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A Capstone Project on Robust Dynamic Positioning and Data Acquisition Systems

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Abstract

The United States Coast Guard is responsible for enforcing Dynamic Positioning System (DPS) standards in the maritime industry. It is important for the members of the U. S. Coast Guard to understand how these systems work. Students have gained a much greater understanding of how DPS platforms work and what might be required to maintain them by building one from scratch. Aside from this, the project has served as a great opportunity to work on a one year term project that may resemble engineering or acquisitions projects that might be encountered in the students' future careers.

The overall goal of the Robust Dynamic Positioning and Data Acquisition System project was to prototype a dynamic positioning system similar to the ones on buoy tenders in the fleet. The primary goal was to maintain a desired heading and position within a certain range. The secondary goals included robust capabilities (the ability to continue functioning despite motor failures) and data acquisition (to analyze system performance post-testing). Students built a vessel from scratch out of a salvage drum and an inner tube for buoyancy. The internal construction consists of three tiers containing batteries at the lowest level, an onboard computer at the second level, and control hardware at the top level (micro controllers, H-bridges, and fuse boxes). Students successfully used a light detection and ranging (LIDAR) device to determine the relative position to two stationary poles. They were able to communicate with the onboard computer via either a wired connection or a remote desktop connection through an ad-hoc wireless network. All programming for this project was done in MATLAB®. Students have completed all project milestones through the application of past courses they have taken in computer control systems, network communication, and digital signal processing at the U.S. Coast Guard Academy.

The first challenge of this project was to focus on constructing the vessel and installing the control hardware. One of the obstacles for the students was establishing communication between the various pieces of software, hardware, and the power distribution system. The LIDAR sensor determined the vessel's relative position and heading to two stationary poles. Using the position and heading resolution algorithms, students conducted a set of system identification tests in an indoor tank to determine how the system reacts to various thrusts from the motors. This allowed students to collect "Open-Loop" system data. Using the data acquisition system, students were able to identify the system and calculate coefficients for the controller and implement a "Closed-Loop" control system. Students successfully implemented a proportional integral derivative (PID) controller that satisfies all design requirements including robust functionality. Currently, all milestones for the project have been accomplished and plans for continuation of the project are underway.

Keywords

Robust Dynamic Positioning System (RDPS), Light Detection and Ranging (LIDAR), System Identification, PID Controller

Introduction

The United States Coast Guard is responsible for enforcing Dynamic Positioning Systems (DPS) standards in the maritime industry; hence, its officers should understand how these systems work. Members of this project have gained a much greater understanding of DPS and what may be required to maintain them by building one from scratch. Aside from this, the project has served as a great opportunity to work on a one-year term project that may resemble engineering or acquisitions project that might be encountered in their future career.

The current paper describes the results of two semesters spent working on a capstone project in the Electrical Engineering major at the U.S. Coast Guard Academy. The U.S. Coast Guard Marine Safety Center (MSC) is the sponsor of the project due to its involvement in enforcing DPS standards in the US. Project milestones included: evaluate the problem and make goal-oriented decisions in terms of the overall planning for the year; experiment with the hardware components as well as their individual communication lines; construct the DPS prototype vessel; perform preliminary open loop control system tests; identify and model the system; and derive controller coefficients and implement a closed loop controlled system.

This project is a continuation of two previous years of work done by prior senior design project teams[1,2]. The hardware components, vessel hull, and motor configuration from 2013-14 were retained and improved upon this year. Based upon issues with multiple programming platforms[1] (MySQL, Python, Arduino, MATLAB, and Linux), the programming was reduced to purely MATLAB this year. Also, while the hardware was retained, the configuration and durability was improved considerably. One final update to this year's project is using a LIDAR instead of GPS for positioning to ensure platform performance in a controlled environment before implementing GPS next year in more realistic maritime conditions.

