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A Detailed Review on Intelligent and Robust Control Strategies for Autonomous Underwater Vehicles with Emphasis on Navigation, Path Tracking, and Stability Enhancement

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Abstract

Autonomous underwater vehicles (AUVs) have gained significant attention due to their applications in ocean exploration, underwater surveillance, environmental monitoring, and offshore industries. The control of AUVs presents various challenges due to the highly dynamic and uncertain underwater environment, nonlinear hydrodynamics, and external disturbances. This review explores various control strategies employed for AUVs, including classical control methods such as Proportional-Integral-Derivative (PID) controllers, modern techniques like Model Predictive Control (MPC), and intelligent control approaches utilizing Artificial Intelligence (AI) and Reinforcement Learning (RL). The study compares these techniques in terms of stability, robustness, adaptability, and energy efficiency. Additionally, hybrid control frameworks that integrate multiple strategies for enhanced performance are discussed. The study aims to provide insights into the latest advancements in AUV control and future research directions for improving their autonomy and operational efficiency.

Keywords: Autonomous underwater vehicles (AUVs), control strategies, proportional-integral-derivative (PID) control, model predictive control (MPC), adaptive control, artificial intelligence (AI), reinforcement learning (RL), hybrid control, underwater robotics, nonlinear hydrodynamics, ocean exploration

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INTRODUCTION

Autonomous underwater vehicles (AUVs) are unmanned, self-propelled vehicles designed to operate underwater without direct human control. They are equipped with various sensors, navigational systems, and propulsion mechanisms, allowing them to navigate autonomously and perform a wide range of tasks in underwater environments. AUVs are capable of operating independently, following pre-programmed missions or dynamically adjusting their behavior based on environmental conditions and sensor feedback. They can navigate through water columns, survey large areas, and execute complex tasks without human intervention. AUVs are equipped with a variety of sensors to collect data about the underwater environment. These sensors may include sonars for mapping the seafloor and detecting objects, cameras for capturing images and videos, acoustic sensors for communication and navigation, and instruments for measuring water properties such as temperature, salinity, and pressure. AUVs use a combination of navigation techniques, including inertial navigation systems (INS), acoustic positioning systems, and satellite-based positioning systems (e.g., GPS), to determine their position and navigate underwater. They can maintain precise trajectories and avoid obstacles using onboard sensors and algorithms [1–4]. AUVs are employed in various applications, including oceanographic research, environmental monitoring, underwater mapping, marine archaeology, offshore oil and gas exploration, pipeline inspection, search and rescue operations, defense and security, and underwater infrastructure maintenance. AUVs are highly versatile platforms that can be customized and adapted for specific missions and applications. They can operate in a wide range of water depths, from shallow coastal areas to deep-sea environments, and withstand challenging conditions such as high pressures and low temperatures. AUVs offer several advantages over traditional manned or remotely operated underwater vehicles, including lower operational costs, reduced risk to human operators, extended mission durations, and access to hard-to-reach or hazardous locations. AUV technology is continuously evolving, with ongoing research and development efforts focused on improving autonomy, sensor capabilities, energy efficiency, and operational reliability [5–8]. Emerging technologies such as artificial intelligence, machine learning, and advanced materials are being integrated into AUV designs to enhance their performance and expand their range of applications. AUVs play a crucial role in advancing our understanding of the underwater world, monitoring marine environments, and supporting various commercial, scientific, and military activities. As technology continues to advance, AUVs are expected to become even more capable and widely used in the exploration and exploitation of the ocean's resources.

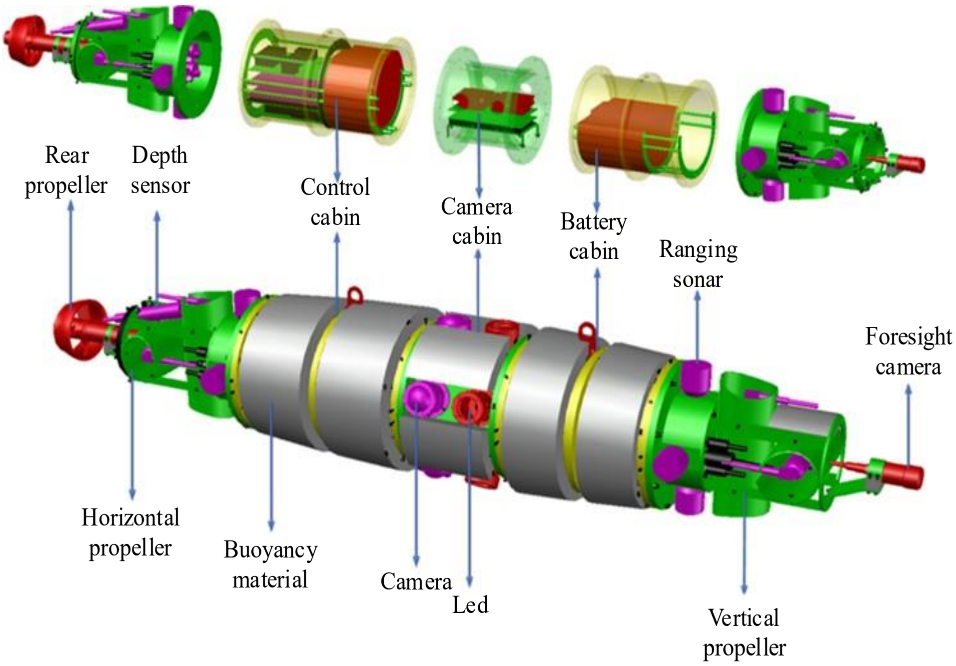

Figure 1. Structure of an AUV.

The design of the AUV shown in Figure 1 described in the passage is tailored for specific tasks, likely involving tunnel inspection or navigation. The main body of the AUV is divided into three watertight compartments: the control cabin, camera cabin, and battery cabin. This compartmentalization helps protect sensitive electronics and equipment from water damage [9, 10]. Annular buoyancy material is equipped outside the compartments to provide buoyancy and ensure the AUV maintains proper trim and stability underwater. The AUV is equipped with a main thruster at the stern, as well as two vertical and two horizontal thrusters. This configuration allows for precise control of the vehicle's motion in six degrees of freedom: surge, sway, heave, pitch, and yaw. The AUV is outfitted with a high-precision depth gauge and four ranging sonars at the stern, along with four ranging sonars around the bow. These sensors enable the AUV to accurately navigate and avoid obstacles in its environment. The camera cabin contains five lights and five high-definition cameras arranged in a circular distribution. These cameras are primarily used to capture video footage of the tunnel walls for inspection purposes. Additionally, a forward-looking camera at the bow assists in recognizing optical signals to aid the AUV in exiting the tunnel. The brightness of the lights in the camera cabin is adjusted using pulse width modulation (PWM) signals to provide optimal illumination for the cameras to capture clear video footage. The design of the AUV reflects a specialized configuration tailored for tunnel inspection or navigation tasks. The compartmentalization of the main body, precision propulsion system, array of sensors, high-definition cameras, and adjustable lighting system are all optimized to ensure efficient operation and data collection in the underwater environment.

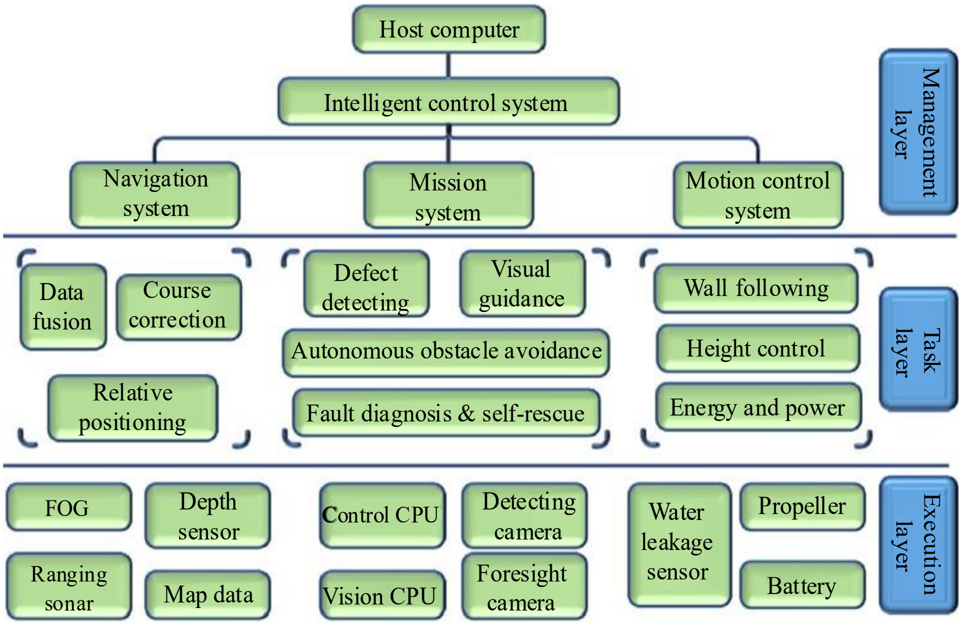

Figure 2. Architecture of the AUV design.

The architecture of the AUV shown in Figure 2 employs a layered design approach, which organizes the system into three levels: execution level, task level, and management level. Each level serves specific functions and interacts with the layers above and below it. The navigation system is responsible for determining the AUV's position, orientation, and trajectory in the underwater environment [11–13]. It integrates data from sensors such as depth gauges, sonars, and GPS to accurately navigate the vehicle along its planned path. This system ensures that the AUV can maintain proper course and avoid obstacles during its mission. The mission system is tasked with defining and executing the objectives of the AUV's mission. It receives input from higher-level command and control systems or mission planning software and translates these objectives into specific tasks for the AUV to perform. This may include tasks such as surveying an area, inspecting a structure, or collecting samples. The mission system coordinates the execution of these tasks and monitors their progress to ensure mission success. The motion control system manages the propulsion and maneuvering of the AUV, controlling its movements in response to navigation commands and environmental conditions. It interfaces with the propulsion system, thrusters, and control surfaces to adjust the vehicle's speed, direction, and attitude as needed. The motion control system ensures that the AUV can maintain stable motion and execute precise maneuvers to accomplish its mission objectives. By dividing the architecture into these three levels, the AUV can achieve a modular and hierarchical structure that facilitates efficient communication, coordination, and control of its various subsystems. Each level is responsible for specific aspects of operation and interacts with the other levels to enable autonomous and adaptive behavior in the underwater environment.

