An Energy Scavenging Autonomous Surface Vehicle for Littoral Surveillance

Gabriel Hugh Elkaim, *Computer Engineering Department, University of California, Santa Cruz*
C.O. Lee Boyce Jr., *Aeronautics and Astronautics, Stanford University*

BIOGRAPHY

Gabriel Elkaim received his B.S. degree in Mechanical/Aerospace Engineering from Princeton University, in 1990, and both M.S. and Ph.D. degrees from Stanford University, in Aeronautics and Astronautics, in 1995 and 2002 respectively. In 2003, he joined the faculty of the Computer Engineering department, at the Jack Baskin School of Engineering, University of California, Santa Cruz, as an Assistant Professor. His research interests include control systems, sensor fusion, GPS, system identification and autonomous vehicle systems. His research focuses on intelligent autonomous vehicles, with an emphasis on robust guidance, navigation and control strategies.

C. O. Lee Boyce Jr. received his B.S. degree in Aerospace Engineering from the University of Maryland, and a M.S. in Electrical Engineering and both a M.S. and Ph.D. in Aeronautics and Astronautics from Stanford University. He has worked for American Rocket Company as a structural engineer, and worked worked as a cognizant engineer at NASA Jet Propulsion Laboratory in Avionics. Co-founder of Delta Technology Associates, Dr. Boyce has been working developing autonomous surface vehicles and indoor positioning technology.

ABSTRACT

A prototype energy scavenging autonomous marine surface vehicle for littoral water surveillance has been developed and experimentally tested. The basic vehicle chassis is a heavily modified Stiletto Catamaran with the center structure removed and replaced with an aluminum box beam supporting a carbon fiber stub mast. A carbon fiber rigid wing, 10.7 meters tall and with a 3 meter chord is suspended on bearings about the stub mast and able to rotate freely in azimuth. Controlled by flying tails attached on booms at mid-span, the wing flies at a constant angle of attack to the relative wind (the vector sum of the true wind and vehicle velocity). Equipped with two 7KW electric motors, and independent battery banks to power them, the vehicle can be propelled either electrically, or via wind power, or both. A simple hybrid drive results from the operation of two independent control systems linked through GPS velocity. Off shore tests have shown the vehicle to be capable of tracking patrol segments to better than 2 meters, with line acquisition and segment transitions taking 50-100 meters to complete. The control system for the wing automatically tacks and jibes the wing as appropriate in order to produce forward thrust.

1. INTRODUCTION

With persistent threats abounding, current maritime resources are stretched providing perimeter patrol, harbor surveillance, force protection, and hydrographic survey. Augmenting these manned resources with autonomous marine surface vehicles capable of navigating and propelling themselves reduces the requirement for patrol and effectively pushed the boundary of the perimeter farther outward in both time and space.

Rather than using valuable human resources, expensive vessel time, and costly fuel for propulsion, an autonomous surface vehicle such as the one described in this work can perform the work of a “forward watch” such that a single human can monitor several vehicles. Once a threat is identified, or a perimeter violated, appropriate action can be taken.

As with all drone type vehicles (be they air, ground, marine surface, or underwater), obstacle avoidance, range, and mission duration remain critical [26] [21]. By specifically using an energy scavenging mode, this vehicle can extend its mission duration while at the same time being environmentally friendly. While on this prototype, only the propulsive force is scavenged using the wing sail to drive the vehicle, it is easy to envision other forms of energy, such as solar and wind, to be scavenged for electronics operational during very long duration missions.

The prototype vehicle is based closely on the Atlantis project [9] [10], a small wing-sailed catamaran, but is larger and more powerful. It uses the same wing sail design, though the control has been modified for hybrid electric/wind drive.

The project is progressing towards environmentally scavenged energy for both propulsion and system power requirements. The wind is the main force used for propulsion, and outside of the doldrums near the equator, provides a reasonable motive force almost anywhere on the planet. The wing, which is passively stable and self-trimming, is used to propel the vehicle both up and downwind (though not directly into the wind).

This work provides an overview of the vehicle, delving into both physical and electrical system architecture, the wing propulsion, the control methodology, and hybrid drive. We present preliminary performance under both protected water and off shore sea states, and provide recommendations for future work.

2. PLATFORM ARCHITECTURE

As pictured in Fig. 1, the basic overall configuration is a catamaran with a single vertical wing at the center of the boat replacing the sails. The wing itself has a forward counter-weight suspended on booms to mass balance the wing about the stub mast, and has two tails mid-span up the wing that are used for aerodynamic control.

