Design and Testing of a Fuzzy Logic Controller for an Autonomous Underwater Vehicle.

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***Abstract*-- This paper deals with the application of a fuzzy logic based algorithm to the control of Autonomous Underwater Vehicles (AUVs). Fuzzy controllers are of simper design since they don't require explicit modeling of the vehicle dynamics. Furthermore, they may be tuned for optimal performance, and replace existing controllers designed using conventional or nonlinear control theory techniques. The discussed fuzzy logic controller has being designed for the Naval Postgraduate School (NPS) Phoenix AUV. The aim of the controller is the vehicle autonomous navigation in an ocean environment. The vehicle's speed, heading, pitch and depth are simultaneously controlled for various simulated test cases considering the presence of undersea currents. Testing is based on the already derived hydrodynamic model and data of the NPS Phoenix AUV, with minor modifications in the added mass coefficients. The overall navigation performance of the proposed control scheme was encouraging and it may be used to estimate vital AUV issues, such as, the level of maneuverability and energy consumption of the vehicle.**

I. INTRODUCTION

An Autonomous Underwater Vehicle (AUV) is an uninhabited, untethered, underwater vehicle, which carries its own power source and relies on an on-board computer in order to execute a mission. AUVs operate independently from the support platform, do not require human operators and they are equipped with various sensors for information gathering [1]. Navigation and mission management are two critical technologies for the future of AUVs, which require design and development of new control methodologies capable of dealing with the increased complexity of AUV missions [2]. The aim of this paper is the design and testing of a fuzzy logic based control algorithm applicable to AUVs.

The Naval Postgraduate School (NPS) AUV, *Phoenix*, is selected as a case study due to the fact that the vehicle's dimensions, specifications and its hydrodynamic model and coefficients, have been accurately defined in [3]. A clear and defect-free dynamic model is essential in the field of control design and simulation, since arithmetic overflows usually occur when the vehicle coefficients do not conform to reality. The NPS-*Phoenix* AUV is suitable for research in shallow water. It is neutrally buoyant and has a hull length of 7.3 ft. It has four paired plane surfaces (eight fins total) and four paired thrusters built in cross-body tunnels. It has two screw bi-directional propellers. Its design depth is 20 ft (6.1 m) and the hull is made of press and welded aluminum. The vehicle endurance of 90-120 min is supported by a pair of lead-acid gel batteries at speeds up to 2 ft/sec (0.61 m/sec).

The rest of the paper is organized as follows. Section 2 presents the equations of motion and the modifications made to ensure the vehicle's good simulated behavior. Section 3 discusses the proposed simulated control architecture and the fuzzy logic based navigation subsystems. In Section 4, extensive simulation testing is presented, while Section 5 concludes the paper suggesting topics for future research.

II. VEHICLE MODELING AND EQUATIONS OF MOTION

AUV dynamics model and related equations of motion in 6 degrees of freedom are extensively described in [4]. The vehicle's position and motion is described with respect to two reference

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frame systems: an earth-fixed and a body-fixed reference frame system. The vehicle velocities (linear and angular) may be expressed in both the earth-fixed and the body-fixed reference frame systems. The vehicle orientation (body-fixed reference frame) is obtained by applying three consequent principal rotations to the earth fixed reference system: first rotate over *head* angle ψ about Z axis, then rotate over *pitch* angle θ about Y axis, and finally rotate over *roll* angle φ about X axis. By applying these consequent rotations, a relationship of linear and angular velocities in the earth-fixed and the body-fixed reference frame systems may be written as a function of the values of the rotation angles (Euler angles velocity transformation).

The vehicle state is described by its position in the earth-fixed reference frame and by its velocity in the body-fixed reference frame system. The equations of motion are written in the body-fixed reference frame system as:

$$M\dot{\vec{v}} + C(\vec{v})\vec{v} + D(\vec{v})\vec{v} + \vec{g}(\vec{\eta}) = \vec{\tau}(controls, \vec{v}, \vec{\eta})$$

where, $\vec{\eta}$ is the vector of earth-fixed vehicle position and Euler angles, $\dot{\vec{v}}$ is the vector of body-fixed linear and angular velocities, *M* is the inertia matrix (with added mass) multiplied by the body fixed accelerations, $C(\vec{v})$ is the matrix of Coriolis and centripetal terms (with added mass) multiplied by the body fixed velocities, $D(\vec{v})$ is the matrix of hydrodynamic damping multiplied by the body fixed velocities, $\vec{g}(\vec{\eta})$ is the vector of gravitational and buoyancy forces and moments depending on the Euler angles, and $\vec{\tau}(controls, \vec{v}, \vec{\eta})$ is the vector of external control forces applied to the vehicle (by its propellers, thrusters, control surfaces etc.), which depend on the control actions (i.e. propellers rpm., thrusters voltage, fin angles) and on the state of the vehicle (surge velocity). The previous equation may be re-written as:

$$M \cdot \dot{\vec{v}} = \vec{F}(controls, \vec{v}, \vec{\eta})$$

where the $\vec{F}$ vector includes the Coriolis $C(\vec{v})\vec{v}$ terms, the damping terms $D(\vec{v})\vec{v}$, the buoyancy and gravitational terms $\vec{g}(\vec{\eta})$, and the external control forces $\vec{\tau}(controls, \vec{v}, \vec{\eta})$. By inverting the M matrix one obtains:

$$\dot{\vec{v}} = M^{-1} \cdot \vec{F}(controls, \vec{v}, \vec{\eta})$$

Then, by applying the inverse linear-angular velocity transformation one obtains the earth-fixed linear velocities and Euler angle rates. By integrating velocities and rates over a time step, and adding the previous vehicle position and orientation, the position and orientation of the vehicle at the new time step are obtained. Adding the ocean current drag then modifies the vehicle's position and the final position is estimated. The analytical expressions of the above form of the equations for the NPS-Phoenix AUV, including all the mass-inertia-added mass – damping and external forces coefficients are given in [3].

A modification is made to the above model, in order to ensure that the added mass matrix is symmetrical, as it is applied in an underwater vehicle moving at low speed, and that the off-diagonal elements to be much smaller than their diagonal counterparts as mentioned in [4]. By setting:

mass = 13.52	Vehicle mass (lbs)
density = 1.99	Mass density of sea water (slugs/ft^3)
length = 7.302	Nominal vehicle length (ft)
i_x*=2.7*	Moment of inertia about the longitudinal axis (ft lb sec^2)
i_y*=42*	Moment of inertia about the lateral axis (ft lb sec^2)
i_z*=45*	Moment of inertia about the vertical axis (ft lb sec^2)
$x_g = 0.01$	XCG location (ft)
$y_g = 0.0$	YCG location (ft)
$z_g = 0.089$	ZCG location (ft)
$x_b = 0.01$	XCB location (ft)
$y_b = 0.0$	YCB location (ft)
$z_b = 0.0$	ZCB location (ft)

and modifying the values of the added mass terms (notation as defined in [5]): $Y_{\dot{r}} = 0.00$ and $N_{\dot{r}} = 0.00$ (suggested values in [3]: $Y_{\dot{r}} = -1{,}78E-1$ and $N_{\dot{r}} = -1.78E-3$) and keeping all the other hydrodynamic derivatives and constants as given in [3], the following *mass-inertia-added mass* matrix is obtained:

$$[M] = \begin{bmatrix} 14.6124 & 0 & 0 & 0 & 2.4066 & 0 \\ 0 & 26.8075 & 0 & -2.4066 & 0 & 0.2704 \\ 0 & 0 & 50.0509 & 0 & 6.8863 & 0 \\ 0 & -1.2033 & 0 & 7.6573 & 0 & 0 \\ 1.2033 & 0 & 7.0215 & 0 & 171.0958 & 0 \\ 0 & 0.1352 & 0 & 0 & 0 & 54.7080 \end{bmatrix}$$

All the hydrodynamic derivatives and coefficients used are constant and not varying with the vehicle's velocity. Thus, the effect of Reynolds number on those coefficients is not included in the present work. A refinement of hydrodynamic coefficients, through theoretical calculations and pool testing, is essential for the proper vehicle's dynamics simulation and results reliability. It should be mentioned that the *M* matrix does not apply to the situation that the vehicle's mass, or the distribution of mass is altered (for example, in the case of weight control by adding or discharging ballast water [6]). In the above cases this matrix should be calculated and inverted after every change before the next time step.

Another significant notice applies to the control actions. The actual control actions (i.e. propellers rpm, thrusters voltage, fin angles) can be obtained by the output of the fuzzy controller (ordered control actions), taking into consideration each control propeller or fin-actuator dynamics and its previous state. In the present work the effect of propellers-shafts, thrusters and fins-actuators dynamics are not considered due to computational efficiency, and the outputs of the controller (ordered control actions) are directly fitted into the dynamics model.

