# Electric Glider Winch
## Project description

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## Introduction

This document will introduce the reader to an Electric Winch Project. The design of the winch will be presented as will the reasons behind many detail design choices. The operation of the winch will also be presented.

This document and the **Onshape** CAD models within will be continuously updated to reflect changes needed to maintain a state-of-the-art design. It is therefore a living document so the reader is advised to obtain the latest version from this site.

These changes mostly represent evolutionary steps to reduce size, weight and cost and to incorporate "lessons learned" from building a prototype. One the lessons is, to paraphrase Prussian Gen. Helmuth Von Moltke, "No set of plans survives first contact with a machine shop" - i.e. expect them to demand changes. These demands are often reasonable and help reduce costs but they can also compromise design integrity – proceed carefully.

**V2.05 Changes:** Replaced builder-made load pins with commercial custom load pins reducing build time. Originally, the DIY route was chosen because of cost. Over the last year the price of commercial pins has dropped to near parity with DIY pins. Load pins are central to winch instrumentation so the availability of calibrated, guaranteed pins is welcome.

**V2.04 Changes:** The evolution toward simpler, smaller, lighter and easier to build continues. The winch was re-packaged as a mirror image to place the motors on the left to simplify wiring and coolant line routing. This reduced the overall width to slightly over 55". The frame base is just over 39" wide. There is now "wiggle room" to facilitate mounting the winch in a stock pick-up bed. An adapter frame was also designed to use the truck bed bolt pattern to mount the winch. Parts were simplified and lightened.

**V2.03 Changes:** The X-W/Fairlead Assembly tube cross section is reduced from 14" SQ to 12" x 10" by redesigning the fairlead which now has 3 fewer parts. This resulted in a height reduction of over 4.5" and a width reduction of 3.5". The height is now below a pickup cab roof.

**V2.02 Changes:** (1) A decision to laser-cut all steel tube and plate with tongue-&-slot self-jigging for alignment. (2) Replace the Motenergy ME1302 auxiliary motors with more powerful, high-voltage ME1616's thereby eliminating a mid-voltage DC bus. (3) Replacing Headway 38120HP cells the far more powerful Liyuan 60AH hybrid LiFePo4-Supercapacitor cells in a single 168 cell series string. (4) Changing the helical-cut gears to straight-cut which significantly reduces cost at the expense of a noisier gearbox. (5) Version 2.02 offers the builder a choice of a steel drum although the cost savings is not great and the rotational energy stored in the steel drum at 60 knots rope speed is nearly double that of aluminum. (6) A further change was to split the project into two **Onshape** documents – "EGW Frame & Drive

Line V2.0” and “EGW X-W/FL V2.0”.  This was to make the CAD side of the project less cumbersome.

**Public Domain**

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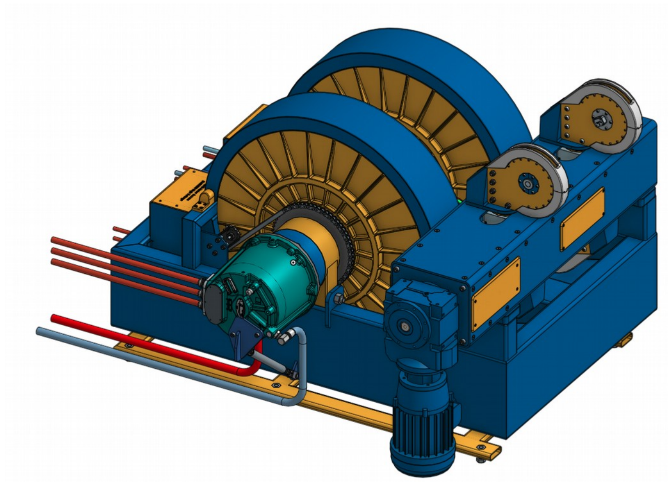
**Overview:** The Electric Glider Winch is a battery-electric winch with two, 3,000m (10,000') capacity drums. It is powered by a 430HP 3-phase AC Permanent Magnet Synchronous Motor. This motor is powered by a large battery pack using a variable frequency traction inverter. The battery is kept charged with a similar motor operating as a generator. A 250 Amp, 3-Phase, 600VAC Delta grid power tap can substitute for the generator feeding the inverter directly should one so wish.



A battery-electric winch operates much like the starting system in your car where the battery supplies a huge surge of current to crank the engine then the alternator recharges the battery for the next start.

Width 55"
Depth 67"
Height 46.7"
Weight: Roughly 3,000 Lbs including battery and power electronics.

**DIY "Fast-Build" kit concept:** Originally, the idea was to design a winch which could be built by amateurs in a garage shop using common tools and materials on hand. However, it quickly became clear that a much better winch could be built by using the services of professional machine shops. Therefore, the winch was re-designed using best industrial practices which makes use of many laser cut and CNC machined parts. Welded parts use self-jigging, tongue-and-slot alignment wherever possible to insure accuracy.

The construction of the winch is mostly assembling vendor supplied parts as would be the case with a "Fast-Build" airplane kit with parts being welded and bolted together. However, it is much less difficult to assemble than building an airplane kit.

Once a builder selects a list of potential vendors, STEP and PDF drawings and documents are emailed to the vendors who provide quotes. The best quote is selected and approval is given to proceed. The vendor produces the parts and ships them to the builder's shop.

**Project Cost**

For practical reasons, it is impossible to determine cost without knowing the builder's choice of machine shops, sources of materials and methods. Quotes for the same part will vary by orders of magnitude so cost can vary dramatically from project to project. A builders procurement skills are as critical as metal working skills for minimizing cost.

A Bill of Materials spreadsheets are included which a builder can use to develop a reasonably accurate estimate of cost using their choice of suppliers and methods.

Detailed 3D CAD models and 2D B&W drawings are included for those builders with access to machine tools and the skills to use them. These builders would find their costs far lower than those who send work to professional machine shops. Drawings can be exported as PDF's and printed at full-scale by Staples or Office Max if desired.

## CAD Platform and Project Organization

The “Project File Cabinet” (PFC) is the “Cloud” based professional CAD application **Onshape** which holds all CAD models, drawings and documents related to the project. **Onshape** runs in a browser on almost any computer.

**Onshape** provides a simplified viewer for those without CAD skills. For those who wish to learn CAD, *www.**onshape**.com* offers a series of short, well made videos which explain the fundamentals of 3D CAD and how to navigate **Onshape**.

**Onshape** PFC contains data sheets for purchased items and PDF reports of FEA runs from **SimScale** which appear as “tabs” along side drawings and models.

**Units of Measure:** This project uses both the metric and imperial systems of measurement. Conversions to – and from - the Imperial system are provided. In a world where manufacturing is dominated by China, it is often the case that purchased components are in metric units. **Onshape** has a feature where a drawing or the entire project can be shifted from Metric to Imperial units, or the reverse, by clicking a box.

**Mea Culpa:** On a project of this size there are no doubt errors, omissions and outright blunders lurking in the package. Consequently, anyone using this winch design or any part thereof does so at their own risk. Corrections will be made on a “time available” basis so the reader should not assume the plans are complete, up-to-date or totally accurate Anyone building a winch using these plans bears the sole responsibility for manufacturing a safe machine. Use of the plans in any way constitutes acceptance of this principal.

## Project Objectives and Design ‘Philosophy’

A glider winch must meet many criteria. It must be efficient delivering high launches at rapid cycle rates yet very simple to set up and operate so ordinary glider club members can run it without frustration. Per-launch costs must be less than $3. Maintenance must be easy to accomplish by typical club members. Above all, it must deliver perfectly consistent launches so pilots always know what to expect.

Electric drive is the only way to accomplish these criteria. Internal combustion engines and automatic transmissions can never come close to being as controllable as electric motors. ICE’s may seem simple, but this is only because we are familiar with them. In fact, they, and their many support systems are immensely complicated with parts counts running to the thousands while an electric motor has just one moving part. Even considering the electronics involved, electric motors are smaller, simpler, and cheaper than ICE’s while being far more versatile.

One example of this is that an ICE can only deliver “forward” torque unless a reverse gear is used while an electric motor can produce instant reverse torque without a gear change. As a result, an electric motor can instantly reduce rope speed whereas an ICE can only ‘coast’ while the load pulls down the RPM. As a practical matter this means an electric winch can adjust rope tension 100 times a second in the presence of heavy atmospheric turbulence and unsteady pilot inputs to deliver a perfectly smooth launch. Another example is that ICE’s must be allowed to ‘idle’ which requires some sort of ‘clutch’ or torque converter to smoothly engage a running engine with a stationary winch drum. Electric motors, on the other hand, can produce maximum torque at 0 RPM so they can be coupled directly to the load. In practice, this means smooth acceleration without the harshness and unpredictability of an ICE.

Costs were carefully considered at each step but when a conflict arose between “do it right” and “do it cheap” the choice was to do it right.  At this point someone will introduce the ‘KISS Principal’.  Know that this ‘Principal’ originated with Albert Einstein who famously said, “Everything should be made as simple as possible – *but no simpler*.” I heartily agree.  The Electric Glider Winch is as simple as it can be while still meeting the above criteria.

To make the winch cheaper while maintaining its performance will require engineering skills superior to those required to design it.  I hope such skills are found and applied to this project.

