Station Keeping of Small Outboard-Powered Boats

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***Abstract*-Three station keeping controllers have been developed which work to minimize displacement of a small outboard-powered vessel from a desired location. Each of these three controllers has a common initial layer that uses fixed-gain feedback control to calculate the desired heading of the vessel. A second control layer uses a common fixed-gain feedback controller to calculate the net forward thrust, one of two algorithms for controlling engine angle (Fixed-Gain PID or PID with Adaptively Augmented Gains), and one of two algorithms for differential throttle control (Fixed-Gain PID and PID with Adaptive Differential Throttle gains), which work together to eliminate heading error. The three selected controllers are evaluated using a numerical simulation of a 33-foot center console vessel with twin outboards that is subject to wave, wind, and current disturbances. Each controller is tested for its ability to maintain position in the presence of three sets of environmental disturbances. These algorithms were tested with current velocity of 1.5 m/s, significant wave height of 0.5 m, and wind speeds of 2, 5, and 10 m/s. These values were chosen to model conditions a small vessel may experience in the Gulf Stream off of Fort Lauderdale. The Fixed-gain PID controller progressively got worse as wind speeds increased, while the controllers using adaptive methodologies showed consistent performance over all weather conditions and decreased heading error by as much as 20%. Thus, enhanced robustness to environmental changes has been gained by using an adaptive algorithm.**

***Keywords*-Station Keeping, Adaptive Control, Ocean Energy, Adaptive PID, Small Vessel Control, Gulf Stream Operations**

I. INTRODUCTION

Station keeping of small boats is a technology that could potentially benefit several different 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. 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. 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 control systems to automatically hold a desired position in the presence of environmental forces acting on the vessel. 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, quantifying the increase in performance afforded by using adaptive algorithms.

Station keeping controllers are commonly used on large overactuated vessels, such as shipping vessels and oil tankers [1,2]. Additionally, there is a station keeping system commercially available from Cummins Mercury Diesel, called Skyhook which is used with the company's Zeus pod drives. Each propeller in the pod drive has the ability to turn 360°, completely independent of the other motor [3]. Other station keeping systems have been developed for a small monohull ASV powered by twin motors and steered with a single rudder [4], and for a catamaran ASV with twin motors which steers with differential thrust [5]. The objective of this station keeping system is novel in that it holds station using only twin, tied outboard motors with turning range of ±35°.

This paper is organized as follows: The testing platform used for development and implementation of the controllers is addressed in Section II. Section III presents all of the adaptive and fixed-gain controllers that have been developed, and Section IV quantifies the performance of these controllers through simulation. Finally, the conclusions are given in Section V.

II. TESTING PLATFORM

For the development and evaluation of these station keeping controllers, the validated numerical simulation presented in [6] is utilized with the modifications presented in [7]. Within this simulation, there are 17 user-defined parameters that define the physical dimensions of the vessel [6]. These parameters are set to match those of FAU's Center for Ocean Energy

Technology's research vessel, the Ocean Power. The Ocean Power is a 10 m (33 ft) center console vessel with 3.3 m (11 ft) beam and 0.75 m (2.5 ft) draft. The vessel in the original simulation had dual inboard motors which used rudders to steer, and the simulation has been modified to represent the dual outboard motors on the current test vessel.

To evaluate the developed controllers, a desired position of [0, 0] in the NED frame is set at the beginning of the simulation to match the vessel's starting location. The desired heading is set using state feedback to drive the bow of the vessel into the prevailing environmental conditions, which are a northward flowing current and varying magnitudes of wind and waves. This was done to mimic the conditions an actual vessel may experience in the Gulf Stream off Florida's southeast coast where FAU conducts many research missions.

In the simulation, various environmental conditions can be set to act on the vessel. For this paper, the following sets of conditions are used: the wind is modeled as a Davenport spectrum [8] with mean wind speeds of 2, 5, and 10 m/s, the current velocity is constant and flows north at 1.5 m/s, and the significant wave height is 0.5 m modeled using the spreading spectrum previously presented in [9]. It should be noted that the wave forces modeled in this simulation only include those induced by the horizontal orbital velocities from the waves [6].

III. Control Designs

The control goal in this paper is to minimize position error and control effort. For twin outboard vessels only three control variables can be used: the angle of the outboard motors with respect to the fore-aft plane of the vessel, and the thrust output from each of the two motors. A two-layer control methodology is used to command the control variables, in which the desired heading is calculated in the first layer, while the net forward thrust, differential thrust, and outboard motor angle are determined in the second layer. Coupling exists between the engine angle control system and thrust system, as the heading of the vessel is controlled using both the steering angle of the outboard motors and differential thrust.

In this paper, two methods for controlling the angle of outboard motors are presented: PID fixed-gain, and PID with adaptively augmented gains. Similarly, two algorithms for throttle control are used: PID fixed-gain, and PID with adaptive differential throttle. This paper compares 3 combinations of the above controllers in the second layer: PID Fixed-gain engine angle controller and PID throttle control (PID-PID); PID Fixed-gain engine angle controller and PID with adaptive differential throttle (PID-Adaptive); and finally PID with adaptively augmented gains engine angle control and the PID with adaptive differential throttle control (Augmenting-Adaptive).

The engine angle controllers used in this paper are based on the heading following controllers developed in [7]. These controllers use the difference between actual and desired vessel heading (described in further detail in Section III A) to command the angle of the boat's outboard engines.

The fixed-gain PID throttle control law used in this paper was previously presented in [10]. To create the PID with adaptive differential thrust controller, the throttle laws in [10] are modified to include adaptive algorithms for differential thrust. This controller is developed in such a way that when the difference between desired and actual heading is consistently large, such as in weather with strong wind and low current, the adaptive gains increase and enable a significant amount of differential thrust. Conversely, when desired and actual heading are consistently close to one another, the adaptive gains become small and differential thrust is minimal, leaving heading control primarily to the vessel's steering system.