A motion path planner provides the target point for the vehicle. The target point is shifting automatically along a predetermined path, and as the vehicle reaches the target point in a circle with determined radius, a new target point is established. Also the motion planner provides a target surge velocity as the vehicle reaches the target point. The desired path can be estimated from a collision avoidance module. First, by using the sensor readings the environment can be determined at the first stage. Accordingly, a collision avoidance strategy can be enhanced, and a desired path can be determined [2], [8]. In the present work there is no collision avoidance implemented and the predetermined path is preset and fed directly to the controller for a number of test cases.

After estimating the vehicle's velocities and Euler angle rates it is essential to add the effect of ocean current in order to simulate the vehicle in a actual ocean environment. Values for the ocean current can be obtained by taking measurements of the actual vehicle position (using Global Positioning System and gyroscopic compasses), then applying Kalman filtering and finally calculating the difference between the vehicle's actual and estimated position over a time period [9]. In this work only the case of horizontal ocean current (with coordinates in X and Y axes) is considered.

III. The Fuzzy Logic Based Navigation Architecture

The overall aim of the navigation control is to determine proper values for the controls of the vehicle, in order to reach the target point having the target surge velocity.

The inputs to the controller are the target point and the actual position and orientation, in earth-fixed coordinates, the target surge velocity and the vector of the actual vehicle velocities in body-fixed coordinates, and also the ocean current velocity.

The architecture of the controller suggests that although the equations of motion are coupled and interacting each other the steering, the velocity and the depth states are decoupled and lightly interacting, as suggested by [7], [10]. Four subsystems are enabled to control the vehicle:

- The *speed control* subsystem, which is responsible for the vehicle's speed and controls the port and starboard propellers by ordering their rpm.
- The *heading control* subsystem, which controls the steering (horizontal plane) of the vehicle and outputs for bow and stern lateral thrusters and bow and stern rudder fins. The ordered voltage and fins angle are equal and opposite for bow and stern lateral thrusters.
- The *depth control* subsystem, which controls (in vertical plane) the bow and stern vertical thrusters and bow and stern plane fins. It contains two fuzzy controllers: the *pitch controller* and the *depth controller*.
- The *ocean current* subsystem, which adjusts the position of vehicle in case of sea current. Although sea current is considered in both the speed and steering controllers this controller adds maneuverability by modifying the steering controls. Its aim is to overcome the lateral drag by adding voltage to the lateral thrusters. Thus in the presence of lateral ocean current the bow and stern lateral thrusters do not have equal and opposite voltage.

The overall architecture of the fuzzy logic based navigation is shown in Figure 1.
The roll motion parameters are left passive since the vehicle is self-stabilized in roll mode. Thus, roll is not dynamically controlled. During simulation this has proven to be satisfying since roll angle and velocity did not take large values.

A. *Speed Control Subsystem*

In this subsystem the distance from the target point is calculated. A modified surge velocity is calculated by subtracting geometrically, from the surge velocity of the vehicle, the projection of the current velocity to the X body-fixed axis, in order to take into consideration the presence of ocean currents, which will alter the vehicle's velocity. Then the modified velocity and the distance are fed to the fuzzy controller with the target surge velocity and the heading error of the vehicle respectively to the target point. The input linguistic variables and their values are as follows: *Distance*: {*zero*, *near*, *far*, *very-far*}, *Surge_Velocity*: {*slow*, *normal*, *fast*}, *Target_Surge_Velocity*: {*slow*, *normal*, *fast*}, *Heading_error*: {*negative*, *normal*, *positive*}.

The linguistic values of the sole output variable *Propeller_rpm* are: {*fast-astern*, *slow-astern*, *zero*, *dead-slow-ahead*, *slow-ahead*, *fast-ahead*}. An example of speed controller rule base, which consists of 22 rules, is given below:

IF <*Distance* is ***far***> AND <*Surge_Velocity* is ***normal***> AND <*Target_Surge_Velocity* is ***normal***> AND <*Heading_Error* is ***normal***> THEN <*Propellers_rpm* is ***slow-ahead***>.

The ordered propellers rpm (same for port and starboard propellers) are given by the *max-min composition* of the 22 rules, after proper defuzzification with the centroid method. A similar procedure, described in detail in [8], is followed in all controllers.

The value of *Propeller_rpm* is *zero* if the vehicle's *Heading_Error* is not *normal*. In this situation the vehicle will first "fix" it's heading by the *heading control* subsystem, described below, and then move towards the target point by its propellers.

