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Simulation and Control of an Unmanned Surface Vehicle

Dr. Lifford McLauchlan, Texas A&M University, Kingsville

Dr. Lifford McLauchlan completed his Ph.D. at Texas A&M University, College Station. After spending time in industry, he has returned to academia. He is an associate professor at Texas A&M University-Kingsville in the Electrical Engineering and Computer Science Department. His main research interests include controls, robotics, education, adaptive systems, intelligent systems, signal and image processing, biometrics and watermarking. He is the current chair of the ASEE Ocean and Marine Engineering Division and is a senior member of IEEE.

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Abstract

Academic exercises that demonstrate the theory give students an understanding of the concepts but generally without "real world" concerns and constraints. Problem based learning (PBL) has been shown to excite students and get them more involved in discussions and the course. Students generally become excited when they design solutions for "real world" or "realistic" problems that are based upon applications and problems as they can visualize how their solutions work or do not work for the given problem. With the continued reduction in resources available to obtain large scale vehicles as well as the high cost of equipment, simulations become ever more important for illustrating control system designs to students. At Texas A&M University-Kingsville a new lab exercise for an unmanned underwater vehicle has been created for students. The lab exercise steps the students through the development of the physics based model for the system. This allows the students to better understand the vehicle's movements in 3D as they explore the vehicle's model. The students analyze the stability of the open loop system using methods they have learned during the lecture and then develop the control for the closed loop system. The model is then simulated in MATLAB, Octave or another similar software program.

With the developed model and closed loop control system, the model (physics based equations) can then be ported to simulation environments such as Autonomous Unmanned Vehicle (AUV) Workbench, which was developed as a modeling tool to study and utilize physics based real time unmanned vehicle simulation operating in "realistic environments." The lab demonstrates how this model can be incorporated into AUV Workbench. Different controllers for the unmanned vehicle can also be implemented in AUV Workbench. AUV Workbench then acts as a visual demonstration of how the vehicle moves in the three dimensional (3D) simulation environment giving the students more feedback on how the controllers would behave on a real system. The new "realistic" lab exercise's efficacy is demonstrated through each of the student's increased understanding of control system concepts.

1. Introduction

"Autonomous Unmanned Vehicle (AUV) Workbench [1]-[5] was developed as a modeling and simulation environment to enable physics based real time simulation of autonomous vehicles, such as surface, underwater, land and air [6]." This or similar software allows a lower cost problem based learning (PBL) capability as compared to "the high cost of large scale underwater, land and air vehicles [6]." PBL has been shown to engage students more thereby increasing student involvement and understanding of lecture materials [7]-[10]. MATLAB is utilized in this assignment to study the closed loop system stability and to design controllers for an unmanned surface vehicle (USV) known as a Sea Fox.

The rest of the paper is organized as follows: the Proposed Method is described in the rest of Section 1, the Student Design is discussed in Section 2, the Results are in the Section 3, and the Conclusions are in Section 4.

1.1 Proposed Method

An unmanned surface vehicle such as the Sea Fox depicted in Figure 1 can be modeled with a six degree of freedom (DOF) model [1]. The mathematical model is developed using the relationships illustrated in Figure 2 [6], [11]-[12]. x (surge), y (sway) and z (heave) directional motions are depicted. Rotations around the x axis (roll) y axis (pitch) and z axis (yaw) are also taken into account. Velocities are given as u, v and w for the x, y and z axis. Angular velocities are given as p, q and r. x, y and z define positions while the roll, pitch and yaw are ϕ, θ and ψ [6], [11]-[12].

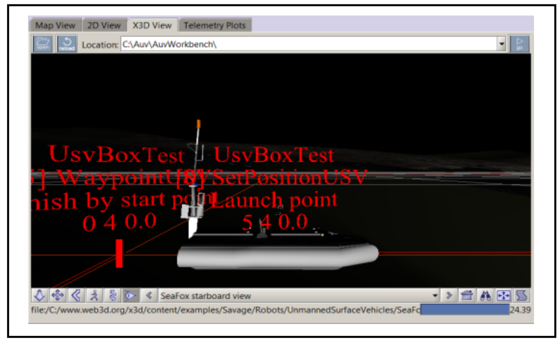

Figure 1 – Unmanned Surface Vehicle Sea Fox Shown in AUV Workbench [1]

"In this assignment, students will step through the development of the physics based model for the unmanned surface vehicle system. This allows the students to better understand the vehicle's movements in 3D as they explore the vehicle's model. The students will analyze the stability of the open loop system using methods they have learned during the lecture and then develop the control for the closed loop system [6]." First the student assignment steps through the various relationships starting with the rotational matrices.

