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# Post Carbon Transportation: Studying Wing Sail Ships

A Major Qualifying Project Report

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# Abstract

A demonstration platform was created for a potential startup venture to show the feasibility of adding multiple wing sails to cargo ships. Ship crews are wary of other green solutions that increase fuel economy by using kites or shipboard windmills because of perceived danger in the varied conditions at sea. Retrofitting bulk carriers with wing sails was assisted by creating a platform to study practical control systems, hull modifications, sail shapes, maneuvers, and efficiency. An autonomous sail position control method was developed that integrated a microprocessor, a wind direction sensor, a boat orientation sensor, and an anemometer. The microprocessor actively adjusts sails to minimize the energy used for propulsion to cut carbon emissions and save money for operators.

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# Introduction

## Objectives

An objective of the project is to study the challenges of adding wing sails to bulk carriers and create a bridge clearance data set to assist in finding investment return on ship retrofits. Additionally, an objective is to design and build a modifiable autonomous control system for wing sails that simulates operating conditions at all points of sail. The final objective is to create a model that can be used for researching different wing sail designs and hull modifications to verify a practical and economical retrofit strategy.

## Rationale

In response to rising oil prices and anticipated future oil shortages, design of more efficient ships is crucial to reducing oil consumption. In the 1890's, some clipper ships achieved speeds in excess of 18.5 knots(Full Sail Ahead.) Ships run on bunker fuel, which is also a key component of asphalt. It costs around $350,000 dollars in fuel for a large ship to cross the pacific and bunker fuel prices are expected to continue rising. Adding sails to bulk carriers could reduce or eliminate their carbon emissions while saving money. Computer controlled wing sails are inherently safer than other options for increasing fuel economy, but commercially sold auto-tillers from sailboats change heading instead of sail angle. Models are often built to test new designs for shipbuilders and would assist in the verification of a wing sail retrofit to a bulk carrier. The America's cup yacht “USA 17” features a carbon fiber wing sail and wing sails continue to gain popularity due to their high performance.

Wing sails must be able to clear bridges and loading facilities. A critical question is how much area is available for use as wing sails. Answering this question is the first major objective of the project. A comprehensive international database of ship dimensions is nonexistent, so a small database of ship sizes and important variables related to area available for wing sail use was complied. Additionally, checks were performed on the world's busiest ports about any bridge height clearance issues. The results are very encouraging for wing sail retrofits to cargo ships. The data suggest that for any given ship, on average, 81% of the length overall will be available for wing sails. The percentage varied from 77% to 86%. Also, maximum deck structure height, counting antennas, is somewhere between 20 meters and 30 meters. A typical panamax vessel with a 225m LOA, should have about 1.33 acres of area for sails. If the height is further expanded, available sail area can be increased much more with little risk of capsizing the boat. There are no major ports that have overly restrictive bridges that would prevent a ship with tall masts from entering.

Research into optimal procedures and data on wing sails will be quite valuable. A control system that allows for research and development does not exist yet for wing sails. It is difficult to test new sail designs without a control system for the sails, so a major objective of the project is to create a research platform for wing sails.

## State of the Art

There are other sail powered commercial sailing vessels but retrofitting cargo ships is a unique niche. A company by the name of *Solar Sailor* makes ferries that use wing sails and solar panels mounted on the wing sails to generate motive force (Solar Sailor website). Solar cells complement wing sails nicely, but are still too expensive to be practical. There are a number of patents related to wing sail development, but most seem to be tangential at best, and few apply to wing sail cargo ships.

As far as retrofits go, the kite is less complicated to attach to a ship, and benefits from pulling low on the hull, which decreases the roll moment and reduces roll. The major drawback from the kite is that maritime officers are reluctant to use it because of perceived danger. A 1.5 acre kite demonstrated a roughly 15% increase in fuel economy over motors alone. (SkySail's Website)

One currently famous wing sail ship is the *Maltese Falcon*, a $300 million dollar luxury yacht that also has tall and sleek wind sails. The luxury yacht, while having sails of similar scale, does not have a cargo ship hull, and thus will be able to sail much closer to the wind than a cargo ship. Thus the *Maltese Falcon* is not much of a starting point for hull research. A less famous ship with wing sails is the *Shin Aitoku Maru*, launched in japan in 1980. She achieved 30% to 40% better fuel economy than if operating without any sails, but was discontinued because of high maintenance costs, and rock bottom oil prices. Now that oil prices have recovered, and oil will be expensive for the foreseeable future, wing sails will be back in fashion. Wing design has advanced significantly since these early days, and carbon fiber emerged as a serious contender for wing sail structural components. While it is fine to explore simple addition of wings, the boat model has the flexibility to experiment with far more radical technologies, to allow a sail technology startup to jump into the wing sail fray after verifying their data. Below is a picture of the *Shin Aitoku Maru* under sail.

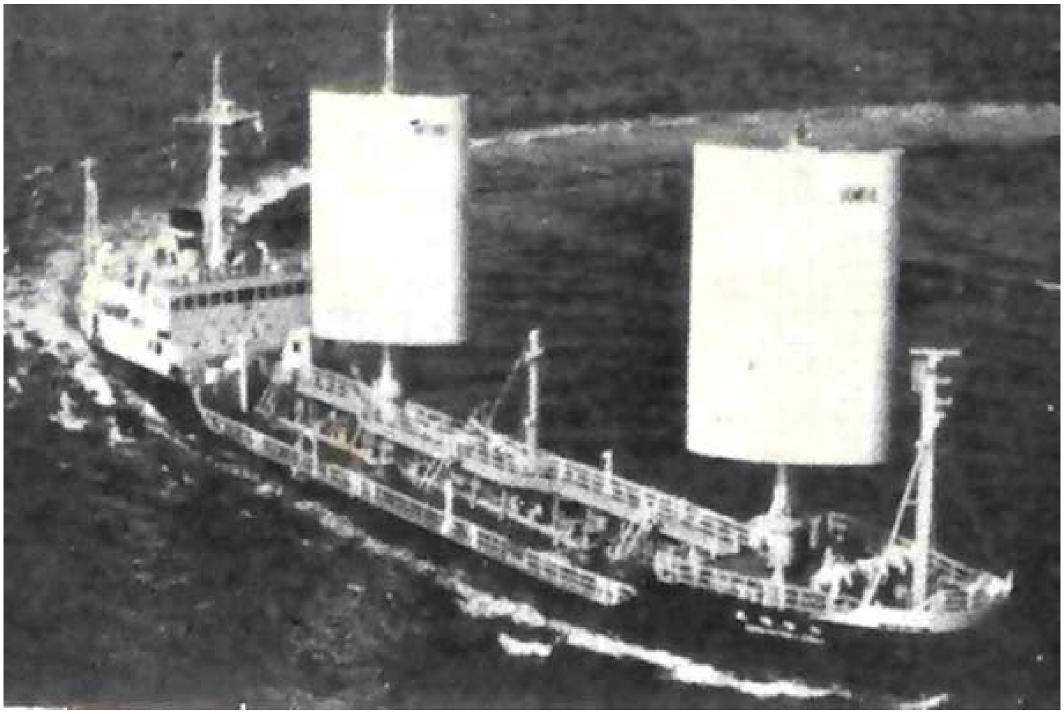

**Figure 1: Shin Aitoku Maru**

There are a number of patents that may have some relevance to wind sails. Schwab–Orga-GmbH holds a patent to a modern square rigged design with automated sails (“Options for Reducing Oil Use.”) Unfortunately the patent referenced was not able to be located, though any company interested in wing sail ships should ensure that their design does not infringe on this design. There are other patents that have some bearing on wing sails though, and these are listed in the patents consulted appendix.

## Approach

In addition to compiling data on area available for wing sails, a model ship will be constructed that allows for research and testing of wing sail concepts. This design will advance the state of the art by allowing testing and verification of existing wing sail data, and will also allow modifications to the hull to be implemented. The project will utilize a microcontroller to adjust sails to sailing positions. A component diagram is shown below in Figure 2. The design will incorporate a number of sensors from wind direction and speed to sail position. These data are fed back to the microcontroller that then optimizes sail position to create motive power.

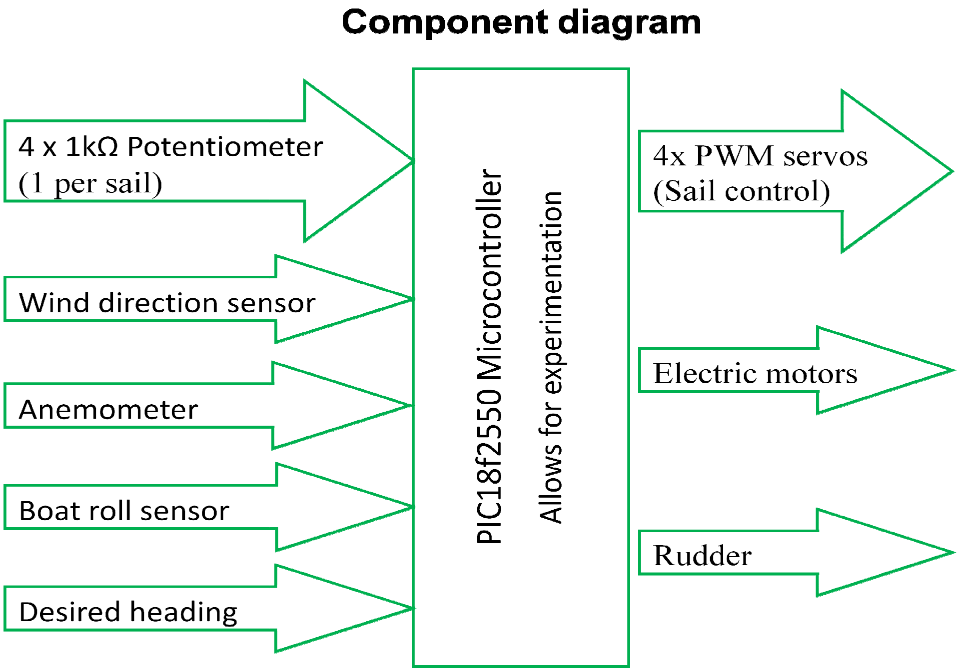

Figure 2: Component Diagram

## Design Decomposition

| **Functional Requirements:** | **Design Parameters** |
|---|---|
| **0.** Provide a platform for wing sail ship research | **0.** Scale Model Ship |
| **1.** Microcontroller can orient sails to create power | **1.** Sail control feedback loop |
| **1.1.** Determine wind speed | **1.1.** Anemometer connected to microcontroller |
| **1.2.** Determine wind direction | **1.2.** Wind vane connected to boat mounted potentiometer |
| **1.3.** Measure sail angle | **1.3.** Potentiometer to read sail angle and relative wind direction back to microcontroller |
| **1.4.** Translate PWM to fwd/rev/stop | **1.4.** PWM Driver chip |
| **1.5.** Issue PWM based on calculated appropriate sail angle, compare to measured angle | **1.5.** Comparison function, PWM output code, chip must be fast enough to issue 0.2ms pulses |
| **1.6.** Change electrical energy into mechanical | **1.6.** DC electric servo motor |
| **1.7.** Increase output torque | **1.7.** Reduction gear train |
| **1.8.** Connect servo to coupler | **1.8.** Grooved output shaft and X adapter to coupler |
| **2.** Accommodate different sails in varied sailing conditions | **2.** Mast connection system |
| **2.1.** Accommodate wide range of sail mast sizes | **2.1.** Universal coupler |
| **2.2.** Accommodate range of sail heights | **2.2.** Metal guide plates to support 20”+ sails |
| **2.3.** Accommodate varying numbers of sails | **2.3.** 4 sail actuator assemblies |
| **2.4.** Provide temporary sails | **2.4.** Bent and riveted aluminum sheet sails |
| **3.** Test keel retrofits on un-streamlined hull | **3.** Fiberglass hull for keel testing |
| **3.1.** Provide realistic hull shape | **3.1.** 150:1 scale approximates panamax bulk carrier |
| **3.2.** Allow for empty and full testing | **3.2.** Clearance for weight to be added |
| **3.3.** Provide temporary keel | **3.3.** Bent sheet metal screwed to keel mount bar |
| **3.4.** Accommodate varying keel geometries | **3.4.** Standardize keel mounting pattern |
| **3.5.** Minimize Depth of keel retrofits | **3.5.** Side keels can be glued to hull |
| **4.** Provide remote control of location and direction | **4.** Remote control system |
| **4.1.** Enable forced retrieval | **4.1.** Two propellers driven by inboard 7.2v motors |
| **4.2.** Enable Steering not under wind power | **4.2.** Rudder and counter-rotating propellers |
| **4.3.** Enable Steering under wind power only | **4.3.** Remotely operated rudder |
| **4.4.** Provide large radio range | **4.4.** High powered transmitter |
| **5.** Looks real | **5.** Hull sanded smooth and painted |
| **6.** Accommodate expansion and modification to control system | **6.** Design for likely additions |
| **6.1.** Provide documentation | **6.1.** Comment code and provide wiring diagram |
| **6.2.** Allow modification of wing control surfaces | **6.2.** Small and lightweight servos |
| **6.3.** Simplify design of servo based systems | **6.3.** Integrated servo + potentiometer modules |
| **6.4.** Allow greater control over servo performance | **6.4.** Wire potentiometer directly to microcontroller |
| **6.5.** Allow for additional electrical components | **6.5.** Extra pins left open on breadboard |
| **6.6.** Allow for additional inputs or outputs to the microcontroller | **6.6.** Microcontroller can control data bus |
| **7.** Maximize simplicity and ease of maintenance | **7.** Simple systems done right the first time that have few interdependencies |
| **7.1.** Maximize identical and repeated parts where possible | **7.1.** Sail actuator assemblies and electronics are identical |
| **7.2.** Provide acceptable battery power and life | **7.2.** Separate sail actuator and main motor drive batteries |
| **7.3.** Neat and compact electronics | **7.3.** Heat shrink, soldered joints, no messy excess |

| | | |
|---|---|---|
| | | cable |
| | **8.** Minimize cost | **8.** Low cost components wherever possible |
| | **8.1.** Inexpensive electronics | **8.1.** Electronics from scratch except 18F2550 |
| | **8.2.** Inexpensive servos | **8.2.** $2.00 per servo; modified for 360° rotation |
| | **8.3.** Inexpensive sails | **8.3.** Made of scrap Al |
| | **8.4.** Inexpensive mast restraints | **8.4.** Made of scrap Al |
| | **9.** Minimize chance of sinking | **9.** Rigid, Lightweight, hull |
| | **9.1.** Prevent hull breach | **9.1.** Fiberglass shell with fiberglass spans across the top |
| | **9.2.** Prevent capsize | **9.2.** Capsize prevention code utilizing tilt sensor |
| | **9.3.** Provide time to get boat to shore | **9.3.** Mount electronics on Styrofoam platforms |
| | **10.** Prevent boat loss | **10.** Styrofoam buoy tied to boat |

