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Station Keeping and Segmented Trajectory Control of a Wind-Propelled Autonomous Catamaran

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Abstract— **Precision guidance and control of an autonomous, wind-propelled catamaran has been demonstrated by the Atlantis, a modified Prindle-19 catamaran, to be experimentally capable of tracking straight line segments to better than 0.3 meters $(1-\sigma)$. This paper extends Atlantis's guidance and navigation system to provide precision control while traversing a series of way-points and adds station keeping functionality, that is the ability for Atlantis to maintain her position at a given way-point in the presence of unknown water currents while motor powered. To achieve this, segmented trajectories are developed using the specified way-points forming line segments and arcs as path primitives. If a segment is unreachable directly due to the wind direction, a real-time tacking control mode is enabled and the Atlantis tacks within a given lane width until its destination is reached. For simulation a nonlinear model of the Atlantis was developed that includes realistic wind and water current models. Monte Carlo simulations of this new guidance and control system on the nonlinear model demonstrates the Atlantis is capable of maintaining a cross-track error of less than one meter throughout the path.**

I. Introduction

Autonomous marine navigation using wind-powered propulsion has been demonstrated by the Atlantis to an accuracy better than 0.3 meters (one σ) for line following applications. This achievement hints at the possibilities of autonomous ocean vehicles which can traverse great distances restricted only by the availability of wind and electronic positioning systems. Wind-propelled Autonomous Surface Vehicles (ASV's) can provide unmanned coastal cruising capabilities with energy efficiency for a myriad of sensing and scientific measurement missions.

The addition of a more advanced guidance system using waypoint navigation to the Atlantis will allow it to perform as a fully functional ASV. The control architecture for this guidance system uses a fixed series of latitude and longitude coordinates to mark points along the way to its final destination. The details of the control architecture for this segmented trajectory following model will be outlined, including details of the simulation models used throughout testing.

The key components of the Atlantis are discussed in Section II, including previous results of precise line following control. An analysis of the closed loop controller used is highlighted in Section III. The generation of segmented trajectories consisting of arcs and lines to connect way-points is then outlined in Section IV, including a real-time tacking procedure to traverse line segments that are unreachable due to wind direction limitations. A station keeping algorithm for a motorboat is then explained in Section V. The nonlinear 3 DOF simulation results are presented in Section VI and finally a conclusion is provided in Section VII.

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Fig. 1. Atlantis with wing-sail, January 2001.

II. The Atlantis

A. System Overview

The Atlantis, pictured in figure 1, is an unmanned, autonomous, GPS-guided, wingsailed sailboat. The Atlantis has demonstrated an advance in control precision of a wind-propelled marine vehicle to an accuracy of better than one meter. This quantitative improvement enables new applications, including unmanned station-keeping for navigation or communication purposes, autonomous "dock-to-dock" transportation capabilities, emergency "return unmanned" functions, precision marine science monitoring [10], and many others still to be developed. The prototype is based on a modified Prindle-19 light catamaran.

The wind-propulsion system is a rigid wingsail mounted vertically on bearings to allow free rotation in azimuth about a stub-mast. Aerodynamic torque about the stub-mast is trimmed using a flying tail mounted on booms joined to the wing. 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.

The system architecture is based on distributed sensing and actuation, with a high-speed digital serial bus connecting the various modules together. Sensors are sampled at 100Hz., and a central guidance navigation and control (GNC) computer performs the estimation and control tasks at 5Hz. This bandwidth has been demonstrated to be capable of precise control of the catamaran.

The sensor system uses differential GPS (DGPS) for position and velocity measurements, augmented by a low-cost attitude system based on accelerometer- and magnetometer-triads. Accurate attitude and determination is required to create a synthetic position sensor that is located at the center-of-gravity (CG) of the boat, rather than at the GPS antenna location.

Previous experimental trials recorded sensor and actuator data intended to excite all system modes. A system model was assembled using Observer/Kalman System Identification (OKID) techniques [7]. An LQG controller was designed using the OKID model, using an estimator based on the observed noise statistics. Experimental tests were run to sail on a precise track through the water, in the presence of currents, wind, and waves.

