A Review on Motion Control of the Underwater Vehicles

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Abstract

Unmanned Underwater Vehicles have gained popularity for the last decades, especially for the purpose of not risking human life in dangerous operations. On the other hand, underwater environment introduces numerous challenges in control, navigation and communication of such vehicles. Certainly, this fact makes the development of these vehicles more interesting and engineering-wise more attractive. In this review study, among the mentioned problems, we focus on the control of underwater vehicles, particularly the motion control. We try to summarize the evolution of the underwater vehicle motion control studies throughout the last two decades, and classify them.

1. Introduction

Studies on Unmanned Underwater Vehicles (UUVs) have showed a dramatic increase especially in the last two-three decades. Many examples of Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) were developed and used successfully on various applications, such as oceanographic surveys, bathymetric measurements, underwater maintenance activities (e.g. those performed at oil platforms, fiber optic communication lines, etc.) and military defense. The design of guidance and control systems of these vehicles requires knowledge of a broad field of disciplines, including vectorial kinematics and dynamics, hydrodynamics, navigation systems and control theory [1]. The main problems of the AUV control are the parametric uncertainties (e.g. added mass, hydrodynamic coefficients, etc.), non-linear and coupled dynamics [2]. In order to achieve a high degree of autonomy, several engineering problems associated with the high density, non-uniform and unstructured seawater environment (disturbances, etc.), and the nonlinear response of the vehicle must be considered and overcome [3].

2. Evolution of the Research Studies Regarding Underwater Vehicle Control

When the literature regarding the underwater vehicles is analyzed, it can be observed that the term ‘control’ addresses a broad range of research studies. To our belief, these studies can be classified under three main categories listed below and a schematic explanation is given in Fig. 1:

- Motion control: Focuses on subjects such as the platform response to an input and stability of a remotely operated/autonomous underwater vehicle,
- Mission control: Focuses on the execution of the behavioral modeling of an autonomous underwater platform, where this behavior is predefined parametrically,
- Formation control: Focuses on coordinated behavior of multiple autonomous underwater vehicles (i.e. swarms or platoons),

where motion control has been under investigation of several researchers especially since the pioneering studies of Fossen and Sagatun [4]. Initial solid contributions on this topic, which constitute the main focus of this review study, have been published in early 1990s. That decade later witnessed the studies regarding motion control; and in the current decade, concentration has increased on the improvement of swarm formations.

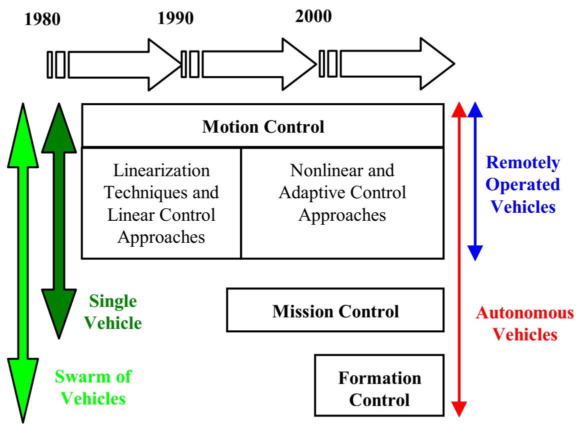

Fig. 1. Studies on motion control

2.1. General Notation for the Motion of Marine Vehicles

The motion of marine vehicles can be described in 6 degrees of freedom (DOF), since 6 independent coordinates are necessary to determine the position and orientation of a rigid body. The 6 different motion components are defined as ‘surge’, ‘sway’, ‘heave’, ‘roll’, ‘pitch’ and ‘yaw’, as shown in Table 1.

When analyzing the motion of marine vehicles in 6 DOF, it is convenient to define two coordinate frames as indicated in Fig. 2. The moving coordinate frame $X_0Y_0Z_0$ is fixed to the vehicle and referred to as ‘the body-fixed reference frame’. The origin O of the body-fixed frame is usually chosen to coincide with the ‘center of gravity (CG)’, when CG is in the principal plane of symmetry or at any other convenient point if this is not the case.

