Design and Prototype of a Personal Ascending Device Based on the Principle of a Capstan Winch

by
Daniel P. Gillund

Submitted to the Department of Mechanical Engineering in
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Abstract

The consumer market currently offers no options for a low-cost, personal ascending device. The purpose of this project is to propose a powered ascender, actuated by common power tool components and operating on the principle of a capstan winch, as a candidate to fill that void. The first objective was to design and construct a working prototype. The second was to explore the feasibility of manufacturing a low cost consumer version of the product. Safety, functionality, and cost drove the design process.

The ascender was designed and built around the motor and gearbox from a Dewalt 36v hammerdrill. Individual components were machined in undergraduate machine shops on the MIT campus and in the MIT Hobby Shop.

Testing of the ascender was carried out using standard gym equipment and weights. The completed unit can lift 100 kg at 0.4 meters per second with an overall efficiency of 8.5%. This result was 57% lower than the predicted speed of 0.7 meters per second with an expected 14.7% efficiency. Analysis revealed a design flaw which can account for most of the discrepancy in the predicted and observed performance and which can easily be remedied.

Powered ascenders within the same speed and load range are sold for several thousand dollars, demonstrating the feasibility of a low cost powered ascender as a viable product.

Thesis Supervisor: Sanjay E. Sarma
Title: Professor of Mechanical Engineering

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I would like to thank all the shop guys at the LMP machine shop, the Papallardo undergraduate machine shop, and the Hobby Shop; especially Jerry from LMP and Jim from Papallardo for their advice and help in fabricating the prototype.

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Table of Contents

Table of Figures & Tables

1. Introduction:

Personal ascenders were once found only on Batman's utility belt. However, in the last decade several companies have begun producing and selling ascending devices. Some of these ascenders are targeted at large corporate or military clients. Others are targeted towards foresters or hunters. All of them are priced at $2,500 or more. This price range is outside the reach of small companies, amateur groups, and individuals who could use such a device for business, research, or recreation.

1.1 Impetus for Project

Although ascending devices are currently sold for thousands of dollars, cordless power tools with similar power requirements are sold for five hundred dollars or less. By emulating the cost efficient design and manufacturing strategies used by power tool companies, it may be possible to produce and sell a personal ascender at a fraction of the price currently offered for ascenders.

1.2 Why a Capstan Winch?

Capstan winches have been used on sailing vessels for hundreds of years. They are simple, low cost, and reliable. Capstan winches first appeared in their modern, electronically driven form in the nautical industries in the early 1950s. Since then they have been adopted for a variety of other uses such as logging and towing.

Capstans hold several advantages over other forms of winches, many stemming from the fact that the cable is not stored on the pulley as it is spooled:

- Unlimited lengths can be pulled through the winch
- The winch can be started at any point along a line, provided there is sufficient slack in the line
- Capstans do not speed up or lose pulling force from the cable building up upon itself; the speed and pulling force are constant
- Capstans can use thicker lines, including rope, which is more versatile than steel cable

- Slack can be taken up and reverse motion easily controlled with the capstan pulley complete stationary relative to the winch (unpowered)

However there are two disadvantages of the capstan winch for this application that must be overcome with proper engineering and thoughtful design:

- Powered decent is not easily accomplished
- Tension must be maintained at all times in the downward line.

1.3 Pre-alpha Prototype

In the fall of 2012, I built a prototype of a compact personal ascender as an independent experiment. Only the roughest calculations were carried out before construction and the device was made with extremely low-cost components. Using an eight-dollar motor with an overall length of less than 8 inches, this pre-alpha prototype was able to lift a 100 kg load several inches off the ground. Although the motor burned out when line bunched up on the pulley, the concept of a cheap, powerful, electric ascender was shown to be viable. Further reflection on the result of this experiment and its implications led me to consider designing and building a much more serious prototype as my senior thesis.

2. Relevant Products:

This project encompasses the intersection of three existing product groups: electric powered ascenders, gas powered capstan winch ascenders, and high-torque cordless power tools.

2.1 Electric Powered Ascenders

Portable, electronic powered ascenders such as the Atlas ascenders, the ACC Power Ascender by ActSafe, and the PowerQuick Ascender are targeted primarily at military, government, and corporate clients. These products are bulky, prohibitively expensive, and are difficult to purchase for individuals or small groups. These ascenders use complicated, proprietary winch designs rather than simple capstan pulleys to provide traction when ascending a rope. According to the specifications posted on their respective websites, the ActSafe ACC II can ascend at 0.37 m/s, the PowerQuick PQ500-1 at 0.22 m/s, and the Atlas APA-3 at 1.52 m/s.

2.2 Gas Powered Capstan Winch Ascenders

Gas powered capstan ascending units such as the SP-CW by Simpson Winch Inc. and the Wraptor Gas-Powered Ascender by Ropetek are targeted primarily to foresters and hunters. They have slow speeds, low weight limits, loud engines, and cost roughly $2,500. Both of these ascenders use simple capstan pulleys to provide traction when climbing a rope. According to the specifications posted on their respective websites, the Simpson CS-CW can ascend at 0.21 m/s and the Ropetek Wraptor at 0.51 m/s.

2.3 High-Torque Cordless Power Tools

Recent advances in battery technology have led to the production and sale of high-torque power tools using lithium based batteries such as 36v Dewalt hammer drills. Many of these power tools have a power output which is well within the range of the power required to lift an average person at 1 m/s. Some of the tools in this category can be purchased for only $500. For example, the Dewalt DC901KL 36 v ½" Hammerdrill can be purchased with a carrying case, two battery packs and a charger from for $499. The DC901 is a product with a strikingly similar list of major components to an electric ascender, and is in fact more complex. This suggests that producing a $500 personal ascender might be a feasible undertaking.

3. Governing Principles

3.1 Capstans

A capstan in its simplest form is a cylinder around which a rope or other form of flexible line is wrapped. Due to the friction between the rope and the cylinder a decrease in the tension between the two ends of the rope is observed. This effect follows a trend that to first order does not depend on the rope size, capstan size, or amount of tension. As shown in Equation 2.1 (Johnson, *Contact Mechanics*, pg. 245), the ratio of the two tensions depends only on the coefficient of friction at the interface between rope and capstan (μ) and the angle through which the rope contacts the surface of the capstan, known as the wrap angle (θ). A diagram of a rope and capstan can be seen in Figure 1.

$$\frac{T_1}{T_2} = e^{\mu\theta} \qquad [2.1]$$

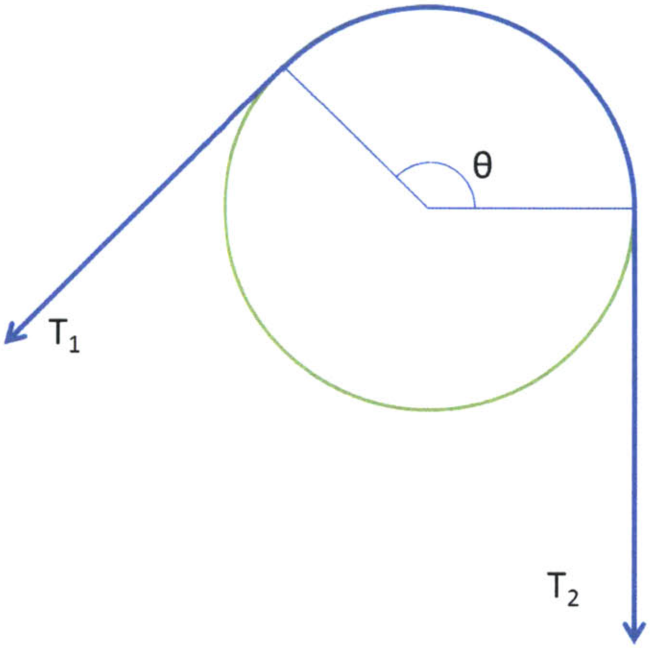


Figure 1. Capstan

Rotating the capstan in such a situation will generate a difference in tension across the two sides of the line which maintains the ratio from Equation 2.1. Flat and round belt drives are able to transmit power because of this effect. A winch can pull large loads with very little tension on the other side of the line by using a wrap angle of several complete rotations. For example, the force needed to hold 500 lbs with hemp rope wrapped twice around a wooden capstan ($\mu = 0.5$) is:

$$\frac{T_1}{e^{\mu\theta}} = T_2 \qquad [2.2]$$

$$\frac{500\ lbs}{e^{0.5\times 4\pi}} = 0.934\ lbs \qquad [2.3]$$

Less than one pound of force is required to support 500 pounds. This result may not be intuitively obvious; however it is a very important one when considering using a capstan winch as an ascender. Such a large ratio between the load tension and the downward tension indicates that weight of many commonplace items (such as a backpack) will provide sufficient tension for the ascender to hoist a person up the rope.

3.2 DC Motors

Direct current electric motors are transducers which use strong magnetic fields to convert electricity into mechanical power in the form of continuous mechanical rotation. Motors are often specified by their stall torque and no load speed. Most brushed DC motors follow a linear trend between these two points. This line is referred to as the torque speed curve. The slope of the line is the motor constant, K_m. An example torque speed curve can be seen in Figure 2. Power transmitted by the motor is equal to the torque times the angular velocity of the output shaft, as seen in Equation 3.4. In other words, power is equal to the rectangular area under the operating point.