The design requirements for the RDPS project this year were established early in the process of development. The system was required to maintain position within +/- 300mm of the desired location, maintain heading within +/- 10 degrees of the desired heading, and be able to do so despite up to two motor failures. A data acquisition system was also necessary for collection and analysis of all test data. In addition to these requirements, the system had to be reliable, portable, and aesthetically pleasing.

The cadet authors accomplished all project goals through the application of past courses they have taken in computer control systems, network communication, and digital signal processing while at the U.S. Coast Guard Academy. The students accomplished all of these tasks ahead of schedule through teamwork and genuine enthusiasm towards learning and the project.

Important Concepts

Before delving into the intricacies of the project, it’s important to understand some of the core concepts. The following are the building blocks of the system and are necessary to understand if one is to understand both how and why this project functions.

Robust Dynamic Positioning Systems (RDPS): A Dynamic Position System is a digital control system used on marine vessels that is able to maintain the vessel’s desired heading and geographic position using its various means of propulsion. The system compensates for error in the vessel’s position and heading due to current and wind effects by incorporating feedback from various shipboard sensors. The system integrates with the vessel’s engineering plants to regulate propulsion outputs to maintain position and heading. A Robust DPS system has the ability to adjust its performance in the event of a critical propulsion casualty and still maintain position and heading.

Light Detection and Ranging (LIDAR): Light Detection and Ranging (LIDAR) is a laser sensor that determines the range between the sensor and its surroundings at various angles. The LIDAR employed is the Hokuyo URG-04LX-UG01. It utilizes a USB 2.0 interface, has a field of view of 240 degrees at 682 steps (separate ranges), and has a range of 20 mm to 5.6 m with an accuracy of a few millimeters. The DPS platform determines its position relative to two stationary poles at a known distance apart.

Platform Construction

The two most important focus points for the construction of the prototype vessel are that the vessel is portable and reliable. The vessel needs to be easily transported to the testing tank to facilitate a smooth troubleshooting process. The vessel also needs to be reliable so that the test results can be easily replicated and so that troubleshooting issues is easy.

In order to accomplish these objectives, members use a 20 gallon steel salvage drum to act as the hull of the vessel with an inner-tube around the outside for additional buoyancy and stability. Six SeaBotix BTD150 thrusters perform the positioning of the vessel as shown in Figure 1. The thrusters are oriented as to create an X-Y plane relative to the front of the vessel. Two thrusters are pointed in the X-direction and two are in the Y-direction. The other two are welded tangentially to the outside of the vessel on opposite sides from one another which provide the ability to apply rotational force to the vessel to control its heading. This thruster set up allows the user to separately compensate for X, Y, and heading error with three individual control algorithms.

Figure 1. Robust Dynamic Positioning Vessel (Middle), LIDAR Sensor (Left), and SeaBotix Thruster (Right)

To satisfy the reliability requirement, the vessel is constructed using a three tier system, each tier being divided by a circular piece of plywood stacked on the previous level to allow for easy access to all tiers. The bottom level contains the batteries for the power distribution system. The vessel is equipped with one 12V, 55 AH battery that is used for providing power to the H-Bridges which control power output to the thrusters. The vessel is also equipped with two 12V 7.5 AH batteries in parallel which provide power to the on-board computer and other auxiliary systems such as the cooling fans.

The second tier of the vessel is equipped with an on-board computer running a Window's 7 operating system with MATLAB. The computer receives raw inputs from the LIDAR sensor, processes the data in MATLAB and communicates with the Arduino to deliver motor commands to the thrusters.

The third and final tier of the internal construction of the vessel contains the direct interface between the computer and the thrusters (see Figure 2). The computer is connected to the Arduino that is receiving motor speed and direction commands from the on-board computer. The Arduino then converts the motor commands into PWM signals that are communicated along with the direction signal to the H-Bridge that corresponds to the desired thruster. There are six H-bridges connected to the Arduino, one for every thruster. The H-Bridges are connected to the thruster power supply through a fuse box for surge protection purposes.