**Project History**

The Electric Winch Project has been in mind for more than a decade.  Until recently, the engineering tools that would permit a detailed design capable of being built were not available – at least not for a unpaid, open source designer.  Suitable components such as powerful electric motors were not available at affordable prices.

In the the early years, much effort went into understanding the worldwide practice of launching gliders by winch and exploring the physics.  Computer models were built which explained the control laws.  This research led to an understanding of what a perfect winch launch is but designing a machine to achieve it proved challenging.

Several attempts using free CAD software failed because of the lack of file format standardization and the difficulty in sharing files with someone using a different CAD system or even a different version of the same system.  As the scope of the project grew, it also became clear that large investments in computer hardware would be needed to work on huge part files 3D CAD systems generate.

In 2017, all of that changed.

Professional engineering design tools (CAD/CAE) became available as cloud applications which which run in browsers on typical PC’s while accessing extremely powerful servers in the background.  For example, CAD was done with **Onshape**, and Finite Element Analysis of parts such as the winch drum were done using **SimScale** (*www.**simscale**.com*) – PDF FEA reports from this Cloud application are included in the project package as are images of the analysis.

Cloud based applications offer many important advantages.  Anyone can examine a project in detail without licensing compatible CAD/CAE software and buying the powerful computer hardware it takes to run it.  All they need is a personal computer with Internet access. When they log into the project, they are using the same software release as everyone else and seeing the latest version of the project.  Part files and drawings can be exported in almost any format which has an important advantages when shopping for professional services.

Like CAD/CAE, CNC machining has become ubiquitous – so much so that it’s hard to find anyone with the skills to operate old-school manual machine tools.  To use a CNC machine shop, simply email a 3D part file and a quote will be in your inbox in a couple of days. Fortunately, CNC costs have become highly competitive.  **Onshape** can export 3D files in the common STEP file format as well as 2D drawings in PDF format.  Shops want both.

Laser cutting shops work in the same way.  Email them a part file and precisely cut parts will arrive in a week.

Building the Electric Glider Winch is then a process of selecting vendors who will make parts, then assembling the winch as parts arrive.

## Platform-Agnostic Concept

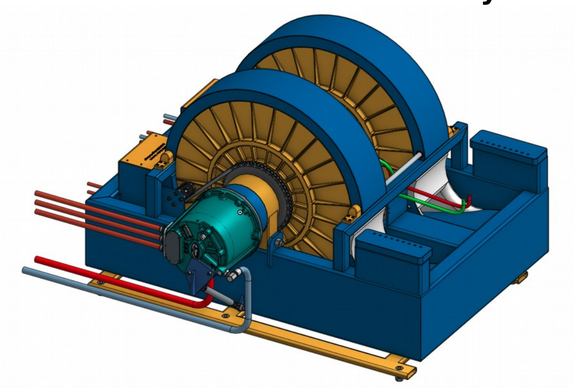
When most glider people look at a winch they mentally categorize it as a vehicle.  This distorts their thinking and may lead them to be overly impressed by fancy paint jobs and bodywork.  It can even lead winch designers to merge vehicle and winch into something that is neither a good vehicle nor a good winch.

A winch is simply the machine that winds in the rope.  It should not be merged, confused or conflated with the platform on which it is mounted.  By making that distinction at the onset, the design which emerged is simple and efficient.  An builder can mount the winch on a trailer, truck or even permanently in a blockhouse as they please.

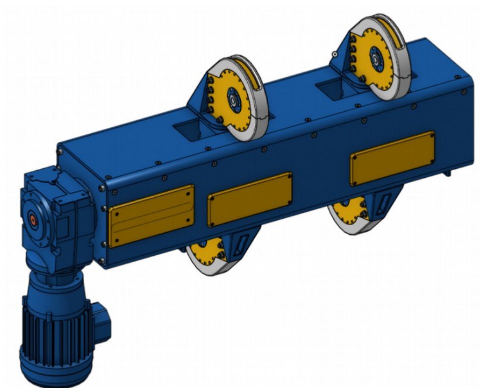
## Mechanical Design

The winch is divided into two major assemblies which together weight about 2,000 Lbs (excluding battery and electronics).  Each can be assembled in a one-car garage shop.

**Frame and Drive Line Assembly**



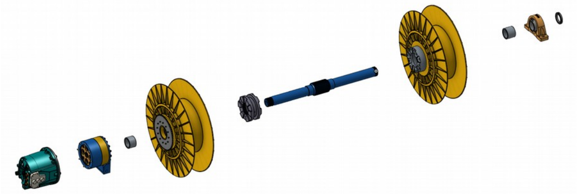
**X-Wind and Fairlead Assembly**



We start with an in-depth look at the Drive Line and Frame.

### Drive Line Assembly

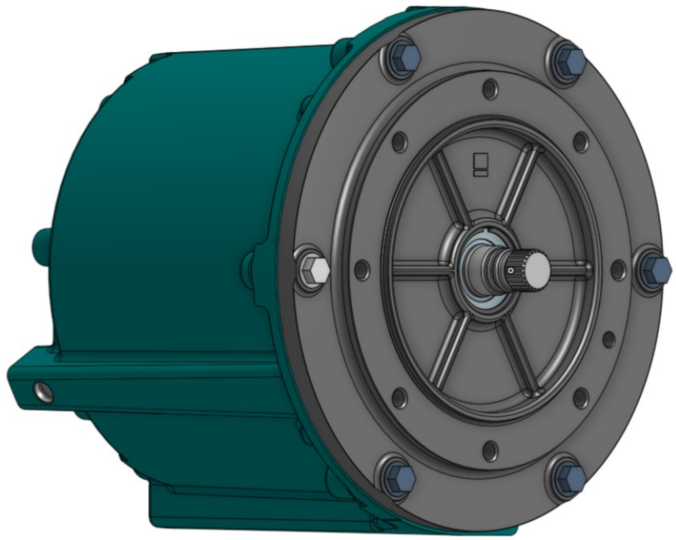
Diameter: 32.5”
Length: 56.6”
Weight: 671 Lbs
Total Moment of Inertia 3.81133 Kg-M$^2$



The entire drive line assembly consists of a motor, gearbox, main shaft, 2 drums, dog clutch and bearings.  It is mounted to the winch frame with 3 large bolts.  The drive line components are assembled by sliding them onto the main shaft.

Bolting the drive line to a welded frame in a way so inevitable small miss-alignments don’t over-load bearings wasn’t easy.   This was achieved with a horizontal bolt beneath the gearbox/bearing and a self-aligning plummer block bearing with slotted mounting holes at the opposite end of the main shaft.  This allows 6 degrees of freedom so the drive line bolts to the frame without imposing any loads on the main bearings.

**Drive Line Component – Main Winch Motor:**



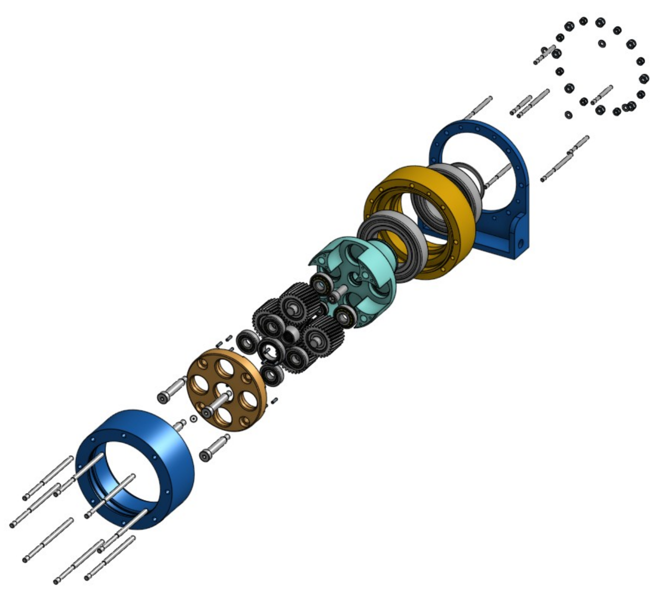
- Remy HVH250-115 DOM “High-Flow”
- Diameter: 10.5”
- Length: 10.9”
- Weight: 57 Kg. (125.6 Lbs.)
- *Peak Power: 330 kW (442HP)
- *Peak Torque: 460 Nm (339 Ft-Lb)
- Rotational Inertia: .069 Kg-M$^2$
- (Remy data sheet is in the **Onshape** project package)
- * < 2 minutes

The HVH250 is a liquid cooled, 3-phase AC Permanent Magnet Synchronous Motor (PMSM) with no brushes or slip rings. The only moving part is the rotor which contains the magnets. It is driven by a variable-frequency traction inverter.

This motor can deliver peak torque from 0 to 6,000 RPM when operated at 500V – (Higher voltage makes peak torque available at higher RPM). Above that RPM, torque diminishes almost linearly to the 10,000 RPM red-line. When driving an 18” core diameter drum through a 5:1 gear reduction, the winch can develop just enough rope force to break a black Tost 1,000 DaN (2248 Lbs-F) weak-link from a standstill up to rotation airspeed with enough rope speed in reserve to handle an unexpected tailwind.