Figure 1. HWT X-1 Prototype vehicle, as viewed from above. The vehicle is based on a modified Stiletto 27 Catamaran.

2.1. Physical Architecture

The prototype platform is based on a modified Stiletto Catamaran, originally 9 meters in length, and slightly less than 4.2 meters in width. The cockpits have been removed, and the hulls extended by a meter on each side at the stern. The center structure has been entirely replaced with a welded aluminum box beam that supports the stub mast for the vertical free-rotating wing. The single center board has been replaced with two longer centerboards fitted to each hull, approximately 2 meters long and 30 cm. wide, with a NACA 0015 section.

In order to hold the two hulls together, the center structure was replaced with two circular aluminum tubes which are pin held to each hull (note that this retains the original designs' ability to be telescoped inwards and thus remain contained on a typical trailer). The box beam fits around the forward tube and is held to the aft one with a bolt and tang structure. By releasing the bolts, the box beam can be rotated about the forward tube, lowering the wing tip to the ground and allowing for the wing to be removed. This is how stepping the 12 meter tall wing is accomplished.

Each hull has been fitted with a folding brass propeller on a supported drive shaft approximately 0.5 meters ahead of the rudders, inclined approximately 15 degrees below vertical.

The most visibly unusual feature of the prototype is the vertical wing which replaces the conventional sail. The wind-propulsion system is a rigid wingsail mounted vertically on bearings to allow free rotation in azimuth about a stub-mast, the design of which is detailed in [2]. Aerodynamic torque about the stub-mast is trimmed using two flying tails mounted on booms joined to the wing at the semi-span. This arrangement allows the wingsail to automatically attain the optimum angle to the wind, and weather vane into gusts without inducing large heeling moments. Modern airfoil design allows for an increased lift to drag ratio (L/D) over a conventional sail, thus providing thrust while reducing the overturning moment. Much previous work involving wings on boats can be found in [1], [4], [13] [19], [22], [23].

The wing is a specifically designed aerodynamic section to match propulsion requirements with the low Reynolds number flow associated with sailing vessels (see [7] [5] [6] [18]). Boundary layer trips are used to ensure that the flow

stays attached [17]. For details on configuration stability see [8] [20] [24].

2.2. Electrical Architecture

Modular design has been emphasized throughout the prototype system, both for robustness as well as for debugging purposes. The system is based on a network architecture, with each sensor and actuator being a node on a dedicated Controller Area Network (CAN) [27].

There are six main subsystems on the vehicle: (1) Guidance Navigation and Control (GNC) computer, (2) Electric Drive system, (3) Rudder Actuator, (4) Wing/Flap Actuators, (5) Lighthouse Unit, and (6) Environmental Sensor Module.

The GNC computer is Pentium class PC running MATLAB's XPC target. A Microbotics MIDG II integrated GPS/INS receiver is attached via serial communications, which outputs filtered position and velocity at 5 Hz. (Note that the MIDG is capable of 50 Hz. position updates, but 5 Hz is sufficient for control). The GNC water resistant container and companion data logger is pictured in Fig. 2. Note that the data logger is a Mac MINI running custom software to log all CAN messages on the system for debugging purposes. Note that both computers are run "headless," that is without either keyboards or monitors.

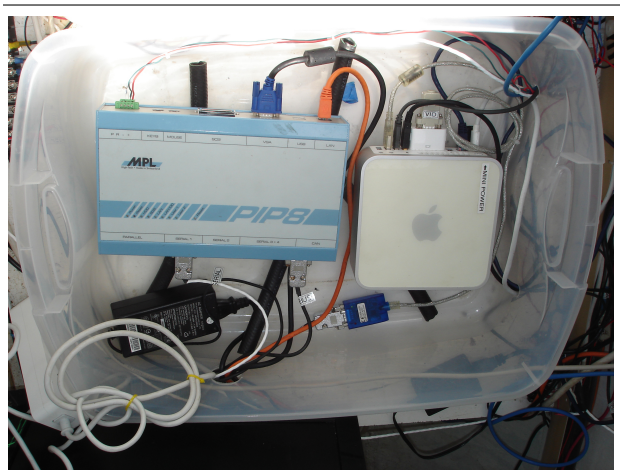

Figure 2. GNC computer and data logger communicate to the rest of the subsystems through CAN and RS232.