B. The Heading Control Subsystem

In this subsystem the difference between the desired heading and the actual yaw angle ψ, is first calculated. This angle, is called "head error angle", rated from -180^o to 180^o. Then the effect of the ocean current is implemented by modifying the head error angle by an angle, in such a way that the vehicle will change its heading in the direction of the ocean current and will equalize the current drift. The modified head error angle, the rate of change of head, and the distance from the target point are "fed" into the fuzzy controller. Their linguistic values are: *Head_Error_Angle*: {*big-negative*, *negative*, *zero*, *positive*, *big-positive*}, *Head_Rate*: {*negative*, *normal*, *positive*}, *Distance*: {*zero*, *near*, *far*}.

The linguistic values of the outputs, namely, *Lateral Thruster Voltage* and *Ruder_Fin_Angle* are: {*big-negative*, *negative*, *zero*, *positive*, *big-positive*}.

The rule base consists of 16 rules of the type:

IF <*Head_Error_Angle* is ***positive***> AND <*Head_Rate* is ***normal***> AND <*Distance* is ***far***> THEN < *Lateral Thruster Voltage* is ***positive***> AND < *Ruder_Fin_Angle* is ***positive*** >.

The ordered bow and stern lateral thrusters voltage and bow and stern rudder fins angle are equal and have opposite signs. The variable *Distance* is taken into consideration, so that there will be no stiff changes in the vehicle's steering and heading angle as it comes closer to a target point with poor accuracy. This situation can occur when there is strong ocean current. In this way the vehicle will point to the next target point and will not make circles around the last point.

C. The Depth Control Subsystem

This subsystem consists two fuzzy controllers each one responsible for pitch angle and depth control, respectively. The reasons that the depth is not controlled only through the pitch angle (like head angle is used to control vehicles position in XY plane), is that the vehicle has greater difficulty to change its pitch, than to change its head (due to bigger added mass and inertia) as it can be seen from the matrix *M*. Also the Euler angles representation has two singularities at pitch angles $\theta=\pm 90^o$, and by using the depth fuzzy controller it is ensured that the vehicle will not have to operate close to this singularities. Furthermore the use of another controller can ensure safe operation of the vehicle without any possible loss in great depths.

The *Pitch Controller* has the following inputs: *Pitch_Error*, *Pitch_Rate*, *Distance*, and *Pitch*. The outputs are: *Vertical Thruster Voltage* and *Plane_Fin_Angle*. The linguistic values are defined as follows: *Pitch_Error*: {*big-negative*, *small-negative*, *zero*, *small-positive*, *big-positive*}, *Pitch_Rate*: {*negative*, *normal*, *positive*}, *Distance*: {*zero*, *near*, *far*}, *Pitch*: {*out-of-limits-negative*, *normal*, *out-of-limits-positive*} and *Vertical Thruster Voltage* and *Plane_Fin_Angle*: {*big-negative*, *negative*, *zero*, *positive*, *big-positive*}. The rule base consists of 18 rules as the one that follows:

IF <*Pitch_Error* is ***small-positive***> AND <*Pitch_Rate* is ***positive***> AND <*Distance* is ***far***> AND <*Pitch* is ***normal***> THEN <*Vertical Thruster Voltage* is ***big-positive***> AND <*Plane_Fin_Angle* is ***big-positive***>.

The variable *Distance* is taken into consideration for the reason mentioned in the heading control subsystem. Also, the variable *Pitch* is taken into consideration to ensure that the actual pitch of the vehicle will not become close to the singular values. In the case of big pitch angles θ, the vehicle will change its depth to the desired one by the depth controller. The ordered bow and stern vertical thrusters voltage and bow and stern plane fins angle are equal and have opposite signs, to create a moment to change the pitch angle.

The input variables of the *Depth Controller* are: *Depth_Error*: {*negative*, *zero*, *positive*}, *Depth_Error_Rate*: {*negative*, *normal*, *positive*} and *Pitch*: {*out-of-limits-negative*, *normal*, *out-of-limits-positive*}. The output variable *Vertical Thruster Voltage* takes the values from the set {*negative*, *zero*, *positive*}. The rule base has 11 rules. An example of a depth controller rule is:

IF <*Depth_Error* is ***negative***> AND <*Depth_Error_Rate* is ***normal***> AND <*Pitch* is ***normal***> THEN <*Vertical Thruster Voltage* is ***negative***>.

The *Vertical Thruster Voltage* is summed (with the same signs) to the bow and stern vertical thrusters voltage given by the pitch controller. Thus the vehicle reaches the desired depth easily and with good accuracy. Moreover the simulation overcomes the singularities as the pitch angles during the flight stay away from them.

