Sailboat Autopilot: Mainsheet Tender Module

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Engineering 90

2007 – 2008

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Abstract

The Art of sailing a wind powered vessel relies heavily on the ability of the crew to trim the sails. Finding the right angle of the sail with respect to the vessel will apply the optimal amount of force with the least amount of drag on the boat. Using the idea that there is an optimal sail angle, a device has been constructed which based on wind direction relative to the boat calculates the optimal sail angle and adjusts the mainsheet accordingly. The tender is designed as a modular system that functions independent of an autopilot program that would be set to maintain a heading, hence it can be used with any autopilot system currently on the market or used independently with a sailor steering the vessel.

Acknowledgements

Without the assistance of the Engineering Faculty and staff at Swarthmore College, this project would not be. I would like to thank the following professors for their assistance in bringing me to where I am today, and helping me complete this project.

Fred Orthlieb

Lynne Molter

Erik Cheever

Ani Hsieh

Tali Moreshet

Bruce Maxwell

Nelson Macken

Carr Everbach

Grant Smith

Doug Judy

Don Reynolds

Holly Castleman

Thank you.

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Overview of the E90 Program at Swarthmore College

"Students work on a design project that is the culminating exercise for all senior engineering majors. Students investigate a problem of their choice in an area of interest to them under the guidance of a faculty member. A comprehensive written report and an oral presentation are required. E90 is offered in the spring semester. This class is available only to engineering majors." – Tri-College Course Guide **NEED PROPER CITATION**

Engineering 90 is a year long single credit design project required for graduation with a B.S. from the Engineering Department at Swarthmore College. The student selected project is led generally by a single or team of faculty from the engineering department. The process begins in the fall semester, which contains two aspects.

Phase 1: Project Selection, Abstract Due

Phase 2: Project Proposal Due

The above two phases of Engineering 90 occur in the fall semester. Upon returning to campus to complete their education at Swarthmore students continue to work on their projects, for which they are given a single credit. While the process focuses on engineering design, students are asked to build a prototype to show functionality. In the senior spring, they present midway through the semester to their peers and faculty.

Phase 3: Midterm Presentations

Phase 4: Rough Draft of Report Due

Phase 5: Project Presentations

Phase 6: Final Report Due

During Phase 3, students seek feedback in a ten minute presentation on their work completed so far, their expected amount of completion, and project goals. This gives students an opportunity to practice presenting, and gain insight into similar projects. The instant feedback allows students to raise questions, and offer insight into their peers work.

The rough of the report gives the department a measuring stick so that they can see where students are in the process of completing their project.

Each student is given 30 minutes to present their project to their peers during finals week. This presentation makes up a part of the students grade and allows them to share their finished work with their peers. At this time, faculty can request that students complete additional work or mark the project as meeting the expectations of the department required for graduation.

The final report submission marks the culmination of the Engineering 90 project and successful completion of the requirements for Engineering 90 (assuming all previous requirements are fulfilled) thus allowing students to graduate from Swarthmore College with a degree in Engineering.

Objective

The main objective of this project was to design a proof of concept mainsheet tender module. The module was designed for use in smaller boats and was built to maintain the optimal sail angle for a tack given the respective wind vane reading. The mainsheet tender was built to control the length of the mainsheet by retracting and releasing it in a controlled fashion. I had two main concerns while building this system. The first design decision was to create a robust system that wouldn't fail. My second goal was to create an idiot proof design that was easy to use. Once installed on the boat, the user would need to have no input on the system in order to control it.

Reasons for Construction

The reasons for designing such a system are many; however, I feel that there are three pressing reasons for designing this apparatus: it's use as a teaching tool, it increases the sailing population by increasing accessibility and it has the potential to broaden the sailing experience into leisure.

Sailing is an art form, and learning to sail can be lifelong experience. Catching the wind to propel a boat is a balancing opportunity cost problem since many factors are involved in optimal sailing conditions, including the sail shape, the boom angle, and the hull angle with respect to the surface, as well as various additional factors. By installing this device on a boat, a sailing education can become modular, and the crewman can be replaced by the mainsheet tender. A beginner sailor can work on other important aspects of sailing such as sailing upwind, or tacking.

Sailing is a sport currently open to those who are in good health and those who can manage more than one task at a time both physically and mentally. The mainsheet tender when installed will allow individuals who lack these capacities to enjoy traveling by wind in a sailboat without having to manage both steering the boat and trimming the sails. Installation on a vessel opens that vessel up to use by handicapped individuals, children, and other persons who wouldn't be capable of sailing alone.

Finally, the trimming of sails is an activity that constantly needs to be performed when sailing. Changes in wind or variation in boat direction require tweaking of the boom angle, the outhaul and other sail related settings. Using a mainsheet tender allows sailors to enjoy sailing as a more leisurely sport requiring little effort.

Theory

The theoretical analysis of sailboats that follows is excerpted from my Engineering 90 final proposal.

My proposal seeks to optimize a sailing vessel, and so to begin, we must first examine the physics behind sailing vessels motion. Sailboats are unique in that the force moving them is found in one type of fluid, air, while the resistance they experience is found in a different fluid, water.

A sailing vessel is comprised of three pieces which interest us: the Hull, the Keel and the Sail. We will begin by exploring the hull as it is the hull which determines the maximum speed that a sailboat can achieve in addition to its ability to accelerate and its available speed in low wind conditions. There are two types of water vessels, those that plane or skip across the water and those that displace and move through the water. Our analysis will only deal with the latter type. It so happens that the maximum speed of any vessel moving through liquid is determined by the length of the hull. The shape of the hull is also important in that it determines the friction or resistance that the vessel experiences during movement through the liquid. Finally, the hull - along with the keel - determines the stability of the boat, which is a crucial aspect of the performance of the boat.

We begin our discussion of hull speed by acknowledging the simple fact that a hull moving through water generates a wave. Smaller velocities generate smaller waves, and larger velocities generate larger waves. The maximum length of the generated wave

- the maximum wavelength so to speak - occurs when a single wave stretches from the bow to the stern of the boat.

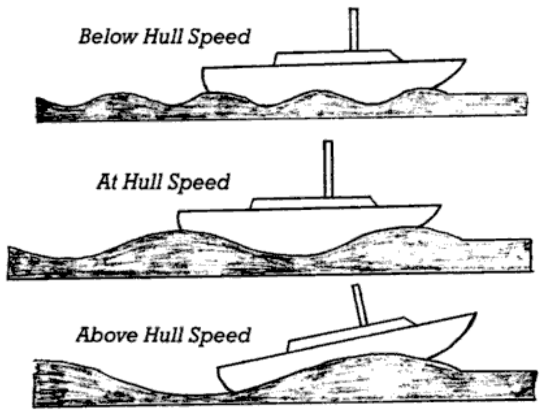


Figure I: Bow wave and Boat Speed ("Hull" speed occurs when there is just one wave along the side of the vessel.) Image courtesy of Bryon D. Anderson

There is a crest at the bow and the stern with a trough between in the center of the boat. If we consider the friction of the boat and the resistance of the vessel in the liquid, this is the velocity at which during steady state the boat is at its maximum. If the vessel were to go any faster, the stern would drop into the trough of the wave and the resistance would increase dramatically forcing the boat to slow down. Thus, we have reached the conclusion that there exists a relationship between speed and length. The speed of the vessel will be limited to the speed of the wave that has a wavelength equal to the length along the waterline of the boat. This “hull speed” effectively limits the speed of most sailboats to less than 10 knots and of most naval vessels to less than 30 knots.

Wavelength (feet)	(ft/sec)	Speed Mph	Knots (1knot= 1.15 mph)
1	2.3	1.6	1.4
5	5.0	3.4	3.0
10	7.1	4.8	4.2
20	10.1	6.9	6.0
30	12.4	8.5	7.4
50	16.0	10.0	9.5
75	19.5	13.3	11.6
100	22.6	15.4	13.4
200	31.9	21.8	18.9
300	39.1	26.7	23.2

Figure II: Wave / Hull speeds courtesy of Bryon D. Anderson

The table above shows the speed as it relates to wavelength, thus giving the maximum velocity of any vessel (without considering the possibility of planing). The table below gives the resistance experienced by a typical sailing vessel having a waterline of approximately 30 ft or 10 meters. The asymptotic nature of the curve suggests that the resistance goes high enough that little can be done regardless of power input via sails or engines.

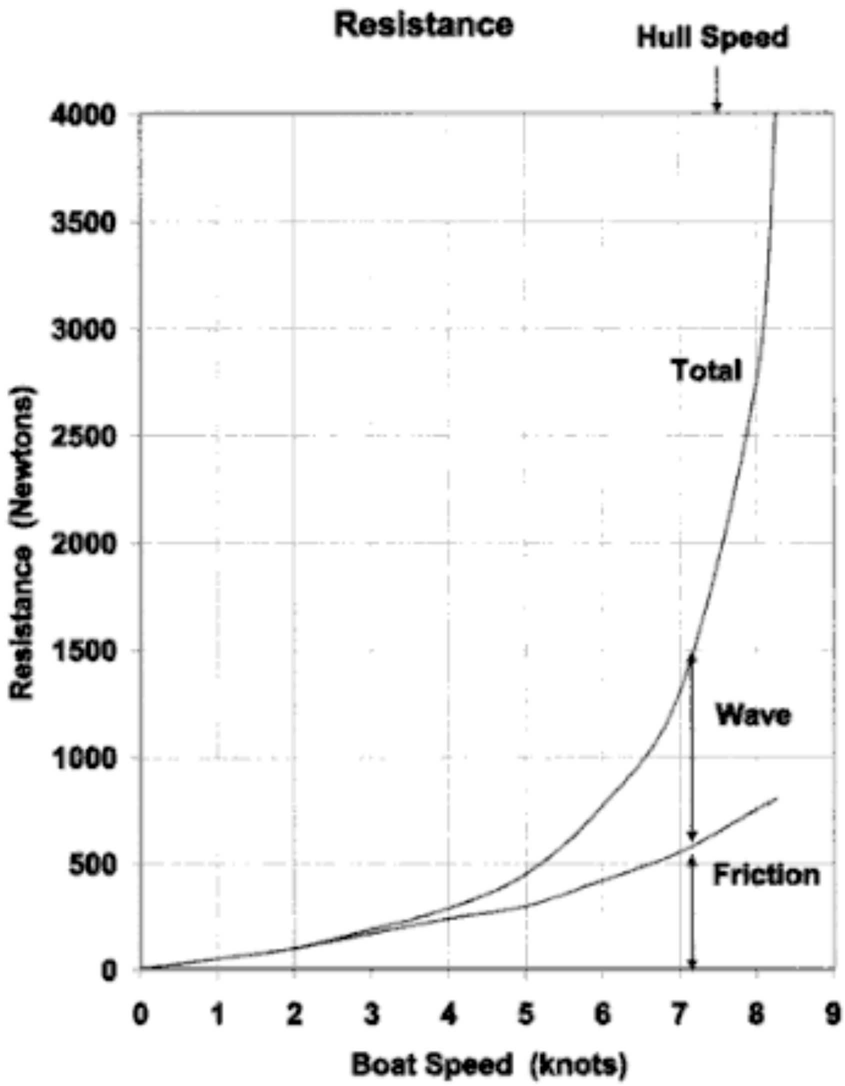


Figure III: The graph above shows drag components and hull speed for a typical sailing vessel with a waterline of approximately 10 meters. Image courtesy of Bryon D. Anderson

Everything experiences resistance as it moves through a liquid or gas. In fluid mechanics we are aware that the smallest layer of liquid surrounding an object doesn't move. The classic analogous example is that of a dust particle remaining on the hood of rapidly moving automobile. However, only the closest molecules remain (due to intermolecular forces). The remaining particles experience a shear force from the resistance, but do not necessarily move, especially as the distance from the hull increases. The perturbations in the water require energy which is taken from the sails of the vessel (on a sailing vessel, we will assume these are the only inputs of energy into the vessel, as is the normal case) thus limiting the amount of energy available to propel the vessel.

The second type of resistance comes from the shape of the hull. Clearly, a streamlined hull will create less resistance than the wider barge shaped hull. This is due to the amount of water deflected. The accepted design is that of a narrow bow and wider keel to allow for room beneath the deck. However, engineers must be wary of the affects of a wider keel which can create backward pulling eddies. These will be discussed in the following section, induced resistance.

The movement of the boat also induces resistance with the creation of small eddies which flow down the side of the vessel and behind the vessel. Larger eddies can actually have the strength to pull the vessel backwards as it moves through the water, and occurs with a wider stern. This turbulence is obviously related to the Reynolds number. Reynolds suggests that when we divide the product of the velocity and length of the vessel by the ratio of the viscosity to the density of the fluid, we begin to see turbulence around 1,000,000.

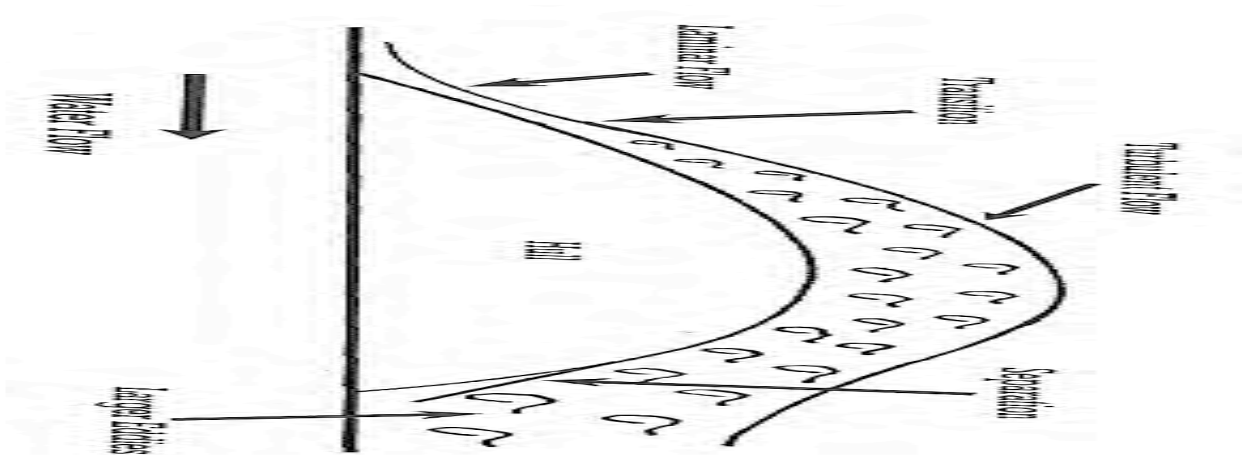


Figure IV: Fluid transitioning to turbulent flow and formation of eddies image courtesy of Bryon D. Anderson

The figure above shows how flow alongside the hull begins as laminar or smooth flow, and depending on the width of the hull will evolve into turbulent flow, separation and even possibly larger eddies which will drag the boat against the intended velocity. Of course, a smooth hull is extremely important in minimizing this resistance. It has been suggested that no bumps above 0.05 mm (0.002 in) can be considered “smooth.”

It should be noted that the numbers presented above are not absolute limits. The winner in the 2001 - 2002 Volvo Ocean Race, Illbruck, with a tapered hull shape was able to travel at approximately two times the theoretical maximum using planing for prolonged periods of time. Most mono hulled sailboats are incapable of performing at this level.

At this point we will continue our discussion, remaining bellow the water line, with the physics behind the fluid mechanics involved in keels.

Keels are very similar to sails, and so we will be able to apply many of the same principles we explore below in our later discussion of sails which serve as the “motors” or sources of energy that propel the boat through the fluid.

A keel can be anything that extends below the hull of the boat. On the modern sailing vessel, this is generally a long narrow piece extending well below the hull; however, a ridge line along the hull is also considered a keel.

Keels serve two purposes on a sailing vessel. First, they serve to prevent the vessel from “side slipping” in conditions when the wind approaches from the side. Secondly, they serve to offset the angle of the boat when it is heeling over in stronger wind. Two approaches exist: the first, a “full” keel runs from bow to stern, the second and more modern is the “fin” keel which can be a centerboard or dagger board or “fins” attached to the hull of the vessel. It was actually with the advancements in aerospace engineering that the keel can not only maintain the boat right side up, it can also provide a force into the direction of the wind. This is of course a reflection of Bernoulli’s principle.

The common misconception is that the wind pushes the boat, as one would conclude from the equations below:

Work = Force x Distance = Kinetic Energy

And $KE = \frac{1}{2} M v^2$, where M is the total mass of air striking the sail, and $M = \rho A v t$

- ρ is the density of the air
- A is the area of the sail
- v is the velocity of the air with respect to the sail
- t is an arbitrary time.

- If we take d in the equation above as the distance the air travels in the time t, then d =v t in and we have

$$F = KE / d = \frac{1}{2} \rho v^2 A$$

Not all the air hits the sail, therefore not all the KE is transferred so we multiply by C whic is a coefficient that is found from an empirical look-up table and depends on the geometry of the sail and the direction of motion relative to the wind direction.

$$F = C \left(\frac{1}{2} \rho v^2 A\right)$$

Because the density of air is usually constant, driving force by the wind is square of the wind velocity.

These equations would suggest that a boat could only sail with the wind. However, we know that sailboats are capable of sailing upwind as well as downwind (except for directly into the wind). So, while the above equations are reasonable in estimating the downwind force, this is not in fact how a sailboat moves, as discussed briefly above.

It is best to consider an airplane foil for understanding how a sail moves a sailboat.

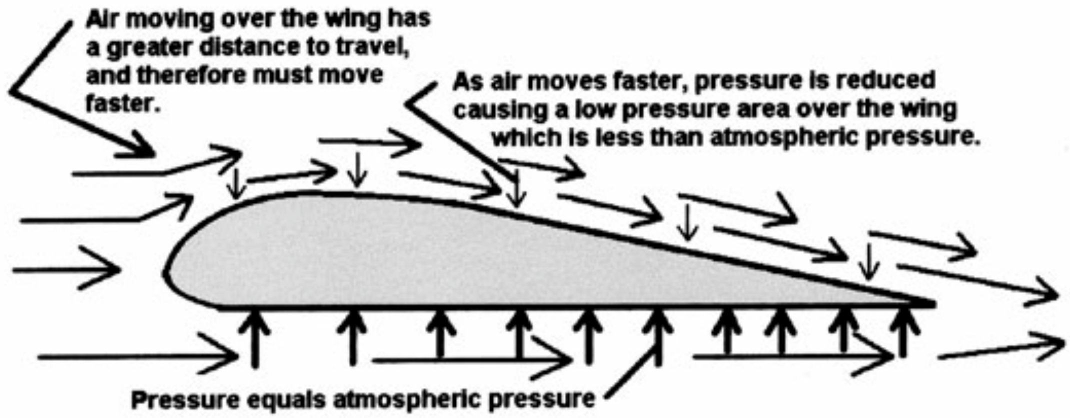


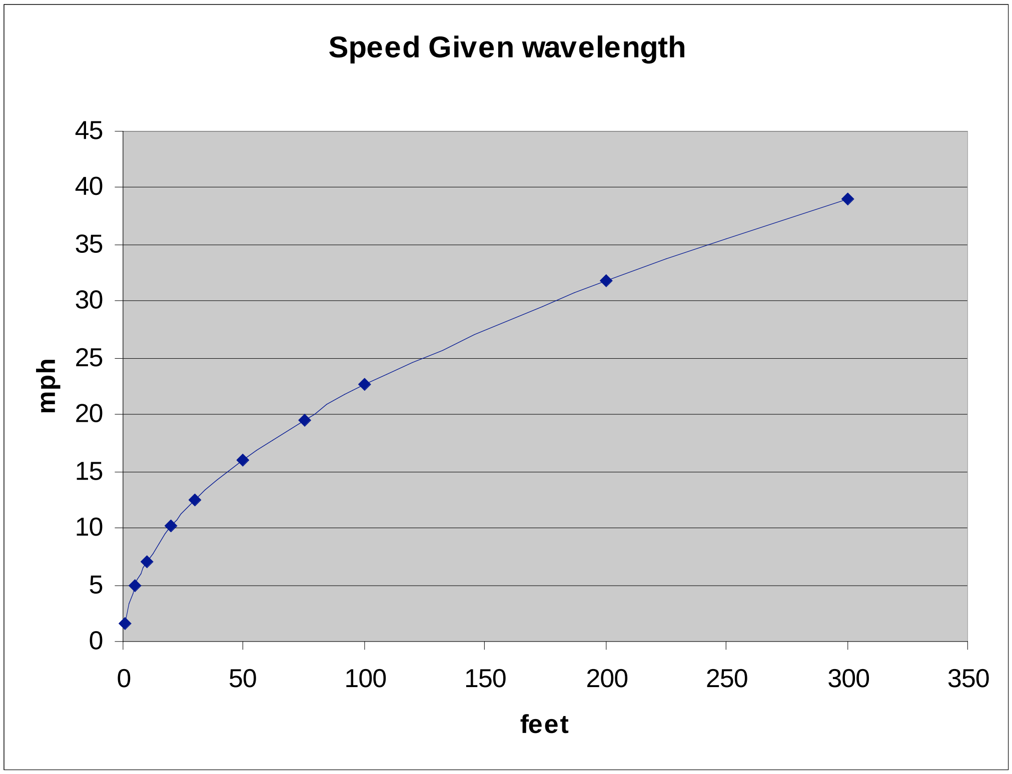
Figure V: Airplane Foil exhibiting pressure differential

The pressure differential in the case of the wind sucks the foil upwards against the force of gravity, keeping it in the air. The plane needs to be moving so that there is airflow over the wing of a magnitude that can overcome the force of gravity. If we transfer this concept into a sail we can understand, especially when considering what an aerial view would look like of the following photograph.

Figure VI: Sail in the shape of an Airplane Foil

Here the sail shape mimics that of an airplane foil which cuts into the wind. However, the only resistance to the tangential propulsion of the force of the sail being sucked forward into the lower pressure air is the resistance to movement. On a sailboat, this means water – but on a sailing vessel designed to travel on a low friction such as ice, it means that the sailboat can travel at speeds much greater than the wind velocity, thus iceboats have been recorded traveling at speeds of 120 miles per hour with wind much less than that. The photograph below shows the nearly frictionless contact that an iceboat makes,

However, in the case of traveling through a thicker fluid such as water, we are reminded from the above that we are limited in the ultimate maximum velocity that the boat can achieve based on the hull speed. A graph of the maximum hull speed allows us to interpolate that the vessel for which the apparatus was designed is limited to about 10 miles per hour according to the graph below.



The difference between the airplane foil which uses the work-energy theorem and asymmetry to maintain lift and the keel on a vessel going into the wind is that a keel does not require the asymmetry to provide a balancing force. As long as the angle of attack is not directly into the wind, the same affect occurs, as the wind races around the angled fin and creates a pressure difference causing a pressure difference. The forces are shown in the figure below of a sail boat traveling at about 30 degrees off of the wind direction. The picture shows the direction of the vessel slightly off from where the boat is pointing. This is called leeway or sidling. It is this motion to the side that causes the keel or fin to have an angle of attack and thus create the pressure situation described with the Bernoulli equation.

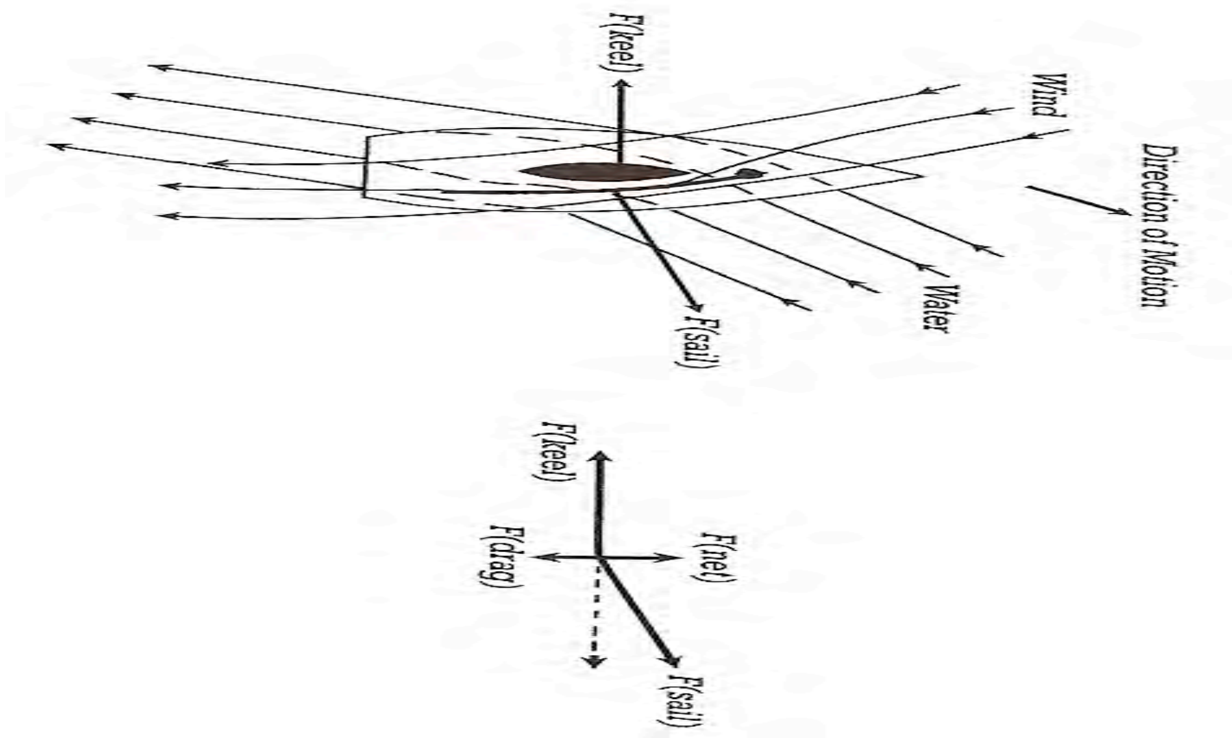


Figure VII: Net force on the Vessel as a summation of Forces of Keel, Drag and Sail. Image courtesy of Bryon D. Anderson, The Physics of Sailing explained:

One concern of course is loss of energy in the keel. After all, a keel with more surface area will create more resistance. And further, a keel will leave vortices as it moves through the fluid, areas of spinning turbulence from where the upward moving and downward moving fluid meet up. The optimal shape for generating lift and minimizing vortices has been shown to be elliptical in distribution moving out to a zero width towards the stern of the vessel. This shape reduces the magnitude of the vortex. One might also place a vane - called a wing on a vortex (and winglet on a wing of an aircraft). Current racing vessels tend to use long keels that can be likened to the wings of a glider (sometimes as long as ten feet!) with a bulb attached at the bottom to control the turbulence experienced at the tips of wings.

Resistance from the boat's surface area remains the dominant resisting force to forward movement of the vessel. Thus, for maximum speed, the vessel should have the least amount of "vessel" below water. This is accomplished because of the narrower hull than deck when the vessel is upright. However, when the wind blows, the vessel will heel over to the leeward (downwind) side which increases form and surface resistance. Heeling over also causes a second undesirable side affect in that it can reduce speed by creating "weather helm." In this scenario, the leeward side of the boat dips into the water causing more resistance and creating a virtual rudder board and aims the boat more into the wind. The helmsman (individual in charge of steering) must right the boat by turning the rudder so as to compensate. However, the rudder is now dragging and creating additional friction.

It so happens that there is an optimal heel angle for any given wind speed and point of sail that balances the negative affects of healing against the positive effects of carrying more sail. This is one of the variables we will be working to maintain by tending the mainsheet.

Of course, there are added benefits to having a heavier keel in its righting ability. As the boat begins to heel, the heavier keel will bring the center of mass back by creating a moment. Weighted keels can often a right a boat that is lying at more than ninety degrees from upright.

Having looked at the various forms of resistance, we can weight them using the chart provided in <u>The Physics of Sailing Explained</u> (Figure 2.14, pg. 67), where friction comprises approximately 34% of the total resistance, Wave about 35% of the total resistance, Induced drag about 10% of the total resistance and Parasitic for the remaining

21% percent of the total resistance. With this knowledge in hand, one can understand the design choices made by sailing vessel designers. These values are calculated at a velocity somewhat below that of hull speed.

Having discussed at some length the relevant ideas behind hulls and keels, we now will turn our attention to sails which are the most relevant aspect of this report. This final aspect of the sailing vessel serves as the motor from which almost all forward motion occurs.

Sails operate in the same way that modern keels operate, by exploiting Bernoulli's principle; they create a pressure difference, and push forward. According to Bernoulli, the faster moving air traveling around the longer edge of the sail will have lower pressure. A wing, like a sail, must present an angle to the oncoming air flow. The sailing vessels we are dealing with, such as a sloop, are incapable of sailing dead into the wind. However, unlike aircraft wings, the net force also includes the pressure of the wind pushing up against the sail. The suction force on the outer edge of the sail is often a larger force than the pushing force of the wind. The pressure curves are dependent on sail shape, one of the variables we will be looking to control, and reading. It is important when examining the forces to consider both the fluid dynamics of Bernoulli and the intermolecular forces as presented in the Van der Waals equation. Typically, the vessel will travel between 30 and 180 degrees of the wind direction.