B. Previous Line Following Control Results

In order to validate the performance of the controllers and all up system, closed loop control experiments were performed in Redwood City Harbor, California, on January 27, 2001. These tests were intended to verify that the closed loop controllers were capable of precise line following with the increased disturbances due to the wingsail propulsion. No modifications were made to the LQR controller design, and the tests were run on a day with approximately 12 knots (or 6 m/s) of wind, with gusts up to the 20 knot (or 10 m/s) range.

Upon analyzing the data, it was demonstrated that the Atlantis was capable of sailing to within 25 degrees of the true wind direction. Figure 2 presents a close-up of the first path of regulated control, and looks at the crosstrack error, azimuth error, and velocities while tracking a line. Note that the dark line in the top of the boat speed graph is the wind speed, and can be seen to vary well over 50% of nominal.

The mean of the crosstrack error is less than 3 cm., and the standard deviation is less than 30 cm., note that this is the Sailboat Technical Error (STE, the sailing analog of Flight Technical Error) defined as the difference between the position estimated by the GNC computer and the desired sailboat position. Previous characterization of the coast-guard differential GPS receiver indicated that the Navigation Sensor Error (NSE) is approximately 36 cm., thus the Total System Error (TSE) is less than 1 meter.

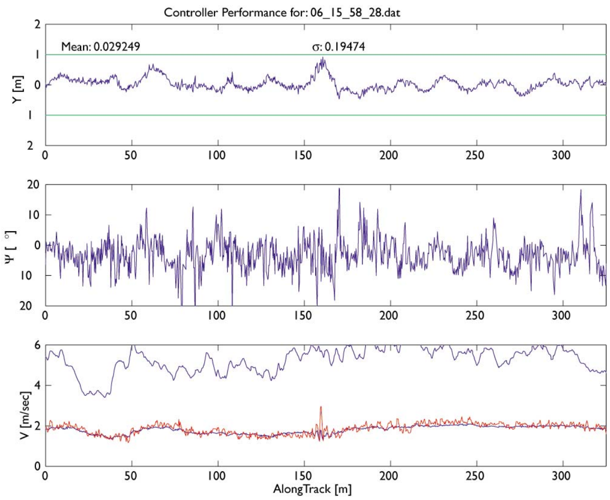

Fig. 2. Sailing path errors.

III. Controller Analysis

A simple proportional plus integral (PI) feedback controller is used to stabilize a nonlinear boat model when following trajectories in the presence of wave disturbances. The controller takes as input the boat's heading error (Ψ_{error}) and crosstrack error (Y_{error}). Proportional and integral gains are then applied to these inputs to generate a reference rudder angle (δ_{ref}) to direct the boat back on its proper trajectory.

It was previously shown [2] that our boat model will loose stability as the boat speed reaches a certain point beyond the controller's design point V_x^{design}. To address this problem, the controller can compensate for the boat's speed using a gain-scheduled controller or by applying input pre-scaling to obtain a velocity invariant controller. In our simplified model, we will instead show that our controller is stable up to a specific boat speed point, which can never be exceeded in any of our simulations.

The boat speed design point V_x^{design} = 2.0 m/s was used to find controller gain values that minimized steady state errors in the presence wave disturbances and provided a quick transient response.

Body and control frame equations [1] were then linearized around a small variance in boat heading providing the linearized equations:

$$\dot{\Psi} = \frac{V_x}{L}\delta \tag{1}$$

$$\dot{N} = V_x \tag{2}$$

$$\dot{E} = V_x \Psi_{boat} \tag{3}$$

A block diagram of the linearized equations combined with the closed loop PI controller gains is shown in figure 3. Assuming the reference heading for the boat is due North ($\Psi_{ref} = 0°$), the transfer function for the closed loop system is then formulated as:

$$Y_{error}(s) = \left(\frac{V_x^2}{L}\right) \frac{s}{s^3 + \frac{K_\Psi V_x}{L}s^2 + \frac{K_Y V_x^2}{L}s + \frac{K_{Y_i} V_x^2}{L}} \tag{4}$$

where for our controller design $K_Y = 3.0$, $K_{Y_i} = 0.25$, and $K_\Psi = 2.0$.