The electric drive system consists of two air-cooled pancake DC motors, each rated at 7 KW, driven at 24 V through a commercial 400 Amp H-bridge. The H-bridge is CAN addressable, and allows for forward or reverse operation. In practice, the electric drive motors are never driven in opposite directions, but are used only in common mode (attempts to use the motors to increase the turn rate by reversing the inside motor thrust demonstrated very little improvement over straight use of the rudders). The H-bridge provides data on battery voltage, and motor drive current which is monitored for telemetry use.

The rudder actuator is a 24 V brushed DC motor running through a custom gear head with incremental and absolute encoder feedback. The rudder draws its power from the same battery pack that powers the port hull drive motor. The rudder actuator accepts commands from the GNC computer in a modified fixed precision format, and reports back actual rudder angles based on the encoder feedback. Initial position is determined using the absolute encoder, and the actuator is joined to the physical rudders using an aluminum tube with two rod end bearing connections. This allows for smooth motion with very little backlash. The rudder actuator is housed within an aluminum housing that has been coated with a reflective white paint to reduce internal temperatures. The rudder actuator is pictured in Fig. 3.

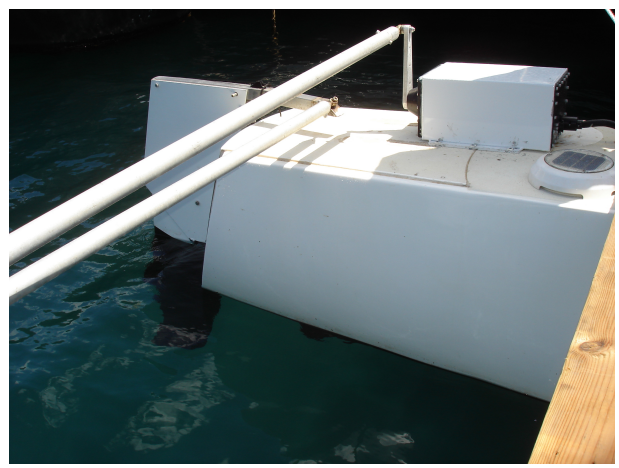

Figure 3. The Rudder Actuator consisting of a 24 V brushed DC motor with custom gear head and encoder feedback. The rudder actuator accepts commands for position from the CAN network and reports back actual rudder angles.

The wing tail and flap actuators are also microcontroller based, with 24 V brushed DC motors and incremental encoders for feedback. Flap and tail limits are read from Hall effect switches located on the surfaces themselves, thus requiring a calibration command on startup. The actuators are located at the base of the wing, and each uses a drum with Spectra line running up through the wing and through pul-

ley blocks and attached to control horns on their respective surfaces. Currently, the tails are set to one actuator, the lower and upper flaps each on another. The flap/tail actuator is commanded by the same modified fixed point CAN commands, and reports back the angles of each of the surfaces at 5 Hz. The actuator is pictured in Fig. 4. Note that the power for the flap/tail actuator comes from the 4 gel cell batteries housed in the wing counter weight on the two carbon fiber booms which extend forward of the wing (this weight serves to bring the mass balance of the wing to the quarter chord line).

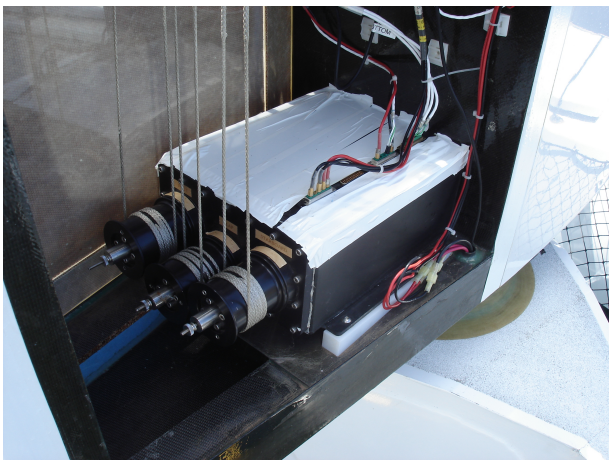

Figure 4. The flap/tail actuators, which are 24 V brushed DC motors with incremental encoder feedback. These are powered from the batteries in the wing ballast box and actuate the surfaces via the pictured Spectra lines.