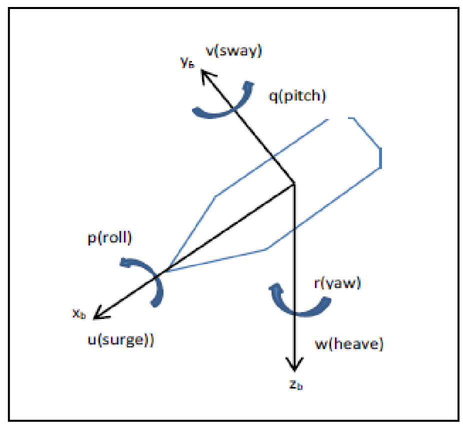

Figure 2. USV Model [6], [11]-[12]

Once the model is developed the students will utilize the control theory they have learned in class to control the system given various constraints. The students next will implement a Proportional Integral Derivative (PID) controller for a linearized model for the Sea Fox. The three general rotation matrices are given below in the following equations.

$$R_{z,\psi} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_{y,\theta} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

The next step in the model is to calculate the rotation. The rotation R_b is then calculated by the following equation [6], [11]-[12]

$$R_b = R_{z,\psi} R_{y,\theta} R_{x,\phi} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

Linearizing the system model around small angles one can make $\sin\theta \approx \theta$ and $\cos\theta \approx 1$. The rotation matrix will then be given by

$$R_b \approx \begin{bmatrix} 1 & -\psi & \theta \\ \psi & 1 & -\phi \\ -\theta & \phi & 1 \end{bmatrix}.$$

The angular velocity transformation matrix T_b can be found by the following matrix [6], [11]-[12]

$$T_b = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}.$$

Again linearizing the system model around small angles results in the transformation matrix.

$$T_b \approx \begin{bmatrix} 1 & 0 & \theta \\ 0 & 1 & -\phi \\ 0 & \phi & 1 \end{bmatrix}.$$

If one assumes no currents and realizing that the following relationships hold [6], [11]-[12]

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = R_b \begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = T_b \begin{bmatrix} p \\ q \\ r \end{bmatrix},$$

the six degree of freedom model can be written by the following matrix equation

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} [R_b] & \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} & [T_b] \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

The students can then model the six degree of freedom equations in MATLAB, Octave or another software program as long as the program can simulate differential equations or transfer function responses. "Since the lab is simulating and controlling an unmanned surface vehicle (USV) the roll, pitch, and heave can be ignored if one assumes relatively calm marine conditions resulting in simulation of the USV only in a horizontal plane. This would reduce the six equations to three and reduce the angles to one that changes [6]."

Since the students will be controlling the USV they will need the course angle χ, heading angle ψ and sideslip angle β. The three equation model, simplified horizontal plane model, assuming relatively calm conditions is given by the following equation [6], [11]-[12].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix}$$

The course angle χ, heading angle ψ and sideslip angle β are depicted in Figure 3 [6], [11]-[12] where

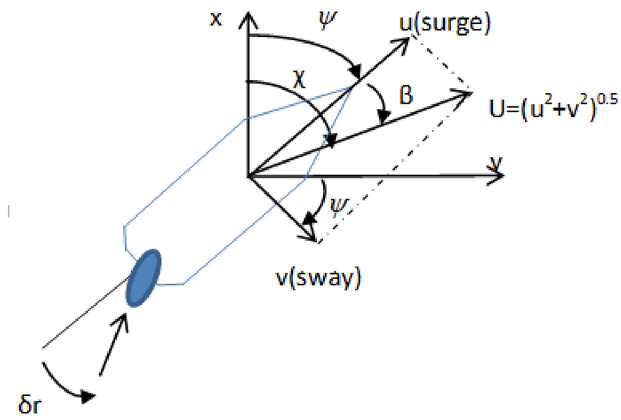

Figure 3. Heading, Sideslip and Course Angles [6], [11]-[12]

equations for the velocity U, course angle χ, heading angle ψ and sideslip angle β are given by

$$\chi = \psi + \beta$$

$$\beta = \tan^{-1}\left(\frac{v}{u}\right)$$

$$U = \sqrt{u^2 + v^2}$$

If one assumes that the USV has no sideslip then the equations become [6], [11]-[12]

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\chi} \end{bmatrix} = \begin{bmatrix} \cos\chi & -\sin\chi & 0 \\ \sin\chi & \cos\chi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} U \\ 0 \\ r \end{bmatrix}$$

A negative unity feedback control system can then be utilized to control as seen in Figure 4 the Sea Fox modeled by a horizontal plane model described previously. The PID for the model can be implemented for the simulation.

