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STATION KEEPING ADAPTIVE CONTROL OF A BOAT WITH TWIN GASOLINE OUTBOARD MOTORS: SYNTHESIS, SIMULATION, AND SEA-TRIALS

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ABSTRACT

There are increasingly more areas in which automatic station keeping technology can be of great benefit for small boat operators. This trend stems from technological advances that allow for smaller and more portable instrumentation and gear, bringing down the necessary size of vessels, which ultimately reduces cost. However, smaller vessels find themselves more adversely affected by sea conditions and have limited thrusting capabilities. Currently a skilled captain is needed on these small vessels to hold position over the area of interest in the presence of wind, wave, and current disturbances. Implementation of an automatic station keeping controller would free the captain from constantly monitoring the navigational instruments, to more closely supervise onboard operations and keep watch for other vessels in the area. Station keeping technology is currently being perused by Florida Atlantic University to enhance the ability of its 33ft boat to make oceanographic measurements in the Gulf Stream pertinent to its ocean energy projects. Such ocean energy projects require water velocity and temperature measurements at specific locations as part of the efforts for assessment of the hydrokinetic and ocean thermal resource. This technology is also a pivotal part of the sea basing goal currently being pursued by the Navy, which would allow vessels to stay in close but acceptable proximity to one another. The ability to hold position over a desired location can also have many additional uses such as for fishing, conducting surveys, deploying instruments, and transferring cargo or personnel.

This text presents a novel approach for doing station keeping, as thus far a system for station keeping on small vessels using only tied twin outboard motors has not been developed and applied to an ocean going vessel by industry or academia. These controllers have been developed using multiple fixed-gain and adaptive control algorithms. Using a custom sensor and control system mounted onboard the test vessel; navigational measurements are used to adjust the throttles and engine angle using these developed algorithms. The performance of each of these controllers has been quantified using both numerical simulations and at sea testing. Using the results from these tests, initial comparisons have been made that show the advantages gained by using adaptive control algorithms instead of fixed-gain control.

INTRODUCTION

Station keeping of small boats is a technology that could benefit many user groups. It can benefit ocean researchers in the launch and retrieval of autonomous vehicles, conducting CTD casts, and communicating with subsea instruments, among many other applications. Station keeping can also be used by commercial and recreational fishermen for launch/retrieval of pots and hovering over fertile fishing areas; dive operators to stay near a certain reef; and the military for applications such as holding position within a sea base.

Technological advances have allowed for smaller instrumentation and gear, which reduces the size of vessel and crew needed for a given mission, ultimately reducing costs [1]. However, smaller boats are more adversely affected by environmental conditions and are typically controlled using only rear propulsion systems, without the aid of bow or stern thrusters. This lack of control authority makes it difficult to hold position in the presence of wind, waves, and current because sway motion cannot be directly controlled [1]-[6]. If manual control is to be used for station keeping, a skilled captain is required to constantly monitor navigational instruments and counteract vessel displacement from the desired location, while remaining aware of the vessel's surroundings. This research develops and evaluates control systems designed to automatically hold a desired position in the presence of environmental forces acting on the vessel. The test vessel for this work is the *Ocean Power*, a 33-foot center console vessel powered by twin outboard motors operated by the Southeast National Marine Renewable Energy Center (SNMREC) at Florida Atlantic University.

The design focuses on the development of two controllers that use adaptive control methodology, providing the capability for self-tuning in response to changes in environmental forces or vessel dynamics. The performance of these controllers is compared against that of a fixed-gain PID controller, to quantify the increase in performance afforded by using adaptive algorithms.

This work outlines the development of three station keeping controllers, the physical implementation of the control system on the *Ocean Power*, and the results from sea trials of these station keeping controllers. This paper is organized as follows: Section 2 presents the developed controllers, Section 3 outlines the control system implementation, results from station keeping sea trials are found in Section 4, and conclusions are given in Section 5.

CONTROLLERS

The controllers developed in this paper have control layers. The first layer calculates desired vessel heading. In the second layer, the net forward thrust, differential thrust, and engine angle are calculated. Figure 1 shows a diagram of the control scheme.