The lighthouse unit is connected to the top of the wing (and can be seen at the top of Fig. 1), but does not rotate with it, and serves three distinct purposes. Firstly, it is a slip ring for both power and the CAN network to electrically connect the wing to the rest of the vehicle. Secondly, it houses the wing encoder, which reports the wing to boat centerline angle at 5 Hz., and lastly, it houses the camera, telemetry radio, and antenna for ship-to-shore communication. The current proof-of-concept camera is a pan/zoom/tilt web camera, that is attached through a conventional ethernet switch to the ship-to-shore radio, which acts as an ethernet bridge. UDP packets are used to transmit telemetry from the vehicle to the ground station, and to receive patrol patterns, goto points, and emergency stop commands from the ground station to the vehicle.

Lastly, the environmental sensor module processes the raw readings coming from the three anemometers mounted on the wing and reports instantaneous and averaged wind speed and directions for each. Note that this module is also capable of monitoring the two hull speed sensors, as well as the strain gauges on the mast used to detect wing loads in real time (these are not currently implemented, but are planned for the near future).

Within the hulls are the main battery banks, consisting of 16 lead-acid deep cycle marine batteries, arranged in series and parallel to create a large capacity 24 V battery. Also in the hulls are the associated chargers which can recharge the batteries. At full power on the drive motors, the HWT X-1 has duration of approximately 4 hours, and a much longer duration at less than full throttle. While solar panels for charging the batteries are planned, they are not currently installed.

3. WINGSAIL PROPULSION

The wing differs in very fundamental ways from a conventional sail. The most obvious is that the motion of the wing is completely decoupled from the motion of the hull underneath the wing. Because the wing is controlled aerodynamically from its tails (which can be controlled to different angles by the control system), and due to the bearings that allow the wing to rotate freely in azimuth about the stub mast, the wing flies at a constant angle of attack to the apparent wind. That is, independent of the hulls, the wing would fly at a constant angle of attack relative to the true wind, and that angle of attack would be determined by the angle of the tail.

Because the wing is mass balanced at the quarter chord line about the bearings, platform heel angle has no affect on the angle of attack (though the effect of the wind gradient can reduce the effective angle). Fig. 5 shows the wind triangle and the lift and drag forces on the wing, including the effect of the vehicle motion.

Almost irrelevant of the motion of the vehicle, the lift generated by the wing is perpendicular to the relative (or apparent) wind. There is an effect of the velocity of the boat, which is to say that if you point directly into the true wind, the boat velocity will slow to zero and the only wind the wing will see is the true wind.

In Fig. 5, the HWT X-1 is on a port tack, heading upwind. That is, the true wind is coming from the forward left of the vessel. First, the vessel is stationary with the tails set at 0°, and the wind blowing from the forward port side. The wing-sail will point directly into the wind, and no motion will result. In order to generate forward thrust, the tails are set to an angle of $-\delta_t$, with the leading edge of the tails pointing to the left or aft of the true wind. The airflow past the tails, now at an angle of attack to the wind, causes a force to develop that rotates the entire wing- sail/tail structure clockwise α degrees, effectively unloading the tails. The wing, now at an angle of attack (α) develops lift (L)

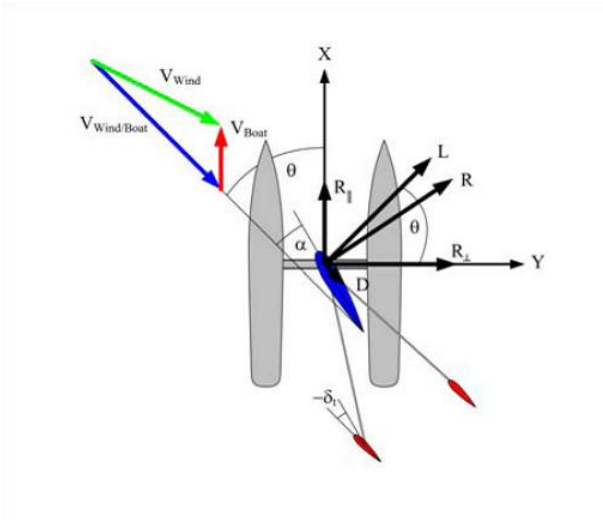

Figure 5. The force vectors of the wind wing interaction while on a port tack resolved into wing and body coordinates. Note that lift and drag are in the aircraft sense.

perpendicular to the true wind, and drag (D) parallel to the true wind (note that the use of lift and drag here is in the conventional aircraft sense). The vector sum of the lift and drag is denoted the resultant (R), which can be resolved into the local body frame as a perpendicular ($R_\perp$) and a parallel ($R_\parallel$) components. As the boat accelerates, the boat velocity (V_{Boat}) adds in a vector sense to the wind in such a way as to rotate the apparent wind towards the front of the boat. As this happens, the tails react so as to keep the wing-sail angle of attack constant with respect to the apparent wind. Note that this happens regardless of why the apparent wind has changed (change in boat velocity or a change in the true wind direction/velocity).