Figure 3: Design Decomposition

## Sail control feedback loop

The sail control feedback loop is the heart of the sail angle positioning subsystem. FR1 requires the microcontroller adjust the sails to optimize their power based on wind direction and speed. A feedback loop measures sail position, then compares it to a desired value. If the sail position is not the desired value, it makes a small correction. If the servos are connected normally, they will overcorrect and overshoot their desired position. To prevent overshoot the servos were modified and slowed down, effectively increasing the damping factor on the loop. The feedback loop would not be possible without the A/D converter on the 18F2550, DP 1.3. DP 1.1 corresponds to the Anemometer, while DP 1.2 corresponds to the wind direction potentiometer. In fact Design Parameters 1.1 to 1.8 are all variously connected to the sail feedback loop. The universal mast base coupler, DP 2.1, is also connected to the output line of the loop, which is shown below.

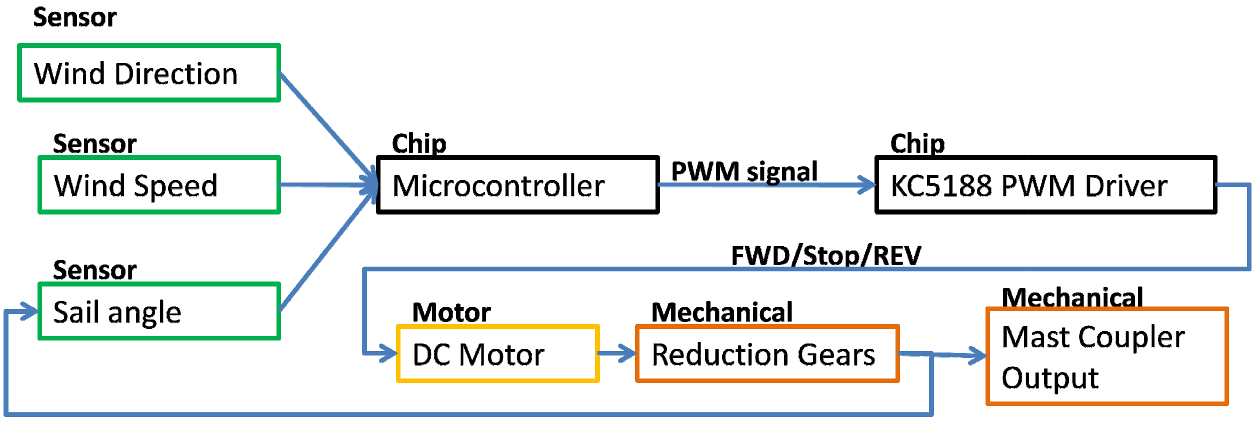

Figure 4: Feedback Loop

It is clear from Figure 4 that the DC motor controls the reduction gears that rotate the sail angle sensor. The sail angle sensor is read by the microcontroller which determines what PWM signals to send to the KC5188 Driver, depending on whether the sail is in the desired position or not. The PWM driver is responsible for switching the high current required for motor operation, This completes the loop, with the output mechanical rotations available at the universal mast coupler.

## Anemometer

To measure wind speed, FR 1.1, an anemometer that sends a pulse every time it rotates is required. The anemometer pulses will be counted by the microcontroller via interrupts. Every time the interrupt triggers, the microcontroller increments a counter that is reset every second after its value is stored in a ‘wind speed’ variable. The process is shown in Figure 5. Each pulse from the anemometer is counted, and a pulse is generated each time the anemometer spins.  Once per second the current variable is saved to the wind speed variable, and the current variable is reset to 0.

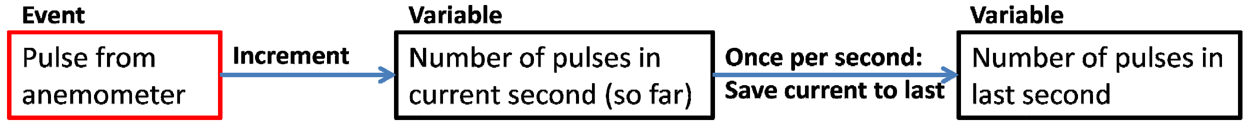

Figure 5: Wind Speed Flowchart

The dual variable system is crucial to ensure that the wind speed will be constant for the program when it needs the wind speed. Anemometer clicks are always being read, so the current variable will constantly be incrementing. If the program read the current variable right after it was reset, it would appear that there was zero wind, even if the ship were in the middle of a gust.

## Weathervane

To measure wind direction, FR 1.2, a wind vane turns a potentiometer that is connected to the microcontroller. As the wind angle changes, the potentiometer rotates, causing the resistance and in turn the voltage of the potentiometer to change. The microcontroller polls the potentiometer a few times per second, and the analog voltage input is converted to a 12 bit digital number which is stored in the program for use determining what the sail angle should be.

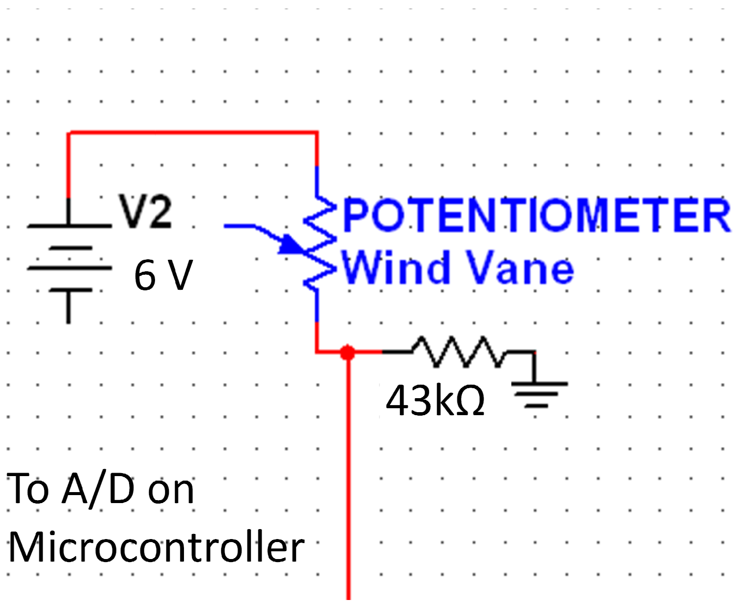

Figure 6: Weathervane Circuit

Above is the circuit diagram of the 20kΩ wind vane potentiometer. The electrical system for the microcontroller, sensors, and servos is a 6V supply, and the potentiometer is wired in series with a 43kΩ resistor to ground, as shown in Figure 6. The resistor is required to limit the current when the potentiometer is at or near zero ohms. The maximum current in the circuit should be around 140µA. It is important to note that in this configuration there is not a linear relationship between wind direction and voltage output. Figure 7 shows three plots of the actual resistance vs. potentiometer angle for this circuit.

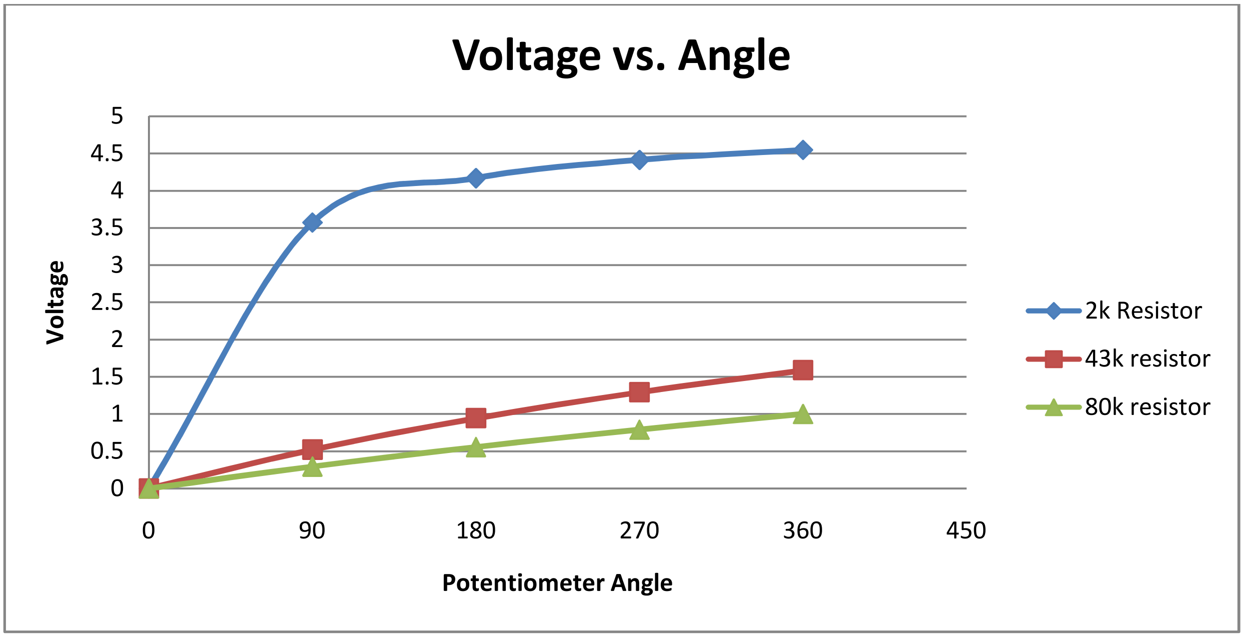

Figure 7: Voltage vs. Angle

The 2k resistor is highly nonlinear, and the 80k resistor, while highly linear, sacrifices sampling range. The 80k resistor will not be precise because it only has a 1V range, and the 2k resistor will not be precise because from 90 degrees to 360 degrees, it only has a 1V range. The 43k resistor offers the best compromise because of its large range and linear behavior over the entire range.

## Sail Angle

To measure sail orientation, potentiometers connected to the motor output shafts measure each sail's orientation. The circuit, shown in Figure 9 is very similar to the wind vane circuit, but a different resistor is used because the potentiometer has a lower maximum resistance rating of 5kΩ. This again ensures the best mix between linear behavior and range of data for the analog to digital converter on the microcontroller.

Figure 8: Sail Angle Pot

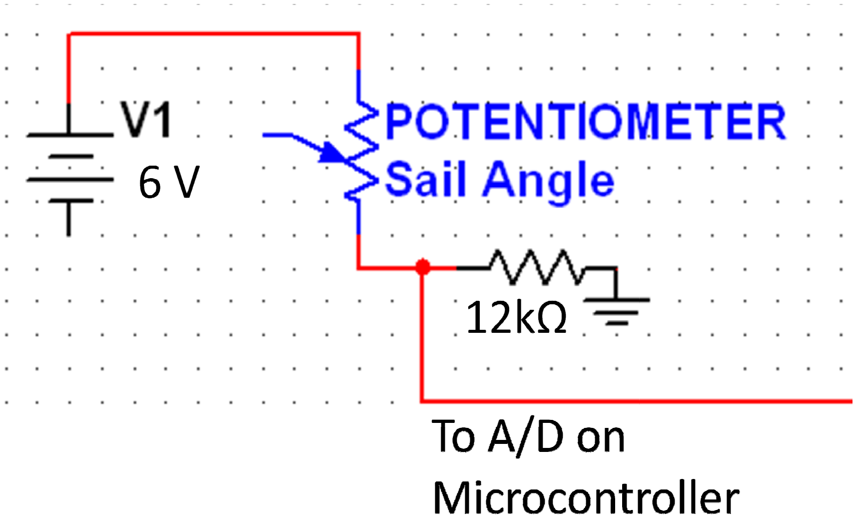

Figure 9: Sail Angle Potentiometer Circuit

The sail angle potentiometer circuit and mode of operation is designed to be nearly identical to the wind vane. The microcontroller reads the voltage between the two resistors, and then converts the analog voltage value to a digital number. This process takes around 12 instruction cycles, but because the chip is running at 8MHZ, this process is nearly instantaneous. The sail position variable in the program is updated a number of times per second to ensure accurate results.