D. The Ocean Current Subsystem

This controller deals with the lateral current velocity, which is the projection of the current velocity to the Y body-fixed axis, and the delta-Y, that is the projection of the distance arrow on the Y body-fixed axis. Its aim is to overcome the lateral drag by adding voltage to the lateral thrusters. Consequently, the output variable is the lateral *Thruster_Voltage*, which is added to bow and stern lateral thrusters. Linguistic values for the input variables *Y_current_velocity* and *Delta_Y* are {negative, zero, positive}, while the values of the output variable *Lateral Thruster_Voltage* are: {*big-negative*, *negative*, *zero*, *positive*, *big-positive*}. A typical rule (out of 9 rules) for the ocean current controller is:

IF <*Y_current_velocity* is ***zero*** > AND < *Delta_Y* is **zero** > THEN < *Lateral Thruster_Voltage* is ***zero*** >

During each time step all the four subsystems mentioned above give their outputs and form a 10x1 vector named "*control vector*", with the values of the ordered propellers rpm, thrusters voltage and fins angles. This is given to the dynamics model witch uses it to estimate the vehicles state during the next time step.

IV. SIMULATION AND RESULTS

The vehicle dynamics model and the described controller were programmed in *Matlab*® and *Simulink*®. A model, which was able to simulate the actual behavior of the vehicle, was constructed and tested for various cases.

The simulation was discrete with fixed steps of 0.5 sec. Simulation time is not greater than real-life time and so this technique can be used for simulation under virtual reality environments. The results can be used for further tuning of the controller as an alternative to costly and possibly hazardous real-life pool or ocean testing. Also they can be used to estimate the level of maneuverability and energy consumption of the vehicle. Two of the test cases are presented bellow.

In the first test the vehicle follows a rectangle saw-tooth curve in the horizontal plane and gradually descents and ascents in the vertical plane. No ocean current is assumed. The overall motion is shown in Figure 2, while the decoupled motion in XY and XZ planes are given in Figure 3. As it can be seen in Figure 3 the vehicle's dynamics are not completely decoupled. A change in the vehicle's steering controls influences changes on depth controls and vise versa. The peaks in XY plane actual path after a command for step change in Y are made because the controller sees a big head error angle, then the propellers are shut down by the velocity controller, and the head angle is modified to the desired one by the thrusters and fins (Fig. 4-b). This action drifts the vehicle to the opposite Y- direction and causes the head controller outputs (*Lateral Thruster Voltage* and *Ruder_Fin_Angle)* to oscillate from positive to negative values.

In the second test case the vehicle follows the same curve but in the presence of ocean current with various lateral velocities. Figure 5 presents vehicle's deviation from the desired trajectory for ocean currents with earth-fixed velocity of 0.3, 0.6, 0.8 1.0, 1.2 ft/sec, respectively.

Figures 6-8 illustrate the test case 2 for lateral sea current velocity up to 0.8ft/sec. As it can be seen in Figure 7 the vehicle reaches the desired trajectory on the vertical plane, while constantly overshoots in the horizontal plane pushed by the lateral current. In Figure 8 the Vertical Bow

Thruster and the Lateral Bow Thruster Voltage versus time are given for lateral current velocity 0.8 ft/sec.

V. DISCUSSION AND FUTURE WORK

This paper presented a fuzzy-logic controller successfully designed and tested for the NPS-Phoenix AUV. The behavior of the vehicle was examined under various situations including step response, and various ocean currents. The overall performance of the controller was found to be encouraging for further research and refinement. Essential for actual estimates is pool testing with the real vehicle. Furthermore techniques for energy saving and managing need to be applied to enlarge the vehicle's endurance.