The LIDAR sensor and a WiFi adapter are mounted on top of the vessel. The LIDAR is mounted in the center of the vessel and connects directly to the on-board computer. The WiFi adapter connects directly to the on-board computer and facilitates communication between the user and the on-board computer via a remote desktop connection over a wireless Ad-Hoc peer-to-peer network.

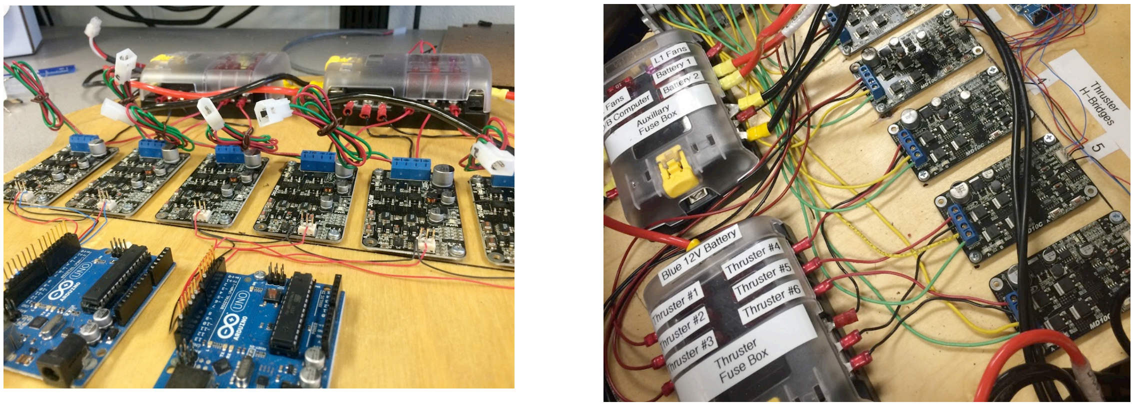
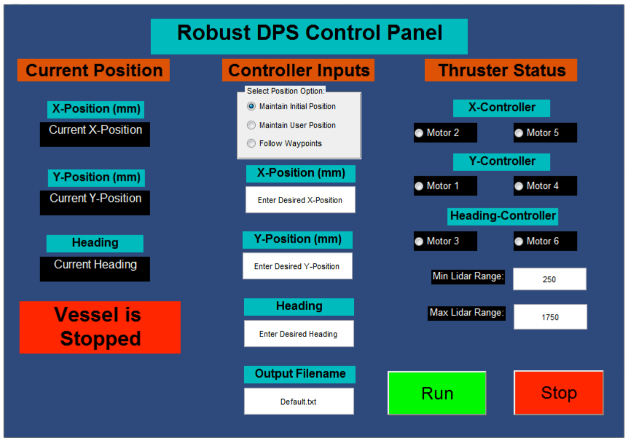


Figure. 2. Robust Dynamic Positioning Vessel Internal Construction Power distributions (Left), H- H-Bridges and Microcontrollers (Right)

Software Components

1) Data Acquisition:

A Robust Dynamic Position system requires an enormous amount of information in order to function. Just within MATLAB, 682 ranges must be acquired from the LIDAR scanner, processed into Cartesian position coordinates and a heading relative to two stationary poles, a control algorithm must process this and output six motor commands, all of which is dependent on motor functionality; for timely system control, this all occurs in approximately one fifth of a second. In order to increase processing speed and system efficiency, only what is essential to understanding the system is collected. There are 32 system critical variables: sample number, timestamp, XYT position (X and Y horizontal position, heading theta), XYT desired, XYT error, motors on/off, motors 1-6 PWM, motors 1-6 direction, and PID controller outputs. These are all collected in discrete time and can be analyzed post-test via a myriad of functions developed by the authors. The main graphical user interface (GUI) created in MATLAB for this project is shown in Figure 3. While many GUI's were designed and implemented in this project, the final GUI allows users to select an operating mode, specify which motors are functioning, run or stop the vessel, view the current position and heading of the vessel, and determine the data acquisition file name. The GUI allows users to modify testing parameters and serves as a data acquisition tool. Through post test data analysis, it is possible to analyze the fitness of the system and identify issues to be resolved.



