Development of the USNA SailBots (ASV)

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USNA SailBot #1

***Abstract*— The development of two 2-meter long autonomous, sail-powered, surface vessels at the United States Naval Academy are described. Key design features and characteristics are presented along with supporting research and relevant background information. Efforts in naval architecture research focussed on velocity prediction program trade-off studies on beam, displacement and stability versus sail area. Systems development included gps-based navigation and vessel control operated through a Rabbit 3000 microprocessor.**

***Keywords*— autonomous surface vessel, SailBot, velocity prediction program (VPP)**

I. Introduction

Autonomous surface vessels (ASV) provide opportunities in surveillance, monitoring and oceanographic research. A requirement of these vessels is the need for power for propulsion as well as control and communications. For long-term endurance on-board storage for traditional fuel sources is problematic, so the energy must be harvested while at sea. While many options are available this paper describes the development of traditional, small, sail-powered ASVs. The mission statement for the vessels described in this paper is only toward competition rather than any specific scientific, military or commercial task.

In 2004 Erik Berzins, an engineering student at the University of British Columbia began developing a small sail-powered ASV for a class assignment. A requirement was that the project could be used in a student competition. After contacting other Canadian universities a set of rules for a "SailBot" competition were developed and the first event was held at Queen's University in Canada in 2006. The rules limit boats in the SailBot Class to two meters in length, three meters in beam (allowing for multihulls), 1.5 meters in draft and 5 meters in height from the bottom of the keel to the top of the fixed mast (not including wind instruments)[1]. The relatively small size allows for easy transportation and handling on shore while also keeping the construction and shipping costs down. Competition is intended for undergraduate students and the contests include a design presentation along with on-the-water events that test navigation, station keeping, performance and endurance[2].

The United States Naval Academy (USNA) started a team in January 2007 through the efforts of Jake Gerlach, a junior majoring in naval architecture and Associate Professor Paul Miller of the naval architecture major. With the assistance of Associate Professor Brad Bishop of the systems engineering major a team was created and funding secured for the following academic year. The USNA team comprising students majoring in naval architecture and systems engineering designed and built a boat the following year for the 2008 SailBot competition. Based on the lessons learned from that event and further research, the team designed and built a second boat for the 2009 competition.

While the mission statement for both boats was to win the SailBot competition, the team has a secondary goal to develop a small, sail-powered ASV for long distance passages. With the knowledge that the current holder of the "smallest vessel to sail across the Atlantic" is a mere 5'4"[3], the team is committed to an endurance vessel that also meets the SailBot Class rules. To date the team has spent approximately 900 man-hours and US$16K on developing the two boats.

II. Vessel Description – Naval Architecture

While the two USNA boats have names (*First Time* and *Luce Canon* respectively), for simplicity in this paper the hulls will be referred to as Boat 1 and Boat 2. Similarly, the keels, rigs and sails will be named according to their chronological design and construction.

Table 1 shows the two boats' principal characteristics with their largest rigs. The influence of the SailBot Class rules is clearly seen in that both boats' designs reflect the performance enhancing characteristics of maximum length and stability (via maximum draft).

TABLE I
PRINCIPAL CHARACTERISTICS

		Boat 1	Boat 2
LOA	m	2	2
LWL	m	2	2
Beam	m	0.36	0.28
Draft	m	1.5	1.5
Sail Area	m2	3.1	3.1
Disp	kg	26.7	24
Cp		0.57	0.54
LCB		-53%	-55%
LCF		-55%	-57%
"SA/Disp"		35.7	37.9
"L/Disp"		6.7	7.0

Figure 1 shows the two boats' hull lines with Boat 1 on the top. The primary differences between the two boats are the trend in the newer boat to a narrower beam and reduced hull weight through lower freeboard amidships. The two boats have approximately the same ballast weight concentrated in a bulb located at the bottom of the keel. Boat 2 also has more V-shaped forward sections.

The two hulls and decks are constructed similarly based on a trade-off between available time, weight, the students' building skills and the tools available to them. The hulls are skinned with one layer of #282 (T300) carbon cloth on both the outside and inside of a foam core. No moulds were used in the hull construction; rather the hull core was milled to shape on a ShopBot 3-axis mill from a solid block of closed cell modelling foam. Boat 1 used a 288 kg/m^3 density foam while Boat 2 used 160. Bulkheads were integrally cut for Boat 2 to reduce flexing during construction and to save time from the secondarily bonded bulkheads on Boat 1. Boat 1 used ProSet 125/226 Epoxy as the adhesive system while Boat 2 used WEST 105/205 due to its greater viscosity and user-friendliness. Figure 2 shows the compartmentalization for Boat 2. The core thickness for Boat 1 was a uniform 12.8 mm and Boat 2's is 10 mm.