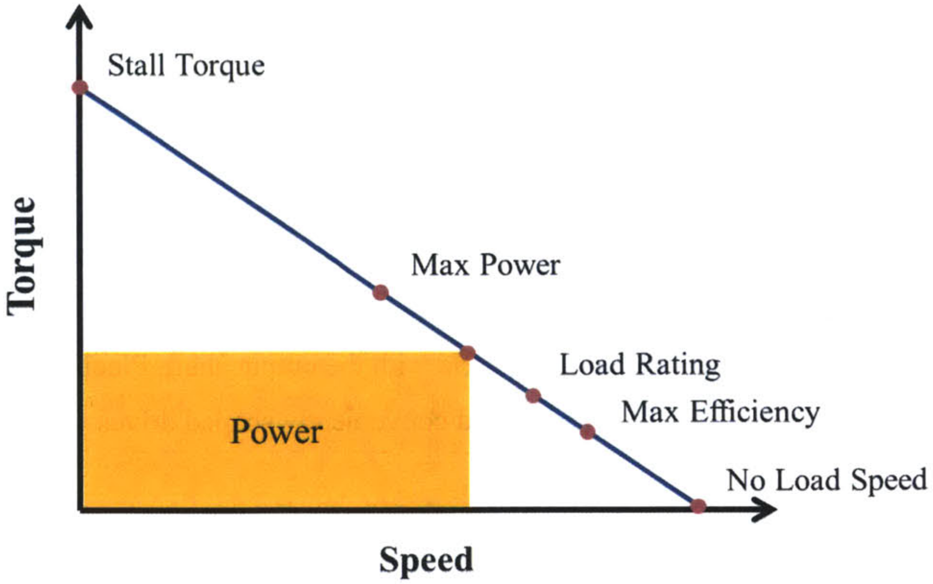


Figure 2. Torque Speed Curve of a DC Motor

$$P = \tau\omega \tag{3.4}$$

Besides the stall torque and the no load speed, there are three other notable points along the torque speed curve. The operating point with the most power output occurs at half the stall torque, which is also half of the no load speed. Maximum power is generally not safe for continuous operation because of the amount of heat which must be dissipated. However, machines are commonly designed to operate at this point for short durations under heavy use. Somewhere between the max power and no load conditions lies the load rating. The load rating is the highest power output at which it is safe to run the motor continuously. The point at which the motor operates with maximum efficiency also lies in this range. The mechanical power output of the motor at this point is closer (percentage-wise) to the electrical input power than at any other point along the curve. For economical reasons, it is typically considered the best place to run a motor continuously.

Considering these characteristics of DC motors, a well-designed personal ascender would be operating at a point near to maximum efficiency when carrying a payload equivalent to the average sized potential user. The maximum rated payload capacity could be set either be at the load rating or closer to the max power point, depending on how long the motor and its mount can safely operate in that range.

3.3 Planetary Gears

Planetary gear drives are gear trains in which one central (sun) gear engages with multiple (planet) gears which orbit around the sun gear, as shown in Figure 3. They are capable of transmitting much more torque for a given gear size than a conventional gear train because many more teeth are being engaged. Planetary gears normally are arranged such that the shaft driving them is concentric with the output shaft. Placing gearing in line with the motor results in more compact and conveniently shaped drives.

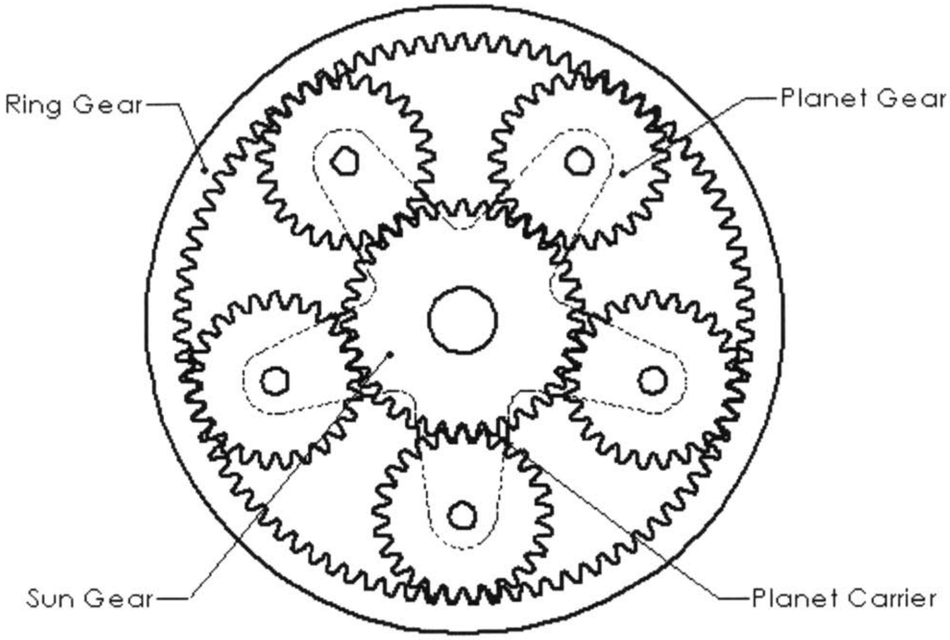


Figure 3. Planetary Gears

Personal ascenders require high torque power transmission and a very compact footprint, making planetary gearing an excellent option.

4. Design Process:

The purpose of this prototype is to offer a solution to fill a very specific, well defined user need; a low-cost personal ascending device. As a result, the design process is somewhat simplified. Functional requirements can be identified on the basis of that need and the design driven by aiming for those requirements.

4.1 Functional Requirements

In order to fill the need for a personal ascender, the device needs to accomplish the purpose of lifting a person up a rope at a reasonable pace and it must do so safely and reliably. Based on the capabilities of competing products, it should be able to lift **100 kg at 0.5 m/s.** The ascender should be stable when stopped partway up a rope, even if the battery has died and should provide a means of safe and expedient decent. It should be comfortable to carry in a backpack. In other words it should have a **total mass of 10 kilograms or less** and have a **volume of 5 Liters or less**. The device must allow spooling to begin in the middle as well as the end of a rope. The entire product should be engineered to last at least 1,000 hours of use with 99.9% reliability; however, since it will be supporting people high above the ground, all the structural components should be designed for infinite life with generous safety factors.

4.2 Safety Considerations

When designing a device to move people, especially vertically, safety is of the utmost importance. Although the alpha-prototype is only intended to lift 250 lbs, every link in the load-bearing structure of the device was designed to hold a load of at least 650 lbs. This gives a safety factor of 2.6 for the maximum recommended load. To prevent the motor from burning out or the battery from discharging too quickly and rupturing, a thermal overload protection breaker was included in the design. As an additional safety feature, a fall arrestor used in series with the ascender would prevent the user from falling if the ascender were to fail.

4.3 Time and Resource Considerations

The design of the alpha-prototype was affected to some extent by limits on the available time and resources. The most expensive components which had to be acquired to build an ascender were the motor, gearbox, and battery. A large capacity 37v lithium polymer battery was available to repurpose for the project, thus narrowing choices for motors down to those that run at 36 v.

The duration of the entire project was only three months. This was a very tight timescale for such an ambitious project and as a result compromises in aesthetics and some non-essential functionality had to be made in order to produce and test a working prototype on schedule.

The breakdown of expenses for building the alpha-prototype can be seen below in Table 1.

Description	Price
150 A Circuit Breaker	$ 53.90
Bearings	$ 35.80
Relay	$ 41.65
Electrical Components	$ 41.97
Structural Components	$ 104.66
Harness Components	$ 95.76
Battery	Repurposed
Motor	$ 78.99
Gearbox	$ 69.99
Water jet cost	$ 80.00
Total	$ 602.72

Table 1. Project Expenses

Including the price of a battery (approximately $150), the alpha-prototype was built at a cost of $750. Although this is higher than the target **selling** price of the end product, it is a point of interest that the cost of building a single unit was less than a third of the selling price of any of the other ascenders currently available. It is important to keep in mind that the components for this project were all purchased in small quantities at retail prices. The cost per unit of mass producing the exact same design would be a fraction of the cost of making one unit. There are also many changes which could be made to the design which would decrease the cost of manufacturing, some of which are discussed in section 8.2.

4.4 Motor and Gearbox

For the purposes of this project, it was necessary to consider motor and gear train options available quickly and at low cost. The motor and gearbox from a Dewalt 36v hammerdrill were the most cost-effective option capable of providing the torque and power required for the ascender. The motor and gearbox are pictured in Figures 4. and 5.

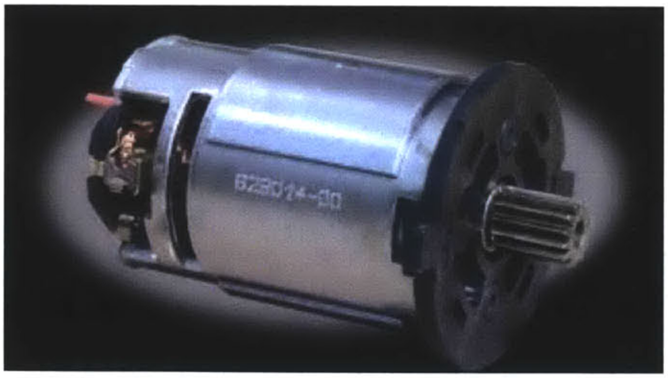


Figure 4. Dewalt Motor

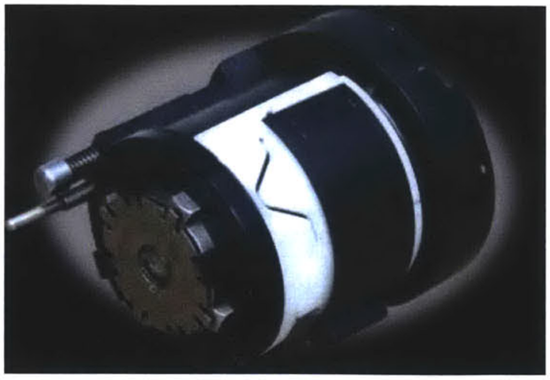


Figure 5. Dewalt Gearbox

The Dewalt motor is rated at 300 amps stall current and 15,600 rpm no load speed, with a torque constant of 0.0184 Nm/amp. The stall torque can be calculated as 5.51 Nm. The expected torque-speed curve with max power and max continuous load can be seen in Figure 6.

