Experimental Validation of GPS-Based Control of an Unmanned Wing-Sailed Catamaran

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Abstract

Precision guidance and control of an autonomous, wing-sailed catamaran has been demonstrated by Harbor Wing Technologies' X-1. Based closely on the Atlantis project, the X-1 is larger, more capable version. The platform is a modified Stiletto, a 9.1 m (30 ft) catamaran, experimentally capable of navigating along straight line segments between GPS waypoints and achieving line tracking with average errors/standard deviations of 1.6 m/1.4 m error in protected water and 3.3 m/1.8 m error in open water, respectively.

The X-1 uses a novel hybrid propulsion system consisting of electric motors, powered from an on-board battery bank, and the wing-sail. If the minimum speed required for the current line segment is not achieved under wind power, the electric motors provide the remaining thrust. Power consumed under electric motor power can be in excess of 7 kW (10 HP) for 3 m/s (6 knots) of boat speed. Under hybrid propulsion, power has been shown to be 240 W for similar speeds.

X-1's control system configures the wing for maximum performance based on the estimated polar angle, the angle between the true wind and the vessel's heading. Currently, travel upwind with a polar angle less than 30° is performed solely under electric motor.

Using the line tracking capabilities of the platform, a new test pattern has been developed to derive performance data for the vehicle. Preliminary boat polar data shows X-1 capable of achieving 50% of true wind speed for 10° of tail angle and no flap deflection.

1 Introduction

Current unmanned surface vessels have mission durations on the order of a 24 hours [2]. While a multi-day mission length is still very useful for near theater operations, month long durations opens up new possibilities for surveillance and patrol missions.

An example of a long-duration mission would include patrolling the perimeter of some protected waters such as the Northwest Hawaiian Island National Marine Sanctuary. Over 1,200 NM long, the monument would require multiple vessels all patrolling autonomously. The concept of operations would include a centralized operator who would monitor the general status of each vessel and periodically adjust the patrol pattern through a satellite communications link. Each vessel would operate autonomously, allowing the operator to focus on high level mission requirements. For example, a vessel would autonomously patrol using feedback, sensing, and actuators to remain on course. Upon detecting an unknown object, the vessel would alert the operator and be ready to either approach the object for closer inspection or take evasive action, depending on the relayed command from the supervising human.

To achieve such a long-duration mission, energy scavenging techniques are required to maintain small cost-effective vessels. As an examination of possible solutions, Harbor Wing Technologies has developed the X-1, a proof-of-concept vessel to demonstrate novel propulsion concepts. Based on the Atlantis project [4], the X-1 is a larger, more capable version. The X-1 is a 9.1 m (30 ft) modified Stiletto catamaran, with nomex/fiberglass hulls and a carbon fiber wing that is 10.7 m (35 ft) tall and has a 3 m (10 ft) chord. For aerodynamic control of the wing, twin tails are suspended on two carbon fiber booms extending back from the semi-span of the wing, as pictured in Fig. 1.

The wind provides the main propulsive force, and outside of the doldrums near the equator, maintains a reasonable motive force almost anywhere on the oceans. The wing, which is passively stable and self-trimming, is used to propel the vehicle both up and downwind, but, like all sailboats, not directly into the wind. To meet the minimum speed requirements in the event that wind propulsion is insufficient, X-1 is equipped with electrical motors driving self-folding propellers on each hull. This hybrid propulsion system is both efficient and operationally redundant which will enable long mission durations.

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

2 Platform Architecture

The X-1 uses a networked architecture for the vessel's sensors and actuators. Details of X-1's architecture can be found in References [3, 5], while Figure 2 diagrams the basic structure. A 800 MHz Pentium-class industrial PC (PIP) running MATLAB xPC real-time system communicates with most of the vessel's sensors and actuators along a Controller Area Network (CAN-bus) running at 250 KB/s. A Microbotics MIDG-II GPS/INS system, which uses RS232 serial communication to report vehicle state at 5Hz, provides the vessel's inertial state, including position, velocity, attitude (pitch, roll, and yaw), rotation rates, magnetic field measurements, and body-fixed accelerations.