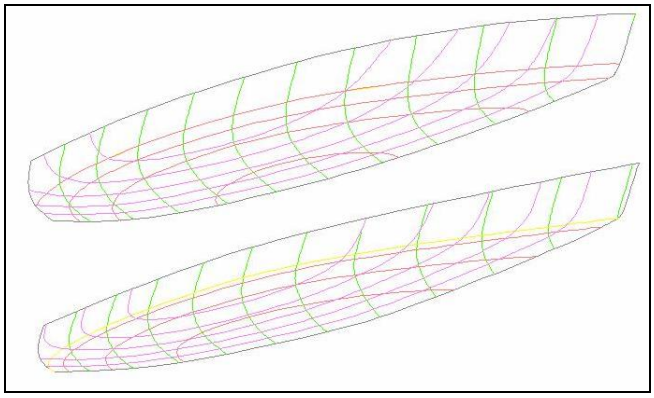

Fig. 1 USNA Boats 1(top) and 2, showing the trend toward narrower beam

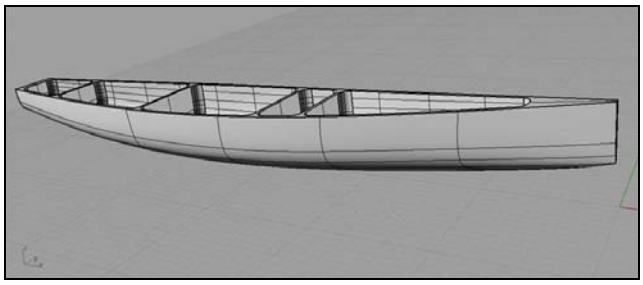

Fig. 2 Integral bulkhead placement allowing for watertight compartmentalization and structural support

Chainplates were fabricated using two plies of #282 over a carbon tube, with the plies extending 40 mm each side on to the hull shell. Keelboxes were built using six plies of 150 g/m^2 E-glass cloth and used the actual keel head as the plug. The rudder for Boat 1 is a NACA0012 section cored with 400 kg/m^3 Renwood closed-cell foam and skinned with one ply of 150 g/m^2 E-glass cloth. Rudder 2 is similar but uses a S8035 12% section[4]. Rudder shafts are 11 mm diameter silicon bronze. A plain bearing is used in the hull and the shaft is keyed for a double-sided tiller arm. To achieve a balanced rudder the shafts were located with 15% area in front of the shaft centreline. Rudder 1 is a simple trapezoid with a 0.4 taper ratio and Rudder 2 is elliptical. Both have a projected area approximately 1.2% of sail area. Experience has shown that a larger area may be beneficial in manoeuvring.

The mast step on Boat 1 was fabricated of Delrin with partial depth holes at two mast diameter spacings to allow for differing mast placements. Boat 2's mast step was redesigned to allow for a wider range of mast step placements and features a fixed aluminium strip with an adjustable aluminium plate acting as a mast-step base plate. The long strip doubles as an additional support for the two keelboxes. Figure 3 shows the deck layout for Boat 2.

Fig. 3 Boat 2 showing mast step and rigging details.

Three keels were built for the two boats. The keel material is 17-4 precipitation hardened stainless steel in an H1150 heat treat. Keel 1 has a 1.64 meter long rectangular (38 x 12 mm) stainless strip covered with a foam fairing to produce an airfoil section. The constant NACA0016 section shape has a 140 mm chord length and is covered with one layer of 150 g/m^2 E-glass cloth. Keel 2 is a machined section of stainless with a 110 mm root chord and 38 mm tip chord. The section varies from 14% at the root to 16% at the tip. Keel 3 is a smaller version of Keel 2 with a 98 mm root chord and a 30 mm tip. The S8035 section is 13% at the root and 16% at the tip. Keels 1 and 2 have a 15 degree aft sweep while Keel 3's is 5 degrees.