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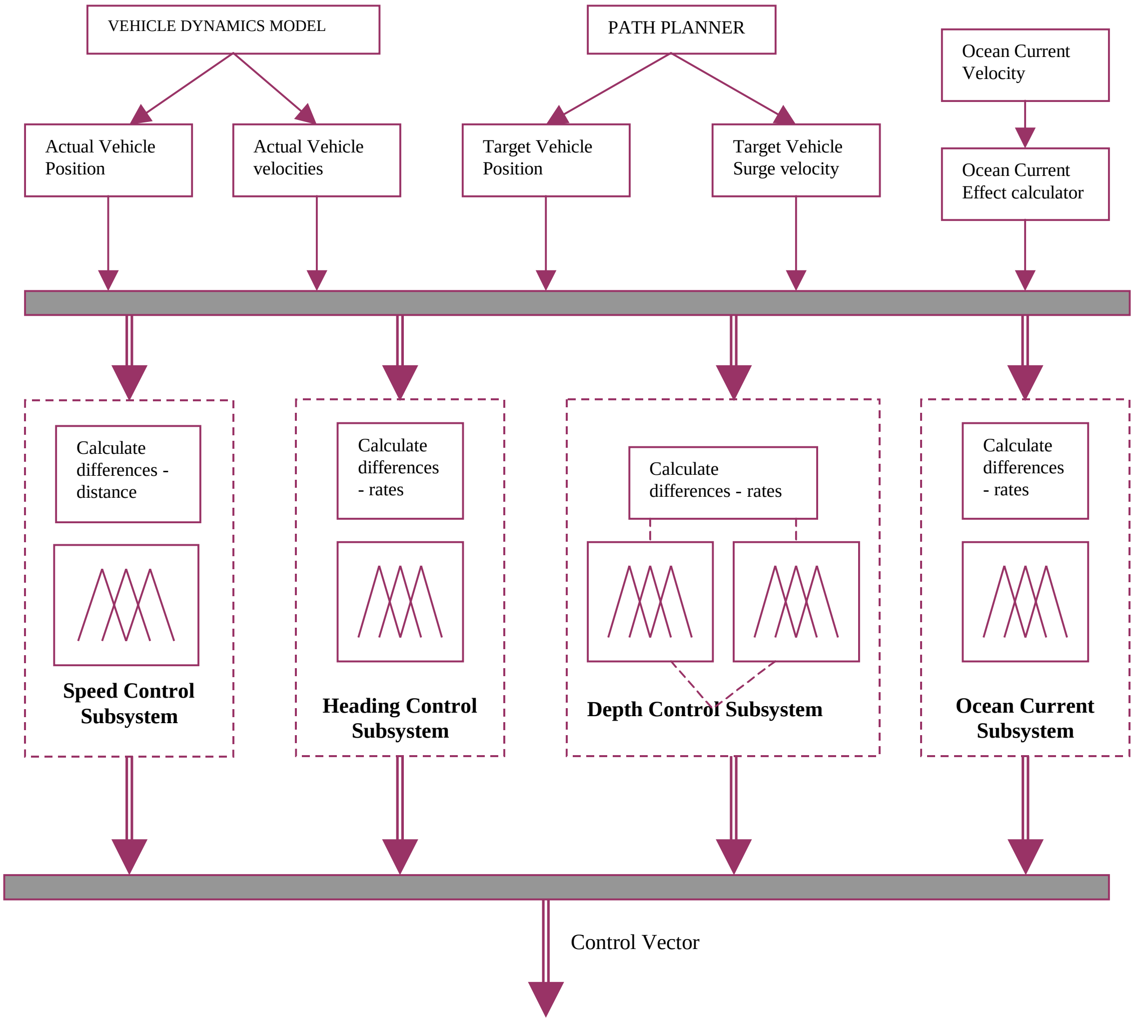


Figure 1: The Fuzzy Navigation Architecture.

