CONTROL SYSTEM PERFORMANCE OF AN UNMANNED WIND-PROPELLED CATAMARAN

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Abstract: Recent experimental testing of an unmanned autonomous marine surface vehicle has demonstrated several key advances in control system performance for a wind propelled platform. The HWT X-1 is a winged catamaran based on a modified conventional sailing vessel intended for use as a surveillance and sensor platform in either littoral or unprotected waters. Using GPS and an off-the-shelf commercial Attitude and Heading Reference System (AHRS) as the primary sensors, in integrated control architecture has been implemented that has demonstrated closed loop control about a figure-8 course while under wind propulsion. A speed regulation control system maintains a minimum speed on course using a combination of electric drive motors and wind propulsion, reducing power on the drive motors as the wing-sail accelerates the vehicle. Trajectory control is accomplished with line acquisition and line tracking controllers. The line acquisition control uses a line-of-sight guidance law, and acquires the line within 100m. The line tracking controller demonstrated an ensemble mean of 1.0m and a standard deviation of 0.7m for sheltered waters, and mean of 1.6m and a standard deviation of 1.2m for open waters.

Keywords: Autonomous Surface Vehicle, Wind Propulsion, Trajectory Control

1. INTRODUCTION

While the role of Unmanned Aerial Vehicles (UAV's) in surveillance, mapping, wild-life monitoring, and defense is well established, Autonomous Marine Surface Vehicles (ASV's) have received much less attention. As a basic sensor platform, ASV's also enable much lower cost surveillance, littoral patrol, oceanographic sampling, and meteorological investigations (Stambaugh and Thibault, 1992; Fryxell and Silvestre, 1994). The ASV in general can have a much larger sensor footprint than an airborne sensor, though of course the sensor is located close to the sea surface. The speed differential between an ASV and the typical UAV creates interesting cooperative possibilities, and having different sensor modalities can complement traditional UAV platforms. In general, ASV's are much less sensitive to payload weight than UAV's (using ships to transport freight is a much older and less expensive technology than aircraft). With the addition of wind-based propulsion, energy is scavenged from the environment, allowing for extremely long duration autonomous operation.

Thus, in order to expand and enable the utility of ASV's, precise control of the ASV trajectory is required. A high level of autonomy allows the ASV to operate without constant human input, thus allowing a single operator to control many ASV's, or even to hand off control from one operator to another. As envisioned, the operator provides only high level commands (patrol trajectories, operating parameters, etc.), and the data from the sensors is relayed back only when some interesting event is detected. This allows a "set-and-forget" type of operation that enables the ASV to overcome scarce human resources.

A typical mission would be to patrol the perimeter of some protected waters, as a remote sentry. In this case, depending on the size of the perimeter, one or more ASV's would run fixed patrols, scanning for other vessels penetrating the keep-out zone. If detected, an alert would be sent back to the command center, and various responses could be taken; the ASV could be vectored to take a closer look at the intruding vessel, or a UAV launched from the command center, or any other appropriate response. Having the ASV out on patrol, however, means that a manned patrol vessel in not required to be doing so, or that a single patrol vessel, networked to a flotilla of ASV's can cover a much larger perimeter.

Precision guidance and control of an autonomous, wing-sailed catamaran has been demonstrated by the HWT X-1, a modified Stiletto catamaran, to be experimentally capable of tracking straight line segments to typically better than 1.0 m (1-σ) in protected water and 2 m in open water. This paper extends the navigation algorithms developed for the Atlantis vessel (Elkaim, 2001; Elkaim, 2006) and demonstrates a more complete architecture for vehicle control. The HWT X-1 is a 9.1 m (30 ft) 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, 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 (though—like all sail boats—not directly into the wind). When wind propulsion is not sufficient to meet the minimum speed requirements of 7 km/h (4 kts), the HWT X-1 is also equipped with electrical motors driving self-folding propellers on each hull.