A second generic PC runs as an auxiliary monitoring device. In the current system, this is a Mac MINI running Windows XP, and serves three purposes: (1) It logs all CAN traffic to a file for later analysis, (2) It reads a joystick which is used for manual interaction with the control system, and (3) It communicates through UDP packets to the ground station reporting the telemetry from the vehicle through a 900MHz FreeWave radio.

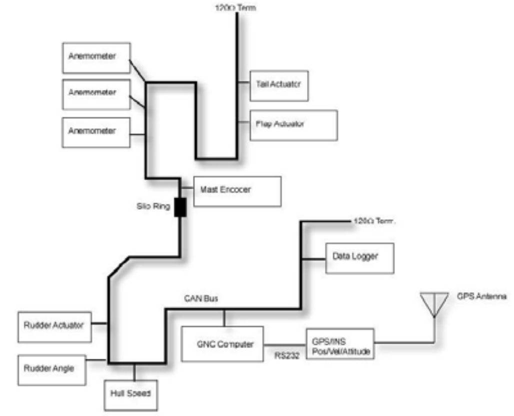

Figure 2. HWT X-1's distributed network bus architecture.

Since wind power is not always feasible, each hull contains a 7.5 kW electric motor to augment the wing propulsion system. Power for the motors comes from several 24 V conventional lead-acid battery banks totaling more than 600 Ah of capacity. The batteries provide thrust for approximately four hours under electric propulsion, and well over 24 hours using the combination of wind and electric propulsion.

A unit that sits atop the mast houses the mast encoder (for wing to hull angle), slip rings for the CAN-bus and power lines, and includes both a camera and the radio for ground communications. Currently, the camera is a simple pan zoom tilt webcam that is used to demonstrate the concept.

3 Wing-Sail Concepts

The most visibly unusual feature of HWT X-1 is the vertical rigid wing-sail which replaces the conventional sail. The wing-sail mounts on bearings that allow free rotation in azimuth about a stub-mast. Aerodynamic torque about the stub-mast is trimmed using two flying tails mounted on booms joined to the wing. This arrangement allows the wing-sail to automatically attain the optimum angle to the wind, and weather vane into gusts without inducing large heeling moments.

The complex nature of the aerodynamics of a sail makes any sort of precise control of the sail difficult to accomplish. In contrast to a conventional sail, the wing-sail is passively stable, meaning that it flies at a constant angle of attack to the relative wind, and that angle of attack is determined solely by the angle of the tail. Also, based on a wing's efficiency over a sail, aerodynamic modeling predicts that X-1's wing-sail will generate three times the lift of an equivalent area of sail. Additionally, the actuation forces on the tails are very light when compared to holding the main sheet on a sail. For a complete description of the wing-sail, and experimental validation of its performance, see [7].

4 Hybrid Propulsion

The X-1 uses independent electric motors and wind/wing propulsion, to form the vessel's hybrid propulsion system. When engaged, the wing provides most if not all of the propulsion needs of the vessel. If the wing is insufficient to meet the desired minimum speed, electric motors make up the remaining required propulsion.

The electric motor speed is maintained by a proportional-integral controller, which is limited to provide positive thrust only. Currently, any speed in excess of the minimum desired speed is allowed up to the safety constraints. The safety constraints ensure that the vessel's roll is less than 5° and the pitch is less than 6°. Until these limits are met, the maximum tail deflection is allowed. Upon reaching these limits, the tail deflection is reduced until the safety requirements are met.

5 Wing-sail Control

The wing-sail may be analyzed using conventional airfoil theory. Figure 3 shows the relationship between the true wind, the relative motion of the boat, and the forces generated by the wing. As shown in the figure for a port tack, a negative deflection of the tails leads to a positive angle of attack to the on coming wind and results in forward thrust. For a starboard tack, where the wind comes from the opposite side of the boat, the tails must have a positive deflection to generate forward thrust.