MATHEMATICAL MODELING OF AN AUTONOMOUS UNDERWATER VEHICLE

Mathematical modelling of autonomous underwater vehicles (AUVs) is essential for understanding their dynamics, control, and performance characteristics [14]. These models allow engineers and researchers to simulate the behavior of AUVs under different conditions and design control algorithms to achieve desired mission objectives. Here are some key aspects of mathematical modelling for AUVs:

- *Kinematics and dynamics:* Mathematical models describe the motion of AUVs in terms of their kinematics (motion without considering forces) and dynamics (motion considering forces). Kinematic models typically involve equations describing the AUV's position, velocity, and orientation in space. Dynamic models incorporate forces such as hydrodynamic drag, buoyancy, and control inputs to predict the AUV's motion over time.
- *Hydrodynamics:* Hydrodynamic modelling is crucial for understanding how AUVs interact with the surrounding water environment. This includes modelling forces such as drag, added mass, hydrostatic buoyancy, and hydrodynamic damping. Hydrodynamic coefficients are determined through experiments, simulations, or empirical data and are used in dynamic models to predict the AUV's response to control inputs.
- *Control system design:* Mathematical models are used to design control algorithms that regulate the AUV's motion and behavior. This involves developing feedback controllers that adjust the AUV's thrusters or control surfaces based on sensor measurements and desired trajectories. Control system design often involves linear or nonlinear control theory, optimization techniques, and simulation-based testing to ensure stability, performance, and robustness.
- *Trajectory planning:* Mathematical models help in trajectory planning, where optimal paths are computed to navigate the AUV to specific waypoints or regions of interest while avoiding obstacles and minimizing energy consumption. Trajectory planning algorithms take into account AUV dynamics, environmental constraints, mission objectives, and operational requirements to generate feasible and efficient paths.
- *Energy and power management:* AUVs are typically powered by onboard batteries or fuel cells, and mathematical models are used to estimate energy consumption, monitor battery state-of-charge, and optimize power management strategies. Energy-aware control algorithms and mission planning techniques help maximize mission duration and accomplish tasks within energy constraints.
- *Sensing and perception:* Mathematical models are used to simulate sensor measurements and perception algorithms that enable AUVs to perceive and interpret their environment. This includes modeling sensor noise, uncertainty, and biases, as well as developing algorithms for sensor fusion, object detection, localization, and mapping.
- *Simulation and validation:* Mathematical models are implemented in simulation environments to validate AUV designs, test control algorithms, and assess performance under various scenarios. High-fidelity simulations provide insights into AUV behavior in complex environments and help identify potential issues before real-world deployment.

The mathematical modeling plays a critical role in the design, development, and operation of autonomous underwater vehicles, enabling engineers and researchers to understand and optimize their performance for a wide range of applications in marine exploration, research, and industry. Achieving accurate position and attitude control of an Autonomous Underwater Vehicle (AUV) is crucial for successfully performing complex underwater missions, especially in highly unstructured ocean environments [15]. Designing a dedicated control system for an AUV requires a thorough understanding of the vehicle's dynamics, which necessitates knowledge of its mathematical model. However, obtaining an exact mathematical model of an AUV is challenging due to the presence of numerous complex and nonlinear forces acting upon it.

These nonlinear forces include hydrodynamic drag, damping, lift forces, Coriolis and centripetal forces, gravity and buoyancy forces, thruster forces, and environmental disturbances such as ocean currents and waves, shown in Figure 3. Estimating these forces accurately is essential for a better understanding of the dynamics of an AUV and designing effective control systems. While these forces can be controllable to some extent, their accurate estimation is crucial for stabilization. In addition to motion control, underwater manipulation tasks often require the use of a manipulator arm mounted on the AUV, forming an autonomous underwater vehicle manipulator system (AUVMS). However, integrating a manipulator arm complicates the control system further due to increased nonlinearity, strong coupling between the manipulator arm and the AUV, and the resulting high-dimensional nature of the AUVMS. In this work, the mathematical models of both the AUV and the AUVMS are considered for the position trajectory tracking control problem in the presence of uncertain oceanic environments. The modelling of the AUV and AUVMS is essential for understanding their dynamics and designing control algorithms that can achieve accurate trajectory tracking despite uncertainties and disturbances in the ocean environment [16]. The accurate modelling of an AUV and its manipulator system is crucial for developing robust control systems that can handle the complexities of underwater missions and effectively navigate and manipulate in challenging ocean environments.

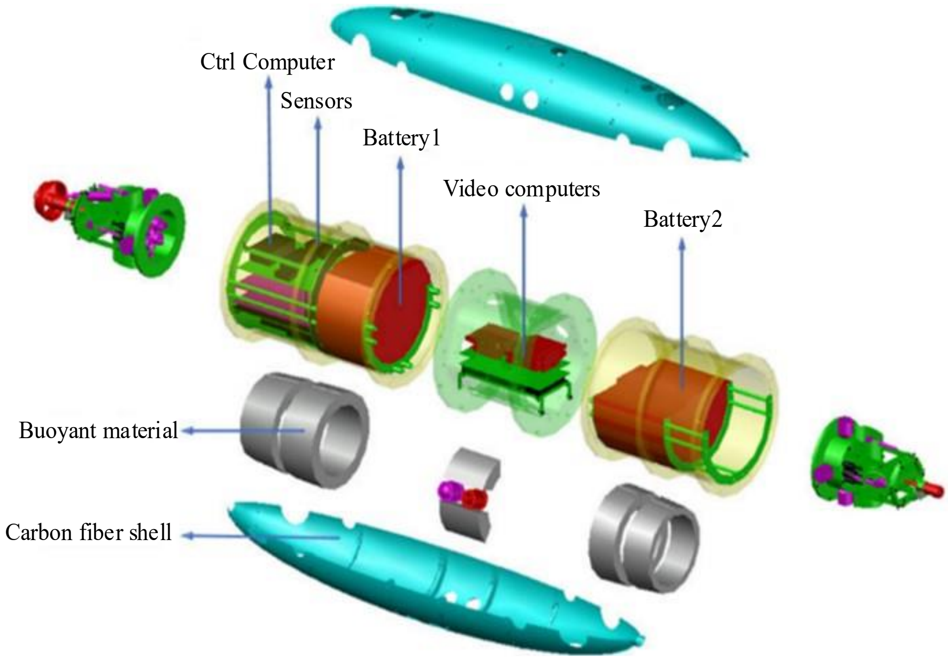

Figure 3. Periphery of the AUV design.

The mathematical modeling of an autonomous underwater vehicle (AUV), shown in Figure 4, typically involves several key elements to describe its motion accurately. These elements include kinematics and dynamics, which are fundamental for understanding and predicting the behavior of the AUV. Let us break down each element:

Kinematics

- Kinematics deals with the geometric aspects of motion without considering the forces causing the motion.
- It describes the position, velocity, and acceleration of the AUV in a given reference frame.
- In the context of AUV modeling, kinematics provide essential information about how the vehicle moves through space and how its position and orientation change over time.
- This aspect of modeling is crucial for tasks such as navigation, trajectory planning, and control system design.

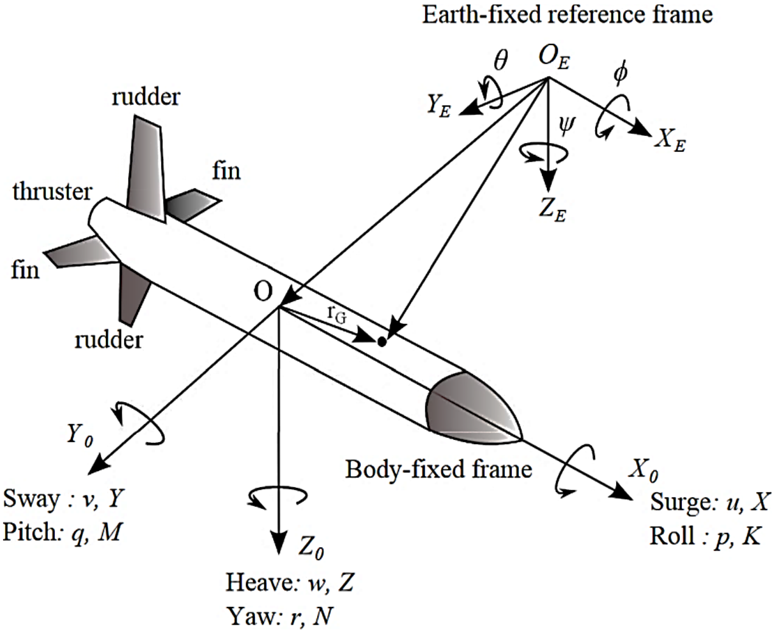

Figure 4. Mathematical model of AUV.

Dynamics

- Dynamics describes the forces and torques that contribute to the motion of the AUV.
- It includes both rigid-body dynamics, which describe the motion of the vehicle as a whole, and mechanics, which deal with the forces and moments acting on the vehicle.
- Rigid-body dynamics involves the inertia matrix of the vehicle, which characterizes its mass distribution and rotational inertia.
- Mechanics encompasses the forces and moments causing the AUV's motion, such as hydrodynamic forces, thruster forces, buoyancy forces, and environmental disturbances.
- Dynamics modeling is essential for understanding how these forces and torques interact to produce the AUV's motion and for designing control systems to regulate its movement.