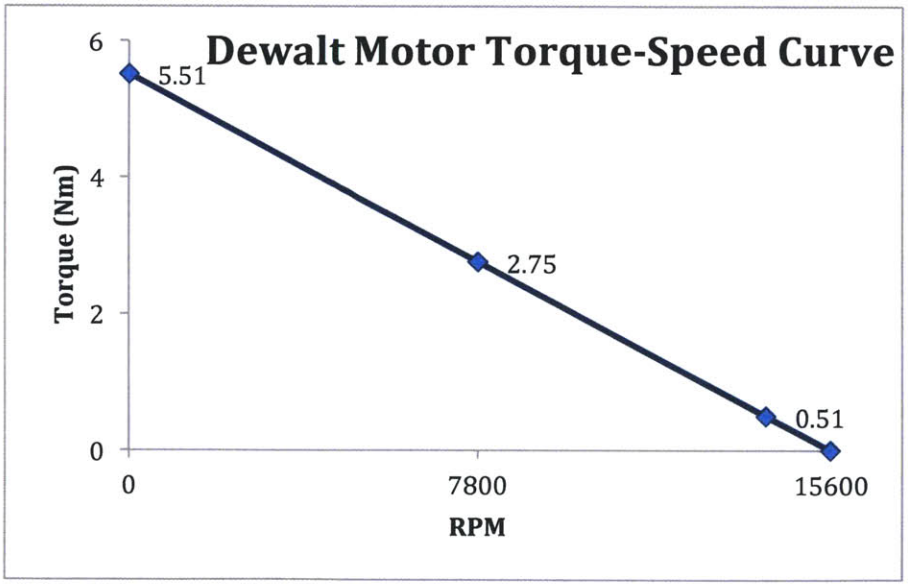


Figure 6. Torque-Speed Curve of 36v Dewalt Motor

The gearbox has three speeds; however, only the lowest, 400 rpm, will be used in the ascender. The max power output of the motor/gearbox combination is listed as 750 watts. (Dewalt, "Owner's Manual")

4.5 Structure

To function together as a machine the motor, gearbox, and capstan pulley need their relative motions constrained appropriately. The machine components such as the battery, circuit breaker, and relay also need a support structure to hold them in place.

Once assembled, the motor and gearbox are constrained from rotating relative to each other. They must be constrained axially to prevent them from falling apart; however, the gearbox must transmit up to 70 Nm of torque and therefore constraining axial rotation was more critical in determining the design of the main structure. The gearbox does not have any mounting holes and most of its external features are round. There is however a boss protruding along its entire length on one side. I designed two aluminum rings (A) with slots matching the boss on the otherwise round body of the gearbox. One more aluminum ring (B) held the motor engaged with the gearbox by pressing against the sleeve which partially covers the exterior of the motor. The ring unavoidably sat over the vents in the sides of the motor, since they are directly adjacent to the sleeve. Two shallow slots aligned with the vents on the sides of the motor allowed proper airflow as shown in Figure 7.

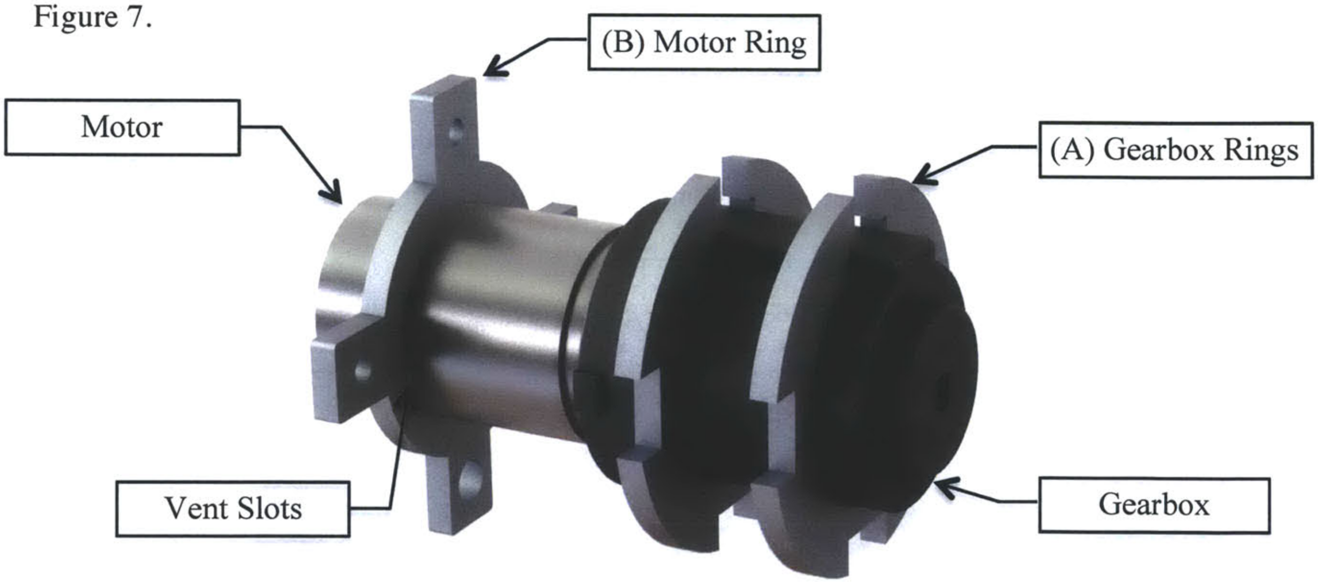


Figure 7. Gearbox and Motor Rings

All three rings were held in place by four square beams of aluminum (C). On one end all four structural beams are bolted to the motor ring (B) and on the other end they are bolted to the innermost of two bearing holders (D). Together, the four beams, the motor ring, the two gearbox rings, and the inner bearing holder form a cage which encloses and sufficiently constrains the motor and gearbox as shown in Figure 8. The cage was also designed to transfer static forces around, rather than through, the motor and gearbox.

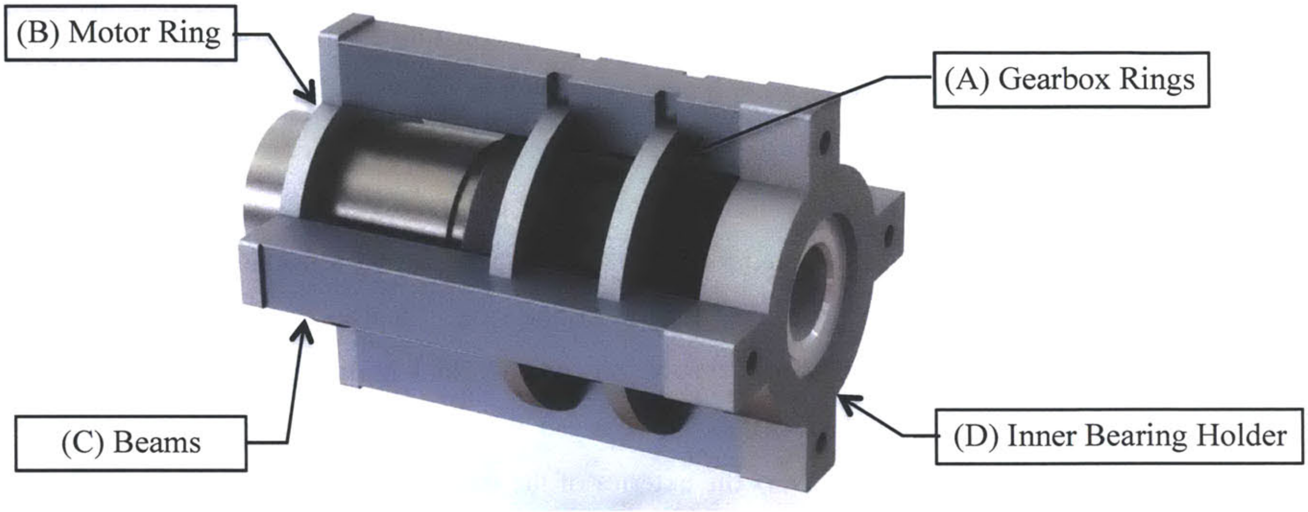


Figure 8. Structural Beams

Power is transmitted from the gearbox to the capstan pulley via a keyed drive shaft (E) as shown in Figure 9. The shaft is supported at both ends of the pulley by ball bearings (F) which are pressed into the inner and outer bearing holders, (D) and (G).