All three bulbs were built by cold casting lead shot in a two-part female mold. The matrix for Bulb 1 was Type 2 Portland cement while epoxy was used for Bulbs 2 and 3. Although the cement has a higher density, it proved too brittle and the curing time was longer than desired. Bulbs 1 and 2 used a NACA0016 section with a 3:2 squash ratio and beaver tail. Bulb 3 maintained the beaver tail and squash ratio but used a 10.5% S8035 section. Keels 1 and 2 are interchangeable. In case of problems with Keel 3, either earlier keel can be mounted in Boat 2 as it has keelboxes installed for both keel designs. Figure 4 shows the installation on Boat 2.

Four rigs were designed and built for the two boats and have seen the most post-launch development. Rig 1 was designed to the Nordic Boat Standards [5]as a strength minimum. While all the rigs have turned out to be durable, the major effort has focussed on finding a rig that works across the wind range. The Rig 1 goal was to create a lightweight rig that would automatically depower through bending. This was accomplished by using a 70% fractional rig with a long unsupported top mast. This rig worked well in winds from 4-24 knots, but the large mast bend in the upper wind ranges led to unreliable wind readings from the anemometer. The solution was to stiffen the top mast with jumpers. While this solved the anemometer issues it decreased the depowering ability.

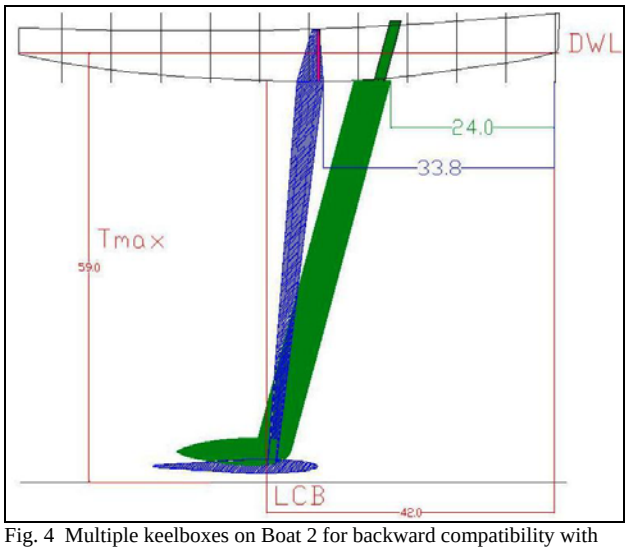

Fig. 4 Multiple keelboxes on Boat 2 for backward compatibility with Keels 1 and 2.

Rigs 2 and 3 were designed as conventional 85% fractional double-spreader rigs with 20 degree swept-back spreaders. The tubes are off-the-shelf braided carbon with a 16 mm diameter and a 1 mm wall thickness. To reduce deck penetrations they are deck stepped. The topmast uses a tapered section. The frontispiece shows Rig 2. The spreaders are 316-stainless tubes that slide over solid stainless rods that are glued through the mast tube. The booms are also carbon tubes and the battens are carbon strips. Rig 4 is a freestanding single sail rig (similar to a Laser) that has not yet undergone evaluation.

Sails were designed and built by the students using SMSW6[6]. Sail cloth is a lightweight scrim mylar. Approximately 85% of the sail area is in the main and each boat has a light air and heavy air main. The mains are attached to the mast with "zip ties" through grommets to allow quick changes. All rigging wire is 1.6 mm 7 x 7 316 stainless.

III. Vessel Description - Systems

While a fast boat is important in winning the SailBot contest or making progress against ocean currents, reliable control systems are equally important. Boat 1 clearly demonstrated this concept as it was the fastest boat at SailBot 2008 but had unreliable controls and finished second. The current control systems are identical in the two boats. The primary controller is a Rabbit 3000 Microprocessor.

To fit within Boat 2's more limited design space the systems constraints included: weight less than 3 kg in the hull and 1 kg at the masthead, able to fit through a 180 mm hatch opening, and minimum 24-hour endurance. Functional requirements include three modes; autonomous control of navigation and sail control, autonomous sail control with manual rudder control, and full manual control. For ease in transition between student year-groups and spares integration, a design driver was the desire to use in-house or off-the-shelf components as much as possible. Figure 5 shows the basic systems assembly.