## PWM Driver

To translate PWM signals from the microcontroller, FR 1.4, a servo driver chip is required. The servos shipped with a KC5188 PWM to +/- DC driver. The chip converts short pulses into positive or negative voltage to the motor. There are a few advantages to using pulse width modulation over an H bridge. An H bridge will short out if both inputs are high, and this can lead to burnt out electronics. Also, an H bridge uses two pins on the bus, taking up valuable space that could be used for other electronics. Finally, the pwm drivers are already wired into the dc motors that power the sails. The KC5188 can source over 500ma of current to the motor, providing plenty of power for the system. A KC5188 is shown below in Figure 10 connected to a motor.

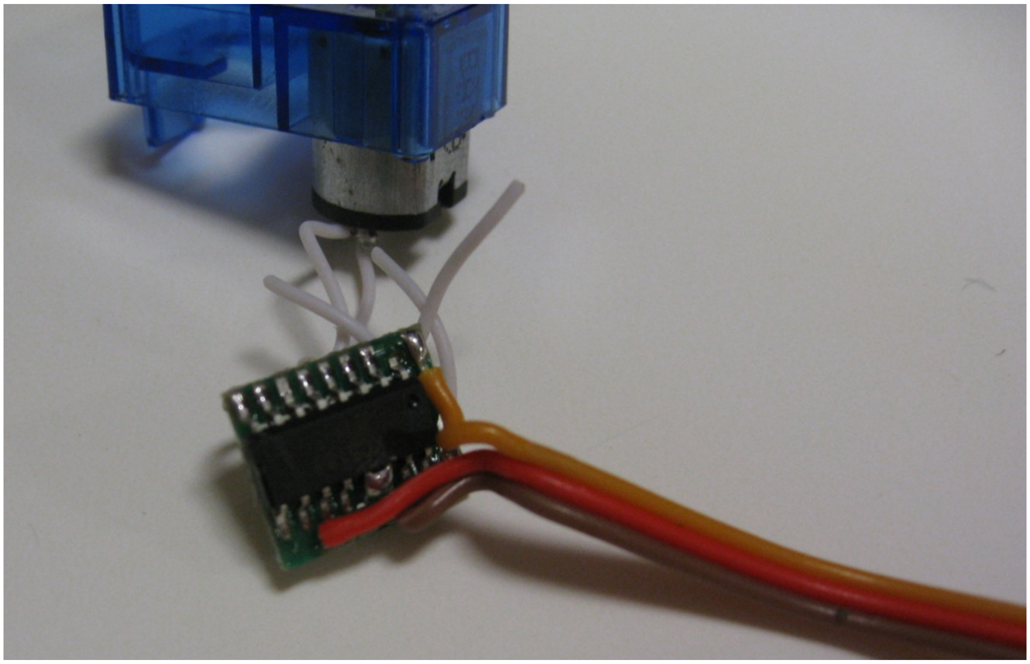

Figure 10: KC5188 PWM Driver

A pulse width of longer than 0.5ms will drive the motor forward, while a pulse width of less than 0.2ms will drive the motor in reverse. If the input is fully on or off, the chip will not provide the motor with any power, and no rotation can occur. A pulse length between 0.2ms and 0.5ms will end with an indeterminate behavior, causing the servo to drive erratically. Figure 11 is a timing diagram of forward, reverse and stop.

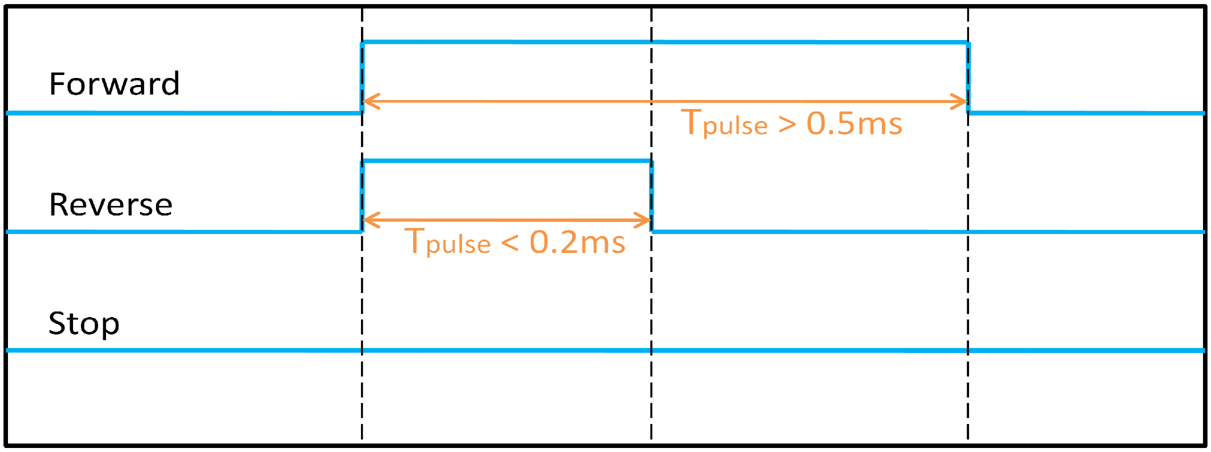

Figure 11: KC5188 Timing Diagram

## Microcontroller Program

The program calculates a desired sail angle from wind speed and direction. If the sail is in the correct position, it makes no changes. If the mast has not rotated to the desired position, it sends forward pulses to the KC5188. If the mast is rotated past the desired position, it sends the shorter reverse pulses to the driver. The chip decides where a sail needs to be using the following piecewise function, shown in Figure 12.

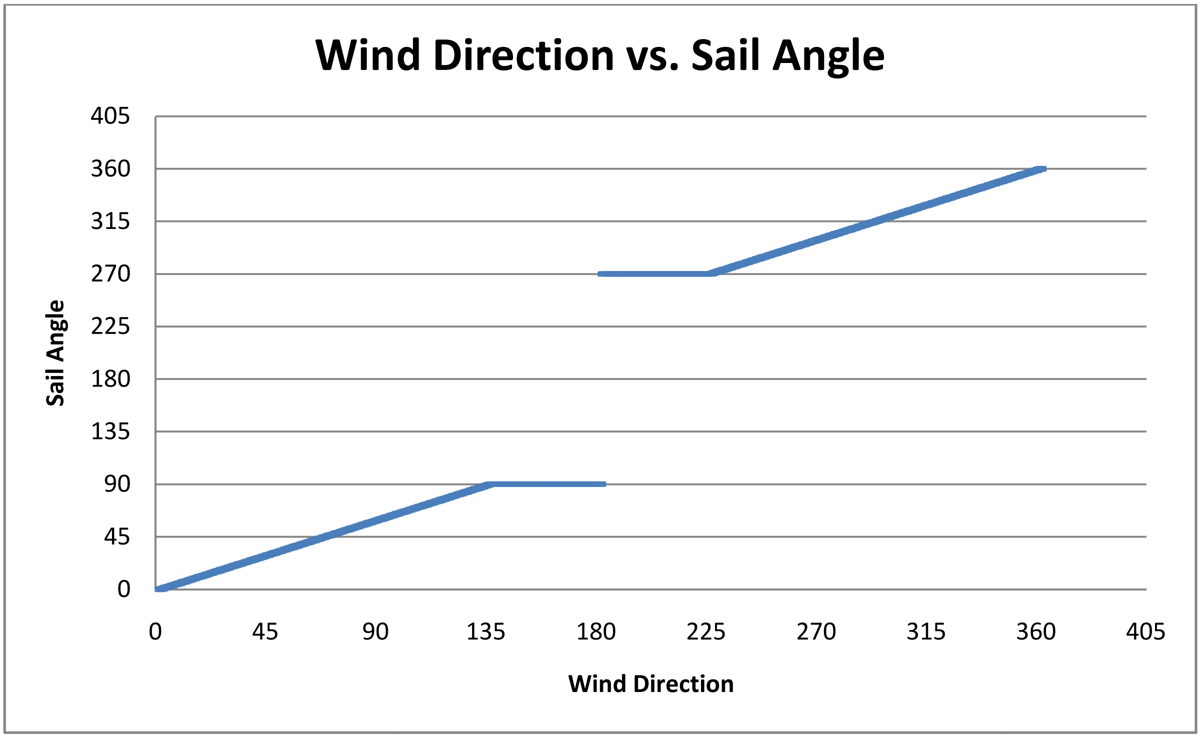

Figure 12: Wind Direction vs. Sail Angle

Where Sail angle is:

And Wind direction is:

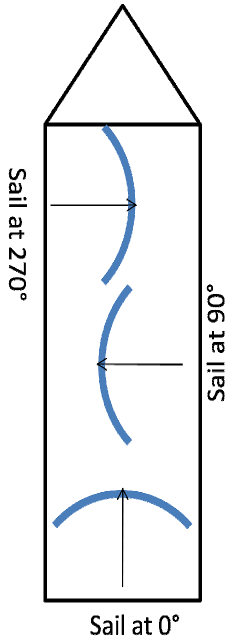

Figure 13: Sail Angle reference

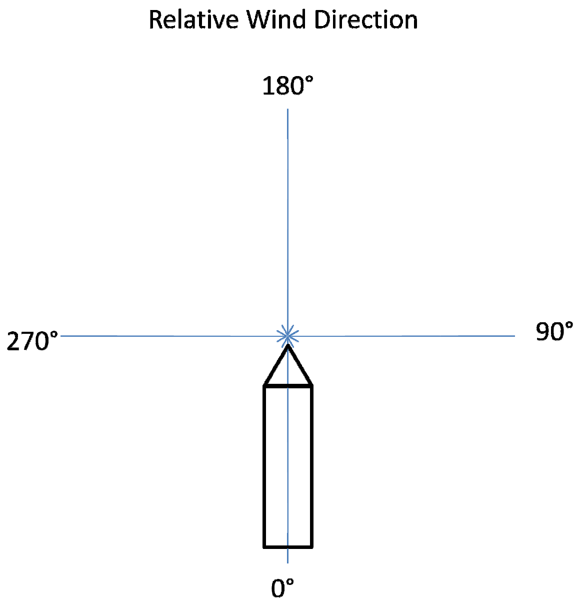

Figure 14: Wind Angle Reference

Sail orientation 0° means sail is facing the bow of the boat, and therefore a 90° orientation means the sail is facing the port side of the boat. Wind direction is measured relative to the ship, and wind blowing from the stern would have a 0° measurement, while wind blowing from starboard size would measure 90° and so on. The wind direction certainly cannot map directly to the sail angle. At some points it is crucial for the sail to be directly in line with the wind, for example if the boat is steaming directly into the wind. At other times, the sails must be slightly offset from the wind, for example on a beam or broad reach. The microcontroller looks up wind direction and adjusts each sail by this function. Sail angle has to be translated from the A/D values, because the weathervane has a slightly different scale, and the servos will have small dead zones.

The chip is responsible for controlling 4 different servos, all of which may be at different positions, so each servo needs to be able to drive in different directions simultaneously. There is not enough time for each chip to be executed individually around a loop, so instead status flags are set in the loop, and pulses are sent out simultaneously to all servos. Sails that need to rotate clockwise have their FWD bits set low, and Sails that need to rotate counterclockwise have their reverse bits set to 0. When the sail evaluation loop completes, each of the four sails has had bits set according to their position. Next, all outputs to sails that are adjusting are set low, and the chip delays for 0.2ms. After the 0.2ms delay, those sails with REV bits set are raised high again, and after a 0.4ms delay, all pwm outputs are raised again. If a sail is in the correct position, the FWD and REV flags for that sail are left as 1's, and no pulses will be sent. This allows the reverse pwm and forward pwm signals to be sent to separate servos at the same time. The microcontroller cannot source enough current to drive the KC5188s. Inverting 2n3906 current MOSFETs are needed to source the current. The outputs from the microcontroller must also be inverted if the signal is to be non-inverted when it reaches a KC5188.