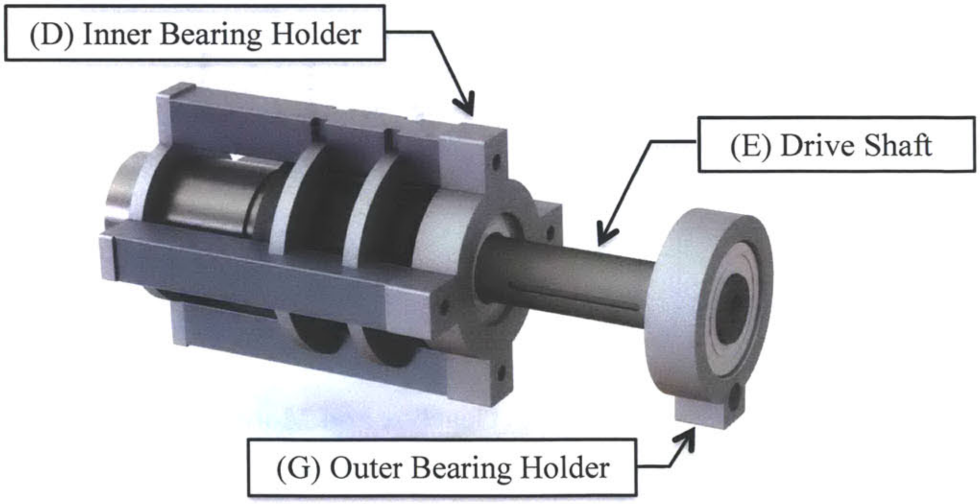


Figure 9. Drive Shaft and Outer Bearing Holder

The capstan pulley (H) has two main functional requirements. First, it must transmit power to the rope through friction and in doing so convert rotary motion into linear motion. This was accomplished by making the pulley long enough to accommodate sufficient wraps of rope for the necessary tension ratio, as dictated by equation 2.1. Second, the capstan pulley must allow the rope to feed onto and off of it in such a way that the rope does not begin to bunch up or cross itself. The ends of the pulley have splined curves forming the transition between a steeply sloped lip and the flat middle of the pulley, as can be seen in Figure 10. This curves acts as a wedge to ease the rope onto the pulley while gently sliding the previous coil towards the center of the pulley.

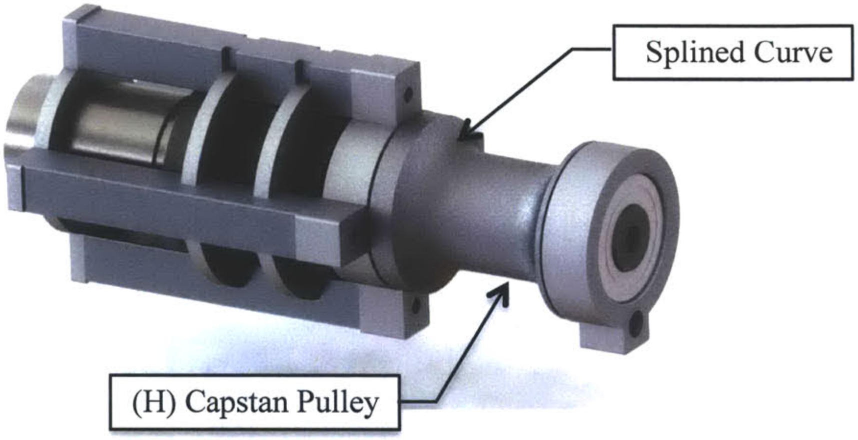


Figure 10. Capstan Pulley

I designed a pulley cover (I) to enclose the pulley, preventing loose clothing or appendages from becoming caught in-between the rope and the capstan pulley. It also was designed to constrain rotation of the outer bearing holder and to help keep rope from crossing over itself and bunching during operation of the ascender. The cover has four slots at one end which interlock with the four lugs of the inner bearing holder. The top slot extends an inch past the edge of the pulley, allowing rope an inlet to the pulley, as can be seen in Figure 11. The bottom slot extends the full length of the cover, allowing rope out of the ascender and securing the outer bearing holder (G).

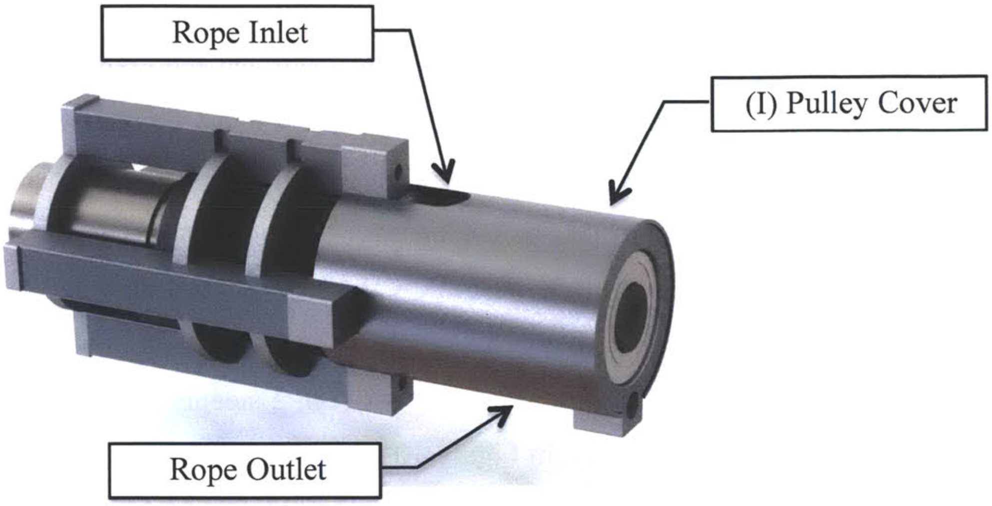


Figure 11. Pulley Cover

The pulley cover is fully detachable, allowing the mid-section of a long rope to be coiled around the pulley for ascent, as can be seen in Figure 12.

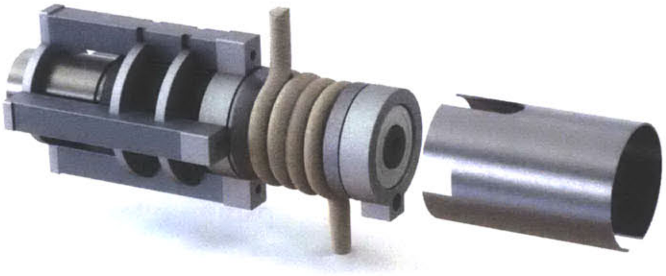


Figure 12. Rope Wound around Capstan Pulley

4.6 Battery and Switching

The battery available for this project is a ten cell, 37 volt, 3.6 Ah, 35C, 45C burst lithium polymer battery. The burst current rating for this battery is:

$$I_b = vC_b \qquad [4.1]$$

$$I_b = 37V * 45\frac{A}{V} \qquad [4.2]$$

$$I_b = 162A \qquad [4.3]$$

The burst current rating quantifies the highest current which is safe to draw from the battery for a few seconds. The tests for the alpha-prototype last less than five seconds each, which keeps the battery operating within the burst discharge regime. I wired a 150 amp circuit breaker into the ascender's circuit between the battery and the relay to prevent the relay, motor, or battery from exceeding safe current limits. Given the voltage and current in a circuit we can find the power:

$$P = IV \qquad [4.4]$$

$$P = 150A * 37V \qquad [4.5]$$

$$P = 5{,}550W \qquad [4.6]$$

Now we can find the maximum ascent speed which could be achieved with an ideal (100% efficient) machine lifting 100 kg:

$$P = v_a Mg \qquad [4.4]$$

$$v_a = \frac{P}{Mg} \qquad [4.5]$$

$$v_a = \frac{5{,}550W}{100kg * 9.8m/s} \qquad [4.6]$$

$$v_a = 5.66\, m/s \qquad [4.7]$$

This model for top ascent speed does not take any losses into account and the estimate is therefore entirely unrealistic. However, it is useful as an upper bound to determine efficiency requirements: the ascender must have an overall efficiency of 9% or above when lifting a 100 kg payload in order to achieve the target functional requirement of 0.5 meters per second.

To transmit power from the battery to the motor requires a switch. Testing the device required a switch connected to the ascender with long leads. Running over 100 amps through a hand held switch is both unsafe and expensive. As an alternative, I used a small momentary switch wired to a heavy duty automotive relay. The contacts in this relay are specifically designed for high amperage DC circuits. Figure 13. below pictures the ascender with battery and circuit breaker attached. Figure 14. is a complete circuit diagram for the ascender, showing the ten cell battery, relay and momentary switch, DC motor, and circuit breaker:

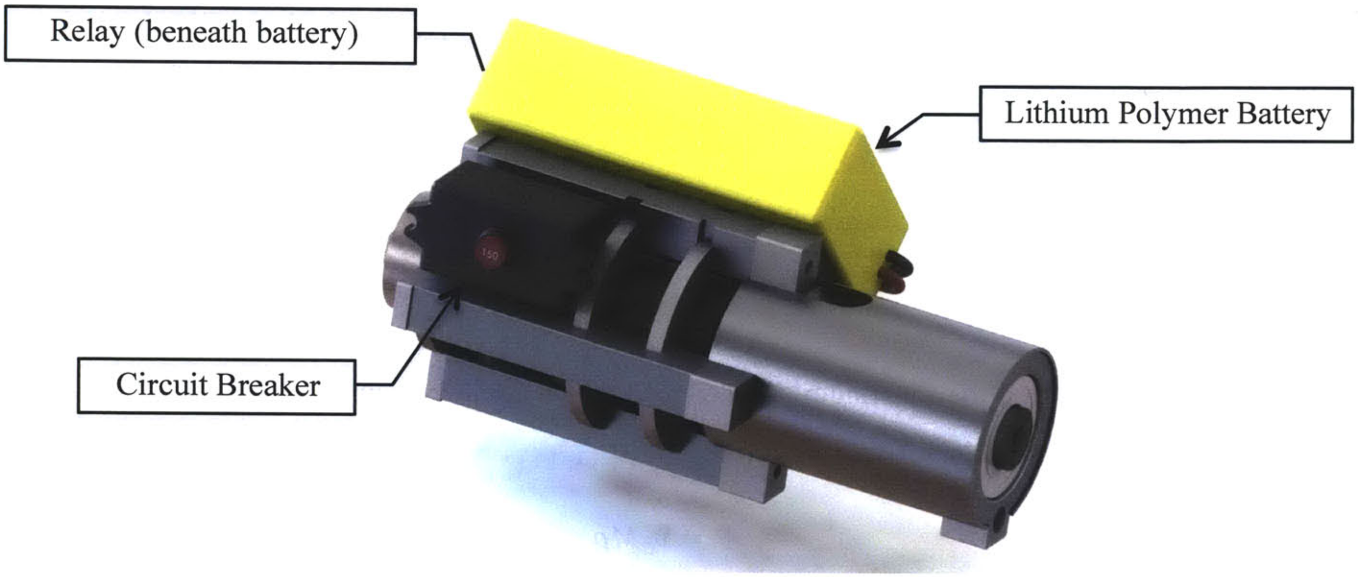


Figure 13. Ascender with Electronics

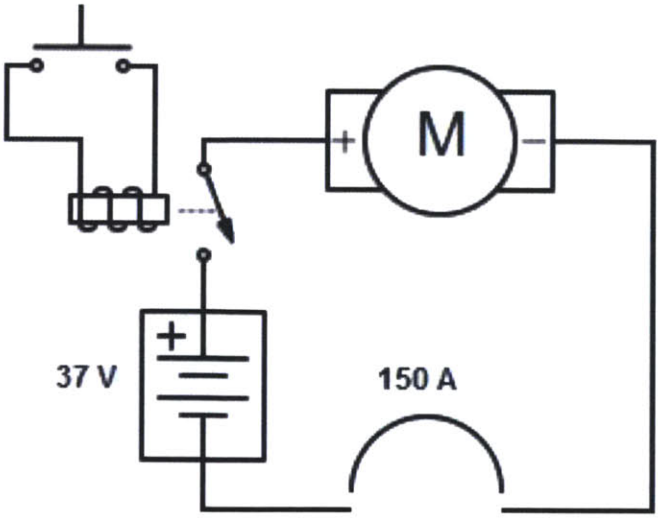


Figure 14. Ascender Circuit Diagram

4.7 Harnessing

Users must secure themself to the device in order to ascend with it. A proper climbing harness is necessary for this purpose. I designed an additional harness, pictured in Figure 15., as a permanent part of the ascender for the purpose of connecting the body of the ascender and the climbing harness in a stable fashion. The design of the structural frame provides two attachment points via mounting plates (A) bolted to the motor ring and the outer bearing holder; one on each side of where rope spools onto the capstan pulley. Stability is maintained by the wide base which keeps the axis of the ascender roughly horizontal during operation. The machine harness consists of two loops of one inch nylon webbing (B) strung through both mounting plates. A carabiner from the climbing harness is looped through an eye in the middle of the webbing (C).

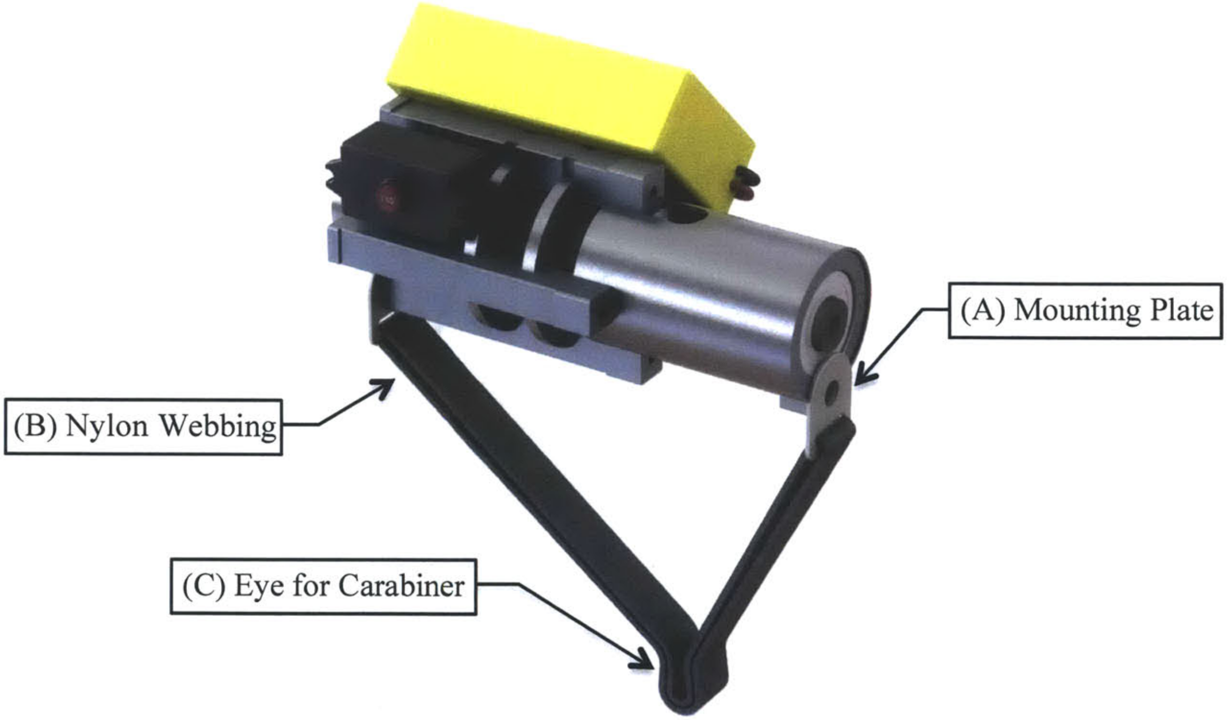
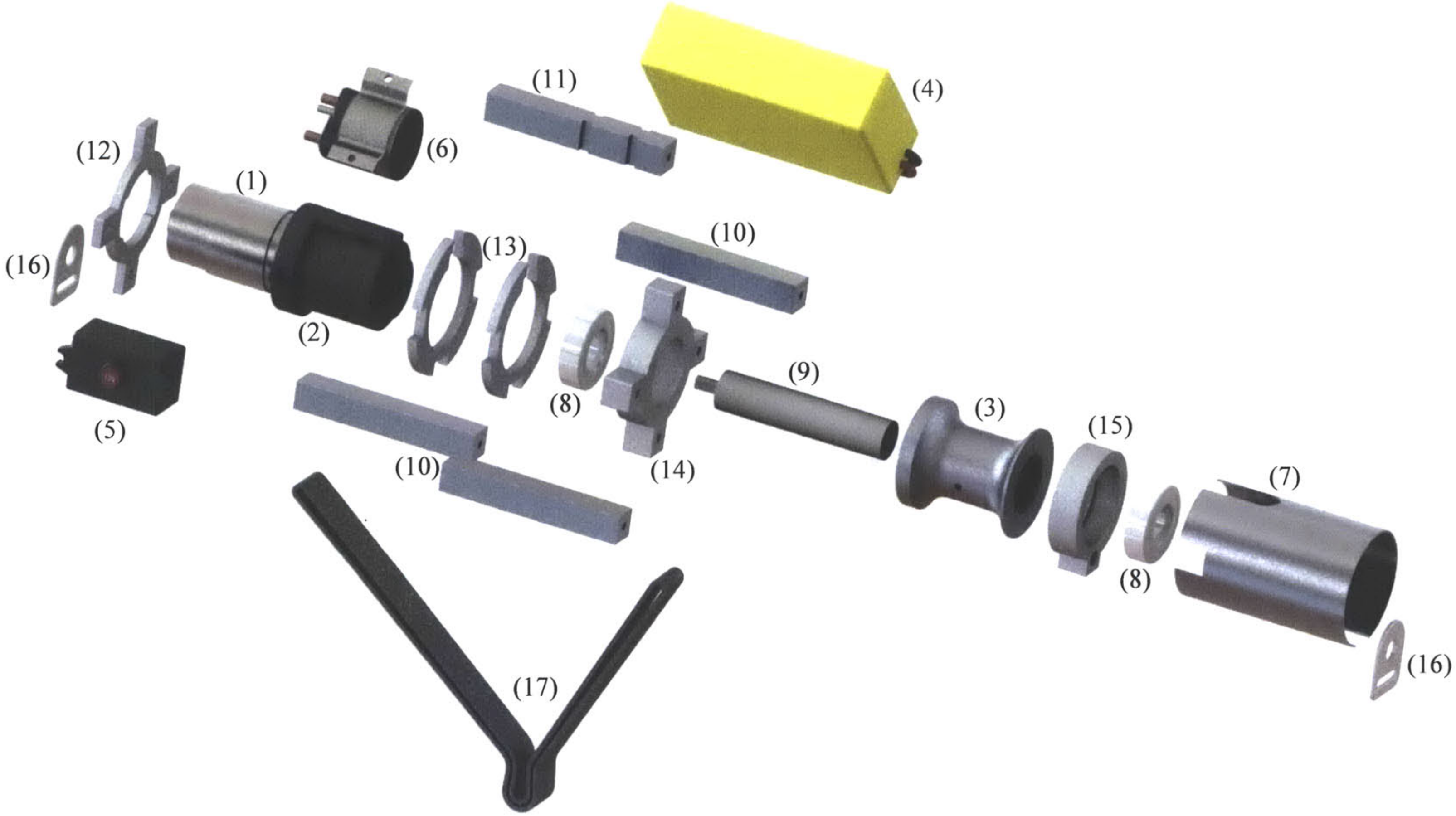


Figure 15. Ascender Harness

5. Building the Prototype:

An exploded view of the final alpha-prototype ascender design, including electronics and harnessing, can be seen pictured in Figure 16.