This is why the wing-sail is called self-trimming, as it is passively stable about a fixed angle of attack [10]. For a more in-depth explanation of the functioning of the wing sail, as well as experimental performance measurements of the wing itself, see [11] [12].

4. CONTROL ARCHITECTURE

The control architecture is based on several simple controllers, combined in a hierarchical state machine implementation in order to switch between controllers as appropriate. The basic controllers are each quite simple: heading hold control, and proportional integral controller with feed-forward for velocity, and a line tracking control that consists of two successive proportional control loops closed around heading and cross-track error.

The line acquisition controller consists of a feedforward heading trajectory that is fed into the heading hold controller, and uses the line of sight guidance ($\Psi_{des} = -\arctan\frac{y}{\tau}$), which generates a heading that points straight at the line segment when far away, and points in the direction of the line segment when close to the line.

Mode switching occurs when switching between line segments in order to achieve a smooth trajectory between segments. The internal angle between two segments is used to compute the distance at which to exit the line tracking control and to use the line acquisition for the next segment.

Mission specification is via a set of ordered GPS waypoints which define a patrol pattern. The vehicle will start from its current location and travel to the first point, and then get on the line segment connecting the first and second waypoints. It will transition to the segment between the second and third segment, and so on. At any point, the patrol can be broken with a *goto* command, which will cause the vehicle to break the current patrol and go to the *goto point and loiter* point. A *resume* command will resume the patrol, re-intercepting the last segment at the point at which it was broken.

Again, for a much more detailed introduction to the control system architecture and performance, see [2]. This builds upon previous work in ocean surface vessel control in [14] [15] [25] [16].

5. HYBRID DRIVE PROPULSION

Vehicle velocity is set for each leg of the patrol pattern, and can be set independently. This is the minimum desired boat velocity, and is the set point for the control system. Independently of the rudder control, the electric drive motors and wing surfaces are used to modulate the boat's velocity.

Two independent control systems run in parallel, but interact due to the physics of the boat in order to work together. First, the electric motors are run on a PI loop with a feed-forward term to hold the boat velocity at the minimum speed along a segment. With no wing propulsion, this controller will hold the boat velocity constant. This controller is not allowed to back drive the motors, and thus in the presence of wind propulsion, will throttle down and shut off the drive motors as long as a velocity at or above the minimum is held by the vehicle.

The other independent velocity control is the wing control, which is pictured in Fig. 6. Here, the mode switching (and bang-bang control) is used to generate the appropriate tail deflections that provide thrust along a given point of sail. The figure shows only the upwind state machine, and while the vehicle can sail within 20° of the true wind, the use of a 30° threshold prevents a premature switching of the tails. Likewise, a 20° hysteresis band is used before actuating the

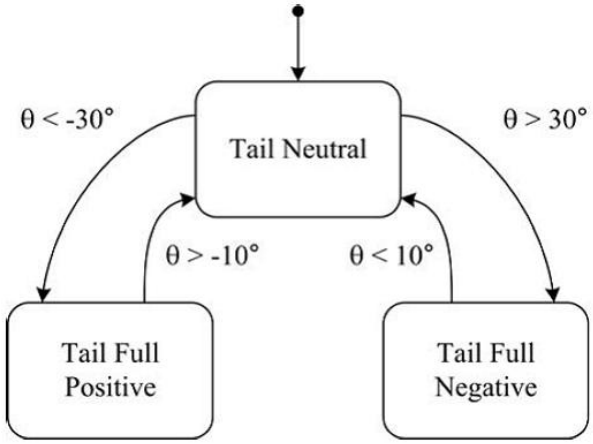

Figure 6. Tail Angle State Machine. Note that only the upwind portion of the state machine is shown. This simple control implements a bang-bang control with hysteresis for wind propulsion.