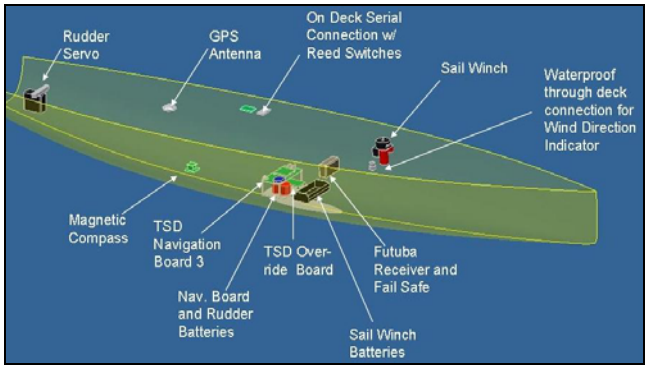

Fig. 5 Systems Assembly for Boats 1 and 2.

The standard USNA (TSD) navigation board includes a Rabbit 3000 Microprocessor, MicroMag 3-axis compass, Trimble IQ GPS, accelerometer, PWM outputs, Zigbee modem, 10 channels of 12-bit analog-to-digital conversion, 4 serial ports, external interrupt, general purpose I/O port, and statues LED. To provide additional watertight integrity for the main electronic components the navigation board was but into a plastic container. Holes were drilled into the side at mid level and a pipe inserted to run wires through. Within this pipe silicon rubber is applied to further reduce the flooding risk.

Accurate positioning is critical in this project as the finish line in one SailBot contest is only 3 meters wide. The standard Trimble GPS accuracy on the in-house navigation board is approximately 7 meters. To supplement the standard GPS a Magellan AC-12 DGPS was added. The AC-12 is a low cost, small, DGPS with an accuracy of 0.8 meter and a power consumption of approximately 200 mA at 3 volts. To improve reception when heeled, the AC-12 uses an on-deck Garmin 29 antenna.

Wind direction is sensed with a Davis anemometer. While heavier than desired and having a 20-degree deadband, it was off-the-shelf and is water-resistant. The rudder servo is a standard servo for remote control sailing yachts although it is upgraded with metal gears. To control the sails a single RMG 380HD Smartwinch is used with a traveller line on deck.

A Futuba transmitter and receiver is used to manually control the SailBot. In order to switch between manual and autonomous modes, a PIC microprocessor is used to read a toggle channel from the Futuba TM/RC, which triggered relays to switch the rudder and sail winch between the two modes.

This system requires constant communication with the Futuba Transmitter. It is expected in a long distance autonomous race that the SailBot will sail beyond the range of the controller. A commercial available Duratrax Failsafe Unit was purchased to address this situation. This devise senses losing the loss transmitter signal, in which case it provides a preset value. We set this value to default to the autonomous mode.

Another SailBot competition requirement is to be able to steer manually but have autonomous sail control. An override switch was added which forces the rudder to receive manual control inputs regardless of the override status. This allows us to always drive the boat while switching in and out of automatic sail control.

Power to the three systems (navigation, winch and rudder) is independent to reduce feedback and for redundancy. The winch is powered by four rechargeable C-cells while the navigation board and rudder servo are powered by 6 volt, 1100 ma NiMH batteries. Figure 6 is the functional block diagram for the two boats.

Programming is accomplished through two methods. To avoid compromising watertight integrity a waterproof serial connector is used on deck. While this is quick and reliable it is not convenient in rough water or at a distance. In those cases the slower Zigbee modem is used to reprogram the microprocessor. A Zigbee modem is also used to serial communicate boat performance data back to the observer.

The code is in multiple parts, including taking in sensor information, navigation, rudder control and sail control. The navigation co-statement begins with assigning values to variables including magnetic wind direction, port and starboard close hauled course, velocity made good (VMG) on the calculated close hauled course angles, bearing to the waypoint, and danger bearings. Magnetic wind direction is then processed through a digital low pass filter. With these values calculated it then decides if the next waypoint is upwind (in the no go zone) or downwind. If it is downwind, it will drive straight there. If the boat has to tack to go upwind, the program then calculates which course (starboard or port tack) has the VMG towards the next waypoint. The program will then head the boat in that direction. If the boat completes a tack then the program with hold the given course for a pre determined about of time to allow it to get stabilized and up to speed. It will then start the above loop again, calculating which tack would have the better VMG and then steering accordingly.

Primarily the sails are trimmed to the current wind direction. The rudder is controlled by comparing the difference between the desired heading calculated in the navigation portion of the control and the current heading. A very simple proportional controller is used. The “gains” were calculated based on experience with sailing the two boats. We have found that this heuristic approach to rudder control to be reasonably reliable, however the sail trim significantly affects the ability to turn the boat. Most prevalently, in higher breezes it is almost impossible to turn the boat from close hauled to a beam reach with out easing the main. Similarly, the main tends to over power the rudder downwind and sometimes will prevent the boat from jibing.