Acceleration is therefore limited only by weak-link strength and not by the weight of the glider or the power of the winch. This is not to say that this much power would always be used. Acceleration is determined by the launch profile program selected by the operator.

**Drive Line Component – Reduction Gear:**



- 5.0526:1 Planetary
- 77 tooth Ring Gear (fixed)
- 29 tooth planet gears (4)
- 19 tooth sun gear (motor input)
- Splined planet carrier (output)
- Taper Roller bearings throughout
- Synthetic grease Lubrication
- Moment of Inertia: 0.8212Kg-M$^2$

Unlike internal Combustion Engines which require a gear-changing transmission with clutch or torque converter, electric motors only need a single-speed reduction gear to match their torque to the load. The simplest and most reliable are planetary gears such as one finds in electric drills. These have large tooth engagement area in a small volume which can easily handle the torque and RPM of a glider winch.

**Drive Line Component – Main Shaft:**

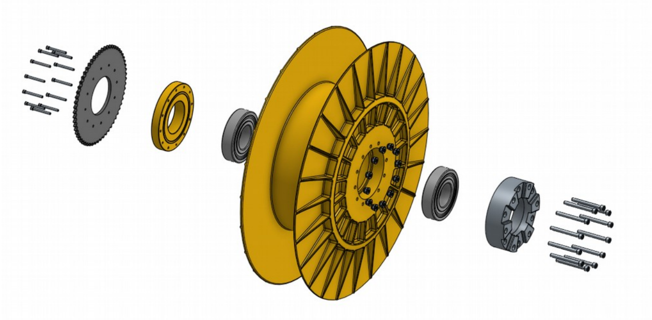
- Weight: 78.8 Lbs
- Maximum Diameter: 101.6mm (4”)
- Length: 1,051.6mm (41.4”)
- 4130 Chrome-Molybdenum Steel
- Rotational inertia: .03517 Kg-$M^2$

The main shaft is splined to the planet carrier in the gearbox. It rides on large ball bearings at the ends. The mid-section is a heavy 4” diameter spline which drives the Dog Clutch Spool. The shaft diameter is “stepped” to allow easy assembly.

A 80 Lb shaft may seem excessive but it must support two drums and a dog clutch with bearings at the ends. Flex is less than .001” at max load.

**Drive Line Component - Winch Drums:**

- Flange OD: 32.5” (800mm)
- Barrel OD: 18” (457.2mm)
- Width: 7” (177.8mm)
- Capacity: 10,421’ (3,176m) of 3/16” rope
- Weight: 148.4Lb (67.3 Kg)
- Material: 7075 T6 Aluminum
- Rotational Inertia: 3.334 Kg-$M^2$



Each drum rides on large ball bearings which allows the shaft to rotate inside a stationary drum – or the drum to rotate on a stationary shaft. The bearing nearest the dog clutch is 75mm ID and the bearing nearest the ends of the shaft is 70mm ID to make it easier to mount on the stepped shaft.

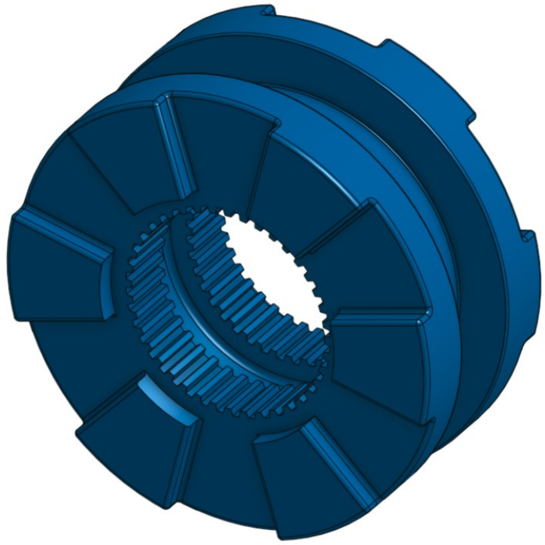
Much engineering went into drum design. When using the full 10,000’ capacity, it was assumed that 4,679 feet of rope can be wound on at launch tension and the rest at about 100 lbs-F. In the worst case, this can result in as much as 3 million pounds of crushing force on the drum. If the rope is parallel wrapped, axial force on the drum flanges can be a large fraction of that as outer wraps try to wedge between lower wraps.

Many designs were analyzed using FEA to insure a 150% safety margin. When designed to that strength, a steel drums’ moment of inertia is 8.703 Kg-$m^2$ whereas an aluminum drum is only 3.334 Kg-$m^{2.}$ Therefore, aluminum was chosen.

Drums begin as 254mm (10”) thick, 800mm diameter 7075 AL billets weighing 763 Lbs. CNC machining reduces these billets to perfectly balanced, 200 Lb drums.

Due to costs of high-strength steel and high-tech welding, a steel drum is not much cheaper than an aluminum one. For the unconvinced, a drop-in an alternative steel drum “Drum 5140” can be found in the **Onshape** Project Document along with its FEA.

**Drive Line Component - Dog Clutch:**



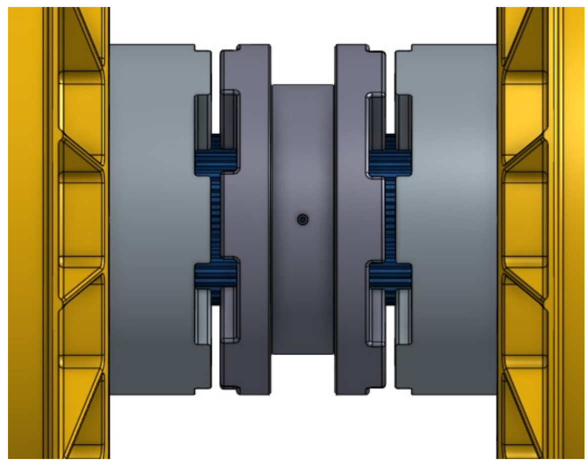
Sliding Dog Spool

- Diameter: 216mm (8.5”)
- Length: 101.6 (4”)
- Weight: 14.6 Kg (32.2 Lbs)
- Rotational inertia: .09813 Kg-$m^2$

Drum Face Dog Disks

- Length: 25.4mm (1”)
- Weight: 9.219 Kg (20.33 Lbs)
- Rotational inertia: .07412 Kg-$M^2$

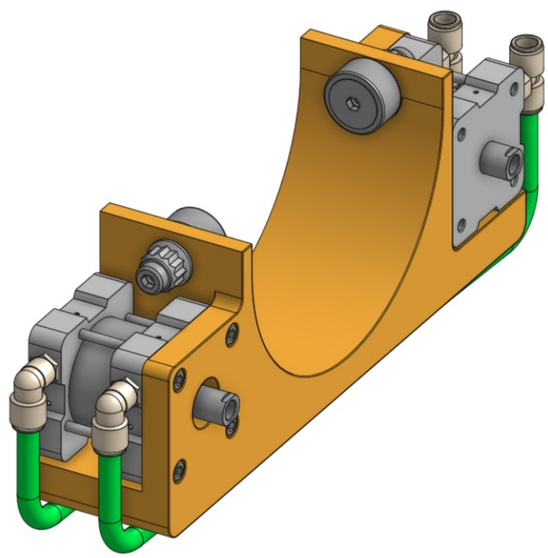
A two-drum winch requires a dead-reliable method for engaging only one drum at a time. This is usually done using a “dog clutch”. In this case “dog” refers to a block of metal on a disk.



A “dog-spool” slides axially on a splined section of the main shaft alternately engaging matching “dog-disks” on the drum faces. A large internal grease reservoir provides lubrication.

As the distance between drums is fixed, only one drum can be engaged at a time with no possibility of engaging both. When the spool is in its spring-loaded neutral position (right), neither drum is engaged as would be the case when pulling out the ropes.

When the dog clutch engages a drum, it is forced to rotate with the shaft and motor. The other drum, which is not engaged, remains stationary while the shaft rotates within on ball bearings.



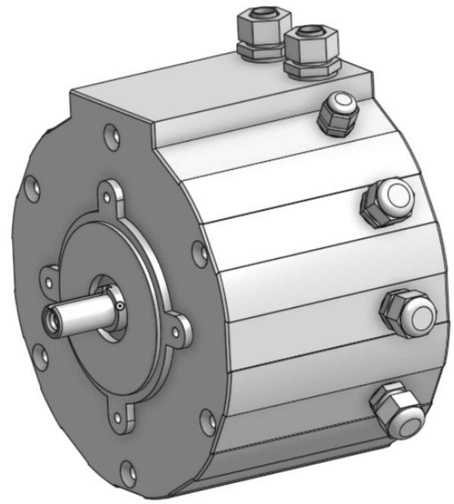
The spool has a central groove for 40mm cam follower bearings which force it to slide it left or right. The cam followers are attached to a shifter assembly which uses air cylinders with their shafts bolted to the winch frame so block, cam followers and spool move together. The linear bearings inside the air cylinders support and guide shifter assembly. Strong springs return the spool to its center, neutral position as air pressure is released.

Compressed air is electrically valved to the cylinders with a solenoid valve so drum selection is controlled electrically.