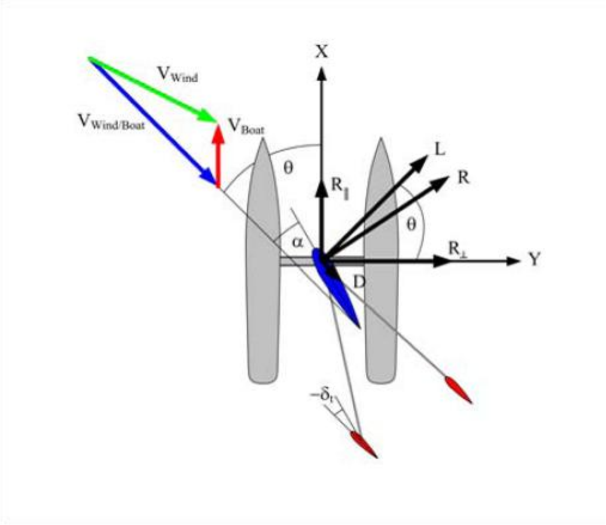

Figure 3. Aerodynamic forces on wing-sail.

The boat's polar angle uniquely determines the type of tack or point-of-sail. Figure 4 shows the polar angle defined as the relative angle between the oncoming wind and the direction of the vessel's motion. Given all possible polar angles, Figure 5 shows the appropriate deflection of the tails to generate forward thrust. A state machine running on the PIP estimates the boats polar angle and sets the tails accordingly. Hysteresis is used along the borders of different tail settings to reduce chatter.

Since X-1 cannot travel efficiently upwind, the control software only engages the tails for polar angles outside of ±30°. Within this zone, the software sets the tails to the neutral position and the electric motors provide all of the vessel's propulsion.

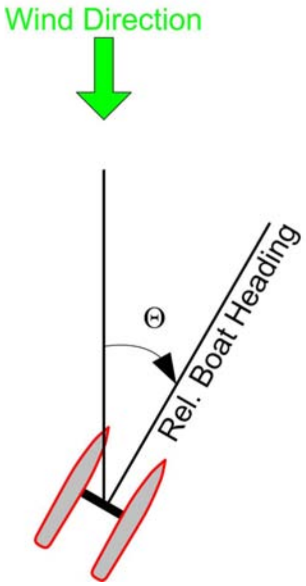

Figure 4. Definition of polar angle.

6 Line tracking algorithm

The concept of operations for an autonomous vessel requires the boat to patrol a path given by a series of waypoints. Between each consecutive pair of waypoints, a straight line segment defines the desired path of the vessel and position deviations from this line are considered cross-track error. Associated with each line segment are additional parameters which govern the minimum required vessel speed and the designated corridor allocated for tacking maneuvers.

Before line tracking can take place, the vessel must first acquire the line. Line acquisition ends when the vessel's heading and cross-track errors are within a specified range, at which time, line tracking may begin.

Reference [3] originally developed the line acquisition and tracking algorithms, while Refences [1, 6] make further improvements. The simplified hierarchical state machine of Figure 6 shows the algorithm behind line acquisi-

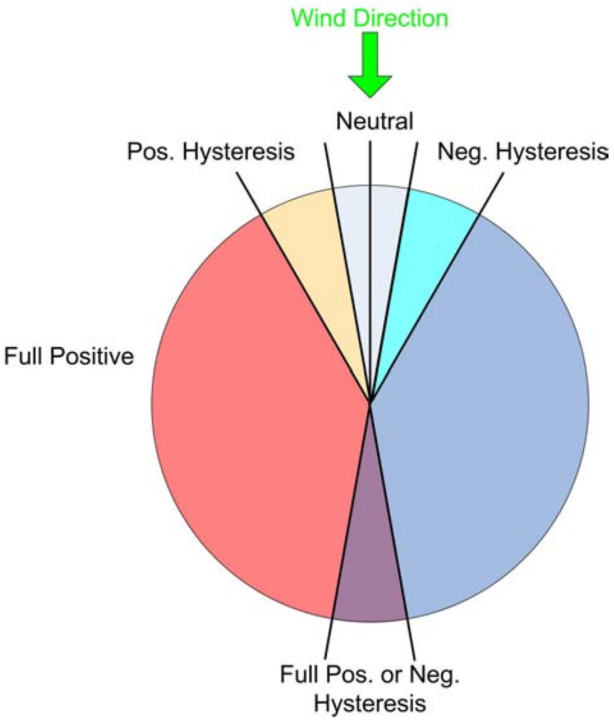

Figure 5. Flap deflection over all polar angles with wing hysteresis.

tion and control. A unique feature of the controllers is that the heading error is scaled by velocity to make for a simple linear control between rudder deflection and heading rate. Figure 7 diagrams the tracking control loop.