IV. Research and Development – Naval Architecture

The primary tool used in developing the two boats from the naval architecture perspective was a velocity prediction program (VPP) called PCSail[7]. A VPP solves for equilibrium of four of the six degrees of freedom (yaw and pitch are ignored). This Excel-based program is typical of simple VPPs in that it uses a relatively simple user interface

with inputs for the key vessel geometry and then solves through iteration using the built-in solver module. Key outputs include speed, heel, and the optimal reefing amount.

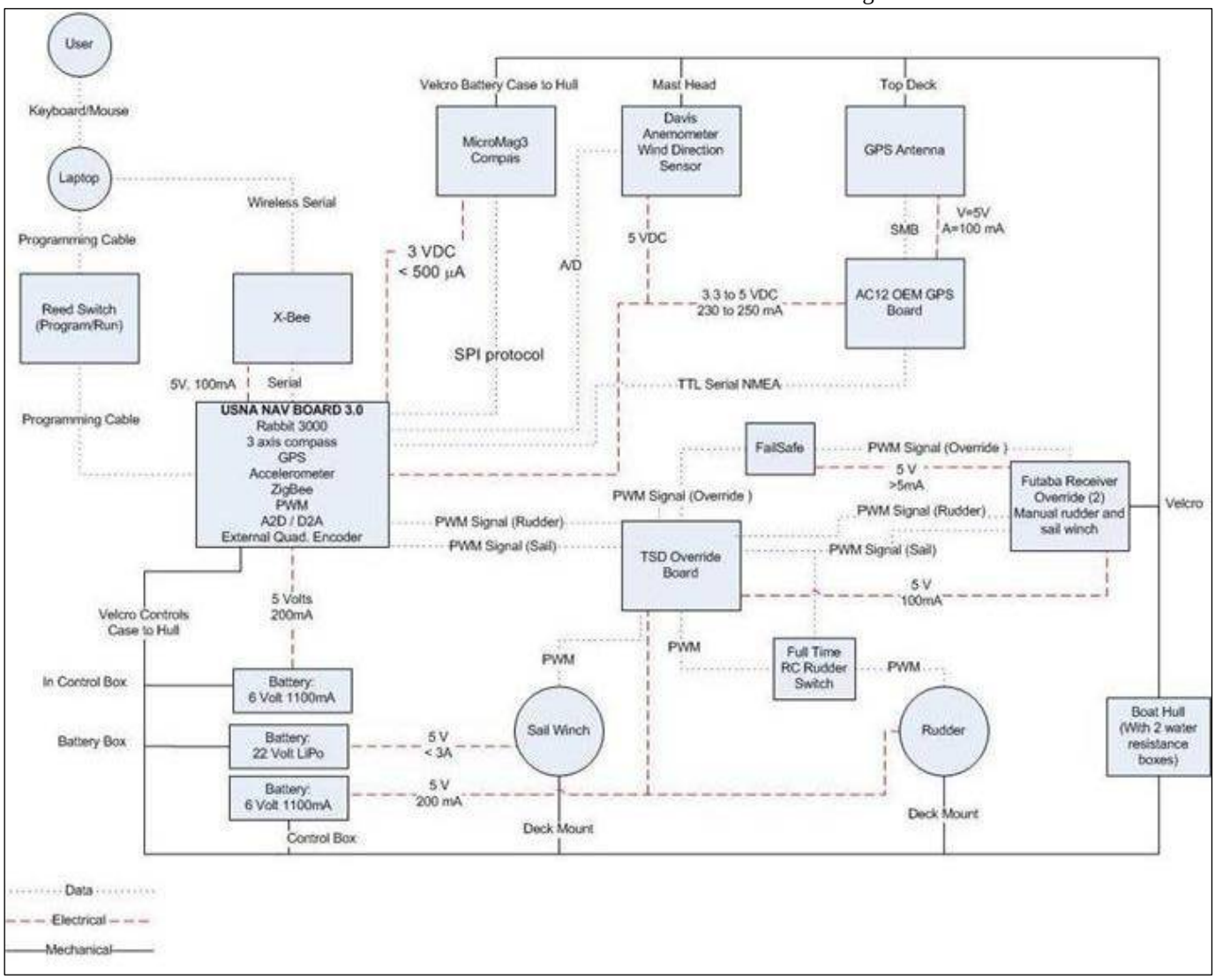

Fig. 6 Functional block diagram for Boats 1 and 2.