**Drive Line Component - Brake:** Traditionally, glider winches have used friction brakes – usually a drum. This brake has two purposes - to stop the drum in an emergency and to provide rope tension as the ropes are pulled back to the start line.

Friction brakes have a number of disadvantages. They never completely disengage which saps winch power and generates unwanted heat. They cannot be precisely controlled so setting the friction exactly the same for each drum during the rope retrieve is impossible. Friction varies unfavorably with RPM and they wear out requiring servicing. Finally, a friction brake can do only one thing – increase resistance to rotation.

Regenerative braking offers another possibility. An electric motor used as a brake can do more than just add resistance – it can actually reverse rotation to remove slack should it develop. Unlike friction brakes, it is possible to set retrieve tension precisely independent of drum RPM. Of course, there are no pads or shoes to replace.



Because the main HVH250 motor can only be clutched to one drum at a time, it cannot provide retrieve braking for both drums simultaneously so two Motenergy ME1616 20kW auxiliary service (AUX) motors are used to provide up to 100 Lbs of braking. These can also be used for any duty not requiring the power of the main motor such as taking up slack.

ME1616's are available with field windings which use the same voltage as the main motor eliminating the need for a mid-voltage DC bus. Energy generated by regenerative braking is fed back into the battery pack for re-use.

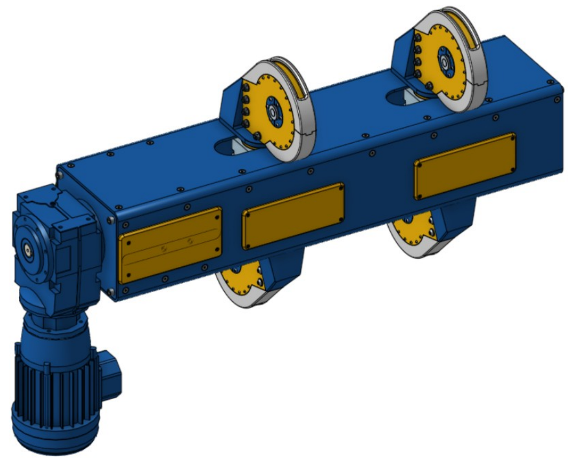
Under severe demand, as with a heavy glider, no wind and high density altitude, the AUX motors can add ~ 15% to the total torque available.

With the dog clutch engaged, the HVH250 provides powerful emergency braking for that drum. It can stop it in less than a second.

**Slack take-up using an AUX motor:** Using a 440HP motor for the delicate job of removing slack can be problematic as it takes skill and time to do it gently enough not to jerk the glider forward.

AUX motors, with their torque set just high enough to remove slack but not so high they can move the glider, are a far better solution. This allows swift slack removal since there is no risk of jerking the glider. This speeds up the launch cycle. Slack can even be removed from one rope – or that rope retrieved - while the other is launching a glider. Pre-set torque makes it just a button press.

**Fairlead/X-Wind Assembly– (Pay-on System):**



O/A Height: 30.647”
O/A Width: 57”
O/A Depth: 18.381”
Weight 700 Lbs (Incl. 200Lb gear motor)
Unique Parts: 78 (Including screws & bolts)

Frequent rope-jam issues experienced in the field has led to close examination of just how rope is wound onto winch drums. These jams can lead to a long, frustrating job untangling the rope and sometimes repairing damage to the rope and winch. The cause is outer wraps “diving” down between inner wraps causing a “hitch” lock-up.

Acknowledging the problem, Sampson Rope, a leading vendor of UHMWPE winch rope, published a white paper directing users to cross-wrap rope on winch drums which prevents “dive-in”.

A great deal of engineering went into addressing this issue. The result, shown in the rendering above, is the most complicated of the sub-assemblies. It contains two fairleads with their guillotines as well as a common traversing mechanism. Once assembled, the fairlead assembly bolts to the frame with 10mm bolts.

Cross-winding requires the fairlead move across the drum much faster than with simple parallel winding system in order to achieve effective crossing angles. At the highest drum RPM (~1,200 RPM), the fairlead has to move over 40 inches per second.

The fairleads themselves each weigh over 100 Lbs. To stop them when moving at 40 IPS in one direction and then accelerate to 40 IPS in the other direction over a distance of one inch requires 2G’s of deceleration/acceleration so the inertial force the pay-on system must overcome is about 200 Lbs-F. The maximum drift angle is assumed to be 30 degrees off the runway center line at release which would produce a lateral force of about 300 lbs. The winding system could see 500 lbs lateral (axial) force in the worst-case scenario. The Benzler 7.5HP gear motor shown is judged to be powerful enough.

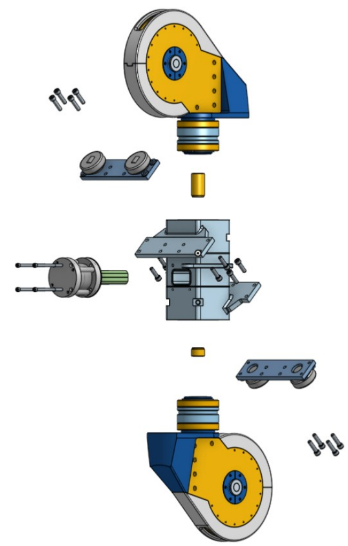
Any pilot drifting as much as 30 degrees would be counseled to keep their ground track over the runway centerline.

That much force and speed rules out self-reversing screws and screw-type linear actuators leaving cams as the best option for producing reciprocating motion.

Given the compact dimensions of the Electric Winch, the best cam is variously known as a cylindrical, axial or “barrel” cam. Only one is needed for a two-drum winch as cam followers are positioned 180 degrees apart so the fairleads oscillate 180 degrees out of phase “boxer” fashion canceling vibration. The non-duty fairlead just flexes its rope.

The traversing fairleads run in parallel “C-Channel” tracks known as Hevi-Rail located inside a 12” x 10” x .25” wall rectangular tube. The Hevi-Rail system is available from PCB Linear. Hevi-Rail uses “combination” bearings which are like big cam followers with a second roller bearing in the hub set at right angles to the first. The big bearing carries the main loads and the smaller secondary bearing keeps it centered in the track.

**Fairlead/X-Wind Component – Fairleads:**



- Height: 970mm (38.2”)
- Width: 225mm (8.6”)
- Length: 310mm (12.2”)
- Weight: 53 Kg (116.8 Lbs)

Fairleads must accept high speed rope at elevation angles of 0° to 70° and azimuth angles of ± 45° then feed it precisely onto a drum with minimum rope wear. Most fairleads have trouble meeting this requirement.

The Electric Glider Winch uses a vertical castering pulley block system. This system can theoretically accept rope coming from anywhere in the sky but the castering angle is limited to ±45° to avoid collisions between pulley blocks.

After bending around the top sheave, the rope travels vertically downward through the hollow axis of the caster “wrist” bearings, through the guillotine to the second sheave then to the drum. The bottom pulley also swivels on caster bearings to insure the rope can snuggle into the sheave groove during rope retrieves. The entire rope path is very smooth, low friction surfaces to minimize rope wear.

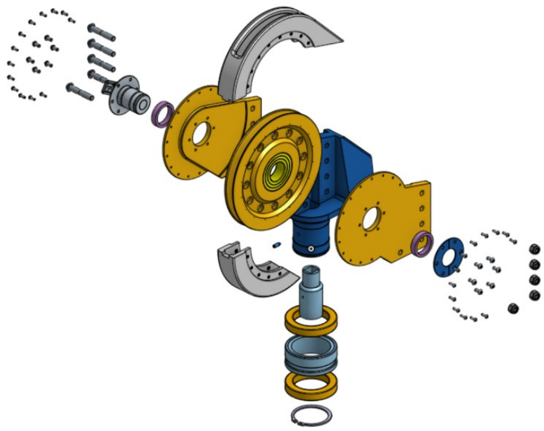
A question sometimes arises about how one threads a new (or broken) rope through the fairlead. With the vertical rope path, one need only tie a small weight to a string and drop it through, remove the weight and tie the string to the rope and pull it back up.

Most winch fairleads use long, thin vertical rollers to guide the rope into a sheave groove. However, a 2” OD roller can turn as fast as 12,000 RPM which takes a toll on the bearings – and on the rope.

The castering pulley block system rotates on low friction ball bearings so the pulley groove is expected to keep sheaves aligned with the incoming rope without using rollers. To insure this happens, the sheave is enclosed in low friction UHMWPE plastic which has 15x the abrasion resistance of steel. It is expected the rope will not contact the UHMWPE unless it is flopping loose.

The launch begins with a 90° wrap angle on the upper sheave declining to just 20 degrees at release. The max force is 14.14 kN (3,179 Lbs-F) on the sheave bearing is at the start of the launch decreasing to just 3.474 kN (781 Lbs-F) at release. The lower sheave’s wrap angle stays close to 90° so the force on the bearing is always a little over 3,000 lbs-f.

**Fairlead/X-Wind component – Castering Pulley Assembly:**



- Weight: 14.5 Kg
- Groove Diameter: 228.6mm (9”)

The caster block sub-assembly is made up of several machined components. The bracket/bearing journal (blue) is fairly complicated part as are the “ears” (gold) which support the sheave bearings. The sheave itself is a fairly straightforward lathe project with a very deep rope groove whose dimensions are specified by Sampson Rope.