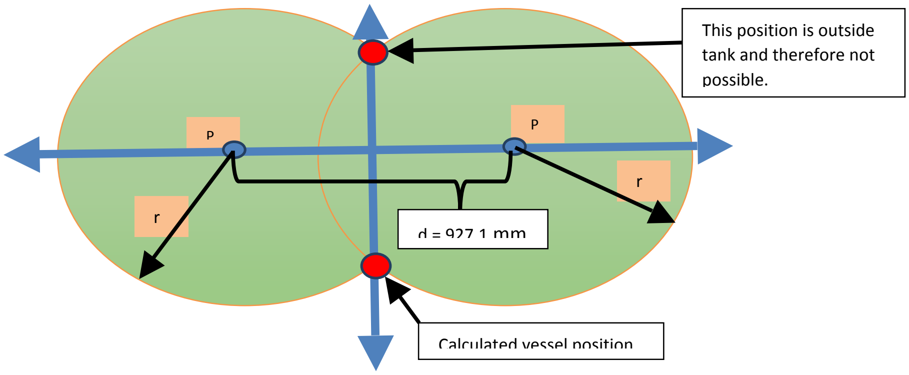
Select Position Option:
● Maintain Initial Position
○ Maintain User Position
○ Follow Waypoints

Min Lidar Range: 250
Max Lidar Range: 1750
Output Filename: Default.txt

Figure 3. RDPS control panel GUI used to run closed-loop tests.

2) Position and Heading Resolution Algorithms:

The LIDAR provides angles and ranges to various objects around it. In the test scenario seen in Figure 4, two poles (P1 and P2) that are 927.1 mm apart are positioned at the edge of the test tank. The LIDAR locates these two poles and provides ranges from the vessel to each pole. The vessel, then, must be located on a circle around each pole with the radius being the range to each pole. Onboard processing then solves for the two possible intersection points of the circles. One of these can be safely eliminated as it will be outside of the test tank.



This position is outside tank and therefore not possible.

Calculated vessel position

Figure 4. Position resolution algorithm visual diagram

Letting x and y represent the vessel location, d the distance between the poles, putting the coordinate origin at the midpoint between the poles (both poles on the x axis), and letting r_1 and r_2 be the two range measurements, we have

$$r_1^2 = \left(x + \frac{d}{2}\right)^2 + y^2 \qquad \text{Eq. (1)}$$

$$r_2^2 = \left(x - \frac{d}{2}\right)^2 + y^2 \qquad \text{Eq. (2)}$$

$$y^2 = r_1^2 - \left(x + \frac{d}{2}\right)^2 = r_2^2 - \left(x - \frac{d}{2}\right)^2 \qquad \text{Eq. (3)}$$

$$x = \frac{r_1^2 - r_2^2}{2d} \qquad \text{Eq. (4)}$$

$$y = \sqrt{r_1^2 - \left(x + \frac{d}{2}\right)^2} \qquad \text{Eq. (5)}$$

Controller Design

1) Open Loop Test

The open loop test was conducted in order to collect data describing the system performance in order to produce a mathematical model of the platform functionality. This test was performed by introducing a 40% step input to the system and recording the movement of the vessel over time. Since there are three controllers (x, y, and heading) with two motors per controller, each of which go both forward and reverse, 18 different tests were conducted to fully identify the system. Each test was conducted three times to provide enough data to average the response of each motor configuration. These tests were necessary because the authors were interested in developing a strategy to allow the vessel to continue operating despite up to 2 motor failures. The data collected allowed for transfer functions to be calculated for the vessel under each possible situation.