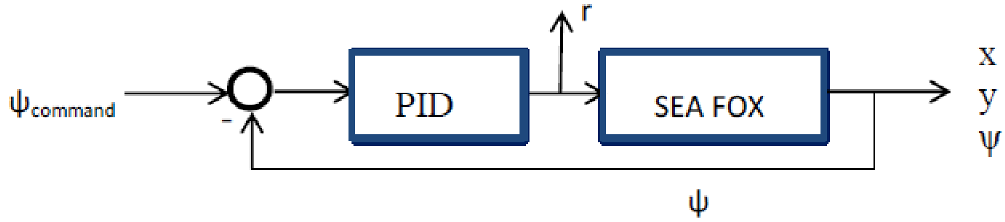

Figure 4. Feedback Control System for Horizontal Plane Model [6] – modified from [11]

2. Student Design

If one assumes in the simulation that the USV's speed is V m/s and is assumed constant, then the Sea Fox model can be further simplified for the simulations [6]. The controller that is utilized by the students in the assignment was a PID controller that can be discrete or analog depending on the simulation environment choice.

The PID controller parameters are determined using techniques, such as design using root locus the students have learned previously in the class. The students then simulated the controller in the system using MATLAB and Simulink. In the first case, the students were given the following design constraints and conditions for the control system utilizing a PID controller [6]:

1) Sea Fox is traveling at a constant speed of 1 m/s,
2) There is no sideslip, thus course angle χ= heading angle ψ
3) Commanded ψ = 1 rad for 20 seconds,
4) Followed by Commanded ψ = -2 rad for 10 seconds,
5) < 10 % overshoot (% OS) for each commanded angle,
6) Zero steady state error (e_{ss}) for each commanded angle, and
7) A settling time T_s of less than 3 sec for each commanded angle.

The students then plotted the trajectory of the USV. In the second case, the students then repeated the simulation but this time the following assumptions and conditions were given [6]:

1) Sea Fox is traveling at a constant speed of 1 m/s,
2) There is no sideslip, thus course angle χ= heading angle ψ
3) Commanded ψ = 0.2 rad for 10 seconds,
4) Followed by Commanded ψ = -0.2 rad for 10 seconds,
5) Followed by Commanded ψ = -0.6 rad for 10 seconds,
6) < 10 % overshoot (% OS) for each commanded angle,
7) Zero steady state error (e_{ss}) for each commanded angle, and
8) A settling time T_s of less than 3 sec for each commanded angle.

The transfer function G_{PID} of a PID controller is given by one of the following

$$G_{PID} = K_D\left(\frac{s^2+\frac{K_{prop}}{K_D}s+\frac{K_I}{K_D}}{s}\right) = \left(K_{prop}+\frac{K_I}{s}+sK_D\right) = K_{prop}\left(1+\frac{1}{sT_I}+sT_D\right)$$

where K_{prop} is the proportional constant, K_I is the integral constant, K_D is the derivative constant, and T_I integration time and T_D rate time are related by

$$T_I = \frac{K_{prop}}{K_I} \qquad T_D = \frac{K_D}{K_{prop}}.$$

3. Results

Assuming the simplified horizontal plane model for the Sea Fox and with the assumptions previously mentioned, Table I. shows examples of the PID parameters and the corresponding transient response values for the commanded angle changes for the first case that are based upon the student groups' determined PID parameters:

Table I – First Case - Example PID Parameters and Time Response Characteristics

K_{PROP}	K_I	K_D	First Commanded Angle			Second Commanded Angle		
			% OS	e_{ss}	T_s	% OS	e_{ss}	T_s
100	120	0.1	1.1	0	0.03	1.7	0	0.04
18	15	0.1	3.7	0	1.15	5.5	0	1.60
1.9	0.9	1	10.0	0	6.70	15.5	0	7.10

As can be seen the first two examples of PID parameters obtained meet all of the desired transient characteristics for both commanded angles, the third was a set one student group determined before redesigning the controller and obtaining a set that met all specifications. The groups generally went through an iterative process retuning the parameters based on a root locus design at least two or three times. All of the other groups succeeded in meeting the design requirements as well. Figures 5-7 show the output and commanded course angles for the first row PID values of Table I. Figures 8-10 show the output and commanded course angles for the second row PID values of Table I. In Figure 11, the output and commanded course angle simulations corresponding to the third row of Table I are shown.