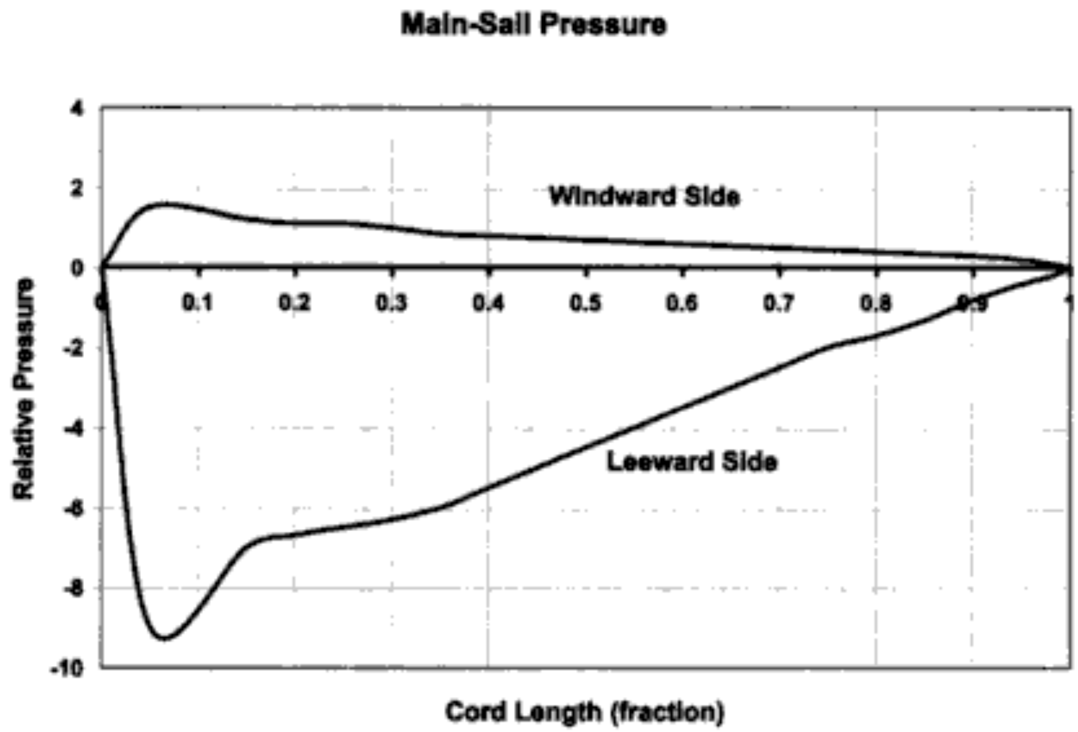


Figure VIII: Pressure Distribution experienced by the sail. adapted from Yacht Design by Larsson and Eliasson

The figure above shows the distribution of pressure experienced by the sail. The total area between the curves is the overall force produced by the sail acting on the boat. Obviously this force travels through the mast which needs to be sturdy enough to take the high pressures, but we will assume here that this is not an issue.

In acknowledging the similarities between the keel and sails, we need to address some of the impediments to movement that both share: resistance and energy loss. Like the keel, the sails create vortexes. Because the air meets at the back of the sail at different angles, there is a twisting effect as the air leaves. Energy is dissipated into the air to make this happen according the laws of conservation of energy. To illustrate the nature of this loss, we can look at the photograph of racing vessels moving through low lying fog, as shown below.

Wind moving along the sail in the same way that the fluid moving along the keel and hull of the boat produced turbulence will experience a shearing stress. Similarly, the no-slip condition of the molecules on the sail will remain in effect; however, these will interact with others causing the shear stress. Similarly, we can predict the point on the sails at which the laminar flow will become turbulent using the Reynolds number. For typical wind speed of 10 knots, the switch will occur about 10 meters in. For higher wind speeds, the turbulence may occur closer to the luff of the sail. Laminar flow is possible in lower wind speeds. One of the situations that sailors tend to avoid is the flapping of the leech, and or the flapping of the telltales which are thin pieces of streamer that used to indicate turbulent flow. For maximum power, you want smooth laminar flow on as much of the sail as possible. This stalling of the telltales and the flapping of the leech is often due to the separation. We can see that separation in the diagram below.

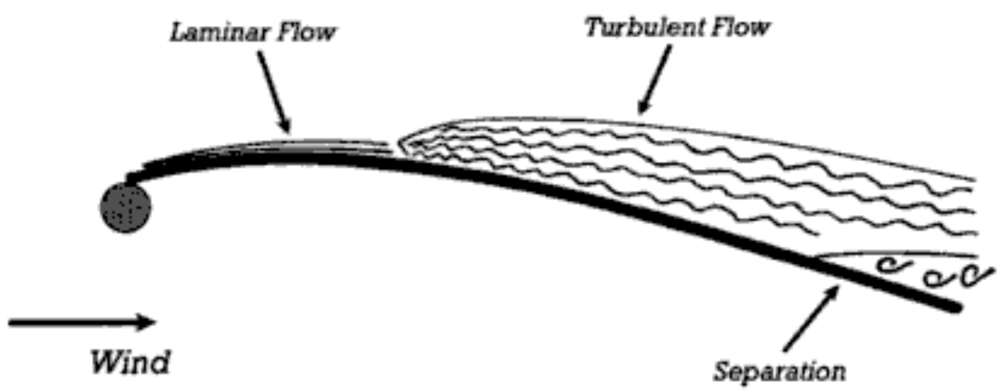


Figure IX: Air Flow along a sail, drawing courtesy of Bryon D. Anderson

Of course, we will ultimately be optimizing for gaining the fastest possible route to our destination. We can see the maximum boat speed in knots with respect to the wind direction on the chart below:

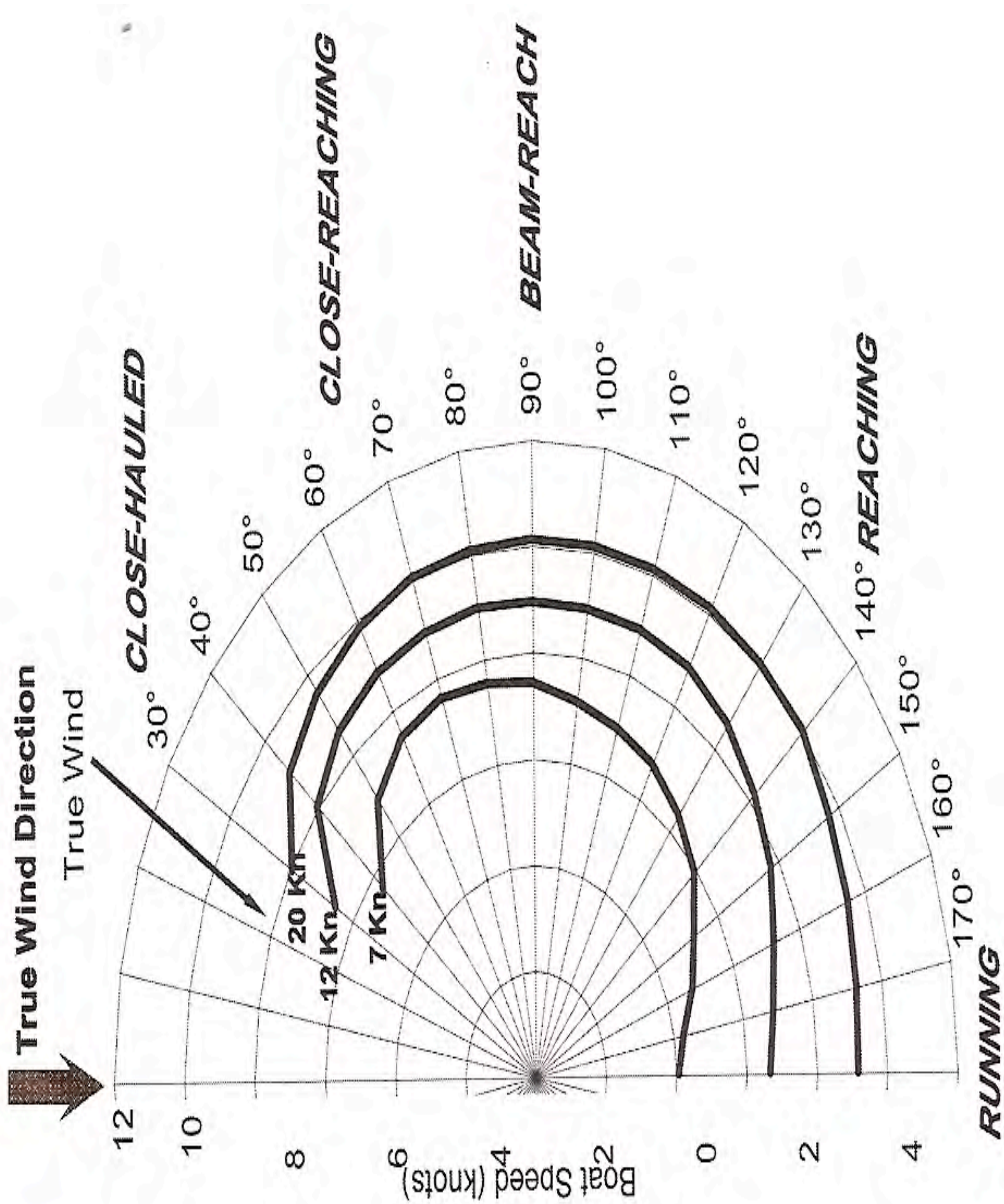


Figure X: Sail Trims for various angles of attack image courtesy of Bryon D. Anderson

The Physics of Sailing Explained

As we have been discussing, the sails are the predominant “motor” force of a sailing vessel, and the fuel for this is the wind. But what is meant by wind? After all, when moving in any vehicle open to the atmosphere one experiences “wind” directly against the direction of the moving vehicle. Consider sticking a hand out of a window of a moving automobile. This is the apparent wind. The wind measured on a moving boat will be the net wind. The wind of the air opposing direction and the wind with respect to the water surface, or atmosphere. Being able to measure the universal wind, that is, the wind not created by the boats movement will be important in our optimization. The wind produced from the boat movement cannot also push the boat forwards.

Having briefly explored the physics behind how sails work, we can now look into the theory behind the trimming of sails. First, we define the different terms for sailing directions with respect to the wind. Running is sailing downwind. Reaching is when the wind is coming from the side. If the wind is from behind - but not directly behind - it is a broad reach. A close reach is when the wind comes from between sideways and directly towards the boat. Close hauled is the term used when sailing as directly into the wind as possible, usually about forty five degrees.

Trimming is the art of making the sail flat or curvaceous. It is commonly understood in the sailing community that when going from downwind to pointing upwind, one needs to angle the sails closer to the centerline of the boat. In a downward sailing situation, one attempts to create a bulbous shape to catch the wind with the sail stretched out at approximately 90 degrees, or perpendicular to the horizontal line of the vessel. This bulbous shape also helps create suction in addition to “catching” the most air.

In a beam or broad reach situation with the wind coming from the side, the sail needs to be oriented at approximately 45 degrees to the horizontal of the boat. The shape of the sail must be slightly less bulbous as a large bulb shape will not allow the wind to remain attached all the way to the leech. As we mentioned above, separation is not a good thing. Higher wind speeds require more flattening of the sail. Part of the program will be messages to the helmsman to adjust the outhaul accordingly. And of course, when traveling upwind, one must have an almost entirely flat sail pulled almost parallel to the centerline of the sailing vessel. The general rule appears to be that the sail moves from perpendicular to the centerline of the boat to nearly parallel as you go from pointing downwind to pointing upwind. And, as wind speed increases for given angle, the sails must be tightened (flattened) to stop separation from occurring. In terms of acceleration such as after tacking, it is generally best to start out with a bulbous sail and flatten it out as the vessel’s speed increases. This process of flattening the sail generally happens quickly, within a minute of tacking or even less time.

The physics behind sails, hulls and keels are relatively simple and much related with the equations paralleling one another. These three components of the sailboat however are each necessary and each have an effect on the speed of the sailboat. The actual process of trimming sails however (the only aspect of sailing that is really controllable once the boat is in the water) remains an art more than a science. Still, while fine tuning can only be accomplished well with a weathered hand, the calculations set forth in the discussion above show that to large degree approximations will place the sailing vessel at a competitive edge based on the parameters presented. In the end, it is so much more that cannot be accounted for in physics that controls the performance of the vessels such as crew communication, smooth operation of equipment, and smart decisions. We hope however that with the creation of the mainsheet tender that a single individual will be capable of competitively sailing a larger vessel single handedly focusing solely on the rudder and enjoying the wind on his or her face.

Project Overview

The mainsheet tender is comprised of three separate pieces which are connected by a simple interconnect. Future renditions of this project will seek to use wireless technology so as to eliminate the extra wires on the vessel which could be responsible for knotting up a line or causing another unexpected mishap on the sailing vessel as they would not be found on a traditional vessel.

The inputs comprise the first aspect of the device, providing the raw data used to control what happens. For the proof of concept, there will be two similar input devices. The variable being examined is the relative wind direction felt by the moving vessel.

Two variable resistors will be used. The first resistor will measure the angle of a wind vane sitting on top of the mast. This will provide a target value for the mainsheet to set the sail to after some modifications have been made. The shaping of the target signal will be discussed below in the discussion of the control circuitry.

The second variable resistor will be attached to the mast and the boom, giving the angle of the boom relative to the boats centerline. This will provide the feedback used during the tending process.

Together, these two resistors will comprise the portion which will be called the input system. They will be connected to the control circuit, which is the second piece of the system.

The analog driven control system takes the two inputs, boom angle and relative wind angle and compares the signals. The circuitry used will be discussed in other sections below in greater detail. After setting the target angle, the comparator circuitry sends a signal to the motor controllers wigwag control system that sends instructions to the motors.

The Motors and mechanical design make up the final pieces of the mainsheet tender. The motors directly control two gears through which the sheet runs. The sheet comes down through the winch, and goes through the mainsheet tender, after which it is coiled up in a small drum with a cone in the middle.

Project Specifications

The apparatus was designed with smaller vessels in mind that don't use winches to control the mainsheet, thus they are boats with a significantly lower amount of tension on the sheet because of sail size and lesser forces resisting the forward movement of the boat. Because this design constraint and availability of boats, I decided to complete the project proof of concept for the O'Day Widgeon. The table below gives the characteristics of the vessel. The image below is the boat from which measurements were taken to ensure that the apparatus would fit within the hull of the boat.

O'Day Widgeon c. 1970

Length: 12 ft. 4 in.

Beam: 5 ft.

Draft: 3 ft. 6 in.

Weight: 318 lbs.

Sail Area: M&J, 90 sq. ft. total

First Built: 1964

Designer: Robert Baker

6000 Built

The second project specification I sought to adhere to was to use as many in house components available as possible. In the end this ended up being my components for the circuitry, the Dexion © used for the frame of the housing, the batteries for both the motors and the circuitry and the motor controller.

Because sailing is water intensive environment I decided to do the entire project using only analog circuitry for what I designed. The control algorithm was implemented using Operational Amplifiers (Op-Amp 411), variable resistors and passive elements. This decision was made to ensure that if things got wet, they could be dried and reused. If components burned out from being shorted from being wet, they are easily interchangeable if necessary unlike a chip which would need to be reprogrammed.

Part of the objective was to create a device that was easy to use and requires no user interface or control. Once set up, it merely runs as determined by the design specifications. For this reason, I controlled the entire circuitry and motor controller using two nine volt batteries. This decision required an additional circuit but the increased ease of use made it a worthy design decision and increased the robust nature of the system. I also ran the two input devices off of the same batteries eliminating the need to change batteries in multiple locations and eliminating the need to check for dead batteries in more than one location.

Design and Construction: Motor Selection

- TM98MTR3114
- 24VDC
- 100 RPM
- Reversible DC Servo Gear head
- Optical Encoder (not used)
- 100 in/lb Torque
- 0.825A No Load
- Gear box ratio 45.5 to 1
- Stall current at 6 volts
- Shaft end mounting with 3 holes on gearbox

The motors were two of the components that were purchased specifically for this project. Important design decisions made it necessary that a motor had a couple of key features such as a reasonably high torque, high enough RPM's to change the sail in a reasonable amount of time, and put out about 50-100 Watts of power.

Both of the identical Panasonic built motors were chosen because of the listed features and they were capable of meeting expected power requirements, which are in the range of 50 100 Watts. The motors to a large extent were overkill, and for the proof of concept, did not need to be so strong, nor did we require two of them. An unexpected additional feature made the motor essentially self locking when not turning.

One of the great parts about the design is that the motors are interchangeable. As long as the motor can be controlled by the specified controller, and can be mounted on a plate for the housing, it can be used. Because the feedback is directly on the mast, the specifications of the motor were irrelevant as long as it could handle the load. The speed at which the changes occurred were less important since the proportional control is only concerned with a difference between the wind direction and boom angle, not how long it takes to reach the specified goal.

Motor Controller Selection

The selection of the motor controller was based on a variety of factors, most notably however was the availability of a specific controller already in the confines of the engineering department. The KBBC Series microprocessor controlled battery powered DC/DC variable speed motor control (Model KBBC-44M: Part No. 9501). Features include High Frequency PWM Operation, Controlled Acceleration and Deceleration, Diagnostic LEDs, Built in reversing Contactor, Run Relay, Brake Driver Circuit, Key Switch Operation with Built-In Battery Power Contactor, Inhibit Circuit, Latching Circuit, Limit Switch Circuit, and Single-Ended or Wigwag potentiometer control.

It was this final feature was the deciding factor in using the controller in conjunction with the Controlled Acceleration and Deceleration and Built in Reversing Contactor. I needed to be able to input with a proportional or integral control algorithm centered on a set voltage with variances in the voltage indicating necessary changes be made in either the positive or negative direction. The Wigwag and reversing contactor combined gives this necessary functionality. The controlled Acceleration and Deceleration removes jerky movements which could set the motors spinning without shifting the mainsheet in either direction once the coefficient of friction switches to the kinetic coefficient as opposed to the static coefficient.

Most importantly, as stated above, this motor was available for the project at no cost and for proof of concept; this important feature allows the project to be demonstrated as meeting the specifications of design.

Battery Selection

- Sun Xtender Series
- Deep Cycle Batteries
- 12Volts each
    - Grounds tied together to form 24 Volt Differential

The Sun Xtender series were chosen because of their availability in Hicks and because they were deep cycle batteries. The size specifications for the battery section of the housing were determined with these batteries dimensions in mind. Unfortunately, they were not finished with charging for the final presentation, and so a power source was used to give the demonstration, the power source is shown below.

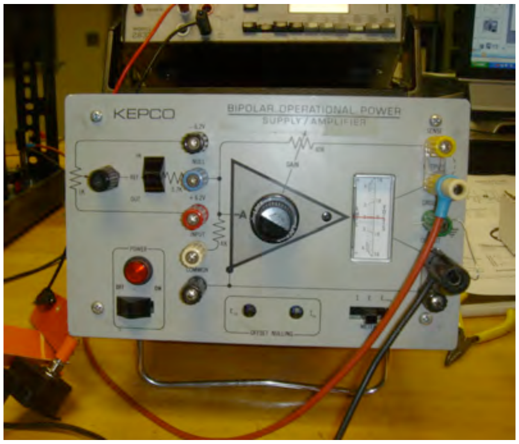
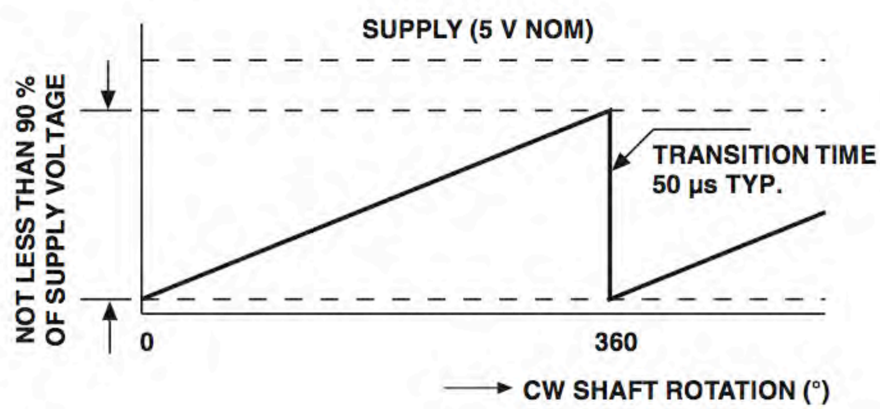


Figure XI: Power source used for testing due to lack of working / charged batteries

Vishay Smart Position Sensors

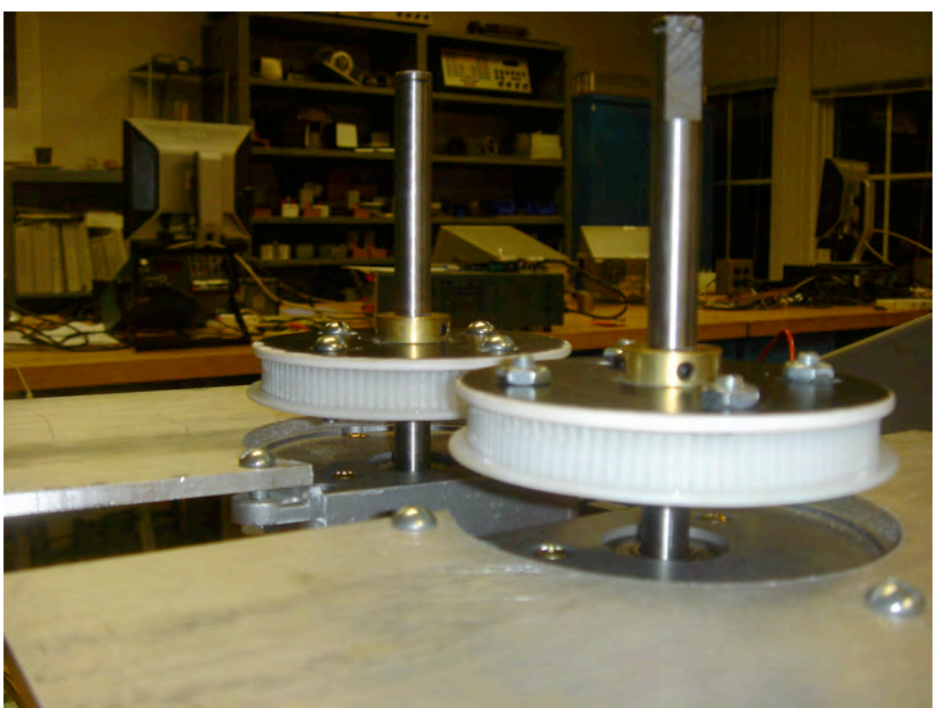
No dead zone
O – 5Volt Operation
Resolution 0.5 degrees



The smart position sensors were chosen because they wouldn't change values for a complete rotation unlike other potentiometers available. Based on a linear relation between angle and resistance, the voltage could be measured between 0 and 5 volts given the angle. They were also the first choice because they have no dead zone unlike other systems. There is the transition zone, but that is limited by time – not angle, and after the elapsed period, a reading is put out and operation continues as normal. In order to not cross this area often, this angle was set for dead into the wind, which is generally not a direction one sails. Because of the 5 volt operation, the 9 volt batteries needed to be stepped down which is part of the first circuit discussed in the forthcoming section.

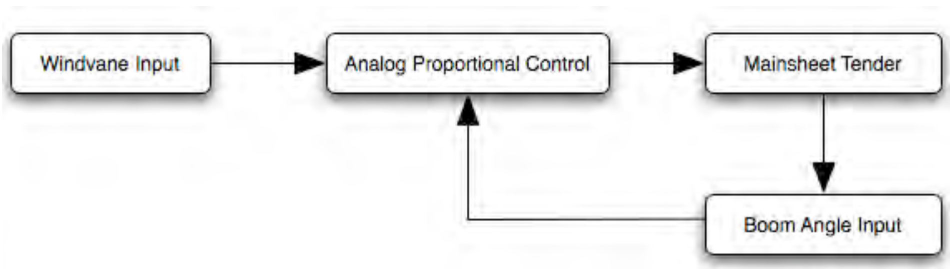
Gears

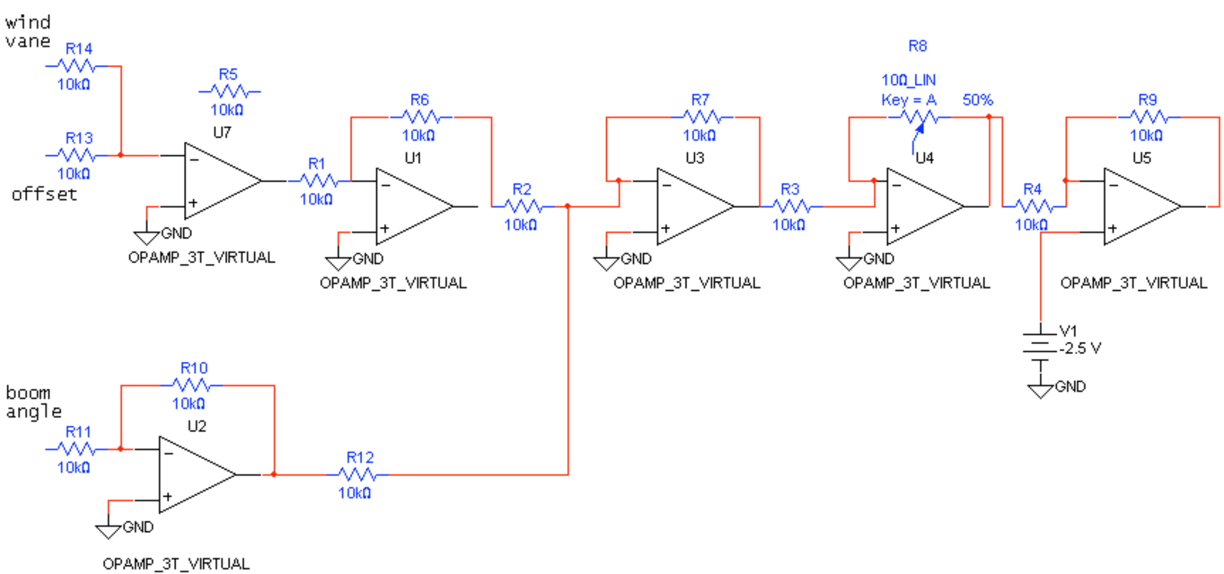
Mounted on the two shafts of the motors were gears. The gears were a combination of in house production and ordered material. The gears themselves came with the gear head motors. Using a lathe, they were modified slightly. Each gear was given two discs that sandwiched each gear. The lower disks were just touching which keeps the line above the plane of the gears. The upper plate is angled slightly to maintain the ropes position between the plates and providing full contact with the gears, but also smoothed out in case the line needs to be pulled out as an emergency decision. The upper plate is slightly smaller as well allowing these ad hoc decisions to remove the line to be made without great resistance from the apparatus.



Circuit Design

The initial proposal called for a microprocessor or other complicated type of electrical system requiring digital components. However, in an effort to make a more robust system, an entirely analog system was put in place for the control. The equation of control is relatively simple; there are two inputs with two variables, a variable and input on each side of the equation. The schematic below shows the entire system with the negative feedback loop.