2. SYSTEM ARCHITECTURE

The HWT X-1 system architecture is based on a central processing unit and distributed sensing and actuation. The main processor is a Pentium-class industrial PC (PIP) running MATLAB xPC real-time system. The main vehicle sensor is the Microbotics MIDG-II GPS/INS system, which uses RS232 serial communication to report vehicle

Fig. 1. The HarborWing HWT-X1 experimental prototype wing-sailed autonomous catamaran

state at 5 Hz. The MIDG provides the vehicle inertial state, including position, velocity, attitude (pitch, roll, and yaw), rotation rates, magnetic field measurements, and body-fixed accelerations. There are an additional set of analog sensors which include hull speed on both hulls, three anemometers measuring wind speed and direction at low, middle, and top elevations along the wing (in order to estimate wind gradients), wing to hull angles, upper and lower flap angles, tail angles, and rudder angles.

Each of these sensor subsystems communicates to the PIP on a Controller Area Network (CAN-bus) running at 250 KB/s. There are several actuator subsystems; these control the tails, rudders, flaps, as well as the electric drive motors. The electric drive motors are each independently controlled through dual Navitas 400 A H-bridges. Each of these actuators (including the Navitas) is also on the CAN-bus. Power for these systems comes from conventional lead-acid batteries that provide for approximately four hours of duration under electric propulsion, and well over 24 hours using wind propulsion.

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 900 MHz FreeWave radio.

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 PROPULSION

The most visibly unusual feature of HWT X-1 is the vertical wing which replaces the conventional sail. The wind-propulsion system is a rigid wing-sail mounted vertically 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. Modern airfoil design allows for an increased lift-to-drag ratio and reduced overturning moment over a conventional sail. Additionally, by virtue of its rigid surface, the wing-sail can point upwind better than a conventional sail since it is not subject to aeroelastic collapse (or luffing).

The wing and airfoil section were designed for equivalent performance to the original sail system, low actuation force, and the ability to precisely control the resulting propulsive system. Note that a sloop rig sail can achieve at best a maximum lift coefficient of 0.8 if the jib and sail are perfectly trimmed (Marchaj, 2002). Realistically, an operating maximum lift coefficient is more likely in the 0.6-0.7 range. Based on computational fluid dynamics modeling using VSAERO (Maskew, 1987) the HWT X-1 wing is predicted to achieve a maximum lift coefficient of 2.2, allowing the wing to generate three times the force of an equivalently sized sail. The distribution of lift is worse for overturning loads due to the aerodynamic loading at the top of the wing (not present on sails due to the extreme taper of conventional sails), however because the drag characteristics of the wing are much improved, and as such the performance of the wing-sailed catamaran should be superior to the original configuration.

A conventional sail requires large and expensive actuators as the forces required are quite large. Additionally, 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. 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 (Elkaim, G.H., and Boyce Jr., C.O., 2007).

4. CONTROL ARCHITECTURE

The control architecture is based on several simple controllers, implemented as a hierarchical state machine in order to switch between modes as appropriate. This architecture extends the previous work done on the Atlantis for segmented trajectory control (Elkaim and Kelbley, 2006*a*; Elkaim and Kelbley, 2006*b*). The basic controllers are each quite simple: heading hold control, non-linear heading line-of-sight guidance, a proportional integral controller with feed-forward for velocity, a bang-bang controller with hysteresis for tail angle, and a line tracking control that consists of two successive proportional control loops closed around heading and cross-track error (effectively making a proportional derivative control).

The line acquisition controller consists of a feed-forward heading trajectory that is fed into the heading hold controller, and uses well known line of sight guidance ($\Psi_{cmd} = -\arctan \frac{y}{\tau}$), which generates a heading that points straight at the line segment when far away, and aligns in the direction of the line segment as the vehicle approaches the line. At the time of trajectory definition, the distance at which to switch out of line tracking and into line acquisition can be precomputed to match the angle between the two lines. That is, the initial heading angle of the line acquisition controller is the angle to the next line segment. In practice, this results in a very small improvement in performance, and a fixed switch distance of 20 m is used.