Section III A explains the calculation of the desired heading in the first layer used by all of the controllers presented in this paper, Sections III B-C present the two throttle controllers (fixed-gain PID and PID with adaptive differential thrust), and Sections III D-E outline the two steering controllers used (PID and PID with adaptively augmented gains).

A. Calculation of Desired Heading

The desired heading is calculated for all three of the developed controllers as previously presented in [10]. This method of calculating the desired heading uses the position error of the vessel in the NED frame to drive the bow of the vessel into the prevailing environmental conditions. The bow is driven into the environmental conditions because this controller will be frequently used to hold station during instrument deployments in the Gulf Stream, with the sensor packages deployed off the stern of the vessel. The heading error is calculated in radians as

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

In this formula $Y_e = Y_{actual} - Y_d$ and $X_e = X_{actual} - X_d$, where X_d and Y_d are the desired X and Y locations respectively, all expressed in meters; a_h is a fixed integral gain; and $\tan_2^{-1}$ is the four-quadrant inverse tangent function, commonly known as atan2.

B. Fixed-Gain PID Throttle Controller

For the fixed-gain PID throttle controller, the thrust generated by each engine is controlled using the PID of position error in meters and the PID of heading error in radians. These equations use only feedback that can be easily measured by navigational instruments common to many vessels, such as GPS and heading sensors. This eliminates the need for costly and potentially cumbersome instruments such as a wind sensor and acoustic Doppler current profiler. The thrust equations for the port and starboard engines respectively are

$$\begin{aligned} T_d^p &= a_1 x_e + a_2 \int_0^t x_e dt + a_3 u\cos(\psi_e) - a_4\psi_e - a_5 \int_0^t \psi_e dt - a_6 r \\ T_d^s &= a_1 x_e + a_2 \int_0^t x_e dt + a_3 u\cos(\psi_e) + a_4\psi_e + a_5 \int_0^t \psi_e dt + a_6 r \end{aligned}, \qquad (2)$$

where $(\bullet)^P$ represents the port engine and $(\bullet)^S$ indicates the starboard engine; x_e is the x- component of the distance from the center of gravity of the vessel to the desired location, expressed in body-fixed frame; $\psi_e = \psi_{actual} - \psi_d$ is the heading error, with ψ_d as described in (1); r is the angular rotation rate in body-fixed frame; and a_{1-6} are constant proportional, integral, and derivative gains. The output of (2) is thrust from each motor given in Newtons.

In this controller, the gains used during the simulations are shown in Table I. These gains were found through iteratively tuning the controller to balance minimize position error with smooth operation and minimized thrust magnitudes for efficient boat operation

TABLE I: PID THROTTLE CONTROLLER GAINS

a_1	a_2	a_3	a_4	a_5	a_6
8 (kg/ s^2)	0.02 (kg/ s^3)	12 (kg/s)	14(kg-m/rad- s^2)	0.005(kg-m/rad- s^3)	10(kg-m/rad- s)

C. PID Throttle Controller with Adaptive Differential Thrust

The PID Controller with adaptive differential thrust is similar to the controller presented in Section III B. The difference is that gains a_{4-6} in Section III B have been replaced with adapting PID gains. This is done so that when the heading error is large, the gains for differential thrust will increase; similarly when heading error is small, the adaptive gains will decrease to near zero. Note that the fixed gains a_{1-3} are the same values as in Section III B. The new equation for thrust is:

$$\begin{aligned} T_d^p &= a_1 x_e + a_2 \int_0^t x_e dt + a_3 u\cos(\psi_e) - g_1\psi_e - g_2 \int_0^t \psi_e dt - g_3 r \\ T_d^s &= a_1 x_e + a_2 \int_0^t x_e dt + a_3 u\cos(\psi_e) + g_1\psi_e + g_2 \int_0^t \psi_e dt + g_3 r \end{aligned}, \qquad (3)$$

where $\dot{g}_1 = -\Gamma_1 e_\psi{}^2 - \sigma_1 g_1$, $\dot{g}_2 = -\Gamma_2 e_\psi \int e_\psi - \sigma_2 g_2$, and $\dot{g}_3 = -\Gamma_3 e_\psi \dot{e}_\psi - \sigma_3 g_3$. $\Gamma_{1,2,3}$ are adaptation rates that are to be chosen by the designer, and $\sigma_{1,2,3}$ is the sigma modification term, used to prevent wind-up. The values for $a_{1,2,3}$, $\Gamma_{1,2,3}$, and $\sigma_{1,2,3}$ are found in Table II. Once again, these values were found through iterative tuning to find a good balance between minimizing control input, maximizing station keeping performance and providing smooth, slow-changing vessel operation.

TABLE II: ADAPTIVE PID THROTTLE CONTROLLER GAINS

	$(\bullet)_1$	$(\bullet)_2$	$(\bullet)_3$
a	8	0.015	12
Γ	5	.0005	-2
σ	0.02	0.02	0.02

D. Fixed-Gain PID Engine Angle Controller

A fixed-gain PID controller is used as a baseline controller for engine angle control because PID is a well-known algorithm and its performance can be easily compared to that of the adaptive algorithm. The desired heading and the actual heading and rotation rates are inputs to this controller. The output of the PID steering controller is the commanded engine angle that is designed to minimize heading error. The commanded engine angle is calculated by:

$$u_\psi = K_P^b \psi_e + K_I^b \int \psi_e + K_D^b r, \quad (4)$$

where $\psi_e = \psi_{actual} - \psi_d$ is the heading error and its approximated derivative is $r_e = r_{actual} - r_d$, with the desired heading calculated as in Section III A and the desired rotation rate is set equal to zero. For this controller, the gains used for the simulation are shown in Table III. These gains were found using iterative tuning that minimized the initial heading overshoot with fast convergence, while balancing this with the desire to keep the commanded engine angle well within its achievable range. Please note that as this controller converts heading error to engine angle in the same units, the units cancel each other out.

