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Research Article

6-DOF Nonlinear Dynamic Modeling and Control of Autonomous Underwater Vehicle

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Abstract

During the design process of an autonomous underwater vehicle (AUV), establishing a dynamic model of the system plays a crucial role. Controller (autopilot) is designed based on the dynamic model of the system before the field tests. The controller must reliably manage the system based on the states of the AUV. This study provides a comprehensive guide for the design process of the 6-DOF nonlinear dynamic model and controller of an AUV. Control method used in this study is the nonlinear dynamic inversion method, based on feedback linearization, to establish robust control strategies with a focus on pitch and yaw control. Numerous studies have been conducted in the field of underwater vehicles; however, this research combines both 6-DoF modeling and controller design. Furthermore, it implements the feedback linearization control approach specifically for AUVs. In this study, the nonlinear dynamic model of the AUV is developed and the nonlinear dynamic inversion method is effectively applied to achieve desired control over pitch angle, depth, yaw angle and yaw angular rate.

1. Introduction

A great deal of effort has gone into developing accurate dynamic models for underwater vehicles in the previous years. To understand the complexity of underwater vehicle dynamics, studies by Fossen (2011) and (1994) investigate the hydrodynamics, hydrostatics and control surface effects that are necessary to develop correct 6-DOF simulation models. These seminal works are a significant step toward understanding the complexity of underwater vehicle motion and lay the foundation for future research.

Effective control of underwater vehicles is critical for accurate navigation in difficult underwater conditions. AUVs have been made more stable and maneuverable using a variety of control tactics, ranging from basic PID controllers to more complicated nonlinear control approaches. A detailed study of the feedback linearization approach is presented by Slotine and Li (1991) and Stevens et al. (2016). This control approach is effective in translating underwater vehicles' inherently nonlinear dynamics into a more manageable and controllable form. Feedback linearization simplifies control design and allows for more precise control of AUVs, particularly in the pitch and yaw planes, by converting nonlinear underwater vehicle dynamic equations into linear equations (Zhou & Eustice, 2014).

The pitch controller can be built using a dual-loop methodology (Dougherty & Woolweaver, 1990). The inner loop controls pitch, while the outer loop controls depth. The depth controller generates a reference pitch angle, which serves as the input for the pitch angle controller (Hong et al., 2010). The pitch angle controller determines the elevator deflection required to meet the reference pitch angle. The yaw plane controller can be built around a framework in which the outer loop regulates the yaw angle and the inner loop controls the yaw rate.

There are various controller design strategies accessible, each with its own set of benefits and considerations. One study looks into the usage of sliding mode control (SMC) to construct a pitch controller (Edwards & Spurgeon, 1998). Different controllers' performances are compared by Shetty et al. (2021). The linear quadratic regulator (LQR) is studied by Joshi (2016). This study employs a distinct controller design: the feedback linearization method. For mathematical convenience, the nonlinear system can be divided into three mostly independent linearized subsystems: speed, steering and depth, as specified by Abkowitz (1964). The feedback linearization approach is a powerful control strategy that converts nonlinear dynamics into a controllable form and simplifies control planning.

This study investigates 6-degrees-of-freedom (6-DOF) nonlinear dynamic modeling, with a focus on the complex motion of underwater vehicles. The model precisely calculates forces and moments, demonstrating how propeller-induced thrust, hydrostatics, hydrodynamics, added mass and control surfaces all interact.

Gaining precise control over depth and yaw is one of the most important things we can do to overcome the challenges of the underwater environment. The feedback linearization method is used to develop the controller for the yaw and pitch plane channels.

This study provides a comprehensive guideline by bringing together all these steps. It explores 6-degrees-of-freedom (6-DOF) nonlinear dynamic modeling, with a focus on the complex motion of underwater vehicles. The model precisely calculates forces and moments, demonstrating how propeller-induced thrust, hydrostatics, hydrodynamics, added mass and control surfaces all interact. Gaining precise control over depth and yaw is one of the most important things we can do to overcome the challenges of the underwater environment. The feedback linearization based nonlinear dynamic inversion method is used to develop the controller for the yaw and pitch plane channels.

A nonlinear dynamic model has been developed for REMUS (Remote Environmental Monitoring UnitS), an autonomous underwater vehicle used for search, recovery and mapping missions. REMUS is an open-source AUV, with its physical and hydrodynamic parameters readily available in the literature. Consequently, the methods employed in this study are applied to REMUS but can be extended to any AUV or underwater vehicle, provided its parameters are accessible.

2. Mathematical Models of AUV Kinematics and Dynamics

Linear systems have proportional and understandable relationships between variables. However, nonlinear systems become increasingly difficult, necessitating the use of specialized modeling approaches (Slotine & Li, 1991).

To construct a nonlinear dynamic model of a system, the forces and moments acting on the system must be defined. There are four distinct forces and moments acting on this AUV system. These include hydrostatic, hydrodynamic, propeller thrust and fin forces and moments (Prestero, 2001).

2.1. Hydrostatic Force and Moment

The underwater vehicle is subjected to hydrostatic force and moment due to its weight and buoyancy. This force and moment can be found in the body fixed axis with Eq. 1-3 (Prestero, 2001).

$$f_G = J_1^{-1}\begin{bmatrix}0\\0\\W\end{bmatrix} \quad f_B = J_1^{-1}\begin{bmatrix}0\\0\\B\end{bmatrix} \tag{1}$$

$$F_{HS} = f_G - f_B \tag{2}$$

$$M_{HS} = r_{GB}\ x\ f_G \tag{3}$$

f_G –Gravity Force

f_B –Buoyancy Force

J_1 –Transformation Matrix from Body to Earth Frame (defined in Eq 4)