Table 1. Notation used for the marine vehicles

DOF		forces and moments	linear and angular vel.	positions and Euler angles
1	motions in the *x*-direction (surge)	X	u	x
2	motions in the *y*-direction (sway)	Y	v	y
3	motions in the *z*-direction (heave)	Z	w	z
4	rotation about *x*-axis (roll)	K	p	ϕ
5	rotation about *y*-axis (pitch)	M	q	θ
6	rotation about *z*-axis (yaw)	N	r	ψ

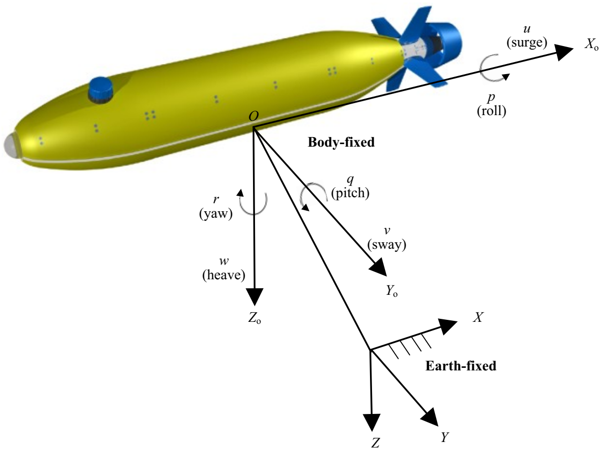

Fig. 2. Body-fixed and earth-fixed reference frames

The motion of the body-fixed frame is described relative to an inertial reference frame. For marine vehicles, it is usually assumed that the accelerations of a point on the surface of the Earth can be neglected. As a matter of fact, since the motion of the Earth hardly affects the marine vehicles due to their low speeds, this can be considered as a good approximation. As a result of this, an 'earth-fixed reference frame' *XYZ* can be considered to be inertial. This implies the following:

- the position and orientation of the vehicle should be described relative to the inertial reference frame;
- the linear and angular velocities of the vehicle should be expressed in the body-fixed coordinate system.

Based on the notation shown in Table 1, the general motion of a marine vehicle in 6 DOF can be described by the following vectors [1]:

$$\eta = [\eta_1^T, \eta_2^T]^T$$
$$\text{where } \eta_1 = [x, y, z]^T \text{ and } \eta_2 = [\phi, \theta, \psi]^T \quad (1)$$

$$\upsilon = [\upsilon_1^T, \upsilon_2^T]^T$$
$$\text{where } \upsilon_1 = [u, v, w]^T \text{ and } \upsilon_2 = [p, q, r]^T \quad (2)$$

$$\tau = [\tau_1^T, \tau_2^T]^T$$
$$\text{where } \tau_1 = [X, Y, Z]^T \text{ and } \tau_2 = [K, M, N]^T \quad (3)$$

Throughout Eq.s(1)-(3), η denotes the position and orientation vector with coordinates in the earth-fixed frame, υ denotes the linear and angular velocity vector with coordinates in the body-fixed frame and τ is used to describe the forces and moments acting on the vehicle in the body-fixed frame.

The rotation sequence according to the *xyz*-convention showing both the linear (u, v, w) and angular (p, q, r) velocities, is depicted in Fig. 3.