The caster journal runs in two 70mm ball bearings which rotate around the vertical axis. These are separated by a spacer and retained by a snap ring. The sheave spins on an AST 5308-2RS 40mm ID Double Row, angular contact, deep groove ball bearing which provides excellent wobble stability and high load carrying capacity. All bearings are loaded below their fatigue limit (Pu) so life should be nearly infinite.

The sheave itself is 7075 AL hard anodized to prevent corrosion and PTFE impregnated to minimize rope friction.

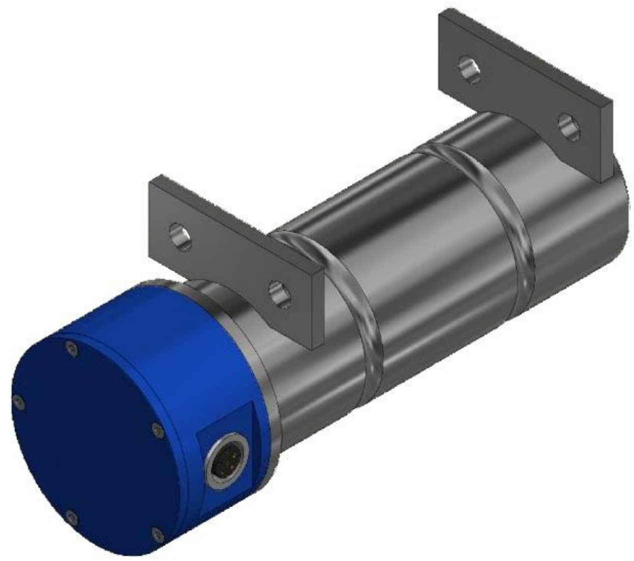
A plastic transition piece guides the rope from a rectangular cross section at the sheave to a round cross section as the rope enters the guide tube leading to the guillotine. The round end allows the caster to rotate without exposing the rope to sharp edges. The transition piece, located inside the caster journal, is a lofted transition. This part is a natural for 3D printing.

The entire assembly is balanced about the caster axis.

The upper caster block assembly contains the tension sensing load pin, Hall Effect speed sensor and the associated electronics plus a battery. It is anticipated data will be relayed to the winch computer via a Bluetooth radio-link.

**Fairlead/X-W Component – Sheave Load Pin:**

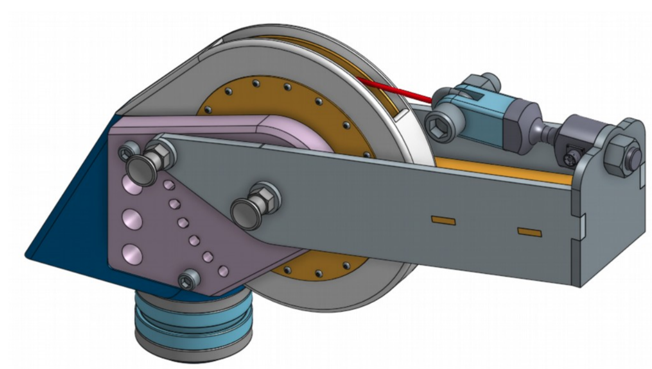
- OD: 40mm (1.575”)
- ID: 20mm (.787”)
- Length: 47.574mm (1.873”)
- Weight: 0.334 Kg (.736 Lb)
- Material: Stainless Steel



The axle of the lead sheave is a load pin which senses radial loads. This pin is sensitive to loads in two planes arranged at right angles to each other and in the plane of the sheave. A simple calculation using these loads gives the rope tension and the rope elevation angle.

A number of vendors can build custom load pins with the requisite force range and precision. Calibration is part of the deal.

The cost is little more than making a pin oneself but for those who want to save a few dollars, a pin design is in the package.



In the event field calibration is desired, this is fairly easy to do with a jig such as is shown at right. The motor can generate full torque at 0 RPM so a jig with a lab-calibrated tension load cell attached to the rope can be used as a calibration reference. An error map will be created which will be used by the winch software to correct raw data insuring very accurate launches.

**Fairlead/X-W Component – Guillotine Assembly:**

- Height: 209.6mm
- Diameter of air cylinder: 108mm (4.25”)
- Weight: 2 Kg (4.4 Lbs)

A guillotine is used to cut the rope in an emergency such as when the glider can’t release. It is an essential safety feature of any winch. There are many ways to make a guillotine but the smallest, lightest and most reliable seems to be an air cylinder driving a sharp blade against a soft brass block.

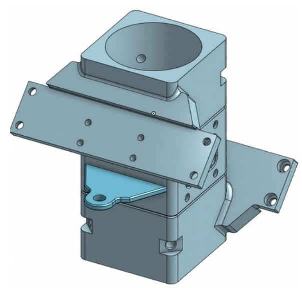
The Electric Glider Winch uses a 2.5” bore single-action, spring-return cylinder from Bimba. An electric solenoid valve sends 100 PSI air to the cylinder in response to an electric signal. When the signal is removed, the valve releases the air pressure and an internal spring retracts the blade. At 100 PSI the 3” cylinder will force the blade into the brass block with more than 1.78 kN (400 Lbs-F) which will cut any rope.

With this much force available, a plastic “crush tube” can be used to protect the guillotine from dirt the rope drags in. This thin-wall plastic tube seals the blade and guide blocks so they stay greased, clean and ready for use.  The blade can easily cut through both the plastic tube and rope.

After use, the whole guillotine can be disassembled by removing 4 bolts.  The brass block is a 1” cube which can be turned to expose a fresh face.  The blade is replaceable by pushing out two dowel pins.  The air hose must be detached before it can be removed for safety.

**Fairlead/X-W Component -  fairlead Weldment:**

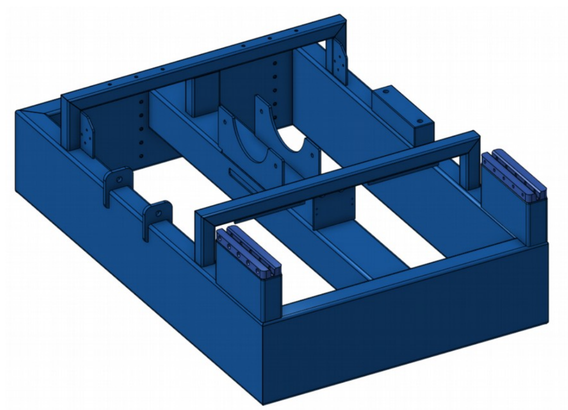
- Weight: 15.89 Kg (35 Lbs)



The weldment holding the fairlead components is a short length of 5” square steel tube welded between machined bearing carriers with tabs with a pushrod bracket welded to the side.

**<u>Frame Weldment</u>**

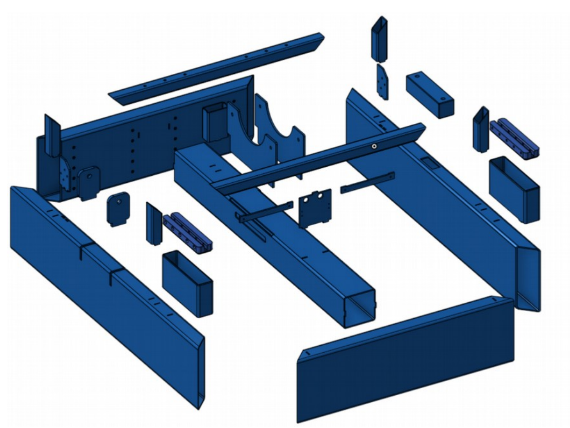
- Size: W 41.5”, L 62.14”, H 19.5”
- Weight: 494 Lbs
- Parts count: 28



Components laser cut with tongue & slot alignment aids for self-jigging.

Building the prototype has shown that working with welding shops can be difficult.  A key question to ask is, “Do you do TIG welding?  If not, look for another shop.

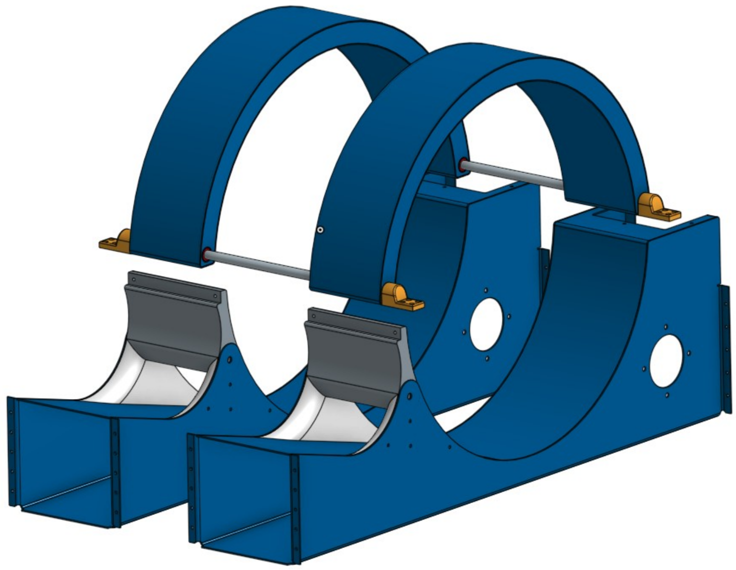
Fortunately, welding the frame is something DIY hobbyist’s can do in their garage for a substantial cost saving.  If the builder has no welding experience, adult courses are available.