W –Weight

B –Buoyancy

F_{HS} –Hydrostatic Force

M_{HS} –Hydrostatic Moment

r_{GB} –Distance between CG (Center of Gravity) and CB (Center of Buoyancy)

$$J_1 = \begin{bmatrix} cos\psi\ cos\theta & -sin\psi\ cos\phi + cos\psi\ sin\theta\ sin\phi & sin\psi\ sin\phi + cos\psi\ sin\theta\ cos\phi \\ sin\psi\ cos\theta & cos\psi\ cos\phi + sin\psi\ sin\theta\ sin\phi & -cos\psi\ sin\phi + sin\psi\ sin\theta\ cos\phi \\ -sin\theta & cos\theta\ sin\phi & cos\theta\ cos\phi \end{bmatrix} \tag{4}$$

Here, r_{GB} vector is defined. Center of the forces and moments is used as the center of buoyancy (CB) point in this study. It is defined in Eq. 5.

$$r_{GB} = x_{CG} - x_{CB} \tag{5}$$

2.2. Hydrodynamics Force and Moment

The AUV is subjected to several impacts as it moves through the water, resulting in a force and moment on the vehicle. These are referred to as hydrodynamic forces and moments. Hydrodynamic parameters are obtained through CFD (Computational Fluid Dynamics) analyses, which are conducted under various conditions such as different speeds and rates of the system. As a result of these CFD analyses, a set of hydrodynamic force and moment parameters is generated. The forces and moments arising from hydrodynamic effects on the system are then expressed using this set of equations.

The hydrodynamic force and moment can be expressed as Eq. 6-11 (Prestero, 2001).

$$X_{HD} = X_{u|u|}u|u| + X_{\dot{u}}\dot{u} + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr \tag{6}$$

$$Y_{HD} = Y_{v|v|}v|v| + Y_{r|r|}r|r| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv \tag{7}$$

$$Z_{HD} = Z_{w|w|}w|w| + Z_{q|q|}q|q| + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + Z_{uw}uw \tag{8}$$

$$K_{HD} = K_{p|p|}p|p| + K_{\dot{p}}\dot{p} \tag{9}$$

$$M_{HD} = M_{w|w|}w|w| + M_{q|q|}q|q| + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{uq}uq + M_{vp}vp + M_{rp}rp + M_{uw}uw \tag{10}$$

$$N_{HD} = N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp + N_{pq}pq + N_{uv}uv \tag{11}$$

X_{HD}, Y_{HD}, Z_{HD} –Hydrodynamic Force Components

K_{HD}, M_{HD}, N_{HD} –Hydrodynamic Moment Components

u, v, w –Linear Velocities

p, q, r –Rates

$\dot{u}, \dot{v}, \dot{w}$ –Linear Velocity Derivatives

$\dot{p}, \dot{q}, \dot{r}$ –Rate Derivatives

Hydrodynamic coefficients in the equations are defined by Prestero (2001) for the REMUS AUV.

2.3. Propeller Force and Moment

Because there is no more shared thrust model data, the easiest way to develop this model is to match the propeller thrust to the vehicle's axial drag. The equation is provided in Eq. 12 (Prestero, 2001).

$$X_{prop} = -X_{u|u|}u|u| \tag{12}$$

X_{prop} –Propeller Thrust Force

X_{uu} –Hydrodynamic Coefficient

2.4. Fin Force and Moment

Fins refer to the control surfaces on an underwater vehicle. The force and moment generated by the fins are referred to as fin force and moment. The equations are presented in Eq. 13-16 (Prestero, 2001).

$$Y_{fin} = Y_{uu\delta_r}u^2\delta_r \tag{13}$$

$$Z_{fin} = Z_{uu\delta_s}u^2\delta_s \tag{14}$$

$$M_{fin} = M_{uu\delta_s}u^2\delta_s \tag{15}$$

$$N_{fin} = N_{uu\delta_r}u^2\delta_r \tag{16}$$

Y_{fin}, Z_{fin} –Fin Force Components

M_{fin}, N_{fin} –Fin Moment Components

δ_r –Rudder Deflection

δ_s –Stern (Elevator) Deflection

2.5. AUV Rigid Body Dynamics

6-DoF equations of the motion for the rigid-body are represented with the below simplified equations in Eq. 17-22 (Prestero, 2001).

$$m[\dot{u} - vr + wq - x_{gb}(q^2 + r^2) + y_{gb}(pq - \dot{r}) + z_{gb}(pr + \dot{q})] = \sum X_{ext} \tag{17}$$

$$m[\dot{v} - wp + ur - y_{gb}(r^2 + p^2) + z_{gb}(qr - \dot{p}) + x_{gb}(qp + \dot{r})] = \sum Y_{ext} \tag{18}$$

$$m[\dot{w} - uq + vp - z_{gb}(p^2 + q^2) + x_{gb}(rp - \dot{q}) + y_{gb}(rq + \dot{p})] = \sum Z_{ext} \tag{19}$$

$$I_{xx}\dot{p} + \left(I_{zz} - I_{yy}\right)qr + m[y_{gb}(\dot{w} - uq + vp) - z_{gb}(\dot{v} - wp + ur)] = \sum K_{ext} \tag{20}$$

$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m[z_{gb}(\dot{u} - vr + wq) - x_{gb}(\dot{w} - uq + vp)] = \sum M_{ext} \tag{21}$$

$$I_{zz}\dot{r} + \left(I_{yy} - I_{xx}\right)pq + m[x_{gb}(\dot{v} - wp + ur) - y_{gb}(\dot{u} - vr + wq)] = \sum N_{ext} \tag{22}$$

$\sum X_{ext}, \sum Y_{ext}, \sum Z_{ext}, \sum K_{ext}, \sum M_{ext}, \sum N_{ext}$ –Total External Force and Moment in 6-DoF

Acceleration and angular acceleration are computed using the 6-DoF Equations of Motion. Following the calculation of acceleration, the velocity profile is calculated by applying the integral operation to the acceleration. These calculations are carried at the body-fixed coordinate system.