(1) Dewalt Motor (2) Dewalt Gearbox (3) Capstan Pulley (4) Battery (5) Circuit Breaker (6) Relay (7) Pulley Cover
(8) Ball Bearing (9) Drive Shaft (10) Structural Beams (11) Locating Beam (12) Motor Ring (13) Gear Rings
(14) Inner Bearing Holder (15) Outer Bearing Holder (16) Mounting Plates (17) Nylon Webbing Harness

Figure 16. Complete Ascender – Exploded View

5.1 Manufacturing Methods

A variety of methods were used to fabricate the various components of the alpha prototype. All fabrication methods were carried out on manual machines with the exception of a water jet. The fabrication procedures for each part can be found in Table 2.

Component:	Material	Process/ Machine(s)
Gearbox rings	¼" aluminum plate	cut with water jet
Motor ring	¼" aluminum plate	cut with water jet holes finished in drillpress
Inner bearing holder	¾" aluminum plate	cut with water jet pocket milled in vertical mill holes finished in drillpress
Outer bearing holder	¾" aluminum plate	cut with water jet pocket milled in vertical mill holes finished in drillpress
Bottom structural beam (used to index the gearbox rings)	¾" aluminum plate	cut with water jet end holes drilled then tapped in lathe
Remaining structural beams	¾" square extruded aluminum bar	rough cut on bandsaw ends cleaned up on vertical mill end holes drilled then tapped in lathe
Drive shaft	1144 Carbon Steel	turned, drilled and tapped on a lathe, keyseat and flats added in vertical mill
Capstan pulley curved	3" aluminum extruded round	bored, faced, and turned in lathe keyway broached in an arbor press set screw hole drilled and tapped in vertical mill
Pulley cover	3" OD aluminum tubing	bored in lathe slots cut in vertical mill

Table 2. Manufacturing Methods by Component

5.2 Difficulties during Build

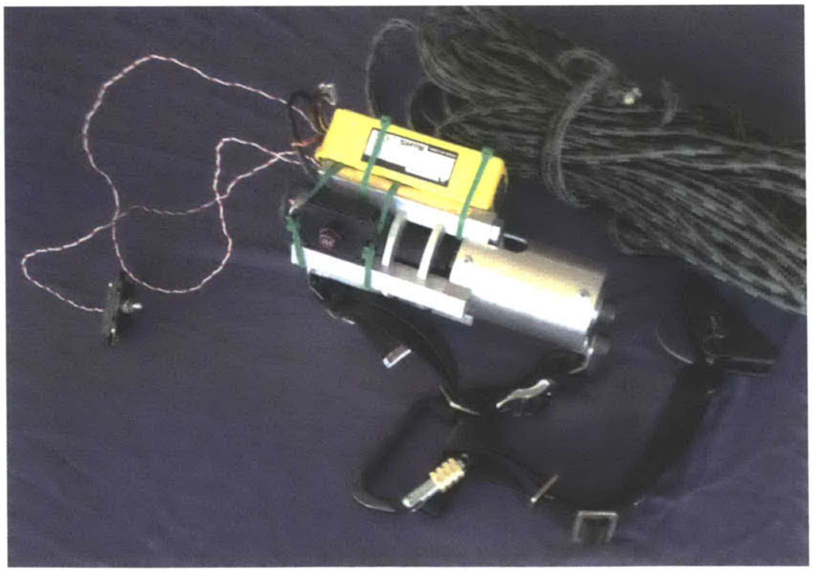
Originally, I intended to machine the pulley on a CNC lathe due to the difficulties in machining a spline with a manual machine. However, the CNC lathes were not available. Instead, I used a custom ground tool bit. The bit was ground to match the spline of the capstan pulley using a 1:1 scale printing of the CAD drawing.

The gearbox had several slight protrusions which were not accounted for when making the original CAD model. During assembly I discovered interference between these protrusions and the structural beams. I marked the beams and milled shallow slots in them to eliminate the interference, permitting me to assemble the ascender correctly.

Both contacts on the automotive relay were located on the same end, quite close together, presenting a dangerously easy way to short circuit the device and inadvertently cause it to begin operating. To prevent this eventuality, I shrunk several layers of shrink tubing around the exposed contacts to insulate them.

The bolt fastening the inner bearing holder to the top structural beam interfered with the rope as it fed into the pulley. This problem arose from using a CAD model which did not contain fasteners. I lengthened the inside lip and the shortened the center by one quarter of an inch to account for this difference.

The completed ascender is pictured in Figures 17. and 18.



Figures 17. Completed Ascending Unit with Cover On

Figure 18. Completed Ascending Unit with Cover Off

6. Mathematical Models of the Ascender

During the construction of the physical ascender, a mathematical model of several key aspects was also created.

6.1 Generating a Load-Speed Curve

The Dewalt motor came with most of the information one would expect to accompany a DC motor for design purposes. However, the gearbox came with only two pieces of information: the no load speed in low gear is 400 rpm, and the max power output of the gearbox motor combination is 750 watts.

Taking our starting point of 400 rpm and the pulley diameter we can find the no load speed for the ascender:

$$v_{nl} = \omega \pi D_p \qquad [6.1]$$

$$v_{nl} = 400\, rpm * 2\pi\, rads * \frac{1\, m}{60\, s} * \pi * 0.0254\, m \qquad [6.2]$$

$$v_{nl} = 1.06\, m/s \qquad [6.3]$$

The no load speed of the ascender model is 1.06 m/s. We know that the maximum in power output occurs at exactly half the no load speed, therefore that the gearbox must be transmitting 750 watts of power when it is running at half the no load speed, or 0.53 m/s. Since power is torque times angular velocity, the torque output at that point is:

$$\tau = \frac{P}{\omega} \tag{6.4}$$

$$\tau = \frac{750\ w}{\left(\dfrac{5.3\frac{m}{s}}{\pi * 0.0254\ m}\right)} \tag{6.5}$$

$$\tau = 35.8\ Nm \tag{6.6}$$

The torque at max power is 35.8 Nm. The no load condition and the point just found for max power together define a load-speed curve for the entire ascender. This model takes into account the no load current because it uses an empirical value for no load speed. It also takes losses into account since it uses the output power and not the input power. However, this model assumes the power rating for the motor was measured precisely at the max power point, a reasonable assumption, but one which has not been verified within the scope of this project. The model predicts stall at a payload of 287.3 kg. The predicted load speed curve can be seen in Figure 19.

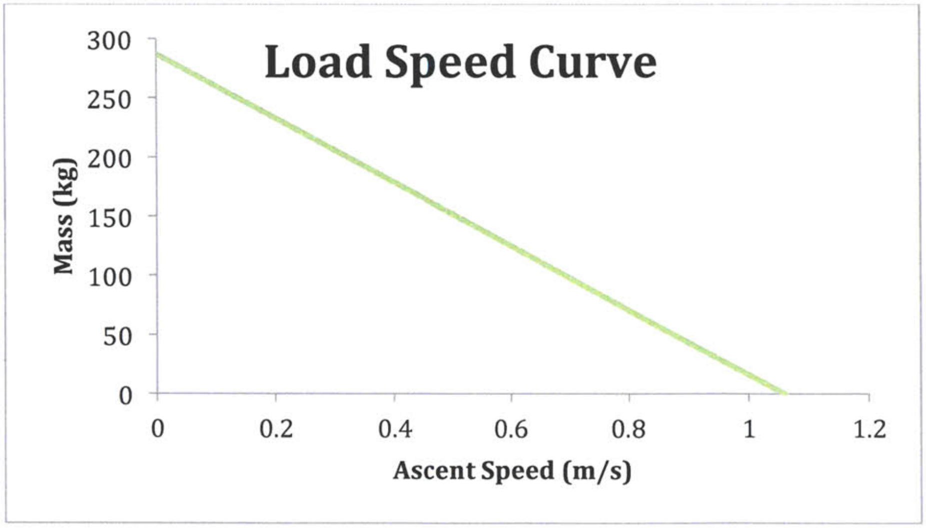


Figure 19. Modeled Load-Speed Curve

6.2 Capstan Model

To predict how much tension is required on the downward line, I made a model of the capstan and rope using Equation 2.1. For μ = .27 as measured between fibrous materials and aluminum, and a wrap angle of θ = 6π, or three complete wraps:

$$\frac{T_1}{T_2} = e^{(0.27*6\pi)} = 0.023 \qquad [6.7]$$

Therefore, for a load of 1000 Newtons, the device requires at least 23 Newtons of tension in the downward rope. If the tension is greater than 23 Newtons, the capstan pulley will transfer enough torque and the ascender will move. If the downward tension is less than 23 Newtons, the rope will slip and the ascender will not lift its payload. This model predicts that hanging 2.5 kg on the downward side of the rope will provide sufficient tension for the ascender to lift a 100 kg payload.

7. Testing and Results

After completing the prototype, I proceeded to conduct tests to determine if the ascender met the target functional requirements and to assess how accurately my models predicted the behavior of the physical system.

7.1 Testing the Ascender

Standard gym equipment provided a frame for attaching the rope and testing the device. Weights for the payload were placed onto a lifting bar attached to the ascender via a heavy carabiner. The rope was then wrapped three times around the capstan pulley and tightened. Tension on the downward side of rope was maintained by hanging smaller weights on the end of the rope. The ascender was controlled by a momentary switch connected by long leads to the power relay.