In the mathematical modeling of an AUV, the motion is typically described using two coordinate frames:

- The body-fixed frame (X0-Y0-Z0) is fixed to the AUV and moves with it. This frame is used to describe the AUV's motion relative to itself, such as its position, velocity, and orientation.
- The earth-fixed reference frame (XE-YE-ZE) is assumed to be stationary and serves as a reference for absolute position and orientation. This frame is used to describe the AUV's motion relative to the surrounding environment.

The motion of the AUV is described with respect to the inertial reference frame, which provides a consistent framework for analyzing its behavior and interactions with the environment. In summary, mathematical modeling of an AUV involves understanding its kinematics and dynamics, which together provide a comprehensive description of its motion and behavior in underwater environments [17]. These models are essential tools for designing, simulating, and controlling AUVs for various applications.

Kinematics of AUVs

The kinematics of autonomous underwater vehicles (AUVs) describe their motion without considering the forces acting upon them. Understanding AUV kinematics is essential for tasks such as navigation, trajectory planning, and control system design. Here are some key aspects of AUV kinematics:

- *Degrees of freedom:* AUVs typically have six degrees of freedom (DOF) of motion, which include three translational DOF (surge, sway, heave) and three rotational DOF (roll, pitch, yaw). Surge refers to forward/backward motion, sway refers to lateral motion, and heave refers to vertical motion. Roll, pitch, and yaw correspond to rotations around the vehicle's longitudinal, transverse, and vertical axes, respectively.
- *Coordinate frames:* AUV kinematics are often described using a set of coordinate frames. The body-fixed frame (also known as the body frame or vehicle frame) is attached to the AUV and moves with it [18]. The inertial frame (or global frame) is fixed relative to the Earth and serves as a reference for absolute position and orientation.
- *Position and orientation:* The position of an AUV in 3D space is typically represented by its coordinates (x, y, z) in the inertial frame. Orientation is described using Euler angles (roll, pitch, yaw) or quaternion parameters, which specify the AUV's attitude relative to the inertial frame.
- *Velocity and acceleration:* AUV velocity describes the rate of change of position over time and includes both linear velocity (surge, sway, heave) and angular velocity (roll rate, pitch rate, yaw rate). Acceleration represents the rate of change of velocity and includes both linear acceleration and angular acceleration.
- *Differential kinematics:* Differential kinematics equations relate the AUV's velocity and angular velocity to its control inputs, such as thruster forces or control surface deflections. These equations describe how changes in control inputs affect the AUV's motion and are used in control system design and simulation.
- *Integration:* AUV kinematics are often integrated over time to compute the AUV's trajectory based on its initial conditions and control inputs. Integration techniques such as Euler integration or Runge-Kutta methods are used to numerically solve the differential equations of motion and predict the AUV's future position and orientation.
- *Constraints:* AUV kinematics may be subject to constraints imposed by the vehicle's physical limitations, such as maximum thruster forces, maximum angular rates, or geometric constraints. These constraints must be taken into account when designing control algorithms and planning trajectories to ensure safe and effective operation.

Understanding the kinematics of AUVs is essential for modeling their motion, designing control systems, and planning missions in underwater environments. By accurately describing how AUVs move and behave, engineers can develop effective strategies for navigating, exploring, and performing tasks in the ocean depths.

The dynamic equations describe the motion of the AUV in terms of its linear and angular velocities and the forces and torques acting upon it. These equations are derived from Newton's second law and Euler's equations of motion. Let us break down the equations given:

- *Linear Motion Equations*

$$m(\dot{u} - vr + wq + z_G(pr + \dot{q})) = X$$
$$m(\dot{v} - wp + ur + z_G(qr - \dot{p})) = Y$$
$$m\left(\dot{w} - uq + vp - z_G(p^2 + q^2)\right) = Z$$

Here, mass matrix (mm) is the mass of the AUV, u˙, v˙, and w˙ are the linear accelerations in the x, y, and z directions, respectively. u, v, and w are the linear velocities in the x, y, and z directions, respectively. p, q, and r are the angular velocities around the x, y, and z axes, respectively. X, Y, and Z are the hydrodynamic forces in the x, y, and z directions, respectively. zG is the distance from the center of gravity to the center of buoyancy.

- *Angular Motion Equations*

$$Ix\dot{p} + m(z_G(\dot{v} - wp + ur)) = K$$
$$Iy\dot{q} + (Ix - Iz)rp + m(z_G(\dot{u} - vr + wq)) = M$$
$$Iz\dot{r} + (Iy - Ix)pq = N$$

Here, Ix, Iy, and Iz are the moments of inertia of the AUV about the x, y, and z axes, respectively. K, M, and N are the torques about the x, y, and z axes, respectively.

These equations describe the complex interaction between the AUV's linear and angular motions and the forces and torques acting upon it. They are fundamental to understanding and modeling the dynamics of AUVs and are essential for designing control systems and predicting their behavior in underwater environments in Figure 5.

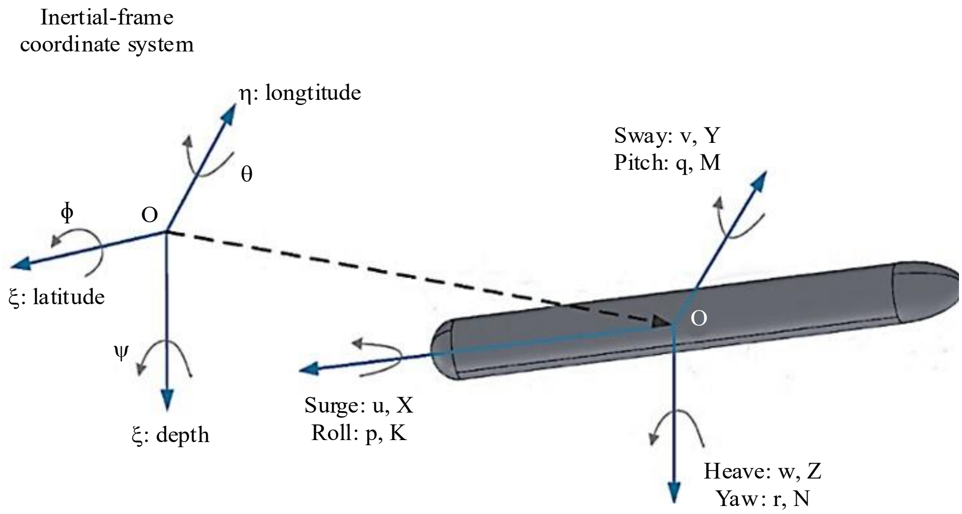

Figure 5. Reference frame for AUV motion.

Table 1 shows a summary of the notation used to describe the motion, forces, and moments of an Autonomous Underwater Vehicle (AUV).

Table 1. Notation for motion, forces, and moments of an autonomous underwater vehicle.

DOF	Motion/rotation	Forces/moments	Linear/angular velocities	Positions/Euler angles
1	In x-direction (surge)	XX	uu	xx
2	In y-direction (sway)	YY	vv	yy
3	In z-direction (heave)	ZZ	ww	zz
4	About x-axis (roll)	KK	pp	ϕϕ
5	About y-axis (pitch)	MM	qq	θθ
6	About z-axis (yaw)	NN	rr	ψψ

Note:

- *DOF (degrees of freedom): Indicates the specific motion or rotation being considered.*
- *Motion/rotation: Describes the direction or axis of motion or rotation.*
- *Forces/moments: Represents the forces or moments acting on the AUV corresponding to each degree of freedom.*
- *Linear/angular velocities: Denotes the linear or angular velocities associated with each degree of freedom.*
- *Positions/Euler angles: Refers to the positions or Euler angles that define the orientation of the AUV relative to a reference frame.*

This notation is commonly used in the analysis and modeling of AUV dynamics, providing a standardized framework for describing the vehicle's motion and dynamics. The hydrodynamic forces and moments of an AUV can be affected by various factors, including the turbulence generated by the propeller shown in Figure 6. The equations provided describe the hydrodynamic forces and moments acting on the AUV, considering the effects of propeller turbulence. Let us break down each equation:

Force Equations

- *X:* The force in the surge direction (xx) is composed of several terms:
- *Xuu|u|:* Hydrodynamic force due to surge velocity (u).
- *Xvrv:* Cross-coupling force due to the product of surge velocity (u), yaw rate (r), and sway velocity (v).
- *Xwqw:* Cross-coupling force due to the product of surge velocity (u), pitch rate (q), and heave velocity (w).
- $t_m K_{m n^2}$: Added mass force due to the product of mass factor (Km) and propeller speed (n) squared, with tm as a thrust deduction factor.
- *Y:* The force in the sway direction (y) is composed of several terms similar to X, including cross-coupling forces and added mass forces.
- *Z:* The force in the heave direction (z) is composed of several terms similar to X, including cross-coupling forces and added mass forces.

Moment Equations

- *K:* The moment around the roll axis (x) is composed of several terms:
- *Mvv˙:* Damping moment due to sway rate (v˙).
- *Mrr:* Damping moment due to yaw rate (r˙).
- *Mvv:* Cross-coupling moment due to sway velocity (v).
- *Mrr:* Cross-coupling moment due to yaw rate (r).
- *(1 - t_b^h) K_t^h n^2_b^h:* Added mass moment due to the product of mass factor (Kth) and propeller speed (nbh) squared, with tbh as a buoyancy deduction factor.
- *(1 - t_s^h) K_t^h n^2_s^h:* Added mass moment due to the product of mass factor (Kth) and propeller speed (nsh) squared, with tsh as a sinkage deduction factor.
- Similar terms apply to the moments M, and N.
- These equations describe the complex interaction between the AUV's motion and the hydrodynamic forces and moments acting upon it, including the effects of propeller turbulence. They are essential for understanding and modeling the dynamic behavior of AUVs and are fundamental to the design and control of these underwater vehicles.