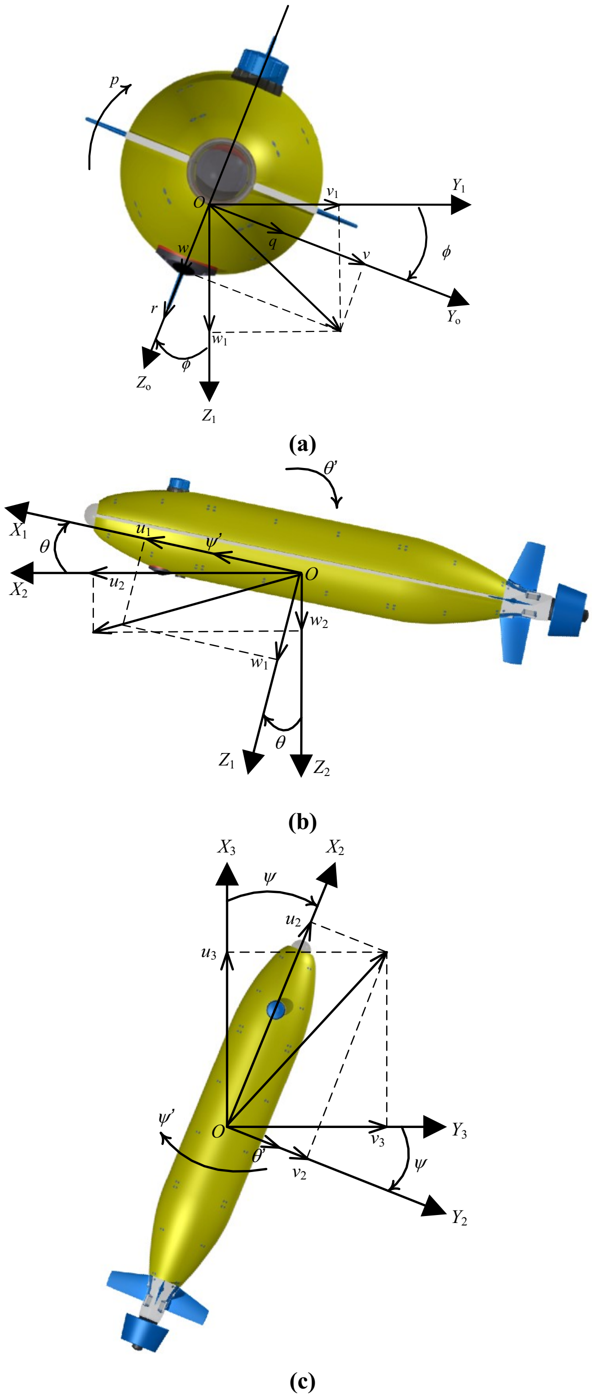

Fig. 3. Rotation sequence according to the *xyz*-convention
(a) Rotation over roll angle ϕ about X_1 ($u_1 = u_2$)

(b) Rotation over pitch angle θ about Y_2 ($v_2 = v_1$)
(c) Rotation over heading angle ψ about Z_3 ($w_3 = w_2$)

2.2. Stability of Underwater Vehicles

Stability of an underwater vehicle can be defined as “the ability of returning to an equilibrium state of motion after a disturbance without any corrective action, such as use of thruster power or control surfaces” [1]. Hence, maneuverability can be defined as the capability of the vehicle to carry out specific maneuvers.

At this point, the following issue about the stability shall be emphasized. Excessive stability implies very high control effort; whereas it would be easy to control a marginally stable vehicle. Consequently, there exists a compromise between stability and maneuverability. Furthermore, it makes sense to distinguish between controls-fixed (open-loop) and controls-free (closed-loop) stability. The essential difference between these terms can be stated as follows [1]:

- Open-loop stability implies investigating the vehicle’s stability when the control surfaces are fixed, and when the thrust from all the thrusters is constant.
- Closed-loop stability refers to the case when both the control surfaces and the thruster power are allowed to vary. This implies that the dynamics of the control system must also be considered in the stability analysis.

3. Motion Control of Underwater Vehicles

In the presence of environmental disturbances, improved robustness and performance for an underwater vehicle can be achieved using closed-loop control system of PID-type (proportional, derivative and integral) instead of an open-loop control scheme. In closed-loop control approach, sensor and navigation data are used for feedback. Using a series of controllers of PID-type where each controller is designed for the control of one DOF is a well-known practice for the conventional autopilot design of remotely operated underwater vehicles.

Traditionally, PID controllers used to be applied for the ROV systems. However, most ROV systems for offshore applications used only simple P- and PI-controllers, since derivative action was very sensitive to measurement noise and it was difficult to measure (estimate) the velocity vector. It should be noted that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability, since the system to be controlled shows highly nonlinear behavior for the underwater vehicle case.

In the early 1990s, decoupled control design approach was mainly applied to unmanned underwater vehicles control problem [5]. In such studies, the main approach was to divide the 6 DOF linear equations of motion into three non-interacting (or loosely interacting) subsystems for speed control, steering and diving. Several closed-loop PID-controllers were used for each of the subsystems [6].

