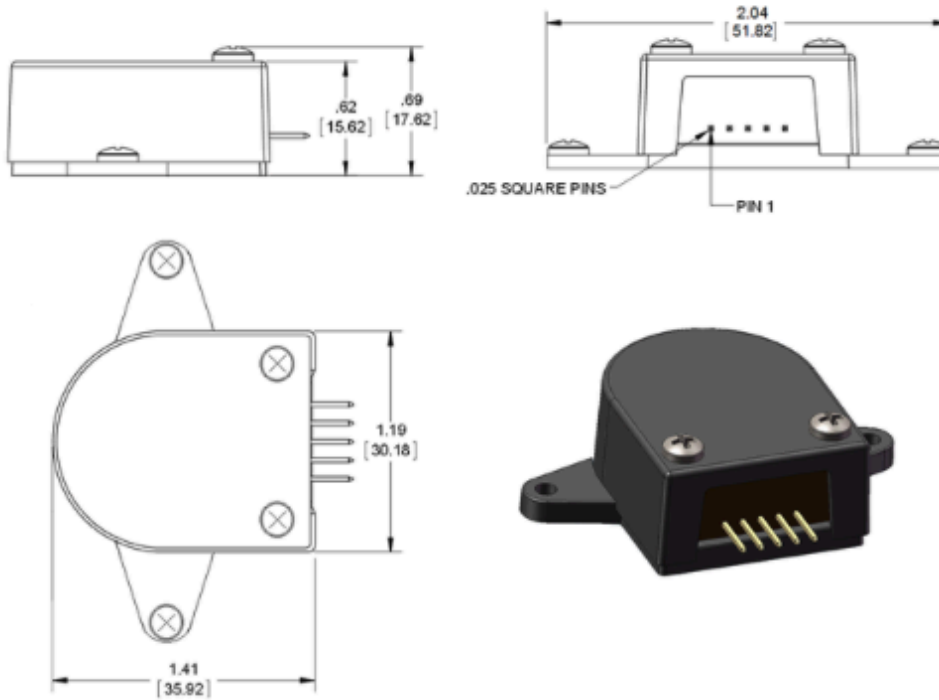
The following parameters are defined by the resolution selected for each encoder. The encoders resolution is listed as Pulses Per Revolution (PPR), which is the number of periods (or high pulses) over the encoders revolution.

Parameter	Description	Expression	Units	Notes
PPR	resolution		Pulses Per Revolution	This is the user selected value and the format all resolutions are listed in
CPR	counts	PPR x 4	Counts Per Revolution	This is the number of quadrature counts the encoder has
T	period	360/R	mechanical degrees	
P	pulse width	T/2	mechanical degrees	
S	A/B state width	T/4	mechanical degrees	This is the width of a quadrature state
I	index width	T/4	mechanical degrees	The width of a once per turn index is the state width for A & B lines

Note: For more information regarding PPR, CPR, or LPR (Lines Per Revolution) view <https://www.ssmeskydevices.com/blog/what-is-encoder-ppr-cpr-and-lpr>

EU Series Optical Encoder: (For use with all MMP motors/gearmotors except all TM series & S17 series)

[DOWNLOAD EU SERIES SPEC SHEET](#)



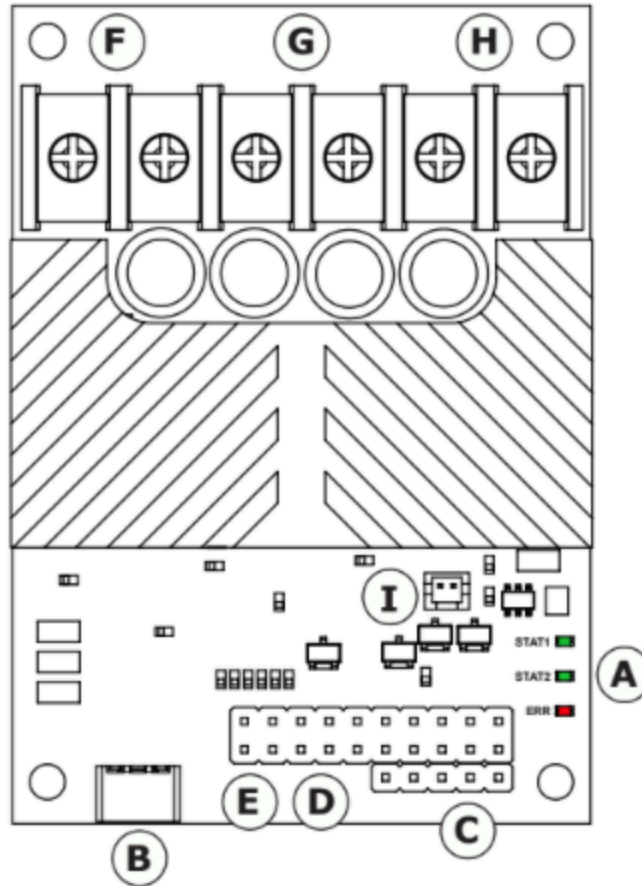
Interconnects / Functions:

Pin :	Description:	Color:
Pin 1	Ground	Brown
Pin 2	Index	Violet
Pin 3	Channel A	Blue
Pin 4	+ 5 Volts	Orange
Pin 5	Channel B	Yellow

- **2 channel quadrature TTL squarewave outputs**
- **Index (3rd channel: 1x/Rev)**
- **12" long flying leads**
- **Encoder is mounted integrally to the back of the motor or brake**
- **Resolutions available: 32 CPR, 100 CPR, 250 CPR, 500 CPR, 1024 CPR**

(Use suffix "EU-xxx" after model # to designate resolution when ordering)

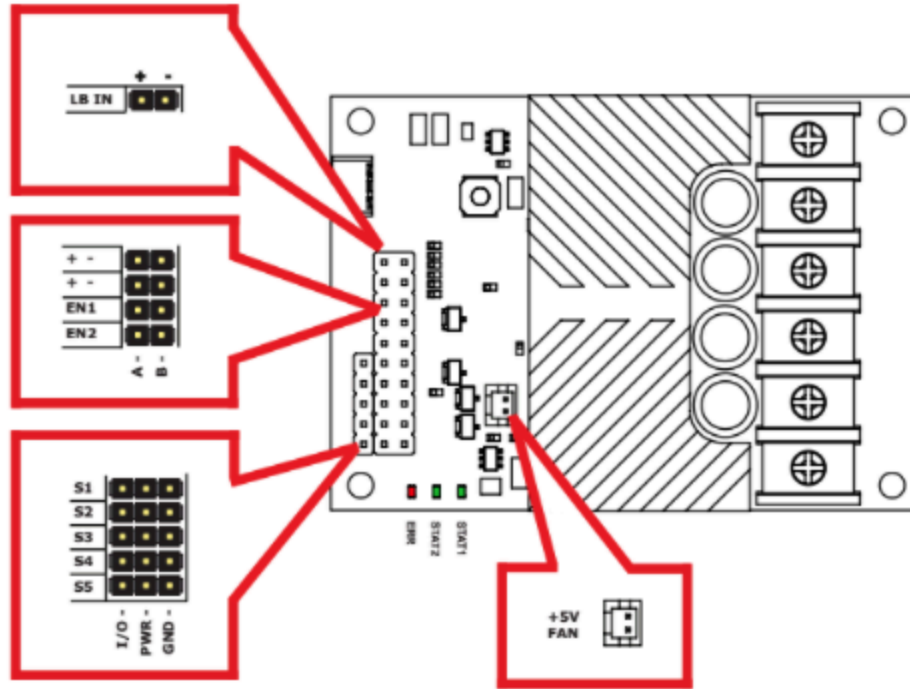
Hardware Overview:



ID	Function	DESCRIPTION
A	Status LEDs	Provides RoboClaw status information.
B	USB Port	Communicate with RoboClaw via USB.
C	Control Inputs	S1,S2,S3,S4 and S5 control inputs.
D	Encoder Inputs	Dual encoder input and power pins.
E	Logic Battery	Logic battery jumper setup and logic battery power input.
F	Motor Channel 1	Motor driver output screw terminals for channel 1.
G	Main Battery	Main battery screw terminal input.
H	Motor Channel 2	Motor driver output screw terminals for channel 2.
I	Fan Control	Fan Controller output. 5VDC. Fan On at 45°C. Fan Off at 35°C

Control Interface

The RoboClaw uses standard male pin headers with 0.100" (2.54mm) spacing. The pin headers are ideal for use with standard servo cables and other popular interface connectors. The table below list the pins and their respective functions. All pins are 5V tolerant and output 3.3V for compatibility with processor such as Raspberry Pi and Arduino. R/C pulse input, Analog and TTL can be generated from any microcontroller such as a Arduino or Raspberry Pi. The R/C Pulse input pins can also be driven by any standard R/C radio receiver. There are several user configurable options available. To configure RoboClaw, install Motion Studio and connect it to an available USB port.