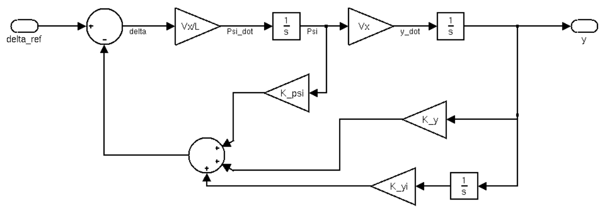

Fig. 3. Block diagram of linearized boat equations combined with PI controller gains.

A mapping of the closed loop system poles from Eq. 4 is shown in figure 4 as a function of V_x. The closed loop system poles will remain stable as the boat's speed is increased for this linearization of our kinematic equations. The natural frequency of the linearized closed loop system for V_x^{design} = 2.0 m/s is 2.0 rad/s. Testing of the nonlinear model was then performed by simulating a step input for the crosstrack and heading errors and observing the resulting steady state system response. A stable response was observed for boat velocities up to 7 m/s, well beyond the maximum operating point for the wing-sail propulsion system.

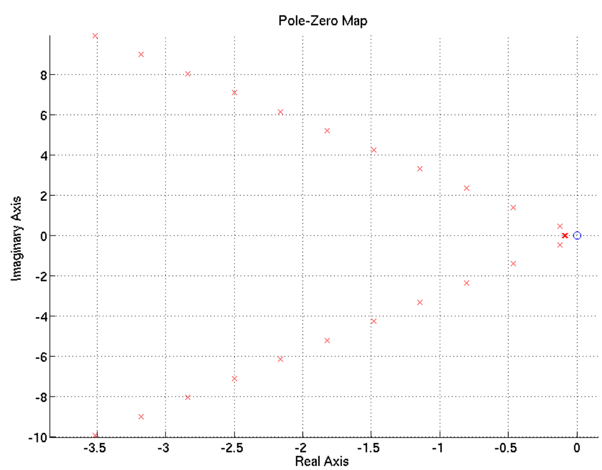

Fig. 4. Mapping of closed loop system pole locations as a function of increasing boat speed.

IV. Segmented Trajectory Generation

A. Arcs and Lines

The waypoint navigation system uses a series of user defined waypoints as reference points for navigation. The Atlantis could simply use these waypoints as heading references, however large crosstrack errors would be produced during waypoint transitions and certain references may be unreachable because of the wind direction. A segmented trajectory of lines connected by arcs of a constant radius is used to provide a path of achievable trajectories.

Arc segments are added between line segments such that the line segments are tangent to the arc where they meet. Figure 5 demonstrates how waypoint inputs are transformed to line and arc segments. In practice, segments will be created in real-time as waypoints are achieved allowing for tacking scenarios to be applied when necessary.