The photograph below shows the layout within the housing:

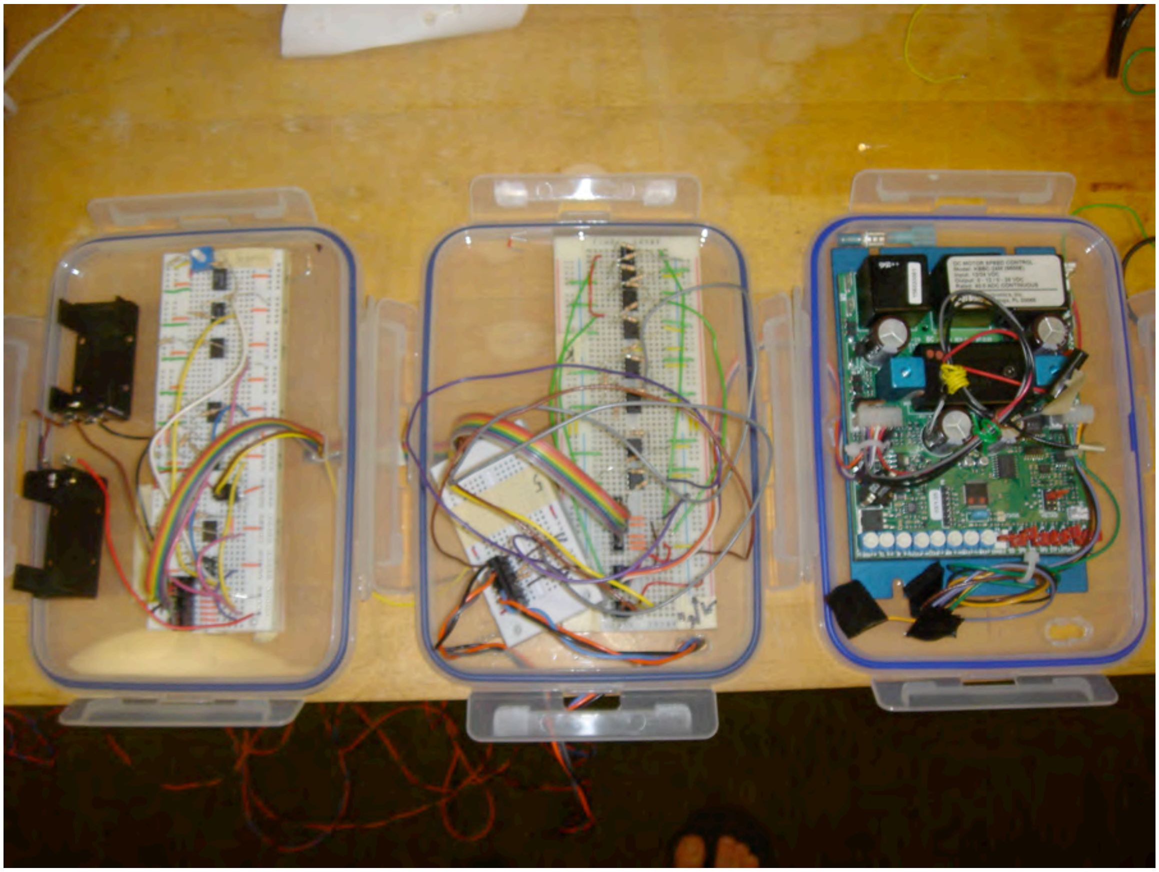


Figure XIII: Electronic components of apparatus

On the left side of the schematic above of the proportional control you can see the two inputs from the wind vane and the boom, and their respective offsets. The first variable is the offset desired between these two angles, for the proof of concept this was set to zero, and the change that would be desired was absorbed into the second variable. The second variable is the angle that the sail makes with the boom, which is approximated at 15 degrees for the proof of concept. Each of these sets of angles and offsets are sent into an operational amplifier with no amplification. On the top, the output of the amplifier is the negative of the angle plus the offset. On the bottom, the same however, this is amplified again.

The outputs of these two signals are then put into another amplifier which gives the difference between the two signals. The error is then sent into an additional operational amplifier, but this time is amplified so that the total range falls within the 5 Volt range of the Wigwag control.

Finally, the output of this is put into a sixth amplifier which centers the new output around 2.5 Volts, which is the zero point for the wigwag control.

Testing

Testing of the apparatus at the time of publication was completed within the lab. An unspecified length of cord was placed between the two rotating gears to simulate movement. The cord was not connected to the boom since no feedback relied on how much the boom moved based on the cord length directly. Then, the two resistors with the actual length wires were set to their "zero" points. Testing involved placing the boom angle at a variety of different locations and determining whether the system reacted and reacted correctly to changes in the wind vane. All tests were conclusive in that the motors retracted or released the rope accordingly and when the boom matched up to the wind vanes new orientation, the system shutdown until the initial conditions changed again.

Discussion

The autopilot mainsheet tender module I designed and put together responded as I had expected it would respond in ideal conditions to a set of stimuli, that is, changing wind direction. I was accurately able to modify the system to be optimized based on my studies of sail trim.

During the final presentation, a question came up reflecting one fallacy in my thinking. In my original design, I always add 15 degrees to the difference of the boom angle and the sail angle to account for the angle that the sail makes with the boom itself. This conclusion that I drew was based on my considerations of an absolute system. During my presentation, and discussions with Professor Nelson Macken following, it became apparent to me that I needed to modify the system that while a starboard might require adding the equivalent voltage of 15 degrees, a port tack would require the opposing decision – that is, the subtraction of 15 degrees from the difference.

Consider for a moment that the driving equation for the control is proportional, that is, the amount is based on the error between the actual and the desired – only before that amount is calculated, one of those values is modified to compensate for the angle made between the sail and the boom. When the sail is on the other side of the boom, then that angle between the sail and the boom as measured is the opposing amount, the negative of the added angle.

I believe that this can easily be fixed. The 0 – 5 Volt readout from the boom angle can be centered at 0 volts with the “dead” area that would be located at 0/5 Volts be pointing directly into the wind, the one direction the orientation of the boat may cross, but the vessel will never sail directly at that orientation. Thus, with the new condition, the direction dividing a port and starboard tack will be the dividing line between 0 and 5 Volts. Once the sign of this has been determined, it will be easy to modify the signal to output the desired voltage with the correct sign adjusting for the changing signs of the difference.

An important side note about sailing with this device is that the optimization takes place for sailing into the wind. Anytime the wind approaches the boat from the stern and ninety degrees to the lift or right of the stern, the system will put the sail on a beam or broad reach as it will not be able to let out the sail beyond that point due to the support lines coming from the top of the mast.

Outside of this glitch, I believe that the device will perform as expected onboard a vessel, bringing the sails to the optimal point. Obviously, one cannot compete with a weathered sailors hand at trimming the sails, and making small adjustments by feel and by watching the sails, but for the basic purpose of traveling in as efficient a way as possible with the lowest amount of user input, the sailboat autopilot: mainsheet tender module fulfills the desired expectations.

Lessons Learned

The entire process before it even began has been a learning process. Time management was the largest lesson. When managing a project, setting realistic guidelines are extremely important. Also, making assumptions that part A will talk to part B is a pretty big assumption. I had to create an entire additional circuit to handle all the different voltages necessary to make the apparatus work.

Talking things through is really valuable, but only if you take notes, and date them. I had a few ideas about documenting things such as bogging the experience which would make it searchable and keep me connected with my advisor were thrown around, but never fully implemented.

Finally, setting small deadlines is a better way to accomplish things without taking off more than you can chew. I found that putting down, "purchase batteries" as a goal was unrealistic. There were so many aspects of something as simple as that, such as compatibility, understanding the parameters of the system and checking whether it falls within the confines.

Everything you expect to finish quickly will take a long time, and the long tasks aren't nearly as bad you predict was the big lesson. And always use the Maxwell method of timing.

CONCLUSIONS

I began this report by outlining the goals and specifications of the Engineering 90 comprehensive exam, and I put down the objectives of this project specifically. I believe that upon completion all goals were fulfilled. The only remaining testing would be on board in a water environment. However, for the proof of concept the needs and demands of the project were met. In the discussion section, I discussed the one minor change to create a more functional design. Beyond this implementation, other adjustments would only improve the apparatus by making it lighter, more durable, more aesthetically pleasing, and easier to set up. In terms of function, the project was a success. I embarked on this journey with the intention of creating an autopilot system that controls the mainsheet of a sailboat. I successfully created a control algorithm that maintains the optimal sail angle. I successfully implemented the proportional control in analog form. I successfully created a housing for the apparatus that protects the circuitry and is durable enough to sustain large loads, while performing the functional needs of the machine. The system at this time is robust and easy to use. I feel that the end result is a successful project that has the opportunity to grow with expansion in various areas, but while keeping that in mind, also realizes that the necessary aspects of the goal was accomplished. In the following paragraphs I will briefly discuss a few minor changes I feel could be made to increase the usability and robustness of the system.

The first major advance would be changing to a printed circuit board. This would combine about 700 cubic inches of space into a much smaller area and make upgrades easier.

The second major advance would be placing wireless connections between the sensors and the circuitry. This means moving to digital circuitry, but I think the tradeoffs of eliminating all wired connections would be invaluable. This would however require a separate power source at the sensor locations, one of which is on top of the mast.

Thirdly, I would completely waterproof the entire machine, as well as add a recon device so that if the boat goes over and the device is lost, it can be found. This might just mean placing flotation within the device.

Finally, I would find a lighter material for the frame so that it could be transported. In its current state, the device weighs far too much to conveniently transport between locations, and moving it into a small boat can be a difficult task, especially, I would imagine from a dock.

Appendix

Appendix A: Proposal

Appendix B: Midterm Presentation

Appendix C: Final Presentation

Appendix D: Project Selection Memo

Appendix E: Motor Controller Data Sheet

Appendix F: Motor Controller Instructions

Appendix G: Vishay Variable resistor Data sheet

ENGINEERING 90 PROPOSAL

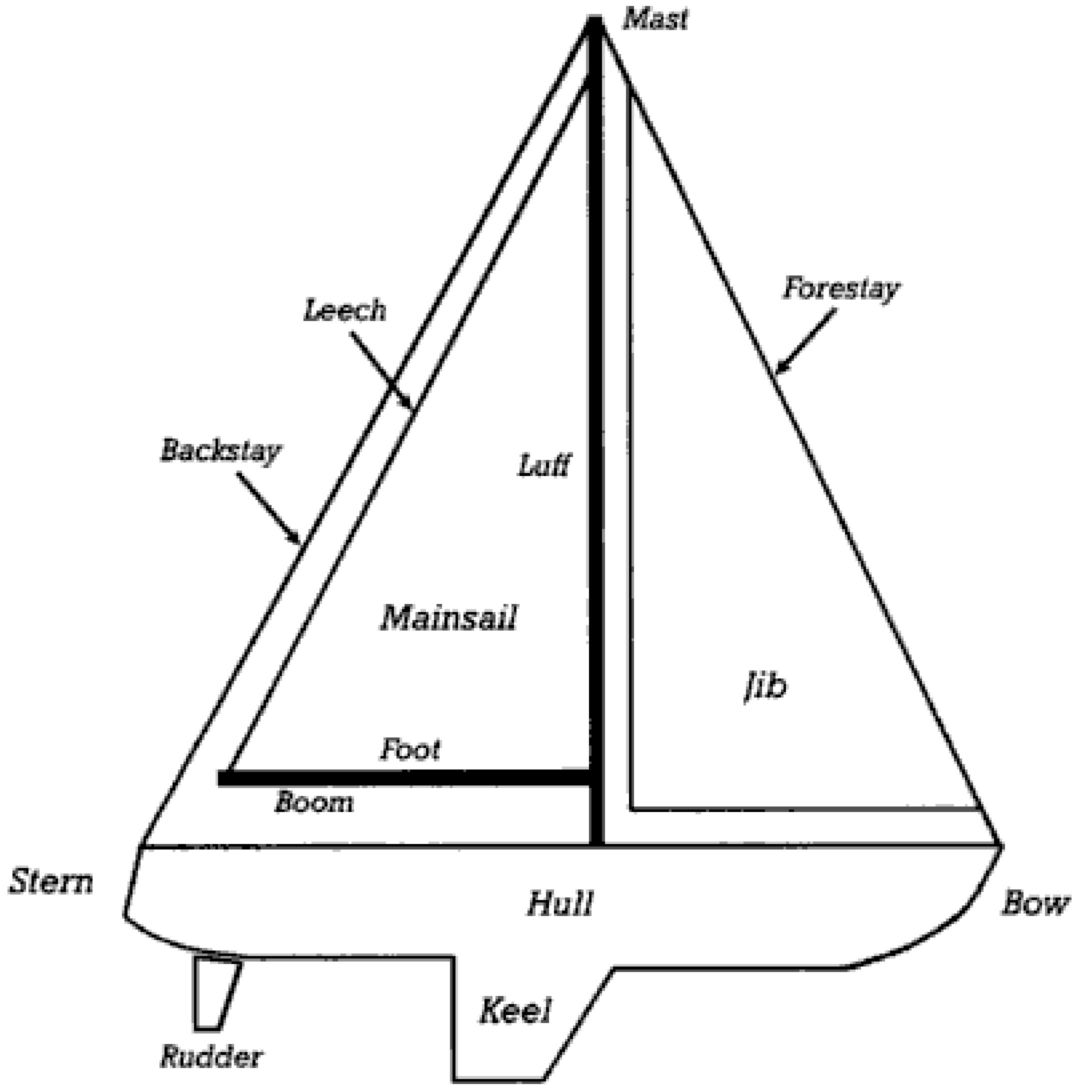
Mainsheet Tender

Jonathan Harris

Fall 2007

ENGINEERING 90 PROPOSAL

Mainsheet Tender



Jonathan Marshall Harris
Professor Fred Orthlieb
Professor Erik Cheever
Fall 2007

Abtract

This paper outlines my proposal for my Engineering 90 senior design project. This proposal will focus on the specifica tasts that I plan to undertake and include their organization into the Critical Path Model which will project my estimation of completion based on time allocation. I intend to build a mainsheet tender for a sailing vessel. The bulk of my time will be divided between two main tasks: creating the physical manifestation of the mainsheet tender and creating the measuring devices for the inputs off of which I will optimize. After testing the mainsheet tender in the lab, it will be field tested using a variety of vessels (with availability) to ensure that it is able to withstand various amounts of force, moment and impulse, and that it is easily configurable for a variety of boats and sails. I hope to create a device that is both universal and durable.

Introduction

The mainsheet tender is device that directly controls the angle of the sail on a sailboat. The angle of the sail is important in that it determines both the shape of the sail, and the amount of wind that can fill the sail. Given a trajectory for the sailboat, there exists an optimal angle that the sail can be kept at which allows for optimal sailing conditions. Using a variety of inputs we will seek to automate the process of setting the mainsheet at that angle and allow for simpler sailing conditions. There are two many possible situation to optimize for. In the case of this proposal, we will seek to optimize for two situations, which are not entirely independent of one another.

1. Maximum Velocity
2. Heel Angle

In both situations we will be looking to optimize a single variable, in the first the velocity of the sailboat (or scalar speed) and in the second, the angle of the boat (the heel of the boat) which generally relates back to the velocity of the boat. One universal idea that will fall under categories is finding the perfect sail shape for any given direction given a constant wind.

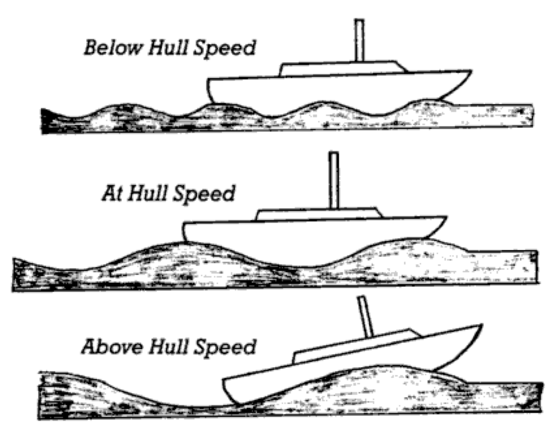
The proposal will begin by exploring the technical aspects of sailboat physics. It will then go into the project plan which will further examine the necessary inputs and the construction of them in order to set the variable mainsheet length. Here we will examine the objective, approach and output of each task individually. This section will also include a timeline and a Critical Path Analysis or Management tool to efficientally and logically arrange the tasks. Finally, it will outline a time budget of required hours per week to complete the project. In the section following, I will dicuss my expertise in the area including my sailing experience, and engineering background. The Project Cost's are discussed in the section following. The final section will outline my journalling method of project reporting which will be explained at depth below.

Technical Discussion

My proposal seeks to optimize a sailing vessel, and so to begin, we must first examine the physics behind sailing vessels. Having examined the physics behind the way sailing vessels work, we will discuss the machines

A sailing vessel is comprised of three pieces which interest us: the Hull, the Keel and the Sail. We will begin by exploring the hull as it is the hull which determines the maximum speed that a sailboat can achieve in addition to it's ability to accelerate and it's available speed in low wind conditions. There are two types of water vessels, those that plane or skip across the water and those that displace and move through the water. Our analysis will only deal with the latter type. It so happens that the maximum speed of any vessel moving through liquid is determined by the length of the hull. The shape of the hull is also important in that it determines the friction or resistance that the vessel experiences during movement through the liquid. Finally, the hull - along with the keel - determine the stability of the boat, which is a crucial aspect of the performance of the boat.

We begin our discussion of hull speed by acknowledging the simple fact that hulls moving through water generates a wave. Smaller velocities generate smaller waves, and larger velocities generate larger waves. The maximum length of the generated wave - the maximum wavelength so to speak - occurs when a single wave stretches from the bow to the stern of the boat.



Bow Wave and Boat Speed ("Hull" speed occurs when there is just one wave along the side of the vessel.)
Image courtesy of Bryon D. Anderson

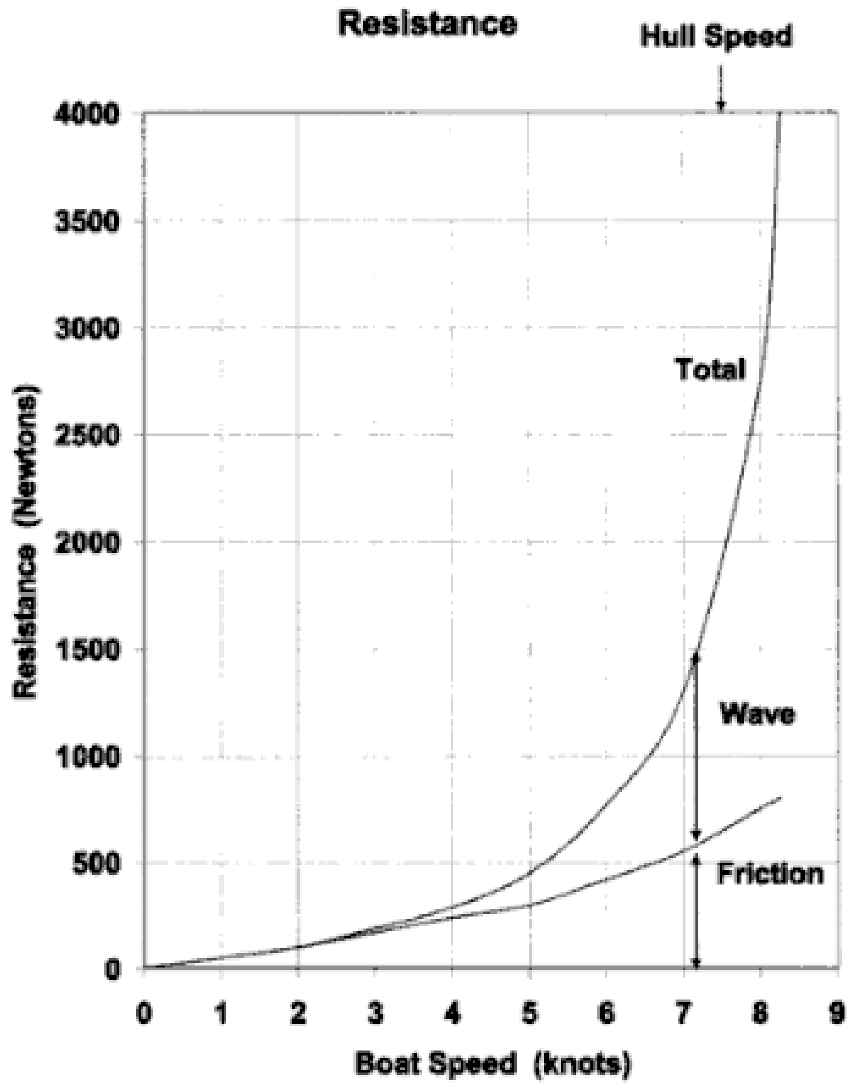
There is a crest at the bow and the stern with a trough between in the center of the boat. If we consider the friction of the boat and the resistance of the vessel in the liquid, this is the velocity at which during steady state the boat is at it's maximum. If the vessel were to go any faster, the stern would drop into the trough of the wave and the resistance would increase dramatically forcing the boat to slow down. Thus, we have reached the conclusion that there exists a relationship between speed and length. The speed of the vessel will be limited to the speed of the wave that has a wavelength equal to the length along the waterline of the boat. This "hull speed" effectively limits the speed of most sailbots to elss than 10 knots and of most naval vessels to less than 30 knots.[1]

Wavelength (feet)	(ft/sec)	Speed Mph	Knots (1knot= 1.15 mph)
1	2.3	1.6	1.4
5	5.0	3.4	3.0
10	7.1	4.8	4.2
20	10.1	6.9	6.0
30	12.4	8.5	7.4
50	16.0	10.0	9.5
75	19.5	13.3	11.6
100	22.6	15.4	13.4
200	31.9	21.8	18.9
300	39.1	26.7	23.2

Wave / Hull Speeds image courtesy of Bryon D. Anderson

The table above shows the speed as it relates to wavelength, thus giving the maximum velocity of any vessel (without considering the possibility of planing). The table below gives the resistance experienced by a typical sailing vessel having a waterline of approximately 30 ft or 10 meters. The asymptotic nature of the curve suggests that the resistance goes high enough that little can be done regardless of power input via sails or engines.

[1] Anderson, Bryon D., The Physics of Sailing Explained. 2003

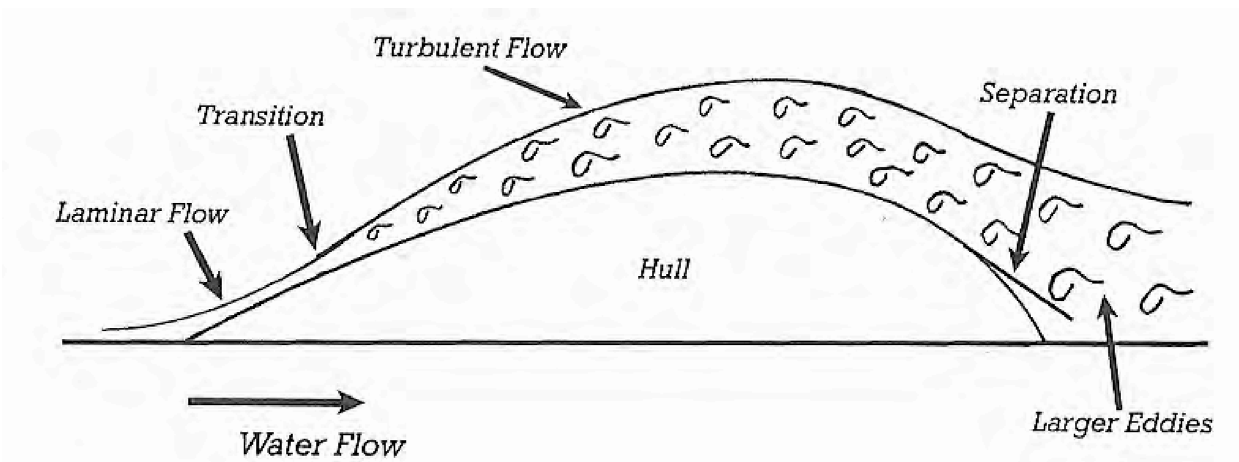


The graph above shows drag components and hull speed for a typical sailing vessel with a waterline of approximately 10 meters. Image courtesy of Bryon D. Anderson.

Everything experiences resistance as it moves through a liquid or gas. In fluid mechanics we are aware that the smallest layer of liquid surrounding an object doesn't move. The classic analogous example is that of a dust particle remaining on the hood of rapidly moving automobile. However, only the closest molecules remain (due to intermolecular forces). The remaining particles experience a shear force from the resistance, but do not necessarily move, especially as the distance from the hull increases. The perturbations in the water require energy which is taken from the sails of the vessel (on a sailing vessel, we will assume these are the only inputs of energy into the vessel, as is the normal case) thus limiting the amount of energy available to propel the vessel.

The second type of resistance comes from the shape of the hull. Clearly, a streamlined hull will create less resistance than the wider barge shaped hull. This is due to the amount of water deflected. The accepted design is that of a narrow bow and wider keel to allow for room beneath the deck. However, engineers must be wary of the affects of a wider keel which can create backward pulling eddies. These will be discussed in the following section, induced resistance.

The movement of the boat also induces resistance with the creation of small eddies which flow down the side of the vessel and behind the vessel. Larger eddies can actually have the strength to pull the vessel backwards as it moves through the water, and occurs with a wider stern. This turbulence is obviously related to the Reynolds number. Reynolds suggests that when we divide the product of the velocity and length of the vessel by the ratio of the viscosity to the density of the fluid, we begin to see turbulence around 1,000,000.



Fluid transiting to turbulent flow and formation of eddies image courtesy of Bryon D. Anderson

The figure above shows how flow alongside the hull begins as laminar or smooth flow, and depending on the width of the hull will evolve into turbulent flow, separation and even possibly larger eddies which will drag the boat against the intended velocity. Of course, a smooth hull is extremely important in minimizing this resistance. It has been suggested that no bumps above 0.05 mm (0.002 in) can be considered "smooth."

It should be noted that the numbers presented above are not absolute limits. The winner in the 2001 - 2002 Volvo Ocean Race, Illbruck, with a tapered hull shape was able to travel at approximately two times the theoretical maximum using planing for prolonged periods of time. Most mono hulled sailboats are incapable of performing at this level.

At this point we will continue our discussion, remaining bellow the water line, with the physics behind the fluid mechanics involved in keels.

Keels are very similar to sails, and so we will be able to apply many of the same principles we explore below in our later discussion of sails which serve as the "motors" or sources of en-

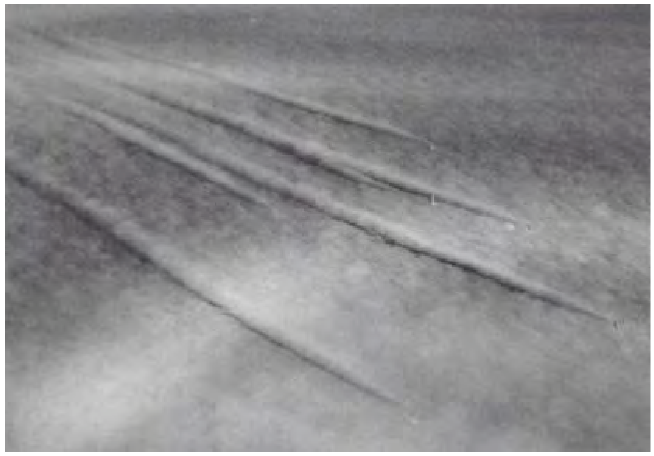


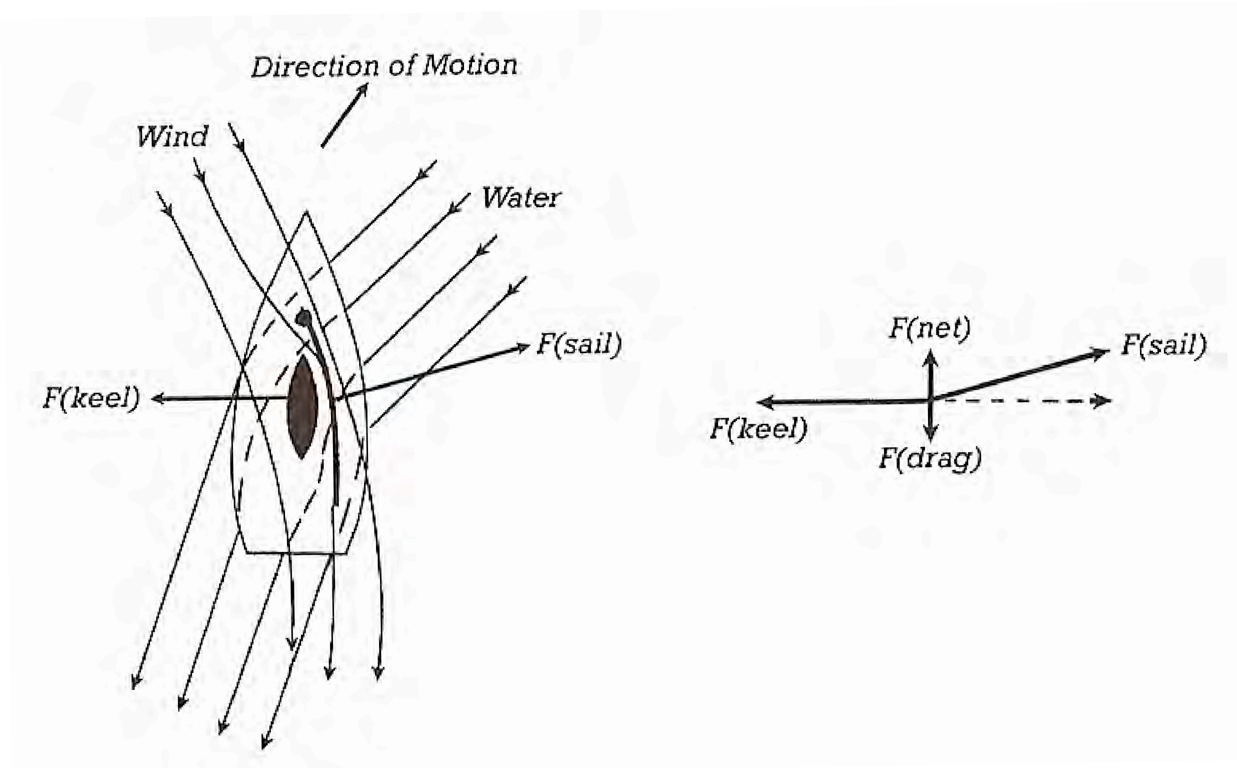
Photo by Daniel Forster, 2001 - 2002 Volvo Ocean Race

ergy that propel the boat through the fluid.