## Servo Output to Masts and Sails

To turn the mast coupler, FR1.1.6-1.8, an electric motor drives a reduction gear train that turns an adapter to the mast base. The electric motors come as part of the servo. The motor can spin at upwards of 8000rpm and is geared down 1:120 for extra torque. The output shaft is splined, and the servo comes with a number of attachments that fit snugly onto the splines. To satisfy FR 2.x, a mast connection system, a coupler designed to interface with the X-shaped servo arms connects to the masts. Set screws on the coupler allow for varying sizes of mast, and transmit torque to the mast. Metal guide plates stabilize masts and allow for tall sails. Temporary sails allow for subsystem testing and sailing on lakes.

# Fiberglass Hull

To satisfy functional requirement 3, a fiberglass hull was constructed on a 150:1 scale that approximated a panamax bulk carrier's dimensions. The hull has excess room and plenty of freeboard that allows for weight to be added, simulating full and not full loading when testing keels and sails. To test keels, there is a keel mounting bar that goes the length of the hull that any keel can be bolted or screwed onto. If the keel mounting bar is not sufficient, it is possible to temporarily attach other keel shapes to the hull to test them out via glue or pressure sensitive contact adhesive. A temporary keel that allows the ship to sail without motor power can be attached via the standardized mounting bolts. The hull is painted to look like a bulk carrier to aid presentations or demonstrations. A major requirement of the hull is that it supports all the electronics and provides a waterproof base to study wing sails from. The hull has fiberglass spans designed to support the sails and increase hull rigidity. The Solidworks rendering of the hull shape with side keels is below in Figure 15.

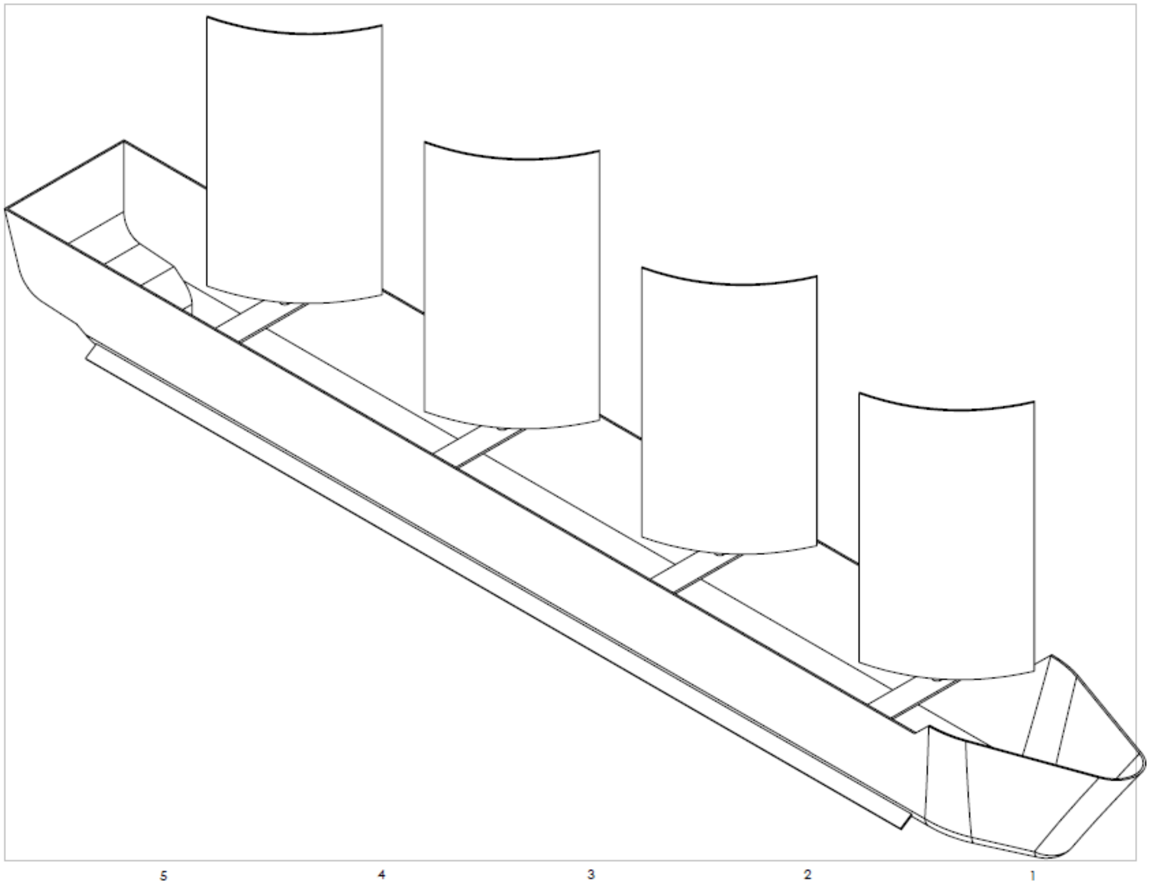

Figure 15: Solidworks Rendering

## Remote Recovery

Testing a new system is not always successful, and the boat needs the ability to recover itself. Functional requirement 4 demands a remote control system with sufficient range that the boat can be driven back to the launch site. Two propellers driven by inboard 7.2V DC electric motors provide the motive power to the remote recovery system. If the system needs to turn under motive power, the rudder turns, and the propellers spin different speeds to turn the boat. It is also useful to be able to control where the boat goes under sail power, and the rudder is functional even when the propulsion motors are not in use. A remote transmitter from a remote control boat allows shore control of the action onboard.

The boat has a variety of anti-sinking measures. There is a tilt sensor that measures the roll angle of the boat, if it becomes too severe, the microcontroller backs off the sails. Similarly, if there is too large of a gust measured at the anemometer, the microcontroller backs off the sails. This prevents the boat from taking on water in the first place. If the ship does begin to leak, or water splashes over the sides for any reason, the electronics are mounted on Styrofoam blocks that should keep them high and dry for long enough to sail the boat back to shore before any major damage is done. Finally, if the boat does sink, to satisfy functional requirement 10, the boat has a Styrofoam 'recovery buoy' that is tied to the boat via 30ft of ¼" nylon line. If the boat sinks in anything less than 30ft of water, the buoy will float up to the surface and provide rescuers a retrieval pathway. Testing in deeper water should be done with a longer buoy cable.

## Design for Modification

The boat's role as a test platform requires that it is versatile enough to accommodate novel approaches to the challenges of wing sail development. To satisfy functional requirement 6.x, the boat must be modifiable to suit any direction that testing needs. Existing and working code written in assembly is a jumping off point for future code development. Each line of code is commented, and wiring diagrams are provided. To satisfy functional requirement 6.2, small and lightweight servos can fit into wings that larger motors would not be able to fit into, or would be too heavy. The servos also have rotation sensors built in as potentiometers. The built in sensors are wired directly to the control board to allow for custom feedback loop design. The system breadboard is mostly open and ready for additional components, from memory chips for data logging to additional microprocessors that use more complex sensors to measure the wind and lift conditions. The 18F2550 has 28 pins and has 3 data ports. It can control a data bus that has dozens of sensors. The implementation leaves extra pins on the microcontroller for immediate use, without the need to create a data bus for small additions to the system. The 6V electrical system can power most sensors with ease. The system is also more modifiable because of its simplicity.

## Minimize Complexity

In a boat with hundreds of tiny parts, minimizing complexity is important when considering repairs or likelihood of failure. To reduce likelihood of failure and satisfy functional requirement 7, the systems are separated and parts are standardized. The entire boat can be maintained with a jeweler’s screwdriver, a #1 Philips screwdriver, and 3 hex wrenches. All exposed wiring joints are soldered and treated with heat shrink tubing. All the servo-mast assemblies are identical. There are two separate batteries to ensure that if one electrical system shorts out, it limits the damage to the entire system. The electronics for each sail are interchangeable, and spare parts are easy to find.

## Minimize Cost

Partially because this project is paid for out of pocket, and partially because frugality is important, a central functional requirement is to minimize cost of components. The entire electronic board is from base components, except the microcontroller, which costs $3. The servos are $2 per servo, and they are rebuilt to achieve 360° rotation. The servos come with KC5188 pwm drivers and those are also modified in the servo conversion process. All metal mounting brackets are made from scrap Aluminum, and the sails are also made from scrap Aluminum riveted together to form a smooth and durable lifting surface. The most expensive part of the boat is the hull, because of the cost of fiberglass.

# Physical Integration

## Controller Board

The electronics in the system were the first part of the project to become functional, and are the link between the hardware and software components of this project. The final circuit schematic is shown below in Figure 16, along with a picture of the finished board, Figure 17.

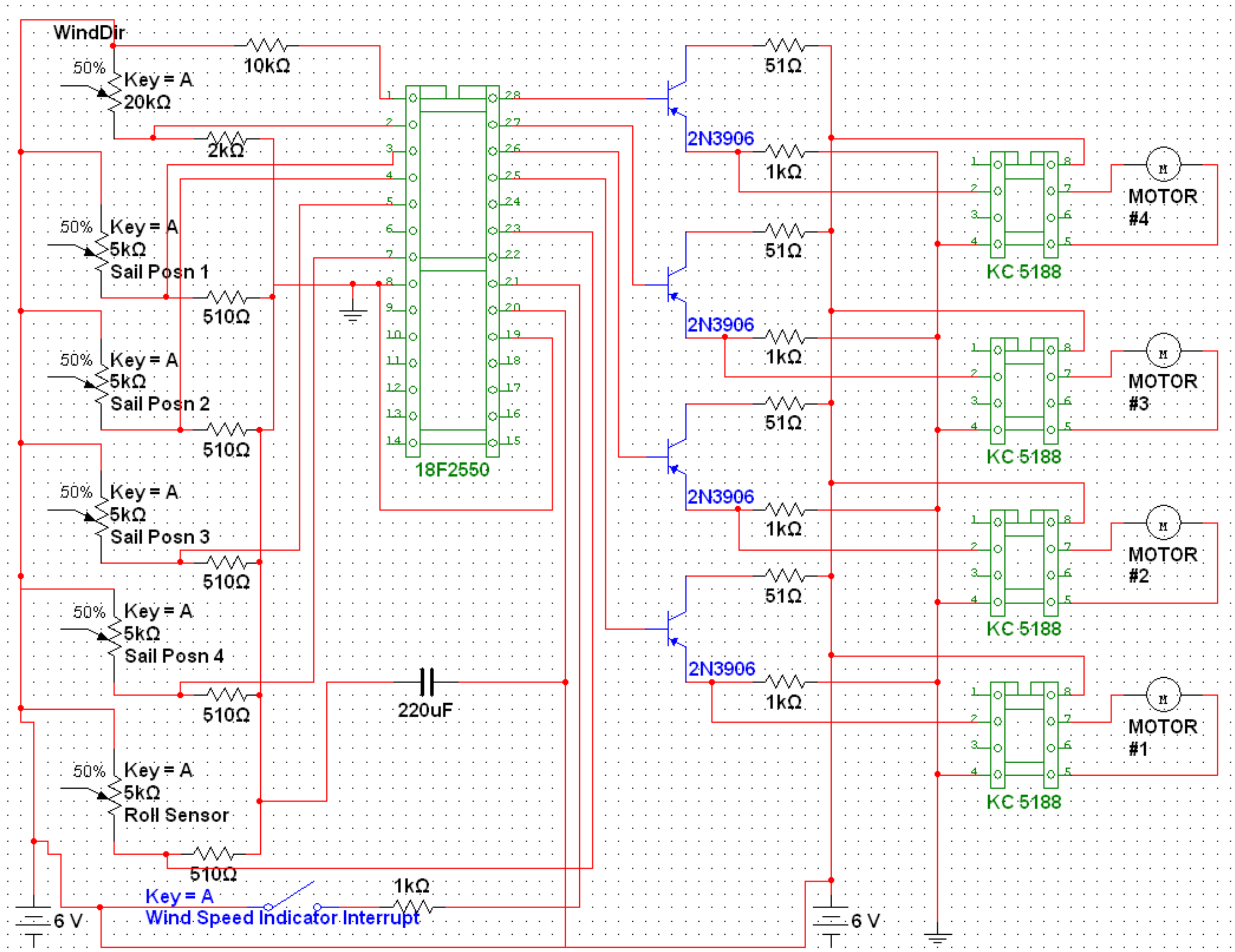

Figure 16: Entire Circuit Schematic

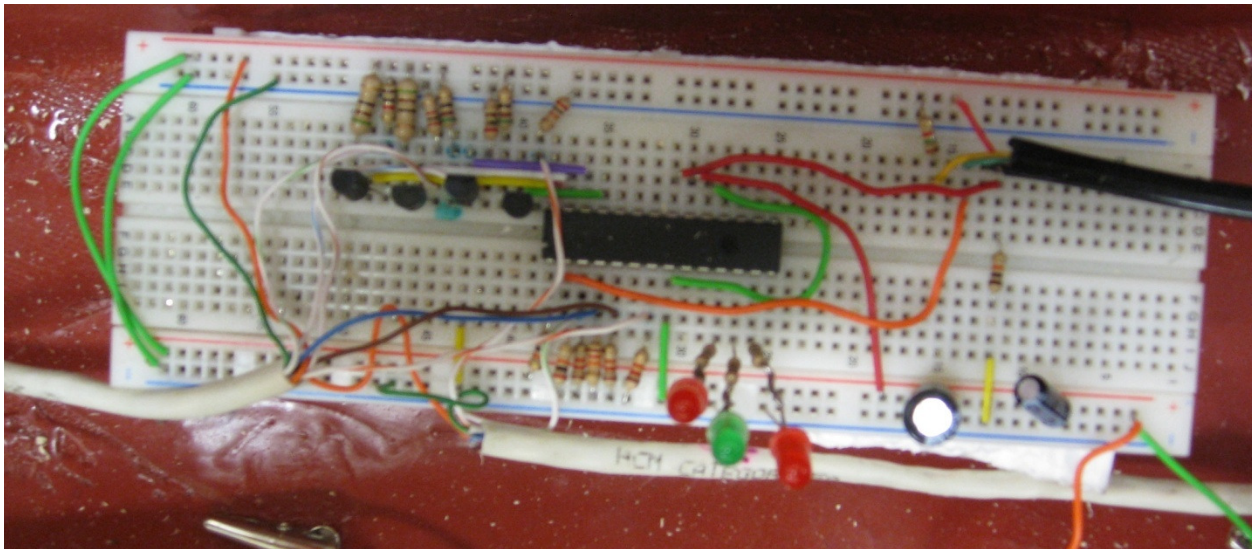

Figure 17: Finished Controller Board

The controller board was originally built with all the components soldered on, but when changes in the design required the board to be re-built, the need for versatility became apparent. The electronics were soldered to a thin copper protoboard but when the radio attached to the copper board proved not strong enough, and other electronics also needed updating, the copper was traded for a classic 100 row breadboard and a higher powered remote control. The circuits were built out of ECE kit scraps from WPI's ECE kits. The new and current controller board is shown above, and the old board is shown below in Figure 18.