2.6. AUV Kinematics

Kinematics of the AUV is the study of its position, orientation and speed in order to understand how it moves in underwater. The AUV force, moment, linear velocity, angular rates, euler angles and coordinate systems are represented in Fig. 1.

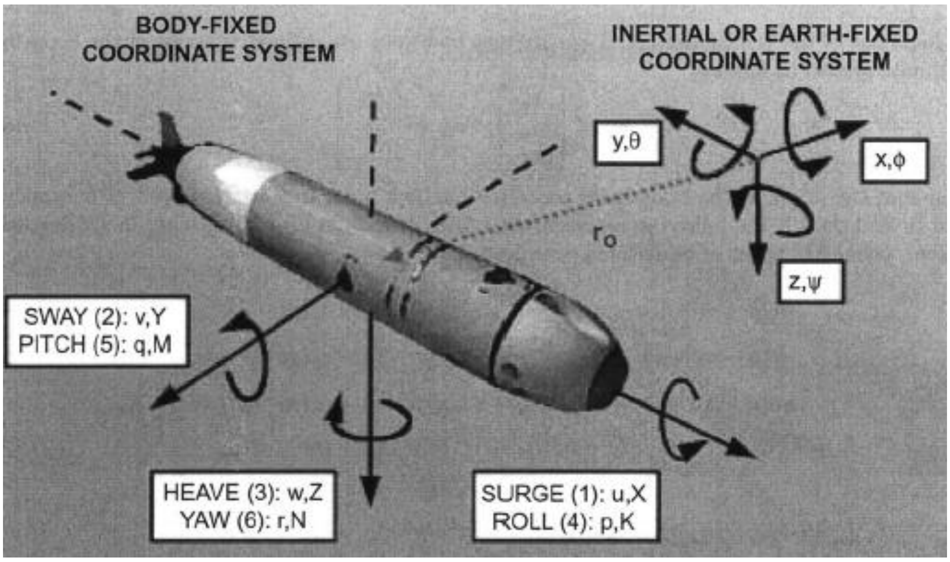

Fig. 1. AUV Coordinate Systems and States

The vehicle's motion in 6-DoF can be specified using the vectors shown in Eq. 23-28 (Prestero, 2001).

$$\eta_1 = [x\ y\ z]^T \tag{23}$$

$$\eta_2 = [\phi\ \theta\ \psi]^T \tag{24}$$

$$v_1 = [u\ v\ w]^T \tag{25}$$

$$v_2 = [p\ q\ r]^T \tag{26}$$

$$\tau_1 = [X\ Y\ Z]^T \tag{27}$$

$$\tau_2 = [K\ M\ N]^T \tag{28}$$

η_1, η_2 –Vehicle's position and orientation with respect to the inertial or earth-fixed reference frame

v_1, v_2 –Vehicle's translational and rotational velocities with respect to the body-fixed reference frame

τ_1, τ_2 –Vehicle's total force and moments with respect to the body-fixed reference frame

Eq. 29 can be used to compute the transformation of translational velocity from the body reference frame to the inertial or earth-fixed reference frame (Prestero, 2001).

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} = J_1 \begin{bmatrix}u\\ v\\ w\end{bmatrix} \tag{29}$$

J_1 –Transformation Matrix from Body to Earth Frame (defined in Eq. 4)

ϕ, θ, ψ –Euler Angles

u, v, w –Linear Velocities

Eq. 30 can be used to compute the transformation of rotational velocity from the body reference frame to the inertial or earth-fixed reference frame (Prestero, 2001).

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = J_2 \begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{30}$$

J_2 –Transformation Matrix of Rotational Velocity from Body to Earth Frame (defined in Eq. 31)

$\dot{\phi}, \dot{\theta}, \dot{\psi}$ –Euler Angle Derivatives

p, q, r –Rates

$$J_2 = \begin{bmatrix} 1 & sin\phi \, tan\theta & cos\phi \, tan\theta \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi/cos\theta & cos\phi/cos\theta \end{bmatrix} \tag{31}$$

6-DOF nonlinear dynamic model design process is shared so far. The next step will be the appropriate controller design.

3. Controller Design for AUV Dynamics

The controller design method is nonlinear dynamic inversion which is based on the feedback linearization method. There are two controllers: the pitch plane controller and the yaw plan e controller. Pitch plane controller has two modes: depth and pitch angle controller. Yaw plane controller has two modes: yaw angle and yaw angular rate controller.

The nonlinear state variable form is defined in Eq. 32.

$$\dot{x} = f(x) + g(x)u \tag{32}$$

Error and its derivative is defined in Eq. 33, 34.

$$e = x - x_{ref} \tag{33}$$

$$\dot{e} = \dot{x} - \dot{x}_{ref} \tag{34}$$

Let's define,

$$\dot{e} + K_1 e + K_2 \int edt = 0 \tag{35}$$

$$\varepsilon = K_1 e + K_2 \int edt \tag{36}$$

$$\dot{x} = \dot{x}_{ref} - \varepsilon \tag{37}$$

After using Eq. 35-37, control input is represented with the Eq. 38.

$$u = \left[\dot{x}_{ref} - \varepsilon - f(x)\right] g^{-1}(x) \tag{38}$$

3.1. Pitch Plane Controller

Pitch angle and depth control are the two different modes of the pitch plane controller. Fig. 2 shows the pitch plane controller.