The similarity in structure between the line acquisition and line tracking controllers allows the same controller to perform both tasks. The line acquisition trajectory generation feeds a heading hold controller, which is a proportional controller that is scaled by vehicle velocity. In the case of line tracking, a second input of cross track error is also injected into the controller. Thus, the cross track error gain is set to zero for heading hold, and set to its nominal gain (k_2) for line tracking. Fig. 2 shows the structure for the heading and line tracking controller. The gains k_1, and k_2, are tuned for desired performance. The gain k_b, represents the dynamics of the vehicle which converts rudder deflections, δ_{rudder}, into heading rate. Formulations for both the line acquisition and the line tracking are made such that the controller is velocity independent, automatically scaling the gains as required. By carefully monitoring and scaling for boat velocity, the controller has the added benefit that it is stable for both forward and reverse platform motion.

Mode switching is used to transition from one line segment to the next, going from line tracking to line acquisition and then back to line tracking once the new segment has been acquired. Fig. 3 shows the switch logic used to transition between these differing modes of control, along with the criteria used to determine when to switch the controllers (in this case, computing the heading feed-forward and zeroing the cross-track gain).

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 2 m/ s, which is 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 2 m/ s or above is held by the vehicle.

The other independent velocity control is the wing control, which is pictured in Fig. 4. 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 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.

These low-level controllers are wrapped into a larger high-level mission control. 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 waypoint, and then acquire the line segment connecting the first and second waypoints. It will then transition to the segment between the second and third waypoints, and so on until the patrol pattern is completed (at which point the vehicle will put itself in safe mode). At any point, the

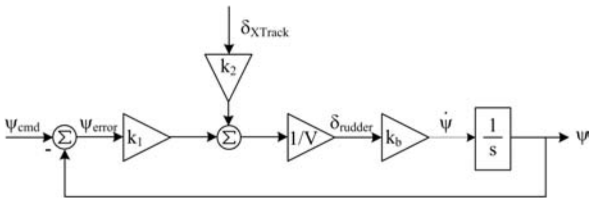

Fig. 2. Control loop for heading and line tracking.

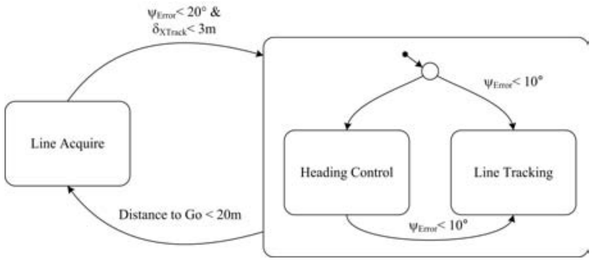

Fig. 3. Mode switching occurs between line acquisition and line tracking.

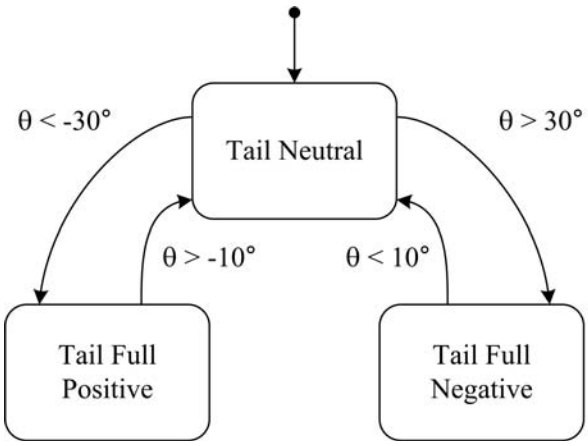

Fig. 4. Tail switching state machine.

patrol can be broken with a *goto* command, which will cause the vehicle to break the current patrol and go to the defined goto point and loiter at that point. A *resume* command will resume the patrol, reintercepting the last segment at the point at which the patrol was broken.