To determine if a particular change is worthwhile the results were displayed in delta seconds per mile for each heading or in VMG. For the SailBot competition these were then applied to each leg of a known course, or were applied as summed weighted averages for unknown conditions. An added level of analysis included comparing the resulting proposed boat against the competitors to determine potential win/loss records. Figure 7 is an example of a predicted match race in six knots showing the potential speed per leg for three boats. Boat 2 (Luce Canon) is shown to have a speed advantage on each leg.

Like most general purpose VPPs, PCSail estimates the hull resistance using parametric analysis of tank test results. The Delft series focused on full-size yachts and the parameters were for relatively beamier and much larger vessels than Boat 1 and 2. To validate the VPP, Boat 1 was tank tested and the results showed acceptable correlation.

While the VPP runs are quick, realistic trade-off studies are time intensive as a change in one hull variable necessitates changes in many others. For instance, an increase in beam requires a reduction in canoe body draft for a constant displacement. This means that in hull studies a new hull must be generated for each data point. A complicating factor is the wide wind range which requires a design that is good across the full range.

First year studies included the key vessel parameters of length, beam, displacement and stability. Length was the easiest to solve as the VPP gave a strong trend toward maximum waterline length and as the freeboard is so small that also meant maximum deck length. The result was a plumb bowed and sterned vessel at the SailBot maximum length of 2 meters. During the second year the VPP used Boat 1 as a baseline.

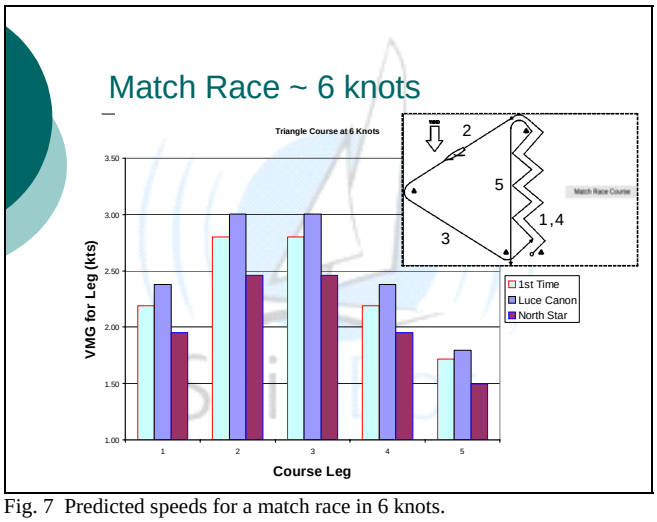

Fig. 7 Predicted speeds for a match race in 6 knots.

Beam was the second variable studied. The decision for the first year was a trade-off in narrow beam versus volume and access. With the systems not yet defined by the time construction started, the decision was made to make the boat just slightly wider than the larger of the two available Holt Allen inspection ports. A more detailed study was done the second year and indicated that narrower beam would significantly increase performance. The beam variation study kept displacement and length constant while beam and canoe body draft varied. Beams from 390 mm down to 228 were compared and the results showed an increase in performance for the narrower boat in all wind speeds and on all courses. The trend appeared to reach a limit near 228 in reaching and running conditions however. The 280 mm final beam was selected based on mast stability considerations and the size of the smallest practical hatches.

It was relatively easy to study some characteristics, such as the prismatic, in isolation. Sail area, stability and displacement however, required a combined study. This was because it quickly became apparent that as sail area increased the boat gained performance if the stability increased, but that was only possible if displacement also increased. In essence, as the rig, hull, deck, and systems became a fixed weight, the variable weights were the keel and primarily the bulb.

It quickly became apparent that the most effective righting moment was achieved with a rule maximum draft. After that the keel weight became fixed and the variable was the bulb weight. The trade-off study thus focussed on variations in bulb weight which effectively was a trade-off in VCG versus displacement. The results showed some sensitivity to wind strength in that in light air a light bulb and light displacement were superior. Once the wind reached approximately 12 knots however the results converged to a 11.6 kg bulb weight of and 24 kg displacement. It is important to point out that VCG was critical and efforts were made to reduce weight in the hull and rig.