Eleven tests were conducted with payloads varying from 10 to 120 kg. The ascender pulled the weights approximately 2 meters up the rope. An assistant videotaped each test for later analysis. An ammeter with sufficient capacity for this project was not available.

As a result the amperes into the motor and thus the power input and the efficiency had to be derived from the data which was collected on ascent speed. See Figure 20.

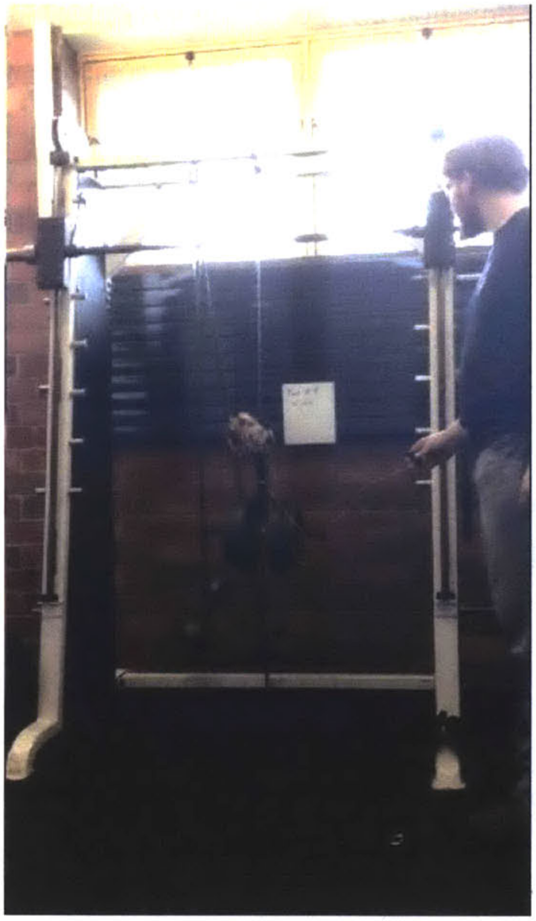


Figure 20. Testing Setup

7.2 Data Analysis

For each test video I used LoggerPro to determine the velocity of the ascender. The gym equipment used as a frame has pegs spaced vertically at exactly 7 inches. These pegs provided an accurate distance scale for each video. The video camera used for the tests has a frame rate of 29.97 fps. To determine the velocity of the ascender in each test, I measured the vertical displacement of a consistent point on the rear end of the motor shaft between successive frames for the entire ascent. Then scaled distance by setting the length between pegs in the video to 7 inches (0.178 meters). To find the ascent velocity in meters per second I took the average of the scaled displacement multiplied by the frame rate.

To find the power output for each test I multiplied the weight (in Newtons) by the speed in meters per second. The efficiency at each point is equal to the power going out of the system divided by the power going into the system and could then be found in one step.

7.3 Results

Total Mass (kg)	Measured Speed (m/s)	Predicted Speed (m/s)
17.291	0.756	0.996
21.836	0.786	0.979
26.382	0.752	0.963
30.927	0.765	0.946
40.018	0.656	0.912
49.109	0.635	0.879
62.745	0.557	0.828
68.182	0.441	0.778
81.818	0.395	0.728
100.000	0.385	0.661
121.836	0.424	0.610

Table 3. Measured and Predicted Ascent Speeds

The results of the eleven tests can be seen in Table 2 along with the velocities predicted by the model shown in Figure Measured velocities ranged from 0.79 m/s for 17.3 kg to 0.42 m/s for a load of 121.8 kg.

The load-speed curve for the ascender was constructed from test data and was extrapolated for the entire range between no-load and stall and can be seen along with the predicted load-speed curve in Figure 21.

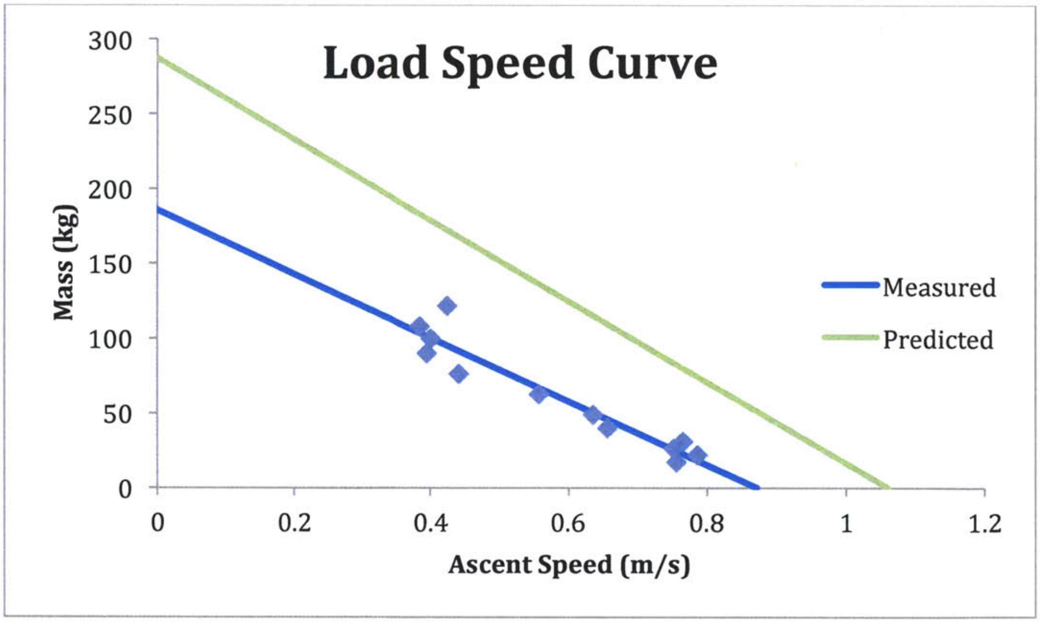


Figure 21. Ascender Load-Speed Curve

The model for the tension drop across the capstan was tested by choosing a T_1 which will be larger than T_2 * 0.023 for the smallest T_2 values and smaller than T_2 * 0.023 for the largest T_2 values. If the model was correct, in one of the tests there would not be enough tension required to lift the payload and the rope would slip on the capstan pulley. The pair of successive tests at which the no-slip/slip event occurs put upper and lower bounds on the ratio, $T_{1/} T_1$, and determine how well the model predicted the outcome.

The initial tension on the downward end of the rope was 2 kg. The model predicted that the rope would slip with a load of 86.4 kg. The rope slipped at the 100 kg test, but not at 81.8 kg, the previous test. The model is therefore confirmed to be accurate to within twenty percent. This is sufficient to create guidelines for users on how much weight to use when tensioning the downward end of the rope.

7.4 Problems and Suggested Solutions

Several problems arose when testing the device, two of which are safety concerns and require a redesign and rebuild of several components before user testing could be safely conducted.

Reaction force between the gearbox and the structural frame broke a piece of the plastic shell surrounding the gear train. Since the part was primarily intended for dust protection and was not required for the gearbox to function safely, testing was continued without it. This problem could have been avoided either by providing more clearance for that part or by using a gearbox with a metal housing.

As it spooled onto the capstan, the rope rubbed against the edge of the pulley cover with enough force to fray it noticeably over the course of the eleven tests. In addition to damaging the rope, the rubbing was found to be a major source of power loss. Power is equal to force times velocity:

$$P = vF \qquad [7.1]$$

Taking the ratio of power out over power in:

$$\frac{P_{out}}{P_{in}} = \frac{T_{out}v_{out}}{T_{in}v_{in}} \qquad [7.2]$$

Since our rope is not elastic, we know that $v_{in} = v_{out}$:

$$\frac{P_{out}}{P_{in}} = \frac{T_{out}}{T_{in}} \qquad [7.3]$$

Power loss can be calculated using the capstan equation:

$$\frac{P_{out}}{P_{in}} = \frac{T_{out}}{T_{in}} \qquad [7.4]$$

$$\frac{T_1}{T_2} = e^{(\mu\theta)} \qquad [7.5]$$

$$\frac{P_{in}}{P_{out}} = e^{(\mu\theta)} \qquad [7.6]$$

The wrap angle of the rope around the edge of the pulley cover is approximately π/3, and since this interface is also rope and aluminum, the coefficient of friction will still be $\mu = 0.27$.

$$\frac{P_{in}}{P_{out}} = e^{(0.27*\frac{\pi}{3})} \qquad [7.7]$$

$$\frac{P_{in}}{P_{out}} = 0.754 \qquad [7.8]$$

The power loss from the rope rubbing on the pulley could easily be as high as twenty-five percent. This problem can be avoided in future iterations by using low friction rolling elements to guide the rope into the capstan, or more simply, by redesigning the pulley cover to allow the rope to enter and leave the capstan tangentially, eliminating any wrap angle around the inside edge of the pulley cover. See Figure 22.