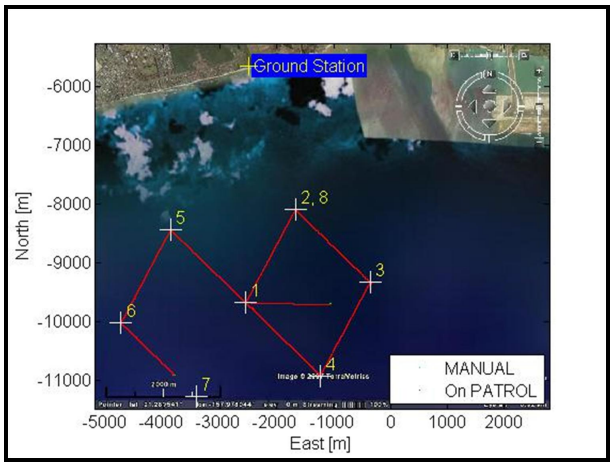

Figure 7. Actual Data from an offshort patrol test in Ewa Beach, Oahu, Hawaii on 9-Jun-2007.

tails. This prevents high speed chatter while the vehicle is pointed high upwind, as the wind is quite unsteady this close to the ocean surface. Note that the feedback from the aerodynamic control to the electric drive control is through the measured GPS velocity, and results in a smooth hybrid operation with the electric motors adding in power when the wind cannot, and shutting down when the wing is providing sufficient thrust.

This simple wing control, coupled with the aerodynamic constant angle of attack of the wing, results in a wing control that automatically tacks and jibes as the true wind or boat hulls move. This if either the wind changes direction, or the boat turns through the wind, the wing will flip the tails to their mirror image in order to continue to have thrust in the correct direction.

6. SYSTEM PERFORMANCE

Several all up system tests have been performed in order to validate the vehicle prototype and control system functionality. One such test was a figure-8 (pictured in Fig. 7 patrol pattern performed off of the southern coast of the Island of Oahu, Hawaii, adjacent to Ewa Beach, on 9-June-2007. A figure-8 was chosen as the patrol path as this would require the HWT X-1 to sail on all points of sail, both upwind and downwind. The size of the pattern was such that the short legs of the figure-8 were approximately 2 km in length, and the long legs were approximately 4 km long.

The wind speed during this trial was from 8 to 10 m/s, and the wave height approximately 1 m at the face of the wave. Note that this corresponds to a Beaufort scale of 5. During this trial, which lasted for just under 2 hours, the electric motors were on only for very brief moments during the waypoint transitions, and then were shut down by the hybrid drive as soon that the wing readjusted to the new point of sail. The entire patrol was propelled by wind scavenged from the environment. During this time, the boat speed varied from approximately 2.5 m/s to 3.6 m/s (above the minimum set speed of 2.0 m/s).

Presented in Fig. 8 is the control performance along the longest leg (between waypoints 4 and 5 reduced to cross track error. Note that the line acquisition controller starts in with a 20 m cross track error and comes into to the line with a small overshoot and then switches to the line tracking controller. While under wind propulsion, and in waves, the HWT X-1 tracks the line with a mean of 1.3 m and a standard deviation of 1.3 m. This performance is very good, considering the magnitude of the disturbances induced by both the wind (through the wing) and the waves, which were pitching and rolling the boat.

The wing greatly increases the vessel's mission duration. All electronic components on the vehicle, excluding motors, total 120 W of power. While under electric motor drive, at full power, the motors consume 4 kW of power and will run down the batteries in 2 hours. By scavenging wind energy for propulsion, the vehicle can spend well over 12 hours maneuvering with little or no draw down in the battery charge. Before 5000 seconds, Figure 9 shows the power consumed by the motors when were used in conjunction with the wing. After 5000 seconds the boat was under solely electric motor propulsion.

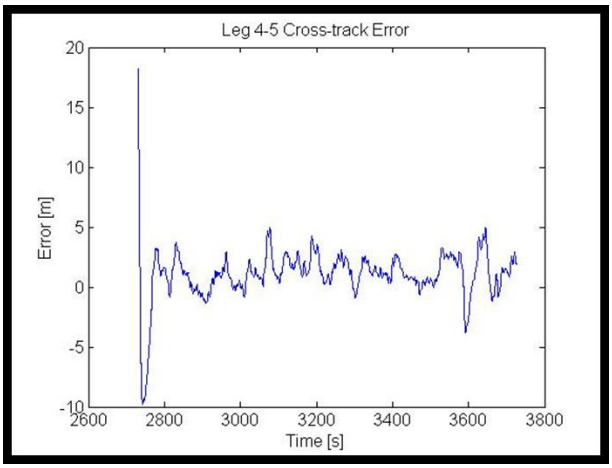

Figure 8. Control System performance in open water patrol test. Control system consists of line acquisition for first 100 meters, and then line tracking for the rest of the segment.