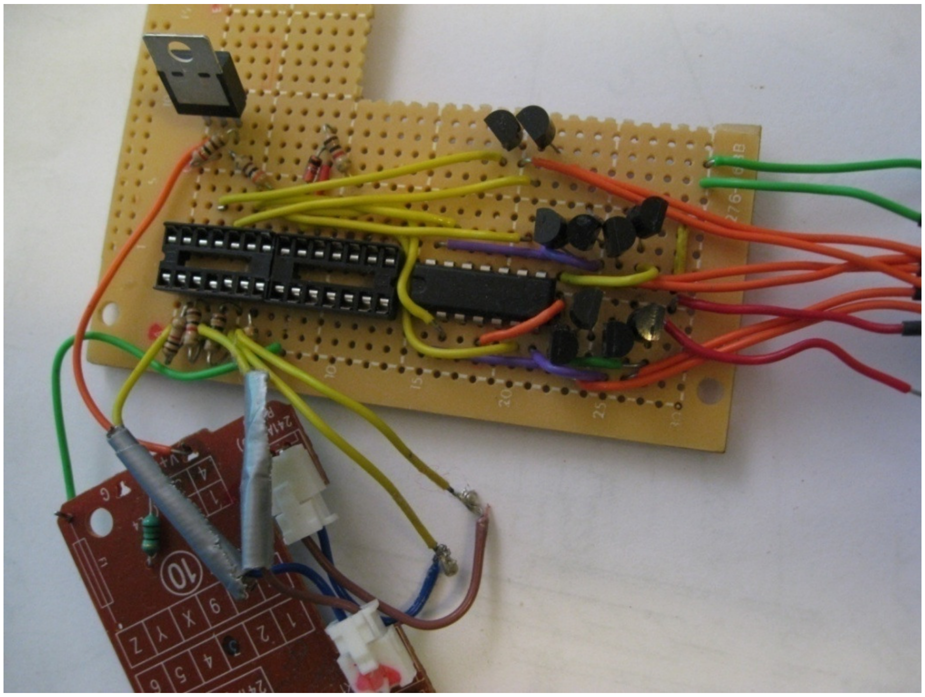

Figure 18: Original Circuit Board

## Programming the 18F2550

The microcontroller used in this project is Microchip's 18f2550. The chip can be programmed in C or microchip's assembly language. Assembly was selected because of the additional control it allows the programmer to have over instruction timing, a particularly important factor when dealing with 0.2msec delays and less. The chip is programmed on a homemade programming board that uses the program WINPIC to load files from the computer to the chip. The code was written in functional blocks, with features being brought online and tested individually. First basic output to ports was achieved, and then input from ports triggering output to other ports. The next step was writing code to turn on and off the servo motors arbitrarily which requires generating short pulses a few milliseconds apart. The pulses were achieved by using a delay function that first counts to 2^16, then counts to 2^18. Additional parts of the code were brought online when the analog to digital converter was coded in, and interrupts were finished after the A/D. All functionality was rigorously tested on the workbench before it went anywhere near a sail, hull or water.

## Forming the Hull

From Solidworks drawings, a Styrofoam mold was created and covered with a plastic sheet. Once warm weather arrived, it was coated with fiberglass using polyurethane resin a minimum of 3 layers deep. The fiberglass occasionally cured too fast, causing bumps and lumps in the hull. These were mostly sanded off or eliminated in future layers, but some still remained. Once the fiberglass had cured, the hull was tested for leaks in Salisbury pond. Cross members and a central strip of wood were added. Bondo was used to smooth out irregularities. The final hull was sanded and painted for display.

## Sail Control Servo Modifications

The sails are rotated by off-brand 9g servos that have been heavily modified. The servos were designed for 180 degree operation, but were modified to achieve full rotation. The servos are driven by a kc5188 PWM driver. This driver receives control signals from the main microcontroller using a common PWM standard, a 0.2 millisecond pulse or shorter selects reverse, while a 0.5 millisecond pulse or longer selects forward. The servo angle measurement potentiometer usually connected to the kc5188 driver has been disconnected and instead is wired to +5v on one side and the variable pin is connected to one of the A/D channels on the microcontroller, and a 10kohm resistor to ground. The servo control and angle measurement circuits are shown in the full circuit diagram in the controller board section.

To convert each servo for use on the boat, numerous changes were made. Each servo first had stops preventing it from rotating 360° shaved off, and the potentiometers had plastic chunks removed to enable them to also rotate 360°. Wires from the KC5188 drivers to the potentiometer and motors were cut. The KC5188s were reconnected to the motors with heavier gage wire that is more durable. The potentiometer was wired to the microcontroller inputs to enable custom control schemes. Finally, wire strain relief tabs were cut off the servos to allow the stronger and heavier gage wire to pass through. A few servos were modified by adding set screws or epoxy to their output gear to keep that gear from stripping. Figure 19 is a picture of a servo in the middle of modification.

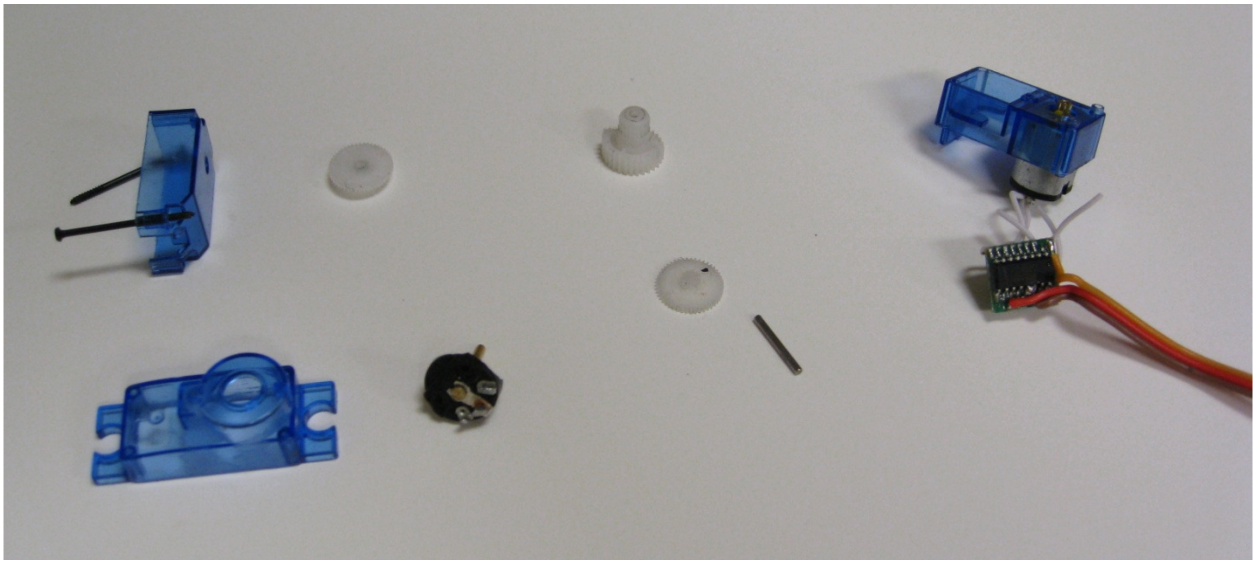

Figure 19: Parts of a Servo

## Universal Mast Base

To connect a wide variety of mast bases, a universal mast base was required to connect servos to varying mast shapes. The mast base was constructed from thin aluminum tubing. One end was notched such that it would engage the servo motor arm and rotate freely. The other end was drilled and tapped with 4-40 holes and four set screws were added. Figure 20 is a picture of the mast base with the servo arm fit into the grooves. The splines on the collar are visible in the figure, as are the set screws used to lock a mast into place.

Figure 20: Mast Base

## Prototype Sail

A prototype sail is created out of thin aluminum that is riveted together. The sail is around 1ft tall, which corresponds to about 150 scale feet tall. This is tall enough that it would not be able to clear many shorter bridges, but would fit into many deep water ports. The sail area available with this size sail is approximately 800ft x 150ft = 2.75acres. On a 15mph day, the power generated from this size area should approach 50% of the power required to drive the boat at a regular cruising speed of 10kts. Taller sails and more slender, sleek ships will open up more area for sail use, either gaining speed or gaining efficiency. This sail allows for the system to be tested and the electronic sail control system to be verified, even if the results are meaningless due to the unlikely sail shape. The sail is shown in Figure 21 below.

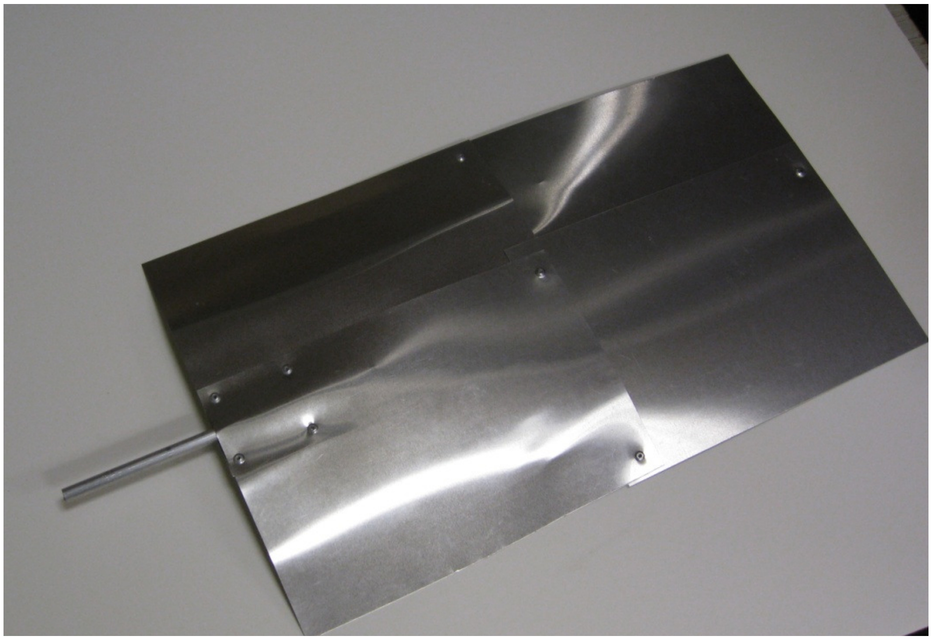

Figure 21: Prototype Sail

## Prototype Keel

Much like the prototype sail, a prototype keel was needed to test the boat's other systems. For the ship to sail, a keel or dagger board is required. This dagger board, shown in Figure 22 below, is simple but functions appropriately, keeping the boat on course while in the water and preventing sideways drift that would occur without any keel. Because the hull was designed to test various keel shapes, no keel was researched or designed except the dagger board for testing. The most important factor in keel design is reducing the draft, so a deep keel is not favorable to shipping. This dagger board sticks down below the hull of the ship, but future designs will likely experiment with keel shape.

Figure 22: Dagger Board

## Remote Control

The remote is an integral part of the system, and is the means for directing the boat from shore. This remote, shown in Figure 23 below, is from a non-sailing remote control boat that has good range and power. The remote has two channels, and allows for proportional control of the motors instead of all on or all off behavior. It also has a reverse, which can be handy when the boat noses into reeds. The remote drives the propellers and the rudder in the boat, while the microcontroller autonomously controls the sail angle.