TABLE III: PID STEERING CONTROLLER GAINS

K_P^b	K_I^b	K_D^b
5	0.0006 (s^{-1})	2 (s)

E. PID Steering Controller with Adaptively Augmented Gains

This controller is a combination of the fixed-gain PID steering controller (Section III.D) and the adaptive differential thrust algorithm from Section III C. This scheme uses the fixed-gain PID controller as a baseline control and has the adaptive PID control augment it for enhanced robustness. An application of such a system is found in [11] to improve accuracy and speed of a laser scanner process. The baseline fixed-gain PID control is the same as was described in Section III.D, with the control equation given by (4),

$$u_\psi^{PID} = K_P^b \psi_e + K_I^b \int \psi_e + K_D^b r. \quad (5)$$

This PID controller is augmented with an adaptive component. Adaptive augmentation adds adaptive gains to the fixed gains of the PID mentioned above with the goal of improving tracking of the desired trajectory [11] and making the closed loop system more robust. Note that in this application, only proportional and derivative terms augmented; the integral term is still a fixed gain. The adaptive portion of the control law that is used to augment the fixed-gain PID controller is:

$$u_\psi^{AD} = g_P^{AD} \psi_e + g_D^{AD} r_e, \quad (6)$$

with the derivative of the adaptive control gains calculated by $\dot{g}_P^{AD} = -\Gamma_P \psi_e^{\,2} - \sigma_1 g_P$ and $\dot{g}_D^{AD} = -\Gamma_D \psi_e r_e - \sigma_3 g_D$.

Summation of the adaptive and fixed-gain control signals gives the total control command,

$$u_\psi^{TOTAL}(t) = g_P^{TOT} \psi_e(t) + g_I^{TOT} \int \psi_e dt + g_D^{TOT} r_e(t), \quad (7)$$

where the total gains are defined by $g_P^{TOT} = (K_P^b + g_P^{AD})$, $g_I^{TOT} = K_I^b$ and $g_D^{TOT} = (K_D^b + g_D^{AD})$.

Each of the values represented by $K_{P,I,D}^b$ is the fixed-gain value used for the baseline PID controller. Each $\Gamma_{1,3}$ value represents adaptive gain multipliers, while each $\sigma_{1,3}$ determines the emphasis on the sigma modification term used to prevent wind-up. Also, a saturation limiter is used on the adaptive gains so that they did not rise too high, where the maximum adaptive gains are set to ±50% of the value of the fixed gains. The values for $\Gamma_{P,D}$, $K_{P,I,D}$, and $\sigma_{P,D}$ can be found in Table IV.

TABLE IV: PID WITH ADAPTIVE AUGMENTATION CONTROLLER GAINS AND LEAKAGE TERMS

	Proportional	Integral	Derivative
Γ	1	--	8
K	5	0.006	2
σ	0.035	--	0.06

IV. Results

Three sets of simulations are analyzed to evaluate performance of the controllers. These simulations are run to quantify how each control algorithm holds position in the face of differing wind conditions with a constant northwardly flowing current. Wind conditions are varied for these simulations because wind is the most difficult environmental force to deal with in station keeping. Current can be dealt with rather easily by stern-powered vessels, as current mainly moves a vessel in the direction of flow and it is not difficult to return to a position. However, wind affects both the heading and position of the vessel. Without direct control over the sway of the vessel and limited heading control, such as that provided by bow and stern thrusters, a change in heading or lateral error can cause boats with only stern propulsion problems in trying to re-orient itself in the desired heading while also holding station. This is the reason for implementing adaptive differential thrust, and this will be tested against a fixed-gain PID differential thrust algorithm.

For this set of simulations, the current for every trial is 1.5 m/s second in the Northward direction (the mean surface water velocity measured near the core of the Gulf Stream off Southeast Florida by [12]) and the significant wave height is 0.5 meters, with the mean wave propagation direction in the same direction as the wind. The mean wind speeds are 2, 5, and 10 m/s, blowing from west to east. These conditions are used because they are conditions which a small vessel would be likely to face in the Gulf Stream off the coast of Fort Lauderdale, where FAU conducts many operations on the Ocean Power during similar conditions. As Ocean Power is a small vessel, it is unlikely that experiments would be carried out in wind speeds much higher than 10 m/s. Note that for each simulation, [0, 0] in the NED Frame is used as both the starting point and the desired position and the initial heading of the vessel is 170°.

A. 2 m/s Wind Speed

The first trial is done with a wind speed of 2 m/s, corresponding to a Beaufort number 2, or Light Breeze. This is the weakest wind force done in these trials, and each controller shows good performance over the length of the trial. Figure 1 shows the North and East displacement for each controller, Figure 2 shows the actual and desired heading for each controller, and Figure 3 shows the port and starboard thrust for each engine.

In this case, each controller shows very similar performance for minimizing displacement from the desired position. Each drifts between 20 and 25 meters north of (0,0) and over the final 300 seconds holds position within ±1 meter east-west and within 5 meters north of the desired position while slowly moving closer to the desired location. In Figure 2, it can be seen that the augmenting steering cuts down on overshoot and oscillation around the desired heading, as the two fixed-gain PID steering controllers take longer to converge to equilibrium heading.