NAME	UART TTL	ANALOG	R/C PULSE	FLIP SWITCH	E-STOP	HOME	LIMIT	V-CLAMP	Encoder
S1	RX	Motor 1	Motor 1						
S2	TX	Motor 2	Motor 2						
S3				X	X			X	
S4					X	Motor 1	Motor 1	X	
S5					X	Motor 2	Motor 2	X	
EN1									Motor 1
EN2									Motor 2
FAN									

Logic Battery (LB IN)

The logic circuit of RoboClaw can be powered from a secondary battery wired to LB IN. A logic battery will prevent brownouts when the main battery is low or under heavy load. The positive (+) terminal is located at the board edge and ground (-) is the inside pin closest to the heatsink.

Encoder Power (+ / -)

The pins labeled + and - are the source power pins for encoders. The positive (+) is located at the board edge and supplies +5VDC. The ground (-) pin is near the heatsink. On RoboClaws with screw terminals, power for the encoders can be supplied by the 5VDC and GND on the main screw terminal.

Encoder Inputs (1A / 1B / 2A / 2B)

The encoders inputs are labeled EN1 and EN2. EN1 is for encoder 1 and EN2 is for encoder 2 which also correspond to motor channel 1 and motor channel 2. Quadrature encoder inputs are typically labeled 1A, 1B, 2A and 2B. Channel A of both EN1 and EN2 are located at the board edge on the pin header. Channel B pins are located near the heatsink on the pin header. Quadrature encoders are directional. When connecting encoders make sure the leading channel for the direction of rotation is connected to A. If one encoder is backwards to the other you will have one internal counter counting up and the other counting down. Use Motion Studio to determine the encoders direction relative to the motors rotation. Encoder channels A and B can be swapped in software using Motion Studio to avoid re-wiring the encoder or motor.

Control Inputs (S1 / S2 / S3 / S4 / S5)

S1, S2, S3, S4 and S5 are configured for standard servo style headers I/O (except on ST models), +5V and GND. S1 and S2 are the control inputs for serial, analog and RC modes. S3 can be used as a flip switch input, when in RC or Analog modes. In serial mode S3, S4 and S5 can be used as emergency stops inputs or as voltage clamping control outputs. When configured as E-Stop inputs, they are active when pulled low. All I/O have internal pull-ups to prevent accidental triggers when left floating. S4 and S5 can be configured as home switch and limit switch inputs. The pins closest to the board edge are the I/Os, center pin is the +5V and the inside pins are ground. Some RC receivers have their own supply and will conflict with the RoboClaw's 5v logic supply. It may be necessary to remove the +5V pin from the RC receivers cable in those situations.

Cooling Fan Control

The fan control will automatically turn on and off a fan based on RoboClaws temperature. The fan will turn on when the board temperature reaches 45°C and will automatically turn off when the board temperature falls below 35°C. The fan control circuit can power a 5VDC fan at up to 230mA. A wide range of fans can be used. The CFM rating of the fan will determine how effective the fan is at cooling. A tested fan is available from DigiKey under part number: 259-1577-ND. However any fan can be used provided it meets the electrical specifications outlined above.