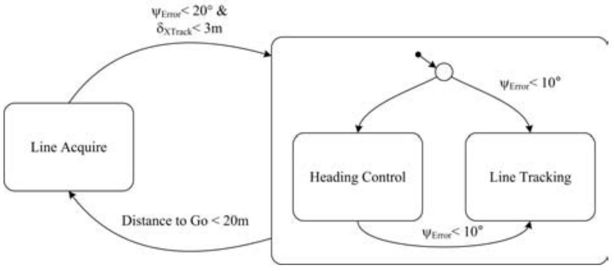

Figure 6. State machine for tracking algorithm.

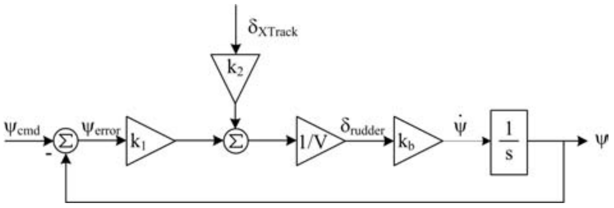

Figure 7. Line tracking control loop diagram.

7 System Performance

7.1 Segment errors

The performance of the line tracking algorithms is measured by the mean error and the standard deviation of cross-track error. By sending X-1 on a closed "figure-8" shaped course of eight waypoints, multiple segments along different points of sail may be evaluated.

Initial testing of X-1 was performed in Pearl Harbor, Oahu. The protected waters of the harbor make for benign testing conditions. Figure 8 shows the waypoints in white and the vessel's trajectory between the test points in red, while Figure 9 shows the cross-track error along each of the segments during a typical test run. The largest mean cross-track error over all segments was 1.4 m with a standard deviation of 1.6 m. This performance is adequate to safely perform testing in open, or unprotected, water.

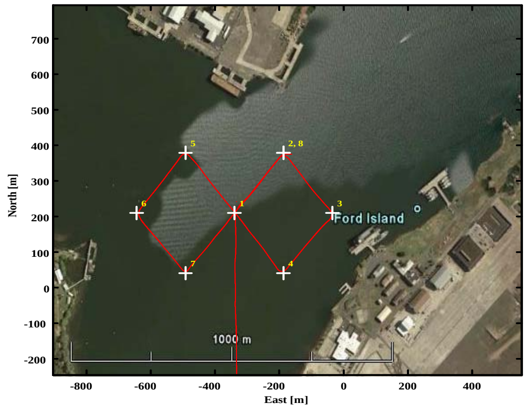

Figure 8. Autonomous sailing "figure-8" pattern in Pearl Harbor.

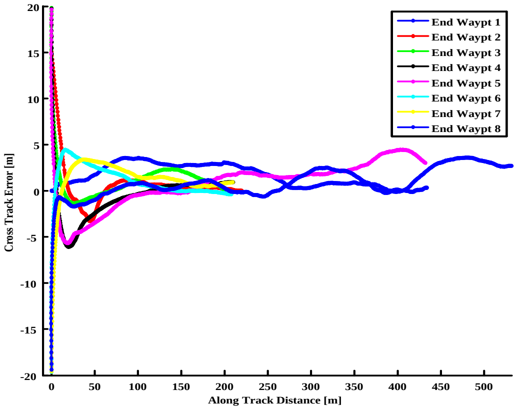

Figure 9. Cross-track performance of vessel autonomously sailing "figure-8" pattern in Pearl Harbor.

On June 9, 2007, Harbor Wing Technologies tested

X-1 off of Ewa Beach, Oahu, outside of Pearl Harbor. Figure 10 shows the waypoints of the defined patrol pattern in white and the vessel's track in red. The test was ended before the pattern was completed due to an increase in sea state. As X-1 is only a proof-of-concept vessel, the 2 m (6 ft) swells and 18 m/s (35 knot) wind were deemed excessive for the vessel's structure.