A keel can be anything that extends below the hull of the boat. On the modern sailing vessel, this is generally a long narrow piece extending well below the hull, however, a ridge line along the hull is also considered a keel.

Keels serve two purposes on a sailing vessel. First, they serve to prevent the vessel from "side slipping" in conditions when the wind approaches from the side. Secondly, they serve to offset the angle of the boat when it is heeling over in stronger wind. Two approaches exist: the first, a "full" keel runs from bow to stern, the second and more modern is the "fin" keel which can be a centerboard or dagger board or "fins" attached to the hull of the vessel. It was actually with the advancements in aerospace engineering that the keel can not only maintain the boat right side up, it can also provide a force into the direction of the wind. This is of course a reflection of Bernoulli's principle.

The difference between the airplane wing as we normally conceptualize it which uses the work-energy theorem and asymmetry to maintain lift and the keel on a vessel going into the wind is that a keel does not require the asymmetry. As long as the angle of attack is not directly into the wind, the same affect occurs, as the wind races around the angled fin and creates a pressure difference causing a pressure difference. The forces are shown in the figure below of a sail boat traveling at about 30 degrees off of the wind direction. The picture shows the direction of the vessel slightly off from where the boat is pointing. This is called leeway or sidling. It is this motion to the side that causes the keel or fin to have an angle of attack and thus create the pressure situation described with the Bernoulli equation.



Net force on the Vessel as a summation of Forces of Keel, Drag and Sail. Image courtesy of Bryon D. Anderson, The Physics of Sailing explained

One concern of course is loss of energy in the keel. After all, a keel with more surface area will create more resistance. And further, a keel will leave vortices as it moves through the fluid, areas of spinning turbulence from where the upward moving and downward moving fluid meet up. The optimal shape for generating lift and minimizing vortices has been shown to be elliptical in distribution moving out to a zero width towards the stern of the vessel. This shape reduces the magnitude of the vortex. One might also place a vane - called a wing on a vortex (and winglet on a wing of an aircraft). Current racing vessels tend to use long keels that can be likened to the wings of a glider (sometimes as long as ten feet!) with a bulb attached at the bottom to control the turbulence experienced at the tips of wings.

Resistance from the boat's surface area remains the dominant resisting force to forward movement of the vessel. Thus, for maximum speed, the vessel should have the least amount of "vessel" below water. This is accomplished because of the narrower hull than deck when the vessel is upright. However, when the wind blows, the vessel will heel over to the leeward (downwind) side which increases form and surface resistance. Heeling over also causes a second undesirable side affect in that it can reduce speed by creating "weather helm." In this scenario, the leeward side of the boat dips into the water causing more resistance and creating a virtual rudder board and aims the boat more into the wind. The helmsman (individual in charge of steering) must right the boat by turning the rudder so as to compensate. However, the rudder is now dragging and creating additional friction.

It so happens that there is an optimal heel angle for any given wind speed and point of sail that balances the negative affects of healing against the positive effects of carrying more sail.[2] This is one of the variables we will be working to maintain by tending the mainsheet.

Of course, there are added benefits to having a heavier keel in it's righting ability. As the boat begins to heel, the heavier keel will bring the center of mass back by creating a moment. A weighted keel can often a right a boat that is lying at more than ninety degrees from upright.

Having looked at the various forms of resistance, we can weight them using the chart provided in The Physics of Sailing Explained (Figure 2.14, pg. 67), where friction comprises approximately 34% of the total resistance, Wave about 35% of the total resistance, Induced drag about 10% of the total resistance and Parasitic for the remaining 21% percent of the total resistance. With this knowledge in hand, one can understand the design choices made by sailing vessel designers. These values are calculated at a velocity somewhat below that of hull speed.

Having discussed at some length the relevant ideas behind hulls and keels, we now will turn our attention to sails which are the most relevant aspect of this report. This final aspect of the sailing vessel serves as the motor from which almost all forward motion occurs.

Sails operate in the same way that modern keels operate, by exploiting Bernoulli's principle, they create a pressure difference, and push forward. According to Bernoulli, the faster moving air traveling around the longer edge of the sail will have lower pressure. A wing, like a sail, must present an angle to the oncoming air flow. The sailing vessels we are dealing with, such as a sloop, are incapable of sailing dead into the wind. However, unlike aircraft wings, the net force also includes the pressure of the wind pushing up against the sail. The suction force on the outer edge of the sail is often a larger force than the pushing force of the wind. The pressure curves are dependent on sail shape, one of the variables we will be looking to control, and reading. It is important when examining the forces to consider both the fluid dynamics of Bernoulli and the intermolecular forces as presented in the Van der Waals equation. Typically, the vessel will travel between 30 and 180 degrees of the wind direction.

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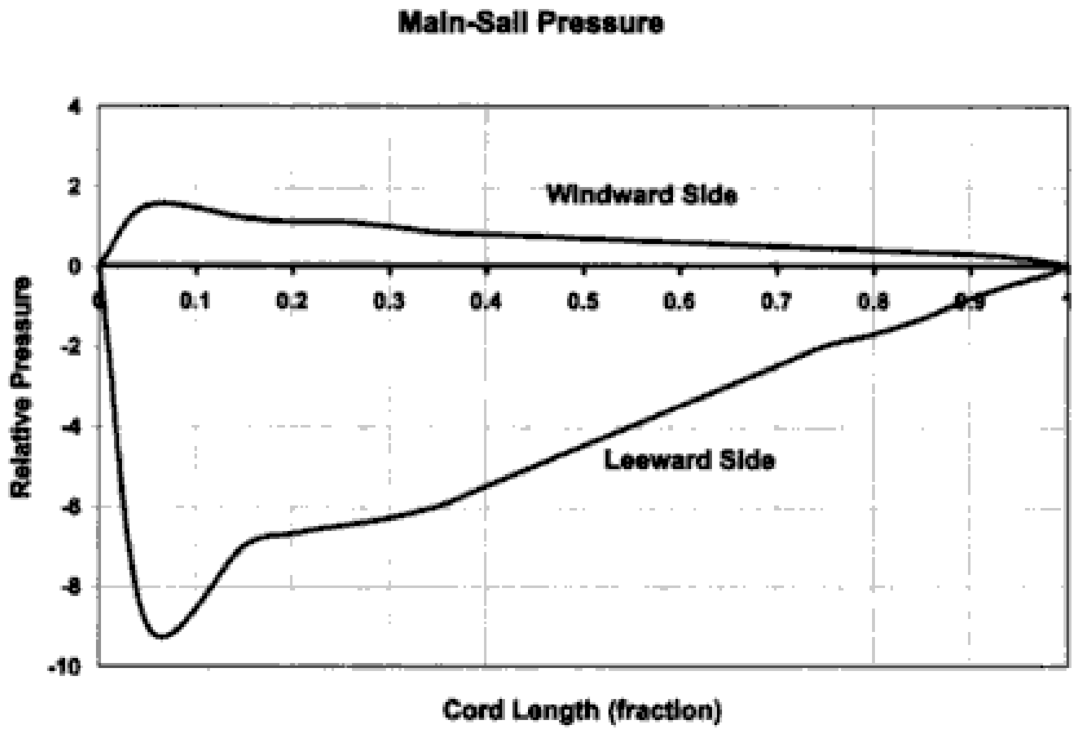
[2] Anderson, Bryon D., The Physics of Sailing Explained. 2003 pg. 61

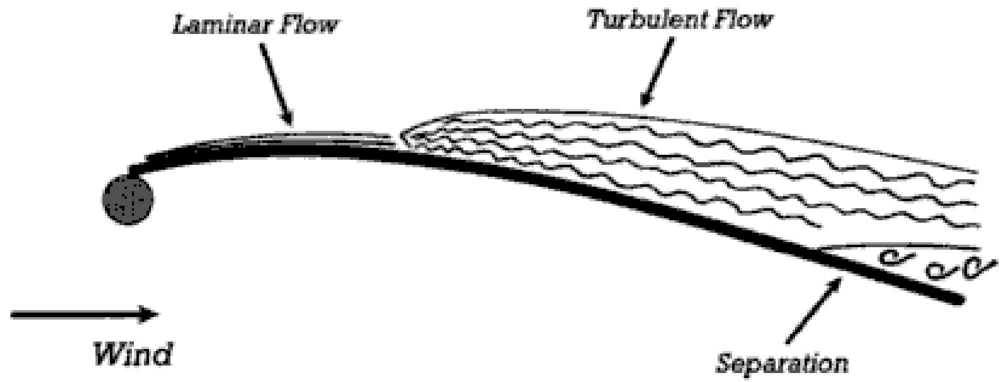


Pressure Distribution experienced by the sail. adapted from Yacht Design by Larsson and Eliasson.

The figure above shows the distribution of pressure experienced by the sail. The total area between the curves is the overall force produced by the sail acting on the boat. Obviously this force travels through the mast which needs to be sturdy enough to take the high pressures, but we will assume here that this is not an issue.

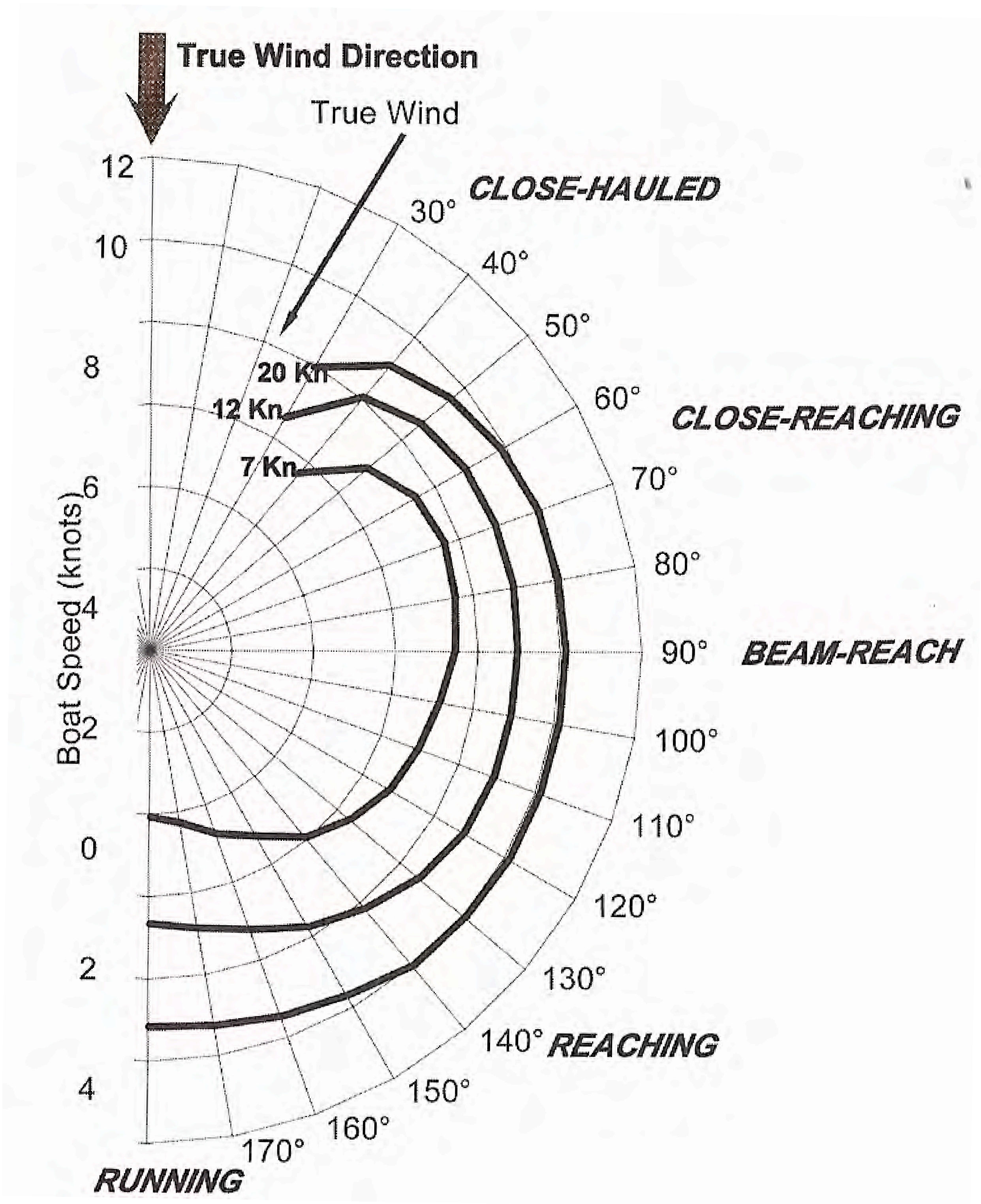
In acknowledging the similarities between the keel and sails, we need to address some of the impediments to movement that both share: resistance and energy loss. Like the keel, the sails create vortex's. Because the air meets at the back of the sail at different angles, there is a twisting effect as the air leaves. Energy is dissipated into the air to make this happen according the laws of conservation of energy. To illustrate the nature of this loss, we can look at the photograph of racing vessels moving through low lying fog, as shown below.

Wind moving along the sail in the same way that the fluid moving along the keel and hull of the boat produced turbulence will experience a shearing stress. Similarly, the no-slip condition of the molecules on the sail will remain in effect, however, these will interact with other causing the shear stress. Similarly, we can predict the point on the sails at which the laminar flow will become turbulent using the reynolds number. For typical wind speed of 10 knots, the switch will occur about 10 meters in. For higher wind speeds, the turbulence may occur closer to the luff of the sail. Laminar flow is possible in lower wind speeds. One of the situations that sailors tend to avoid is the flapping of the leech, and or the flapping of the telltales which are thin pieces of streamer that used to indicate turbulent flow. For maximum power, you want smooth laminar flow on as much of the sail as possible. This stalling of the telltales, and the flapping of the leech is often due to the separation. We can see that separation in the diagram below.



Air Flow along a sail, drawing courtesy of Bryon D. Anderson

Of course, we will ultimately be optimizing for gaining the fastest possible route to our destination. We can see the maximum boat speed in knots with respect to the wind direction on the chart below:



Sail Trims for various angles of attack image courtesy of Bryon D. Anderson.

The Physics of Sailing Explained

As we have been discussing, the sails are the predominant "motor" force of a sailing vessel, and the fuel for this is the wind. But what is meant by wind? After all, when moving in any vehicle open to the atmosphere one experiences "wind" directly against the direction of the moving vehicle. Consider sticking a hand out of a window of a moving automobile. This is the apparent wind. The wind measured on a moving boat will be the net wind. The wind of the air opposing direction and the wind with respect to the water surface, or atmosphere. Being able to measure the universal wind, that is, the wind not created by the boats movement will be important in our optimization. The wind produced from the boat movement cannot also push the boat forwards.

Having briefly explored the physics behind how sails work, we can now look into the theory behind the trimming of sails. First, we define the different terms for sailing directions with respect to the wind. Running is sailing downwind. Reaching is when the wind is coming from the side. If the wind is from behind - but not directly behind - it is a broad reach. A close reach is when the wind comes from between sideways and directly towards the boat. Close hauled is the term used when sailing as directly into the wind as possible, usually about forty five degrees.

Trimming is the art of making the sail flat or curvaceous. It is commonly understood in the sailing community that when going from downwind to pointing upwind, one needs to angle the sails closer to the centerline of the boat. In a downward sailing situation, one attempts to create a bulbous shape to catch the wind with the sail stretched out at approximately 90 degrees, or perpendicular to the horizontal line of the vessel. This bulbous shape also helps create suction in addition to "catching" the most air.

In a beam reach situation with the wind coming from the side, the sail needs to be oriented at approximately 45 degrees to the horizontal of the boat. The shape of the sail must be slightly less bulbous as a large bulb shape will not allow the wind to remain attached all the way to the leech. As we mentioned above, separation is not a good thing. Higher wind speeds require more flattening of the sail. Part of the program will be messages to the helmsman to adjust the outhaul accordingly. And of course, when traveling upwind, one must have an almost entirely flat sail pulled almost parallel to the centerline of the sailing vessel. The general rule appears to be that the sail moves from perpendicular to the centerline of the boat to nearly parallel as you go from pointing downwind to pointing upwind. And, as wind speed increases for given angle, the sails must be tightened (flattened) to stop separation from occurring. In terms of acceleration such as after tacking, it is generally best to start out with a bulbous sail and flatten it out as the vessel's speed increases. This process of flattening the sail generally happens quickly, within a minute of tacking or even less time.

The physics behind sails, hulls and keels are relatively simple and very related with the equations paralleling one another. These three components of the sailboat however are each necessary and each have an effect on the speed of the sailboat. The actual process of trimming sails however (the only aspect of sailing that is really controllable once the boat is in the water) remains an art more than a science. Still, while fine tuning can only be accomplished well with a weathered hand, the calculations set forth in the discussion above show that to a large degree approximations will place the sailing vessel at a competitive edge based on the parameters presented. In the end, it is so much more that cannot be accounted for in physics that controls the performance of the vessels such as crew communication, smooth operation of equipment, and smart decisions. We hope however that with the creation of the mainsheet tender that a single individual will be capable of competitively sailing a larger vessel singlehandedly focusing solely on the rudder and enjoying the wind on his or her face.

Project Plan

In this section I will describe the necessary tasks that I plan to accomplish over the course of this project. The listing will be followed with a critical path analysis of the presented list of tasks.

1. **Obtain Machine-shop certification** In order to make the main sheet feeder and create the various inputs, I will need to be allowed to use the machine shop. I have already taken the class once through, but would like to brush up on my usage of the machines. This will be very important for the feeder which will be completely customized.

2. **Decide on and design the inputs** I intend on having a variety of inputs which will feed into a processor of some sort. Choosing this processor or micro controller will be a part of the input process as I decide how many inputs to have and the extent of the calculations I intend on performing. My objective is to select a few reliable inputs that will be durable and give accurate information off of which I can make key decisions such as maintaining the angle of the sail, or changing the angle. I will also be outputting visual (and possibly verbal) commands to tighten or release the outhaul. The definite measures will be the heel of the boat, the actual wind velocity which will be found by measuring the relative velocity from the top of the mast and subtracting from this vector the induced velocity taken from a short pipe at the front of the boat. I will measure the velocity of the boat using a variety of features, and averaging the response. My primary method will be using a GPS device. I will of course be measuring the angle of the sail to provide negative feedback for the sail angle relative to the horizontal line of the boat. Finally, I will be measuring the sail shape. This will be the most interesting. I intend to run a very thin line across the sail a few feet above the the boom. It will run entirely around the sail and have lines running at set intervals to

the sail on sliders. They will report back to the main controller. The specifics I am still working out, but I hope to be able to recreate the sail shape and angle and wind direction along with speed in a visual program in Matlab which will allow for better insight on the helmsman's part in making the decisions on how to approach any direction of sailing. Previous methods involved tiny barometers which give readings at various locations and allow for a visual representation of what is going on with respect to the fluid mechanics of the system as the vessel moves through water.

3. Test Inputs I will need to design a test process for measure how accurate the inputs are. Having this accuracy will allow me to weight them prior to the optimization and calibration. I would ideally like to use a wind tunnel (such as exists in hicks for the fluids labs) for the testing of the devices to make sure that they concur in their readings. Failing this, or perhaps in addition, I will measure in the field against tested instruments already mounted on a vessel. I can also test on a land vehicle such as a car for things such as the absolute wind direction and velocity measurement device.

4. Design Mainsheet Feeder Under the direction of Professor Orthlieb, I will work on a design for a compact, waterproof durable mainsheet feeder. Because I don't have information on the torques, impulses, moments, and forces experienced by the mainsheet, I don't have the specifications necessary to build this as of yet. It will however have a motor controlled by a chip. In order to lock the device, the rope will be cinched down from either side as it passes through a loop. The entire device will swivel so that the main sheet feeds directly out of the motor to the boom. There will be a winch to wind it in for close hauls, and an emergency release for when the boat has heeled beyond a reliable amount. The rigging will remain in the boat so that the boat can be returned to land in the case of malfunction. There will also be automatic controls for slight adjustments to be made which will remain in affect unless there is drastic change in one of the input variables.

5. Motor Selection I will have a working knowledge of the types of impulse I will require to select a motor that will be able to provide the torque (using a pulley system if necessary) to change the length of the mainsheet during sailing operation. I will also be looking for something that can be quickly recharged, is silent, small, and lasts for long periods of time.

6. Battery Selection to control the motor, and input devices, a battery will be required. I will select a rechargeable battery capable of powering my motor. Considerations will be weight, and characteristics such as voltage, current, etc.

7. Build Mainsheet Feeder I will work in the shop to construct the actual feeder designed prior to battery selection. Prior to this I will need to order materials which will be determined during the design period. The device will be created in Solidworks.

8. Test Mainsheet Feeder before continuing, I will require a bit of testing on the feeder to ensure that it is properly responding to my input controls. The serve motors will need to be timed to compress or release at the same time, and the device must spin approximately 180 degrees freely.

9. Create Optimization Program I will begin working on the program which will read in the inputs, and place them into the calibration curves. The output will be messages to a crew man such as the helmsman and instructions to the motor. It will calculate the fastest possible velocity for a given direction based on the inputs, ask the user what speed they would like to travel at (leisurely or racer) and trim the sails accordingly. Testing of this will require a test device.

10. Build Water Proof Container Because electronics don't like the wet or the cold, and we will be on the sea, I will develop or find a waterproof box that allows for wires to come in and out. This box will hold the battery and winch and be attached via a locking device to the boat itself.

11. Build Test Device Once each aspect is working I will design a test device that will be a makeshift model sized sail attacked to a mast locked in the ground. I will use a fan to simulate a wind tunnel pushing air over the device and optimize variable by variable. This will be the final phase of land testing, and the only time prior to mounting on the boat that the

12. Final Testing on a Boat Professor Orthlieb has suggested that we might be able to gain access to a vessel in the spring for some testing on the open water to see if the mainsheet controller does in fact function as expected.

The following three items are self explanatory.

13. Prepare and Deliver mid-semester presentation

14. Prepare a final project report

15. Prepare and deliver final project presentation

The table below shows each task described above along with an estimate of the duration of time necessary to work on it. It will be the basis for the critical path diagram included in this report.

#	Task	Duration (Days)	Effective (hours)	Needs	Feeds
1	**Obtain Machine-shop certification**	Done	Done		2, 7, 11
2	**Decide on and design the inputs**	5	25	1,	3,
3	**Test Inputs**	5	25	2,	
4	**Design Mainsheet Feeder**	3	15		5, 6, 7, 8
5	**Motor Selection**	.5	2.5	4,	6, 7, 8,
6	**Battery Selection**	.5	2.5	4, 5,	7, 8,
7	**Build Mainsheet Feeder**	3	15	1, 4, 5, 6,	8
8	**Test Mainsheet Feeder**	1	5	4, 5, 6, 7	
9	**Create Optimization Program**	7	35		
10	**Build Waterproof Container**	.5	2.5		
11	**Build Test Device**	2	10	1, 2 - 8	12
12	**Final Testing on a Boat**	5	40	1 - 11	
13	**Prepare and Deliver mid-semester presentation**	3.5	17.5	Depends	Depends
14	**Prepare a final project report**	8	40	1 - 12	15
15	**Prepare and deliver final project presentation**	8	40	1 – 12, 15	
Totals	--	50	250	--	--

I come onto this job qualified in both regards. First, and foremost, I have grown up a sailor attending sailing camp when I was younger, and sailing with my cousins at the beach during the summer. For the past few summers I have competed in the Georgica pond races. I bring a passion to this project to learn and explore and optimize.

Equally important in my preparation for taking on this project is that I approach this after the iterative and recursive process of three and half years of engineering classes taken at

Swarthmore. While my experience to date has mostly been in electrical, my dynamics class taken in the fall of 2007 has strengthened my analytic mechanical skills and I feel comfortable with the math. Most importantly I feel comfortable with my abilities as an engineer to ask questions, find help, and persevere both as an individual and as a team backed by the support of the Engineering department at Swarthmore College.

Project Cost's

#	Item	Expected Cost	Funding Source
1	**Microcontroller**		
2	**Input Devices**		
3	**Wiring**		
4	**Building materials for mainsheet feeder**		
5	**Motor**		
6	**Battery**		
7	**Building Materials for test set**		
8	**Boat usage fees**		
9	**Travel Costs to testing site**		
10	**Waterproof Container**		

E90 Midterm Presentation

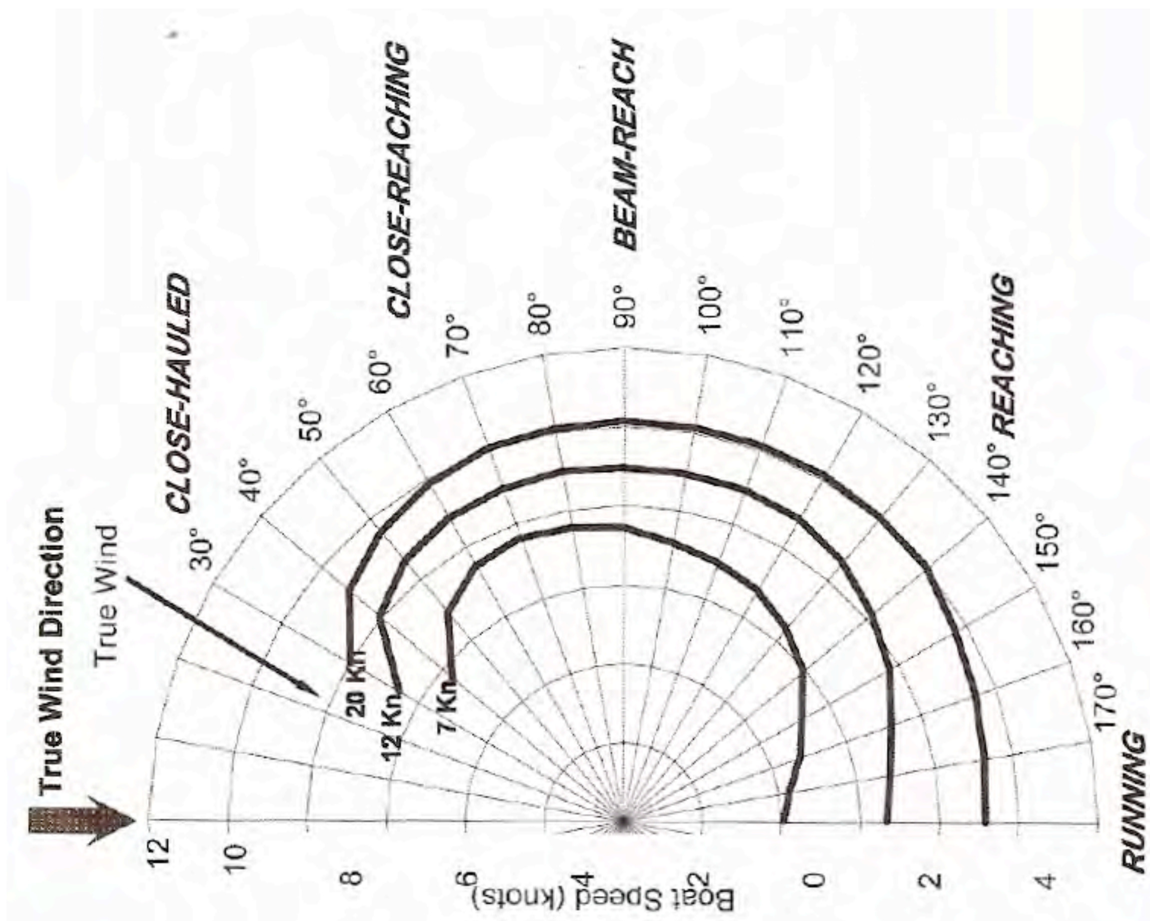
Jonathan Harris
Under direction of Fred Orthlieb