With the displacement and stability determined a trade-off study in sail area was performed. The results were somewhat disconcerting in that light air performance was strongly influenced by sail area. Essentially in winds less than six knots it was critical to put as much sail on the boat as possible! The concern however was that in winds above 10 knots a large sail area would cause significant control issues. The solution was to have different main sails for light and heavy winds and have a relatively quick means for switching sails. Clearly this approach is not acceptable for long distance events. Current development focuses on sails and rigs that depower automatically but are robust.

As mentioned above, the need for stability forced the keels to the maximum 1.5 meters draft. At the same time a deep draft keel using normal proportions would create a large wetted surface area, decreasing performance. The solution was to aim for a very high aspect ratio keel. This created a design challenge in that a thin, high aspect ratio keel would bend, decreasing righting moment. Material selection for the keel focussed on a high stiffness material with good strength, durability and relatively low cost. Weight was not a significant concern due to the keel's secondary function as ballast and the relatively small volume.

Keel 1 had a short lead time and was designed for easy fabrication. While this design was stiff, strong and easy to construct, it had more surface area than desired.

Keel 2 addressed this by cutting an 80 x 19 mm strip to an airfoil on a 5-axis mill, with a 0.4 chord/root taper ratio. The structural foil comprised the airfoil section from 15-75%. The leading edge used foam and a 4 mm rod to create the airfoil shape, while the trailing edge was constructed using filled epoxy. While this keel was both lighter and had less area, it was significantly more difficult to produce due to the added work on the leading and trailing edges.

Keel 3 was designed for Boat 2 and applied the lessons learned from the first two keels' construction. While similar in construction to Keel 2, the structural portion extends from a constant 3mm aft of the leading edge all the way to the trailing edge. A 3mm diameter rod is glued on the leading edge to form the correct leading edge radius on the S8035 section.

To balance stiffness and strength a series of finite element analyses were performed on Keels 2 and 3. The limit state to yield was 90-degrees heel with the keel in air and a dynamic amplification factor of 2. The maximum permitted deflection at that condition was 125 mm with a 2 degree rotation. Figure 8 shows a typical plot. In practice, Keel 3's torsional stiffness is a little less than desired.

Keels 1 and 2 were designed with 15 degrees of sweep in an effort to improve weed shedding and increase the second moment of area in yaw to aid directional stability. Keel 3 had the sweep reduced to 5 degrees to reduce induced drag and torsional stress. An unintended benefit of the relatively large keel deflections is that the boats have positive righting moment throughout the stability curve which means they will always self-right in a capsize.

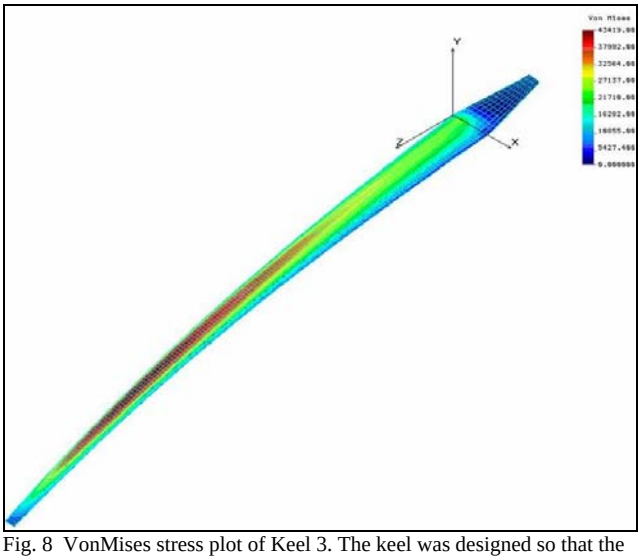

Fig. 8 VonMises stress plot of Keel 3. The keel was designed so that the highest stress was away from the connections.

Other studies looked at hull shape and seakeeping. Boat 1 has relatively U-shaped sections and has a tendency to pound which shakes the rig. In response to this, Boat 2 has more V-shaped sections forward. The trade-off in this approach became apparent in early trials when the shaking was clearly less, but the boat showed a tendency to track divergently. The forward sections on Boat 2 were reshaped after the SailBot competition.

Future research areas include a more detailed look at added resistance in waves, automatically depowering rigs and low-power steering and sail trim systems.