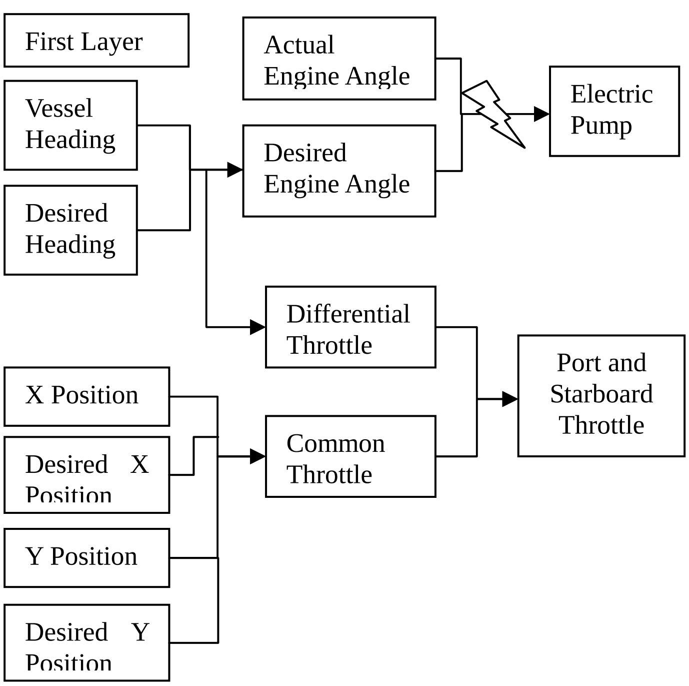

Figure 1: Control System Overview

As the controllers in this work were created to be implemented on small boats, they were designed to use only data which is easily accessible using standard navigational instruments. The only inputs to the system are data obtained from a DGPS unit and a measurement of the outboard motor's steering angle with respect to the fore-aft axis of the boat. This reduces the complexity of the controllers as well as removes the need for costly and cumbersome instruments such as ADCPs and anemometers.

The three algorithms presented in this paper differ in their second layers; all controllers use a common first layer fixed gain PID algorithm. The first controller (PID-PID) uses fixed-gain PID algorithms for all calculations. The second controller (PID-Adaptive) uses a fixed-gain PID controller for controlling steering and forward thrust and an adaptive PID controller for differential thrust. The final controller (Augmenting-Adaptive) uses fixed-gain PID for net forward thrust, adaptive PID for differential thrust, and fixed-gain PID control with adaptively augmented gains for steering.

The control equations were initially tested using a 6 degree of freedom numerical simulation described in [8]. This general simulation allows the user to command magnitude and direction of wind, wave, and current forces acting upon a vessel. The user also inputs 17 physical parameters describing the geometry of the vessel being modeled. This paper will present the equations used for each controller and the sea trial results; additional background information and simulation results for each control scheme can be found in [9].

The equation for the first layer, which calculates desired heading, is

$$\psi_d = \tan_2^{-1}\left(Y_e + a_h\int_0^t Y_e dt, X_e + a_h\int_0^t X_e dt\right) + \pi \,, \qquad (1)$$

where X_e and Y_e are the north and east errors, respectively in meters; a_h is a fixed gain; and ψ_d is the desired heading, in radians.

Each controller uses a PID control structure for its second layer. The difference is in the gains, between whether the gains are fixed values, fully adaptive, or have fixed values with adaptive augmented gains. The common control structure for controlling steering is

$$u_\psi = K_P^b\psi_e + K_I^b\int\psi_e + K_D^b\dot{\psi}_e \,, \qquad (2)$$

where ψ_e is the heading error, $\dot{\psi}_e$ is the heading error rate, u_ψ is the desired engine angle, and $K_{P,I,D}^b$ are the gains.

For the fixed gain steering controller, $K_{P,I,D}^b$ are fixed values which are found iteratively through testing. In the augmenting steering controller, $K_{P,D}^b$ are the adaptively augmented gains, while K_I^b remains a fixed gain. The augmenting gains are found by $k_P^{TOT} = (K_P^b + k_P^{AD})$ and $k_D^{TOT} = (K_D^b + k_D^{AD})$, with the update laws of $\dot{k}_P^{AD} = -\Gamma_1\psi_e{}^2 + \sigma_1 k_P$ and $\dot{k}_D^{AD} = -\Gamma_3\psi_e\dot{\psi}_e - \sigma_3 k_D$. In these equations $\Gamma_{1,3}$ are parameters which define the rate of adaptation and $\sigma_{1,3}$ are sigma modification terms which prevent wind-up.

For thrust calculations, the PID control structure is

$$T_d^p = a_1 x_e + a_2 \int_0^t x_e dt + a_3 u \cos(\psi_e) - a_4^T \psi_e - a_5^T \int_0^t \psi_e dt - a_6^T r$$
$$T_d^s = a_1 x_e + a_2 \int_0^t x_e dt + a_3 u \cos(\psi_e) + a_4^T \psi_e + a_5^T \int_0^t \psi_e dt + a_6^T r \quad (3)$$

where x_e is the north error in body-fixed frame; u is the north velocity in body-fixed frame; ψ_e is the heading error in radians; r is the rotation rate in rad/s; a_{1-6} are gains; and $T_d^{p,s}$ are the desired port and starboard motor RPMs. Not that in both cases the D-term was dropped in order to avoid noise being introduced in the control loop.