Project Goals / Status

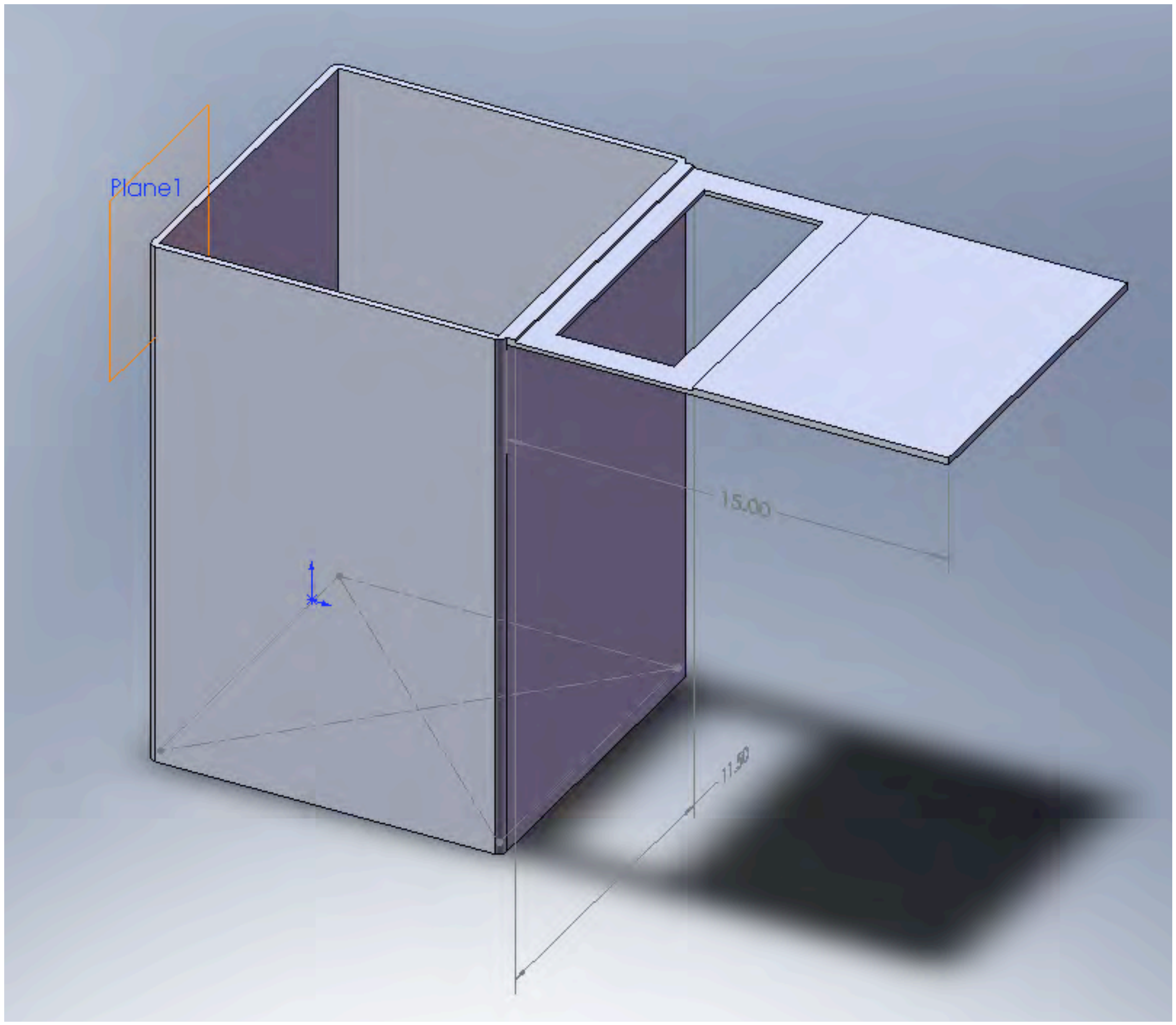
- Design and Build a Mainsheet Feeder
  - Work in Progress
- Design and Build anemometer like device for relative wind direction
  - Under Construction by students in E14
- Create Optimization Program (boom angle and heel of boat)
  - Work in Progress

Theory of Sail

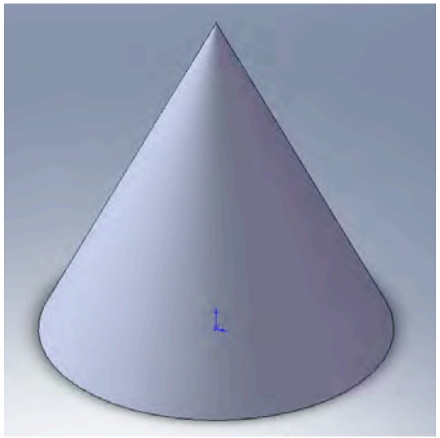
- For a given relative wind angle and velocity there is an optimal sail angle and angle and sail shape

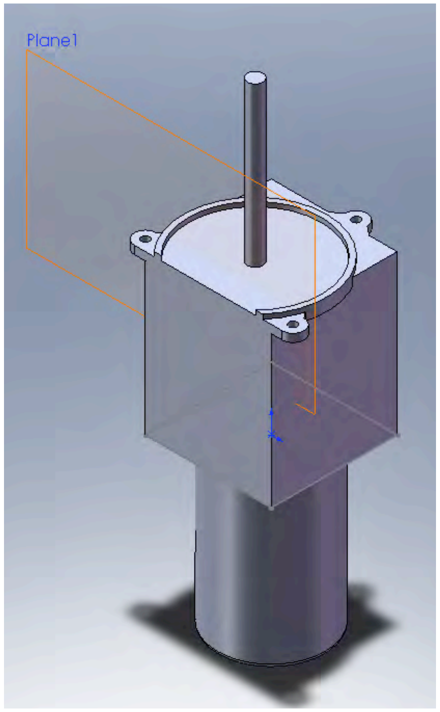


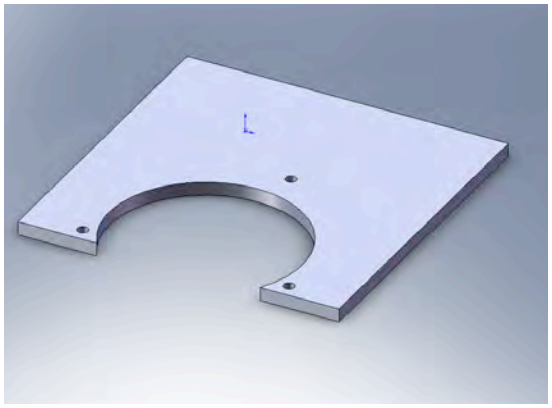
Housing Design for Mainsheet Feeder



Winding Cone, Motor and Plate







Soon to be completed

- Complete Building of housing, assembly
- Settle on Motor Control Algorithm
- Implementation of acquisition devices
  - wind direction and velocity
  - boom angle (negative feedback for system)
- Routing of harness system (wiring)
- Battery Selection

Questions?

- Thank you Professor Orthlieb for your support and enthusiasm for my project
- Thank you to the Engineering Department and Faculty for your general guidance and funding.

Sailboat Autopilot: Mainsheet Tender Module

Engineering 90

Jonathan Harris

6 May 2008

Acknowledgements

- Engineering Faculty and Staff
- More specifically:
  - Professor Fred Orthlieb, Engineering 90 Advisor
  - Professor Erik Cheever
  - Professor Carr Everbach
  - Holly Castleman
  - Don Reynolds
  - Doug Judy
  - Ed Jaoudi
  - All of my peers in the department

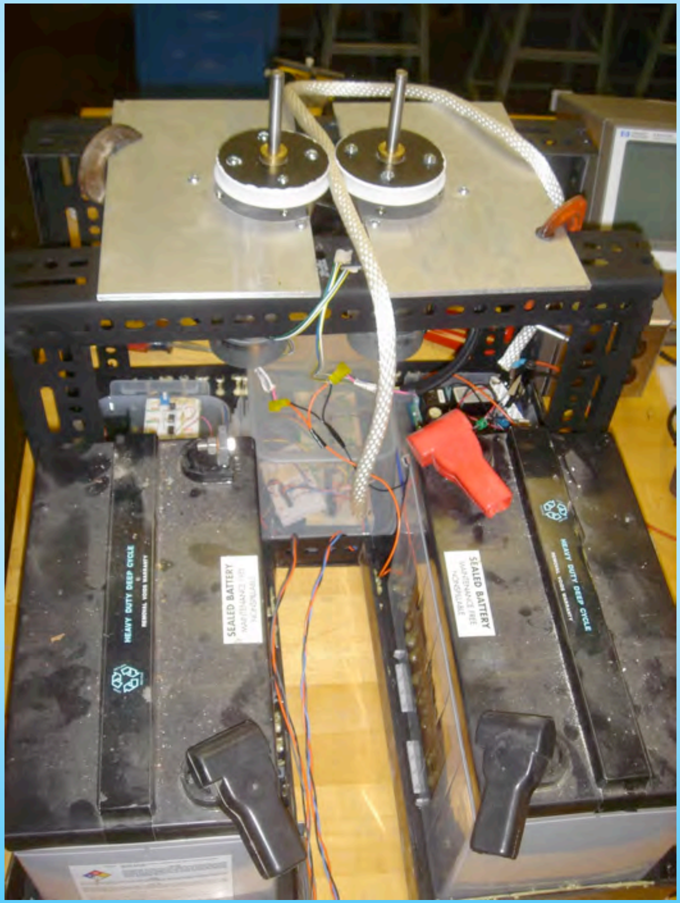
Outline

- Personal Appeal of this project
- Project Objectives
- Why build a mainsheet feeder?
- Current Technology
- Background Material
- Concept Design
- Components
- Video of testing
- Results
- Future Work
- Conclusions
- Lessons Learned

Personal Appeal

www.georgicapond.com

Project Objectives



Project Objectives

To build a sheet tender, to be used on a small craft, that maintains the optimal angle for the boom of a sailboat by retracting and releasing the mainsheet in a controlled fashion.

- Robust System
- Easy to use

Why?

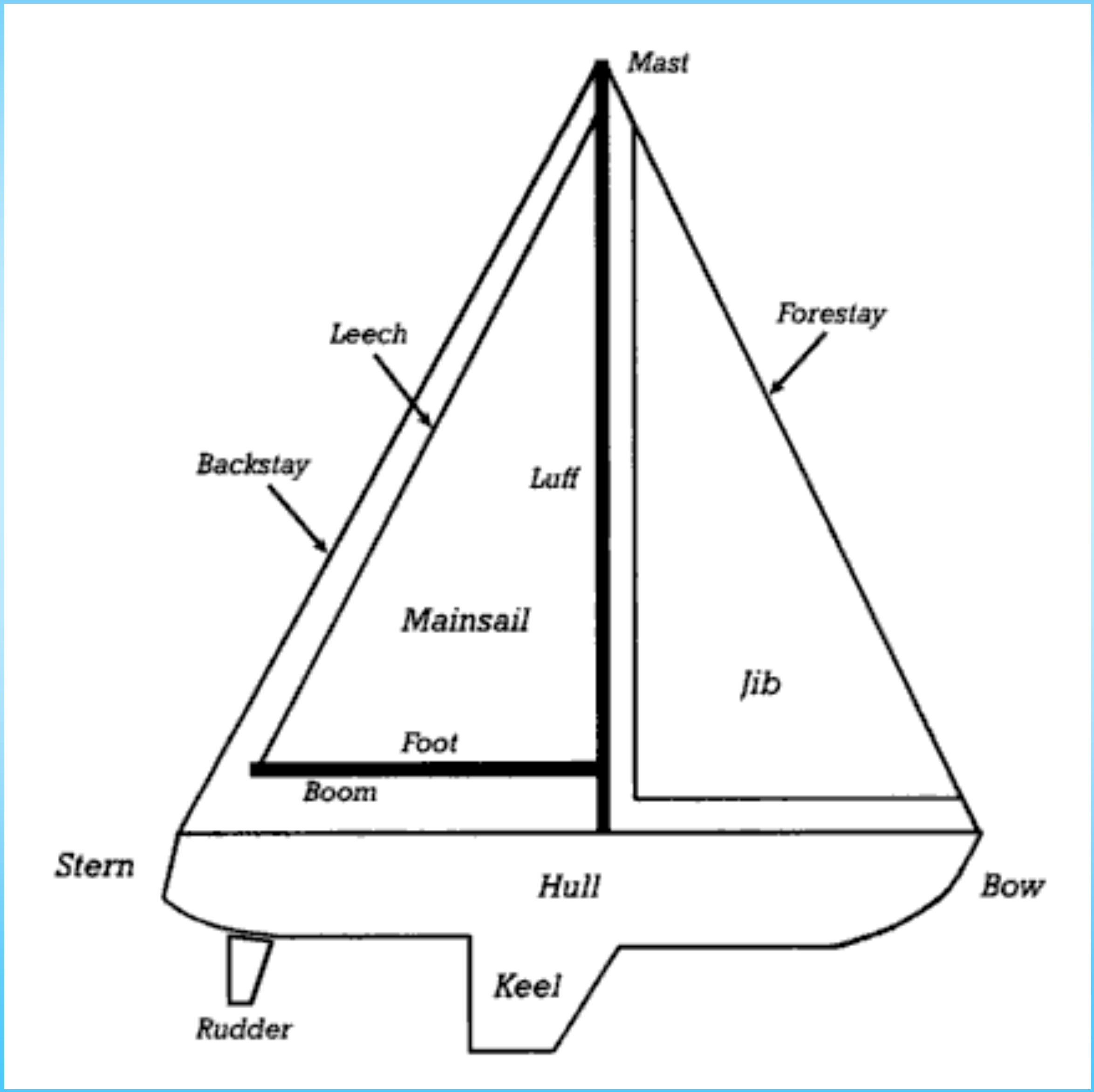
- Teaching tool
- Larger population
- Less Work = Greater Leisure

Mainsheet Tender Technology Currently Available

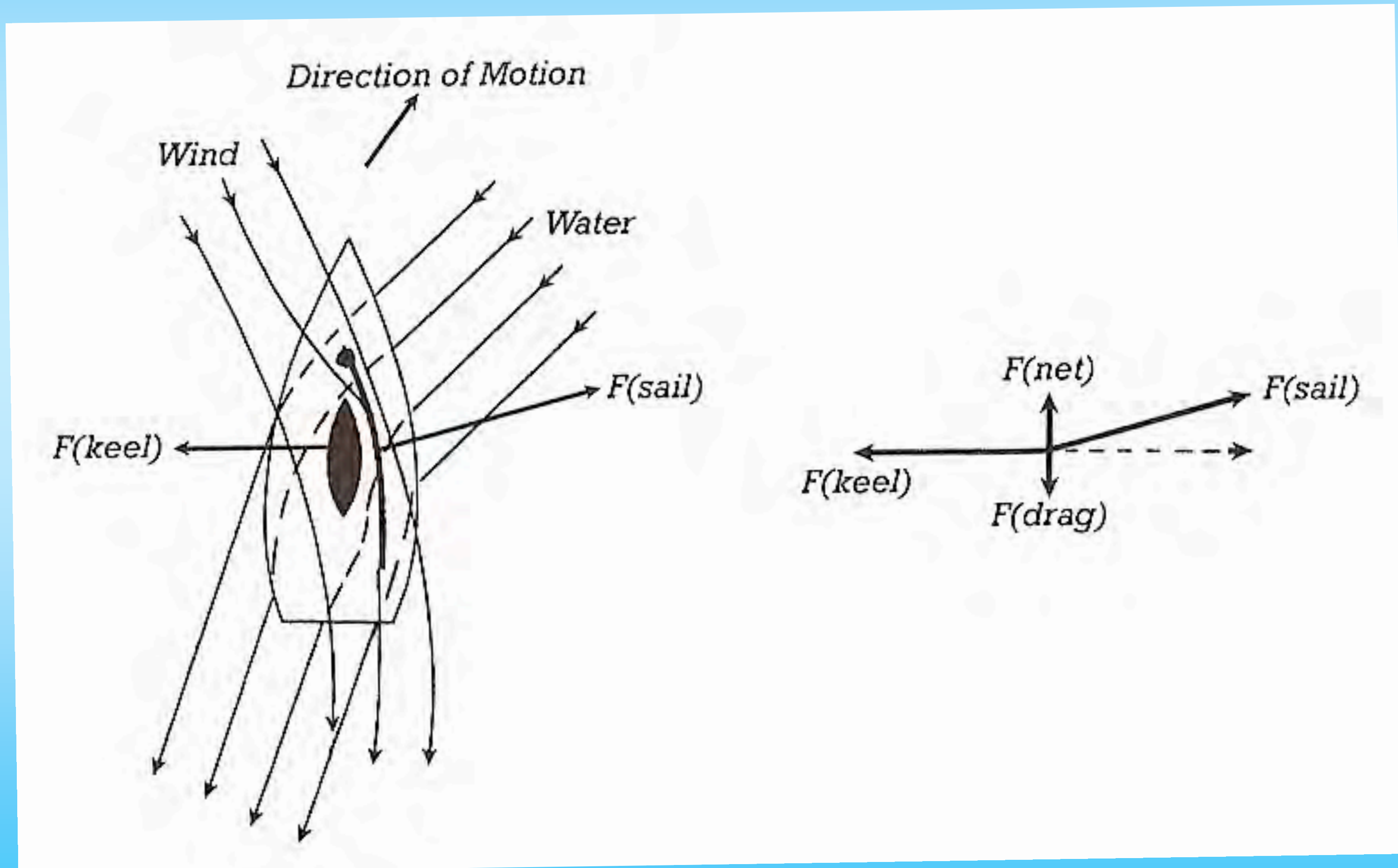
Background Material

- Basic Sailing Vessel
- Forces experienced by a sailing vessel
- Common Misconception of how it works
- Foil => Sail
- Maximum Velocity

Boat Outline



Forces on a sailing Vessel



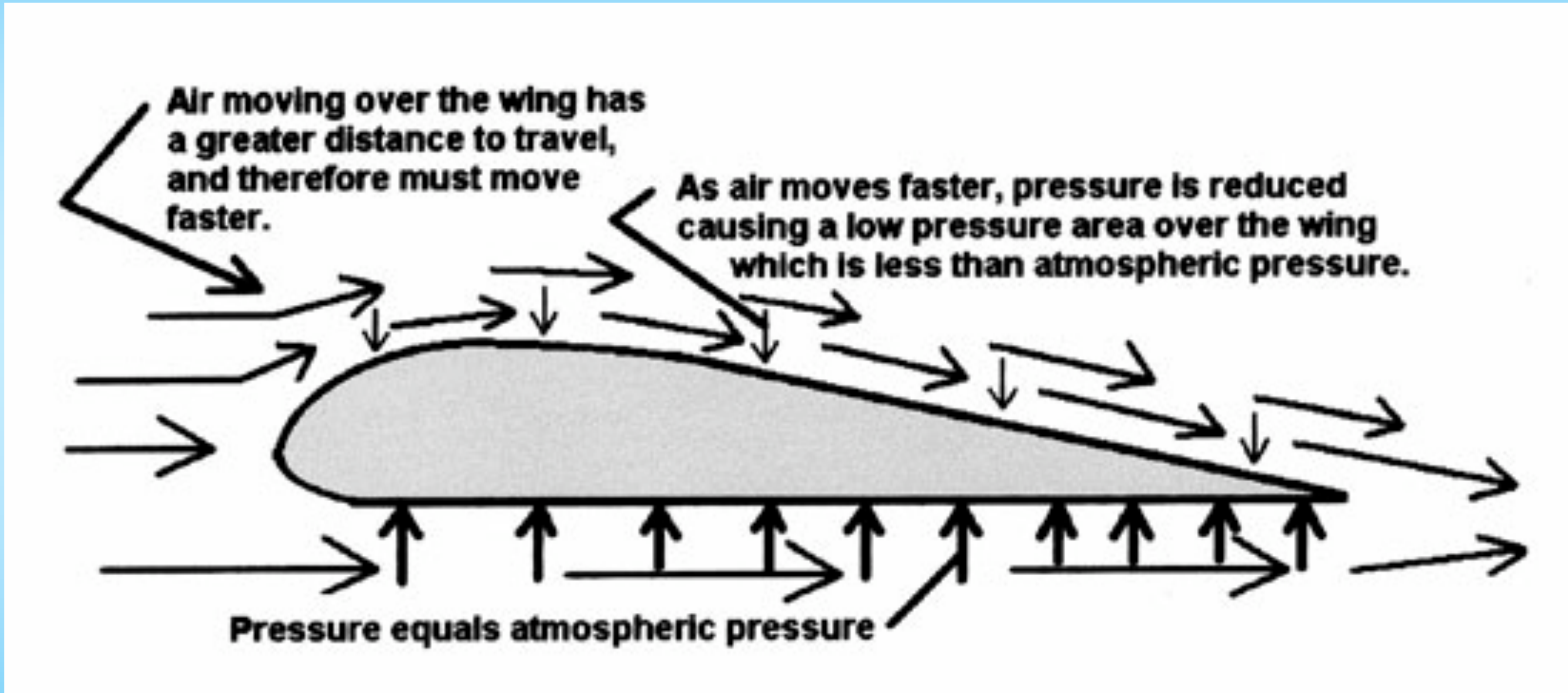
Powering a Vessel by Wind

- **Work = Force x Distance = Kinetic Energy**
- **And KE = ½ M v^2 ,**
  - where **M** is the total mass of air striking the sail, and **M = ρ A v t**
    - **ρ** is the density of the air
    - **A** is the area of the sail
    - **v** is the velocity of the air with respect to the sail
    - **t** is an arbitrary time.
    - If we take **d** in the equation above as the distance the air travels in the time **t**, then **d =v t** in and we have

$$\mathbf{F = KE / d = \tfrac{1}{2} \rho v^2 A}$$

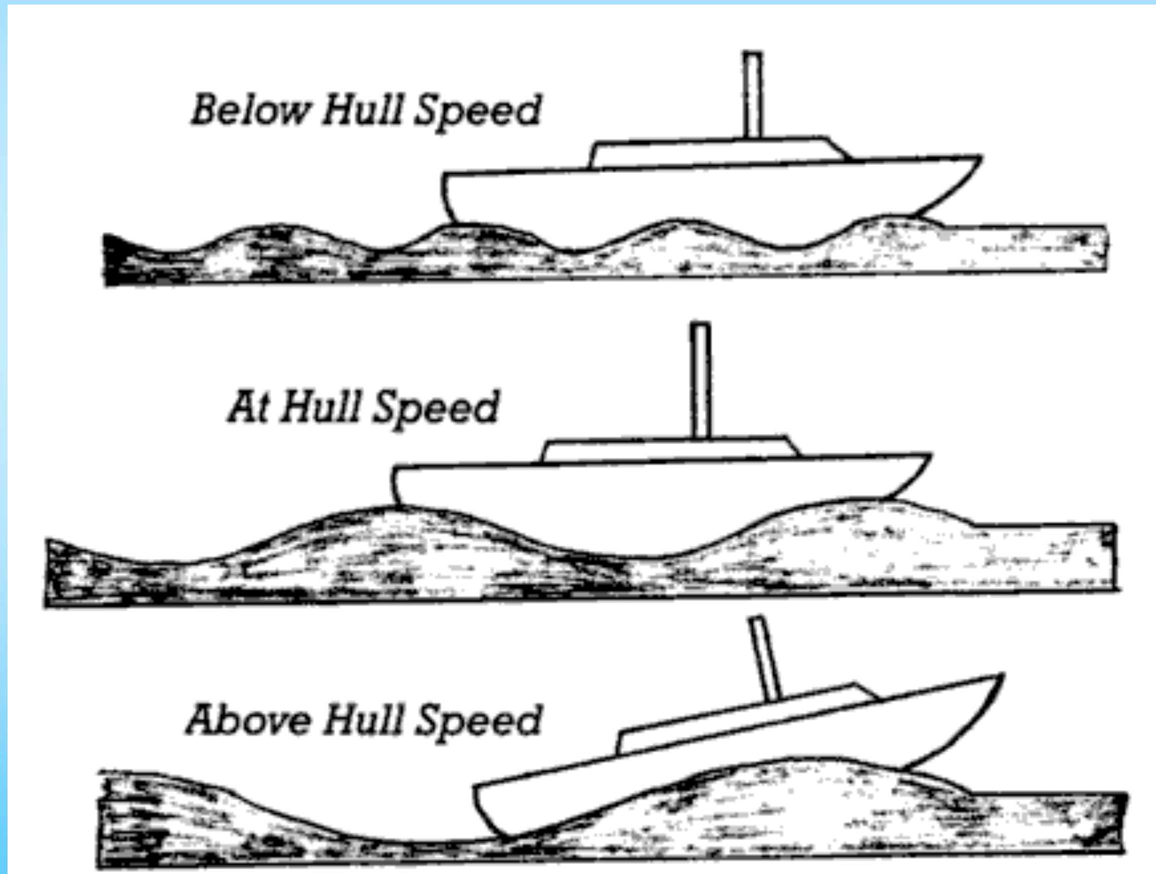
$$\mathbf{F = C (\tfrac{1}{2} \rho v^2 A)}$$

Airplane Foil…

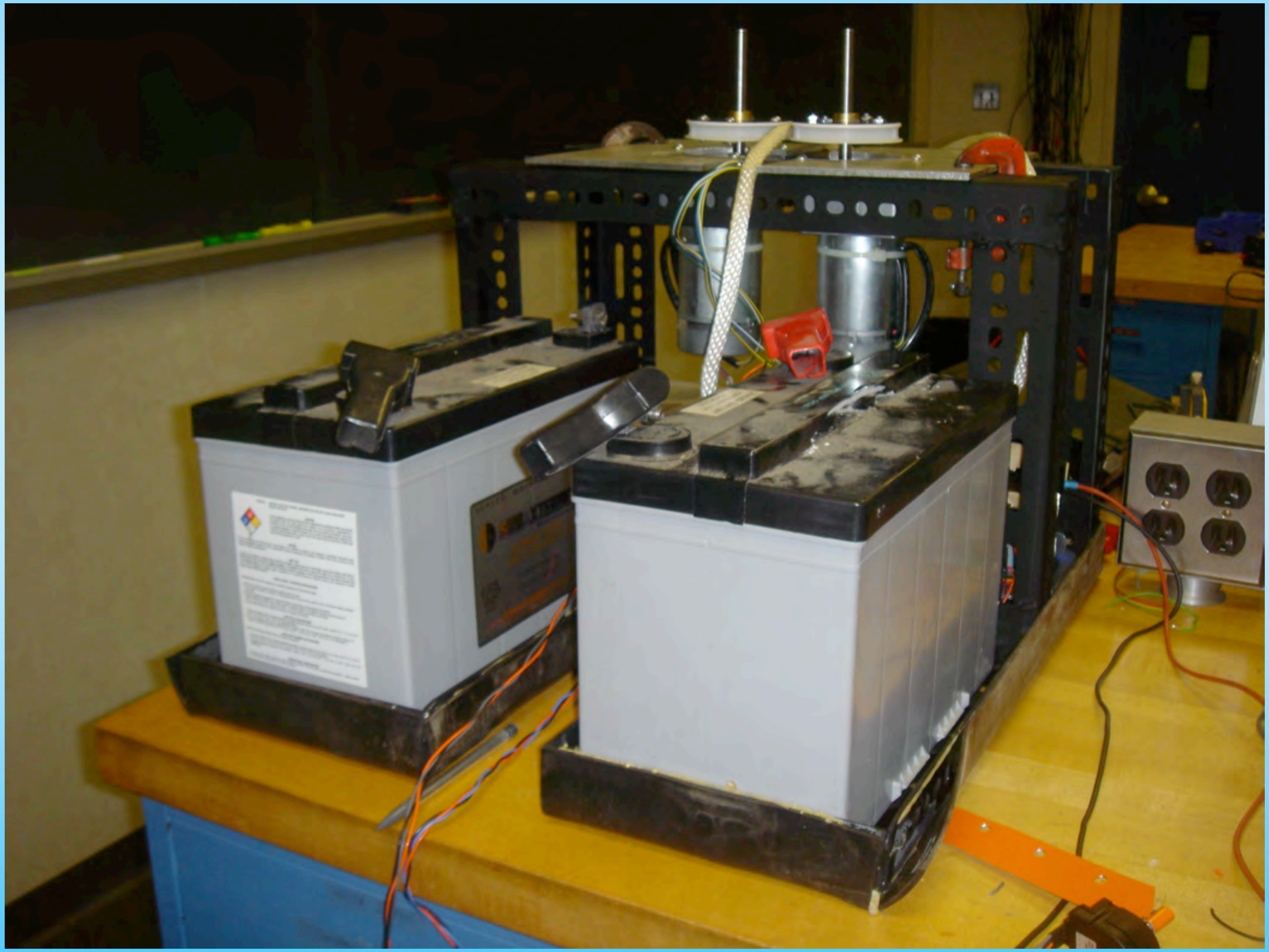


… To Sail

Maximum Velocity



Mainsheet Tender Construction



Design Choices

- Build for O’Day Widgeon
- Use available in house components when possible
- All Analog Circuitry
- Only 9-Volt Batteries to power Circuitry, Controller and Input Devices

Boat Specifications

O’Day Widgeon c. 1970

Length: 12 ft. 4 in.

B*eam:* 5 ft.

Draft: 3 ft. 6 in.

Weight: 318 lbs.