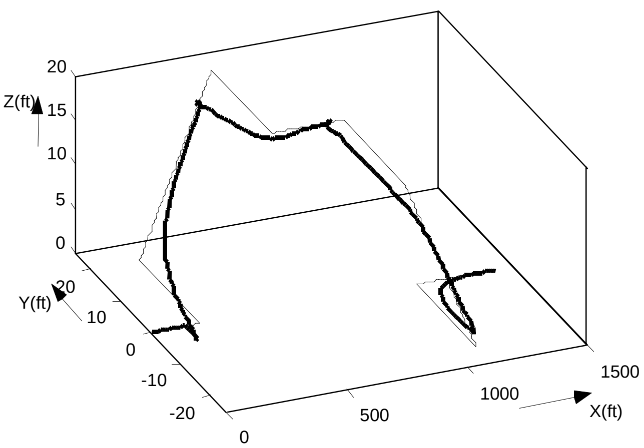
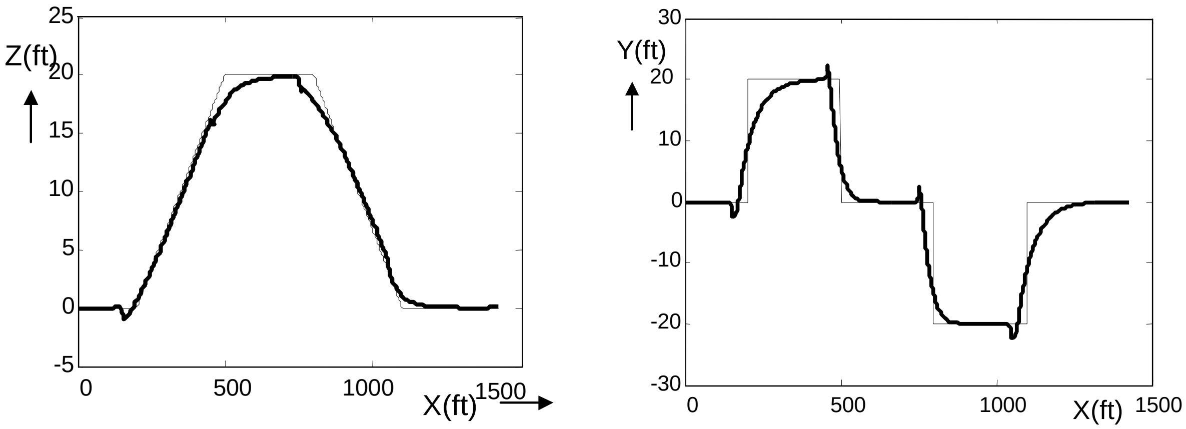
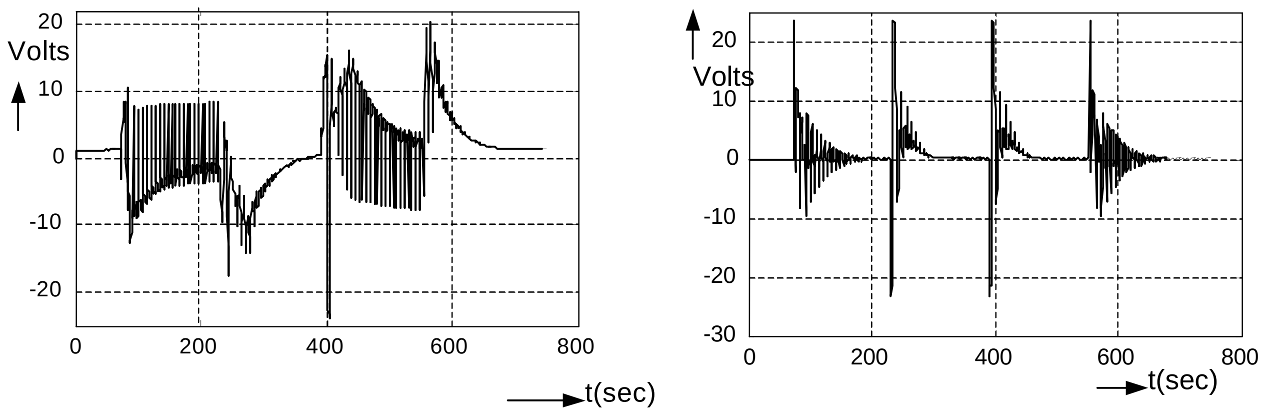


Figure 2**:** Test Case 1: Ordered and actual path.



a) b)

Figure 3: Test case 1: Ordered and actual path in (a) the vertical and (b) the horizontal plane



a) b)

Figure 4**:** Test case 1: (a) Vertical Bow Thruster Voltage and (b) Lateral Bow Thruster Voltage versus time

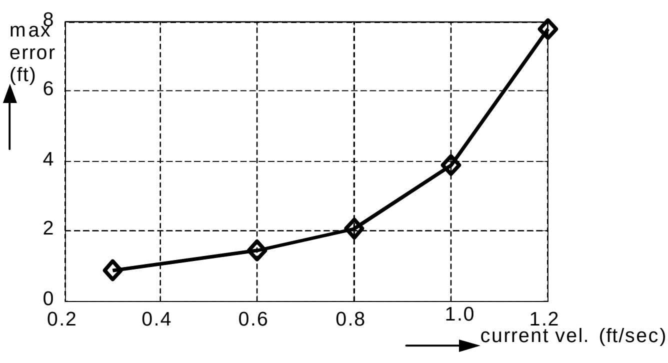


Figure 5: Maximum deviation from ordered path versus lateral current velocity

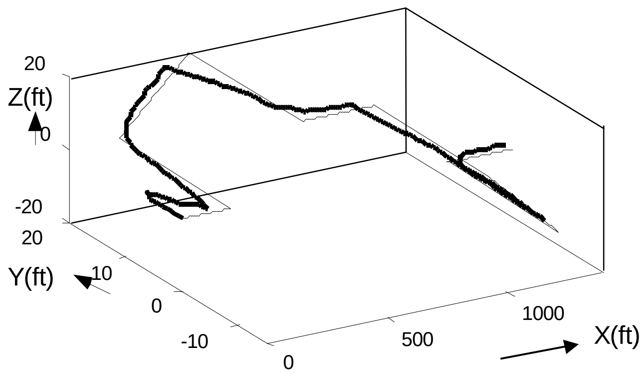


Figure 6: Test case 2: Ordered and actual path with lateral current velocity 0.8 ft/sec