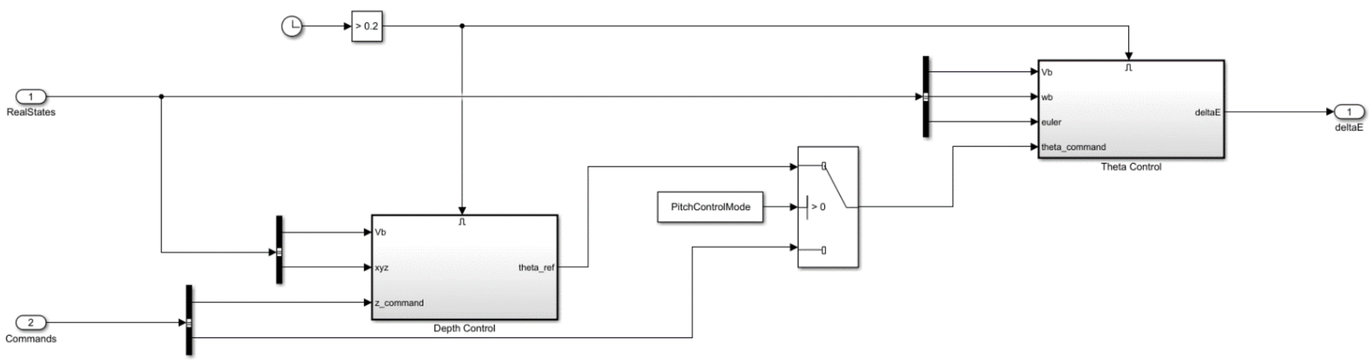

Fig. 2. Pitch Plane Controller

Theta is the inner loop of the pitch plane controller and depth is the outside loop.

To control the depth, a reference depth must be specified as z_{ref}. The θ_{ref} will be determined using the Eq. 39-43 (Kaya, 2024).

$$e = z_{real} - z_{ref} \tag{39}$$

$$\dot{e} + K_1 e + K_2 \int e = 0 \quad (40)$$

$$\dot{z} = \dot{z}_{ref} - K_1 e - K_2 \int e \quad (41)$$

$$V sin\theta = -\dot{z} \quad (42)$$

$$\theta_{ref} = \sin^{-1}(-\frac{\dot{z}}{V}) \quad (43)$$

e –Error

K_1, K_2 –Proportional Gain and Integral Gain

$z, \dot{z}$ –Position-z (Depth) and Position Derivative

z_{real} –AUV Real Depth

z_{ref} –Reference (Desired) Depth for Controller

V –Total Velocity

θ, θ_{ref} –AUV Pitch Angle and Reference Pitch Angle for Controller

The given equation calculates θ_{ref}. The pitch angle controller will use the first and second derivatives of θ_{ref} as input. In the second method, θ_{ref} can be sent directly to the autopilot, as illustrated in the pitch plane controller picture. Autopilot will calculate the necessary δ_e angle to achieve the specified θ_{ref}. Eq. 44-50 shows the process.

$$e = \dot{\theta} - \dot{\theta}_{ref} \quad (44)$$

$$\int e = \theta - \theta_{ref} \quad (45)$$

$$\dot{\theta} = q cos\phi - r sin\phi \quad (46)$$

q, r –Pitch and Yaw Rate

ϕ –Roll Angle

Assume, $\phi = 0$. Then, $\dot{\theta} = q$,

$$\dot{e} + K_1 e + K_2 \int e = 0 \quad (47)$$

$$(\ddot{\theta} - \ddot{\theta}_{ref}) + K_1(\dot{\theta} - \dot{\theta}_{ref}) + K_2(\theta - \theta_{ref}) = 0 \quad (48)$$

$$\ddot{\theta} = \ddot{\theta}_{ref} - K_1(\dot{\theta} - \dot{\theta}_{ref}) - K_2(\theta - \theta_{ref}) \quad (49)$$

$$\dot{q} = \ddot{\theta}_{ref} - K_1(\dot{\theta} - \dot{\theta}_{ref}) - K_2(\theta - \theta_{ref}) \quad (50)$$

Following this technique, δ_e is determined and transmitted to the system dynamic model. The nonlinear dynamic model calculates the states and sends them to the autopilot again. The system can reach the desired depth or theta angle by applying the controller's δ_e instruction.

3.2. Yaw Plane Controller

Yaw rate and yaw angle controller are the two different modes of the yaw plane controller. Simulation model of the yaw plane controller is given in the Fig. 3.

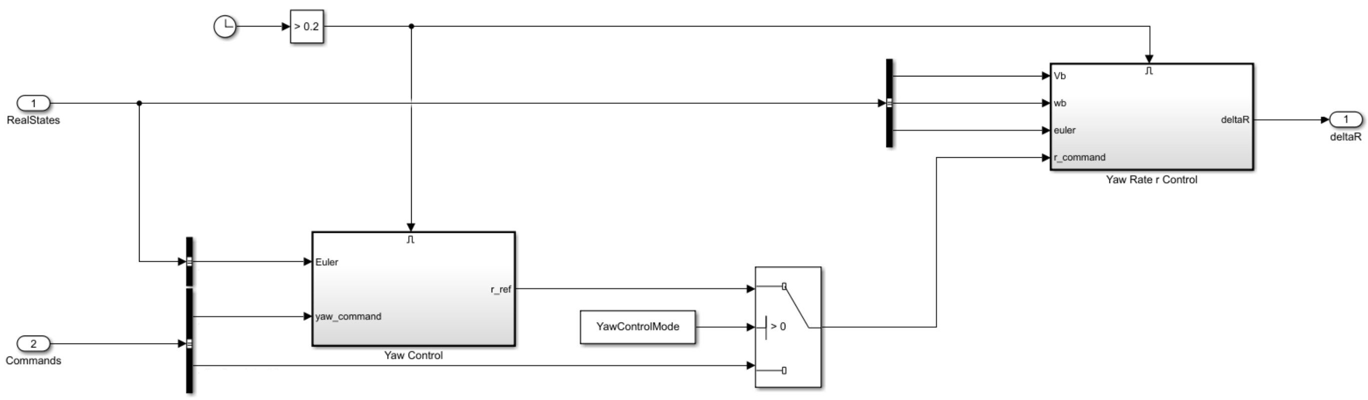

Fig. 3. Yaw Plane Controller

The yaw plane controller has an inner loop that controls the yaw rate and an outside loop that controls the yaw angle.