Electric welders are getting much cheaper.  Look for one with the capability to do both TIG and MIG welding.  While most welds will be MIG, there are a few areas where TIG welding is appropriate since it can make very thin, deep penetration weld seams. For MIG, plan on using shielding gas instead of flux core wire.

The all-up weight of the frame weldment – as well as other winch components - is such that some sort of lifting device will be required.  Engine hoists can work but a better solution is a small portable gantry crane which can be pushed around on its caster wheels.  Northern Tool lists one with a 2,000 lb capacity for $429.

**Drum Enclosures**



An important feature of all winches is drum enclosures.  If the rope can jump off a drum, it will causing delays and sometimes expensive repairs.

A drum enclosure is both a convenience and a safety item. Eliminating rope fouling maintains pace of launches. The shrouds also protect the winch itself and those around the winch from the danger of being caught by a rope loop.  Properly designed drum shrouds pay big dividends in rope service life.

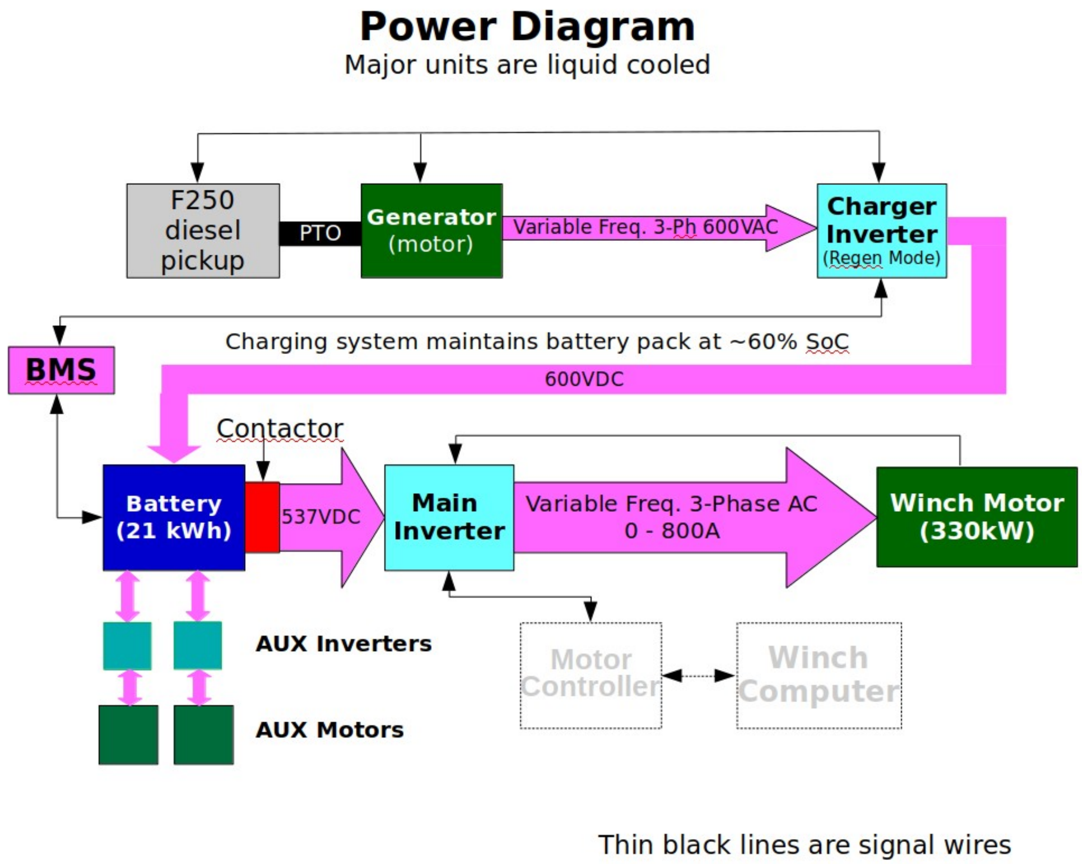
Drum shrouds must fit tightly around a drum to prevent the rope’s escape but also allow quick and easy access to the interior of a drum so any tangles which do occur can be dealt with.  These shrouds leave only a 2mm gap around the drum flanges.

The Electric Glider Winch uses fixed lower shrouds and movable upper shrouds.  The lower shrouds also mount the AUX motors.  The lower shroud includes a UHMWPE “Guard Bar” and “Cheeks” which guide the rope onto and off the drum.

The upper shrouds slide axially (sideways) towards the center of the winch on simple linear bearings running on 0.75” shafts.  This uncovers the top of a drum for easy access.  Strong magnet latches keep them in place over the drums when operating the winch.

Both the upper and lower shrouds mount to 2” square track bars on the frame.  These bars close the gap between upper and lower shrouds.

## Winch Battery Pack and Power Electronics

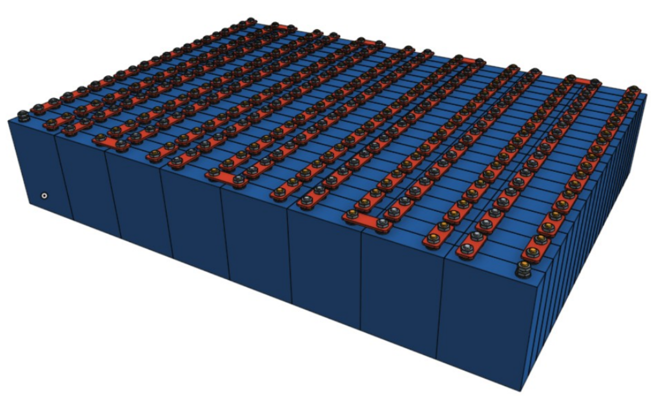



**Battery Pack:**

To make the winch truly portable, a large battery pack is needed to provide the surge of power needed for a winch launch. The main criteria for a winch battery is power capacity (Amps - kW) which is different from energy capacity (kWh).

Batteries are rapidly evolving. Costs are dropping at a compound rate of 40% per year while performance is increasing at about the same rate. Therefore a decision to buy should be delayed to near the end of the project. In 2017 the best option was 840 Headway 38120HP cells arranged in a 168s5p pack. This pack would have weighed 600 lb with a volume of about 5 $ft^3$ and contained about 20 kWh of energy. It could have delivered 500kW of power.

A year later, Liyuan 60 AH supercapacitor-LiFeO4 hybrid cells look like a far better option. These prismatic cells can be arranged in one, 168 cell series string providing 37 kWh energy capacity in a 5.7 $Ft^3$, 641 Lb. pack.



The Liyuan pack can deliver almost a megawatt while the Headway pack can ‘only’ deliver 538kW. However, in winch duty, the Headway pack would be operating in it’s “instantaneous’ discharge mode while the Liyuan pack would operate in a more benign “continuous” discharge mode.

The Remy HVH 250-115 and its John Deere PD400 inverter can use as much as 900VDC but will still work down to 180V. A 538VDC pack is a compromise judged adequate for the expected duty.

Liyuan claims a service life of 5,000 cycles. Some have jumped to the conclusion that this means the battery pack will need replacement after a few thousand launches which would not be economically feasible.

Even considering conversion and cycling losses, a typical winch launch will consume less than 2kWh of battery charge. A high-power charging system operated in the “charge-while-launching” mode means that the State of Charge (SoC) of this 37kWh pack will be “pulled down” 3 - 4% and then be recharged immediately. This minimizes pack discharge-charge heating which is a big killer of Lithium cells. If the pack is cycled in this way, it will have virtually no effect on battery life so the pack will likely survive to its shelf life limit.

Even if one takes the life-cycle number literally, 5,000 full discharge/recharge cycles is 50,000 launches. That works out to less than $0.30 per launch for battery replacement at current prices. Battery cell prices are dropping at nearly 40% per year measured in $/kWh and the power density measured in $/kW output is dropping even faster. One can confidently forecast the price of a replacement battery pack will be less than half the current price.

**Power Electronics:**

The design anticipates using a John Deere dual PD400 traction inverter charging the battery and driving the main motor. Two smaller Rinehart traction inverter’s will drive the Motenergy ME1616’s. One 15kW inverter will drive the X-Wind gearmotor. All are liquid cooled using the same coolant loop as the main motor.

The electronics must be protected so a weather tight enclosure is planned.

**Generator**

The proposed generator is a HVH250 motor running in regenerative mode assuring the correct voltage to the inverter and battery pack. This robust generator would deliver as much as 160kW to keep the battery pack charged. At max output it would restore the pack to its designated SoC in less than a minute.

**Mounting on Pickup Truck**

A pickup truck is a particularly interesting platform as the winch just fits in a standard bed. However, due to the weight of the winch, it will have to be a Ford F350 class truck with dual rear wheels. A frame adapter picks up the bed mount bolts and the bolt pattern on the winch frame.

An essential feature of the truck is a “PTO Ready” transmission. A PTO gear adapter drives a HVH250 generator mounted between frame rails. The truck’s engine provides the power to drive the generator which charges the battery.