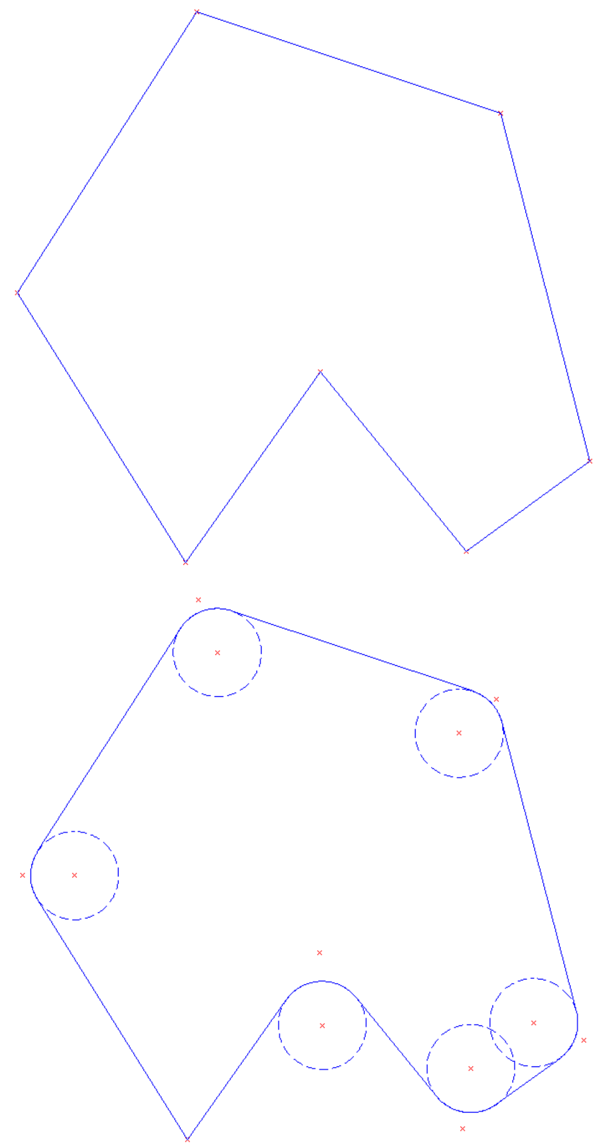

Fig. 5. User defined waypoints (top) transformed into arc and line segments (bottom).

B. Tacking Algorithm

In sailing, a tack is performed when the boat turns such that the bow passes through the wind. Tacking (as a sailing procedure) then refers to the process of making alternate tacks as close as possible to the wind, allowing a sailboat to effectively sail upwind. If the Atlantis attempts to sail directly upwind it will eventually be "in irons" meaning it will lose all speed and stall out. A *lane width* for the desired line segment is defined and used to tack back and forth through the desired heading until the next waypoint is reached. The Atlantis must be prepared to tack at any point should the wind change and the waypoint become unreachable. As such, a real-time tacking algorithm was developed for the guidance system that provides navigation within the defined lane width allowing waypoints to be achieved while avoiding unreachable points of sail.

Figure 6 depicts an ocean vehicle traversing a line segment with a varying wind direction (left side). As the wind shifts inside a defined wind heading allowance, the water craft adjusts its heading to navigate within the desired lane width.

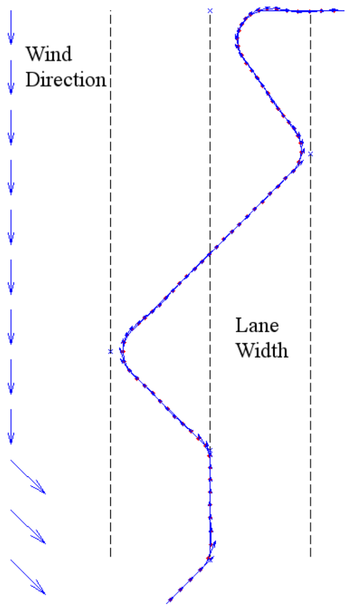

Fig. 6. Surface vehicle adjusting to tacking routine in reaction to changing wind headings (left side).

C. Initial Segment Acquisition

Unless the vehicle starts in the exact same position as the first line segment, a line of sight control that provides a reference heading to progressively lock on the first segment must be used. A reasonable heading for the vehicle would be to command the boat to a 90° angle towards the line until it gets closer, and then angle towards the line in the direction of the desired navigation.

An easy method to achieve this curved trajectory is to create a reference heading to the line that is a function of the vehicle's crosstrack in the control frame. By definition, as the surface craft moves closer to the desired line segment, its crosstrack will approach zero. Therefore, a desired heading to the line can be derived as:

$$\Psi_{ref}^{control} = \arctan\left(\frac{Y}{\tau}\right) \quad (5)$$

where Y is the crosstrack value and τ is a constant that determines how steep a trajectory the boat will take to acquire the line. Figure 7 shows the Atlantis using this technique for line acquisition using $\tau = 5$ and then switching to the PI controller for line following when $Y < 0.5\ m$.