The basic tasks in autonomous underwater systems are depth and steering control. Numerous control strategies have been adopted; certainly, all of them have advantages and disadvantages. It is possible to classify the algorithms into two main groups: Linear and Nonlinear [2].

1) Linear methods: They are designed by using a vehicle’s linear model, identified in a specific behavior case (nominal forward speed, angle of attack, etc.). These methods enable to control easily a vehicle, but they work in specific conditions and model nonlinearities are not considered. The PID-based methods mentioned in the previous paragraphs also fall into this category, since the mathematical operators applied in these methods (e.g. proportion, integration, differentiation) are linear. An example for the application of PID control to the underwater vehicles is [7]. A modified PD, namely the ‘decoupled PD set-point controller’ for UUVs is presented in [8].

Another approach falling into the linear control category is the Linear-Quadratic-Gaussian (LQG) method, which is suitable for uncertain linear systems disturbed by:
- additive white Gaussian noise,
- incomplete state information (i.e. not all the state variables are measured and available for feedback) ,

where the available state information is also disturbed by additive white Gaussian noise and quadratic costs. This method was applied to the underwater vehicle control problem in [9].

2) Nonlinear methods: In the literature, the nonlinear control methods have been applied for particular problems and specific unmanned vehicles developed throughout various research projects. Among those, one of the most commonly used methodologies is the Sliding Mode Control (SMC), a robust control scheme in case of parameter uncertainties.

Even though SMC is a nonlinear control method, several studies (such as [6] and [10]) still assume linear vehicle model in the nominal control. Another example of SMC using a simplified nonlinear vehicle model for the nominal control is [11]. The main drawback of SMC is the chattering effect, which can excite un-modeled high frequency modes. These modes degrade the performance of the system, and may even lead to instability. Chattering also leads to high wear of fins and increase electrical power consumption. A chattering-free SMC is proposed for the trajectory control of ROVs in [12].

Later, other approaches, which use full nonlinear model, have been proposed. Particularly in [2], Lyapunov and back stepping techniques are used. In [13], PI-type task functions enabling a conventional Lyapunov-based guidance system to counteract the effects both of unmodeled, i.e., unmeasured kinematic interactions between an UUV and the environment, and of bias in velocity measurements, is introduced. An adaptive nonlinear controller based on traditional back stepping method for diving control of an AUV is presented in [14]. In [2], a method called Higher Order Sliding Mode (HOSM) is implemented in order to avoid the chattering problem and to improve control performance. A nonlinear output-feedback control technique based on the HOSM approach is applied to the motion control problem for an underwater vehicle prototype that is equipped with a special propulsion system based on hydro-jets with variable-section nozzles and the results are presented in [15].

Due to the challenging nature of the underwater vehicle control problem, researchers have been continuing to pursue (general or ad-hoc) novel approaches for the solution throughout the last and the current decades. Regarding their strength and robustness, recent studies have concentrated on intelligent and/or adaptive control methods. State of the art publications on this topic apply neural network based, fuzzy reasoning oriented, even the hybrids of these methods.

Due to their capability of estimating various mathematical functions, including highly nonlinear functions, neural networks are powerful tools. Furthermore, in many cases, such networks can be trained to adapt to changing input-output relationships.

Hence, neural networks may have a great potential in control systems for nonlinear and unknown systems, such as AUVs [16].

In addition to handling nonlinearity, several other properties of the neural networks make them suitable for control purposes [16]:

- Parallel structure: The parallel structure of neural networks, which facilitates the construction of parallel implementation of control systems, yields robust and fast processing systems.
- Applicability to hardware implementation: Neural networks can easily be implemented in hardware. A number of integrated circuits (IC) for artificial neural networks (ANN) purposes are available in the market.
- Multivariable nature: Their potential ability to correctly map functions with many inputs and outputs make neural networks interesting for the control of multivariable systems.

Several different neural network controller schemes have been suggested and implemented in the past [16], some of which have been particularly applied to the underwater vehicle control problem:

1. Identification and modeling:
   (a) Forward Modeling;
   (b) Direct Inverse Modeling; and
   (c) Indirect Inverse Modeling.
2. Direct control:
   (a) Supervised Control;
   (b) Direct Inverse Control;
   (c) Model Reference Control;
   (d) Critic Control;
   (e) Internal Model Control; and
   (f) Predictive Control.