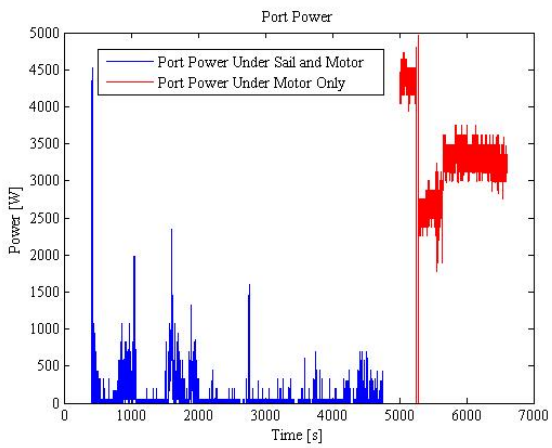

Figure 9. Power performance in open water patrol test. Before 5000 seconds, the vessel is under wing and electric propulsion. After 5000 seconds, the vessel is solely under electric propulsion.

7. CONCLUSIONS AND FUTURE WORKS

7.1. Conclusions

This work presents the system architecture for an unmanned energy scavenging surface vehicle for littoral water surveillance. The prototype vehicle, the HWT X-1, is based on a modified Stiletto Catamaran, which has been extended in length, had twin dagger boards installed, and had the center structure replaced with an aluminum box beam that supports the stub mast for the wing sail. The wing sail is a carbon fiber wing 10.7 m. tall with a 3 m. chord. The wing is mounted on a vertical bearing such that is can freely turn in azimuth, and is controlled aerodynamically by twin tails mounted on booms attached to the wing at mid-span. A deflection of the tails causes the wing to fly at a constant angle of attack to the relative (or apparent) wind.

Using a hierarchy of simple control state machines, autonomous control of both the hull trajectory as well as the wing control for energy scavenged propulsion is achieved. Using two independent simple control strategies for electric propulsion (a PI controller) and aerodynamic wing control (a bang-bang controller with hysteresis) which are linked indirectly through the vehicle GPS velocity, a hybrid propulsion strategy is implemented.

Control system performance demonstrates experimental line tracking performance while under wind propulsion of 1.3 meters mean, and 1.3 meters standard deviation off of the ideal path. Line acquisition control is triggered 20 meters from the waypoint and switches to line tracking within 50 - 100 meters of the line. The wing tacks and jibes as the boat rounds the waypoints in order to keep sailing on its patrol path.

Overall, basic functionality has been demonstrated, and is shown to be environmentally friendly, and energy efficient.

7.2. Future Work

The test shown in Fig. 8 was aborted just before waypoint 7 due to deteriorating environmental conditions. The wind speed had increased to 13 m/s, and the wave height was over 2 meters as measured on the face in under a minute, and the stresses placed on the vehicle were considered excessive. Note that we had transitioned from a Beaufort 5 to a 6.

There are several areas of additional future work that need to be completed before the vehicle can be considered truly operational. First, the wing thrust needs to be modulated dynamically to keep the vessel within structural and dynamic stability limits, based on measured forces while underway. Second, station keeping algorithms, though developed, have not yet been implemented. Lastly, in terms of propulsion, currently when the patrol segment is within 25° of the true wind, the electric motors will solely propel the vehicle. A sailing algorithm that will tack and jibe up or downwind while keeping within the desired lane width would work to have the vessel make progress directly upwind while still conserving more power.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of HarborWing Technology Inc. which has generously provided the platform for development of this vehicle, and the Pearl Harbor Naval Personnel for their support.

References

[1] Birchill, J., "The Windform Sail," *The Ancient Interface II, Proceedings of the Second AIAA Symposium on the Aer/Hydronautics of Sailing*, AIAA Lecture Series, Vol. 9, AIAA Los Angeles, 1970. Pages 59-73.

[2] Boyce Jr., C. O., Elkaim, G. H., "Control System Performance of an Unmanned Wind-Propelled Catamaran," *Proc. Of the IFAC Conference on Control Applications in Marine Systems*, IFAC CAMS, Bol, Croatia, 19-21 Sept. 2007

[3] Bradfield, W., "Predicted and measured performance of a daysailing catamaran," *Marine Technology*, January 1970, pp. 21–37.

[4] Cornell University, *Rigid Airfoil Team*, available online at: http://www.dcaonline.com/raft/index2.html

[5] Drela, M., "A new transformation and integration scheme for the compressible boundary layer equations, and solution behavior at separation," *MIT GTL Report #172*, MIT Press, May 1983.