Figure 23: Handheld Transmitter

# Prototype Production

## Anemometer and Weathervane Mounting Tower

A tower, shown below, was constructed to move the weathervane into the same clean wind the sails use. The Anemometer and Weathervane are from a home weather station kit. The anemometer and weathervane are secured to an aluminum rod which connects to the two vertical members while a triangle brace keeps the parallelogram from flopping around. The whole assembly is screwed to the mounting bar that runs down the center of the boat. A full implementation on a cargo ship would likely have many different wind sensors to try to better optimize flow over the wings. Bigger cups for the weathervane were purchased but not installed because the existing cups are large enough to measure even light wind speeds. The weathervane tower takes the place that an additional sail would fit on a larger retrofit.

Figure 24: Annemometer and Weathervane Mounted to Hull

## Inboard Electric Motors

All fossil fuel powered ships have propellers, and most cargo ship retrofits will have them too. The hull has two inboard DC electric motors, shown in Figure 25, that are wired directly into the remote control. The motors use 16 gage wire as their drive shafts, and the wire is coupled to the propellers by wrapping it around them. The driveshaft is connected to the motor with a press fit collar made from plastic tubing. The electric motors are secured to aluminum motor mounts with zip ties. Initially the motors were thought to be underpowered, and were considered disposable, but once weighted down, they have plenty of purchase on the water. The drive shafts exit the hull under the waterline, and as such, need to have waterproof bearings. The drive shafts go through plastic tubing that is approximately the same inside diameter as the shaft diameter. Lithium grease fills the tubing and keeps the water out of the boat even when loaded to capacity. Figure 25 shows the motors and drive shafts inside the boat, and Figure 26 shows the drive shafts after exiting the boat, and the propeller connections.

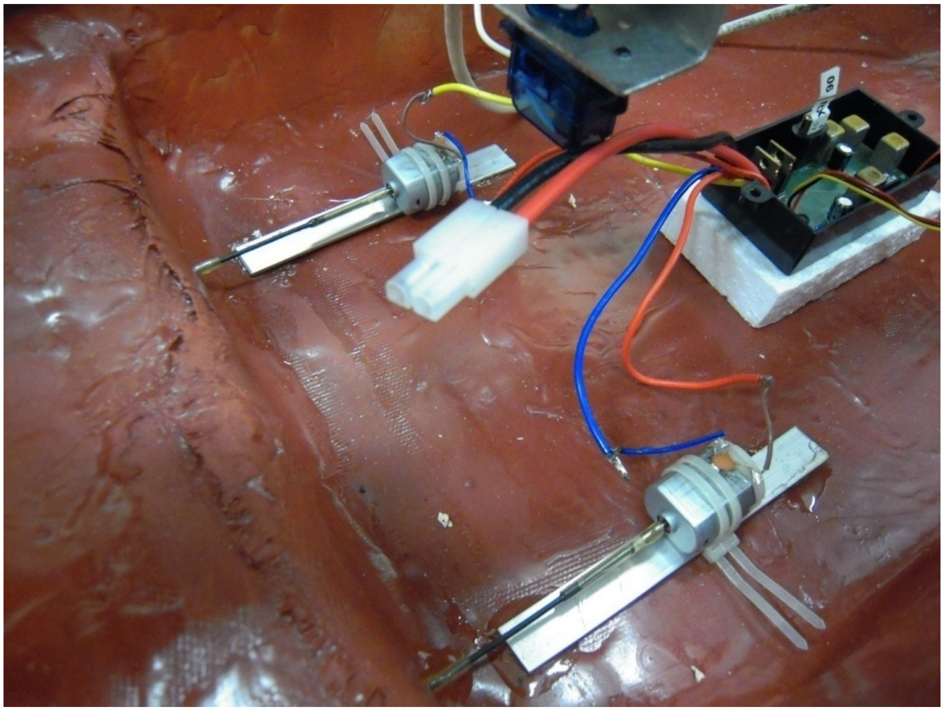

Figure 25: Inboard DC Electric Motors

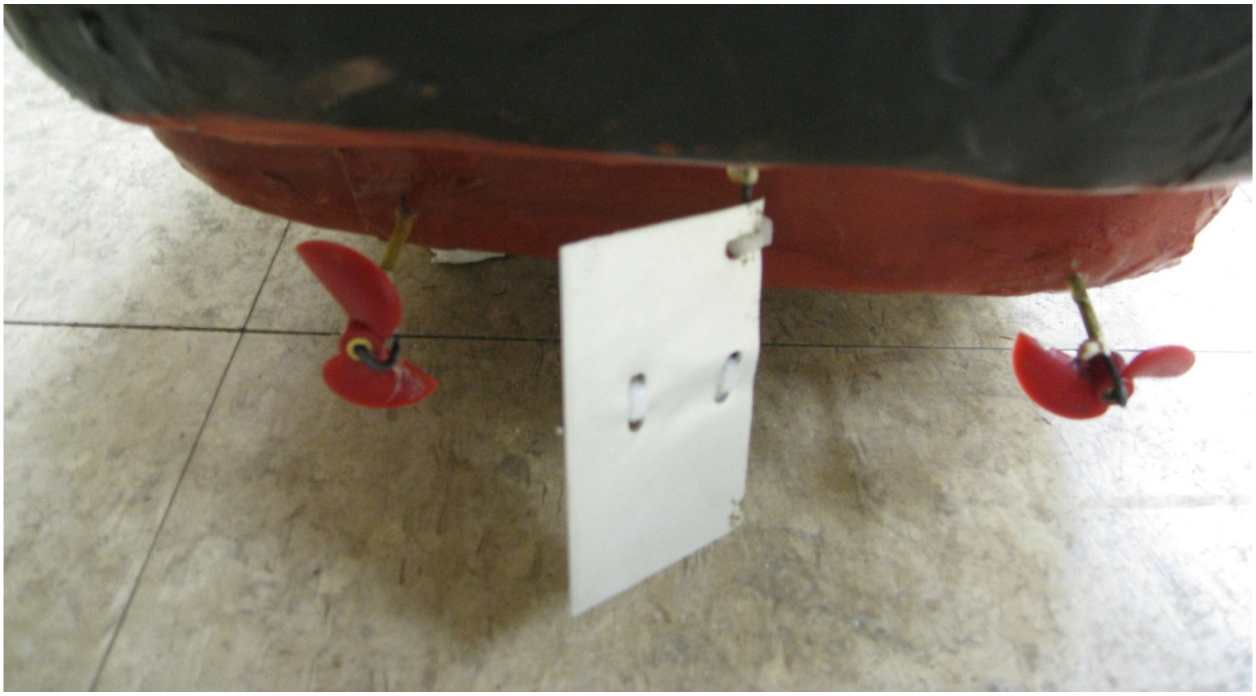

Figure 26: Rudder, Screws, and Driveshaft

## Rudder

Initially a rudder was included in the design, but the new control board and higher power remote control did not have an extra channel with which to drive a rudder. Instead, the two drive motors would be driven at different speeds to achieve directional control on the boat. This change left the boat unable to steer itself due to the large moment from the sail. The new rudder is pictured above in Figure 26. The rudder control signals were achieved by using the change in voltage between the propulsion motors to drive a rudder gear motor without a PWM chip. The servo-converted to gear motor uses a non-grashoff linkage to rotate the rudder of the vessel. The four bar linkage and motor are pictured in Figure 27. The rudder axle passes through a plastic tube that is glued where it passes through the hull. The tube extends past the top of the hull, so water can go into the tube, but cannot overflow the top of it.

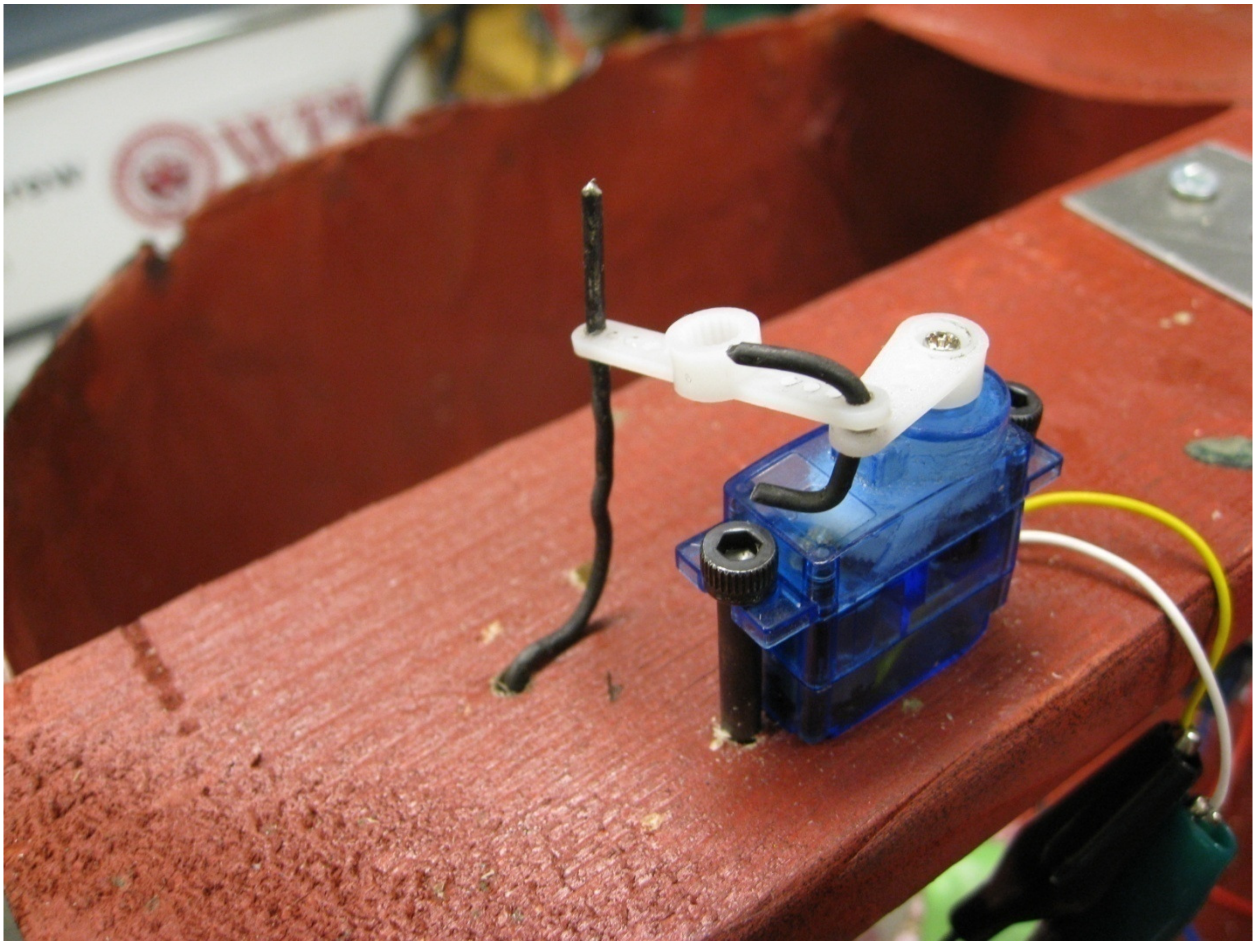

Figure 27: Four Bar Rudder Actuator

## Servo mount plates and mast restraints

To keep the servos from falling off the boat, servo mount brackets were created that the servos bolted into. Additionally, a plate holds the masts in place so they rotate around an even center. Both a servo mount plate and the mast restraint are shown on the next page, after being attached to the prototype wing sail boat. Each of four sails has a servo and mast 'bearing.'

Figure 28: Mast Restraint

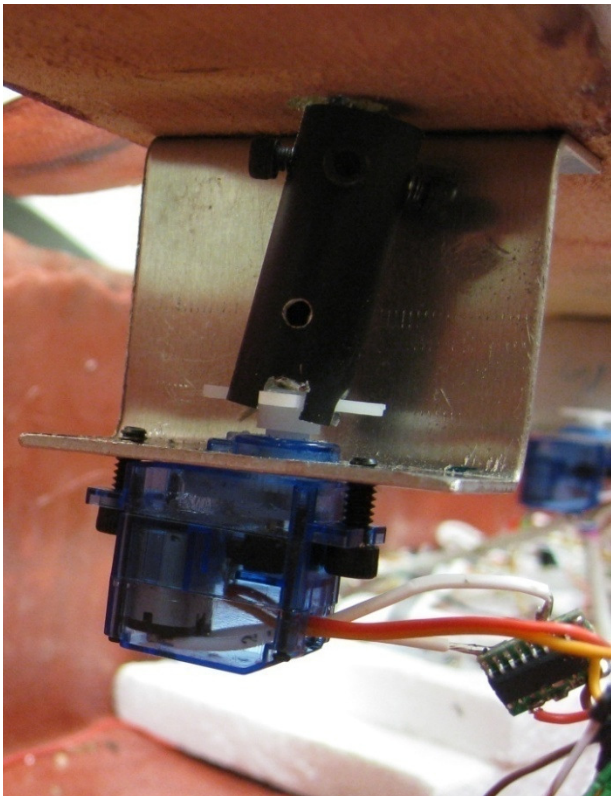

Figure 29: Servo Bracket

## Troubleshooting of Entire System

With all systems connected to the boat, testing the code for basic functionality was possible. The electronics worked correctly, and ran off battery power as expected. The feedback loop appeared to have major problems though, and all the sails spun wildly on system power up. After days of hunting for the problem, a solution was found. The PWM for the KC5188 is not documented correctly, and though the datasheet says a 2.0msec pulse or less is required to enter reverse, the chip actually requires a 0.2msec pulse. With this change enacted, the system is finally able to execute basic position seeking behavior. Another bug was quickly uncovered. The Sails would oscillate wildly because the code did not give the servos enough time to bring the system to a halt, and the sails would rock endlessly. The solution was to force the microcontroller to slow down. The microcontroller now polls sail position and wind direction about four times per second. The code can run much faster, but the servos will overshoot their objective, causing overshoot and overcorrect behavior. With the system in working order, pond sailing could commence.