2) System Identification

After the coefficients were calculated for each possible configuration of the system, they were implemented and tested in the control algorithm. The authors' original controller design was a proportional derivative (PD) controller. Testing revealed the need to implement a proportional integral derivative (PID) controller to correct for steady state errors.

This algorithm was implemented for the x, y and heading controllers and tests were run to analyze their performance. In order to facilitate the optimization of the control algorithm coefficients, a script called PID_Analysis was used to see how the proportional, integral, and derivative components were individually affecting the output of the motors. Figure 5 shows the output of the PID_Analysis program. This program takes the output of a closed loop test and plots the positional error versus time in the first plot. The second plot is the output of the proportional term of the controller which is expected to closely mirror the current error. The third plot shows the response of the integral term which should increase as error accumulates over time. The fourth plot is the derivative term of the controller which is expected to compensate for the vessel's current velocity. Finally, output of the controller is shown in the form of motor commands to the system. This analysis can be used to tune the coefficients so the components of controller perform as expected.

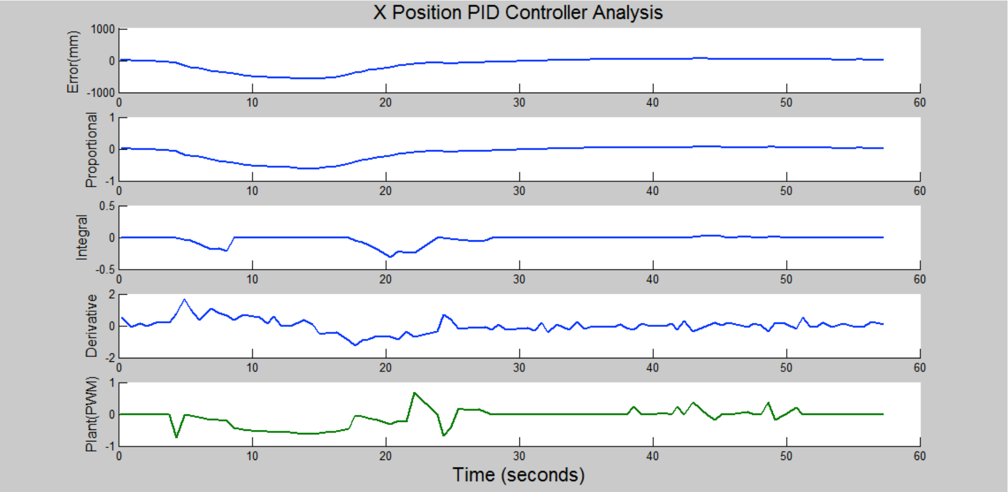


Figure 5. Graphic analysis of the PID controller performance.

An issue encountered during this phase of testing was that the system was often over correcting for really small errors as it moved closer to the desired position. The cause was determined to be the fact that the LIDAR sensor was not sampling the data at a consistent rate. Upon analysis of the data it was discovered that the sampling rate of the LIDAR was varying from 20 Hz down to nearly 6 Hz. This extremely unreliable sampling time made it difficult for the derivative component of the controller to accurately compensate for the velocity of the system.

To fix the problem, the algorithm MATLAB was using to calculate the vessel's position was refined so that it was not as sensitive to minor changes in heading or position. The serial communications between the LIDAR scanner and MATLAB were also optimized which helped refine the sampling time but it did not make it completely consistent. The sampling time averages out to be about 6 Hz when it is most stable. The capabilities of the LIDAR scanner are the greatest limiting factor in the performance of the vessel. Looking forward, however, the goal would be to eliminate this issue by installing a GPS receiver or accelerometer in future years of the project for outdoor applications of the project.

3) Robust Capabilities

Robust capabilities enable the system to continue functioning despite up to two motor losses. Based on the current motor orientation, up to one of each X, Y, and Theta controllers could break and the system would continue to function. This was accomplished through conducting system identification not just for a fully functioning system, but for each possible scenario of motor failure as described above.