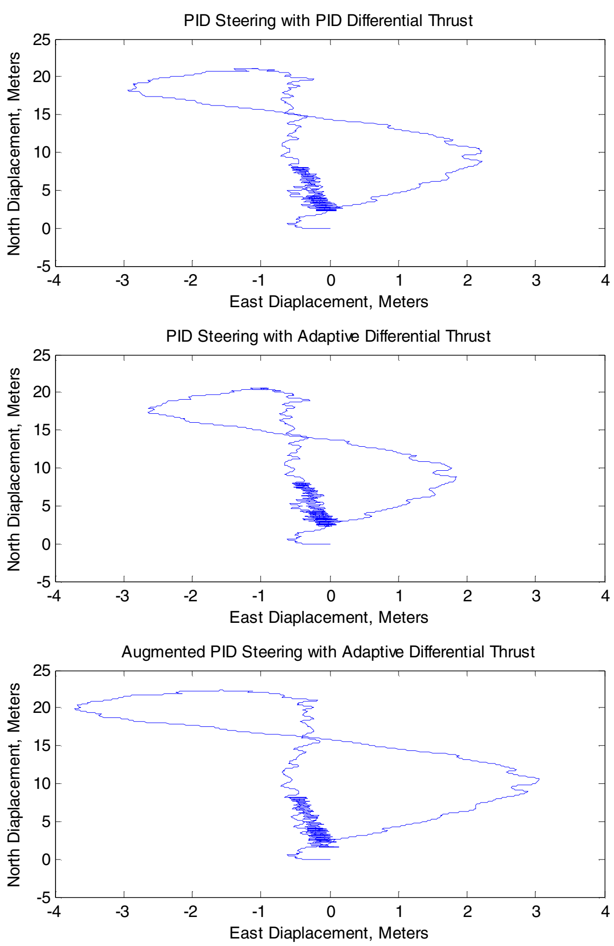

Figure 1: Plot of North and East Displacement for 2 m/s West Wind

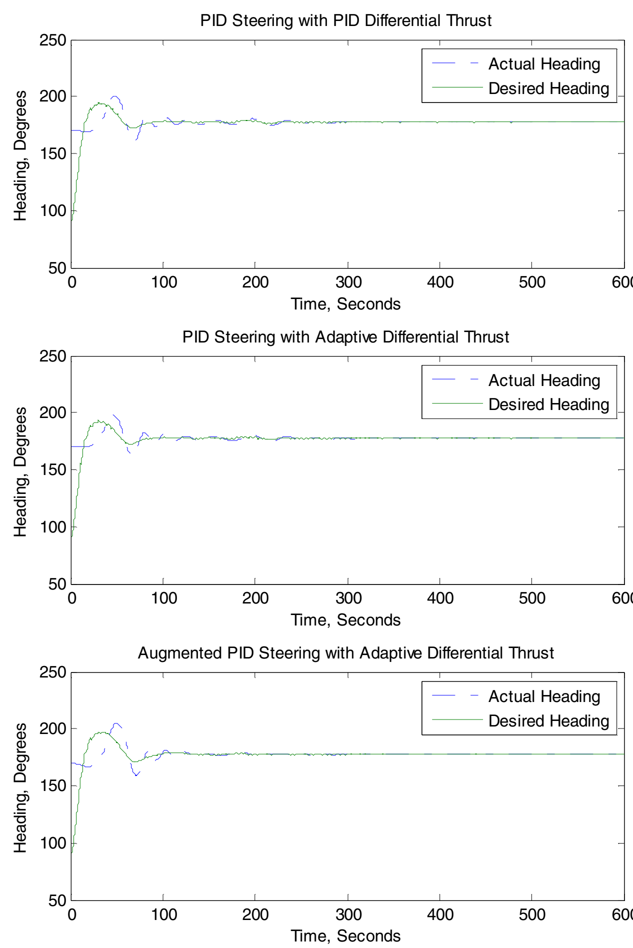

Figure 2: Plot of Actual and Desired Heading, 2 m/s West Wind

Figure 3 shows the thrust profiles for each trial. The PID-PID controller uses the least differential thrust at the beginning, but uses some differential thrust over the first 100 seconds. Conversely, the adaptive differential thrust controllers used greater magnitude of differential thrust for about the first 15 seconds, then the vessel uses only steering. After the initial convergence periods, each controller uses only the steering angle of the outboards for controlling heading, as shown in Table V where the mean and standard deviation of differential thrust is less than 1 N.

As can be seen in Table V, the controllers have very similar performance in terms of position error. There is only 0.12 m difference between the controller with the least average position error (Augmenting-Adaptive) and that with the most average position error (PID-Adaptive). Note that the position error was found by finding the straight-line distance between the center of gravity of the vessel and the desired location, or $e_p = \sqrt{X_e^2 + Y_e^2}$. It is interesting to see that the Augmenting-Adaptive controller has the least average position error, but the highest position error standard deviation.

The three controllers had very similar results for average heading error and performed well, each keeping average heading error under 0.12°. There becomes a larger discrepancy in the standard deviation of heading error, however. The Augmenting-Adaptive controller had heading error standard deviation of 0.248, compared to 0.2882 for the PID-Adaptive and 0.2901 for the PID-PID, representing 15% more heading error variation than the Augmenting-Adaptive controller. This is important to watch, because as there becomes more error variation, the magnitude of error increases, and with this the ability of the vessel to hold station significantly decreases.