The truck will also need an air compressor to operate the guillotines and dog clutch, a heat exchanger (radiator) mounted behind the grille and a 12V coolant pump installed to circulate the coolant to cool the motors and power electronics.

**Instrumentation and Automation:**

Most builders are expected to settle for a traditional “human-in-the-loop” control system where the operator runs the winch manually using hand controls and an information display. However, a few builders may want to add some level of automation.

Electric drive greatly facilitates automation of a winch. While the operation of a glider winch might seem complicated, in fact it is very easy compared to many common, reliable, automated systems such as elevators. The goal would be to capture the best winch operator technique in software and then distribute that software to anyone wishing to achieve perfect launches.

It is imagined the operator will eventually be at the start line managing the winch from there through a highly secure, high-bandwidth wireless data link. It would even be possible - should anyone be so bold - to operate an automated winch from a glider cockpit.

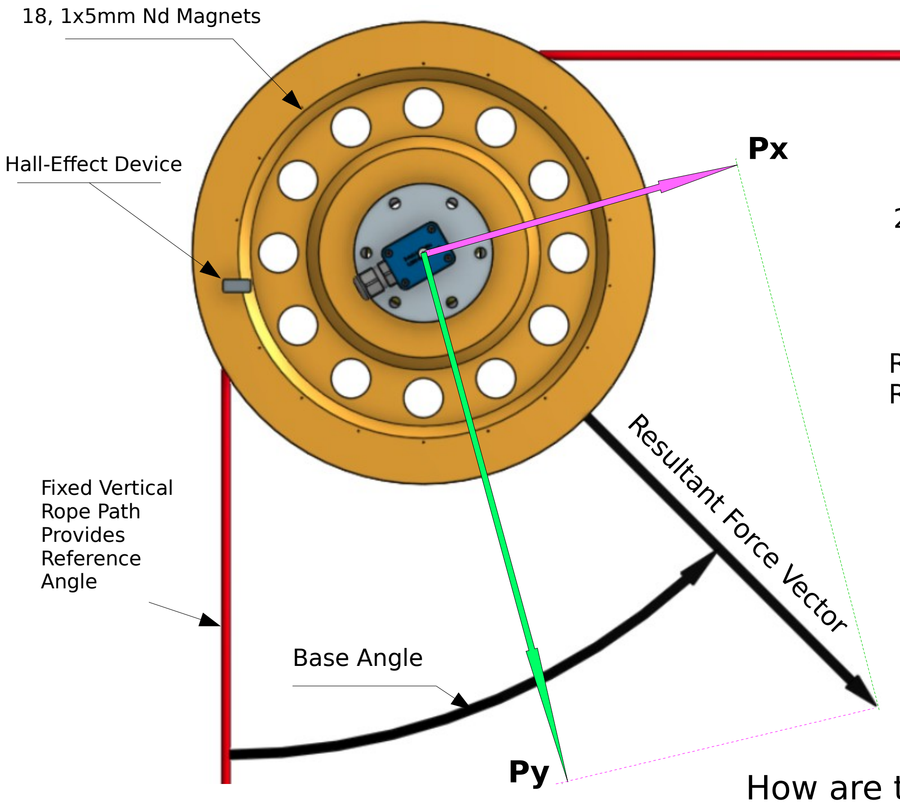
Full automation eliminates the hand ‘throttle’. The winch computer will adjust the rope tension thousands of times a second based on the output of a sensors built into the fairleads.

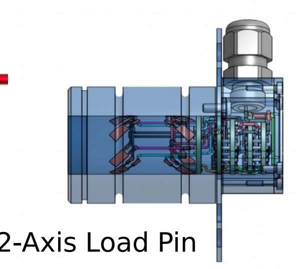
To initiate a launch, the operator will select the glider type and pilot and then press the “arm” button causing the winch to run a self-test and report itself ready. To take up slack, the operator just pushes a button and the slack is swiftly but gently removed with no possibility of jerking the glider. When all is ready, the operator just pushes another button to initiate the launch. These commands must be in the correct sequence or the winch will reset. The rest will be automatic including the rope recovery after release. The operator’s main duty is to operate the guillotine should the launch start to go wrong.

First, we look at the sensors and information display starting with the fairlead sensors.

# Instrumented Sheaves

Provide Rope Tension, Angle, Speed & Length




Rope Angle = 2 x BA - 90°

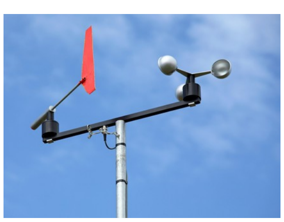
$$\text{Rope Tension} = \frac{Px^2 + Py^2}{2Px}$$

How are these data displayed?

A winch operator – or winch computer - needs five real-time data streams. These are rope tension, rope elevation angle, rope speed, rope length remaining plus environmental data such as wind and temperature. Sensors on the fairlead provide the first four as shown above.

A ring of tiny magnets in the sheave is sensed by a Hall Effect device providing sheave RPM and number of revolutions which are used to determine rope speed and rope length odometry. The load pin provides the force vector acting on the sheave axle from which rope tension and angle can be computed.

Environmental data is from a automatic weather station near the start point.

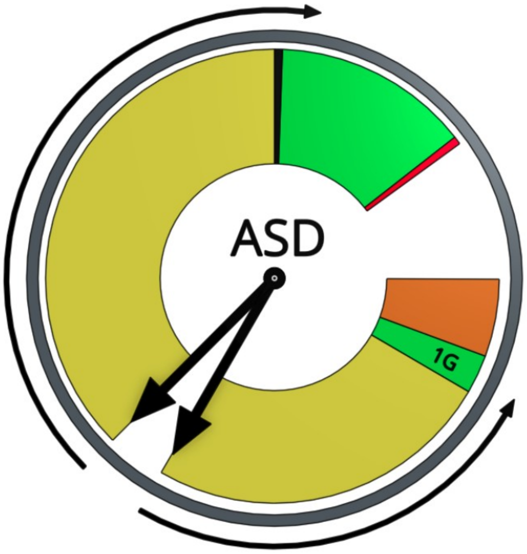


True Airspeed (TAS) = Rope Speed + Headwind Component
Calibrated Airspeed (CAS) = TAS corrected for Density Altitude
Acceleration = Rate-of-change of Rope Speed (19 kts/sec. = 1G)
WX data from near launch point used for headwind component & DA

Rope speed and environmental data are used to computer the gliders calibrated airspeed (CAS) which is valid as long as the glider is traveling directly at the winch. Once the glider begins to rotate into the climb, these data are no longer valid – nor needed.

**<u>Instrument Panel:</u>**

**Acceleration phase:** Instrumentation display will use the screen of a laptop or tablet computer to display large, easy to read graphics. The information displayed there will change for different gliders and different phases of the launch. After a glider has been selected but before a launch begins, the screen display will be as shown below. Numbers are not used nor are they needed. The fast pace of winch launch would make them unreadable anyway.

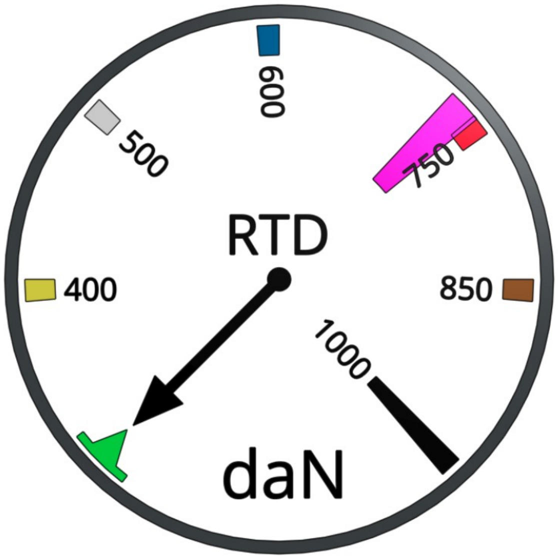



The ASD dial includes two scales. The 7:00 – 2:00 O'clock arc in the upper left is inferred glider airspeed. The yellow sector indicates the glider is too slow to safely begin rotation. The black line is the minimum airspeed for starting the rotation phase and the red line is the $V_W$ or never exceed speed for ground launch. The green sector between the black and red lines is a safe airspeed range. If a different glider is selected, markings will change to show the appropriate 'V-speeds'. These airspeed markings are corrected for headwind and so closely approximate what the pilot sees on the airspeed indicator.

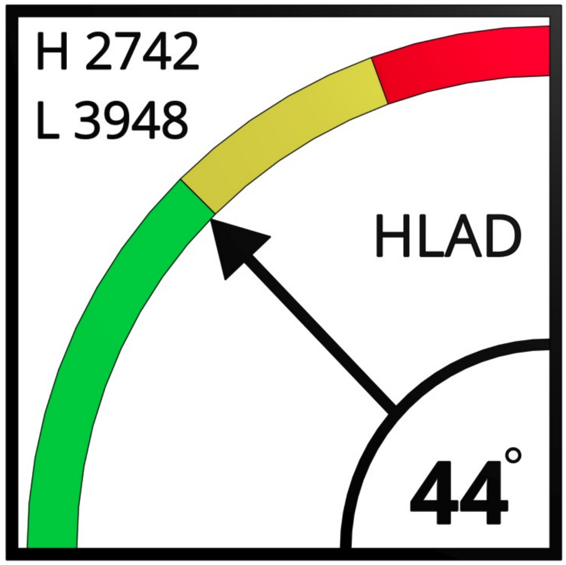
The 7:00 – 3:00 O'clock sector in the lower right displays glider acceleration with the green sector representing 1G or 19 knots per second. Yellow arcs above and below the green sector represent unsafe acceleration. Low acceleration risks a wing drop and ground loop and high acceleration places unnecessary stress on the glider and risks disorientating the pilot. Acceleration is measured two ways – one is Newtonian F=MA restated to read A=F/M where rope tension equal to a glider flying weight will produce 1G acceleration. The other uses the rate of change in rope speed where an increase of 19 knots/sec = 1G.