Offline learning method has been a simple but a common way of implementing control systems utilizing neural networks. Since the neural network controller is first trained prior to use (analogous to tuning of a conventional controller), the speed of the resulting network is generally considered to be high enough. During runtime, no weight adjustments take place and the response of the controller is rapid. However, the resulting controller is not adaptive, and hence inaccuracies in the network weights or changes in system parameters are likely to result in poor performance of the controller system.

Continuously updating the neural network weights while the controller is in use, is a very powerful alternative to offline training. In adaptive (or online trained) neural network controllers, initially a measure of the system performance is set up, and the controller weights are adjusted in a manner which improves this performance, generally through minimizing some output error. The main challenges of this approach are calculating the optimal weight changes from the system input and output as well as the reference trajectory for the system and ensuring the stability.

In literature, it is observed that most of the network controllers designed for AUVs are direct controllers constituting the main part of the control system. Offline trained, non-adaptive AUV neural network controllers are presented in [17, 18], and online controllers are proposed in [19-25].

In order to have effective robust controllers for various applications, fuzzy logic controllers are being developed and used. It is logical to design a fuzzy controller, if the dynamics of the controlled system is fully known. For motion control of underwater vehicles, fuzzy logic control is presented in [26-28], and the sliding mode fuzzy logic control is presented in [29, 30].

4. Conclusions

Control problems of autonomous underwater vehicles (AUVs) bring out several difficulties, due to their non-linear dynamics, the presence of disturbance, and observation noises. Particularly in shallow, confined water areas, shallow water phenomena from the interaction among wave dynamics, tidal currents, coastal currents, and artificial objects create a complex environment for operating unmanned underwater vehicles. Therefore, controlling AUVs to satisfactorily track trajectories in shallow waters remains a challenge [30].

For controlling the motion of underwater vehicles, various control strategies have been developed in years, such as PID, LQG, SMC, neural network, fuzzy logic, SM fuzzy logic controllers, etc. As new control system strategies are being developed, researchers apply those to motion control problem of underwater vehicles. Regarding motion control of underwater vehicles, utilization of more advanced system control systems is inevitable in order to design more intelligent, adaptive, and robust controllers that provide optimal control solution in terms of non-linearity handling, and cost minimization.

3 (three) different national underwater vehicles are being developed by ‘TR Technology Inc.’:

- ROV: Remotely operated underwater vehicle that is under development. It is essentially an unmanned underwater vehicle (UUV) that allows the vehicle’s operator to remain in a comfortable environment while the ROV works in the hazardous undersea environment below.
- Single Shot ROV (SSR) Çanakkale: The SSR Çanakkale provides Mine Countermeasures (MCM) and Time Critical Strike (TCS) and is in fact, a ‘one-shot’ mine destructor remotely operated vehicle.
- AUV Barbaros: This is an autonomous underwater vehicle. It provides: Intelligence, Surveillance and Reconnaissance (ISR), Mine Countermeasures (MCM), Anti-Submarine Warfare (ASW), Inspection/Identification, Oceanography, Communication/Navigation Network Nodes (CN3), Information Operations (IO), Barrier Patrol (Homeland Defense, Anti-Terrorism/Force Protection), and Barrier Patrol (Sea Base support).

Underwater vehicles that are being developed by ‘TR Technology Inc.’, differ from each other in terms of:

- Autonomy,
- Navigations aids, sensors, payload,
- Application area (purpose),
- Mission duration,
- Thruster configuration,
- Energy and fuel capacity,
- Processing power,
- etc.

Obviously, each underwater vehicle should have a motion control system specific to its characteristics and needs. Although, numerous control strategies which were successfully applied for the motion control problem of underwater vehicles exist and are literally accurate, it is hard to determine which approach is the most suitable and furthermore applicable to our cases. Not only for the motion, but also for the mission and formation control, the most optimal algorithms should be adopted and strategies should be carefully chosen in order to acquire robust underwater vehicles that will perform critical applications. For the time being, navigation and motion modeling problems of these vehicles have been solved, and motion control structure is being developed.

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