At any time within the main GUI, the user may opt to turn any number of the six motors on or off to test the robust capabilities of the system. Essentially, the user has the ability to test the systems responses to various simulated motor casualties. While the current GUI simulates broken motors and notifies the user when too many motors are malfunctioning, future plans might include a system that determines when the motors are broken automatically and display feedback to the user. Some more room for improvement in terms of the robust capabilities of the system would include auxiliary sensors as well as the ability to use rotating propulsion systems or azipods.

Results and Analysis

Open Loop Test: After conducting three separate tests for all 18 possible motor functionality scenarios, the data collected was analyzed in order to find controller coefficients and transfer functions. Displayed below in Figure 6 is one of six tests for the "Y" controller. By examining the plot shown below, and assuming a first order system, the steady state response of the vessel or the terminal speed of the vessel was estimated by plotting and averaging three separate tests. In this case, the approximate terminal velocity was 93 mm/sec. A time constant was estimated for each set of tests as well. The time constant is the amount of time required to reach 63% of the steady state response. In this case, the average time constant was approximately 8 seconds. This information allowed for first order open loop transfer functions to be written. These transfer functions were used to conduct system identification and controller design as explained below.

System Identification: Through the use of assorted controller design functions, time constants and steady state responses were processed in order to create transfer functions and associated controller coefficients for all 18 controller options. These 18 transfer functions theoretically model the entire system. These transfer functions were then used to calculate PD controller coefficients which were implemented in the control algorithm and tested. Performance testing of these coefficients revealed that the system was unstable, as shown in Figure 7. It was then decided to repeat the system analysis using the linear least squares regression method based upon the data collected during the most recent performance test. The new transfer functions derived from this analysis were then used to calculate PID controller coefficients.

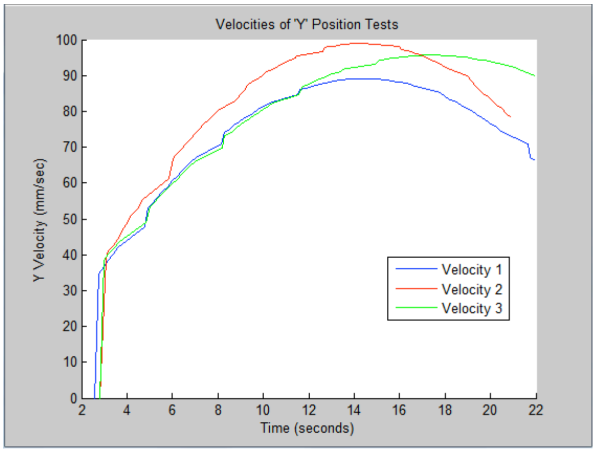


Figure 6. Open-loop test of Y-controller.

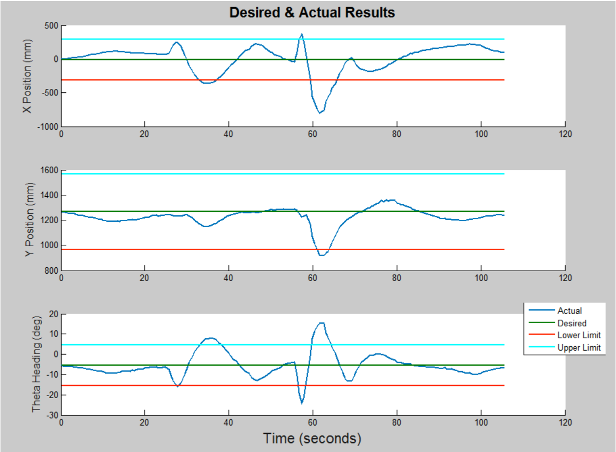


Figure 7. PD Controller coefficient performance.