Dynamics of AUVs

The dynamics of autonomous underwater vehicles (AUVs) describe how forces and torques affect their motion. Understanding AUV dynamics is crucial for designing control systems, predicting their behavior, and optimizing their performance. Here are key aspects of AUV dynamics:

- *Rigid-body dynamics:* Rigid-body dynamics deals with the motion of the AUV as a whole, considering its mass distribution and rotational inertia. This includes equations of motion for translational motion (surge, sway, heave) and rotational motion (roll, pitch, yaw). The dynamics of AUVs are typically described using Newton-Euler equations, which relate forces and torques to linear and angular accelerations.
- *Forces and torques:* AUV dynamics consider various forces and torques acting on the vehicle:
  - *Hydrodynamic Forces:* Forces due to the interaction of the AUV with the surrounding water, including drag, lift, and added mass effects. These forces depend on the vehicle's shape, speed, and orientation.
  - *Control forces:* Forces generated by thrusters or control surfaces to maneuver the AUV. These forces are used to regulate its motion and achieve desired trajectories.
  - *Buoyancy forces:* Forces due to the displacement of water by the AUV, which contribute to its overall stability and buoyancy.

  - *Environmental forces:* Forces from external factors such as ocean currents, waves, and underwater obstacles, which can affect the AUV's motion.
  - *Torques:* Moments that cause rotational motion around the AUV's center of mass, including moments generated by control surfaces, thrusters, and hydrodynamic effects.
- *Equations of motion:* The dynamics of AUVs are governed by a set of differential equations that describe how forces and torques influence their motion. These equations include terms for linear and angular acceleration, inertia, hydrodynamic coefficients, and control inputs. Solving these equations allows engineers to predict the AUV's trajectory and behavior under different operating conditions.
- *Modeling complexity:* Modeling AUV dynamics can be complex due to nonlinearities, uncertainties, and environmental factors. Hydrodynamic coefficients, for example, may vary with speed, depth, and vehicle orientation, requiring empirical data or computational fluid dynamics (CFD) simulations for accurate estimation. Control system design must also account for the coupling between translational and rotational motion and the interaction between control inputs and environmental disturbances.

Understanding the dynamics of AUVs is essential for developing effective control strategies, optimizing vehicle performance, and ensuring safe and reliable operation in diverse underwater environments. By accurately modeling AUV dynamics, engineers can design vehicles that meet the requirements of specific missions and applications, from marine research and exploration to underwater surveillance and infrastructure inspection. The dynamics of an Autonomous Underwater Vehicle (AUV) are typically formulated in a body-fixed reference frame and derived using the Newton-Euler formulation scheme. The dynamics equation is expressed as:

$$M\dot{\nu}+C(\nu)\nu+D(\nu)\nu+G(\eta)=\tau$$

Where:

- M is the inertia matrix of the vehicle, which includes both the rigid body mass matrix M_{RB} and the hydrodynamic added mass M_A.
- $\dot{\nu}$ represents the time derivative of the velocity vector.
- C(ν) is the sum of matrices of rigid-body Coriolis and centripetal forces $C_{RB}(\nu)$ and hydrodynamic Coriolis and centripetal forces $C_A(\nu)$.
- D(ν) is the hydrodynamic damping matrix, including both linear $D_L(\nu)$ and nonlinear $D_Q|\nu|$ terms.
- G(η) is a vector of restoring forces and moments, which represent the forces and moments acting on the AUV due to its buoyancy and other environmental factors.
- τ is the control input vector, describing the forces and moments applied to the AUV. It is typically divided into two components: τ1 for forces (surge, sway, heave) and τ2 for moments (roll, pitch, yaw).

The equation describes how the dynamics of the AUV are influenced by various factors, including its mass distribution, hydrodynamic effects, external forces, and control inputs. By solving this equation, engineers can predict the AUV's motion and behavior under different operating conditions and design control strategies to achieve desired trajectories and performance.

Equations of Dynamic AUV

$$M_{RB}=\begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_x & -I_{xy} & -I_{xx} \\ mz_G & 0 & -mx_G & -I_{yx} & I_y & -I_{yz} \\ -my_G & mx_G & 0 & -I_{zx} & -I_{xy} & I_z \end{bmatrix},$$

$$M_A = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix}$$

$$C_{RB} = \begin{bmatrix} 0 & 0 & 0 & m(y_G q + z_G r) \\ 0 & 0 & 0 & -m(y_G p + w) \\ 0 & 0 & 0 & -m(z_G p - v) \\ -m(y_G q + z_G r) & m(y_G p + w) & m(z_G p - v) & 0 \\ m(x_G q - w) & -m(z_G r + x_G p) & m(z_G q + u) & I_{yz} q + I_{xz} p - I_z r \\ m(x_G r + v) & m(y_G r - u) & -m(x_G p + y_G q) & -I_{yz} r - I_{xy} p + I_y q \\ -m(x_G q - r) & & & -m(x_G r + v) \\ m(z_G r + x_G p) & & & -m(y_G r - u) \\ -m(z_G q + u) & & & m(x_G p + y_G q) \\ -I_{yz} q - I_{xz} p + I_z r & & & I_{yz} r + I_{xy} p - I_y q \\ 0 & & & -I_{xz} r - I_{xy} q + I_x p \end{bmatrix}$$

$$C_A = \begin{bmatrix} 0 & 0 & 0 & 0 & -a_3 & a_2 \\ 0 & 0 & 0 & I_{xz} r + I_{xy} q - I_x p & 0 & -a_1 \\ 0 & 0 & 0 & -a_2 & a_1 & 0 \\ 0 & -a_3 & a_2 & 0 & -b_3 & b_2 \\ a_3 & 0 & -a_1 & b_3 & 0 & -b_1 \\ -a_2 & a_1 & 0 & -b_2 & b_1 & 0 \end{bmatrix}$$

where

$$a_1 = X_{\dot{u}} u + X_{\dot{v}} v + X_{\dot{w}} w + X_{\dot{p}} p + X_{\dot{q}} q + X_{\dot{r}} r$$
$$a_2 = X_{\dot{u}} u + Y_{\dot{v}} v + Y_{\dot{w}} w + Y_{\dot{p}} p + Y_{\dot{q}} q + Y_{\dot{r}} r$$
$$a_3 = X_{\dot{u}} u + Y_{\dot{v}} v + Z_{\dot{w}} w + Z_{\dot{p}} p + Z_{\dot{q}} q + Z_{\dot{r}} r$$
$$b_1 = X_{\dot{u}} u + Y_{\dot{v}} v + Z_{\dot{w}} w + K_{\dot{p}} p + K_{\dot{q}} q + K_{\dot{r}} r$$
$$b_2 = X_{\dot{u}} u + Y_{\dot{v}} v + Z_{\dot{w}} w + K_{\dot{p}} p + M_{\dot{q}} q + M_{\dot{r}} r$$
$$b_3 = X_{\dot{u}} u + Y_{\dot{v}} v + Z_{\dot{w}} w + K_{\dot{p}} p + M_{\dot{q}} q + N_{\dot{r}} r$$

$$D_L = \begin{bmatrix} X_u & X_v & X_w & X_p & X_q & X_r \\ Y_u & Y_v & Y_w & Y_p & Y_q & Y_r \\ Z_u & Z_v & Z_w & Z_p & Z_q & Z_r \\ K_u & K_v & K_w & K_p & K_q & K_r \\ M_u & M_v & M_w & M_p & M_q & M_r \\ N_u & N_v & N_w & N_p & N_q & N_r \end{bmatrix}$$

$$D_Q(v) = \begin{bmatrix} X_{|u|u} & X_{|v|v} & X_{|w|w} & X_{|p|p} & X_{|q|q} & X_{|r|r} \\ Y_{|u|u} & Y_{|v|v} & Z_{|w|w} & Z_{|p|p} & Z_{|q|q} & Z_{|r|r} \\ Z_{|u|u} & Z_{|v|v} & Z_{|w|w} & Z_{|p|p} & Z_{|q|q} & Z_{|r|r} \\ K_{|u|u} & K_{|v|v} & K_{|w|w} & K_{|p|p} & K_{|q|q} & K_{|r|r} \\ M_{|u|u} & M_{|v|v} & M_{|w|w} & M_{|p|p} & M_{|q|q} & M_{|r|r} \\ N_{|u|u} & N_{|v|v} & N_{|w|w} & N_{|p|p} & N_{|q|q} & N_{|r|r} \end{bmatrix}$$

$$g(\eta) = \begin{bmatrix} (W-B)\sin\theta \\ -(W-B)\cos\theta\sin\phi \\ -(W-B)\cos\theta\cos\phi \\ -(y_G W - y_B B)\cos\theta\cos\phi + (z_G W - z_B B)\cos\theta\sin\phi \\ (z_G W - z_B B)\sin\theta + (x_G W - x_B B)\cos\theta\cos\phi \\ -(x_G W - x_B B)\cos\theta\sin\phi - (y_G W - y_B B)\sin\theta \end{bmatrix}$$

To design a controller for an Autonomous Underwater Vehicle (AUV) and analyze its stability in a closed-loop system, it is often preferable to work in an earth-fixed reference frame. This ensures that every state of the AUV is maintained with respect to a single reference frame, simplifying the control design process and facilitating stability analysis. The dynamics of an AUV in an earth-fixed representation can be obtained by applying kinematic transformations to the equations of motion. These transformations allow dynamics to be expressed in terms of variables referenced to the earth-fixed frame, rather than the body-fixed frame. The transformation equations typically involve rotations and translations to account for the relative motion between the two frames. The specific form of the kinematic transformations depends on the orientation and position of the AUV relative to the earth-fixed frame. These transformations are often represented by rotation matrices or quaternion representations, which allow for efficient computation and accurate representation of orientation. Once the dynamics of the AUV are expressed in the earth-fixed reference frame, controllers can be designed to regulate its motion and achieve desired objectives such as trajectory tracking, path following, or stabilization [19, 20]. Closed-loop stability analysis techniques can then be applied to analyze the stability of the controlled system and ensure that it behaves predictably under various operating conditions. Overall, working in the earth-fixed reference frame simplifies control design and stability analysis for AUVs, allowing for more efficient and effective control strategies to be developed.