To control the yaw angle, specify a reference yaw angle ψ_{ref}. Then r_{ref} will be determined using the Eq. 51-54 (Kaya, 2024).

$$e = \psi - \psi_{ref} \tag{51}$$

$$\dot{e} = \dot{\psi} - \dot{\psi}_{ref} \tag{52}$$

$$\dot{e} + K_1 e + K_2 \int e = 0 \tag{53}$$

$$\dot{\psi} = \dot{\psi}_{ref} - K_1 e - K_2 \int e \tag{54}$$

e −Error

K_1, K_2 −Proportional Gain and Integral Gain

$\psi, \dot{\psi}$ −Yaw Angle and Yaw Angle Derivative

ψ_{ref} −Reference (Desired) Yaw Angle for Controller

V −Total Velocity

Eq. 55 shows the conversion of the rotational velocity from the body reference frame to the inertial or earth-fixed reference frame.

$$\dot{\psi} = \left(\frac{\sin\phi}{\cos\theta}\right) q + \left(\frac{\cos\phi}{\cos\theta}\right) r \tag{55}$$

q, r −Pitch and Yaw Rate

ϕ, θ −Roll and Pitch Angle

Assume $\phi = 0$, then Eq. 56-57 is formed.

$$\dot{\psi} = \frac{r}{\cos\theta} \tag{56}$$

$$r_{ref} = \dot{\psi} \cos\theta \tag{57}$$

r_{ref} is calculated and the first derivative is fed into the yaw rate controller. In the second option, r_{ref} can be supplied directly to the autopilot, as illustrated in the yaw plane controller picture. Autopilot will compute the necessary δ_r angle to achieve the target r_{ref}. Eq. 58-62 represents the process.

$$e = r - r_{ref} \tag{58}$$

$$\dot{e} = \dot{r} - \dot{r}_{ref} \tag{59}$$

$$\dot{e} + K_1 e + K_2 \int e = 0 \tag{60}$$

$$\dot{r} - \dot{r}_{ref} + K_1(r - r_{ref}) + K_2 \int (r - r_{ref}) = 0 \tag{61}$$

$$\dot{r} = \dot{r}_{ref} - K_1(r - r_{ref}) - K_2 \int (r - r_{ref}) \tag{62}$$

Following this technique, δ_r is determined and transmitted to the system dynamic model. The nonlinear dynamic model calculates the states and sends them to the autopilot again. Applying the controller's δ_r command allows the system to achieve the specified yaw angle or rate.

4. Results and Discussion

This section presents some of the controller's results and performance with true states.

The engine model is based on a basic transfer function. The engine model receives an RPM command and responds accordingly. It is used to simulate an RPM changeover. The engine model is shown in Fig. 4.

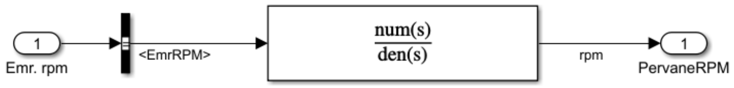

Fig. 4. Engine Model

RPM response for 5000 RPM command is given in the Fig. 5.

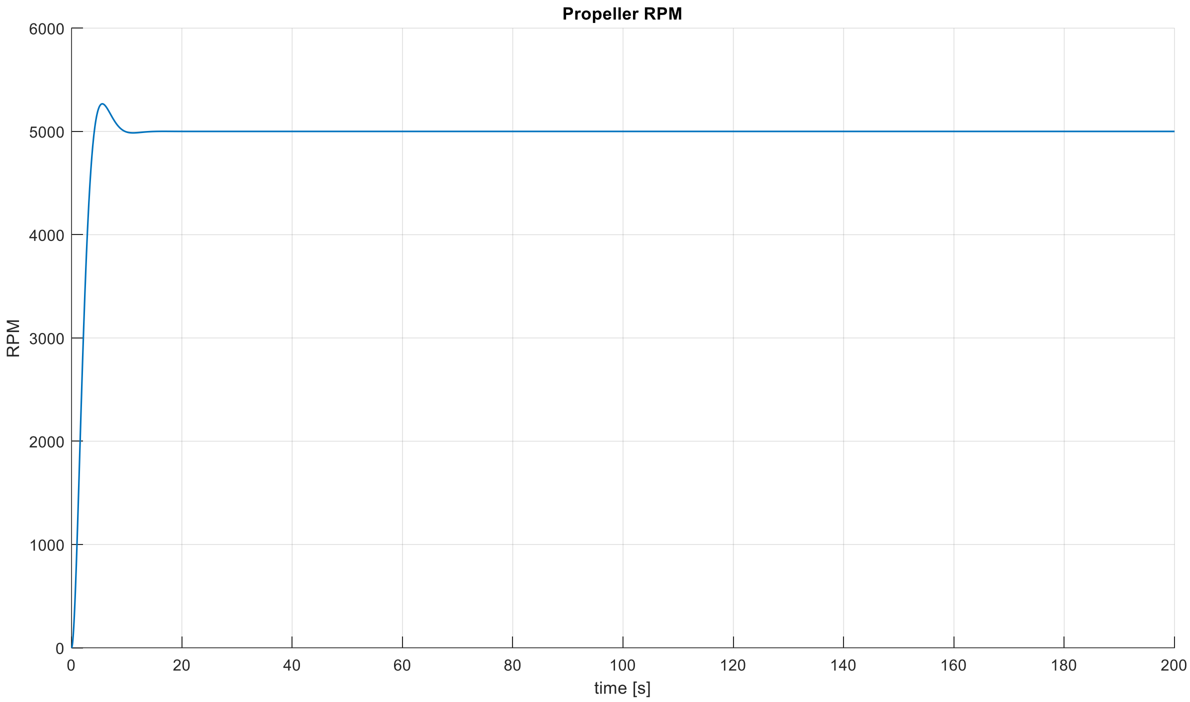

Fig. 5. Propeller RPM Graph

AUV velocity reaches around 5 m/s with this RPM. Graph is given in the Fig. 6.