In the fixed gain thrust calculation, all gains a_{1-6} are fixed values which are found through tuning. However, for the adaptive differential thrust controller, gains a_{1-3} remain fixed values, while a_{4-6} are adaptive gains, governed by the update laws $\dot{a}_4 = -\Gamma_4 \psi_e^2 + \sigma_4 a_4$, $\dot{a}_5 = -\Gamma_5 \psi_e \int \psi_e + \sigma_5 a_5$, and $\dot{a}_6 = -\Gamma_6 \psi_e \dot{\psi}_e + \sigma_6 a_6$. The control equations are derived based on a direct adaptive regulation scheme as introduced in [10] (Ch. 7). The direct adaptive regulation scheme is in turn obtained as a special case of adaptive pole placement control. The Lyapunov-like function employed is based on a linearized plant of the form $\dot{y} = ay + bu$. For this plant a control of the following form is assumed.

$$u = -\hat{k}_1(t)e - \hat{k}_2(t), e = y - c, \tilde{k}_1 = \hat{k}_1 - k_1, \tilde{k}_2 = \hat{k}_2 - k_2, \quad (4)$$

In the above *c* is the set-point and the certainty equivalence principle has been employed. By plugging the above directly in the plant's dynamic equation, the following dynamic equation for the error can be obtained.

$$\dot{e} = -a_m e - b\left(\tilde{k}_1 e + \tilde{k}_2\right), \quad (5)$$

In effect, the following Lyapunov-like function can be constructed.

$$V = \frac{e^2}{2} + \frac{\tilde{k}_1^2 |b|}{\gamma_1} + \frac{\tilde{k}_2^2 |b|}{\gamma_2}, \quad (6)$$

In the above the two gammas are arbitrary positive constants. The time derivative of the Lyapunov function above is forced to satisfy the following constraint along the trajectory defined by equation (5).

$$\dot{V} = -a_m e^2 \Rightarrow \dot{\hat{k}}_1 = \gamma_1 e^2 \operatorname{sgn}(b), \dot{\hat{k}}_2 = \gamma_2 e \operatorname{sgn}(b), \quad (7)$$

The above equations for the direct estimates of the control law gains yield the following control law.

$$u = -\hat{k}_1 e - \gamma_2 \operatorname{sgn}(b) \int_0^t e(\xi) d\xi, \quad \dot{\hat{k}}_1 = -\gamma_1 e^2 \operatorname{sgn}(b) \quad (8)$$

Note that the direct regulation approach of the form in equation (4) in [10] leads directly to a PI control law without the need of a D-term altogether.

These control equations were tested extensively in the numerical simulation, through a variety of environmental conditions, the results of which can be found in [8], [9]. The environmental conditions were modeled after those which a small boat may expect to experience in the Gulf Stream off Fort Lauderdale, FL. Two northward current speeds, 1.5 and 3 knots, were tested with wind speeds from the West of 4, 10, and 20 knots. The controllers showed very similar performance in the lighter wind conditions, but as the wind speed increased to 20 knots, the adaptive controllers exhibited much better performance [11].

CONTROL SYSTEM IMPLEMENTATION

After thorough testing and evaluation of the controllers in simulation, the next step was to outfit the vessel for sea trials. *Ocean Power* was used as the vessel of opportunity because of its availability and its twin outboard motors, for using differential thrust to aid in steering in high wind and low current conditions. To achieve station keeping, it was necessary to control three variables: the steering angle of the motors, and the thrust output of each motor.

Ocean Power is equipped with twin Suzuki DF300 outboard motors, each motor outputting 300hp, and are controlled by a unique fly-by-wire system. The steering system is a SeaStar hydraulic circuit, and also has a Nautimatic autopilot integrated into the hydraulic circuit.

Data for vessel position and speed is provided by a vector sensor differential GPS unit [12]. The positional data has published positional error of <60cm and is provided at 2 Hz. The heading information is provided at a rate of 10 Hz and has published error of <0.15°.

The control software is written in LabVIEW and is run on a laptop for trials. This allows for easy code debugging, as well as gives an easy user interface for modifying gains and other settings in trials on the boat which may be pitching and rolling in seas.

STEERING CONTROL SYSTEM

To control heading, it was necessary to both measure the angle of the outboard motor with respect to the fore-aft axis of the boat and to be able to automatically turn the motors to the desired angle.

As stated above, *Ocean Power* is equipped with a hydraulic steering system, and multiple methods were considered for measuring steering angle. Ultimately, it was decided to mount a potentiometer over the point of rotation of the motor. A 14mm hex nut was attached to the rotating shaft of the potentiometer to mate with the bolt at the point of rotation, and a custom bracket was designed to hold the sensor in place. This installation can be seen in Figure 2.