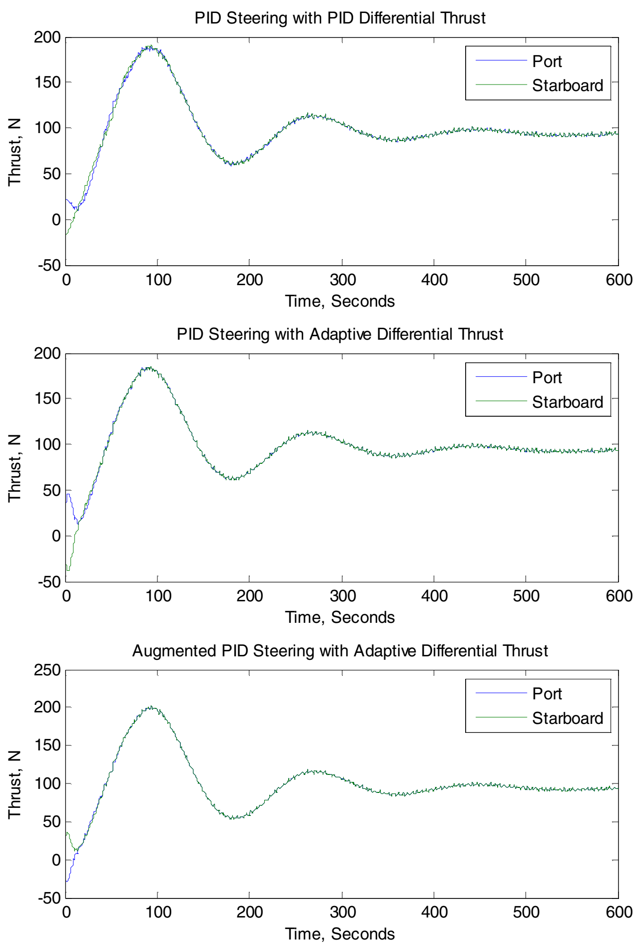

Figure 3: Plot of Port and Starboard Thrust, 2m/s West Wind

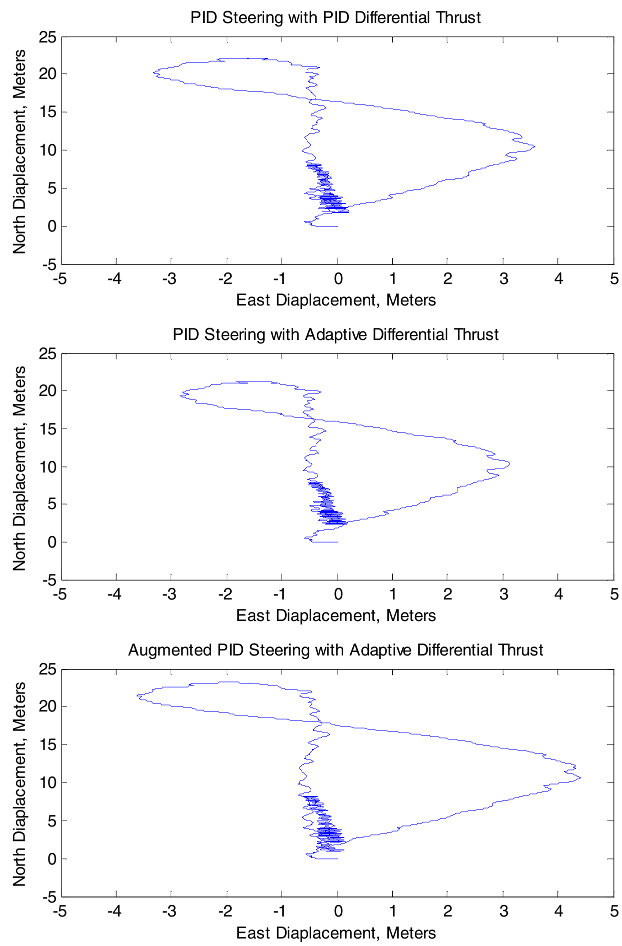

Figure 4: Plot of North and East Displacement, 5 m/s West Wind

B. 5 m/s Second Wind Speed

The second set of trials has an increased wind speed of 5 m/s westerly wind. The test is run the same way, with a simulated trial of 10 minutes, and 1.5 m/s northward current. Similar to Section IV.A, Figure 4 shows the North and East displacement, desired and actual heading are in Figure 5, and the throttles for each controller are in Figure 6.

As Figure 4 shows, the augmenting PID steering with adaptive differential thrust has the most East-West error during convergence, while the performance of the PID-PID and PID-Adaptive look to be similar to one another, although the PID-PID controller has slightly more East-West movement. After the initial tuning phase, each controller holds position well with respect to one another, as can be seen in the error quantization found in Table V. Again, the Adaptive-Augmenting controller has the highest standard deviation and lowest average position error of the three controllers.

As can be seen in Figure 5, the Augmenting-Adaptive controller has the least heading error. This is evident in Table V, where the Augmenting-Adaptive controller has 20% less standard deviation of heading error than the PID-PID and PID-Adaptive controllers, as well as slightly less average error. It should be noted that each controller does successfully converge towards the desired heading and stays within 2 degrees of the desired heading during the last 5 minutes of the simulation.

Differential thrust is used about the same as before in this case, as shown in Figure 6. The PID-Adaptive controller uses more differential thrust at the beginning than the other controllers. At the beginning, the difference between port and starboard thrusts approaches 100 Newtons. Each controller has a smooth and controlled thrust profile, which is good for crew working onboard. Each controller uses strong differential thrust for the first 15 seconds, then the port and starboard thrusts stay at about the same value for the remainder of the simulation. Again, mean and standard deviation of differential thrust are all well below 1 N, although the PID controller did see an increase in average differential thrust from 0.0065 N in 2m/s wind to 0.2360 N in 5 m/s wind, showing an increase by a factor of 36.