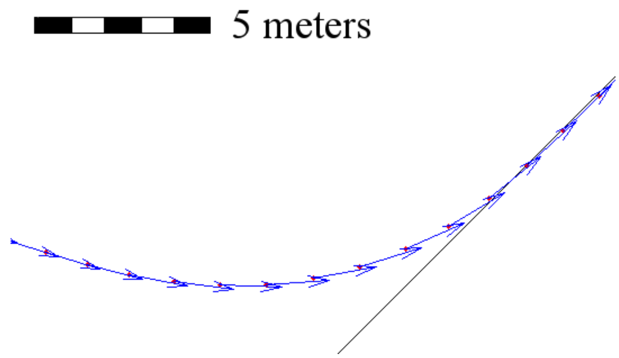

Fig. 7. Acquisition of first segment from distant initial vehicle position.

V. STATION KEEPING

A station keeping algorithm has been developed allowing the Atlantis to stop at a specified waypoint while under motor propulsion, despite water currents pushing against the boat hulls. The goal of the algorithm is to position the boat at a heading directly into the water current, and then to adjust the thrust of the boat until its velocity reaches equilibrium with the water current velocity, converging to the specified station keeping way-point. Even though the angle and magnitude of the water current velocity vector is unknown, the boat will still converge to a heading pointing into this vector and "hover" at the specified station keeping point. Previous weathervaning techniques are described in [5].

First, a radius r_{SK} is defined around the station keeping point to determine when to initiate the algorithm. As the Atlantis is traversing the line segment to the designated station keeping waypoint its heading error (Ψ) will converge to a steady state value (Ψ_{SS}) dependant upon the water currents' magnitude and angle with respect to the boat. If $\Psi_{SS} > 0$ it can be deduced the water currents are flowing from the port side of the boat and if $\Psi_{SS} < 0$ the currents are flowing from starboard side.

As the boat enters r_{SK}, the control frame is switched to a new line segment with a heading placing the boat into the the water currents by changing the heading $\Psi_{ref} = \Psi_{ref} \pm 90°$. The line segment acquisition controller discussed in Section IV is then used to track this new line segment.

After the first new line segment is acquired the controller is switched to a heading tracking controller that will adjust the boat to maintain Ψ_{ref} and ignore any cross-track errors. A thrust modulating controller is also enabled capable of adjusting the thrust of the boat propulsion system in response to alongtrack position changes in the control frame. The thrust of the boat propulsion system (T) is defined as:

$$T = -K_T X_{err} - K_T^I \int X_{err} \quad (6)$$

The boat should now drift along its cross-track axis Y and the starting time for this controller configuration is defined as t_{drift}.

When $|Y_{err}| > r_{SK}$, a heading adjustment is calculated that will adjust the boat to a heading that is pointing more sharply into the water current depending on the sign of Y_{err}. This adjustment is defined as:

$$\Psi_{ref} = \Psi_{ref} \pm \frac{K_{\Psi}^{SK}}{t - tdrift} \tag{7}$$

where t is the time value when the boat drifts past the r_{SK} threshold. To maintain stability K_{Ψ}^{SK} must not exceed a certain value, otherwise Ψ_{ref} may just oscillate by $\pm 90°$. Using a conservative estimate for the maximum magnitude of the water current ($|V_{current}|_{max}$) a stability constraint is specified as:

$$K_{\Psi}^{SK} < 90° \frac{r_{SK}}{|V_{current}|_{max}} \tag{8}$$

The thrust modulating controller is now disabled and again the line segment acquisition controller is enabled to track the new reference segment. Once the new line segment is successfully acquired Ψ_{ref} is updated using (7) and the boat is again allowed to drift along the cross-track axis. Over time the heading adjustments in response to the amount of time it takes the boat to drift out of the radius r_{SK} will put the Atlantis on a heading which converges into the opposite direction of the water current heading.

Fig. 8 shows the Atlantis executing the station keeping algorithm to maintain a position at the specified waypoint. Initially, the vehicle is traveling to the station keeping point on the red line segment and then adjusts to track line segments 1-4, successively. Finally, tracking line segment 5 provides a trajectory directly into the oncoming water currents, allowing the Atlantis to maintain its position at the station keeping point without drifting further than r_{SK}. This preliminary algorithm assumes the Atlantis is propelled by a variable speed, on-board motor. Future enhancements will include provisions allowing the Atlantis to drift within a specified radius even under the previously discussed point of sail reachability constraints.