This permits a safety cross-check. If rate of change in rope speed differs significantly from the F=MA solution, it's probable the flying weight was entered wrong. For example, if an instructor climbs out of a 2-seater to solo a student without informing the winch operator of the change in flying weight, that student would get a memorable solo flight. To avoid this, the winch will warn the operator to use the flying weight inferred from rate-of-change data. A computer would do this automatically.

The Rope Tension Display (RTD) is on the right. The short 'tics' are in Tost weak-link colors representing rope tension equal to the strength of that link. The magenta icon represents the glider flying weight expressed as rope tension. The long black tic represents the weak-link used by the glider – in this case 1,000 daN. The green icon is a command bug which the operator positions at the rope tension desired. A feedback loop causes the needle to point at the bug.



**Climb Phase:** As soon as the glider begins rotating into the climb phase, the pilot will assume responsibility for controlling airspeed so the ASD is no longer needed. Rotation causes an unmistakable signal as tension rises and rope speed drops suddenly. This signal causes the ASD display to be automatically replaced by the HLAD. (Height, Length, Angle Display)




"L" is the rope length remaining as measured by the Hall Effect odometer which was zeroed as the previous rope retrieve began. "H"is glider height AGL computed using rope angle and length to solve a right triangle. The top of the green arc is 45° where the operator must start reducing rope tension. The top of the yellow arc is 70° where the operator must cut power to force an automatic back-release.

**Normal launch:** After slack is out and a signal to launch has been received, the operator will advance the command bug to the magenta icon thereby initiating a 1G acceleration ground roll. As the airspeed needle approaches the green sector, the command bug is retarded about 25% to mitigate airspeed overshoot.

As the glider begins rotation, the ASD is automatically replaced with the HLAD. At completion of the rotation phase, the operator smoothly advances the command bug to the magenta icon or a bit above it depending on the glider. This tension is held until the rope angle reaches 45° where a smooth reduction in tension is begun until at 70° the operator forces an automatic back-release by sharply reducing tension below 400 daN causing the rope to sag triggering release. The operator then recovers the rope at about 50 daN so the parachute falls about 100 feet in front of the winch.

**Automation:**

It should be clear to any automation engineer that a normal launch would be easy to automate. An abundance of data is available with multiple redundancies to handle data loss. The winch controls are one-dimensional consisting of just motor torque. However, with humans at risk, more attention must be paid to failure modes and safety.

**Exception handling:** Obviously, not every launch will be "normal" and winch automation must handle all abnormal conditions with aplomb. The theory is called "Fail Soft" rather than "Fail Safe". In the event of a system failure, the winch will continue the launch - perhaps at reduced power - and then signal its human supervisor for help.

Rope breaks and premature releases are easy to identify as tension drops to zero with the drum still turning in which case the winch will simply stop and ask for help.

If the glider encounters a thermal, the winch will reduce motor torque so the rope tension is unchanged allowing the glider to rise in the thermal without being pulled down. If the glider enters sink, the winch will ramp up torque to maintain rope tension pulling the glider through.

If a pilot fails to climb steeply enough, airspeed will rise signaling the pilot to raise the nose more. If a pilot climbs too steeply, airspeed will decrease signaling the pilot to lower the nose.

If a pilot can't release or fails to release, the rope will be automatically cut an a 90° elevation angle.

Sensor failures need backups.  If the tension sensor fails the winch will continue the launch at reduced power using using motor current as a surrogate for tension data – or, if available, data from the in-rope load cell at the parachute.  If rope angle data is unavailable, the winch will signal release by cutting power based on rope length.

If the sheave RPM sensor fails, the launch will continue at reduced power using main motor RPM and effective drum diameter as determined by the number of drum rotations as a surrogate for odometry data.

The winch may also use RFID tags in the rope as a back up for odometry data.

If RFID/odometry/rope speed data make it appear the parachute is going to be pulled into the fairlead, the guillotine will cut the rope if it can't stop the motor.

In case of a weather station failure, the operator can enter an estimate of headwind.

Of course, not every sensor problem will be an outright failure.  A sensor may just start sending bad data.  In every case the winch cross checks sensors with backup systems.  For example, the winch builds a database of motor current vs. rope tension for every point in a launch.  If motor current and rope tension data disagree, the winch just continues the launch at lower power and signals its human it needs re-calibration.  Similarly, the winch compares rope length, rope angle and rope speed with drum RPM and number of rotations.  If a discrepancy is found, the winch continues the launch at reduced power and signals the need for service.

It should be noted that the safeguards which would of necessity be part of an automated winch are not typically present in winches manually operated by humans.  It is argued that this alone makes an automated winch safer than one operated by a fallible human.

**Security:** The idea of an autonomous winch raises concerns regarding the physical security of an unattended winch.  Curious interlopers, it is suggested, might be tempted to poke around the winch endangering themselves.  A greater concern is glider pilots, who are authorized to be on the airfield, but who may be unaware of the danger of standing near a winch.

If it is deemed necessary, modern vehicle security systems are very good and relatively inexpensive.  Video cameras with motion detection can easily detect anyone approaching the winch in which case, they will hear: "Please step away –  this is a dangerous area – the winch will not operate with persons nearby."  At the same time the "Emergency shut-down" would be automatically activated and the winch operator at the start line would be notified.  This should be sufficient security but a human, other than a winch operator, could be assigned to police the winch area.

**Human operator duties:**  "Robowinch" has a pet human who watches it carefully.  The humans main duty is to operate the guillotine if necessary.  If the human is at the launch point, any deviation from a perfect launch during the critical ground roll and early rotation can be seen easily.

For example, if a wing tip should drag threatening a ground-loop, the human can cut the rope with the guillotine.  While this may not prevent a ground-loop, it will instantly remove the power of the winch.  The accident record contains many instances of severe accidents which could have been avoided this way. The winch will treat it as a rope break and stop.  The human is also in a good position to discuss launches with pilots. Placing the human at the launch point also completely eliminates winch-launch point voice communication to the relief of others using the same radio frequency.

**Winch to Start Line data-link:** In order to operate the winch from the start line the human must have comprehensive real-time information on the status of the winch. The latest versions of WiFi have the bandwidth to send not only winch operation parameters, and receive launch commands but also handle several channels of video and audio.

HD video cameras have become very small and cheap so it makes sense to place several in and around the winch. With this level of communication, the human could see and hear the dog clutch engaging and rope winding onto and off the drum. This sort of "telepresence" would actually make it easier – and safer - to monitor the winch from the start line than if actually at the winch.

Data-link integrity and security is an obvious concern. However, a winch is generally operated at some distance from other W-Fi networks and, in fact, is likely to be the only one in the area. Nonetheless, the net will be locked down tight with all available security measures. The arming process will sniff for other networks and if there is danger of interference, the system will fail to arm and send an error message explaining why.

Operation of the guillotine is on a completely different data-link independent of other winch operation systems with its own power supply. If the winch became totally uncontrollable, the human operator would still have the option of cutting the rope which not only separates the glider from the winch, it also saves the winch from itself by pulling the master circuit breaker.

**Future Developments:**

Will this design be obsolete tomorrow?

Should battery cost drops by half, it would be welcome, but make less difference in overall cost than one might imagine. PMSM motors with integrated power electronics are on the way which will simplify the design. A motor with enough torque to eliminate the gearbox would be particularly welcome. At 3,500 NM, the TM4 SUMO MD 9-phase motor has the required torque. Hopefully, the price of these "torque monsters" will drop far enough.

Machine vision and AI are advancing at an astonishing pace. It's not unlikely a winch equipped with video cameras could learn to scan the rope at very high temporal and spatial resolution as it approaches and leaves the winch. It could learn to recognize, for example, a weak spot then alert its human of the exact location on the rope that needs attention.

Some parts of the Electric Glider Winch would be suitable for advanced AM manufacturing – particularly the drums. Some 3D printing materials such as carbon fiber reinforced polymers are almost as strong as 7075 aluminum however the material properties are not sufficiently predictable to be able to use FEA in the design process eliminating this option for now. One hopes AM will evolve to become suitable.

Foreseeable developments such as these could be incorporated into the design with few changes while offering the possibility of significantly lower cost.

What about winches themselves? Will the popularity of self-launch motor-gliders render them obsolete? More likely it will be seen that gliders with small, inexpensive electric sustainer motors can be launched with winches to preserve its battery charge for use later in the flight or to greatly extend the search area for finding a thermal on the $1^{st}$ launch.