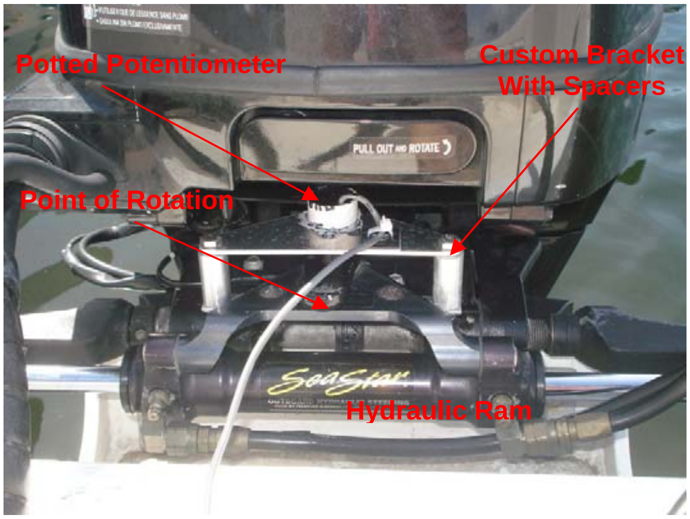

Figure 2: Engine Angle Sensor Installation

The potentiometer is supplied a constant 5VDC, and as its shaft rotates the resistance across it changes. The output voltage is run into a 12 bit analog-to-digital card, where the output is a number between 0 and 4095. By obtaining a relationship between angle and the A-D output, engine angle is measured. Figure 3 shows the results of the engine angle sensor calibration. The results were repeated multiple times, giving a linear relationship between A-D output and engine angle.

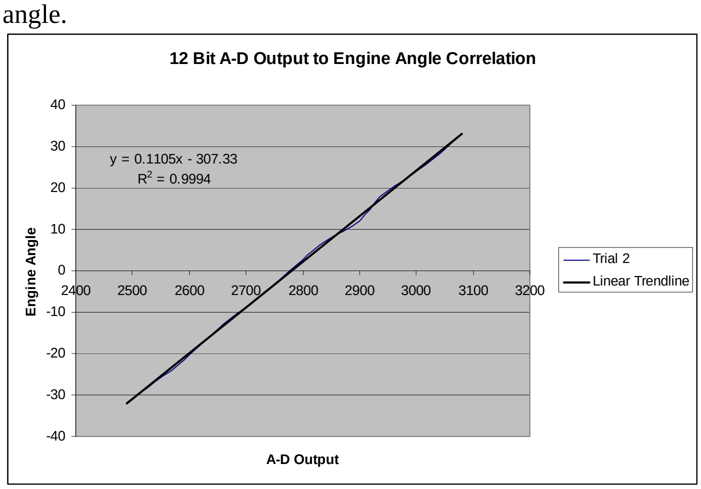

Figure 3: Engine Angle Sensor Calibration

After installing and calibrating the engine angle sensor, engine angle control is possible. This is done by disconnecting the electric pump from the Nautimatic autopilot and supplying power to the pump from a motor controller which is commanded by the control algorithm. The pump can accept ±12VDC (Where polarity determines direction of pump flow) which is supplied by a Roboteq AX1500 motor controller. Note that the automatic steering control can be manually overridden by turning the steering wheel in case of obstacle avoidance.

A PI controller is used to match actual engine angle to the desired engine angle. No derivative term is used because there is currently no way to measure engine angle rate using the applied sensors; on the other had directly differentiating the angle reading either in the analog domain (using op-amp circuitry) or in the digital domain could introduce noise unnecessarily since, as explained earlier, a D-term is not needed in the control scheme envisioned. Gain sets were found iteratively through dockside tests, which measured how well various gain sets had the motors follow sine and square waves with 15° magnitudes [3]. The square wave was used to see how well the motor converged to a desired angle with minimal over- and under-shoot, while the sine wave tested the ability of each controller to follow a desired angle which slowly and continually changed.

THROTTLE CONTROL SYSTEM

The DF300 motors use a fly-by-wire system to control throttle and gearing; there are no mechanical cables used for either of these tasks. Figure 4 shows a diagram of this system.