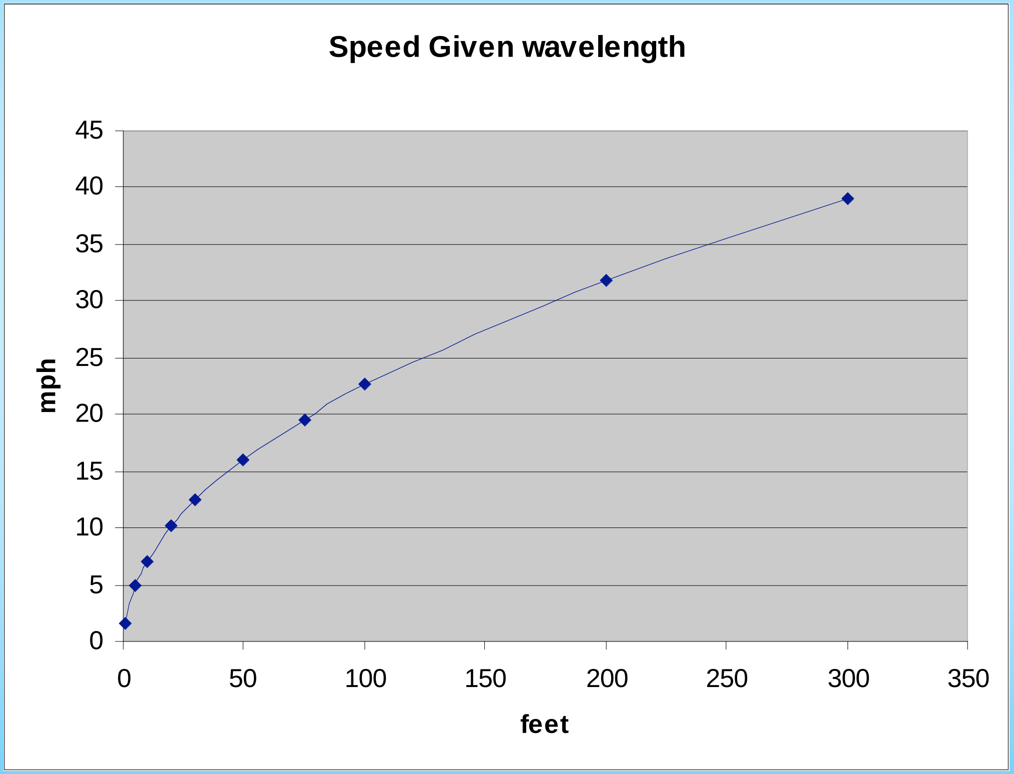
Sail Area: M&J, 90 sq. ft. total

First Built: 1964

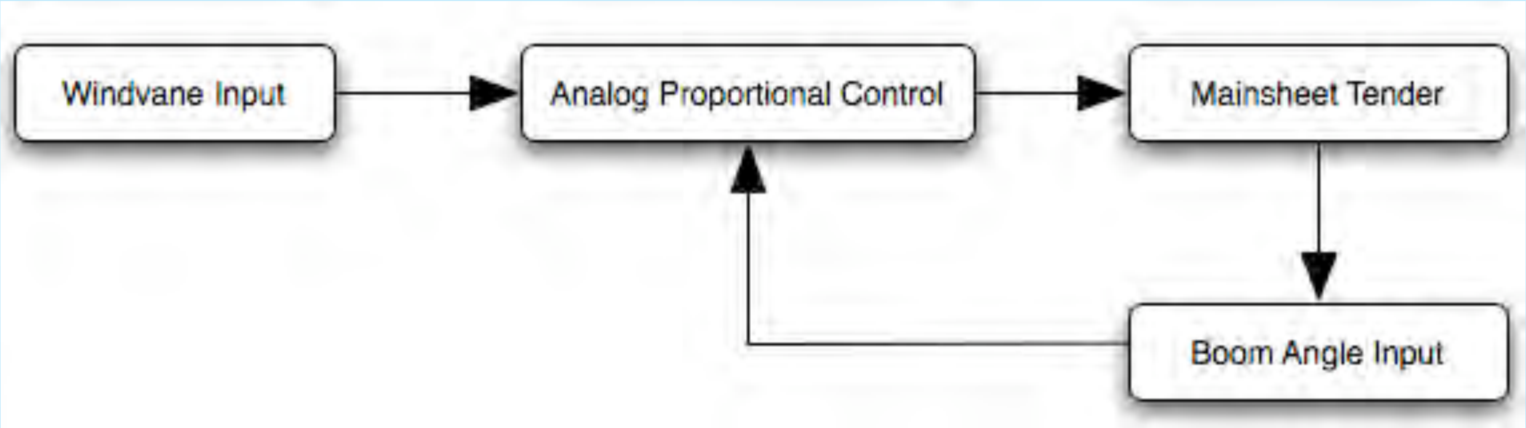
Designer: Robert Baker

6000 Built

Maximum Velocity of our Boat



Concept Design



Purchased Components

- Motor
- Motor Controller
- Batteries
- Variable Resistors

Motors

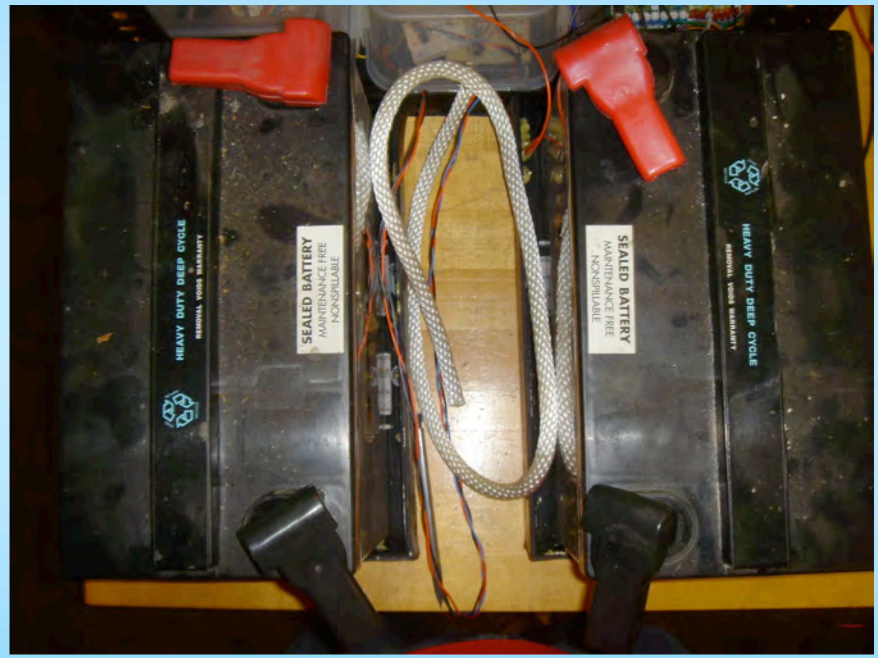
- TM98MTR3114
- 24VDC
- 100 RPM
- Reversible DC Servo Gearhead
- Optical Encoder (not used)

Motor Controller

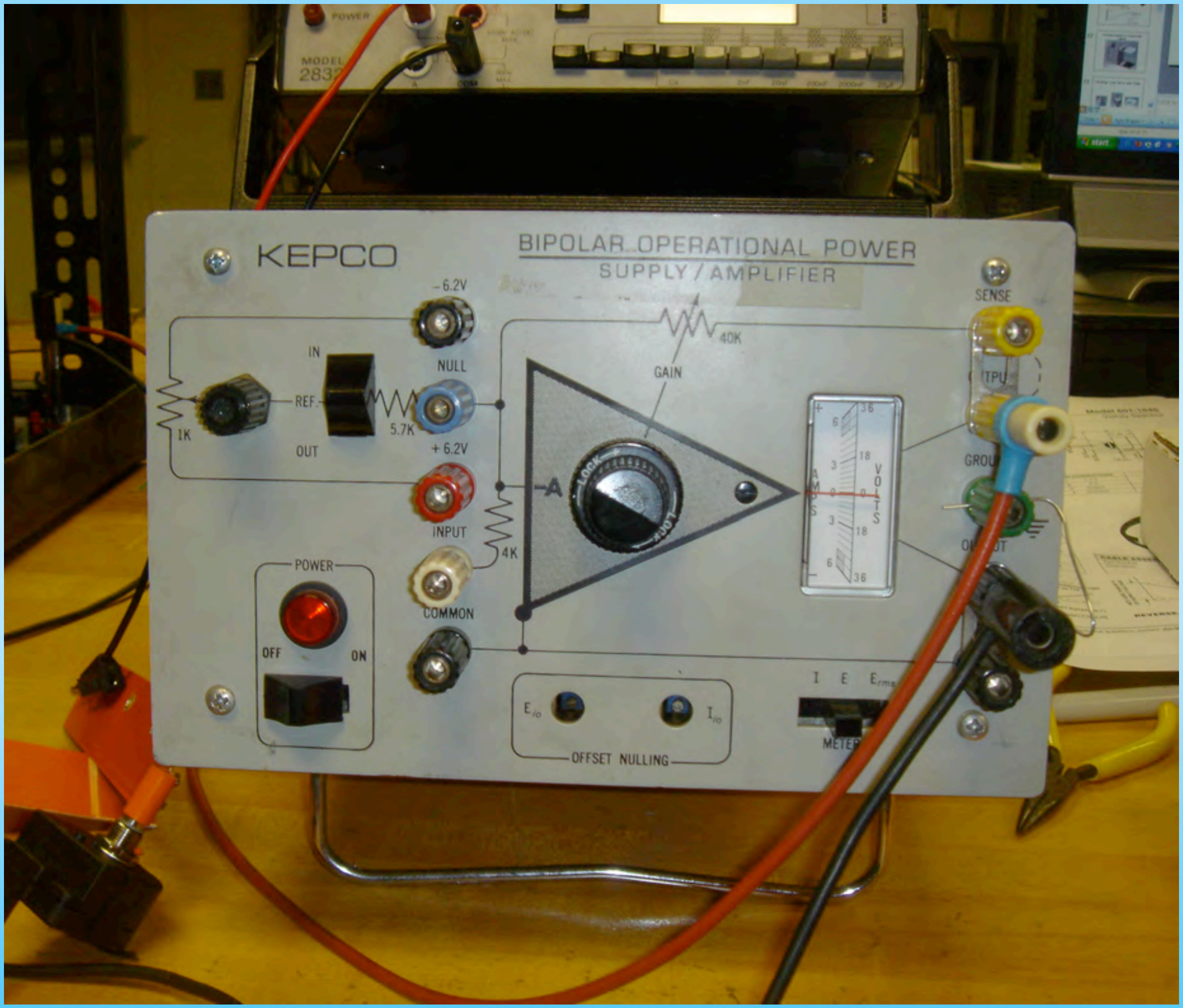
- KBBC-24M
- Variable speed Motor Controller
- For 12, 24, 36 and 48 Volt
- PM and Series Wound DC Motors
- 2HP Continuous Duty and 4HP Peak Duty

Batteries

- Sun Xtender Series
- Deep Cycle Batteries
- 12Volts each
  - Grounds tied together to form 24 Volt Differential

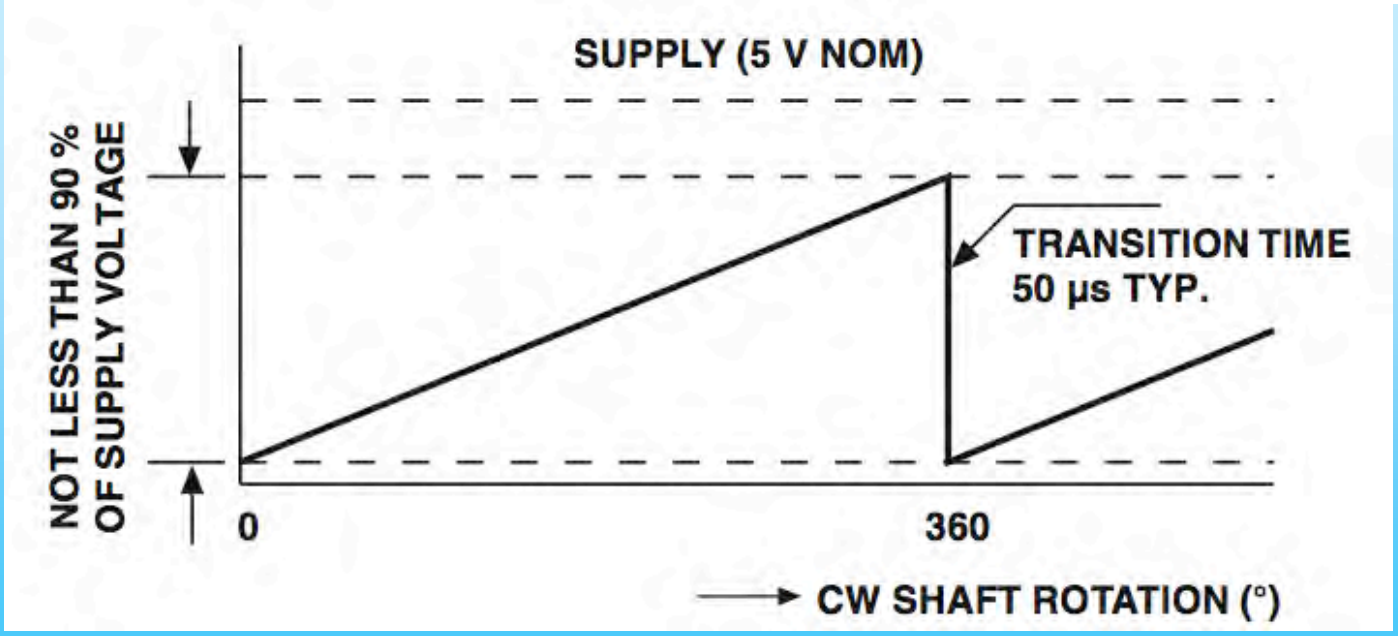


Actual Motor Power Source



Boom Angle / Wind Vane Inputs

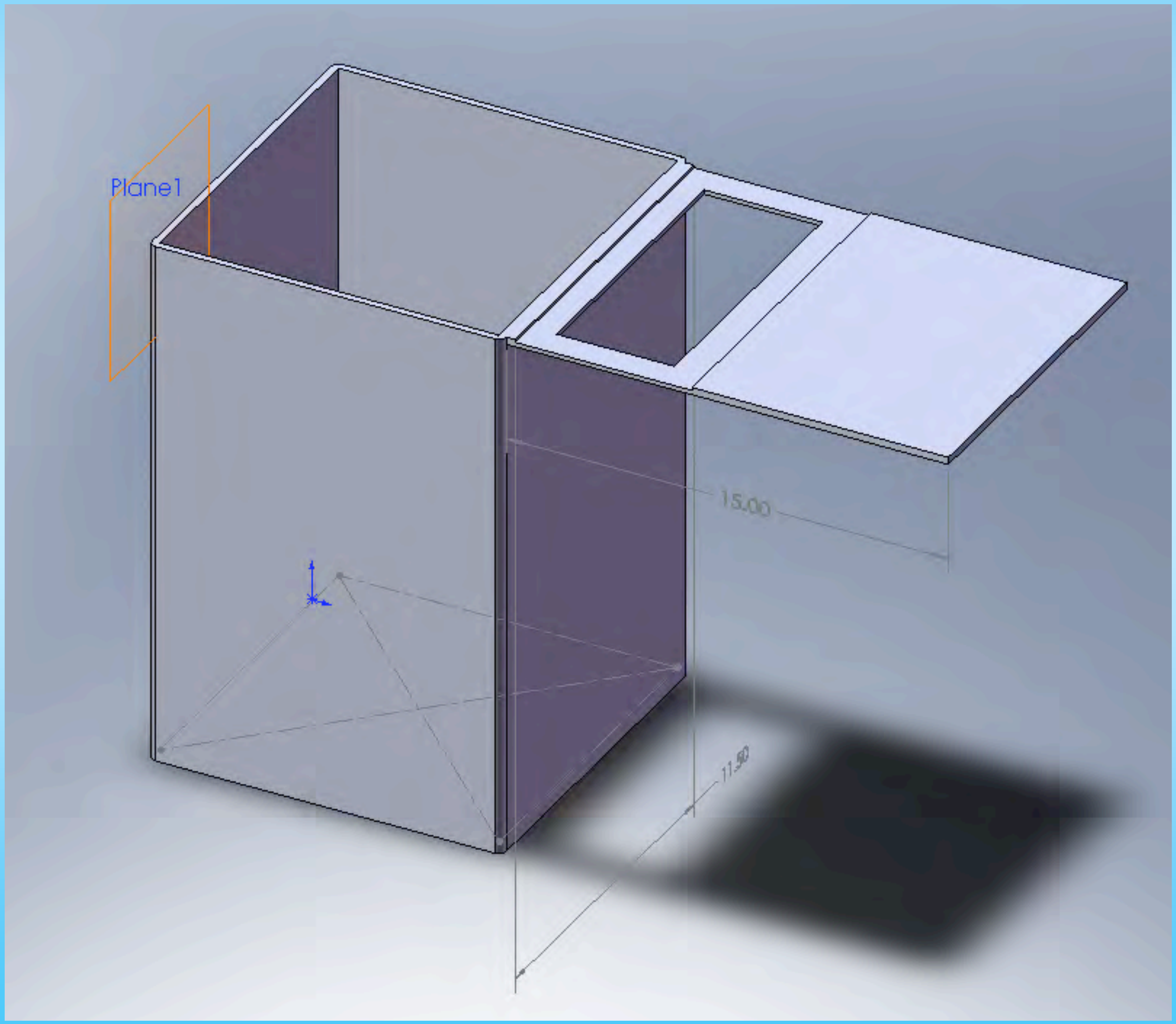
- *Vishay* Smart Position Sensors
  – No dead zone
  – O – 5Volt Operation
  – Resolution 0.5 degrees



Fabricated Components

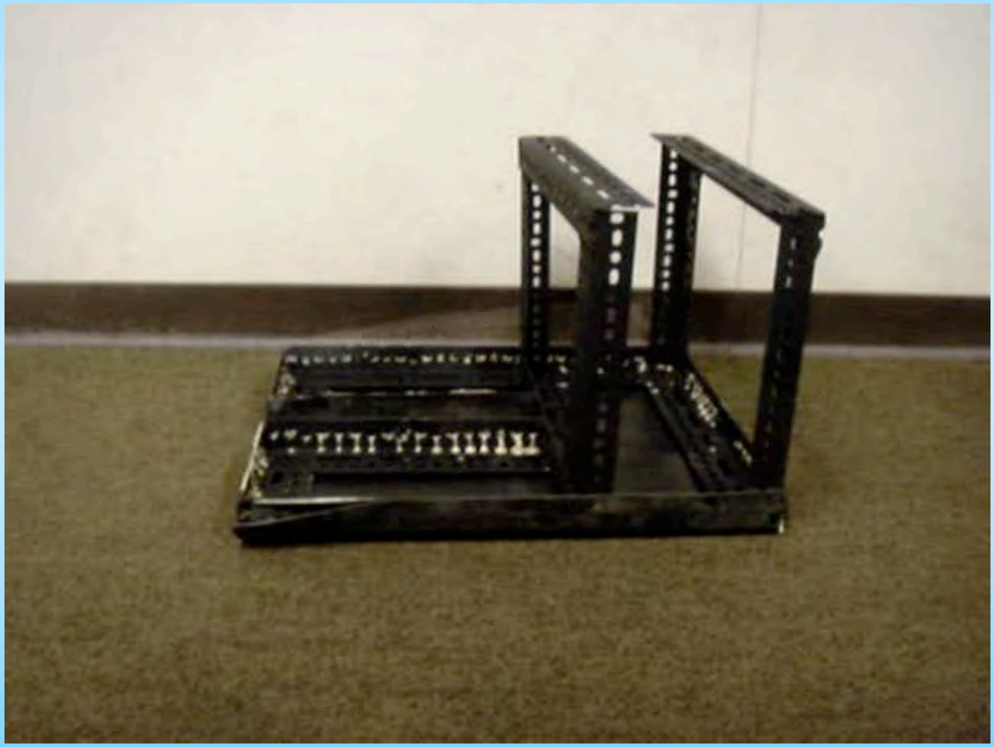
- Housing
- Motor Plates
- Gears
- Analog Circuitry