[6] Drela, M., "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils," *Conference on Low Reynolds Number Airfoil Aerodynamics*, University of Notre Dame, June 1989.

[7] Drela, M., *XFOIL website*, available online at: http://raphael.mit.edu/xfoil

[8] Elkaim, G. H., "Airfoil Section Design and Configuration Analysis of a Free-Rotating Wing-Sail for an Autonomous Marine Surface Vehicle," *AIAA Journal of Aircraft* (2008), doi:10.2514/1.27284

[9] Elkaim, G., *System Identification for Precision Control of a Wingsailed GPS-Guided Catamarn*, Ph.D. thesis, Stanford University, 2001.

[10] Elkaim, G., "The Atlantis Project: A GPS-Guided Wing-Sailed Autonomous Catamaran," *Navigation*, Vol. 53:4, 2006, pp. 237-247.

[11] Elkaim G. H. and Boyce Jr., C. O., "Experimental Aerodynamic Performance of a Self-Trimming Wing-Sail for Autonomous Surface Vehicles," *Proc. Of the IFAC Conference on Control Applications in Marine Systems*, IFAC CAMS, Bol, Croatia, 19-21 Sept. 2007

[12] Elkaim, G. H. and Boyce Jr., C. O., "Experimental Validation of GPS-Based Control of an Unmanned Wing-Sailed Catamaran," *ION Global Navigation Satellite Systems Conference*, ION GNSS 2007, Fort Worth, TX, Sept. 25-28, 2007, pp. 1950-1956

[13] Fekete, G., Newmann, G., "Design and Testing of a Sailboat with Self-Trimming Wingsail," *Canadian Aeronautics and Space Journal*, Vol. 29, No. 2, June 1983. Pages 121-130.

[14] Fossen, T., *Guidance and Control of Ocean Vehicles*, Wiley and Sons, New York, NY, 1994.

[15] Fossen, T., "A Nonlinear Unified State-Space Model for Ship Maneuvering and Control in a Seaway," *Intl Journal of Bifurcation and Chaos*, Vol. 15, 2005, pp. 2717–2746.

[16] Lefeber, E., Pettersen, K., and Nijmeijer, H., "Tracking Control of an Underactuated Ship," *IEEE Transactions on Control Systems Technology*, Vol. 3, 2003, pp. 52–61.

[17] Gopalarathnam, A., Broughton, B. A., McGranahan, B. D., and Selig, M. S., "Design of low Reynolds number airfoils with trips," *AIAA Journal of Aircraft*, Vol. 40, No. 4, July-August 2003, pp. 768-775.

[18] Lyon, C. A., Selig, M. S., and Broeren, A. P., *Boundary Layer Trips on Airfoils at Low Reynolds Numbers*, AIAA Paper 97:0511, 1997.

[19] Marchaj, C. A., *Sail performance: techniques to maximize sail power*, International Marine, Camden, ME, 1996.

[20] McCormick, B., *Aerodynamics, Aeronautics, and Flight Mechanics*, John Wiley and Sons, New York, NY, 1979.

[21] Pascoal, A., Olivera, P., and Silvestre, C., "Robotic Ocean Vehicles for Marine Science Applications: The European ASIMOV Project," *OCEANS 2000 MTS/IEEE Conference and Exhibition*, Vol. 1, 2000, pp. 409–415.

[22] Quinton, B., *Boatek website*, available online at: http://www.boatek.demon.co.uk

[23] Ross, J. C., "Aerodynamic Design of a Rigid-Wing Sail for a C-Class Catamaran," *The Ancient Interface XVIII, Proceedings of the Eighteenth AIAA Symposium on the*

Aer/Hydronautics of Sailing, AIAA Lecture Series, Vol. 35, AIAA Stanford, 1989. Pages 17-27.

[24] Shevell, R. S., *Fundamentals of Flight*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1983.

[25] Skjetne, R. and Fossen, T., "Nonlinear Maneuvering and Control of Ships," *MTS/IEEE OCEANS 2001*, Vol. 3, 2001, pp. 1808–15.

[26] VanZwieten, T., *Dynamic Simulation and Control of an Autonomous Surface Vehicle*, Ph.D. thesis, Florida Atlantic University, 2003.

[27] Wolfhard, L., *CAN System Engineering: From Theory to Practical Application*, Springer Verlag, New York, NY, 1997.