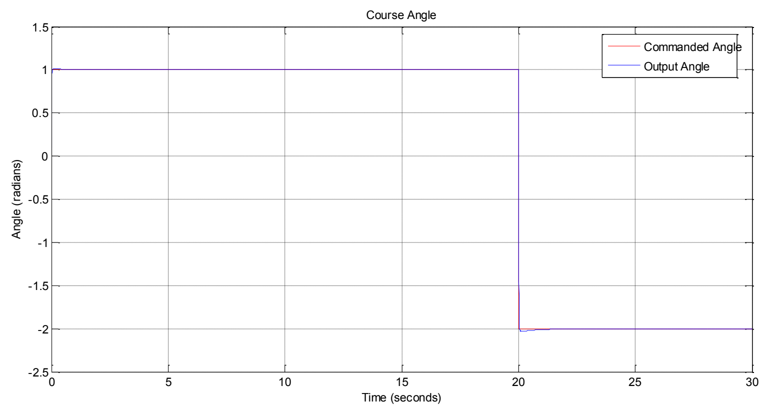

Figure 5. First Case –Output Angle Given Two Commanded Angles, One at 0 and One at 20 Seconds
K_{prop}=100, K_I=120, K_D=0.1

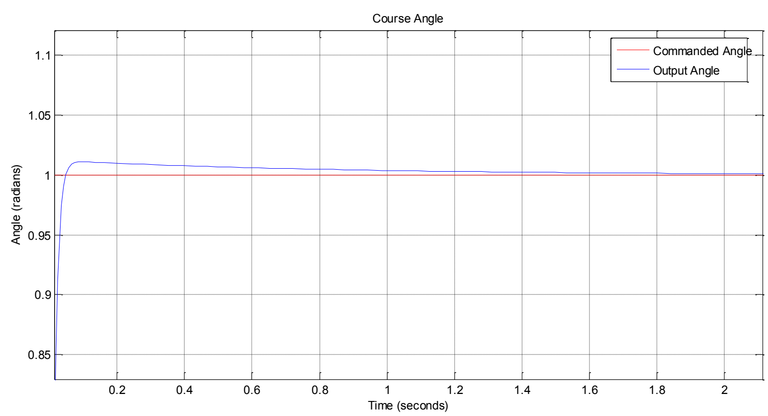

Figure 6. First Case – Close-up of Output Angle After First Commanded Angle 1 rad at 0 Seconds
K_{prop}=100, K_I=120, K_D=0.1

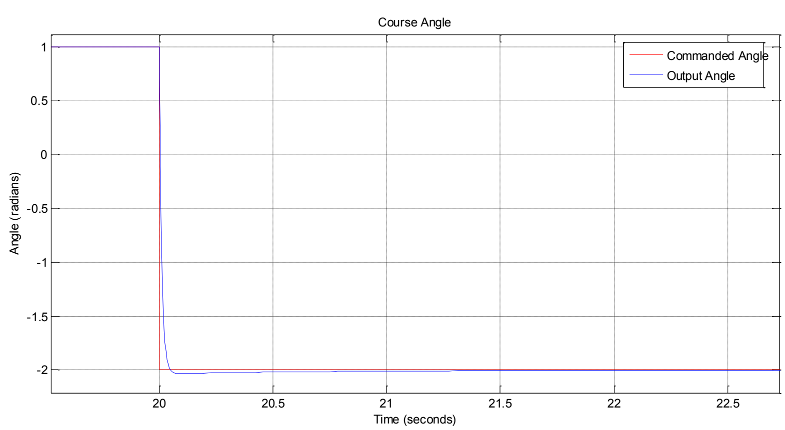

Figure 7. First Case – Close-up of Output Angle After Second Commanded Angle -2 rad at 20 Seconds
K_{prop}=100, K_I=120, K_D=0.1