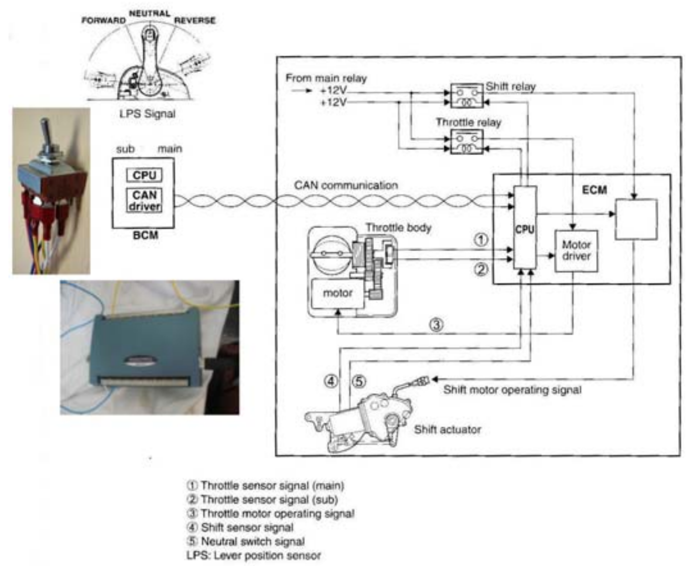

Figure 4: Throttle Control System Diagram

Within the throttle lever, the Lever Position Sensor (LPS) outputs 2x 0-5VDC signals (Main and Sub) for each motor, which vary with the lever's position. The signals are sent from the LPS to the Boat Control Module (BCM), which then communicates via a proprietary controller area network with a computer in the motors themselves which commands actuation of throttle and shifting.

Measurements were taken dockside to obtain a correlation between LPS voltage and motor RPM at various motor speeds thanks to a "Throttle Only" switch which will increase RPM without turning the propellers. This was done for each motor separately, measuring main and sub voltages from neutral gear to 2000 RPM in forward and reverse gears. This is done because station keeping is to be done at slow speeds and the motor speed will not be allowed to exceed 2000 RPM.

The relationship between LPS voltage and RPM is used to create a function of output voltage to RPM, and again these numbers give a nearly linear fit as seen in Figure 5. Note that separate functions need to be obtained for each motor in forward and reverse, and that the main and sub voltages are differential; that is, $SubV = 5V - MainV$.

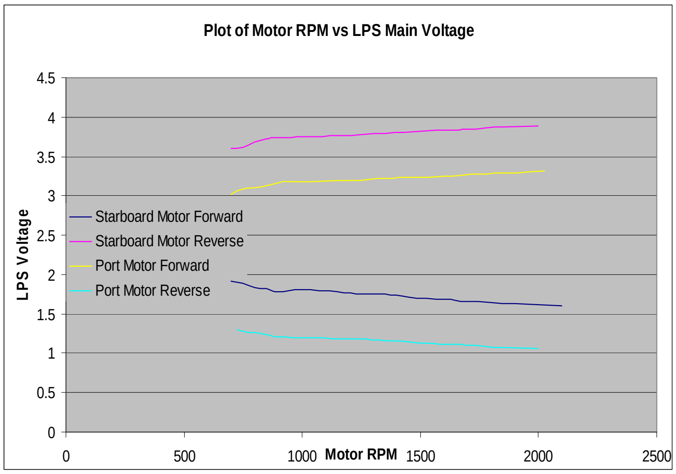

Figure 5: Motor RPM vs. LPS Voltage

To control the throttle and gearing, the signal out of the LPS is replaced with one generated by a 16 bit D-A converter. The unit used for this is a Measurement Computing USB 3102 unit which is powered via USB port. This allows for very high precision voltage output. Switches are installed in-line to allow for switching control of the throttle and gearing between the LPS and the computer control system. Note that when the computer has control of the throttle, the throttle lever has no effect on throttle; the only way for the lever to have any control is to switch control back to the LPS or turn the switch to the middle position which shifts the motors back to neutral.

SEA TRIAL RESULTS

The three controllers were tested onboard *Ocean Power* on July 26, 2010 in the Gulf Stream offshore Fort Lauderdale, FL. The trials were conducted from 10:00am to 4:00pm on this day. The environmental conditions on this day included wind out of the east with a mean velocity of 8 knots; 2 foot significant wave height; and net environmental forces providing a 3 knot northward drift speed.

Each controller was tested for its ability to drive the vessel to a fixed desired location upstream of the starting point and remain near this position. Because of concerns of the engine trying to switch gears rapidly in the first seconds of operation, a 5 seconds delay was implemented after controller initialization to allow the boat to drift slightly. In addition to the delay, the desired location was chosen forward of the original location to further prevent against the rapid shifting in the initial phase. In a future implementation, a reference model might be considered which in combination with a state observer might mitigate the need of this initial 5sec delay.

PID-PID STATION KEEPING

The PID-PID station keeping controller was the first tested in the sea trials. This is used as a baseline controller for comparison with the other algorithms which used adaptive gains.

It can be seen in Figure 6 that the controller does cause the vessel to track the desired heading, although with some primarily high frequency oscillations about the desired heading. During this test there is an initial heading error of about 17° which is mitigated within 25 seconds. For most of the trial the heading error is due to the relatively high frequency wind and wave disturbances.

The two spikes in heading error, around the times of 1100 and 1600 seconds as (Figure 6), are caused by errors in the East-West direction, which necessitate large changes in the desired heading to negate the lateral errors.