Housing Design for Mainsheet Feeder in Solidworks

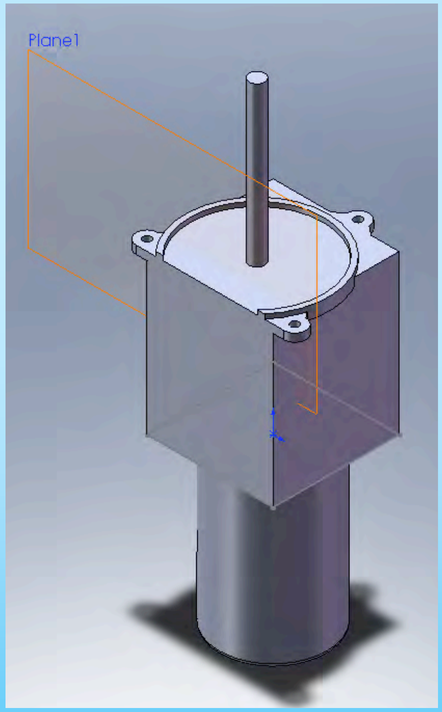


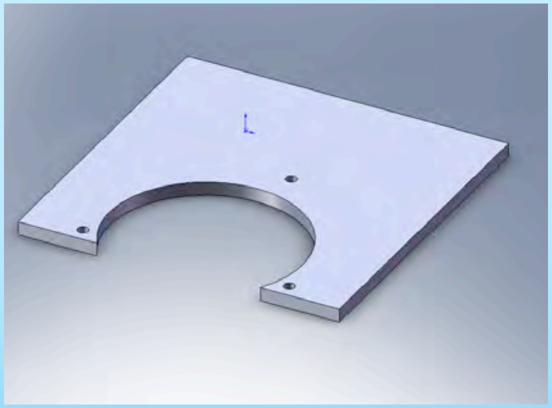
Actual Housing Specifications

- Dimensions:
  - 13 Inches high
  - 19 Inches wide
  - 23 Inches long



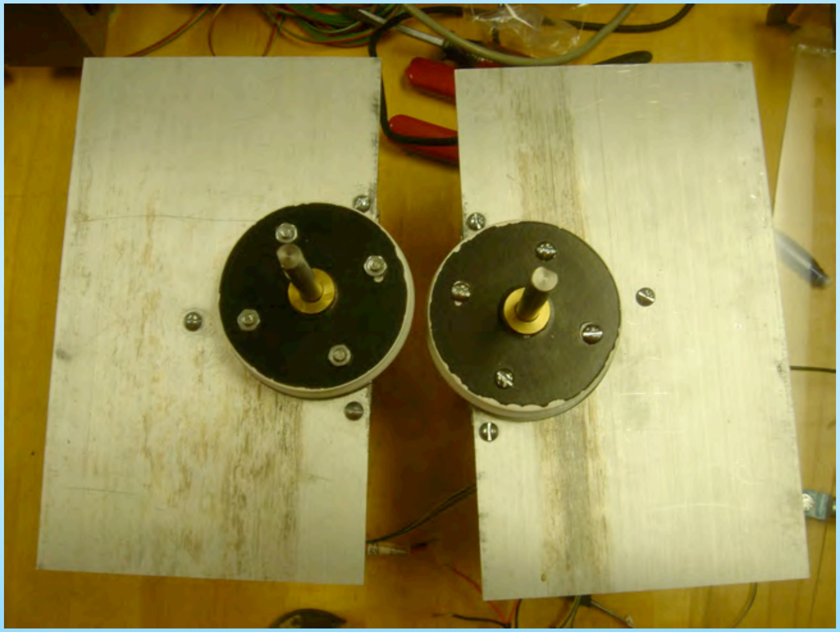
Motor and
Motor Plate in Solidworks





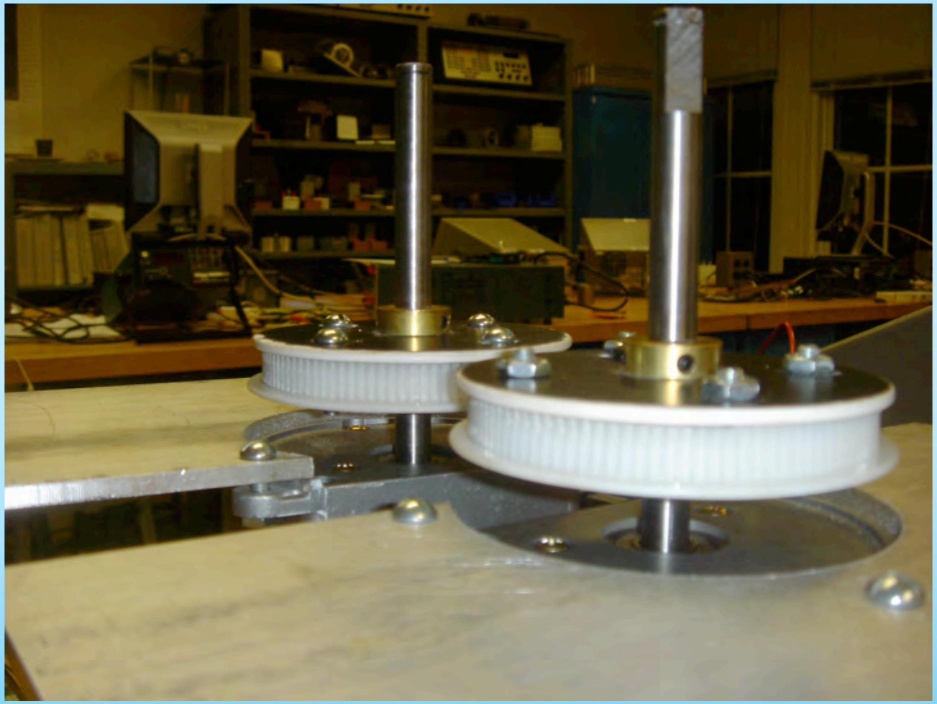
Motor Baseplates

- 3 Screws
- 10 Inches long
- 6 Inches wide
- Clamped to Housing

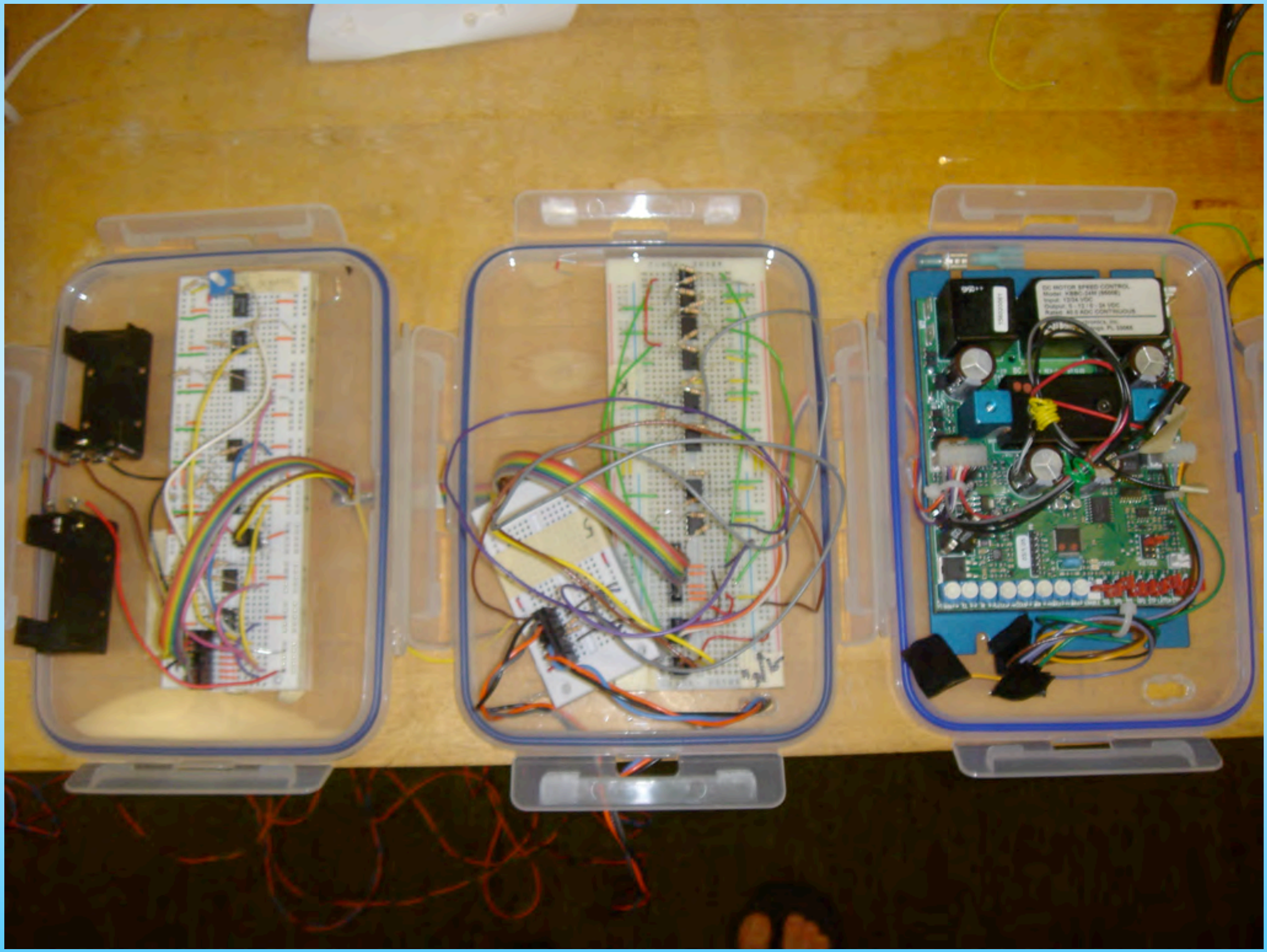


Gears

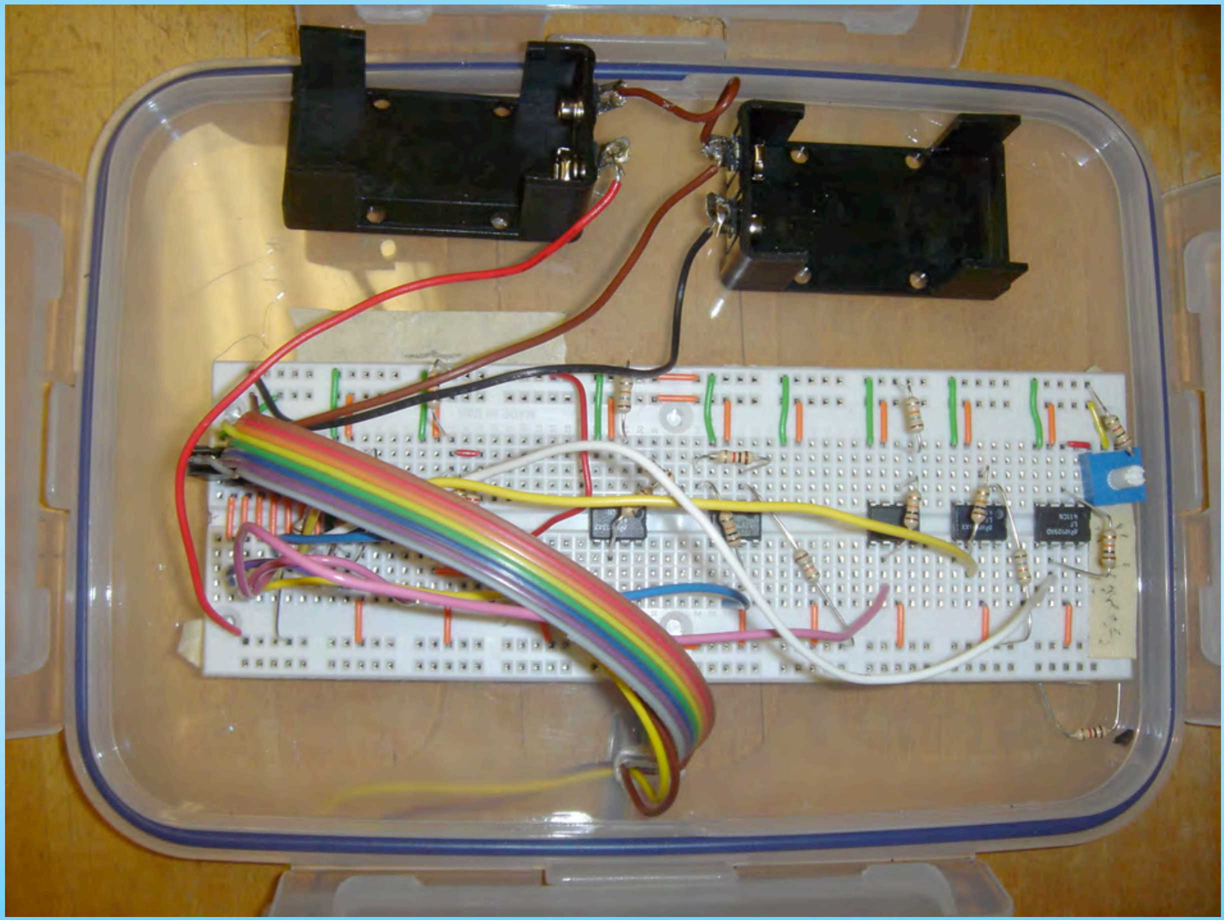
- Custom Built using lathe
- Modification of gears that came with motor
- Lower plate is slightly larger to ensure rope does not fall below gears
- Plates have slight angle to maintain ropes position between plates



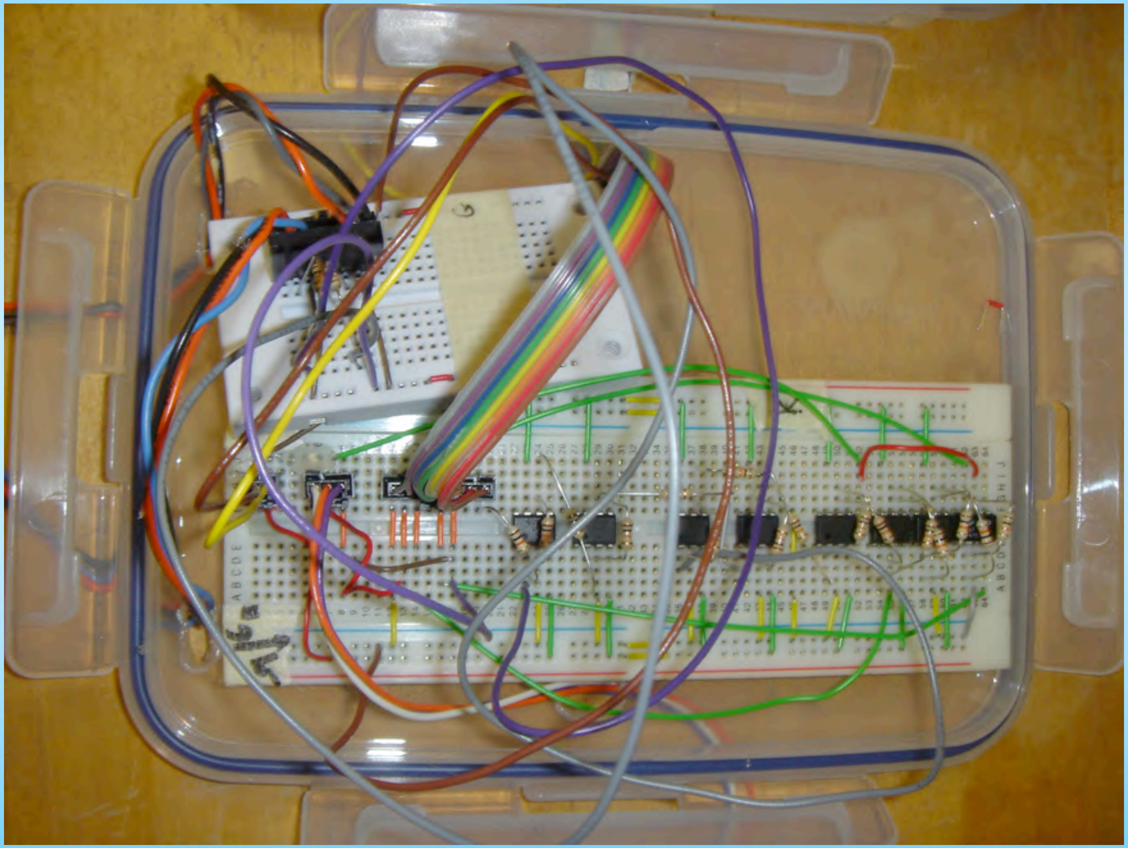
Analog Circuitry



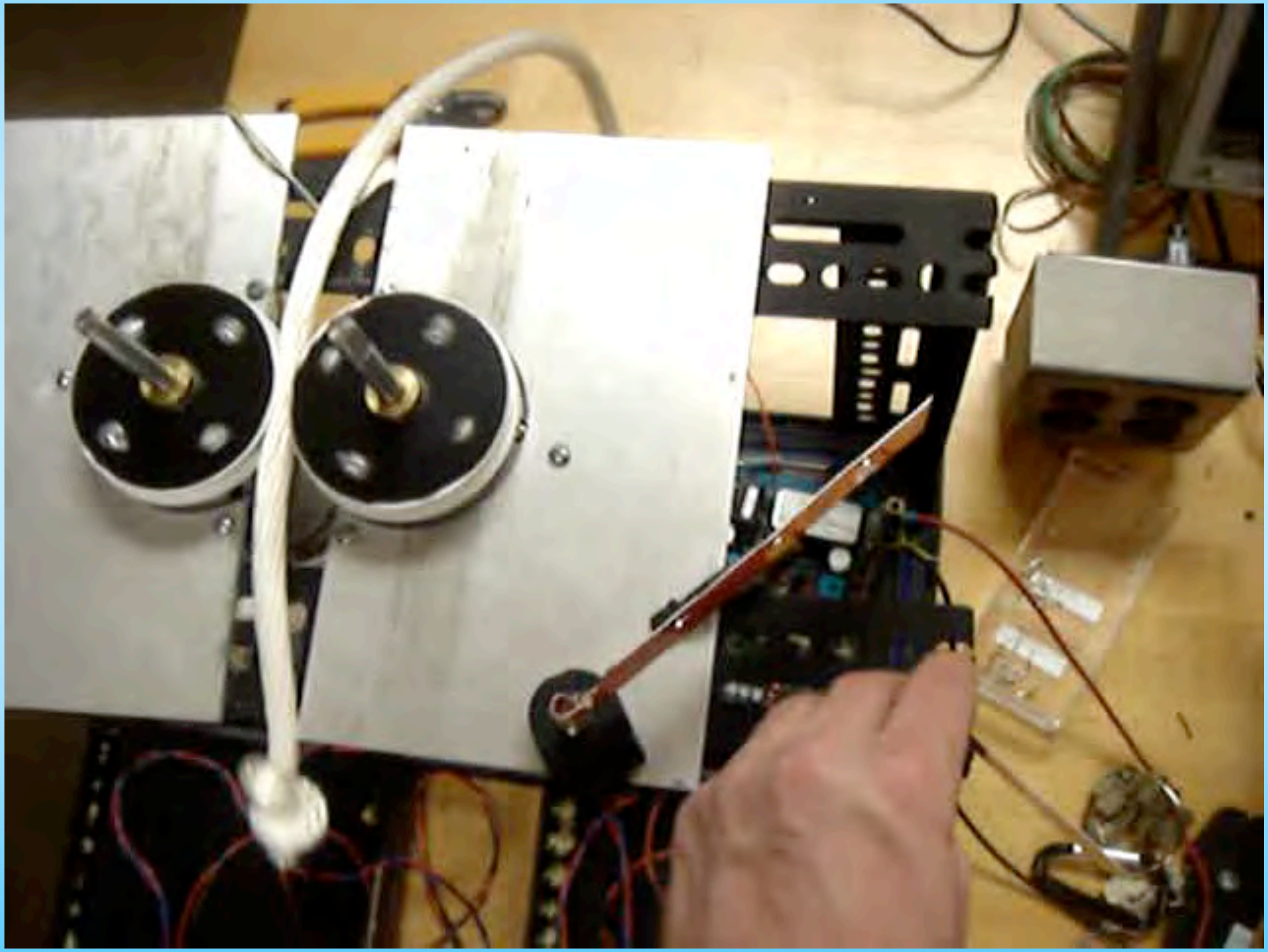
Power Circuitry



Proportional Control



Testing of Complete System



Review

- My objective was to design a Mainsheet Tender for a small sailboat that could be used to maintain the optimal boom angle for a measured wind direction.

Results / Discussion

- I Accomplished my project goals
  - Built a mainsheet tender that responds to varying wind direction by making changes in the length of the mainsheet
  - Designed and built proportional control that runs solely off of two 9-Volt batteries
  - Designed and built a housing unit for the specified vessel
- Everything I planned to complete I finished, except for actual testing on the vessel which I hope to complete during finals week.

Future Work

- Minor
  - Gears with larger teeth
  - Fine tune the circuitry
  - Batteries that work
  - Make PCB's
- Major
  - Lighter Material for housing, lighter batteries
  - Wireless communication to eliminate wires
  - Fully Waterproof housing

Conclusions

- I completed what I set out to do
- Yet, I hope to find time to put the system on the boat for testing before I leave Swarthmore

Lessons Learned

- Always using the Maxwell timing method
- Check your connections before pulling all your wires and starting over
- The things you think that you think will be the quickest will end up taking the most time

Jonathan Marshall Harris
28 September 2007
Engineering Department, Swarthmore College

Engineering 90: Fall Memo: Project Topic Selection

The culmination of my time at Swarthmore will begin as I plan out my Engineering 90 project this fall, and prepare to work on it in the coming spring. To be blunt, I have spent many hours looking through IEEE publications, Wired, and various other current sources to find inspiration – yet I have not come across a project that has, so to speak, excited me beyond all means.

However, my taking Engineering 91: Dynamics has deeply impacted my decision on how angle I would like to approach the Engineering 90 project. Previously, I limited myself to Electrical Engineering and occasional Computer Engineering – and struggled in both. My reintroduction to Dynamics this fall has proved equally difficult, yet I find myself increasingly aware of a fundamental interest in the problems.

Thus, I would like to work in the electrical mechanical field. One possible route I am interested in looking in for possible projects is biomedical engineering. However, I am also open to more general electrical mechanical projects such as an optimization control circuit board for a motor to be used in a Hybrid – Electric Vehicle, or for another device. These are again just ideas in my mind, and the extent to which I could possibly involve myself in with reference to their individual scope and size – remains beyond my current subset of knowledge. Another idea I have considered is a winch for a sailboat that would direct the sails based on optimized angles to catch the wind creating an electronic sailboat. The requirements would be some sort of controlling device to bring in the rope, a spool of some sort, and then an optimization done by some circuitry based on wind direction relative to the boat with feedback coming from a monitor of the boats velocity and acceleration.

In terms of my plans for next semester, I will be completing my Sociology and Anthropology Thesis and taking one or two additional credits in the form of a thesis, directed reading or regular class. I will of course be taking Engineering 90. In addition, I may take German 5 to maintain my speaking and possibly sit in on / take control theory depending on my project, the time I will need to put into it, and the application of control theory to my final engineering project.

At the end of this semester I will have taken: E6, E11, E12, E15, E28, E41, E72, E73, E77, E78, and E91. E90 will be my 12th Engineering class.

KBBC SERIES

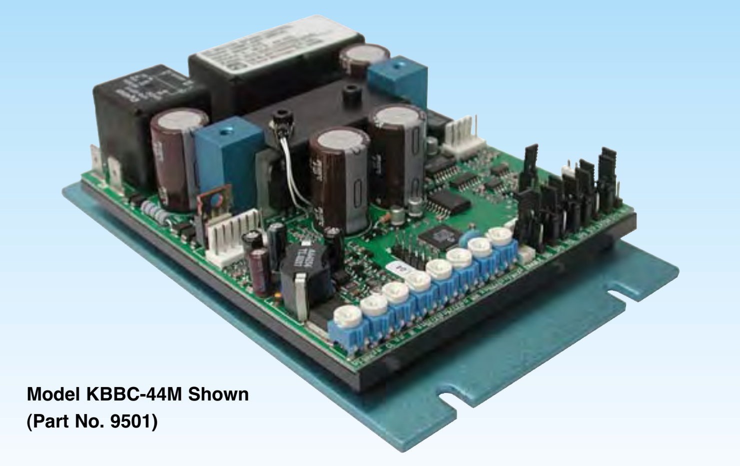
MICROPROCESSOR CONTROLLED BATTERY POWERED DC/DC

Variable Speed Motor Control

for 12, 24, 36 and 48 Volt PM and Series Wound DC Motors thru 2HP Continuous Duty and 4HP Peak Duty

TYPICAL APPLICATIONS

• Scooters • Personnel Carriers • Carts • Electric Boats • Portable Pumps • Lifts • Floor Polishers



Model KBBC-44M Shown (Part No. 9501)

STANDARD FEATURES

- **High Frequency PWM Operation:** Reduces motor noise and increases efficiency.
- **Controlled Acceleration and Deceleration:** Provides timed acceleration to set speed and deceleration to zero speed.
- **Diagnostic LEDs:** Provide indication of power on (PWR ON) and control status (STATUS).
- **Built-In Reversing Contactor:** Provides forward/reverse operation with a low power reversing switch or with a center-off throttle potentiometer (wigwag).
- **Run Relay:** Used to turn on or off equipment or signal a warning if a fault has occurred.
- **Brake Driver Circuit:** Powers an optional electromechanical brake (current regulated and short circuit protected).
- **Key Switch Operation with Built-In Battery Power Contactor:** Allows the use of a low power switch to turn control on and off.
- **Inhibit Circuit:** Allows control to be turned off electronically with a separate low power switch.
- **Latching Circuit:** Allows momentary switches to start, stop, and reverse the control.
- **Limit Switch Circuit** (Stop Forward and Stop Reverse)**:** Allows limit switches to be used to immediately stop the control in forward or reverse directions.
- **Single-Ended or Wigwag Potentiometer Control:** Allows the Main Speed Potentiometer to be used as single-ended (zero speed is at 0% rotation) or wigwag (zero speed is at 50% rotation).

PROTECTIVE FEATURES

- **Electronic Current Limit:** Protects the motor and control against overload.
- **Polarity Protected:** Prevents control damage if the battery is wired incorrectly.
- **Short Circuit Protected:** Protects main power transistor from failure due to a short at the motor.
- **Overtemperature Protection:** Reduces control output as the transistors reach maximum operating temperature.
- **Overvoltage Protection:** Will turn off the control if the battery voltage exceeds 125% of nominal.
- **Undervoltage Protection:** Will turn off the control if battery voltage reduces below 65% of nominal.

SAFETY FEATURES

- **Potentiometer Fault Circuit:** Turns the control off if a short, open, or ground occurs at the potentiometer.
- **High Pedal Disable Function:** Prevents control startup until the potentiometer returns to zero.

DESCRIPTION

The KBBC series of battery powered variable speed controls are designed for 12, 24, 36, and 48 Volt PM and Series Wound DC motors. Microcontroller design provides superior performance and ease of tailoring to specific applications. Operating in a regenerative mode, precise and efficient control is obtained using state-of-the-art MOSFET technology. The KBBC operates at a switching frequency of 16 kHz, which provides high motor efficiency and quiet operation.

The KBBC contains many standard features such as current limit, short circuit protection, speed potentiometer fault detector, overtemperature sensing, and undervoltage/overvoltage protection. A variety of trimpots are provided, which can be used to tailor the control to exact specifications. The control also contains LEDs that indicate “power on” and “status.” A DC power contactor allows a low power switch to turn the control on and off. Reversing contactors provide arcless forward, stop, and reverse operation. In addition, a brake driver circuit is used to power an optional electromagnetic brake.

The KBBC can be controlled in several ways, such as single-ended or wigwag speed potentiometer and 0 - 5 Volts DC signal following. The controls contain a built-in heat sink that also serves as a mounting base.

TRIMPOT ADJUSTMENTS

- **Timed Brake Delay (T-BRK):** Sets the delay time before the brake is engaged.
- **Current Limit (CL):** Sets the current limit (overload), which limits the maximum current to the motor.
- **IR Compensation (IR):** Sets the amount of compensating voltage required to keep the motor speed constant under changing loads.
- **Deceleration (DECEL):** Sets the amount of time for the motor to decelerate from the set speed to zero speed.
- **Acceleration (ACCEL):** Sets the amount of time for the motor to accelerate from zero speed to the set speed.
- **Minimum Speed (MIN):** Sets the minimum motor speed.
- **Reverse Maximum Speed (RMAX):** Sets the maximum motor speed in the reverse direction (a % of FMAX setting).
- **Forward Maximum Speed (FMAX):** Sets the maximum motor speed in the forward direction.

GENERAL PERFORMANCE SPECIFICATIONS

Parameter	Specification	Factory Setting
Input Voltage Range (% Nominal)	75 – 125	100
Intermittent Duty Operation (Minutes)	2	—
Peak Duty Operation (Seconds)	7	—
Overvoltage Shutdown (% Nominal Input Voltage)	125	—
Undervoltage Warning (% Nominal Input Voltage, ± 10%)	85	—
Undervoltage Shutdown (% Nominal Input Voltage)	65	—
Nominal Carrier Frequency (kHz)	16	—
Electromagnetic Brake Delay Trimpot (T-BRK) Range (Seconds)	0.2 – 2.5	1
CL Trimpot (CL) Range (% Range Setting)	0 – 200	150
IR Compensation Trimpot (IR) Range (% Nominal Battery Voltage)	0 – 25	4
Acceleration Trimpot (ACCEL) Range (% Base Speed)	0.1 – 15	2
Deceleration Trimpot (DECEL) Range (% Base Speed)	0.1 – 15	2
Minimum Trimpot (MIN) Range (% Base Speed)	0 – 30	0
Forward Maximum Speed Trimpot (FMAX) Range (% Base Speed)*	60 – 100	100
Reverse Maximum Speed Trimpot (RMAX) Range (% Forward Maximum Speed)	50 – 100	100
Electromagnetic Brake Current Rating (Amps DC)	1	—
Heat Sink Overtemperature Protection Point (°C)	100	—
Deadband in Wigwag Throttle Mode (Volts DC)	± 0.3	—
Wigwag Throttle Signal Input Voltage for Maximum Forward (Volts DC)	2.5 – 5.0	5
Wigwag Throttle Signal Input Voltage for Neutral (Volts DC)	1.2 – 2.5	2.5
Wigwag Throttle Signal Input Voltage for Maximum Reverse (Volts DC)	0	0
Single Ended Throttle Signal Range for Full Speed Forward or Reverse (Volts DC)	0 – 2.5 to 5.0	0 – 5
Timed Current Limit (TCL) Trip Time (Seconds)	7	—
Run Relay Output Contact Rating (Amps at 30 Volts DC, Amps at 125 Volts AC)	1, 0.5	—
Auxiliary Power Connector (P2) Rating (Maximum Amps DC)	10	—
Operating Temperature Range (°C)	0 – 45	—

*FMAX trimpot is also used as an input/output gain potentiometer.

ELECTRICAL RATINGS

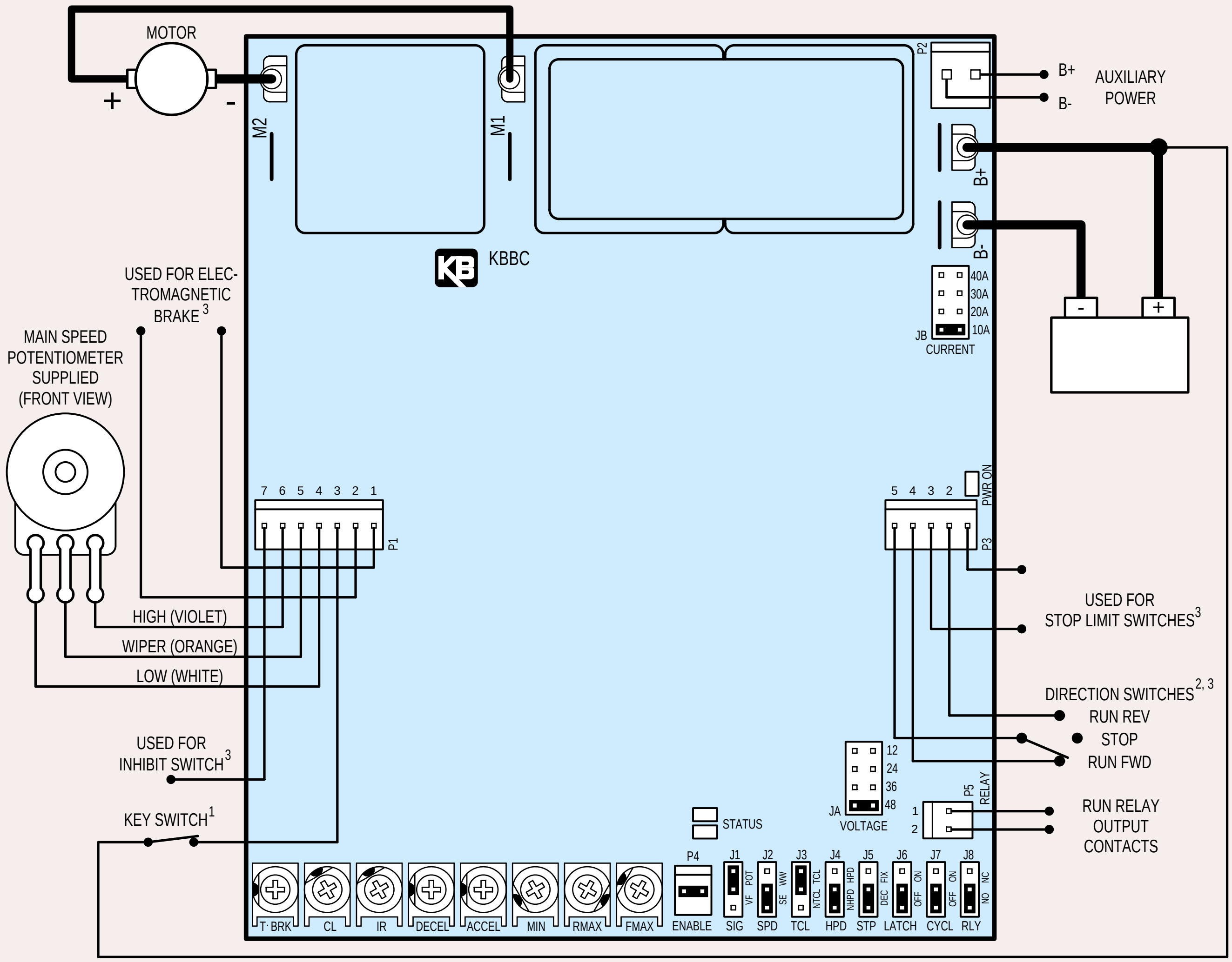
Model No.	Part No.	Nominal Battery Voltage (Volts DC)	Nominal Motor Voltage (Volts DC)	Continuous Duty		Intermittent Duty (2 Minutes)		Peak Duty (7 Seconds)	
				Maximum HP	Amps DC	Maximum HP	Amps DC	Maximum HP	Amps DC
KBBC-24M	9500	12	0 – 12	1/2	40	3/4	60	1	80
		24	0 – 24	1	40	1½	60	2	80
KBBC-44M	9501	12	0 – 12	1/2	40	3/4	60	1	80
		24	0 – 24	1	40	1½	60	2	80
		36	0 – 36	1½	40	2	60	3	80
		48	0 – 48	2	40	3	60	4	80

Note: Custom units are available with various voltages and currents with or without DC Power Contactor or Reversing Contactor.

JUMPER SELECTABLE FEATURES

- **JA - Battery Voltage (VOLTAGE - 12/24/36/48):** Selects nominal battery voltage.
- **JB - Motor Current (CURRENT - 10A/20A/30A/40A):** Selects nominal motor current.
- **J1 - Signal Type (SIG - VF/POT):** Selects voltage following or potentiometer operation.
- **J2 - Speed Potentiometer Mode (SPD - SE/WW):** Selects single-ended or wigwag speed control.
- **J3 - Current Limit Mode (TCL - NTCL/TCL):** Selects non-timed current limit or timed current limit.
- **J4 - High Pedal Mode (HPD - NHPD/HPD):** Selects non-high pedal disable or high pedal disable.
- **J5 - Deceleration Mode (STP - DEC/FIX):** Selects adjustable or fixed (0.1 second) deceleration when a stop command is given.
- **J6 - Direction Switch Type (LATCH - OFF/ON):** Selects maintained or momentary direction commands.
- **J7 - Cycling Mode (CYCL - OFF/ON):** Selects cycling of relay which is used to brake the motor.
- **J8 - Relay Output Contacts (RLY - NO/NC):** Selects normally open or normally closed Run Relay contacts.