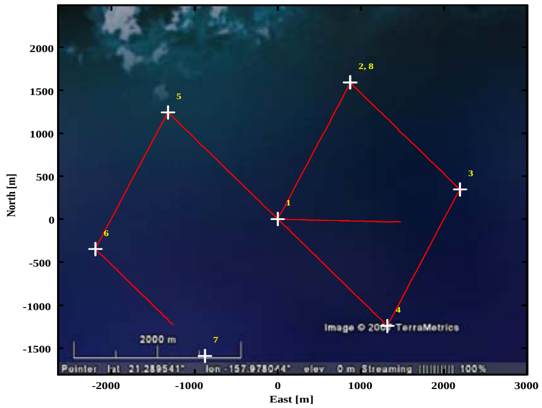

Figure 10. Autonomous sailing "figure-8" pattern in open water off Oahu.

Figure 11, shows the tracking performance along each of the segments. Each color denotes the ending waypoint of the segment. The largest mean error over all of the segments was 3.3 m, while the largest standard deviation was 1.8 m. The increase in mean errors was due to the increased disturbance by both wind and waves encountered at sea.

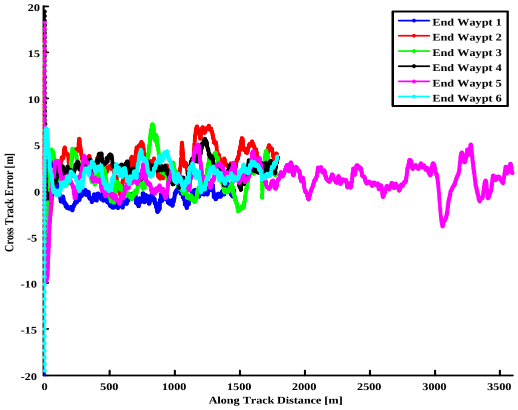

Figure 11. Cross-track performance of vessel autonomously sailing "figure-8" pattern in open water off Oahu.

7.2 Power diagram

In most USV designs, mission duration is governed by the quantity of fuel or the size of the batteries carried on the vessel. This limits operating times between 8 and 48 hours [2]. By using the free energy available in the wind, a wing-sailed vessel can augment its fuel resources and extend its mission duration to weeks.

Figure 12 shows power measurements from X-1's port motor during two different propulsion schemes. The blue trace denotes the power used under hybrid mode where both the wing and the electric motors generate propulsion. Spikes in the data appear as the vessel slows down during the switching between line segments and the electric motor must turn on to maintain speed. Average vessel speed along the line segments was 2.8 m/s (5.4 knots) and the vessel averaged 120 W of power on each motor. The red trace shows the power consumption by the port motor while the vessel was solely driven by electric motors and was being returned to Pearl Harbor. Over this period, the average vessel speed was 3.3 m/s (6.4 knots) and the average power was 3.5 kW. For the overall vessel power, these numbers are doubled to account for the motor in each hull.

Under motor power alone, X-1 will run for a few hours. With more than a 29 times reduction in power due to the use of the wing, X-1 can be expected to run for almost two days. Such an increase in the efficiency of power utilization can be further enhanced by energy scavenging schemes such as solar cells and the use of wind and water turbines and is the subject of future work.

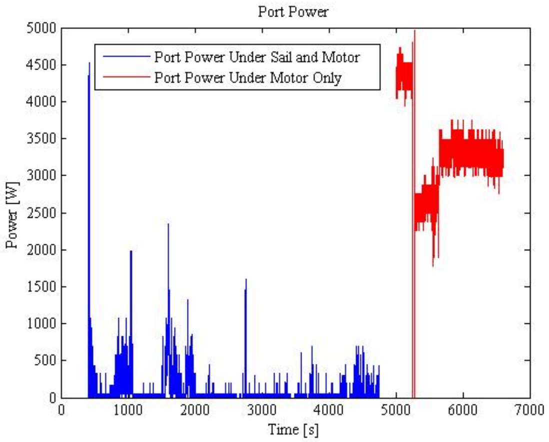

Figure 12. Average power of port motor during autonomously sailing of "figure-8" pattern in open water.

7.3 Wind Polar

As discussed in Section 5, the propulsive force generated by the wing is a function of both wind speed and the polar angle. With the vessel's capacity of line tracking established, a new wagon-wheel pattern was designed in order to collect wing performance data along various polar angles. The performance data consist of the ratio of the vessel's speed to true wind speed.