VI. Simulation Results

Using the boat, wind, and wave models outlined in [1], the PI controller discussed in Section III was used to follow the set of trajectories generated from predefined waypoints as described in Section IV. The controller monitors both the heading error Ψ and crosstrack Y to adjust the rudder position δ. First, a surface vehicle propelled by a constant speed source such as an outboard motor is simulated. Figure 9 shows the resulting path and figure 10 displays the heading error and crosstrack error for such a boat. Monte Carlo simulations providing different random values for wind and wave disturbances show the boat to have an average heading error of 2.2^o and an average crosstrack error of 2 cm. as shown in Table I.

Using the same PI controller, the varying wingsail speed model was used with the tacking algorithm to follow the same set of waypoints with identical disturbances. The vehicle path and average wind direction is displayed in figure 11 and resulting heading error and crosstrack error information

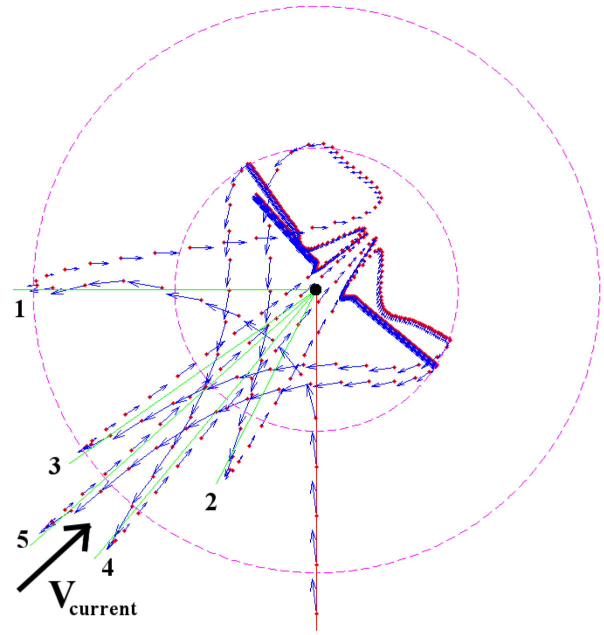

Fig. 8. First the Atlantis enters from bottom of the figure traversing North, then adjusts to line segments 1-4, finally converging to heading 5 allowing the Atlantis to maintain its position at the designated station keeping way point.

	Motorboat			Sailboat		
	Lines	Arcs	Total	Lines	Arcs	Total
$\Psi_{avg}(^o)$	0.69	10.9	2.20	1.20	11.7	3.25
$\Psi_{\sigma}(^o)$	4.85	18.6	9.42	8.99	17.8	12.6
$\Psi_{max}(^o)$	18.3	34.8	34.8	53.9	40.1	63.0
$Y_{avg}(m)$	0.01	0.15	0.02	0.01	0.27	0.06
$Y_{\sigma}(m)$	0.08	0.30	0.16	0.10	0.45	0.28
$Y_{max}(m)$	0.42	0.82	0.82	0.47	1.22	1.23

TABLE I

Simulation Results.

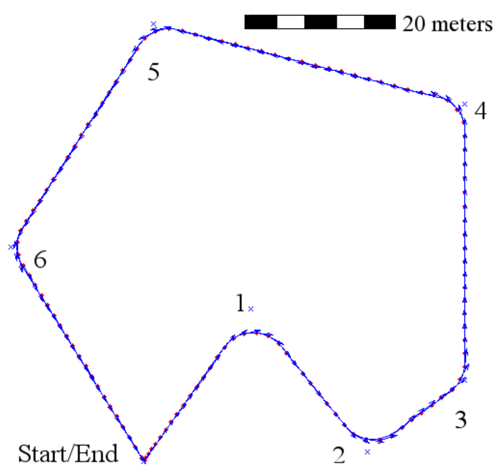

Fig. 9. Control architecture applied to surface vehicle simulated with constant speed propulsion with water current and wave disturbances.

is shown in figure 12. As with the motorboat, Monte Carlo simulations were completed showing the Atlantis to have a simulated average heading error of 3.25^o and an average