8.13 Total Estimated Cost Savings

Cost Savings	
FAC	\$50,000.00
Foundation	\$5,000.00
Gearbox Efficiency	\$5,000.00
Wire Rope (assumption that reduced wear saves cost of a rope)	\$30,470
Translating Drum Costs	
2 I-Beams	\$2,200.00
Carts	\$5,000.00
Sensors	\$5,000.00
Translational Motor	\$2,000.00
Cables and Pulleys	\$2,000.00
Net Savings	\$74,270.00

8.14 Profit Model

Profit Model

$$E = (0.8)(mgh)$$

$$E = (0.8) \times (30000 \text{ lbs} \times 2.205 \text{ lbs/kg}) \times (9.8 \text{ m/s}^2) \times (4000 \text{ ft} \times 3.281 \text{ ft/m})$$

$$E = 130 \text{ MJ}$$

$$\text{Profit} = E \times \left(\frac{\$0.30}{\text{kWh}} \right)$$

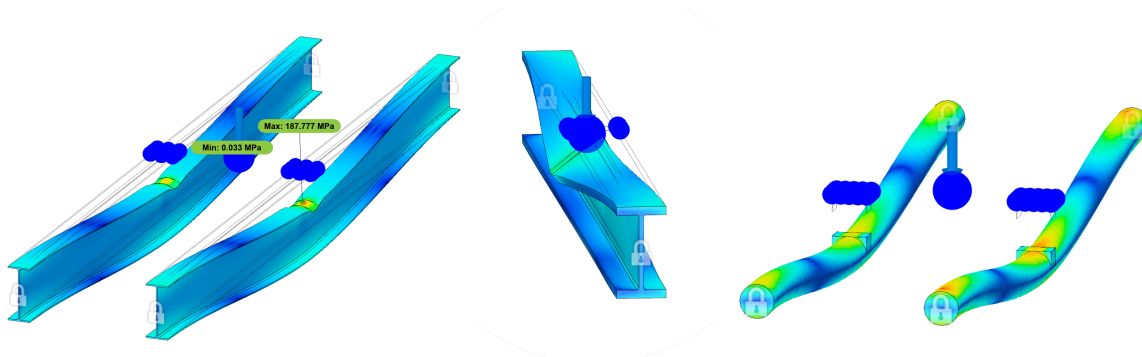
$$\text{Profit} = (130 \text{ MJ}) \times \left(\frac{1 \text{ kWh}}{3.6 \text{ MJ}} \right) \times \left(\frac{\$0.30}{\text{kWh}} \right)$$

$$\text{Profit} = \$10.80 \text{ per day}$$

8.15 Full Scale System

In configurations with a safety factor of 3, we determined that I beams were the most cost-effective option, and that 2 I beams compensated for torsion from a changing load at the lowest price point.

For the FEA of the supports, each setup had two load cases. The two load cases represented the extreme conditions of a fully spooled drum and a fully unspooled drum. Our design mounts the load directly under the beam/beams when the drum is half spooled, so a fully unspooled and spooled load would shift the load 2 inches off the center of the beam and unspooled would shift the load 2 inches the other way. 2 inches is the diameter of the cable (1 inch) multiplied by 2 (half the total number of wraps). In addition to the added offset, we identified the worst-case condition as when the drum translates fully to one side, so the load would be directly in the center of the beam. The constraints here were simply fixed on both ends as that represents the rails being mounted in the foundation.



FEA simulations left to right: two I beams, one I beam, linear rails

Linear Actuation Motor Specification

We used the rated speed of the drum and lift time to determine the necessary translation speed:

$$\text{wrap time} = 60 \text{ sec} / \text{rated rpm} = 11 \text{ sec}$$

$$\text{translation speed} = (\text{cable width} + \text{spacing}) / \text{wrap time} = 2 \text{ mm/sec}$$

We then understood the total loads on the motor pulling the cart:

$$\text{rolling friction (steel on steel)}: 40000 \text{ lbs} * 0.002 = 80 \text{ lbs}$$

$$\pm 0.5^\circ \text{ levelness results in } \pm 400 \text{ lbs}$$

$$\text{Extreme load case: } \sin(0.5 \text{ deg}) * 50000 \text{ lbs} = \sim 480 \text{ lbs}$$

$$\text{selected pulley size: } 150 \text{ mm}$$

$$\text{rated torque} = 32.6 \text{ kg*m}$$

Using the extreme load case (a result of Renewell's foundation levelness tolerance) we determine that the motor must be able to drive 480 lbs in their full scale system. Renewell can adjust their pulley system and gearbox/motor drives to meet this requirement. Additionally, the simplifications to the foundation that our proposed system allows could result in a lower tolerance foundation, reducing the overall load.