The standard deviation of heading error was 2.9912° over the whole trial, and reduced to 2.2408° over the second half of the trial. This shows good vessel following of the desired heading, over the course of the trial. A maximum heading error of 15° was experienced after initial convergence, which was quickly eliminated.

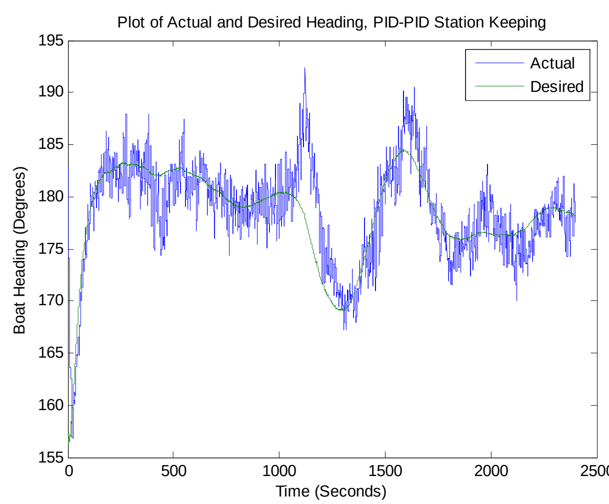

Figure 6: Actual and Desired Heading over Time

The vessel's position in the NED frame can be seen in Figure 7. The boat starts at a position 22 m north and 9.5 m west of the desired location and initially drifts northward with the Gulf Stream current to a maximum northward displacement of 34 meters, or roughly 3.5 boat lengths.

The boat then gradually works its way southward towards the desired point of (0,0) with the throttle slowly increasing. However, once the boat gets within 5 meters of (0,0), it begins to oscillate laterally about the desired location. The boat reaches the maximum lateral error magnitudes of 13 m both to the port and starboard directions during the second oscillation before the magnitudes begin to decrease. This large sway oscillation caused the large heading errors seen in Figure 6.

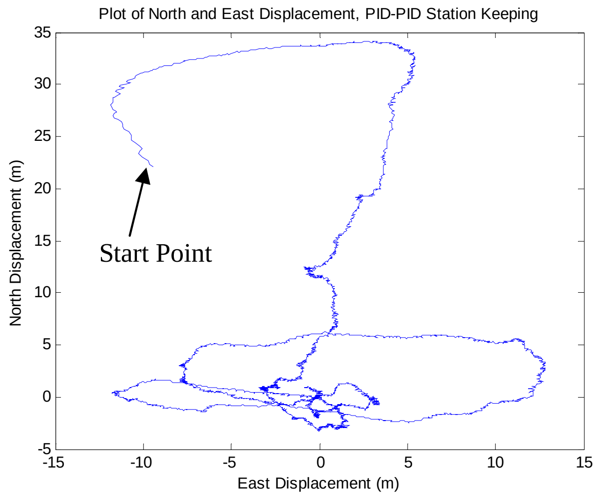

Figure 7: North and East Displacement, PID-PID

Even with the lateral errors, this controller does work to keep the vessel within close proximity to the desired location. For the entire trial, the mean position error was 8.4642 m and the RMS position error was 12.3427 m. Over the final half of the trial these numbers reduced to mean error of 4.6117 m and RMS error of 5.2878m.

It is believed that using adaptive algorithms for differential thrust will allow for increased control over the vessel's heading by modifying the gains in accordance with the heading error. The next two controllers will test this hypothesis.

PID-ADAPTIVE STATION KEEPING

The second controller tested uses a fixed-gain PID algorithm for commanding the motor steering angle, along with an adaptive PID control scheme for differential thrust. This controller is used to see any increase in performance is found by using adaptive differential thrust.

Figure 8 presents the actual and desired heading, while the position in NED frame can be found in Figure 9. Note that this is the shortest of the three trials.

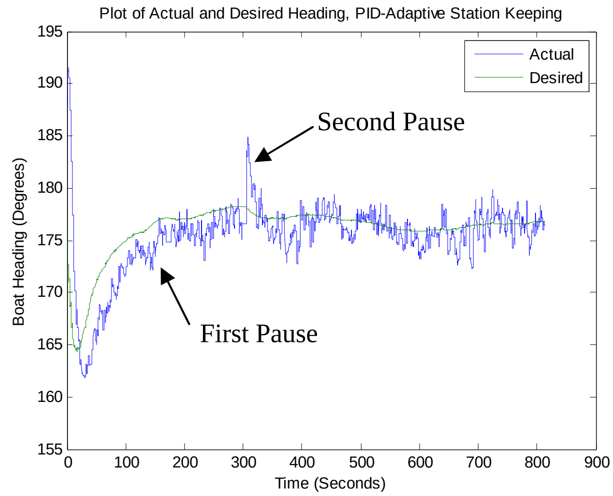

Figure 8: Plot of Actual and Desired Heading over Time

As can be seen in Figure 8, after an initial convergence, the heading works very well to follow the desired heading. The initial heading error is about 20° at the beginning of the trial, which is again quickly mitigated. There is a slowly decreasing offset between the actual and desired heading, which is due to the integrator term in the steering and differential thrust controllers needing time to build up to compensate for the moment caused by the wind forces.