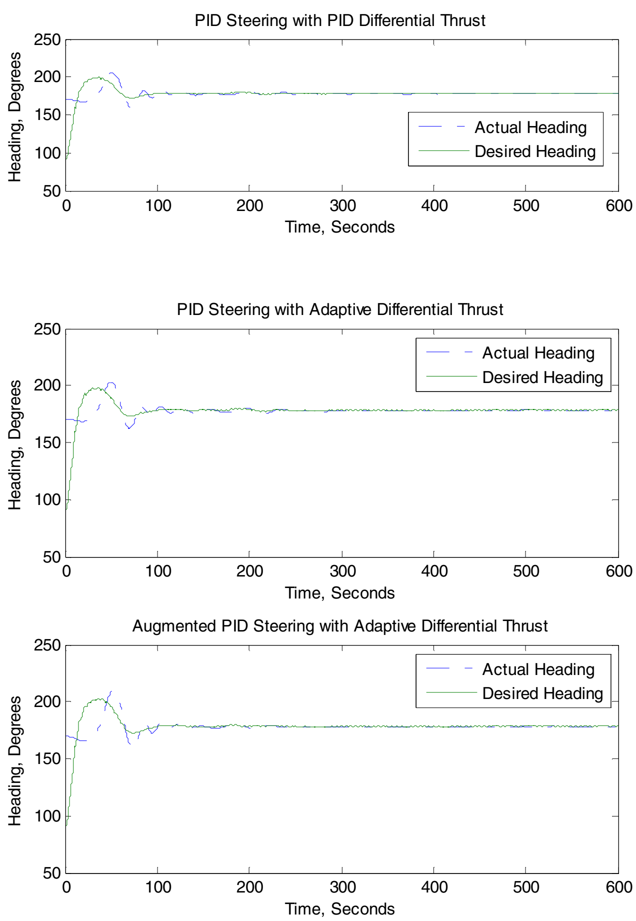

Figure 5: Plot of Actual and Desired Heading, 5 m/s West Wind

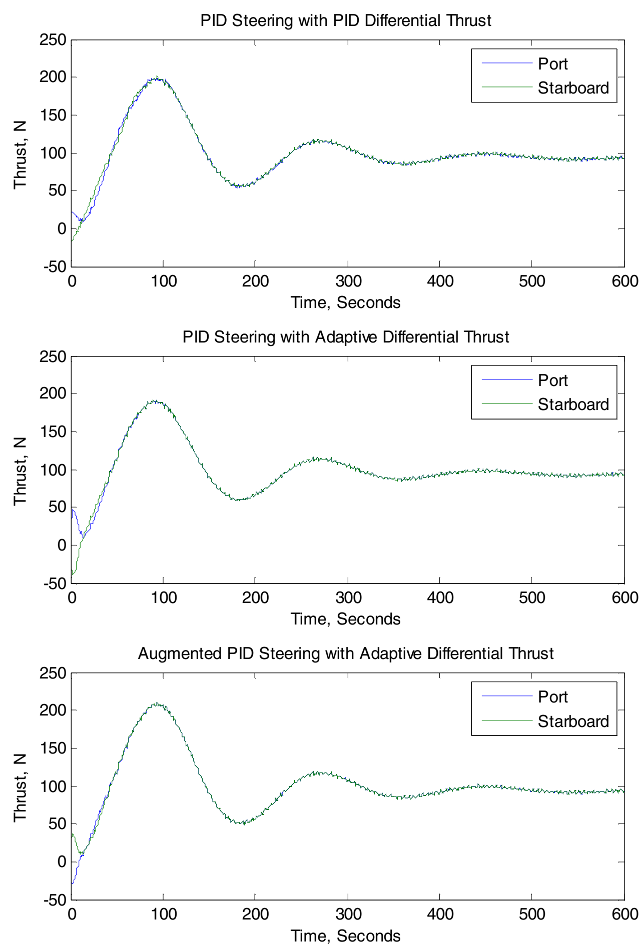

Figure 6: Plot of Port and Starboard Thrust, 5 m/s West Wind

C. 10 m/s Wind Speed

Lastly, each controller is tested to hold position in 10 m/s westerly wind and 1.5 m/s northward current. This is the most difficult set of environmental conditions done in this paper, as maintaining a desired heading gets more difficult as wind speed increases. Because of this, it can be expected that the use of differential thrust will increase disproportionally fast for the adaptive differential thrust when compared to the fixed-gain controller to better hold a heading while staying close to a desired position. This is shown in Table V, where the average differential thrust increases about 5 fold (0.236 N to 1.086 N) for the PID-PID controller, while it increases over 1000 times (0.0040 N to 11.04 N) for the PID-Adaptive controller in going from the 5 m/s wind case to 10 m/s wind.

As Figure 7 shows, the vessel gets blown almost 10 meters East in each test case, far more East-West error than either of the two previous test cases. This can be attributed to the stronger wind blowing from West to East. After the initial Eastward and Northward movement, each controller gets the vessel back to position close to the desired location, with each controller actually having less average position error in this case than the previous two. In this case, the PID-Adaptive and Augmenting Adaptive controllers had almost identical performance in position error standard deviation, while the variation of the PID-PID controller is slightly higher.

It is interesting to see Figure 8, where both of the PID engine angle controllers did not hold the desired heading as well as the augmenting-adaptive controller. While the adaptive-augmenting controller went to nearly match the desired heading, the PID steering controllers never seemed to match the desired heading, and even had oscillation in heading towards the end of the simulation. This is shown in Table V, where the standard deviation of heading error is 0.5934° for the Augmenting-Adaptive controller, while the other controllers have greater than 20% more heading error. Additionally, the Augmenting-Adaptive controller has the lowest average position error at -1.5593°m while the PID-Adaptive has the most at -1.7045°.

Figure 9 shows more differential thrust is being used by the controllers, especially the adaptive differential thrust controllers. Once again, the PID-adaptive controller had the largest difference between port and starboard thrust at the beginning of simulation and also has the most at the end, with an average difference between port and starboard thrust of 11.04 N. The PID-PID controller does not use much differential thrust after the first minute, while the PID-Adaptive and