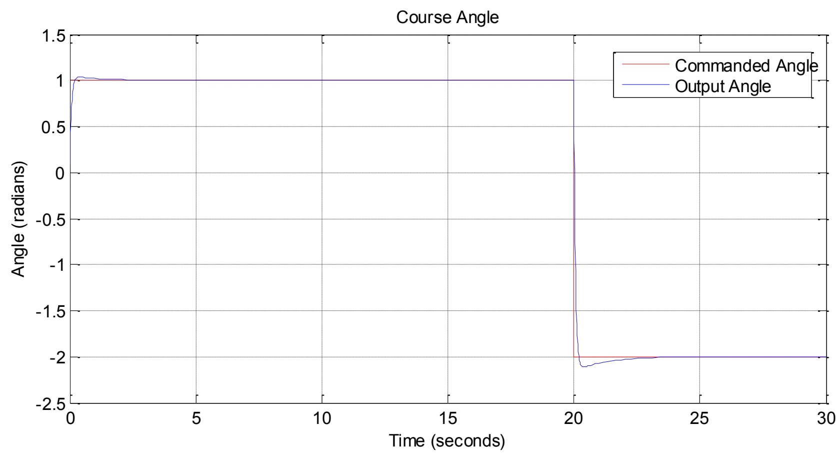

Figure 8. First Case –Output Angle Given Two Commanded Angles, One at 0 and One at 20 Seconds
K_{prop}=18, K_I=15, K_D=0.1

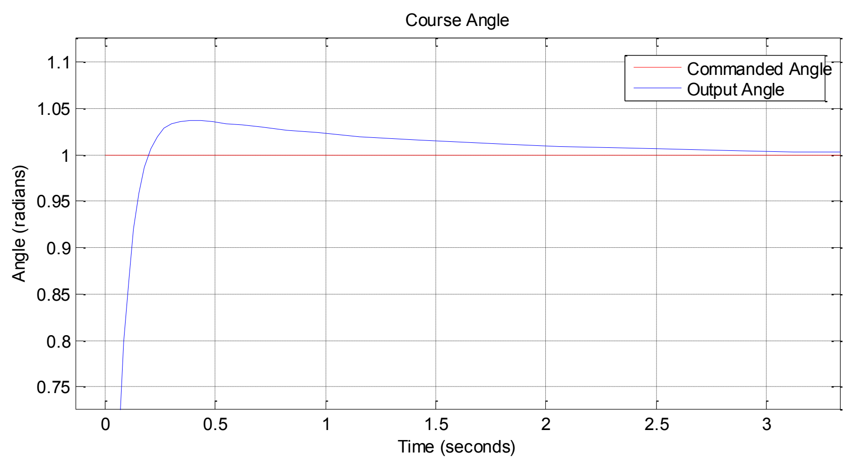

Figure 9. First Case – Close-up of Output Angle After First Commanded Angle 1 rad at 0 Seconds
K_{prop}=18, K_I=15, K_D=0.1

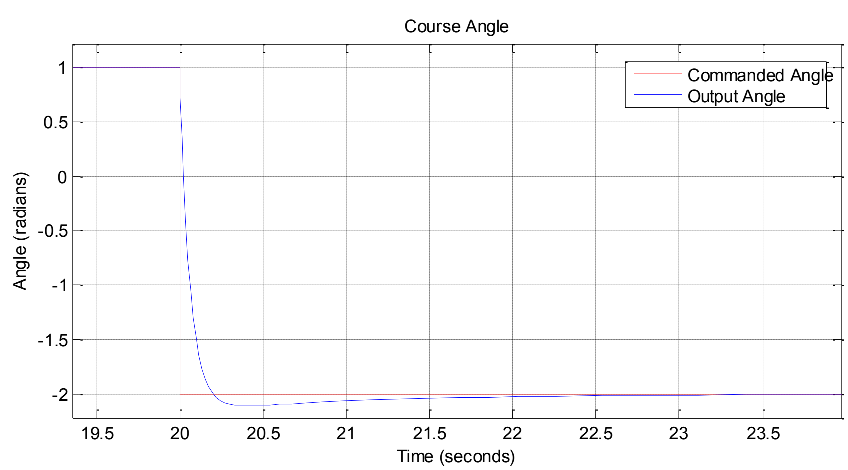

Figure 10. First Case – Close-up of Output Angle After Second Commanded Angle -2 rad at 20 Seconds
K_{prop}=18, K_I=15, K_D=0.1