The controller was paused and restarted twice during the trial. One of the pauses was around 298 seconds into the trial and is the reason for the spike in heading error seen in Figure 8. Even with the pauses, this controller works considerably better than the fixed-gain PID to follow the desired heading. Over the entire trial the heading error standard deviation is 3.0193°, which reduces down to 1.2228° over the second half of the trial. This shows a reduction of heading error standard deviation of almost 50% over the second half of trial in comparison to the PID-PID controller evaluated prior.

The vessel's position over the course of this trial can be seen in Figure 9. In this trial the boat begins at a position of 10.5 m north and 0.2 m west of the (0,0) point. This trial also has a higher northward drift, traveling almost 40 meters northward with the Gulf Stream before throttle kicks in and begins converging towards the desired location. Compared to the PID-PID controller, the PID-Adaptive controller has much less lateral movement, keeping magnitude of sway motion to about 6 m.

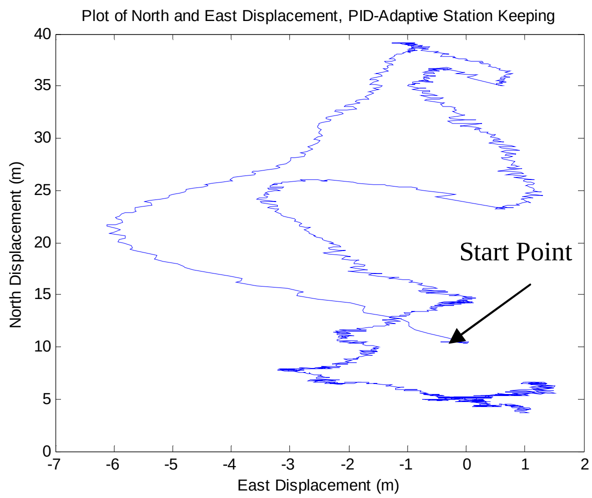

Figure 9: Plot North and East Displacement, PID-Adaptive

Once within 10 m of the desired location, the boat hovers very close to (0,0) without the large sway motion seen in Figure 6. The two pauses of the control system occurred at 170 and 298 seconds into the trial, and are outlined in Figure 8.

This controller does show higher positional error than the PID-PID controller. The mean positional error is 12.5961 m, while the RMS error for the entire trial is 17.8824 m. These values decrease to average displacement of 4.0039m and RMS error of 7.5976 m over the final half of trial. As noted above, this was the shortest of the three trials, and the positional error values are expected to decrease over the course of a longer trial.

AUGMENTING-ADAPTIVE STATION KEEPING

The final controller tested uses a fixed gain PID controller with adaptive augmentation for steering control, along with an adaptive PID controller for differential thrust. This algorithm utilizes the most adaptation of the three controllers evaluated in this paper. This controller will examine if any further increases in performance can be obtained by increasing the amount of adaptation in the algorithm, by using adaptation in both the steering and in the differential thrust. Note that the steering controller uses fixed gains with adaptive gains added on so that the gains don't converge to zero when heading error is consistently small.

It can be seen in Figure 10 that this controller had the largest initial heading error, about 70°. This was done intentionally, to test the ability of the adaptive differential thrust algorithm to quickly eliminate this heading error while minimizing overshoot past the desired heading, and to see how the differential thrust ramps down once the actual and desired heading become close to another.

This initial heading error is mitigated within 30 seconds of beginning the trial, and the starboard motor shifted into reverse during this period, as expected. There was some overshoot of the desired heading, but this was quickly minimized and afterwards the boat had excellent following of the desired heading.

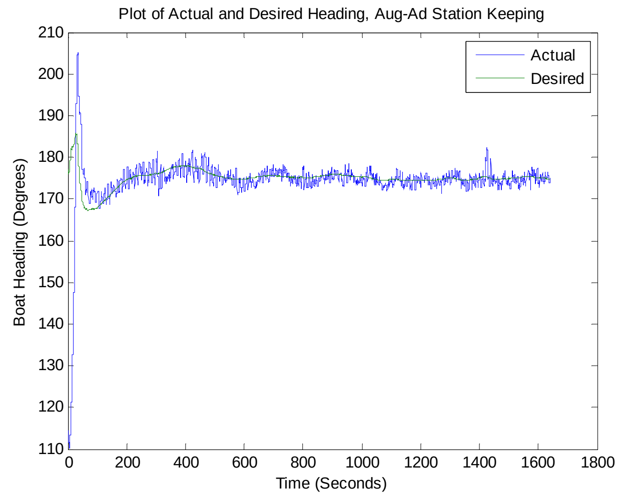

Figure 10: Plot of Actual and Desired Heading over Time

Over the entire trial, this controller did have relatively high standard deviation of heading error, ending up with 7.2341°. However, most of this can be attributed to the high heading error in the beginning of the trial. This is confirmed when looking at heading error standard deviation over the second half of the trial, where this value drops to 1.2673°. While this is slightly higher than the heading error of the PID-Adaptive controller, this is still excellent heading following.