5. EXPERIMENTAL SETUP

In order to validate the performance of the control architecture, a series of patrol patterns were performed in Pearl Harbor, Hawaii. The location was chosen to provide sheltered waters for development, while at the same time having winds strong enough to test out the wing propulsion system robustness. At its current incarnation, the autonomous portions of the control are performed using a hybrid of electric and wind propulsion system. If the wind is insufficient to achieve the desired speed, the electric motors will turn on to compensate for the difference.

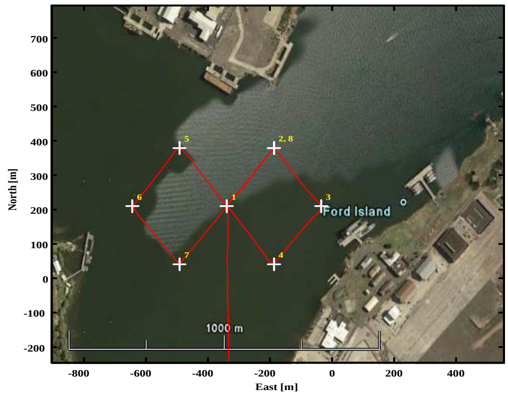

Fig. 5. HWT X-1 path tracking in Pearl Harbor.

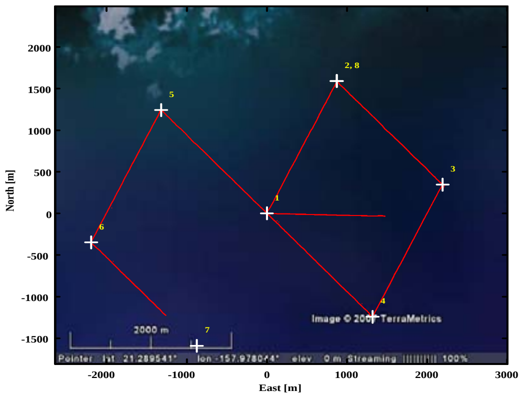

Fig. 6. HWT X-1 path tracking in open water.

The patterns run were in the shape of a figure-8, which provides for diversity in terms of wind and current angles. Note that the figure-8 pattern is completely arbitrary, and was simply chosen as a demonstration of capability on patrol, rather than having any significant meaning. The ratio of the figure-8 pattern is such that both obtuse and acute angles are present within the segment transitions, which does a good job of demonstrating the line acquisition feed forward controller.

The figure-8 pattern for Pearl Harbor, shown in Fig. 5, has legs that are approximately 150 m long, with the two long legs being approximately 300 m long. A view of the vessel's path along the figure-8 pattern in open water is pictured in Fig. 6. Here, the legs are approximately 1850 m in length.

Note that the open water patrol was aborted shortly before waypoint 7 due to increasing winds from 31 to 46 km/ h (17 kts to 25 kts) and seas (wave heights increased from 1 m to 2 m). While the control system gave no indication of problems, it was felt that deteriorating environmental conditions could push the vehicle to the edge of its roll stability margins.

6. EXPERIMENTAL RESULTS

As can be seen from Figs.5 and 6, the HWT X-1 performed very well, demonstrating smooth transitions between segments, good control performance, and completing a complicated and arbitrary patrol pattern. The straight line segments generated are quite unnatural, and that no human would be capable of following such a tight pattern.

Note that the wind and waves are disturbances on the system, and the control system must work at effectively rejecting these disturbances for good tracking control. Also, by nature of the wind-based propulsion, the largest portion of the wing force is a lateral disturbance, trying to drag the vehicle off-track. Again, the vehicle was only given the waypoints, and the control systems automatically compensated for wind direction to sail the vehicle appropriately.