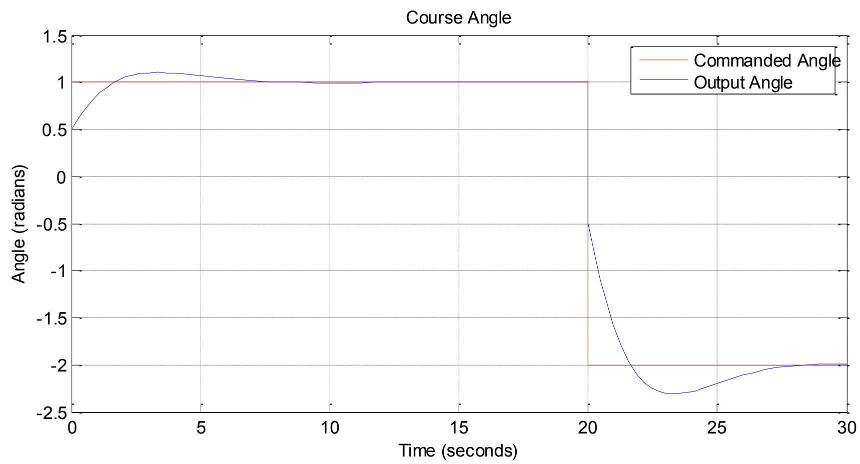

Figure 11. First Case –Output Angle Given Two Commanded Angles, One at 0 and One at 20 Seconds
K_{prop}=1.9, K_I=0.9, K_D=1

Assuming the simplified horizontal plane model for the Sea Fox and with the assumptions previously mentioned, Table II. shows examples of the PID parameters and the corresponding transient response values for the commanded angle changes for the second case.

Table II – Second Case - Example PID Parameters and Time Response Characteristics

First Commanded Angle			Second Commanded Angle			Third Commanded Angle		
% OS	e_{ss}	T_s	% OS	e_{ss}	T_s	% OS	e_{ss}	T_s
1.0	0.00	0.04	2.2	0.00	0.18	0.7	0.00	0.04
3.7	0.00	1.15	7.5	0.00	1.95	2.5	0.00	0.7
10.2	0.01	6.7	21.0	0.02	7.3	6.8	0.00	6.3

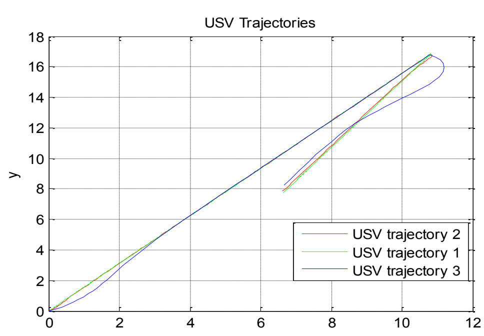

Figure 12. First Case – Comparison of USV Trajectories

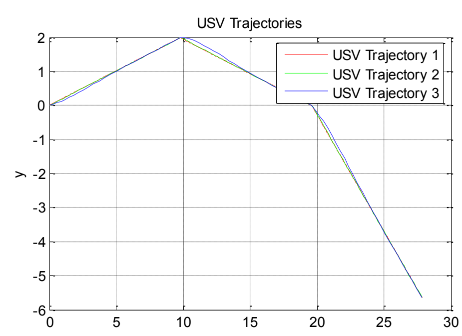

Figure 13. Second Case – Comparison of USV Trajectories

The only trajectory in Figures 12 and 13 to not closely follow the commanded course angles was the third row in the Tables I and II. This corresponds to USV trajectory 3 in Figures 12 and 13 both of which have the greatest overshoot and error for the displayed trajectories.

4. Conclusions

The student lab groups succeeded in meeting all of the design requirements after performing redesigns to ensure their controller designs met the constraints. After performing this lab, the student groups appeared more confident in their abilities to design PID controllers. The students have followed the development of the USV model. In addition, the students were shown how the controller could then be implemented in AUV Workbench which includes the Sea Fox as one of the models. The file controlCoefficients can be modified to implement their designed PID controllers. AUV workbench though considers the full 6 DOF model in order to include movements in 3D not just the horizontal plane. The students next used the model in a follow on lab on path planning.

Acknowledgements

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