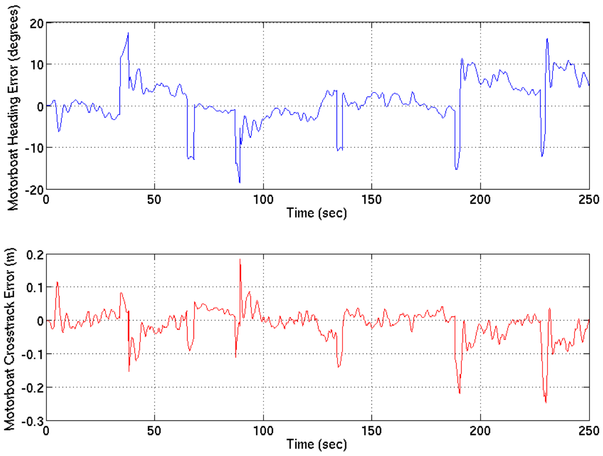

Fig. 10. Heading and crosstrack error for constant speed surface vehicle simulation

crosstrack error of 6 cm. Sailboat results are also shown in Table I.

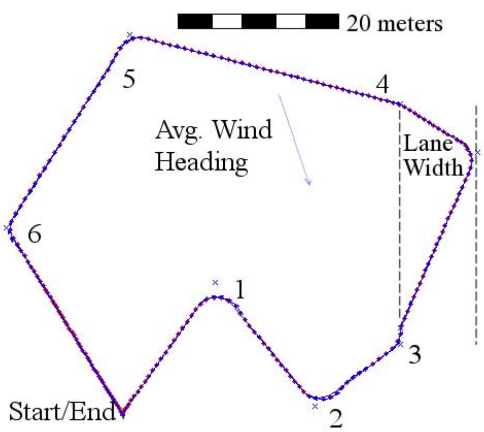

Fig. 11. Control architecture applied to wingsailed vehicle simulated with water current and wave disturbances.

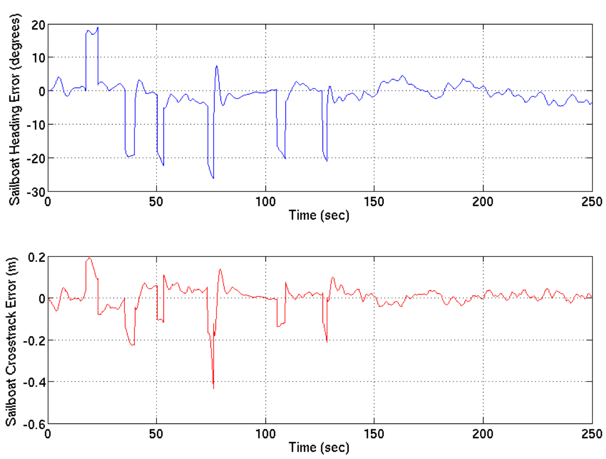

Fig. 12. Heading and crosstrack error for wingsailed surface vehicle simulation.

VII. CONCLUSIONS

A control architecture for an autonomous sailboat using a waypoint navigation system that includes station keeping functionality was simulated with a PI controller and shown capable of providing robust and reliable guidance. This architecture was applied to a simplified model of the Atlantis, a wingsail propelled catamaran previously shown capable of line following accuracy better than 0.3 meters. Simulations modeling similar experimental conditions previously encountered show that precision control is possible for waypoint navigation requiring segmented trajectory following of arcs and lines and real-time waypoint management to prevent unreachable points of sail. Simulations show the sailboat can be controlled to better than one meter accuracy.

This control architecture is not limited to PI controllers, and more advanced controllers will presumably allow for better system accuracy. The simulation environment discussed will also serve as a development platform for controller comparisons and Hardware-in-the-Loop testing of the ship's sensors, actuators, and complete GNC system.

Future work will include a waypoint generation methodology that will avoid stationary obstacles and also optimally determine trajectories given only a destination point and weather data forecasts to predict future wind activity. This added guidance system combined with advancements in Atlantis sensors and actuators will create a wind-propelled ASV capable of robust navigation that can be used for a variety of future marine applications.

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