$$M_n(\eta)\ddot{\eta} + C_\eta(v,\eta)\dot{\eta} + D_\eta(v,\eta)\dot{\eta} + G_\eta(\eta) = T_\eta$$

where

$$\begin{aligned} M_\eta(\eta) &= J^{-T}(\eta)MJ^{-1}(\eta) \\ C_\eta(v,\eta) &= J^{-T}(\eta)[C(v) - MJ^{-1}(\eta)\dot{J}(\eta)]J^{-1}(\eta) \\ D_\eta(v,\eta) &= J^{-T}(\eta)D(v)J^{-1}(\eta) \\ G_\eta(\eta) &= J^{-T}(\eta)G(\eta) \\ \tau_\eta(\eta) &= J^{-T}(\eta)\tau \end{aligned}$$

Expressing the dynamics of an autonomous underwater vehicle (AUV) in an earth-fixed vector representation offers several advantages and properties regarding the finite-dimensional system dynamics:

- *Consistency with earth frame:* By working in the earth-fixed reference frame, the AUV's dynamics are consistent with the fixed frame of reference provided by the Earth. This simplifies the interpretation of the AUV's motion and facilitates communication with other Earth-based systems.
- *Simplified control design:* Designing controllers in the earth-fixed frame simplifies the control design process. It allows for controllers to be developed based on the AUV's position and orientation relative to fixed landmarks or reference points on the Earth's surface.
- *Stability analysis:* Stability analysis of the AUV's dynamics becomes more straightforward when expressed in the earth-fixed reference frame. Stability properties such as asymptotic stability, boundedness, and robustness can be analyzed using standard stability analysis techniques.
- *Trajectory planning:* Trajectory planning and path following become more intuitive when working in the earth-fixed frame. Desired trajectories can be defined relative to fixed points or features on the Earth's surface, allowing for more natural and meaningful planning.

- *Navigation and localization:* Navigation and localization algorithms can leverage the fixed reference frame provided by the Earth to estimate the AUV's position and orientation accurately. This enables precise navigation and localization even in challenging underwater environments.
- *Sensor fusion:* Sensor fusion techniques, such as integrating data from GPS, inertial sensors, and sonar systems, can be performed more effectively when working in the earth-fixed reference frame. Fusion algorithms can combine information from various sensors to improve the accuracy and reliability of state estimation.

Expressing the dynamics of an AUV in an earth-fixed vector representation enhances its compatibility with Earth-based systems, simplifies control design and stability analysis, and facilitates navigation, localization, and sensor fusion algorithms. These properties contribute to the effective operation of AUVs in real-world applications, including marine research, underwater exploration, and environmental monitoring.

Subsystem Structure of AUVs

The subsystem structure of autonomous underwater vehicles (AUVs) refers to the decomposition of the vehicle's overall functionality into distinct subsystems, each responsible for specific tasks or functionalities. This decomposition allows for a modular design approach, simplifies system analysis, and facilitates maintenance and upgrades. The subsystem structure of AUVs typically includes the following components:

- *Power and energy management:* This subsystem is responsible for managing the power supply and energy consumption of the AUV. It includes components such as batteries, power converters, and energy-efficient systems to ensure the AUV's sustained operation.
- *Propulsion system:* The propulsion subsystem is responsible for generating thrust to propel the AUV through the water. It includes thrusters, propellers, motors, and control mechanisms for maneuvering and controlling the vehicle's speed and direction.
- *Navigation and control:* This subsystem encompasses sensors, actuators, and control algorithms for navigating the AUV autonomously. It includes components such as inertial measurement units (IMUs), GPS receivers, depth sensors, sonar systems, and control software for autonomous navigation, obstacle avoidance, and path planning.
- *Communication system:* The communication subsystem enables the AUV to communicate with external operators or other vehicles. It includes communication devices such as acoustic modems, radio transceivers, and antennas for transmitting data, commands, and status updates.
- *Sensing and perception:* This subsystem consists of sensors and perception algorithms for collecting data about the AUV's environment. It includes sensors such as cameras, sonars, hydrophones, and environmental sensors for detecting obstacles, mapping the underwater terrain, and monitoring water quality.
- *Payload and mission-specific equipment:* The payload subsystem includes mission-specific equipment, scientific instruments, and payload modules tailored to the AUV's intended applications. It may include devices for oceanographic research, underwater inspections, marine biology studies, or search and rescue operations.
- *Mechanical structure and Hull Design:* The mechanical structure subsystem comprises the physical framework, hull design, and mechanical components of the AUV. It includes materials, structural elements, sealing mechanisms, and pressure housings to ensure the AUV's structural integrity and durability in harsh underwater environments.
- *Environmental sensing and monitoring:* This subsystem focuses on monitoring environmental conditions such as temperature, pressure, salinity, and water currents. It includes sensors and data acquisition systems for gathering environmental data to support scientific research, environmental monitoring, and habitat mapping.

By organizing the AUV's functionality into distinct subsystems, designers and engineers can manage complexity, optimize performance, enhance reliability, and maintainability. This modular approach also facilitates the integration of new technologies, upgrades, and customization to meet evolving mission requirements and operational needs.

In this work, the dynamic modeling of an Autonomous Underwater Vehicle Manipulator System (AUV) is derived using both Newton-Euler and recursive Newton-Euler formulation schemes. The frame assignment of the AUVMS is illustrated in Figure 6, where, Ixyz is the Earth-fixed (inertial) frame, Bxyz is the vehicle body-fixed (moving) frame, Exyz is the manipulator end effector frame, and Mxyz is the manipulator base frame.

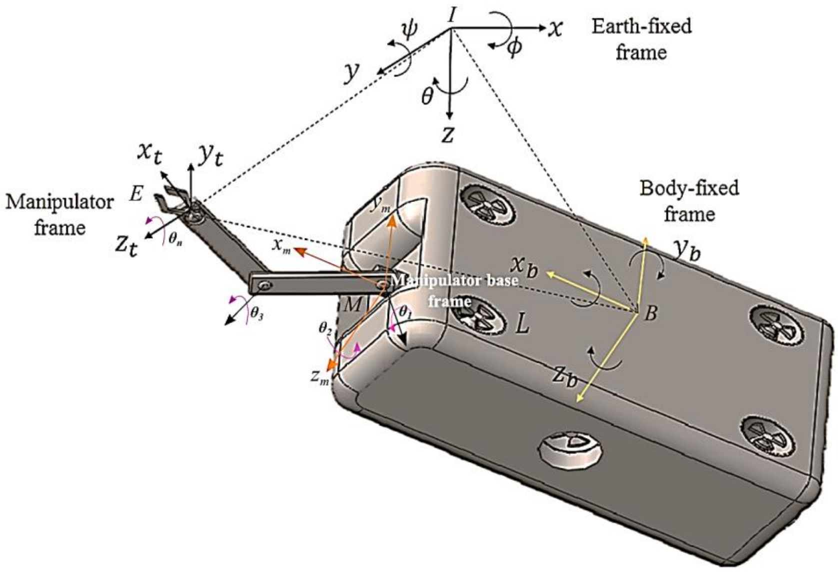

Figure 6. Coordinate frame arrangement of an AUV.

The dynamic equations of motion in the inertial (Earth-fixed reference) frame of an AUV can be expressed as follows:

$$M(q)\dot{q}+C(q,\dot{q})\dot{q}+D(q,\dot{q})\dot{q}+G(q)+F(q,\dot{q})=\tau_t+\tau_{dis}$$

Where:

- q represents the generalized coordinates (e.g., joint angles) of the manipulator, corresponding generalized velocities,
- M(q) is the inertia matrix,
- $C(q,\dot{q})$ represents the Coriolis and centrifugal forces matrix,
- $D(q,\dot{q})$ represents the damping matrix,
- G(q) represents the gravity vector,
- $F(q,\dot{q})$ represents the friction forces,
- T_t represents the control torque inputs, and
- τ_{dis} represents the disturbance torque inputs.

These equations govern the dynamic behavior of the AUV manipulator system, taking into account inertia, Coriolis and centrifugal effects, damping, gravity, friction, as well as control and disturbance torques. The formulation allows for a comprehensive representation of the system's dynamics, essential for accurate modeling and control design.

The subdivision of the 6-DOF linear equations of motion into three non-interacting subsystems: speed, steering, and diving control, represents a modular approach to controlling the motion of an autonomous underwater vehicle (AUV). This decomposition allows for separate control strategies to be developed for each aspect of the AUV's motion, simplifying the control design process and enhancing maneuverability. Here is a breakdown of each subsystem and its associated state variables:

Speed System State

- *State variable:* u(t)
- *Description:* This subsystem focuses on controlling the forward speed of the AUV along its longitudinal axis (surge motion). By regulating u(t), the AUV's velocity can be controlled to achieve desired speeds or maintain a constant velocity.

Steering System States

- *State variables:* v(t), r(t), ψ(t)
- *Description:* This subsystem is responsible for controlling the lateral motion (sway) and rotational motion (yaw) of the AUV, as well as its heading angle. By controlling v(t)v(t), r(t)r(t), and ψ(t)ψ(t), the AUV's trajectory can be adjusted to follow desired paths or headings.

Diving System States

- *State variables:* w(t), q(t), θ(t), z(t)
- *Description:* This subsystem focuses on controlling the vertical motion (heave), pitch, pitch rate, and depth of the AUV. By regulating w(t), q(t), θ(t), and z(t), the AUV's depth and orientation relative to the water surface can be controlled.