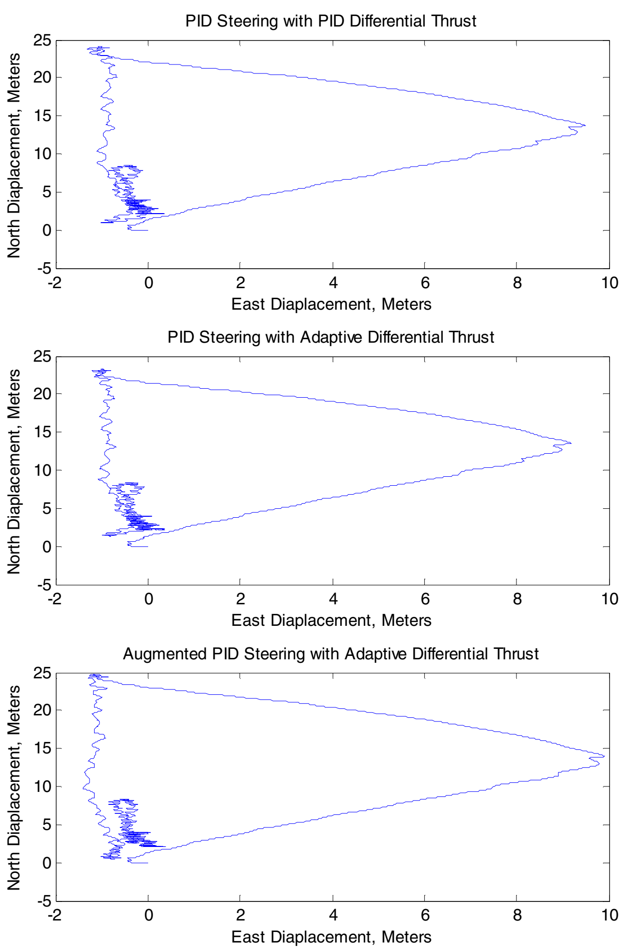

Figure 7: Plot of North and East Displacement, 10 m/s West Wind

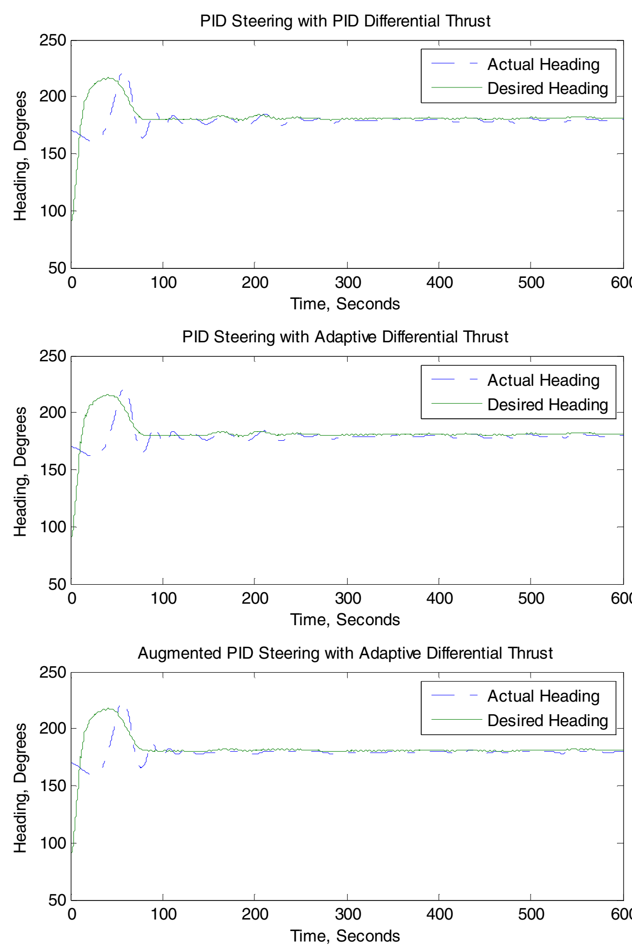

Figure 8: Plot of actual and desired heading, 10 m/s West Wind

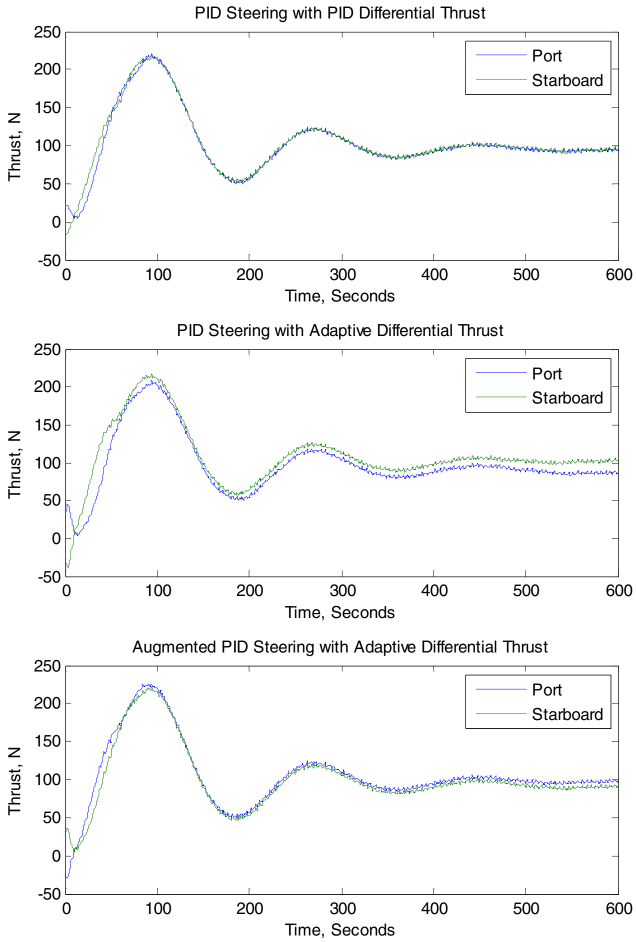

Figure 9: Plot of Port and Starboard Thrust, 10 m/s West Wind

Augmenting-Adaptive controllers increase their use of differential thrust through the simulation.

D. Results Summary

It can be seen that all controllers developed here successfully have the simulated vessel hold station over a variety of weather conditions. While all controllers have similar performance in the light wind conditions, it can be seen that the fixed-gain steering methodology has a more difficult time holding a desired heading than does the adaptive methodology.

It is interesting to see that for each controller, average position error decreases as wind speeds increase. It can also be seen in Table V that as the average position error decreases, the standard deviation of position error tends to increase.

Advantages of adaptive control can be seen in the higher wind cases. In the 5 m/s and 10 m/s wind cases, the position performance of the PID-PID and PID-Adaptive controllers continually degrades. However, the Augmenting-Adaptive controller has less position error standard deviation in 10 m/s wind than 5 m/s wind (0.8923 m in 10 m/s wind as opposed to 0.9082 m error in the 5 m/s case), and shows consistent performance over the three tested environmental conditions.

In controlling vessel heading, the Augmenting-Adaptive controller significantly outperforms the PID-PID and PID-Adaptive. In each case, the PID-PID and PID-Adaptive have at least 15% more heading error than the Augmenting-Adaptive controller and as the wind speed increases, so does the difference between these controllers and the Augmenting-Adaptive, as the Augmenting-Adaptive controller has more than 20% less heading error than the other controllers in 10m/s wind.