## Recovery Insurance

Before the boat went onto the lake, a buoy was included with the prototype to ensure that if the ship did sink, it would still be recoverable in all but the deepest water. Additionally, the circuit board was raised using Styrofoam block, in theory allowing the boat to function even when taking on water. The buoy and raised electronics are shown in Figures 30 and 31.

Figure 30: Recovery Buoy

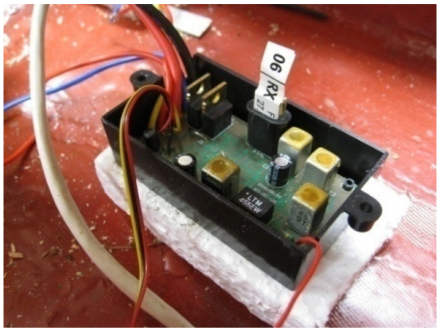

Figure 31: Raised Electronics

## Testing of the Final Design

The finished prototype was tested on two occasions on Salisbury pond in Institute Park. Figures 32-34 are of the test and are shown below. There were a number of criteria that were tested on each outing. Primary attention was given to whether the boat sank, how the boat sailed, and how the remote control worked. The boat never sank, even loaded down with weight. The first trip to the pond had mixed results as far as sail control was concerned, but the propellers and motors functioned correctly, the waterproof bearings did not let a drop of water in even under load. It did however sail out of range of the cheap remote control that originally was on the boat. Eventually the boat blew back to shore and was recovered.

After the initial test run, the sail control problems were fixed, and the remote was upgraded to a longer range model. A rudder was added to improve maneuverability both when sailing and under power. The second test was much more successful and the boat was able to sail across the wind without motor power. The boat still had difficulty turning, specifically tacking. A larger rudder or possibly just more weight in the boat will allow the boat to force the bow through the eye of the wind. When the craft turns up into the wind, the sails should compensate to make it easier to turn, not to try to pull more power out of the sail. Despite still having turning difficulties, the boat was able to sail with and without motor power. When sailing the boat kept an even keel and never listed past even five degrees in the 10mph gusts. The sails correctly orient to generate motive force from the wind, and the keel was able to keep the boat from drifting only downwind. Directly below is a picture of the boat next to the pond before the keels were attached.

Figure 32: On the Edge of Insitutue

One interesting finding of the second test day is that if a single sail is opposing the other sails, it appears that the system can continue moving forwards with little difficulty. However, when two sails are pitted against the other two sails, the whole system comes to a complete halt and begins to drift downwind. This is good news for wing sail retrofits, because the likelihood of all sails failing simultaneously is low, and the system degrades acceptably. Figure 33 is a picture of the model making its first sail power only reach.

Figure 33: First Sail Without Power

Finally, after a number of unsuccessful tack attempts, a jibe attempt ended with the boat stuck in the trees on the other side of the pond. The recovery operation is shown in Figure 34 below. The boat was recovered successfully and will sail again soon.

Figure 34: Recovery Operation

# Discussion

It is clear from research done for this project that wing sails will end up on many bulk carrier cargo ships in the next 100 years. Fuel savings of between \$1.8M and \$6.3M per year for a large vessel are attractive combination for a venture if a efficient procedure to retrofit cargo ships with wing sails can be devised. Bridge height studies showed that most major harbors have few height restrictions, and the real limit on sail area is the strength of the mast to support a very tall wing sail. The theoretical power from the envelope ranges from around 10% of operating cost to well over 70% for an efficient design on a windy day. If speeds, and therefore power requirements, are reduced, 100% of the power required to move the ship can be provided by wing sails. This is a very attractive option when considering bulk goods that have a long delivery time. Taking bids for installing equipment onto ships is probably the logical next step, and finding a ship renovation yard to pair up with could re-energize the field.

The test platform has basic sailing functionality, and is ready to be expanded in whatever direction is most valuable or interesting for cargo ship wing sail retrofit research. If future research is undertaken, it will be crucial to come up with a scaling procedure that will allow tests on the small scale to be relevant to the large scale. While the boat can adjust its sails to create lift, its maneuvering abilities need polishing. The model has the potential to be a useful research tool to someone developing wing sail boats, or testing other radical changes to cargo ships. The model may also serve as a marketing tool to show off how well wing sails work to potential customers or investors.

There were two very different objectives for this project. The first was a feasibility study and payoff period estimate that would determine whether it was worth investigating the idea as a potential business venture. The second objective of the project was to create a research and demonstration platform for wing sail retrofits. Elements of axiomatic design were used to bring clarity and simplicity to the design process. The tasks of the project were planned out from the first day of the term, and though the project got off schedule, the deliverable of an RC boat that autonomously adjusts sails was achieved. The project's huge scope and limited manpower are a lesson in what to expect when planning a project, and what is required to achieve an objective. One particularly effective solution in the prototyping process was the methodical and individual testing of features of the microcontroller. Another important factor in the success of the project was the access to the resources in the machine shop, from the old HP oscilloscope to the drill press, it is critical to have the right tool for the job. The project spanned 3 disciplines: computer science, electrical engineering, and mechanical engineering. Each part of the project was interdependent on the other two, and having full control over each system made for a more functional and integrated prototype in the end.

While wing sail ships have been built in the past, there is currently no company designing wing sail retrofits for bulk carriers. There is also no platform to study wing sail retrofits, or the control methods that are required to achieve optimal performance. None of the existing commercially available control systems adjust the sail angle based on heading.

It is hard to estimate the impact of this solution. One possibility is that wing sails are never heard of again, and global trade halts when bunker fuel becomes prohibitively expensive. A much more plausible outcome is that wing sails will be found on a large population of cargo ships by 2040, and streamlined sail-power-only cargo ships will be the standard for global shipping. With any luck, the sail area size study will convince the Portland Oregon project contact to seek venture funding to begin a wing sail retrofit company.

The value of the invention is hard to measure. Adding a wing sail to an existing cargo ship will save ship operators between $1.82M and $6.38M per year. If the modifications can be done at an acceptable price under $12 million (Sailing Ships with a New Twist), it's possible the payoff period could reach under 2 years for an extensive retrofit to a panamax class ship. A ten year payoff period is not extremely competitive, but as bunker fuel prices rise with demand for oil, the payoff period will shorten drastically. There is huge value in being able to sail without any fuel at all, and to help make this achievable, the model will be a crucial step in verifying the sail size, shape, and control system.

## Future Work

There are a number of areas that could use development. By far and away the most important problem is the question of exactly how wings and keels scale between the model and full scale. What does it mean when the boat goes 0.1 m/s? 0.5m/s? It is certain that sailing ships can go very fast, but what of efficiency measurements on the same scale. Do they scale the same way? How about small propellers vs. large propellers, surely there are different efficiencies and losses between the two. The question of how to measure the two is not terribly difficult: simply videotape the boat traveling on a lake first without sail power, then on sail power only and finally combining sail and battery power. This will allow for concrete readings on how effective the various systems are. This data remains useless without an exact method of converting between large ships and tiny models.

The only other major issue with the boat is that its sail position sensors can be intermittent and sometimes even stop working altogether, requiring a servo rebuild. One solution is to buy some real 360° servo motors that are designed to operate at any angle. Another solution would be to employ encoders or just better potentiometers that are not integrated directly into the servo motor. This solution has many drawbacks though, particularly that the boat no longer has integrated gear motors/angle feedback sensors. A final option might be to modify some better potentiometers to replace the existing pots. The most radical solution is to use a camera to determine sail angle of each sail, and report back to a central computer. At any rate, the cheap servos worked well eventually, but required a good deal of tinkering before they even had acceptable results.

The temporary keel was not quite rigid enough in the last test, and using a stiffer metal would probably improve performance. A peculiarity that wants examination is why the wing sail ship has such resistance to tacking, and how to ease the tacking procedure. As it stands the rudder cannot push the nose of the boat into the wind when the microcontroller is engaged. The motors must be used. Perhaps it is possible to change the front sails to create lift in one direction, and the back sails in another direction to achieve a rudderless tack?

Data logging would be nice to have, but is not crucial to study of wing sail retrofits, as a video camera can be used from shore to determine effective sail power. A major wish of the software developer is for the remote to input commands to the microcontroller. This would allow for different batteries of tests to be run, or simply for cool experiments like rudderless tacking. The ship is a wonderful platform for maneuver research and is a unique experience to pilot.

There are no major iterations required from the software perspective, and most of the improvements are hardware upgrades to the existing system. This shows that the underlying architecture is sound, and that the system will remain useful for as long as peripherals can be added and remain compatible.

## Conclusions

- Determined area available for sails based on ship size and bridge clearance data (see Appendix)
- Programmed a functioning and versatile control system that trims sails automatically
- Created a 1:150 scale model suitable for control system testing
- To the author’s knowledge, this is the first demonstration of a model wing sail sailboat that autonomously adjusts sails based on remotely controlled heading

# Appendices

## Acknowledgement

Many thanks to Torbjorn Bergstrom for being an excellent advisor and providing me a place to work. I would not have been able to finish this project without his guidance and patience. Thanks again!