CONTROL LAYOUT & CONNECTION DIAGRAM

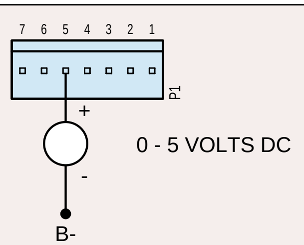


Notes: 1. *If Key Switch is not used, a connection must be made between the red wire of Connector P1 and quick-connect Terminal B+ for the control to operate.*

2. *RUN FWD and RUN REV Direction Switches are not used in wigwag operation.*

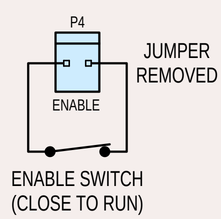
3. *Customer supplied.*

VOLTAGE FOLLOWING CONNECTION



Note: Set Jumper J1 to the "VF" position

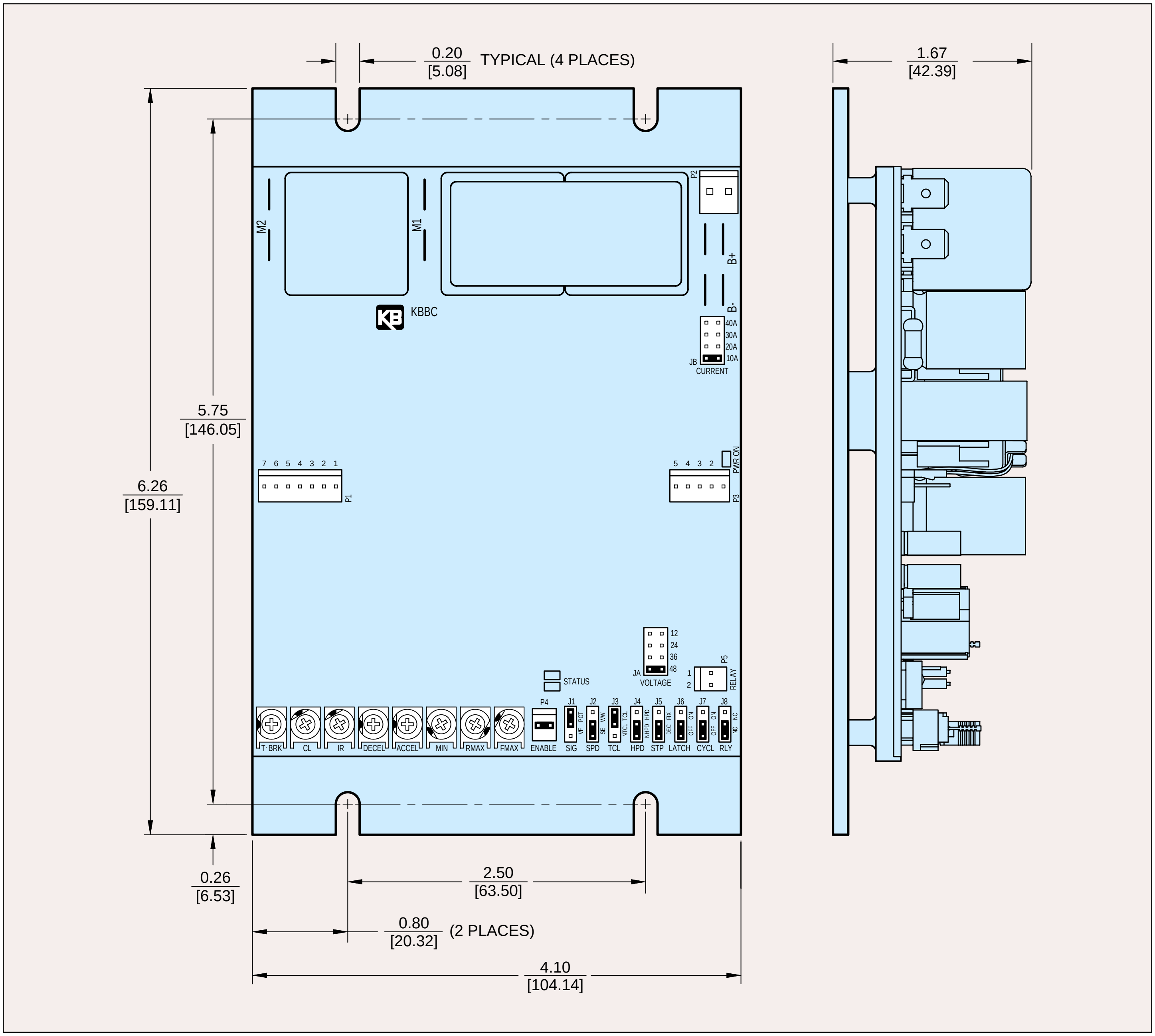
ENABLE SWITCH CONNECTION



PENTA KB POWER™

A Complete Line of Motor Drives

MECHANICAL SPECIFICATIONS (Inches / [mm])



GREEN AND RED STATUS LEDs

Control Status	Green LED	Red LED	Flash Rate*
Run	On	Off	Slow
Stop	On	Off	Quick
Curent Limit (Warning)	Off	On	Steady
Undervoltage (Warning)	On	On	Slow
Overvoltage/Undervoltage Fault (Shutdown)	On	On	Quick
Overtemperature Fault (Shutdown)	On	On	Slow Alternating
Main Speed Potentiometer Fault (Shutdown)	On	On	Quick Alternating
Motor or Brake Fault (Shutdown)	On	On	Double Quick Alternating
Timed Current Limit (Shudown)	Off	On	Quick

*Flash Rate: Slow = 1 second on / 1 second off. Quick = 0.15 second on / 0.15 second off.

KB ELECTRONICS, INC.
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Outside Florida Call **TOLL FREE** (800) 221-6570 • **E-mail** – info@kbelectronics.com
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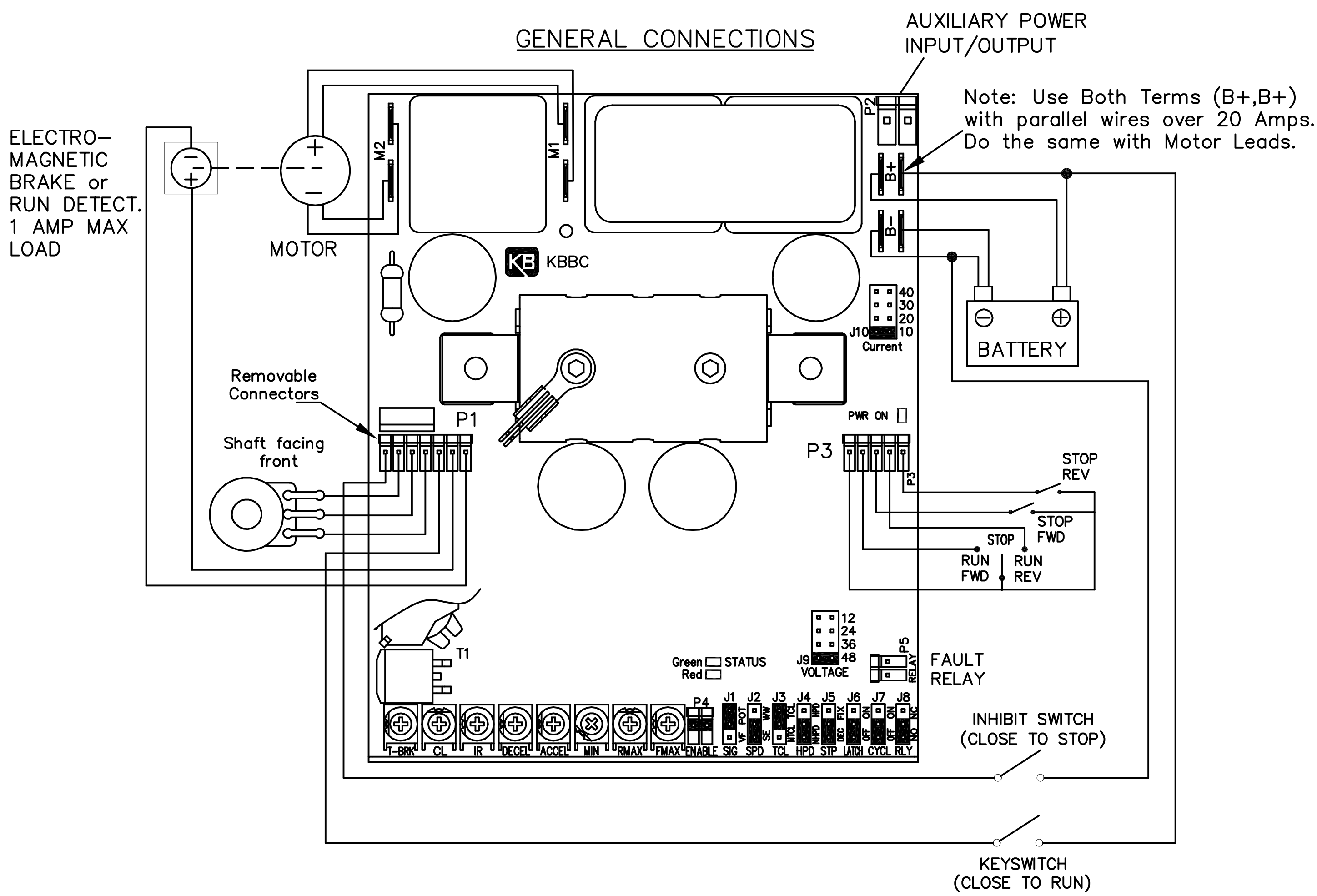
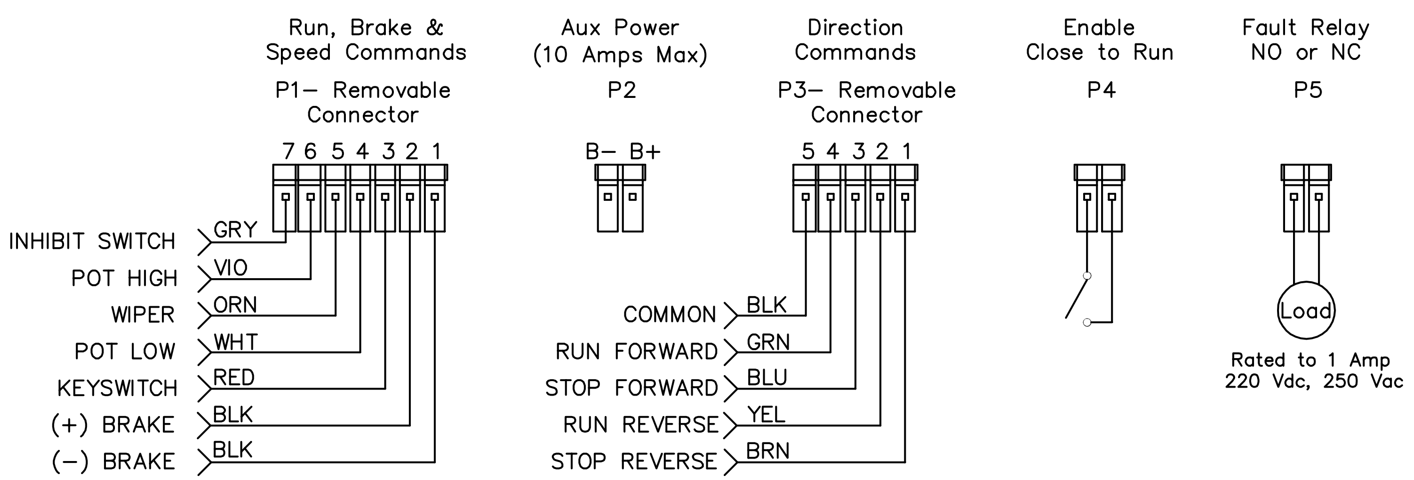
"The Right Control for your Application"

KBBC-MICRO CONNECTION DIAGRAM

GENERAL CONNECTIONS





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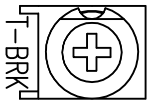
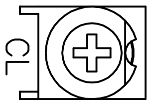
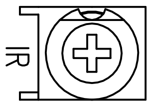
KBBC-MICRO FUNCTIONAL DESCRIPTIONS



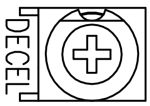
TIMED BRAKE DELAY (T-BRK)- This adjusts time delay before the brake engages after the drive is told to stop. Brake is initiated by Enable, or Keyswitch opening, or inhibit terminals closing.



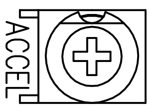
CURRENT LIMIT (CL)- Allows adjustability of current limit setpoint. Typically set at 1.5 X the Motor FLA. When Current Limit engages the status light will indicate by turning red.



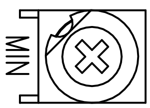
IR COMPENSATION (IR)- Allows adjustment of load compensation for different motors. Smaller motors require more compensation to overcome losses in armature winding. Typically set by checking No Load to Full Load speed changes.



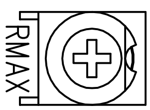
DECELERATION (DECEL)- Allows for controlled deceleration from full speed to zero speed, from 0.1 to 15 seconds as pot is turned clockwise. Decel works with all stop modes except inhibit. When inhibit is used the decel pot has no effect, output will go to zero in 0.1 seconds.



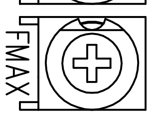
ACCELERATION (ACCEL)- Allows for controlled acceleration from zero to full speed. From 0.1 to 15 seconds as pot is turned clockwise. Accel is active in any turn on condition, including Enable, Keyswitch, or release of inhibit.



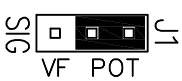
MINIMUM SPEED (MIN)- Sets the minimum speed the motor will run. Factory set to zero speed, but can be adjusted from 0-30% of full speed.



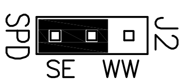
MAXIMUM REVERSE SPEED (RMAX)- Limits the maximum allowable speed in the reverse direction. Range is 50-100% of Forward speed (RMAX is dependant on FMAX setting).



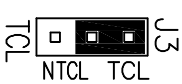
MAXIMUM FORWARD SPEED (FMAX)- Limits the maximum allowable speed in the forward direction. Range is 60-100 % of full speed. Set for Full Travel 5K Pot. For limited travel of Pot (ex. 1/4 rotation=desired full range), FMAX can be turned clockwise to compensate.



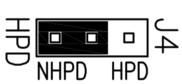
SIGNAL JUMPER (J1)- Voltage Following/ Potentiometer. Selects either potentiometer speed control, or remote 0-5 Vdc signal input. (See page 4).



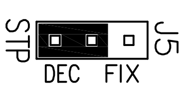
SPEED MODE JUMPER (J2)- Wig Wag/ Single Ended. Allows for choice of Wig Wag speed control, (center of pot is zero speed, clockwise is forward, counter is reverse), or Single Ended, (contact closure chooses direction). (See page 4).



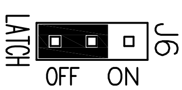
TIMED CURRENT LIMIT JUMPER (J3)- Non Timed Current Limit/ Timed Current Limit. Disables or enables the shutdown of the drive due to motor overcurrent after 7 seconds.



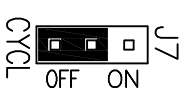
HIGH PEDAL DISABLE JUMPER (J4)- Non High Pedal Disable/ High Pedal Disable. In HPD the main speed pot needs to be reset to zero before motor is allowed to run.



STOP MODE JUMPER (J5)- Decel/ Fixed. Allows stop function (Enable, Keyswitch, Direction Command) to use deceleration trimpot for controlled stop, or fixed stop of 0.1 second.

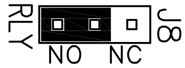


LATCH JUMPER (J6)- Off/ On. Allows choice of how direction commands are activated. If latch is in "OFF" position, direction commands need to be maintained to run. If Latch is in the "ON" position, direction commands are momentary to run or stop. (See page 4).

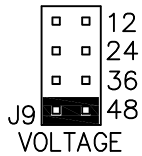


CYCLE (J7)- Off/ On. When the drive is commanded to stop, an output relay closes to short motor leads together. This action will act like a dynamic brake and impede motor travel. If this action is not desired, the cycle jumper can be placed in the "ON" position. (see page 4).

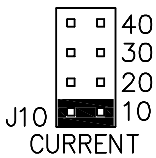
KBBC-MICRO FUNCTIONAL DESCRIPTIONS



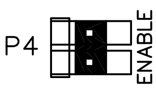
RELAY (J8)- NO/ NC. Used to give option of fault relay output condition.



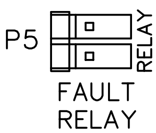
VOLTAGE SELECTION JUMPER (J9)- This Jumper calibrates the Drive to input and output for 12, 24, 36, or 48 Vdc inputs. This Jumper primarily sets up the Overvoltage and Undervoltage set points.



CURRENT SELECTION JUMPER (J10)- This Jumper calibrates the Drive for motors rated 10, 20, 30 or 40 amps. The Current Limit will be set up based on this setting X 1.5. The CL Trimpot can be used to modify this setting.

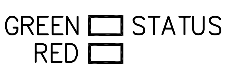


ENABLE (P4)- This connection is an additional method for Run/Stop. Close to Run, Open to stop.



FAULT RELAY CONNECTOR (P5)- Provides a dry contact to indicate fault condition has occured. This output is used in conjuction with Jumper J8 for NO or NC operation. The fault relay will change state when the Keyswitch is applied. The relay will trip on any fault condition: Speed Pot Fault (open lead), Over Temperature Fault, Over/Under Voltage, Motor Brake Fault, Internal Fault (micro failure), and Timed Current Limit. Reset by cycling Keyswitch.

POWER ON LED- This green LED is illumiated when the Keyswitch is engaged.

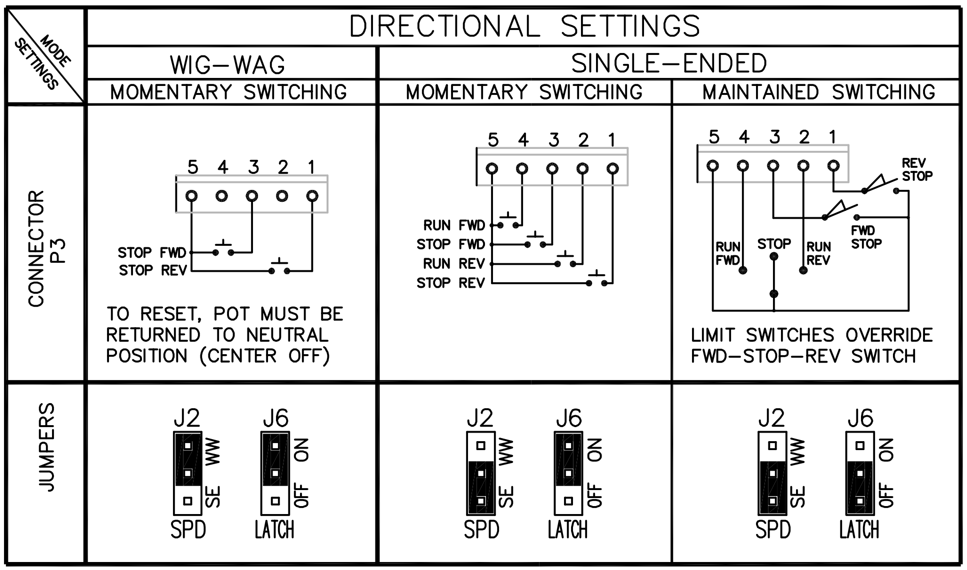


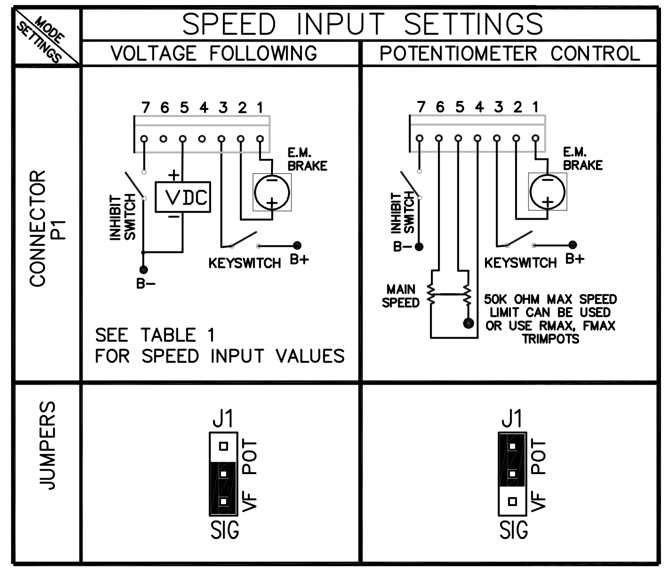
STATUS LEDs- These two LED's are used to indicate drive status. The top LED is green, the one directly below it is red. The Drive condition will be determined by the table shown below:

LED Ref.	Function	Flash Code	LED Color
	Normal Control Operation	Slow	Green
	Stop Mode	Quick	Green
	Speed Pot Fault	Quick	Red/Green (Alternate)
	Temperature Fault	Slow	Red/Green (Alternate)
STATUS	Over/Under voltage	Quick	Red+Green
Green, Red	Undervoltage Warning	Slow	Red+Green
	Motor/Brake Fault	Quick	Red, Red / Green, Green
	Internal Fault)	Slow	Red, Red / Green, Green
	Current Limit	Steady	Red
	TCL (Current Limit Time Out)	Quick	Red
"PWR" (Power)	Normal Control Operation	Steady	Green
Green	Bus & Power Supply Fault	Off	
Slow flash: 1 Sec. on, 1 Sec. off			
Quick flash: 0.15 Sec. on, 0.15 Sec off			

KBBC-MICRO FUNCTIONAL DESCRIPTIONS

DIRECTION AND SPEED COMMAND SETTINGS





Notes:

1) Inhibit Function is used for immediate (0.1 sec) deceleration. Close to stop.

2) Keyswitch Function is used to enable power to the drive. "Power On" light will illuminate to indicate the keyswitch is activated.

3) Main speed potentiometer (included) is rated 5 Kohm, 1/3 watt, wirewound.

4) Wig-Wag applications typically use a spring return to center potentiometer (not supplied or available through KB Electronics).

5) Cycle Jumper (J7)- The mechanical life of a relay is 10 million cycles. The Cycle Jumper is useful for repetitive cycling ON/OFF. When in "OFF" position the relay will engage to brake. When in "ON" position it will not. This will limit the use of the relay.

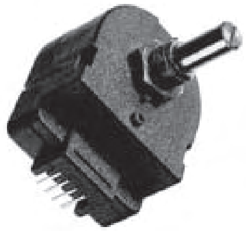
6) Keyswitch Function is used to enable power to the drive. "Power On" light will illuminate to indicate the keyswitch is activated.

TABLE 1, SPEED INPUTS.

DIRECTION	INPUT SIGNAL (VDC)	
	WIGWAG	SINGLE END
MAXIMUM FORWARD	4.7 + 0.3	4.7 + 0.3 (RUN FWD SELECTED)
NEUTRAL	2.5 ± 0.3	0 + 0.3
MAXIMUM REVERSE	0 + 0.3	4.7 + 0.3 (RUN REV SELECTED)

7) Momentary Limit Switch bypass protection. If limit switch is engaged in either direction (Stop Fwd, Stop Rev), the same direction run command will not allow continued travel. Ex. Run Fwd, Stop Fwd, will not allow Run Fwd Command until Run Reverse is called. If indexing is required, (Momentary Run Fwd, Momentary Stop Fwd, then Momentary Run Fwd in same direction), the stop reverse (P3-1) must be connected to COM (P3-5), otherwise unit will not go forward the second time.

Full 360° Smart Position Sensor



FEATURES

- Ratiometric output over 360° range with no dead band
- Self-contained package not requiring external electronic interface
- Angular response 50 µs
- Reverse polarity protection
- Absolute and non volatile positioning output

RoHS COMPLIANT

The model 601-1045 represents a new generation of Smart Sensors. This unique electronic device is a self-contained package which provides an analog electrical output over a full 360° without the need of external electronics. The low power consumption and non-volatile output makes this universal sensor the real cost-effective alternative to encoders. It's versatile design makes it suitable for a variety of industries and applications, such as CCTVs, Medical Instruments, Robotic arm control, CNC machinery, Rotational control systems, Pick n' place machines and Angular feedback applications.

STANDARD ELECTRICAL SPECIFICATIONS

PARAMETER	
Supply	4.5 to 5.5 V_{DC}
Supply Current	20 mA max.
Absolute Maximum Supply	6 V
Independent Lineaity	± 1 % typical
Resolution	Resolves down to a min. of 0.5°
Electrical Track	360° continuous
Analog Voltage Output	Not less than 90 % of supply (ratiometric) - see graphs on next page
Output Ramp Slope	Electrically switchable - see graphs
Output Impedance	1 Ω typical
Temperature Characteristic	± 1° max. over - 40/+ 70 °C
Insulation Resistance	1000 MΩ min.
Dielectric Strength	1000 V_{RMS}, 50/60 Hz

MECHANICAL SPECIFICATIONS

Rotation	360° continuous
Rotational Speed	5 max. revs/s (duration 60 s)
Operating Torque Maximum	3.68 (0.5) mNm (oz. - in)
Weight	30 g

ENVIRONMENTAL SPECIFICATIONS

Operating Life	5 000 000 cycles
Operating Temperature Range	- 40 °C to + 70 °C
Storage Temperature Range	- 40 °C to + 105 °C
Sealing	IP54

ORDERING INFORMATION/DESCRIPTION

601-1045	XXXX	BO1	e4
MODEL	STANDARD CONFIGURATION CODE	PACKAGING	LEAD FINISH

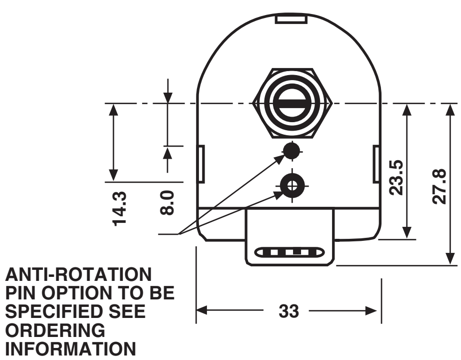
PRODUCT NUMBER	Ø 1.57 PIN	Ø 3.18 PIN
0000	Yes	Yes
0001	Yes	-
0002	-	Yes
0003	-	-

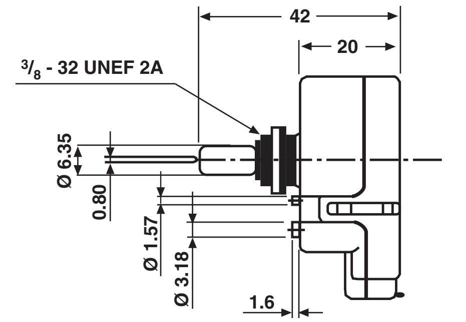
SAP PART NUMBERING GUIDELINES

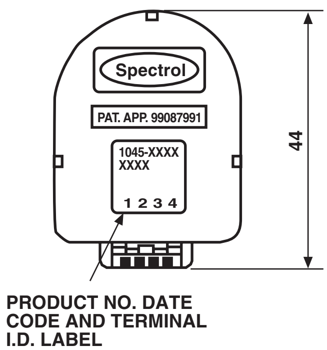
601	1045	0001	B01
MODEL	STYLE 1045 or 1056	PIN CONFIGURATION	PACKAGING

For technical questions, contact: sfer@vishay.com

DIMENSIONS in inches (millimeters)



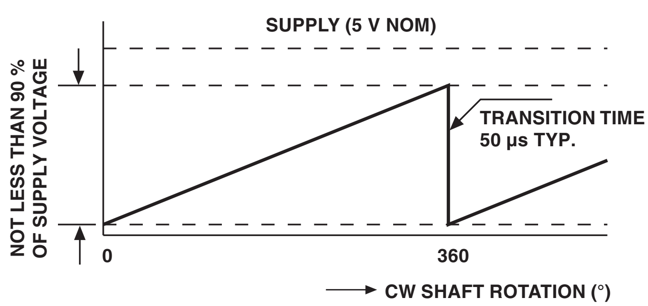




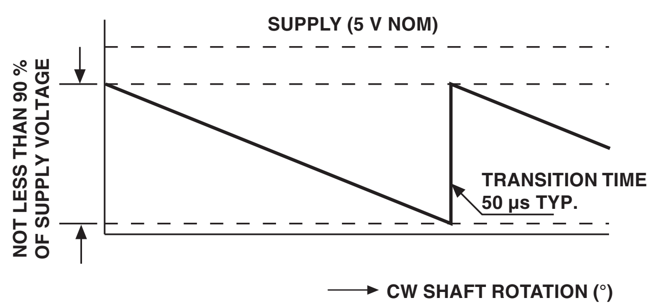
PIN CONNECTIONS		FUNCTION
1	+ 5 V	Supply
2	0 V	
3	Output	O/P voltage
4	Direction	Ramp polarity

MATERIAL SPECIFICATIONS	
Housing	Plastic
Bushing	Brass, nickel plated
Shaft	Stainless steel
Pin Terminal Connector	Gold plated
Output Connection	Pin header to suit IDC connectors. e.g. Panduit C100 - F22 and Molex 7880
Bushing Mount Hardware Lock Washer, Internal Tooth	Steel, nickel plated
Panel Nut	Brass, nickel plated

CABLE ASSEMBLY FOR CONNECTION	
Part Number	601-1056-0000
Description	Molex KK
	4-way crimp connector
	4 wire (250 mm)



DEFAULT OUTPUT [Terminal #4 Open-Circuit]



REVERSE SLOPE [Terminal #4 Connected to OV]

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