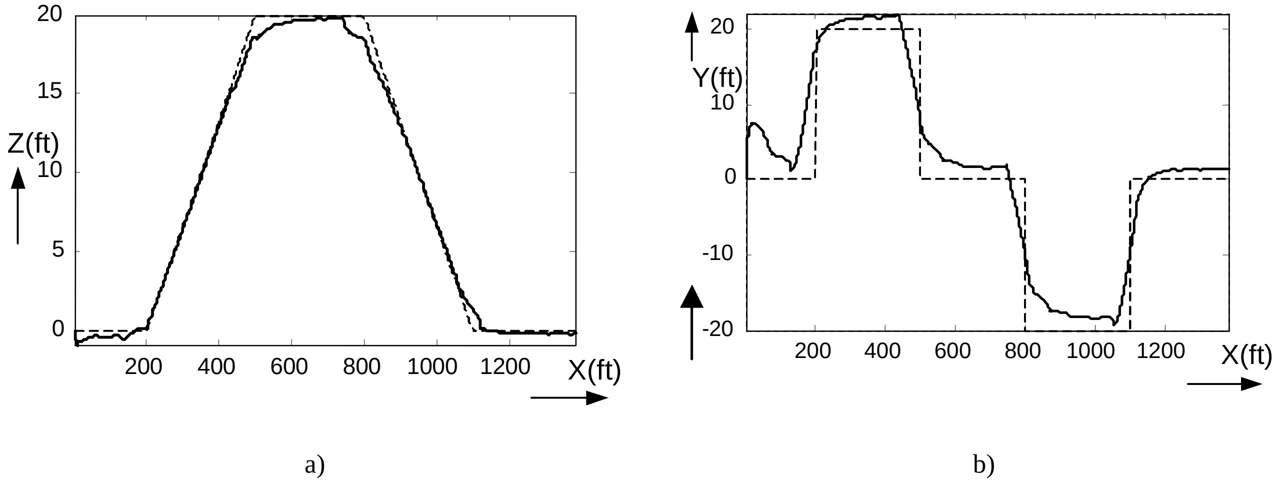
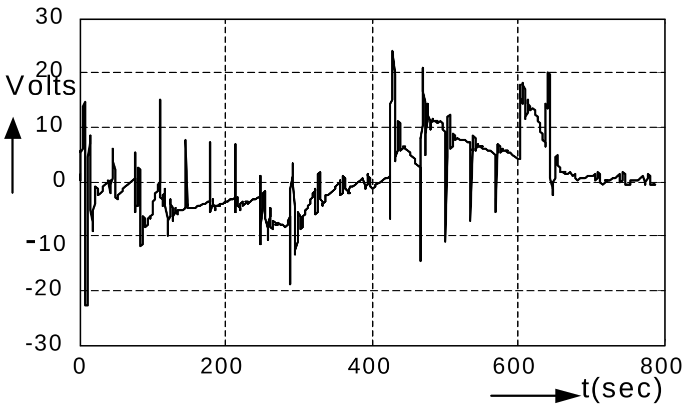
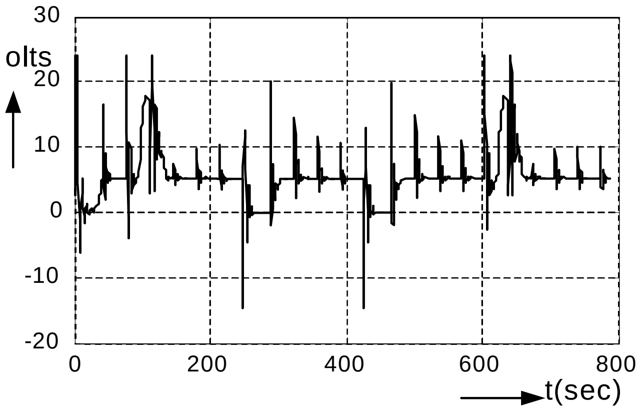


Figure 7: Test case 2: Ordered and actual path in (a) XZ plane and (b) XY plane with lateral current velocity 0.8 ft/sec



a)



b)

Figure 8: Test case 2: (a) Vertical Bow Thruster and
(b) Lateral Bow Thruster Voltage versus time with lateral current velocity 0.8 ft/sec