## Program Code

```
;SimpleAsPie.asm: Written by Collin Strid, March 2010. Generate Absolute code.
	LIST p=18f2550 ; set target processor
	include <C:/Program Files/Microchip/MPASM Suite/P18F2550.INC>

	CONFIG WDT=OFF; disable watchdog timer
	CONFIG MCLRE = ON; MCLEAR Pin ON!!! OFF CAN MAKE IT UNPROGRAMABLE.
;	CONFIG DEBUG = ON; Enable Debug Mode
	CONFIG LVP = OFF; Low-Voltage programming disabled (necessary for debugging)
	CONFIG FOSC = INTOSCIO_EC;Internal oscillator, port function on RA6

	CBLOCK 0x10
W_TEMP : 1 ;temp for isr  (why do I only have 1 byte numbers! am SO using c on all future projects.)
STATUS_TEMP : 1 ;temp for isrv
BSR_TEMP : 1 ;temp for isr
SPEED : 1 ; number of rotations since reset * multipler
Delay1 : 1
Delay2 : 1
Delay0 : 1
Direction : 1 ;wind direction (1 byte) (unused)
SailAngle : 1 ;A sail angle (1 byte)
DesiredAngle : 1
FWD	: 1 ;which pwms are going fwd
REV : 1 ;you guessed it; which PWMS are going backward.
SAILCOUNTER : 1 ; hopefully this isn't a reserved word, it's short an sweet!
NUMSAILS : 1; sails left to check for A/D loop.
ROTATIONS : 1 ;Number of rotations in last second
	ENDC

	ORG 0x00
	goto Start

;This program should : light 1 led for more than 1 rotation per second, 2 for 1 rotation every .2 seconds, 
3 for faster than 20rps.
;pseudocode:
;count number of times led triggers in one second.
	ORG 0x0008
	MOVWF W_TEMP ; W_TEMP is in virtual bank
	MOVFF STATUS, STATUS_TEMP ; STATUS_TEMP located anywhere
	MOVFF BSR, BSR_TEMP ; BSR_TMEP located anywhere
	goto Increment
```

```
        ORG 0X0018 ; shouldn't have any low priority inputs with setup.
        goto Increment

        ORG 0x002A
Start
        MOVLW 0xF3 ; SEE PAGE 35 OF MANUAL FOR CLOCK SPEED, THIS IS 8MHZ INTERNAL.
        MOVWF OSCCON

        ;A/D CONFIG
        MOVLW 0X06 ;VSS,VDD ref. AN0-AN8 analog, everybody else digital
        MOVWF ADCON1
        MOVLW B'00001000' ;ADCON2 setup: Left justified, SLOW??? Tacq=2Tad, Tad=2*Tosc (or
Fosc/2)
        MOVWF ADCON2

;For A/D conversions: set channel, then enable AND TURN ON whenever ready (or simultaneous I'd
assume..)
;CLRF ADCON0 ;clear ADCON0 to select channel 0 (AN0)
;BSF ADCON0,ADON ;Enable A/D Conversion Module
;       BSF ADCON0,GO_DONE ;Start A/D Conversion


        CLRF TRISC ;SHOULD MAKE TRISC outputs. OUTPUT TO LATC
        ;bcf LATC, LATC0
        MOVLW 0X0F
        MOVWF TRISB ;So in theory this makes TRISB inputs?
        CLRF LATB

        MOVLW 0XB8 ;enable  interrupts on INT0 and TMR0 interrupts
        MOVWF INTCON



        CLRF TMR0L ; Clear Timer0 register
;       BCF INTCON2, RBPU ;             NOT SURE ABOUT THIS ONE....
        MOVLW 0x84 ; PortB pull-ups are disabled, (CHANGE THE 8 TO C TO GET 16 BIT COUNTER)
PRESCALER IS LAST 3 BITS
        MOVWF T0CON ; Interrupt on rising edge of RB0, (?)
; TMR0 = 16-Bit Time
; Timer0 increment from internal clock
; with a prescaler of 1:32



;Two ISR's one increments a variable (how many times it has triggered) and the other resets the variable,
and depending on it's size lights LEDs
```

```
        CLRF SPEED ; clear rotations.

Loop:
        ;rotations -> windspeed
        ;for now would be happy with just servo on until it is close to the desired angle (measured by
pot)
        ;pseudocode:

;Get desired position
        ; get wind direction (A/d) (speed is updated using interrupts *could have pwm counter that is
compensated on interrupts...)
        CLRF ADCON0 ;clear ADCON0 to select channel 0 (AN0)
        BSF ADCON0,ADON ;Enable A/D Conversion Module
        BSF ADCON0,GO_DONE ;Start A/D Conversion
        BTFSC ADCON0,GO_DONE ;Loop here until A/D conversion completes
        GOTO $-2
        MOVFF ADRESH,WREG
        ;translate speed and direction into desired sail position
        ;ADDWF SPEED ;maybe should be subtract??
        MOVWF DesiredAngle ; current equation for sail position: direction +8*speed

        ;is Beam roll too large? (if so set desired position for decreasing power)
                ;not implemented yet. probably just an A/d conversion and check it's between two
values

;are we in desired sail position yet?
        ;check sail posn (A/d conversion)
;       BCF ADCON0, ADON



        ;Init sail posn loop: A/D chan to be 1 and number of sails etc...
        MOVLW 0X10
        MOVWF SAILCOUNTER ;SHIFT RIGHT EACH TIME AND ADD TO FWD OR REV TO SET.
        Movlw 0x04
        Movwf NUMSAILS
        Movlw 0x05 ; select channel 1 (AN1), enable A/D Conversion Module, //and start 'er up.
        movwf ADCON0
        clrf FWD
        CLRF REV
GetSailPosns:
        BSF ADCON0,ADON ;Enable A/D Conversion Module
        BSF ADCON0,GO_DONE ;Start A/D Conversion
        BTFSC ADCON0,GO_DONE ;Loop here until A/D conversion completes
        GOTO $-2
        MOVFF ADRESH,SailAngle ;SAIL ANGLE IS SET! But is it within acceptable limits?
```

```
;INTERMITTENT WHEN DESIREDANGLE IS LESS THAN SAIL ANGLE (when going forward)
        MovFF SailAngle,WREG ;WHY NOT GO STRAIGHT TO WREG... WHATEVS...
        ;IF LARGER THAN SAIL ANGLE + 5 .... (SET DELAY OR JUMP SOMEWHERE OR BOTH)
        ;IF SMALLER THAN SAIL ANGLE -5 .... (SET DELAY OR JUMP SOMEWHERE OR BOTH)
        ADDLW 0X0A
        CPFSGT DesiredAngle ;skip next if f > W (DesiredAngle > SailAngle + 5)
        goto CheckRev
                MOVFF SAILCOUNTER, WREG
        ADDWF FWD ;set correct fwd bit
        goto ExitPoint

CheckRev:
        ADDLW 0XEC ;2'S c OF 10: 0000 1010 -> 1111 0101 -> +1: 1111 0110 (works!) (2's c of 10: F6. 20: EC
        CPFSLT DesiredAngle; skip next if f < W
        goto ExitPoint
        MOVFF SAILCOUNTER, WREG
        ADDWF REV ;set correct rev bit
ExitPoint
        MOVFF ADCON0, WREG
        ADDLW 0X04 ;INCREMENT AD CHANNEL
        MOVWF ADCON0;update ADCON0
        rlcF SAILCOUNTER ; ROTATE SAILCOUNTER LEFT (MULTIPLY BY 2!)
        DECFSZ NUMSAILS ;decrement NUMSAILS, skip the loop if zero (time to set the servos)
        goto GetSailPosns

;;;;;;;;;;;;;PWM Section Below ;;;;;;;;;


        MOVLW 0XF0
        IORWF LATB ;TURN ON TOP HALF OF PORTB

        MOVLW 0X15
        MOVWF Delay0 ;load delay0 with 20 msec delay time
        CALL Delay



        ;Bcf LATC, LATC6 ; eventually bits for each servo
        ;AND FWD AND REV W/ LATB (formatt of fwd: 1 = on, 0 = off)
        ;NEGF FWD
        MOVFF FWD, WREG ;LOAD UP FWD
        COMF WREG       ;NEGATE (WE'RE WRITING ZEROS WHERE THERE AREN'T ANY!) (ANYTHING THAT'S STILL ON NOW WON'T HAVE PWM STUFF)
        ANDWF LATB ;DO IT LATB.
        MOVFF REV, WREG ;Similarly turn off reverse bits, they won't be turned back on for another cycle.
        COMF WREG
```

```
	ANDWF LATB

	MOVLW 0X02 ;was originally 0x02 without any of our code running.
	MOVWF Delay0 ;load delay0 with 1 msec delay time
	CALL Delay

	;turn on fwd stuff again.
	MOVFF REV, WREG ;changed FWD on this line to REV 5:28AM 4/20/2010
	IORWF LATB ;TURN ALL OF FORWARD BACK ON.

	MOVLW 0XA ; finally: reverse is anything over 0.2msec!
	MOVWF Delay0 ;load delay0 with 2 msec delay time
;leave bkwd stuff for later
	CALL Delay

	MOVLW 0XF0
	IORWF LATB ;TURN ON TOP HALF OF PORTB
	;shift forward over till LED's line up with relevant ports
	RRCF FWD
	RRCF FWD
	RRCF FWD
	RRCF FWD
	RRCF FWD
	MOVFF FWD, LATC ;write fwd to latc

	MOVlW 0XFF ;load with a few msec of delay time)
	movwf Delay0
	CALL Delay
	MOVlW 0XFF ;load with a few msec of delay time)
	movwf Delay0
	CALL Delay
	MOVlW 0XFF ;load with a few msec of delay time)
	movwf Delay0
	CALL Delay

	GOTO Loop


	;AN0 LOWER THAN AN1, SOMETIMES GOES OTHER DIR.

	;is it quicker to rotate forward or backward?
	;make pulse of correct length (fwd or bkward)
	;delay (off time - time to execute other code)



	 ;put rotations into latc ( should test interupt feature)
```

```
;ISR Increment
Increment:
;
        MOVF PORTB, W ;AVOIDS A MISMATCH CONDITION
        NOP
        NOP
        BTFSS INTCON,INT0IF ;
        GOTO TimerInterrupt                          ;(if not rotating jump to lower)
        INCF ROTATIONS ;increment rotations (FOR ROTATION INTERRUPT rotating)

        BCF INTCON, INT0IF
        MOVFF BSR_TEMP, BSR ; Restore BSR
        MOVF W_TEMP, W ; Restore WREG
        MOVFF STATUS_TEMP, STATUS ; Restore STATUS
        RETFIE 0x00;RETURNS from interupt.

TimerInterrupt: ;test bits of rotations to determine how many LEDs to light interrupts should come once every second?

;       MOVLW 0xFF
;       MOVWF LATA ;TURN ON led if we get  into interrupt.


        ;uncomment if you want to flash leds or something....
        ;MOVFF SPEED, LATC ;(as a start)

        MOVFF ROTATIONS, WREG
;       MOVWF LATC ;OUTPUT TO LEDs (commented out 12:22am april 20 2010)
        MULLW 0X10 ;MULTIPLY SPEED BY 8 SO WHEN WE ADD IT TO DESIRED HEADING IT MATTERS
        MOVWF SPEED
        CLRF ROTATIONS


        BCF INTCON, TMR0IF
        BCF INTCON, RBIF

        MOVFF BSR_TEMP, BSR ; Restore BSR
        MOVF W_TEMP, W ; Restore WREG
        MOVFF STATUS_TEMP, STATUS ; Restore STATUS
        RETFIE 0x00;RETURNS from interupt.

Delay:
        DCFSNZ Delay0,F ;skip if NOT zero.
        RETURN
LoopSetup:
        MOVLW 0x02
        MOVWF Delay1
        MOVLW 0x5F
```

```
        MOVWF Delay2
Inner0:
        DCFSNZ Delay1,F
        GOTO Delay
Inner1:
        DECFSZ Delay2,F ;skip if zero.
        GOTO Inner1
        GOTO Inner0

        end
```

## Ship Dimension Table

| Type | Year | Dead weight | LOA(m ) | Beam | Draft | Cape Size length Availible for sails | Height from Deck to Mast | Engine power | | % of deck length that is sail-possile |
|---|---|---|---|---|---|---|---|---|---|---|
| Bulk Carrier | 2009 | 54500 | 189.9 | 32.2 | 12.68 | 154.9 | 32 | 9480kW | 14.6kts | 0.81569247 |
| Crude Oil Tanker | 2008 | 17000 | 150 | 23 | 8.8 | 120 | 20 | 4400KW | | 0.8 |
| Bulk Carrier | 2009 | 23000 | 159.9 | 24.2 | 10.15 | 127.92 | | | | |
| Oil Chemical | 2009 | 12600 | 137.76 | 20.8 | 8.1 | 110.36 | 18 | 3824KW | | 0.801103368 |
| Bulk Carrier | 1984 | 7988 | 110.3 | 18.3 | 7.25 | 88.24 | | 4330KW | 13kts | |
| Oil Carrier | 1990 | 6612 | 100 | 16.8 | 6.5 | 80 | | 3550BHP | | |
| General Cargo | 1992 | 2050 | 70.74 | 12.8 | 5.6 | 56.592 | | ? 3.5tons of fuel/day | 10 kts | |
| Bulk Carrier | 2010 | 35000 | 179.9 | 31 | 9.95 | 144.9 | 20 | 7860KW | 14kts | 0.805447471 |
| Bulk Carrier | 2009 | 32000 | 178 | 27.6 | 9.6 | 138 | 30 | | | 0.775280899 |
| Bulk Carrier | 1993 | 70000 | 225 | 32 | 13.6 | 180 | | 12250BHP | | |
| Bulk Carrier | 1986 | 342035 | 342 | 63.5 | 23 | 295 | | 20,590KW | | 0.862573099 |

## Major Port Clearances

| | Height |
|---|---|
| Bridge over panama canal: | 62.5m |
| Golden gate bridge | 227m |
| Portland Oregon bridges | Drawbridges or 60m |
| Rotterdam | No restrictions |
| Shanghai | No restrictions |
| Singapore | No restrictions |
| Shenzhen | No restrictions |
| Busan | No restrictions |
| Dubai | No restrictions |
| Los Angeles | No restrictions |
| New York | verranzo-Narrows bridge: 69.5m |

## References

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"*Sailing Ships with a New Twist," The Economist,* September 15, 2005, available online at [ http://www.skysails.info/fileadmin/user_upload/Upload_Pressespiegel/2005/05-09_Economist.pdf].

*"Shin_Aitoku_Maru.jpeg,"* image available online at [http://www.marine-marchande.net/groupe%20mar-mar/Documents/Perchoc/Navires%20a%20voiles/871_Shin%20Aitoku%20Maru.jpg] April 28, 2010.

*"Time to Seek Fossil-Free Propulsion?" The Naval Architect,* November 2004, p. 3, [ http://www.rina.org.uk/rfiles/navalarchitect/editorialnov04.pdf]

*"Full Sail Ahead"* The Rotarian. James F. Schlais, Nov 1981.

*"Navy Ship Propulsion Technologies: Options for Reducing Oil Use"* Ronald O'Rourke, June 2006. Available online at[ http://www.ibiblio.org/hyperwar/NHC/CRS/propulsion.htm#cn51]

Bridge clearance data from Wikipedia and Google maps

Boat data largely from apolloduck.com and other online cargo ship vendors that supply blueprints.

## Patents Consulted

Flap control of wing sails: http://www.freepatentsonline.com/4945847.pdf

aerodynamic improvements: http://www.faqs.org/patents/app/20090288585

Hydrogen producing ship http://www.faqs.org/patents/app/20080272605

Relating to wingsail craft: http://www.patentstorm.us/patents/4473023/description.html

Because the first wing sail ship was sailed in 180, many of the innovations patented during that time will no longer be protected, and this accounts for the lack of patents in the area.