Figs. 7 and 8 show the control system performance while tracking the line segments that make up the patrol pattern in protected waters and in the open ocean 3 km offshore, respectively. These cross-track errors are plotted against the along track distance, showing the line acquisition and then the line tracking. Based on this data, the line acquisition controller requires 50 to 100 m to converge to the line, and shows a small amount of overshoot (most likely induced by actuator lag).

Using the tracking data from 100 m onwards, the statistics of the controller performance are summarized in Tables 1 and 2. The protected water data have an ensemble mean of 1 m, and an ensemble standard deviation of 0.7 m, while the open water data have an ensemble mean of 1.6 m and an ensemble standard deviation of 1.2 m. Note that little effort has been made to tune the control system, and yet the control system performed quite admirably. In the case of the open water testing, this included wind speeds of up to 46 km/ h (25 kts) and waves of 2 m height. A reduction in mean error could be achieved using integral control on the cross-track error, though at the cost of a larger tracking standard deviation.

Table 1. Performance of HWT-X1 line tracking along completed segments in Pearl Harbor.

Segment Waypoints	Mean Cross-Track Error [m]	Std Cross-Track Error[m]
1-2	0.4	0.3
2-3	1.5	0.7
3-4	0.5	0.3
4-5	1.6	1.4
5-6	0.1	0.3
6-7	1.0	0.4
7-8	0.6	0.8

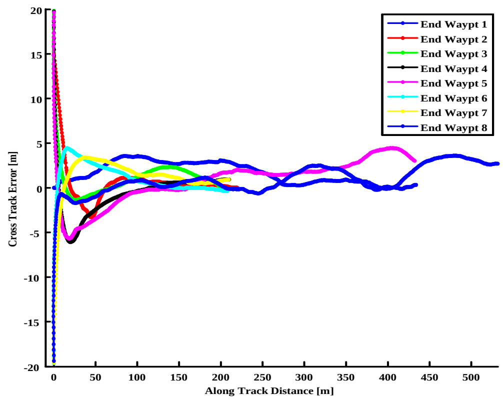

Fig. 7. Control system performance in Pearl Harbor.

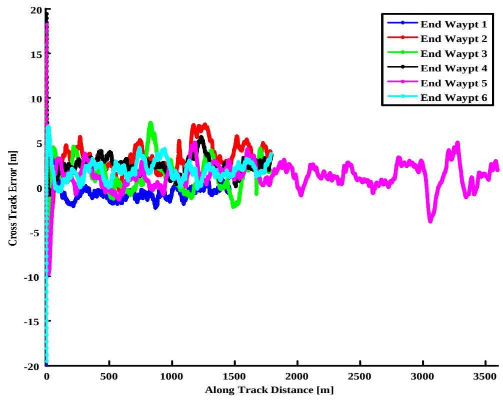

Fig. 8. Control system performance in open water.

Table 2. Performance of HWT-X1 line tracking along completed segments at sea.

Segment Waypoints	Mean Cross-Track Error [m]	Std Cross-Track Error[m]
1-2	3.3	1.4
2-3	1.6	1.8
3-4	2.4	0.9
4-5	1.3	1.3
5-6	1.9	1.0

7. CONCLUSIONS

Using wind propulsion for autonomous marine surface vessels is a promising technology for long endurance and energy scavenging missions. We have developed a simplified control architecture to guide the vessel on arbitrary patrol paths, regulating both cross-track error and velocity along each segment.

The HWT X-1 was run autonomously both in the protected waters of Pearl Harbor, HI, as well as offshore in the open ocean 3 km south of Ewa Beach, HI. In both cases, the control architecture guided the vehicle onto the patrol path, and tracked that path through segment changes using the line acquisition and line tracking controllers. The velocity control worked to autonomously sail the vehicle, tacking and jibing as appropriate during the segment transitions.

The line acquisition required between 50 and 100 m to converge to the line segment, with a small amount of overshoot. The line tracking controller demonstrated an ensemble mean of 1 m and a standard deviation of 0.7 m for sheltered waters, and mean of 1.6 m and a standard deviation of 1.2 m for open waters.

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