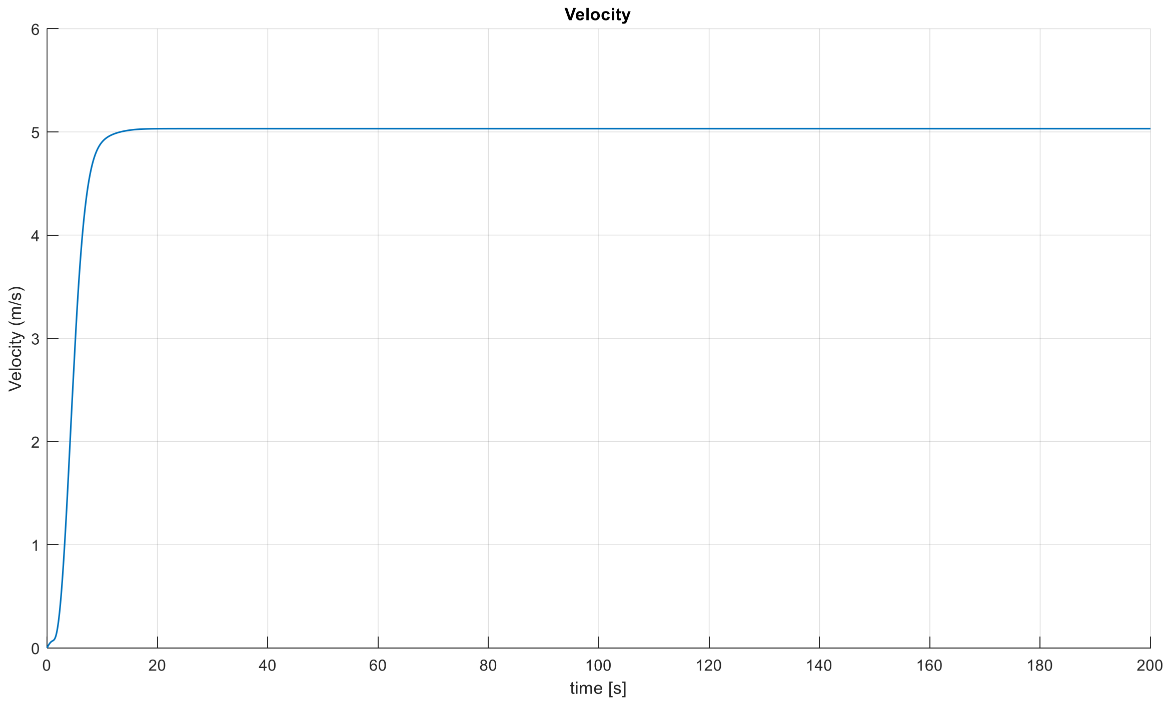

Fig. 6. AUV Velocity Graph

When the AUV moves at this velocity, several commands are issued to the system. Different controller modes are tested. First, the depth control mode is examined. Fig. 7 shows the AUV's command depth as well as its actual depth.

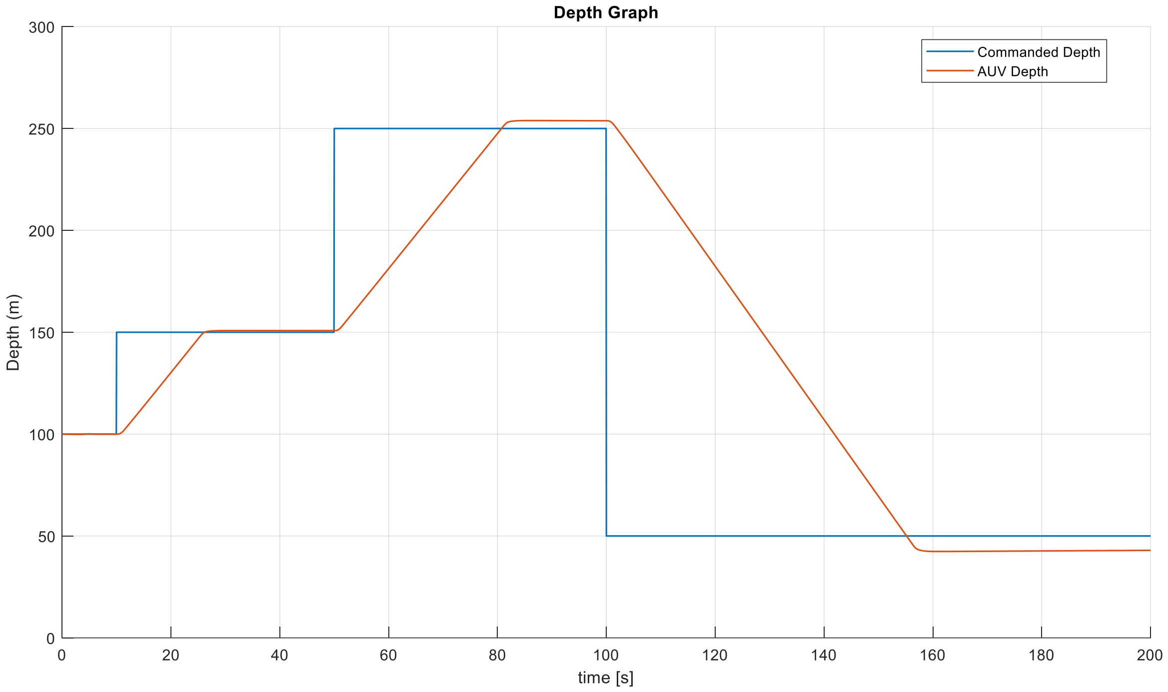

Fig. 7. Commanded Depth vs. AUV Depth Graph

Secondly, theta angle control mode is evaluated. Fig. 8 shows the AUV's commanded and real theta angles.