Closed Loop Test: In this test, the PID controller coefficients calculated in the System ID process were used to physically implement control algorithms in the X, Y, and Theta directions. When working in conjunction, the goal was for the vessel to maintain a desired position and heading. Testing revealed that the system had a moderate stability problem where the vessel would oscillate around the desired position and heading. In order to maximize the performance of the PID controller, it was decided to implement the components of the controller in stages. Margins were established around the desired position and heading to determine when each component would be active. If the vessel were greater than 400mm from the desired position, the proportional component was active. If the vessel was between 400mm and 100mm from the desired position, the integral component was active. Finally, if the vessel was between 100mm and 50 mm, the derivative term was active. The control algorithm is completely inactive when the vessel is within 50mm of the desired position. A similar strategy was implemented for the heading controller as well. Figure 8 shows a visual representation of this marginalized controller implementation.

Figure 9 shows the results of this controller marginalization technique by showing the vessel's position versus time. The green line in this figure shows the user's desired position and heading, while the teal and red lines show the boundaries of the system performance based upon design requirements. This data shows that the system is able to correct for a manually induced error and maintain position and heading within the design requirements.

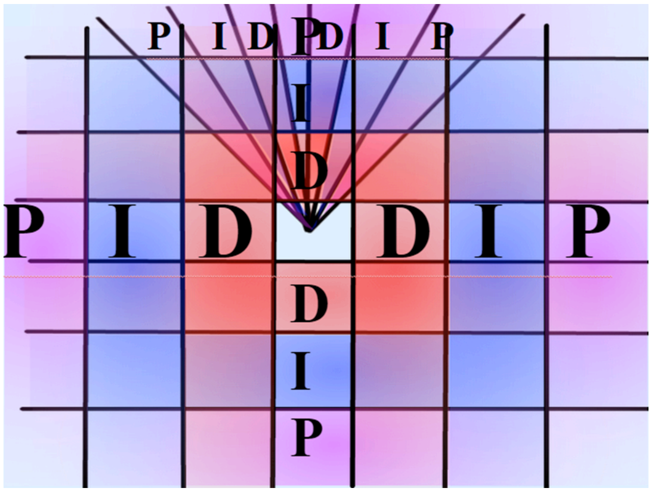


Figure 8. PID controller margin implementation.

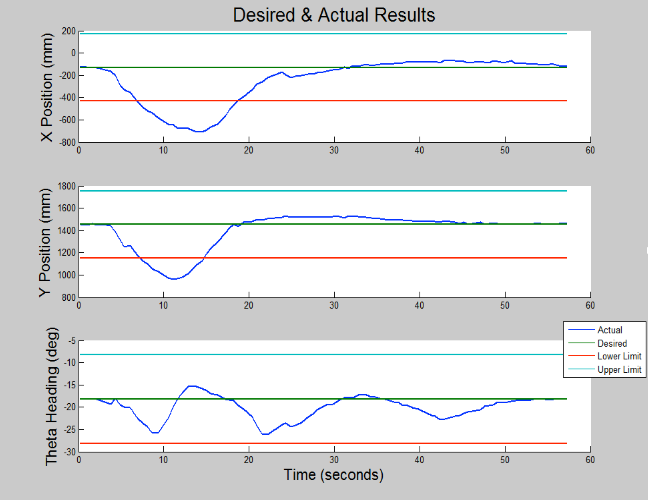


Figure 9. PID controller performance with margin implementation.

Conclusion

This robust dynamic positioning system (RDPS) project set out with the goal to design a prototype vessel that maintains a desired position and heading despite up to two motor failures. The vessel was constructed out of a steel salvage drum using a three-tier internal construction strategy consisting of a power distribution system, on-board computer, various controller components, and a LIDAR scanner. Using traditional system identification techniques, a complete system model was derived. Based on these models, PID controllers were designed for all operational configurations. The final result was a robust system capable of maintaining a desired position and heading within the design requirements while collecting the data necessary for performance analysis.

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