In this approach, the rolling mode (roll motion) represented by p(t) and ϕ(t) is left passive, meaning it is not actively controlled. This decision is influenced by the slender form of the AUV used as the basis for this work. The above three subsystems can be controlled using two single-screw propellers with revolution n(t), a rudder with deflection δr(t), and a stern plane with deflection δs(t). This choice of actuators is inspired by control systems used in flight and submarine applications and provides an effective means for controlling the AUV's speed, steering, and diving motions. By decomposing the AUV's motion into these subsystems and selecting appropriate actuators, control strategies can be developed to achieve desired performance and maneuverability in various operating conditions and mission scenarios.

Dynamic Modeling of AUVs

Dynamic modeling of autonomous underwater vehicles (AUVs) involves describing the motion of the vehicle in response to various forces and torques acting upon it. This modeling is essential for understanding the vehicle's behavior, designing control systems, and predicting its performance under different conditions. There are several approaches to dynamic modeling of AUVs, including:

- *Newton-Euler formulation:* This approach applies to Newton's laws of motion and Euler's equations to derive the equations of motion for the AUV. It involves analyzing the forces and torques acting on each component of the vehicle and integrating them to obtain the overall dynamics. This method provides a detailed understanding of the vehicle's motion but can be complex, especially for AUVs with complex geometries or dynamics.
- *Recursive Newton-Euler formulation:* This method extends the Newton-Euler formulation by using recursive algorithms to compute the dynamics efficiently. It recursively propagates the forces and torques through the kinematic chain of the AUV, allowing for real-time computation of the vehicle's dynamics. This approach is particularly useful for real-time control and simulation applications.
- *Lagrangian mechanics:* Lagrangian mechanics provides an alternative approach to dynamic modeling by formulating the equations of motion based on the system's kinetic and potential energies. It involves defining a Lagrangian function for the system and applying the principle of least action to derive the equations of motion. This method can simplify the modeling process for certain types of AUVs and is well-suited for studying the system's energy behavior.

- *Hydrodynamic modeling:* AUVs operate in a fluid environment, and hydrodynamic forces play a crucial role in their dynamics. Hydrodynamic modeling involves characterizing the forces and moments exerted on the AUV by the surrounding water. This typically includes contributions from drag, buoyancy, added mass, and hydrodynamic interactions with the seabed or nearby objects. Hydrodynamic models are often combined with other dynamic modeling approaches to provide a comprehensive understanding of the AUV's behavior.
- *Control-oriented modeling:* In addition to predicting the AUV's motion, dynamic modeling can also be used to design control systems for regulating its behavior. Control-oriented models focus on capturing the essential dynamics relevant to control design, often simplifying the system's complexity to facilitate controller synthesis and analysis.

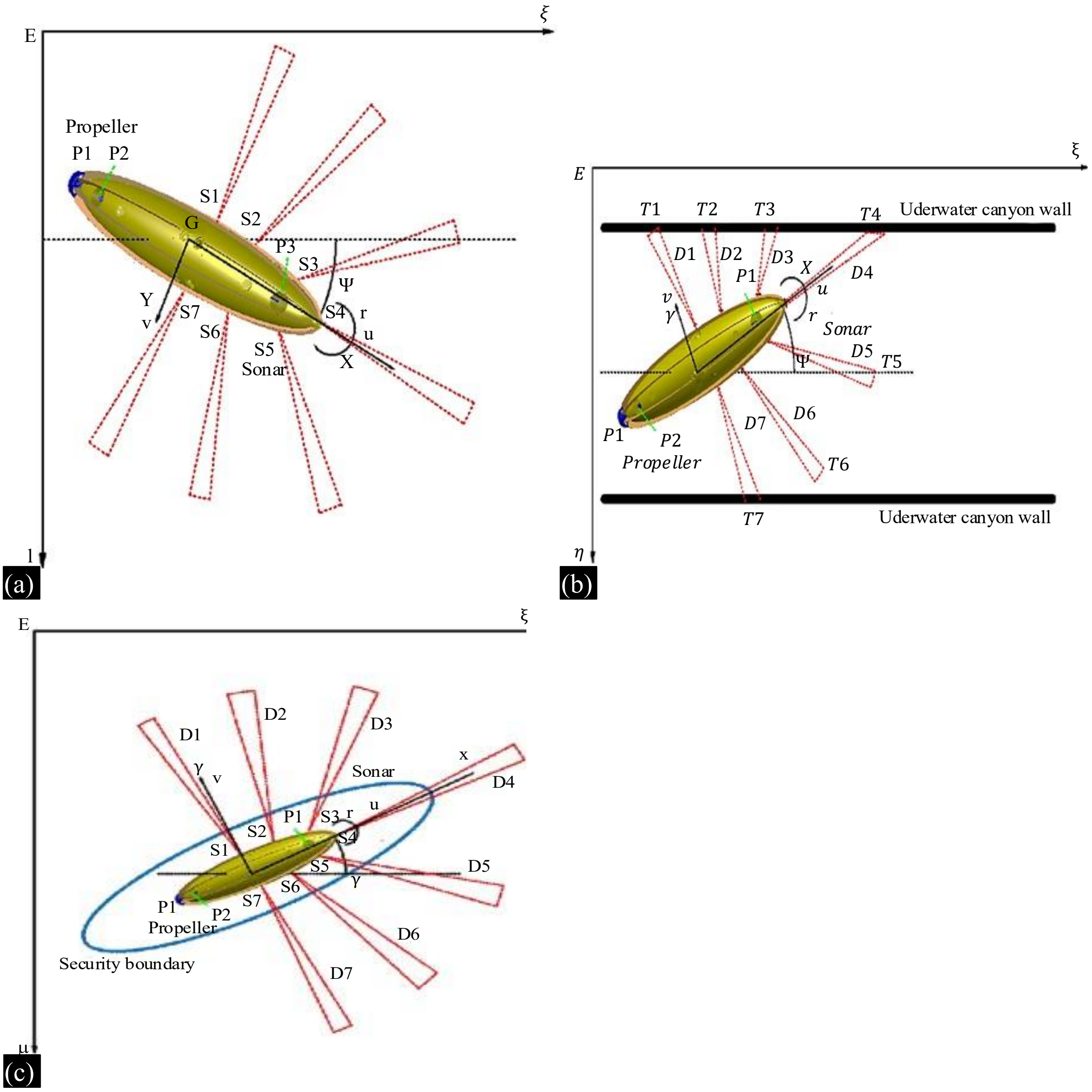

Figure 7. (a)–(c) The geometric dynamics of AUV.

Dynamic modeling of AUVs is a multidisciplinary endeavor that draws upon principles from mechanics, fluid dynamics, control theory, and numerical methods. By accurately capturing the vehicle's dynamics, these models enable engineers to design AUVs that are capable of performing complex tasks in challenging underwater environments as shown in Figure 7.

- Surge Motion

$$m\left[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})\right] = X$$

- Sway Motion

$$m\left[\dot{v} - wp + ur - y_g(p^2 + r^2) + z_g(qr - \dot{p}) + x_g(pq + \dot{r})\right] = Y$$

- Heave Motion

$$m\left[\dot{w} - uq + vp - z_g(q^2 + p^2) + x_g(pr - \dot{q}) + y_g(qr + \dot{p})\right] = Z$$

- Roll Motion

$$I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m\left[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)\right] = K$$

- Pitch Motion

$$I_y\dot{q} + (I_x - I_z)pr - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz} + m\left[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)\right] = M$$

- Yaw Motion

$$I_z\dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx} + m\left[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)\right] = N$$

The various hydrostatic forces, added mass terms, propeller thrust, lift force, and drag force components relevant to the dynamics of an AUV. Here is a breakdown of each term:

- *Hydrostatic Force (XHS, YHS, ZHS, KHS, MHS, NHS)*
  - These forces arise from the static pressure distribution acting on the AUV's submerged hull. They typically include forces in the X, Y, and Z directions (surge, sway, and heave) as well as moments about the body-fixed axes (roll, pitch, and yaw).
- *Added Mass Terms (Ẋu, Ẏv, Żw, K̇p, Ṁw, Ẏr, Żq, Ṁq, Ṅv, Ṅr):*
  - Added mass refers to the virtual mass that an AUV experiences due to the inertia of water displaced by its motion. These terms represent the rate of change of added mass with respect to the corresponding velocity or angular velocity components. They contribute to the dynamic response of the AUV and are typically incorporated into the system's equations of motion.
- *Propeller Thrust (Xprop)*
  - This term represents the thrust generated by the propeller(s) of the AUV. It contributes to the overall propulsion force and affects the AUV's motion in the surge direction.
- *Lift Force (Zuuδs, Yuuδr, Nuuδr)*
  - These terms represent the lift forces generated by the stern planes (horizontal fins) of the AUV. They are typically functions of the control inputs (e.g., deflection angles δs and δr) and contribute to the AUV's motion, particularly in the heave and yaw directions.
- *Drag Force (Mww, Mqq, Xuu, Yvv):*
  - Drag forces arise due to the resistance of the water against the AUV's motion. These terms represent the drag forces acting on the AUV in the roll, pitch, surge, and sway directions. They oppose the motion of the AUV and affect its velocity components.

These forces and moments play crucial roles in the dynamic modeling and control of AUVs, influencing their motion and stability in underwater environments. Proper understanding and modeling of these terms are essential for designing effective control strategies and optimizing the performance of AUVs in various missions and operating conditions. In this study, the AUV relies on its sonar system to detect dynamic obstacles in its environment. When a dynamic obstacle is detected by the sonar, the AUV determines whether the obstacle is within its repulsive force field. If the obstacle is outside the scope of the AUV's repulsive force field, the AUV is considered safe, and no further action is taken. However, if the dynamic obstacle enters the repulsion field of the AUV, the AUV initiates avoidance maneuvers. This involves continuously adjusting its heading angle and navigation speed to avoid collisions with the obstacle. The AUV dynamically modifies its trajectory to steer clear of the obstacle and maintain a safe distance. It is important to note that this study does not delve into the details of processing techniques, such as kinematic modeling, for predicting and estimating dynamic obstacles. Instead, the focus is on the reactive behavior of the AUV when encountering obstacles. The AUV responds in real-time to the presence of dynamic obstacles by adjusting its course to prevent collisions. If the dynamic obstacle remains within the repulsion potential field of the AUV and the distance between the obstacle and the AUV decreases to a critical threshold known as the safe distance, the AUV faces a collision risk. In such a scenario, further collision avoidance measures are required to prevent a potential collision.