Figure 13 shows the waypoints and the boat traces under autonomous mode. In completing the wheel pattern, the boat travels in each direction along every "spoke" giving a minimum of two polar angles per spoke. Since the wind's direction is dynamic, measurements over numerous polar angles are achieved. The ratio of boat speed to wind speed is collected and averaged for polar angles in ten degree sectors. Figure 14 shows the speed ratio for the various average polar angles attained for one run of the pattern. Since the wing's tails are not engaged when the absolute value of the polar angle is less than 30°, this sector is delineated in red on the plot.

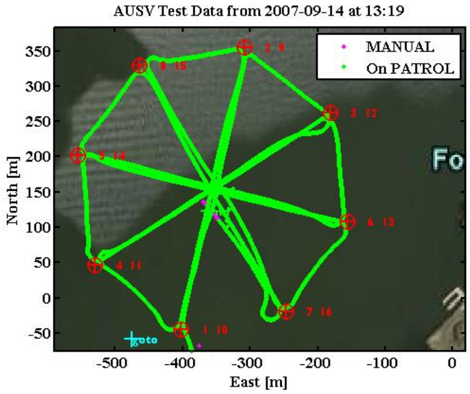

Figure 13. Wagon wheel pattern of vessel for determining boat polar.

Figure 14 is referred to as the boat's "polar" or butterfly plot. From the plot, the maximum speed achievable by the vessel is when it is "reaching" or moving perpendicular to the wind direction. At that point of sail, the vessel can attain roughly half the wind speed. Also, down wind performance is seen to drop to 20% of wind speed. Traveling directly down wind is inefficient both for conventional and wing-sailed boats. Typically, a high performance sailboat will jibe back and forth down wind (much the same as tacking up wind).

While difficult to determine based on the limited data set, the best upwind speed appears around ±50°. This would be the optimal polar angle to take during a tack in order to make the maximum progress upwind or velocity made good, V_{mg}. On this point of sail, the vessel would achieve 37% of the wind speed at a tail setting of 10°.

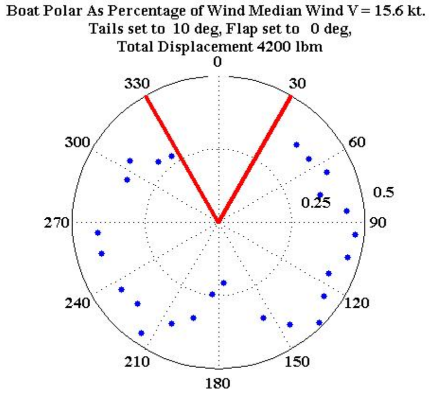

Figure 14. Boat polar for 10° flap deflection.

8 Conclusions and Future Work

Harbor Wing Technologies' X-1 is the first vessel to demonstrate autonomous sailing along a closed course. Tracking performance for the X-1 was achieved with an average cross-track error of 1.6 m and a standard deviation of 1.4 m in protected water and with an average cross-track error of 3.3 m and a standard deviation of 1.8 m in open water. These errors stem from gains used in the rudder's control laws. Since these gains were empirically obtained, they are non-optimal. Further refinement into the gains will continue.

In utilizing the wing, the vessel reduced its power consumption by more than a factor of 29. Even more such savings can be achieved by an improvement in the processors on board and a refinement of the steering algorithms.

In addition, energy scavenging systems such as solar cells, wind and water turbines will be added to further increase the mission duration. Also, tacking algorithms to reduce the reliance on electric motors will be developed.

A simple boat polar was generated from a single run of a wagon-wheel pattern. The maximum speed was found to be approximately half of the true wind speed for tail deviations of 10°. These tests will be repeated with tail deflections up to the mechanical limit of 30°.

Future work includes installing load cells on the mast to act as a balance and leading to real-time direct measurements of the wing's forces. These forces will not only provide better aerodynamic data for the wing, but will also provide an additional measure of the over-turning force on the vessel. Such a measurement will be developed into a safety monitor to ensure the stability of the vessel.

9 Acknowledgements

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