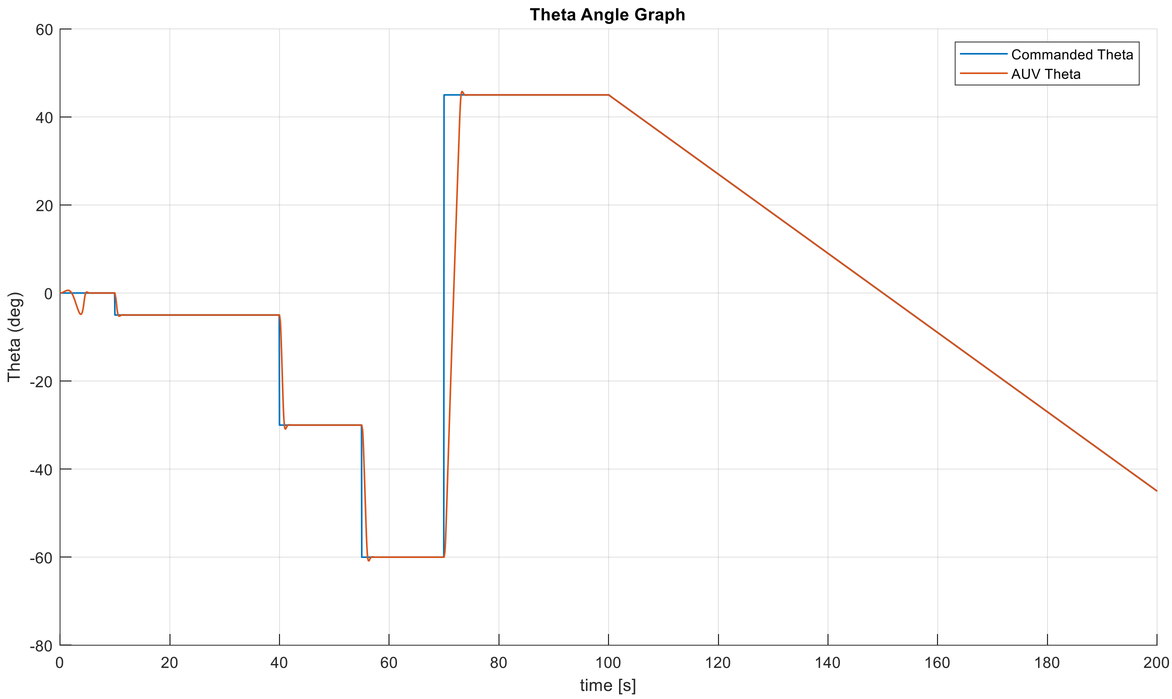

Fig. 8. Commanded Theta vs. AUV Theta Graph

As seen in Fig. 7, 8, the system is capable of executing the appropriate commands in pitch plane. Controller is able to reach the desired the values of theta angle or depth, depending on the pitch plane control mode.

Finally, the yaw controller is tested. The first control mode is yaw angle controller. Fig. 9 depicts the AUV's commanded and actual yaw angles.

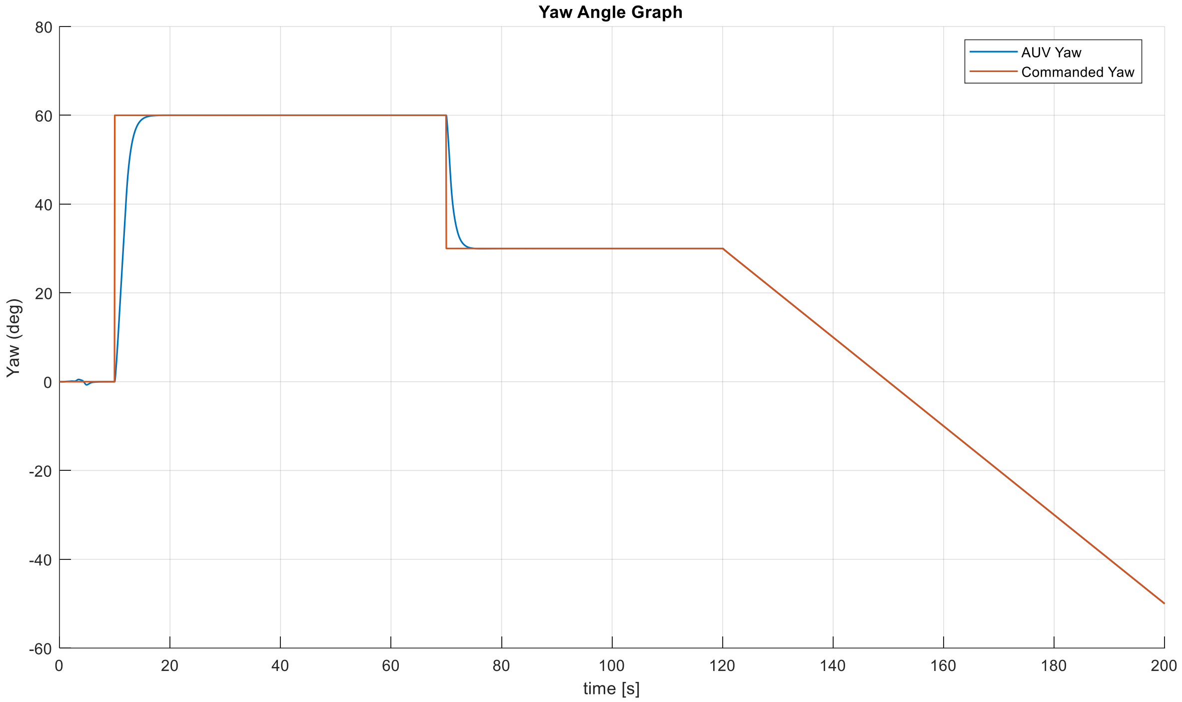

Fig. 9. Commanded Yaw vs. AUV Yaw Graph

Next, the yaw rate controller mode is tested. Fig. 10 shows the system's commanded and true yaw rates.