Linearizing an Autonomous Underwater Vehicle Model

Linearizing an autonomous underwater vehicle (AUV) model involves approximating the nonlinear dynamics of the system with a linear representation around an operating point. This linear model is useful for control system design and analysis, as linear control techniques can often be applied to stabilize and regulate the AUV's behavior.

The process of linearization typically involves the following steps:

- *Choose an operating point:* Select a nominal operating point around which the system will be linearized. This point should represent a typical operating condition for the AUV.
- *Define state variables:* Identify the state variables that describe the AUV's behavior. These may include position, velocity, orientation, and rates of change of these quantities.
- *Linearize dynamics:* Linearize the nonlinear dynamic equations of motion of the AUV around the chosen operating point. This can be done using methods such as Taylor series expansion or linearization of nonlinear functions.
- *Linearize sensor models:* If the AUV is equipped with sensors, linearize their measurement models around the operating point. This step is essential if the linearized model will be used for sensor-based feedback control.
- *Derive state-space representation:* Express the linearized dynamics in state-space form, which consists of a set of first-order ordinary differential equations. The state-space representation includes state equations that describe how the state variables evolve over time and output equations that relate the state variables to sensor measurements.
- *Linearize control inputs:* If the AUV is controlled using actuators, linearize their effects on the system dynamics. This step is necessary for designing feedback control laws that stabilize and regulate the AUV.
- *Verify validity:* Validate the linearized model by comparing its predictions to the behavior of the nonlinear system over a range of operating conditions. Ensure that the linearized model accurately captures the essential dynamics of the AUV.

Once the linearized model is derived and validated, it can be used for various control system design tasks, such as designing stabilizing controllers, trajectory tracking controllers, and state estimators. Additionally, linearized models are often used for stability analysis to determine the robustness of the AUV's control system against disturbances and parameter uncertainties.

Linear Model of the AUV Dynamics in the Horizontal Plane

To derive a linear model of the AUV dynamics in the horizontal plane, we typically start with the equations of motion for the AUV. In the horizontal plane, we consider the surge (motion along the x-axis) and sway (motion along the y-axis) dynamics. Assuming small perturbations around an operating point, we can linearize these equations to obtain a linearized model. Here is a general outline of the process:

- *Equations of motion:* Start with the nonlinear equations of motion for the AUV in the horizontal plane. These equations will include terms representing hydrodynamic forces, control inputs, and external disturbances. The general form of the equations will be:

  $$\dot{\nu}=M^{-1}(C(\nu)\nu+D(\nu)\nu+G(\eta)+B\tau)$$

  Where:
  ν is the velocity vector (surge and sway).
  η is the pose vector (position and orientation).
  M is the mass matrix.
  C is the Coriolis matrix.
  D is the damping matrix.
  G is the gravitational and buoyancy vector.
  B is the control input matrix.
  τ is the control input vector.
- *Linearization:* Linearize the equations of motion around an operating point. Typically, this involves neglecting higher-order terms and approximating nonlinear functions as linear functions near the operating point.
- *State-space representation:* Express the linearized equations in state-space form. Define state variables (e.g., surge velocity, sway velocity) and write the dynamics as a set of first-order ordinary differential equations.
- *Stability analysis:* Analyze the stability of the linearized system. This can involve techniques such as eigenvalue analysis to determine the poles of the system and assess stability properties.
- *Controller design:* Once the linear model is obtained, design a controller using linear control techniques such as PID control, state feedback control, or LQR control. The controller aims to stabilize the AUV and achieve desired performance objectives.
- *Simulation and validation:* Simulate the linear model to verify its behavior and validate the effectiveness of the designed controller. Adjust controller parameters as needed to achieve the desired performance.

By following these steps, you can develop a linear model of the AUV dynamics in the horizontal plane and design a controller to regulate its motion. This linear model can then be used for analysis, simulation, and control design purposes. Given the assumptions mentioned, we can simplify the dynamics of the AUV in the horizontal plane or yaw steering plane. Here is how we can derive the linearized model:

- *Origin at center of gravity:* With the origin at the center of gravity, we assume that the linearized model is developed around the equilibrium point where the AUV is balanced and aligned with the desired heading.
- *Constant forward velocity:* Assuming the forward velocity u0u0 is constant implies that we are considering small deviations from this constant velocity. This assumption simplifies the dynamics as we don't need to consider variations in the forward velocity in the linearized model.
- *Null diving plane states:* Setting the state vectors related to the diving plane (surge velocity ww, roll rate pp, pitch rate qq, roll angle ϕϕ, pitch angle θθ) to zero means we are neglecting vertical motion and rotation about the roll and pitch axes. This simplification is reasonable if we are focusing solely on sway (motion along the y-axis) and yaw (rotation about the z-axis) dynamics.

With these assumptions, the rigid-body dynamics of the AUV in sway (motion along the y-axis) and yaw (rotation about the z-axis) can be simplified. The resulting linearized model will likely involve equations describing the relationship between lateral forces (e.g., hydrodynamic forces, control inputs) and lateral motion (sway) and between yaw moments (e.g., control moments) and yaw motion (rotation).

The linearized model can then be expressed in state-space form as:

$$x^{\cdot}=Ax+Bux^{\cdot}$$

Where:

- x is the state vector representing sway motion and yaw rotation.
- u is the control input vector.
- A is the system matrix describing the dynamics of the system.
- B is the input matrix relating control inputs to changes in the state variables.

This simplified linear model can then be used for control design and analysis, particularly for designing controllers to regulate the heading of the AUV.

Linear Model of the AUV Dynamics in the Vertical Plane

To derive a linear model of the AUV dynamics in the vertical plane, or heave plane, we will make similar assumptions as we did for the horizontal plane:

1. *Origin at center of gravity:* As before, we will assume that the origin of the coordinate system is located at the center of gravity of the AUV.
2. *Constant forward velocity:* We will maintain the assumption of a constant forward velocity (u0u0) to simplify the dynamics.
3. *Null horizontal plane states:* Now, we will set the state vectors related to the horizontal plane (sway velocity (vv), roll rate (pp), roll angle (ϕϕ)) to zero, assuming no lateral motion or roll motion.

With these assumptions, the rigid-body dynamics of the AUV in heave (motion along the z-axis) and pitch (rotation about the y-axis) can be simplified. The resulting linearized model will likely involve equations describing the relationship between vertical forces (e.g., buoyancy, hydrodynamic forces) and vertical motion (heave) and between pitch moments (e.g., control moments) and pitch motion (rotation). Similar to the horizontal plane, the linearized model in the vertical plane can be expressed in state-space form:

$$x^{\cdot}=Ax+Bux^{\cdot}$$

Where:

- x is the state vector representing heave motion and pitch rotation.
- u is the control input vector.
- A is the system matrix describing the dynamics of the system.
- B is the input matrix relating control inputs to changes in the state variables.

This linear model can then be used for control design and analysis, particularly for designing controllers to regulate the depth and pitch of the AUV. In the simplified AUV rigid-body equations of motion in heave (vertical motion) and pitch (rotation about the lateral axis), the assumptions mentioned lead to a simplified dynamic model. Specifically, considering the deflection of the stern planes for control of depth errors, the corresponding pitch moment is altered, resulting in changes to the pitch angle of the AUV, thereby affecting its depth.

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The linearized model in the vertical plane, or pitch diving plane, can be represented as:

$$x^{\cdot}=Ax+Bux^{\cdot}$$

Where:

- $x^{\cdot}$ is the rate of change of the state vector xx, representing heave motion and pitch rotation.
- u is the control input vector, which in this case may represent the deflection of the stern planes.
- A is the system matrix describing the dynamics of the system, incorporating the effects of heave and pitch motion.
- B is the input matrix relating control inputs to changes in the state variables, specifically how the deflection of the stern planes influences heave and pitch.

This linearized model simplifies the complex dynamics of the AUV in the vertical plane, allowing for control design and analysis to regulate depth and pitch during underwater operations. The assumptions made enable a focused approach to understanding and controlling the AUV's behavior in these specific motion modes.

Control Techniques for AUVs

Control strategies play a crucial role in ensuring the successful operation of autonomous underwater vehicles (AUVs), particularly in accurately tracking desired trajectories. Accurate trajectory tracking is essential for AUV missions to achieve specific objectives such as surveying, mapping, inspection, or environmental monitoring. Maintaining precise control over the AUV's position and orientation is critical for navigating through complex underwater environments, avoiding obstacles, and reaching target locations. Performance metrics such as tracking error, control effort, convergence rate, and stability margins are used to assess the effectiveness of control strategies in achieving desired trajectory tracking performance. In summary, selecting the appropriate control strategy for AUV trajectory tracking depends on factors such as mission requirements, system dynamics, environmental conditions, and desired performance criteria. Each control approach has its strengths and limitations, and the choice of strategy should be based on the specific characteristics and objectives of the AUV mission, as shown in Figure 8.