In Figure 11 the displacement of the boat can be seen. The Augmenting-Adaptive controller had the best station keeping performance in terms of mean and RMS of positional error. Figure 11 shows that this controller has the smallest maximum northward displacement, under 30 m, after starting from an initial position of 5 m north of (0,0). After overcoming the environmental forces, the boat makes its way close to the desired location quite quickly and does an excellent job of staying there.

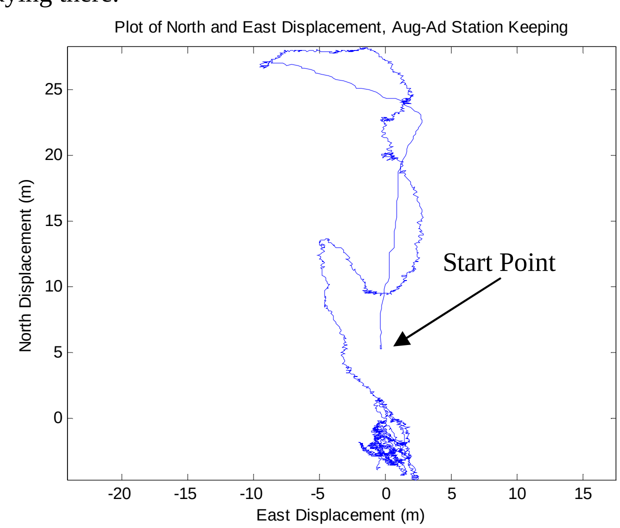

Figure 11: Plot of North and East Displacement

Whereas the PID-PID controller had large sway errors, this controller maintained sway errors of less than 3 m after convergence, which is less than the boat's beam. Similarly, the magnitude of the north-south error was kept within 5 m after convergence, which is less than half the boat's length.

As can be expected from seeing Figure 11, this controller produced the lowest positional error of the three tested. Over the entire trial, the average positional error was 8.0836 m and RMS error was 9.5210. These values dropped to mean positional error of 1.8531 m and RMS error of 2.5242 m over the second half of this trial. Note that this trial was run for the longest of the three, and this trial was run for significantly more time than the PID-Adaptive trial.

STATION KEEPING CONCLUSIONS

All three station keeping controllers worked effectively to keep the *Ocean Power* within 5 meters RMS of the desired position after initial convergence. Furthermore, increases in performance were found by using adaptive control theory in place of fixed gain PID with the results summarized in Table 1.

Table 1: Error Quantification for Station Keeping Trials

	Head Error STD Last Half	Position Error RMS Last Half	Avg Position Error Last Half
PID-PID	2.2408°	4.6117 m	5.2878 m
PID-Ad	1.2228°	4.0039 m	7.5976 m
Aug-Ad	1.2673°	1.8531 m	2.5242 m

While these results suggest that adaptive control offers increased performance, these results are not conclusive. These trials were performed with differing initial conditions, at different distances from the desired location, and run for different amounts of time. Indeed, any tests run in the open ocean will experience different operating conditions.

For conclusive results, more trials need to be run in various wind, wave, and current to make definite conclusions about the performance of each controller. These trials will also need to be run in a more standardized manner. That said, these results show that the developed station keeping controllers work with the implemented system to hold the vessel near a desired fixed location.

CONCLUSIONS

In this work, three station keeping controllers have been developed and initially tested in a validated numerical simulation. The *Ocean Power* vessel operated by the SNMREC at FAU was outfitted with sensors and actuators for implementation of the station keeping controllers. After extensive dockside testing of the physical system and translation of the controllers to LabVIEW software, the station keeping algorithms were successfully tested at sea.

Each station keeping controller effectively held position near the desired location after initially drifting northward with the environmental conditions. This research, while not conclusive, provides a good basis upon which to expand research in station keeping. The installed system can be used for further testing of these controllers in differing environmental conditions, as well as with various control architectures such as LQR or neural networks, among many others. Specifically for the LQR architecture, the PI controllers developed here can serve as the control law to be employed when combined with a state observer. However, other control structures beyond the PI(D) ones can be tuned and evaluated when employing the LQ constraint apparatus for synthesis.

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