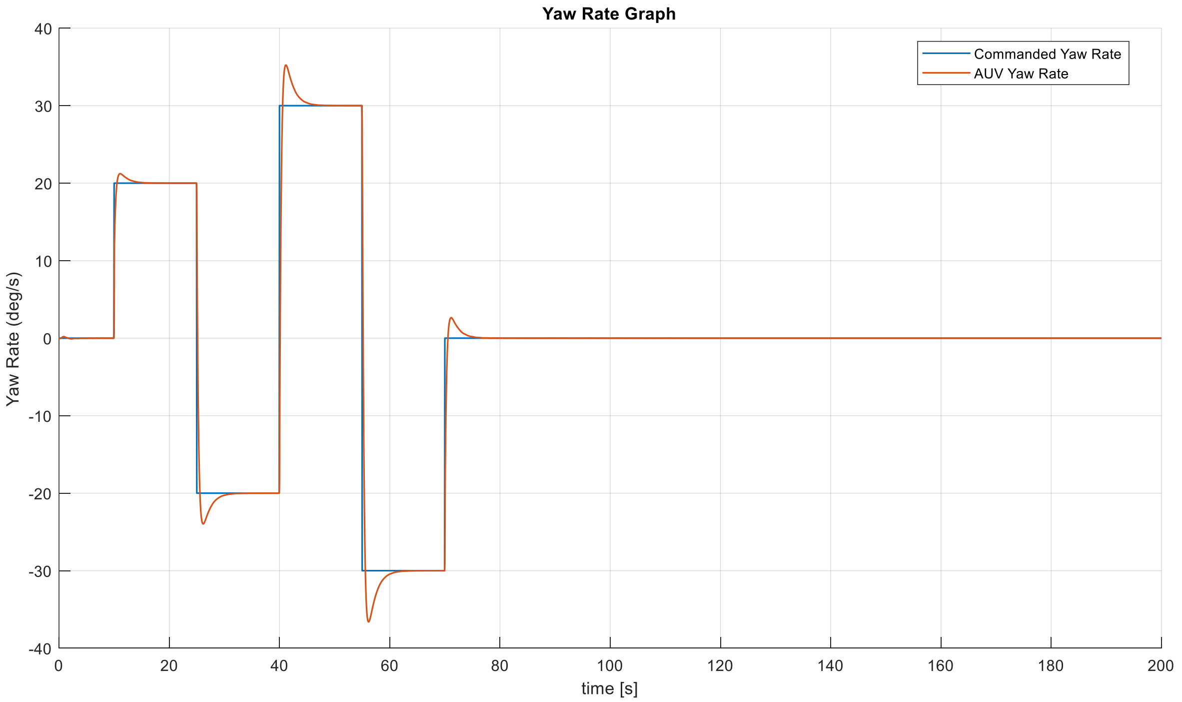

Fig. 10. Commanded Yaw Rate vs. AUV Yaw Rate Graph

As seen in Fig. 9, 10, the controller carries out the desired commands. In the yaw plane, controller is able to successfully reach the desired yaw angle or yaw angular rate, depending on the yaw plane control mode.

5. Conclusions

Autonomous underwater vehicles are being utilized to investigate underwater habitats. This topic is rapidly expanding and has significant implications for research, business and the military. This paper investigates the complex dynamics of nonlinear models with six degrees of freedom (6-DOF) for underwater vehicles. The major goal was to develop an effective control strategy for precise pitch and yaw control utilizing the feedback linearization method.

The 6-DOF dynamic simulation model played an important role in determining how forces and moments affect underwater vehicle movement. Careful consideration of propeller thrust, hydrostatics, hydrodynamics, added mass and control surfaces paved the way for a comprehensive modeling framework. The use of feedback linearization has proven to be an effective solution to problems caused by the nonlinear dynamics that are widespread underwater.

The feedback linearization method was used to convert nonlinear dynamics into a manageable form, making it easier to develop control systems. The proposed technology enhances the mobility and flexibility of autonomous underwater vehicles by providing precise depth and yaw control. This is an important step toward making them more usable in real-world applications.

There are many studies in the underwater vehicles area; however, this research brings up the 6-DoF modelling and controller design topics together. Moreover, this research applies the feedback linearization controller method for the AUVs. This study has made significant progress in helping us understand how to control the state of an underwater vehicle. To ensure that the proposed approaches operate, they should be thoroughly tested in actual underwater fields. Field tests would allow us to learn more about potential difficulties and how effectively the control system performs in various scenarios. Field testing determine whether or not the real-world system dynamics match the simulation model. Simulation models needs to be regularly updated based on field experiments.

Abbreviations

6-DOF : 6 Degree of Freedom

AUV : Autonomous Underwater Vehicle

CG : Center of Gravity

CB : Center of Buoyancy

m : Meter

N : Newton

PID : Proportional – Integral – Derivative Controller

rad : Radian

REMUS : Remote Environmental Monitoring Unit

rpm : Revolution per Minute

F : Force

M : Moment

X : Force on X Axis

Y : Force on Y Axis

Z : Force on Z Axis

K : Moment around X Axis

M : Moment around Y Axis

N : Moment around Z Axis

u,v,w : Velocities at Body Fixed Coordinate Frame

ϕ, θ, ψ : Euler Angles

p,q,r : Angular Velocities (Rates)

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