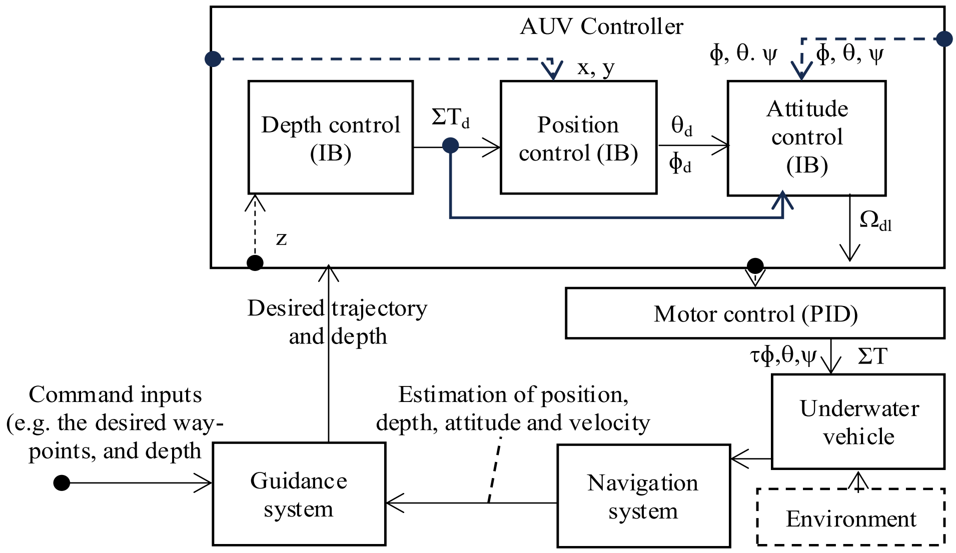

Figure 8. Control techniques for autonomous underwater vehicles.

Conventional Control Techniques for Autonomous Underwater Vehicles

Conventional control techniques for autonomous underwater vehicles (AUVs) play a crucial role in ensuring their efficient and safe operation in various underwater environments. Several control methods and strategies have been developed and utilized to address the challenges associated with AUV motion control, navigation, as shown in Figure 8, and mission execution. Some of the prominent control techniques for AUVs include:

- *PID control:* Proportional-Integral-Derivative (PID) control is a widely used control technique that provides simple yet effective control by adjusting the output based on the proportional, integral, and derivative terms of the error signal. PID controllers are often employed for basic motion control tasks such as depth keeping, heading control, and trajectory tracking.
- *Model predictive control (MPC):* MPC is an advanced control technique that utilizes a dynamic model of the system to predict future behavior and optimize control inputs over a finite time horizon. MPC considers constraints on control inputs and system states, making it suitable for AUVs operating in constrained environments or performing complex maneuvers.
- *Adaptive control:* Adaptive control techniques adjust controller parameters based on the system's changing dynamics or environmental conditions. These techniques enable AUVs to adapt to variations in hydrodynamic forces, actuator dynamics, or disturbances encountered during operation, enhancing robustness and performance.
- *Sliding mode control (SMC):* SMC is a robust control technique that aims to drive the system states to a sliding surface, where they are controlled using discontinuous control laws. SMC is well-suited for AUVs operating in the presence of uncertainties, disturbances, or nonlinearities, providing robust performance and stability guarantees.
- *Optimal control:* Optimal control techniques, such as Linear Quadratic Regulator (LQR) or Linear Quadratic Gaussian (LQG) control, aim to minimize a cost function while satisfying system dynamics and constraints. These techniques provide optimal control strategies for AUVs, considering performance objectives, control effort, and system constraints.
- *Neural network control:* Neural network-based control approaches leverage artificial neural networks to learn complex mappings between sensor inputs and control actions. These techniques can adapt to nonlinearities and uncertainties in AUV dynamics, enabling adaptive and data-driven control strategies.
- *Behavior-based control:* Behavior-based control architectures decompose control tasks into multiple behaviors or modules, each responsible for a specific aspect of AUV behavior. These behaviors are combined or selected based on environmental cues or mission requirements, allowing for flexible and adaptive control strategies.
- *Reinforcement learning (RL):* RL algorithms enable AUVs to learn control policies through interaction with the environment, maximizing cumulative rewards over time. RL techniques have shown promise in autonomous navigation, path planning, and task execution for AUVs operating in unknown or dynamic environments.

These control techniques can be tailored and combined to address specific challenges and requirements encountered in AUV missions, such as navigation in cluttered environments, obstacle avoidance, precision maneuvering, and cooperative operations with other underwater vehicles or marine assets. The selection of an appropriate control strategy depends on factors such as mission objectives, environmental conditions, system dynamics, and computational resources available onboard the AUV.

Robust Control Techniques for Autonomous Underwater Vehicles

Robust control strategies are essential for ensuring the reliable and stable performance of autonomous underwater vehicles (AUVs) in the presence of uncertainties, disturbances, and varying operating conditions. Here are some robust control strategies commonly employed in AUVs:

- *H∞ control:* H∞ control is a robust control technique that aims to minimize the worst-case sensitivity of the system to uncertainties and disturbances. It provides robust stability and performance guarantees by shaping the frequency response of the closed-loop system to attenuate disturbances and uncertainties within a specified bandwidth.

- *μ-synthesis:* μ-synthesis is a robust control technique that extends the H∞ control framework to handle systems with structured uncertainties. It involves synthesizing controllers by optimizing a performance criterion while ensuring robust stability and performance across a range of uncertain parameters.
- *Robust model predictive control (RMPC):* RMPC integrates robust optimization techniques with model predictive control to handle uncertainties and disturbances in real-time control applications. It formulates optimization problems with robust constraints and objectives, enabling AUVs to adaptively optimize control inputs while ensuring robust performance.
- *Sliding mode control (SMC):* SMC is a robust control technique that maintains stability by driving the system states to a sliding surface, where they are controlled using discontinuous control laws. SMC is particularly effective in handling uncertainties, disturbances, and bounded modeling errors, making it suitable for AUVs operating in harsh or uncertain environments.
- *Adaptive control:* Adaptive control techniques adjust controller parameters based on online estimates of system parameters or uncertainties. These techniques enable AUVs to adapt to varying operating conditions, parameter changes, or disturbances, ensuring robust performance and stability over time.
- *Fault-tolerant control (FTC):* FTC techniques aim to maintain system stability and performance in the presence of actuator or sensor faults. By reconfiguring control strategies or adjusting control inputs, FTC enables AUVs to mitigate the effects of faults and continue mission execution safely and reliably.
- *Decentralized control:* Decentralized control architectures distribute control tasks across multiple subsystems or modules, reducing dependencies and improving fault tolerance. By decentralizing control functions, AUVs can maintain stability and performance even in the presence of communication failures or subsystem faults.
- *Neural network-based control:* Neural network-based control approaches leverage machine learning techniques to learn complex mappings between sensor inputs and control actions. By training neural networks on historical data or simulations, these techniques can adapt to uncertainties and disturbances, providing robust control capabilities for AUVs.

By incorporating these robust control strategies into AUV control systems, engineers can enhance the reliability, stability, and performance of AUVs in challenging underwater environments, ultimately enabling safe and effective mission execution in real-world applications.

Protection Systems and Developments

Protection systems are integral to the safe operation and longevity of autonomous underwater vehicles (AUVs), especially in challenging and harsh environments. Here is an overview of protection systems and recent developments in AUV technology:

- *Hull Design*
  - AUVs often feature robust hull designs constructed from durable materials such as reinforced polymers or composites to withstand underwater pressure and impacts.
  - Advanced hull designs may incorporate streamlined shapes and hydrodynamic features to enhance maneuverability and reduce drag, improving overall efficiency and performance.
- *Pressure Compensation Systems*
  - Pressure compensation systems are essential for AUVs to maintain internal pressure equal to the external hydrostatic pressure experienced at different depths.
  - These systems typically include pressure-resistant enclosures for sensitive electronics, such as sensors, navigation systems, and communication equipment, ensuring their functionality and reliability in deep-sea environments.
- *Collision Avoidance Systems*
  - Collision avoidance systems utilize various sensors, including sonar, LiDAR, and cameras, to detect and avoid obstacles, underwater structures, and other AUVs in the vicinity.

  - Advanced algorithms and real-time processing capabilities enable AUVs to analyze sensor data, identify potential hazards, and autonomously adjust their trajectories to navigate safely in complex underwater environments.
- *Corrosion Protection*
  - Corrosion protection measures are implemented to safeguard AUV components and hulls from degradation caused by exposure to saltwater and marine environments.
  - Protective coatings, sacrificial anodes, and corrosion-resistant materials are commonly used to mitigate the effects of corrosion and extend the lifespan of critical AUV components.
- *Fault Tolerance and Redundancy*
  - AUVs may incorporate fault-tolerant designs and redundant systems to mitigate the impact of component failures or malfunctions.
  - Redundant propulsion systems, power sources, communication links, and navigation sensors can enhance system reliability and ensure mission continuity in the event of unexpected failures.
- *Environmental Monitoring*
  - Environmental monitoring systems enable AUVs to collect data on water quality, temperature, salinity, and other parameters to assess environmental conditions and potential threats to the vehicle.
  - Integration with onboard sensors and communication networks allows AUVs to transmit real-time environmental data to operators or remote monitoring stations for analysis and decision-making.

Recent developments in AUV technology have focused on enhancing protection systems through advancements in materials science, sensor technology, autonomy, and system integration. These developments aim to improve the robustness, reliability, and operational capabilities of AUVs in diverse underwater environments, expanding their potential applications in marine research, exploration, surveillance, and underwater inspection.

CONCLUSION

This review highlights the diverse control strategies applied to AUVs, emphasizing their strengths and limitations in real-world underwater operations. Classical control methods, such as PID and state feedback controllers, offer simplicity and reliability but struggle with complex underwater dynamics. Advanced methods like MPC and adaptive control improve robustness and predictive capabilities, while AI-driven techniques provide enhanced adaptability and decision-making in dynamic environments. Hybrid control frameworks combining these approaches show promise in overcoming individual limitations. Future research should focus on improving real-time adaptability, minimizing energy consumption, and integrating advanced machine learning models for self-optimization. AUV control strategies must continue evolving to meet the increasing demands of deep-sea exploration, surveillance, and environmental monitoring.

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Conflict of Interest

The authors declare no conflict of interest.

Ethical Approval

Not applicable.

Data Availability

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