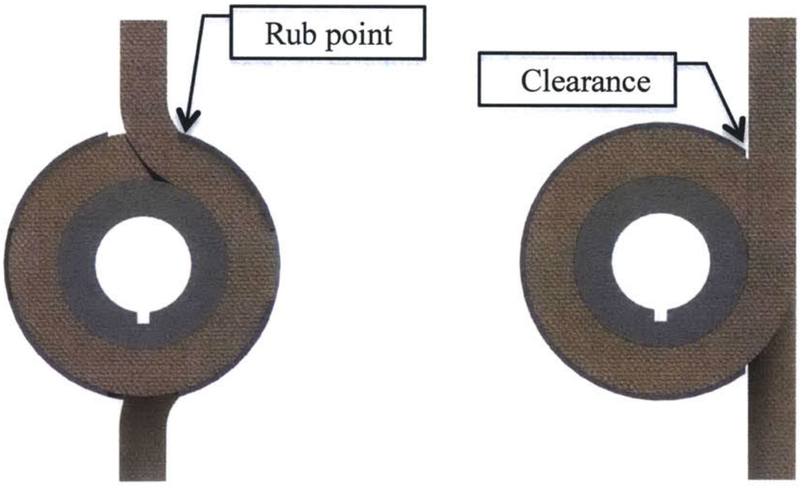


Figure 22. Current Pulley Cover and Proposed Pulley Cover Interact with Rope

The gearbox contains an integral mechanical brake. It was my intention to use this brake to provide holding ability when the ascender paused in the middle of a rope. However, the location of the actuator made the brake difficult to the point of impractical to use in the alpha-prototype. As a result, the alpha-prototype can be back-driven by payloads exceeding 30 kg. During testing the fall arrester was used to prevent damage to the ascender from uncontrolled falls. However, it would be unsafe for a user to operate the ascender in this fashion. The fall arrester is meant to be a safety measure, and once engaged it would leave the user caught in the middle of the rope without the ability to further ascend or even to descend without assistance.

7.5 Discussion

The model from section 6.1 gave an expected stall load of 287 kg. An extrapolation of the measured data gives a stall load of 185 kg. There are several possible explanations for the discrepancy. The rubbing of the rope on the pulley cover can account for a significant amount of power loss, however the exact amount is difficult to determine without know exactly what the wrap angle was under the testing conditions. Another possible source of error is the model itself. The model is based on a very small amount of factual information which was stretched a long way to arrive at a load-speed curve to predict the behavior of the ascender. There may be other internal losses or other effects which are not accounted for in the 400 rpm and 750 watts.

Another round of tests using a modified pulley cover would reveal whether those losses are responsible for the primary deviation from the model. Eleven trials with payloads matching the initial tests could be carried out in the exact same manner, albeit with a new pulley cover installed. Video of each test could be analyzed in the same way to determine the velocity for each payload. A load-speed curve could be generated and then compared with the curves given by the model and the first round of tests. If the new curve was more similar to the model than to the first tests the rope rubbing on the pulley cover could be positively identified as the primary cause of the deviation. If the new curve was more similar to the first round of testing, then it could be at best considered a contributing factor to the discrepancy, and further investigations would need to be made into the physical defects of the prototype and the validity of the model to determine the true source or sources of the deviation.

8. Conclusion

The alpha-prototype successfully demonstrated the feasibility of an inexpensive personal ascender. Transitioning that ascender from the prototype stage to a mass-manufactured product would require many changes to the methods employed in its construction.

8.1 Feasibility

The alpha-prototype successfully lifted over 100 kg up a rope at speeds of nearly half a meter per second, matching or beating every other ascending device currently on the market, with the exception of the atlas ascenders. Several aspects of the design still need to be optimized to reduce manufacturing costs and increase efficiency; however the feasibility of such a product has been conclusively established.

8.2 Design Changes for Mass Production

Instead of a structure comprised of eight water jet-cut and machined aluminum parts, the structure would be made of fewer parts stamped from steel plate and bolted or riveted together. A structure made by this method would be more compact and less expensive to produce.

The interior of the capstan pulley in the alpha-prototype is entirely wasted space. The volume of this space is comparable to the volume of the planetary gear train, as shown in Figure 23.

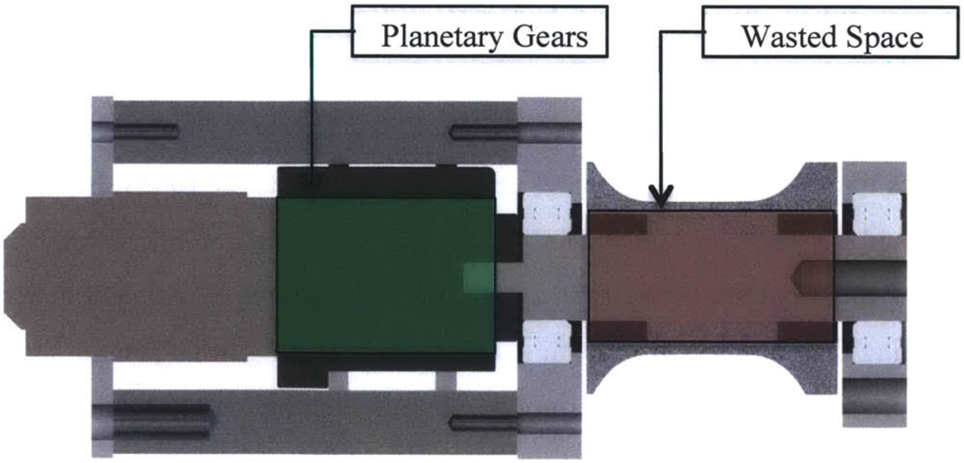


Figure 23. Current Configuration of Capstan Pulley and Planetary Gears

This wasted space could be eliminated and the overall length of the ascender shortened by three inches or more by positioning the gearbox inside the capstan pulley. As shown in Figure 24.

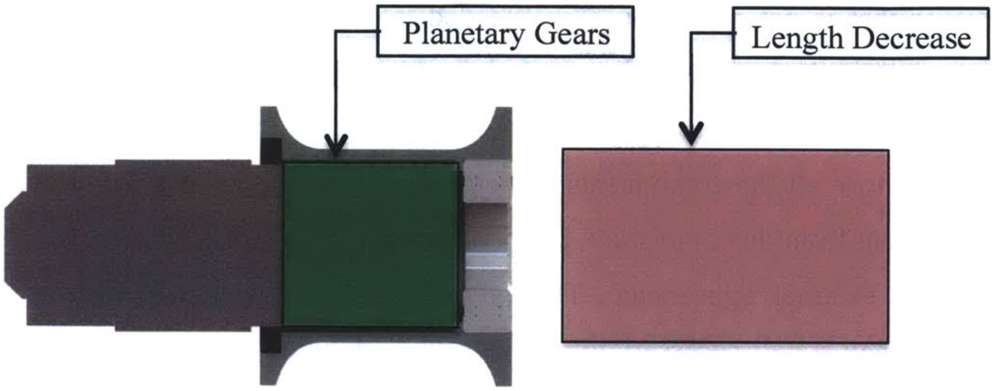


Figure 24. Improved Configuration of Capstan Pulley and Planetary Gears

In this configuration, a bearing large enough to fit over the motor housing would support the inner end of the pulley. The capstan pulley would be larger in diameter. As a result it would rotate more slowly, lowering the fatigue cycles on many components of the ascender and extending its useable life.

Inside the pulley the motor pinion would engage with a custom planetary gear train. For a modest production run the steel gears would be outsourced and the gear train assembled in house due to the highly specialized nature if gear hobbing machinery. A prawl and ratchet wheel would be built into the first stage of the gearbox. This would prevent the device from having a powered reverse feature, but it would also completely prevent the ascender from being back-driven and provide stability when pausing in the middle of an ascent. A steel ring gear would be press fit into the body of the pulley, forming the last stage of planetary gear reductions. This ring gear would share a matching feature, such as parallel flats or a hexagonal outer perimeter. Either option would ensure robust torque transmission without the possibility of slipping. The outer bearing would fit into the end of the pulley just outside the ring gear. Such a configuration would eliminate the drive shaft, inner and outer bearing housings, and the gearbox housing by effectively using the capstan pulley for all of those purposes. Decreasing the part count for the ascender would decrease material, manufacturing, and assembly cost.

Instead of being machined from a large aluminum blank, the pulley would be die cast. Die-casting is a less expensive process than machining and it does not waste as much material. A machined pulley could hold much tighter dimensional tolerances, however that is not needed a is not needed in this case, making die casting the most appropriate method when considering any metric.

A production model would require an injection molded plastic shell. The shell would enclose all the components and structure, locate them relative to each other, and protect them from dust, moisture, tampering, and falls. It would also create a much more appealing external appearance. These factors were neglected in the alpha-prototype, however they are all necessary to consider when designing a marketable product because of consumer expectation regarding these metrics.

The pulley cover would still be necessary and would be metal to avoid problems with excessive wear; however, it would be of a design which remained attached to the rest of the machine when it was not covering the pulley. A kill switch would be installed in the pulley cover to prevent the ascender from operating when the cover is open. This feature would serve to increase user safety by preventing many types of potential accidents at low cost.

The battery would be rechargeable, quickly exchangeable, and have its own custom shell that fit sleekly into the rest of the unit. This battery form-factor is common in the power tool industry and is already well liked and intuitive to use for many potential customers.

The switch would be a momentary grip switch allowing the user to gradually engage the motor, instead of full on or full off which causes unpleasant jolts. Dewalt uses momentary switches in its 36v power tools which provide limited variable speed capability and can safely handle high currents at 36 volts. A similar switch would be the most suitable option for use in this device.

Overload protection would be much more carefully and exactly tuned, but would still have a manual reset button on the exterior of the ascender. All electronics would be made to operate properly in light to moderate rain to ensure full usability and safety for users.

8.3 Future Work

The next steps in the development of this project are to solve the remaining engineering challenges; including a safe and effective braking system, an appropriate switch mechanism, and fitting a planetary gear train inside the capstan pulley. Once these challenges are overcome, a beta-prototype can be built using the form and manufacturing methods outlined in section 8.2, which are better suited for mass production than the methods used to construct the alpha-prototype. After extensive testing and fine-tuning of several beta-prototypes, the product would be ready for approval by regulatory agencies and then production.

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