The use of adaptive control for differential thrust can also be seen in Table V. In the PID-Adaptive and Augmenting-Adaptive controllers, minimal differential thrust is utilized in the 2 m/s and 5 m/s cases. However, the differential thrust standard deviation increases by a factor of about 1000 in the 10 m/s case, showing the differential thrust activated when it is needed. The average differential thrust for the PID-PID controller looks to show a steady increase over the three cases, while the average differential thrust is near zero for the PID-Adaptive and Augmenting-Adaptive controllers in the first cases, until it increases exponentially in the 10 m/s wind case. Comparatively, the differential thrust for the PID-PID controller is almost constant for the 2 m/s and 5 m/s cases, then increases by a factor of approximately 2 in the 10 m/s case, when it performed worst. This shows that the adaptive differential thrust has increased authority to activate when necessary to hold heading, and as an extension, position better.

TABLE V: QUANTIZATION OF ERRORS OVER FINAL 300 SECONDS OF SIMULATION

	Position Error Standard Deviation			Heading Error Standard Deviation			Differential Thrust Standard Deviation		
	2m/s Wind	5m/s Wind	10m/s Wind	2m/s Wind	5m/s Wind	10m/s Wind	2m/s Wind	5m/s Wind	10m/s Wind
PID-PID	0.8664	0.8934	0.9109	0.2901	0.3459	0.7811	0.1413 N	0.1682 N	0.3786 N
PID-Adaptive	0.8482	0.8693	0.892	0.2882	0.3416	0.7745	0.0041 N	0.0045 N	2.5473 N
Augmenting-Adaptive	0.8912	0.9082	0.8923	0.248	0.268	0.5934	0.0010 N	0.0129 N	1.1852 N
	Mean Position Error			Mean Heading Error			Mean Differential Thrust		
	2m/s Wind	5m/s Wind	10m/s Wind	2m/s Wind	5m/s Wind	10m/s Wind	2m/s Wind	5m/s Wind	10m/s Wind
PID-PID	3.4305	3.3484	3.1586	-0.1122	-0.4398	-1.16511	0.0065	0.236	1.086
PID-Adaptive	3.4854	3.4213	3.2357	-0.1189	-0.4455	-1.7045	0.0343	0.004	11.04
Augmenting-Adaptive	3.3632	3.2839	3.1729	-0.1188	-0.4293	-1.5593	0.0035	0.0385	5.1046

V. CONCLUSION

One fixed-gain station keeping controller and two station keeping control systems utilizing adaptive theory have been developed, tuned, and tested within a simulation for three separate environmental conditions. From the results of these tests, it can be seen that all three controllers have good performance in station keeping. Further, while the fixed-gain controller has good performance, as weather degrades its ability to hold a desired heading diminishes, while the adaptive differential thrust controller has upwards of 20% less variance in holding a heading and slightly better station keeping performance in adverse conditions. The use of adaptive algorithms for differential thrust can be seen to be effective for improving the ability to hold a heading, as these controllers use almost no differential thrust in the light wind cases, then increase its use greatly for the 10 m/s wind case.

Work is currently underway to implement these controllers on Ocean Power for sea trials. The system for controlling steering angle has undergone sea trials and performed well. The system for controlling engine thrust on the Ocean Power is now in the process of being assembled, after which it will be installed on the vessel, undergo dockside testing, and then be taken offshore for validation using the three control systems developed in this paper.

REFERENCES

[1] AJ. Sorensen, S.I. Sagatun, and T.I. Fossen, *Design of a Dynamic Positioning System Using Model-Based Control.* Control Engineering Practice, 4 (3) 359-368.
[2] T.I. Fossen and T. Perez, *Kalman Filtering for Positioning and Heading Control of Ships and Offshore Rigs.* IEEE Control Systems Magazine, pp.32-46, December 2009.
[3] K. Falvey, "A New Generation." Boating Magazine, Vol 82, No. 7, pp.48-50, July 2009.
[4] A. Pereira, J. Das, and G.S. Sukhatme, *An Experimental Study of Station Keeping on an Underactuated ASV.* 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, 14 October 2008, pp. 3164-3171.
[5] A. Matos and N. Cruz, *Positioning Control of an Underactuated Surface Vessel.* OCEANS 2008 MTS/IEEE Conference, 15-18 September 2008.
[6] J.H. VanZwieten and F.R. Driscoll. (2008) "A comprehensive general simulation of twin screw displacement hull vessels with validation" Journal of Mathematical and Computer Modeling of Dynamical Systems, 14 (4) 269-301
[7] A.D. Fisher, J.H. VanZwieten, T.S. VanZwieten, *Adaptive Control of Small Outboard Powered Boats for Survey Applications.* OCEANS 2009 MTS/IEEE Conference, 26-29 October 2009.
[8] M.K. Ochi and Y.S. Shin, *Wind turbulent spectra for design consideration of offshore structures*. Proceedings of the Offshore Technology Conference, 2-5 May, Houston, Texas, 1988 pp.461-467.
[9] M.A. Donelan, J. Hamilton, and W.H. Hui, *Directional spectra of wind-generated waves*, Philos. Trans. R. Soc. Lond. A315 (1985), pp. 509-562.
[10] J.H. VanZwieten and F.R. Driscoll, "A Comparison of Station Keeping Controllers for Twin Screw Vessels," unpublished.
[11] M. Lugmair et al. *Result-Adaptive PID Control Improves Laserscanner Positioning.* Baasel Lasertech.
[12] R. Raye, "Characterization study of the Florida Current at 26.11 North Latitude, 79.50 West Longitude for ocean current power generation." Master's Thesis, Florida Atlantic University, 2002.
[13] Fossen, T.I. Guidance and Control of Ocean Vehicles. New York: Wiley, 1994.
[14] Ioannou, Petros and Baris Fidan. Adaptive Control Tutorial. Philadelphia: SIAM, 2006.
[15] Lavretsky, Eugene. Adaptive Control: Introduction, Overview, and Applications. NASA Adaptive Control Workshop. NASA Marshall Space Center, Huntsville, AL. 24 Feb 2009.
[16] Zilouchian, Ali and Mo Jamshidi. Intelligent Control Systems Using Soft Computing Methodologies. New York: CRC Press, 2001
[17] Budny, Dan. Introduction to Engineering Analysis. Champaign: Stipes, 2003.