V. Research and Development - Systems

Choosing an appropriate wind sensor was difficult as no sensor is made in a small lightweight and watertight size. The Davis anemometer was picked because of its relatively easy interfacing, minimal price and perceived accuracy. It is heavier than desired, with a two pound weight. The intent was to reduce the weight by rewiring it and rebuilding its frame. As the wind speed was not needed; additional weight was saved by taking these parts off. Wind direction is sensed with a potentiometer which returns an analog voltage back to the navigation board.

Initial testing showed the anemometer was not adequate. At heel angles greater than 30 degrees or light winds the instrument did not register properly. The Davis instrument seemed to have a high threshold velocity while our specifications required a starting threshold of less than 1 knot. These failures prompted us to make our own sensor using a potentiometer which would offer a lower threshold and create a new tail wing design.

The prototype used a Bourns 6534S-1-502 potentiometer with a carbon fibre rod for the structural support. We added a large plastic tail feather and counter-weighted it with a bolt and nut. Figure 9 shows the completed wind sensor.

Fig. 9 In-house lightweight wind direction sensor.

To test the anemometer we placed an aluminium ladder in front of a ventilation fan. We then took a handheld wind speed sensor and mounted it to the ladder in order to measure wind speed. Comparing the Davis to our design we found they had the same 20-degree deadband, but our design had a lower threshold. The Davis wind direction sensor was water resistant however! Given the lower threshold from our larger tail fin we modified the Davis to include a larger tail fin.

While the RMG 380HD SmartWinch is strong enough to trim the sails in all normal conditions, it has no ability to prevent back turning the gears when the motor is turned off. This unfortunately means it requires significant amounts of current (1.5+amps) when holding the sail. This will quickly run the batteries down, and is unacceptable for long duration sailing. One solution we explored is a winch system that uses a worm gear to prevent the back turning. Using a Maxim motor and a worm gear we designed our own sail winch. Figure 10 shows the new winch.

The winch is controlled with the navigation board through a LM298 Dual Full Bridge Driver. A 10 turn potentiometer is attached to the output shaft in order to provide feedback on the winch position. The Maxim motor only draws 200mA, which is great for long distance racing. Unfortunately, to get the proper torque we had to run the motor at 22 volts and the response rate was too slow for round-the-buoys racing.

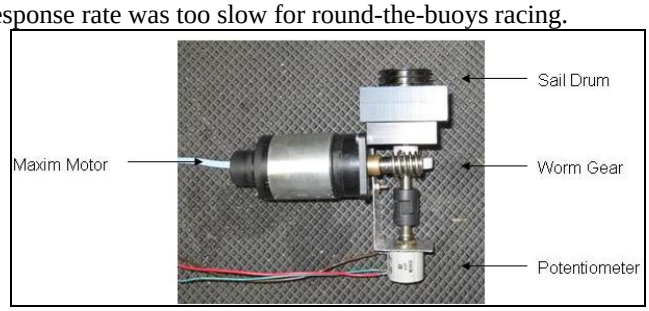

Fig. 10 In-house worm gear winch.

The Maxim motor was a convenient choice as it was in stock, and was used for a proof-of-concept. Better selection would reduce the voltage needed with the same low current draw.

Future research includes power consumption and generation. Solving the winch's power consumption problem, coupled with the low current draw of the navigation board and rudder (approximately 6 volts, 30mA each) application of

solar cell technologies can be used to allow self sustainability for a transatlantic crossing.

Geographic positioning for a transatlantic crossing is important but not as important for buoy racing. A high degree of accuracy on the race course is needed in order to round marks. DGPS is one solution, but since buoys tend to have swing circles, the exact location of the buoy may change. One solution is to use GPS to get close to the mark then use cameras and image tracking for close in navigation. We experimented with using two CMUcam2 giving us a ninety degree field of vision in front of the boat. These cameras would be set to track the highly visible orange color of the buoys. The microprocessor on these cameras would then send a serial signal to the navigation board with information including the size of the image and location of its centroid. This data would allow the boat to navigate around the mark. Limitations of this camera include glare off the water in some satiations, this could be fixed with the application of an IR filter.

VI. Conclusion

While small, sail-powered autonomous vessels offer promise in numerous applications, the field is still young and numerous opportunities exist for development. This paper highlighted the initial development of two "SailBots" by the students at the United States Naval Academy. This information may help others in developing their vessels. In addition to the educational objectives reached through the boats' design and construction, competition encouraged more rapid development of the vessels and will encourage others to participate.

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